Ventilation Systems and their Impact on Indoor Climate and Energy Use in Schools

Studies of air filters and ventilation control

by
Mads Mysen

Norwegian Building Research Institute
RTD dept. Building Services

and

Norwegian University of Science and Technology
Department of Energy and Process Technology

Thesis submitted in partial fulfilment of the requirements for the degree of
Doktor Ingeniør

at

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Energy and Process Engineering

June 2005

ACKNOWLEDGEMENTS

This work was carried out at the Norwegian Building Research Institute in Oslo during 2001-2005 and supported by the same institute and by the Norwegian Research Council as a part of the research program “Environmentally favorable energy use in buildings”.

I am indebted to the Norwegian Building Research Institute for giving me this opportunity, and to my supervisors and co-authors prof. Per Olaf Tjelflaat and dr.ing Peter Schild and to all the other co-authors, Knut Inge Fostervold, Geo Clausen, Gabriel Bekö, Oto Halás, Sveinung Berntsen, Per Nafstad, James Rydock, Vidar Hellstrand and Kari Thunshelle, for their valuable contributions.

I am grateful to the International Centre of Indoor Environment and Energy at DTU in Copenhagen for receiving me as a guest student the first half of 2003, and to Nordic Academy of Advanced Study (NorFA), Norsk VVS stiftelse for forskning and Fondet for Dansk-Norsk Samarbejde for making the stay at the Centre economical possible.

I also wish to express my gratitude to the all the schools and pupils that has repeatedly filled in questionnaires and tiring performance tests.

But above all, I am grateful to my wise and patient wife Tonje, and to my children Ingvild and Anders.

SUMMARY

Indoor environment in schools is of particular public concern and there is a need for extensive upgrading of school buildings in Norway. The choice of ventilation systems for improving indoor climate is one of the main issues when retrofitting or building new schools. It has a major impact on investment- and running costs and area- and volume use. Several schools are recently built with alternative ventilation systems. The basis for this dissertation was to see if such solutions have any main effects on the indoor climate and energy use compared with conventional balanced ventilation and hopefully find the major causes of any differences.

Several studies are conducted. These are based on different approaches such as use of questionnaires among pupils, field measurements, field interventions, laboratory experiments and theoretical considerations. Sufficient conclusive studies are reported in seven different papers addressing the following issues:

- Effect of conventional filtration techniques on perceived air quality and indoor-air related symptoms
- Cooling performance of ground-coupled ducts
- Effect of demand-controlled ventilation on energy use and indoor climate
- Air supply through the façade in a cold climate

One factor of major influence on the perceived air quality (PAQ) is the presence of used bag air filters in the supply air path. Pupils' PAQ in 16 classrooms with filtered supply air has been compared with corresponding PAQ in 10 classrooms without air filters in the supply air path. The air quality was perceived to be significantly better in the classrooms without filtration. This result was confirmed by a refined experimental design conducted in a school where the supply air filters were removed for one week. Removing the used air filters

significantly improved PAQ. PAQ returned to its original level when the same air filters were put back one week later.

These results demonstrate that conventional use of bag air filter can contribute with a significant pollution load to the indoor air even in well functioning ventilation systems. These results do not challenge the benefits of air filtration with respect to removing particles from the supply air, but it demonstrates that normal use of bag-filters are associated with negative by-effects influencing the quality of supply air and the indoor climate. This is consistent with results from field studies in other type of buildings and studies conducted in controlled laboratory environment. Conventional practice on documenting filter performance is inadequate because it does not take into account emissions from particles trapped in supply air bag-filters. These emissions deteriorate the air quality. This implicates a need to improve standards and filtration products for comfort ventilation. Outdoor air filtration is of crucial importance for protecting air-handling units and removal of filter is not meant as a practical measure for improving PAQ.

Turning the air-handling unit (AHU) off, or reducing the airflow outside school hours implies a further elevation of the pollution load from the used bag air filters the initial period after the AHU is turned back on. An AHU with used bag filters should be switched on at least two hours before the occupants enter the ventilated areas.

Another factor with major influence on PAQ and thermal comfort is indoor air temperature. Measurements at two Norwegian schools show that sufficient temperature control can be achieved with ground-coupled fresh air intake ducts in climates with cool night temperatures. Air-cooling with this method requires a culvert surface area of 1-2 m^2/pupil and forced ventilation at nights to cool down the thermal mass in the ground-coupled duct. This cooling method is well suited for handling considerable peak loads.

All the investigated alternative ventilation systems have some sort of demand-controlled ventilation (DCV). DCV considerably reduces the ventilation airflow rates and energy use compared to constant air volume (CAV) ventilation system. This conclusion is based on an inspection of 157 classrooms in primary schools. In average 74% of the design capacity is utilized when the classroom is in use, in terms of number of occupants. The classrooms are typically used for four hours during days with normal school activity. CO_2-sensor based DCV reduces the ventilation air volume in the average classroom to about 43% of the corresponding air volume for a CAV-system operating with full airflow from 7 AM to 5 PM. The energy use for ventilation purposes is reduced to about 38% of the corresponding energy use for a CAV-system. Comparison of perceived indoor climate in schools with CAV-systems and DCV-systems does not indicate that CAV-systems add extra quality to the indoor climate. The purpose of extra ventilation with CAV-systems is therefore questionable as it leads to additional energy use.

A ventilation system with air supply through the façade in a cold climate has been evaluated. The supplied airflow rate was controlled to prevent the CO_2 concentration exceeding 800 ppmv (DCV). It was no heating of the supply air. The indoor thermal climate was not satisfactory on days with low outdoor air temperature. Use of DCV with a combined CO_2- and temperature target seems more appropriate for such ventilation concepts. Further evaluation of an improved solution is needed before such a ventilation concept can be recommended in cold climates.

SAMMENDRAG

Innemiljø i skoler har stor samfunnsmessig betydning og det er behov for en omfattende oppgradering av skolebygninger i Norge. Valg av ventilasjonssystem for å forbedre inneklima er et av hovedtemaene ved rehabilitering og bygging av skoler. Det har stor innvirkning på plassbehov, investerings- og driftskostnader. Mange skoler har den senere tiden blitt bygget med utradisjonelle ventilasjonssystemer. Utgangspunktet for denne avhandlingen var å se om slike alternative løsninger påvirker inneklima og energibruk i forhold til vanlig kanalbasert ventilasjon og forhåpentligvis finne hovedårsakene til eventuelle forskjeller.

En rekke studier er gjennomført. Disse er basert på forskjellige fremgangsmåter som bruk av spørreskjemaer blant elever, feltmålinger, felt intervensjoner, laboratorieforsøk og teoretiske betraktninger. Tilstrekkelige konkluderende resultater er rapportert i sju vitenskaplige artikler innenfor følgende temaer:

- Posefilterets betydning på oppfattet luftkvalitet og innemiljørelaterte plager
- Passiv luftkjøling fra kulverter
- Behovstyrt ventilasjon sin betydning på energibruk og inneklima
- Lufttilførsel direkte gjennom fasaden i et kaldt klima

En faktor av stor betydning for oppfattet luftkvalitet er filtrering gjennom brukt posefilter. Oppfattet luftkvalitet i 16 klasserom med filtrert tilluft er sammenlignet med oppfattet luftkvalitet i 10 klasserom uten filtrert tilluft. Oppfattet luftkvalitet var signifikant bedre i klasserom uten filtrert tilluft. Dette resultatet ble bekreftet med et raffinert eksperiment i en skole hvor det brukte tilluftsfilteret ble tatt ut i en uke. Fjerning av filteret ga en signifikant forbedring av oppfattet luftkvalitet. Oppfattet luftkvalitet falt tilbake til sitt opprinnelige nivå når filteret ble satt tilbake i tilluftsstrømmen.

Disse resultatene viser at filteret i praksis kan bidra til merkbar reduksjon av oppfattet luftkvalitet selv om ventilasjonsanlegget har en normalt god funksjon. Dette gir ikke grunnlag for å betvile fordelene med å filtrere bort partikler fra tilluften, men resultatene viser at normal bruk av posefilter har negative tilleggseffekter som påvirker kvaliteten på tilluften og inneklima. Dette er i samsvar med resultater fra feltstudier i andre typer bygninger og studier gjennomført i et kontrollert laboratoriemiljø. Gjeldende standarder for å dokumentere filterytelse er ikke adekvate fordi de ikke tar hensyn til emisjoner fra partikler som fanges opp i filteret. Disse emisjonene forringer luftkvaliteten. Dette viser at det er et stort behov for å forbedre standarder og filtreringsprodukter for komfortventilasjon. Filtrering av uteluft er av avgjørende betydning for å beskytte luftbehandlingsaggregatet og fjerning av filteret er ikke ment som et praktisk tiltak for å forbedre oppfattet luftkvalitet.

Skrur man av luftbehandlingsaggregatet, eller reduserer luftmengden utenom brukstid, får man en ytterligere økning av det sensoriske forurensningsnivået forårsaket av det brukte posefilteret, når luftbehandlingsaggregatet slås på igjen. Ventilasjonsanlegg med brukt tilluftsfilter bør startes minst to timer før lokalene tas i bruk.

En annen faktor av stor betydning for oppfattet luftkvalitet og termisk komfort er innetemperaturen. Målinger på to norske skoler viser at tilstrekkelig temperaturkontroll kan oppnås ved hjelp av nedgravde luftinntakskulverter i klima med kjølig natt-temperatur. Luftkjøling med denne metoden krever en innvendig kulvertoverflate på 1-2 m^2/elev og forsert natt-ventilasjon for å kjøle ned den termiske massen i kulverten. Slik kulvertkjøling kan håndtere store effekttopper.

Alle de undersøkte utradisjonelle ventilasjonsystemene hadde en eller annen form for behovsstyrt ventilasjon (DCV). Slik behovsstyring kan redusere luftmengdene betydelig i forhold til anlegg med konstant luftmengde (CAV). Denne konklusjonen er basert på en inspeksjon av 157 klasserom i barneskolen. I gjennomsnitt blir 74% av dimensjonerende kapasitet utnyttet når klasserommet er i bruk. Gjennomsnittlig brukstid av klasserommene er fire timer på vanlige skoledager. CO_2-kontrollert behovstyring reduserer ventilasjonsluftmengden i det gjennomsnittlig klasserommet til ca 43% av tilsvarende luftmengde ved CAV-ventilasjon som går med full luftmengde fra klokken 7 til 17. Energibruk til ventilasjonsformål blir redusert til 38% av tilsvarende energibruk med et CAV-anlegg. Sammenligning av oppfattet luftkvalitet i skoler med CAV-anlegg og DCV-anlegg tilsier ikke at CAV-anlegg gir bedre inneklima. Formålet med økt ventilasjon med CAV-anlegg er derfor tvilsom siden dette medfører ekstra energibruk.

Et ventilasjonsanlegg med direkte tilførsel av uoppvarmet tilluft gjennom fasaden har blitt evaluert. Tilført luftmengde ble styrt i forhold til et maksimalt CO_2-nivå på 800 ppmv (behovstyrt ventilasjon). Dette ga ikke tilfredsstillende termisk inneklima på kalde dager. Styring mot et kombinert CO_2- og temperaturmål ville sannsynligvis gitt et bedre totalresultat. Det er behov for ytterligere evaluering av en forbedret løsning før slike ventilasjonskonsepter kan anbefales i kaldt klima.

PREFACE

This *doktor ingeniør* study has been a part of the research program "Environmentally favourable energy use in buildings", established at Norwegian Building Research Institute year 2000, and supported by the Norwegian Research Council.

Prior to this study, I worked as a researcher at the Norwegian Building Research Institute from 1997, and as a HVAC-engineer in Techno Consult AS from 1990 to 1997. I received my Master of Science degree in 1989 at the Norwegian University of Science and Technology, Department of Refrigeration and Air Conditioning.

This dissertation is based on seven papers, of which five are journal papers and two are conference papers. Two of the journal papers are published, one is accepted for publication, while the last two are submitted for publication (status April 2005).

Authorship

I hold the 1st authorship in all seven papers and I am primarily responsible for the scientific quality, originality of ideas, study design, accuracy of the data, and quality of reporting. I am primarily responsible for the scientific quality of this dissertation.

Originality

Several elements in this dissertation can be considered as original contributions to knowledge.

- Effect of bag air filters on perceived air quality and indoor-air related health symptoms in real school environment.
- Impact of different operation strategies of the air-handling unit on the sensory pollution load emitted by used supply air filters.
- Utilization of classrooms and benefits of demand-controlled ventilation in schools.
- Practical method for analysing energy use and profitability with demand-controlled ventilation.
- Cooling potential of ground coupled supply air ducts and practical guidelines for optimum design.
- Utilization of façade supply ventilation system in a cold climate.

Basis for the dissertation

This dissertation is based on seven different studies, presented in the following papers, which are reprinted or printed in the latter part of this dissertation:

Paper I	Mysen M, Fostervold KI, Schild PG. A questionnaire survey of the impact of used supply air filter on health symptoms and perceived air quality in schools. *Submitted for publication.*
Paper II	Mysen M, Fostervold KI, Schild PG. An intervention study of the impact of supply air filters on perceived air quality and health symptoms in a primary school. *Submitted for publication.*
Paper III	Mysen M, Clausen G, Bekö G, Halás O. The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters. In: *Proceedings of Healthy Buildings 2003*, Vol. 3, pp. 267-272.
Paper IV	Mysen M, Berntsen S, Nafstad P, Schild PG. Occupancy density and benefits of demand controlled ventilation in Norwegian primary schools. *Accepted for publication in Energy and Buildings.*
Paper V	Mysen M, Rydock JP, Tjelflaat PO. Demand controlled ventilation for office cubicles – can it be profitable? Energy and Buildings **35** (2003) pp. 657-662.
Paper VI	Mysen M, Schild PG, Hellstrand V, Thunshelle K. Evaluation of simplified ventilation system with direct air supply through the façade in a school in a cold climate. Energy and Buildings, **37** (2005), pp. 157-166.
Paper VII	Mysen M, Schild PG, Tjelflaat PO. Cooling performance of ground-coupled air intake ducts. In: *Proceedings of HVAC Cold Climate 2003*, Paper 83.

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1 INTRODUCTION

1.1 Background

Public concern about adverse health effects of indoor air has increased in recent decades, beginning with episodes during the 1970s in which occupants of residents and commercial and institutional buildings reported health problems associated with their buildings [1,2]. Wider recognition of this problem has also produced concern that health problems due to poor indoor environment may reduce the performance of occupants in buildings [3]. Indoor environment in schools has been of particular public concern for three primary reasons:

1. Schools, relative to other kinds of buildings, are seen as particularly likely to have environmental deficiencies because chronic shortage of funding contributes to inadequate operation and maintenance of facilities [4,5,6].
2. Children have greater susceptibility to some environmental pollutants than adults, because they breath higher volumes of air relative to their body weight and their tissues and organs are actively growing [7,8].
3. Children have higher allergy prevalence than the rest of the population since half the allergies experienced in childhood are resolved by the age of 30 [9].

There is a need for extensive upgrading of school buildings in Norway. This is caused by several factors like new standards regarding indoor climate and pedagogical development affecting the built learning environment in schools, together with poor maintenance of official buildings over many years. The cost of this upgrading was in 2002 estimated to 40 billions NOK [6]. The choice of ventilation systems for improving indoor climate is one of the main issues when retrofitting or building new schools. It has a major impact on investment- and running costs, and area- and volume use.

Several schools have recently been built with alternative ventilation systems. The consequences of these alternative solutions regarding indoor air climate and energy use are disputed [10]. This shows a need for more knowledge within the field of indoor environment in schools. The need for this is especially well documented by Mendell [2]. Comprehensive field studies in different parts of the world have demonstrated that a high percentage of occupants find indoor air quality unacceptable and have a high prevalence of indoor-air related health symptoms [11]. This occurs even though existing guidelines for thermal comfort and indoor air quality are met and measured concentrations of pollutants in the air are far below limits or guideline values.

1.2 Hierarchy of design needs for ventilation system

The main purpose of a school and its technical installations is to provide an environment that is acceptable and does not impair health and performance of the pupils and working staff, without unnecessary use of energy. The design needs for a ventilation system can be placed in a hierarchy [12] based on the same principles as Maslow's hierarchy of human needs [13].

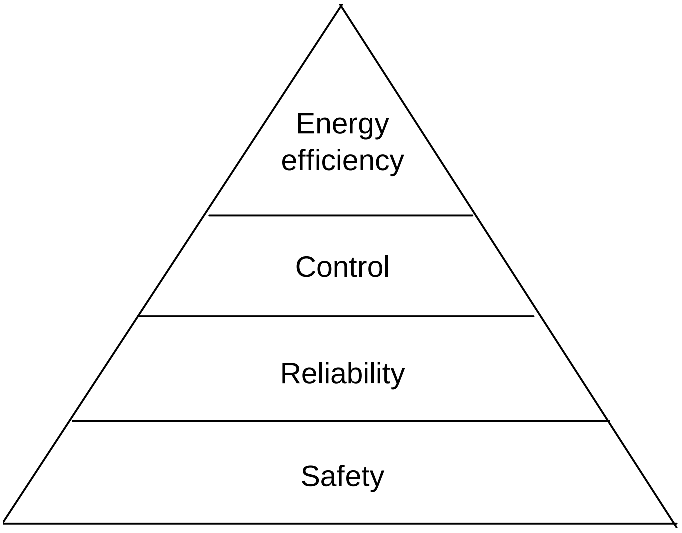

Figure 1. The hierarchy of design needs for ventilation systems.

Safety is the lowest level. This can be defined as a measure of how secure a piece of equipment or the system is from threat of loss, danger or harm. **Reliability** is a measure of the stability, dependability and capability of a piece of equipment or system *to continuously perform its intended function* at all required operating conditions. **Control** is a measure of a piece of equipment's or system's ability to accurately restrict or constrain selected HVAC-variables such as temperature, air velocities and air flow rates within their intended range. **Energy efficiency** is the last of the design needs.

Robustness is included in the reliability aspect. Robustness is a measure of how well the system lives up to its design purpose in a real life situation [14]. Robust systems are insensitive to violations of their assumptions, appearing in real life situations.

Reliability throughout the lifetime of the system is a more basic design need for a ventilation system than to satisfactorily maintain a limited number of control parameters. It is likely that a more restricted range of HVAC-variables like temperatures and air flow rates will influence the complexity of the ventilation system. This again might influence the reliability and functional availability of the ventilation system. The choice of design criteria for indoor climate should not circumvent any reliability requirements. Neither should design criteria for energy efficiency circumvent health and environment requirements. Energy efficiency can first be addressed when the system is safe, reliable and sufficiently controlled for achieving a good indoor climate.

The need for preventive maintenance is important for the continuous well-functioning of any kind of ventilation systems. The consequences of periods of insufficient maintenance will however depend on the system design, making it beneficial to have systems where it is easy to re-establish its intended function after such a period. Failure can occur for all kinds of systems, and it will take time to re-establish the intended operational state. This time will probably be influenced by the system design, making it beneficial to have systems where it is easy to detect and diagnose faults and easy and cheap to repair them. It is not in the scope of this dissertation to go into the depth of any reliability differences of different ventilation systems in school buildings. Myrefelt [15] has however shown that system reliability depends strongly on the technical solutions and the number of components. More components gives a lower reliability in most cases, forming a rational basis for evaluating alternative ventilation system with a possible reduced complexity relative to conventionally designed ventilation systems.

1.3 Conventional design approach for ventilations systems

The conventional design approach in building projects is based on control towards selected indoor climate parameters and energy efficiency. Measurable design criteria for thermal comfort, indoor air quality (i.e air flow rates) and energy use are implemented in the bidding terms of the project, to ensure that the building and its technical installations gets the requested quality. These bidding terms are based on national and international standards and guidelines, and lead to specific constraints (regarding indoor air temperatures, air velocities and target values for particle filtration efficiency, specific ventilation air flow rates, energy use, etc). An example of an internationally approved standard for ventilation system design is CR 1752 [16]. This standard gives a set of design criteria for the indoor environment related to different levels of indoor air quality.

Criteria's towards robustness, operational reliability like fault detection and functionality re-establishment are seldom specified. The design approach is, in other words, based on the top levels of the hierarchy of design needs for ventilation systems.

1.4 Description of the conventional ventilation concept used in schools

Normal use of bidding terms based on accepted design criteria, leads in most cases to a conventional ventilation solution. The evolution of such a ventilation system is adapted to the corresponding evolution of the design criteria, or vice versa. Making them simple to specify in a precise way. Further, it is easy to control if the design criteria are met, and it is easy to document that the system satisfies national requirements for such systems.

The conventional ventilation solution in Norwegian schools is balanced mechanical ventilation (BMV) with filtered, heated air, distributed in sheet metal air ducts. Bag-filter, typically fibreglass class F7, is used in 90-95% of the comfort ventilation systems in Norway [17]. Heat is recovered from the exhaust air in an energy-efficient way to minimize the need for additional heating of the ventilation air. The supply air is based on 100% outdoor air. It is not normal to apply mechanical cooling in HVAC-systems for school facilities in Norway. The main HVAC-components are placed in a standard air-handling unit (AHU). It is normal to provide a standard classroom with 270 to 330 ℓ/s. This air volume is based on the following assumptions.

- The Norwegian building regulations require at least 2 m^2 for each occupant, or a maximum occupancy density of 0.5 pupils/m^2 [18].
- Classrooms in Norway are traditionally sized for a maximum of 28 pupils and two teachers, which implies a required area of 60 m^2.

- The building regulations suggest a ventilation rate of 7 ℓ/s for each occupant, with an additional 0.7 to 2.0 ℓ/s·m² depending on the expected emissions from the building materials and fittings [19].

This airflow rate is kept constant during the operational hours of the air-handling unit (Constant Air Volume). Enova [20] suggests an operation time for CAV-systems of 11 hours/day and 188 days/year in schools.

1.5 Description of alternative ventilation concepts used in schools

Several schools in Sweden, and some schools in Norway, are built with alternative ventilation concepts. The two most common alternative solutions in Norway are denoted as (i) Hybrid ventilation and (ii) Façade ventilation in this dissertation.

Hybrid ventilation is defined here as a balanced mechanical ventilation system designed for utilizing natural driving forces with a ground-coupled concrete duct (culvert) where the fresh supply air passes with very low air velocity (Figure 2). The use of air filters is optional. A heat exchanger, or additional heating-coil, heats the air for thermal comfort reasons. The ventilation flow rates are controlled by the principle of Demand Controlled Ventilation (DCV) and designed for displacement ventilation of the occupied areas.

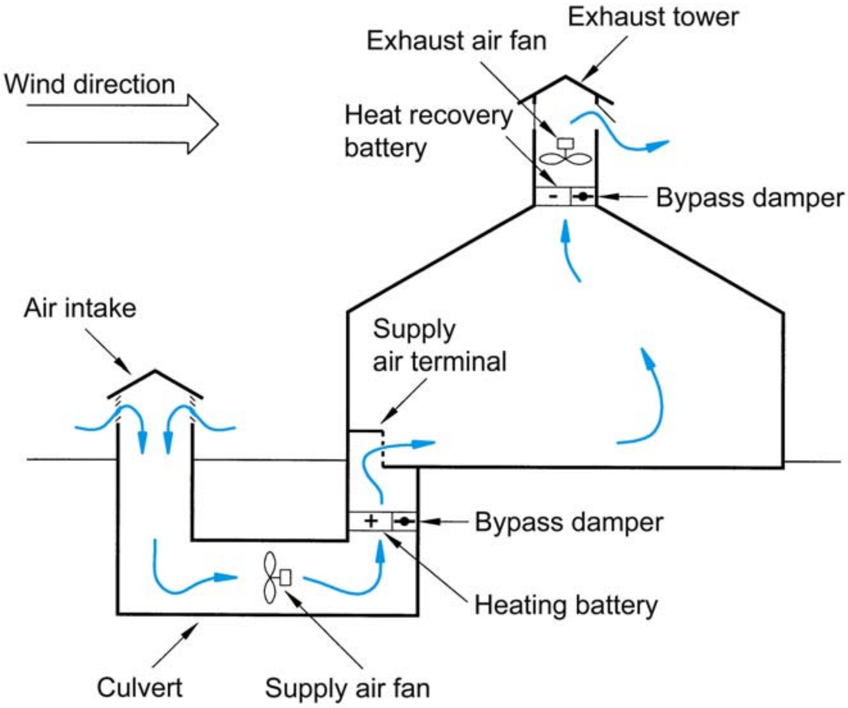

Figure 2. The concept of hybrid ventilation with ground coupled duct.

Façade ventilation is here defined as mechanical exhaust ventilation with supply air taken in through the façade and distributed unheated to the classrooms at ceiling level via an insulated air-distribution duct with air-supply nozzles (Figure 3). Extract ducts from each classroom are connected to a central fan at roof level. This fan generates a negative pressure in each classroom relative to outside. The supplied airflow rate is controlled by a temperature- or combined temperature-/CO_2-sensor in each classroom, which controls the position of a damper in the extract duct from each classroom. There is no filtration of the supply air.

Figure 3. The concept of façade ventilation. The right figure shows Prestetrød school (source: White Arkitekter AB).

1.6 Preliminary results

Figure 4 presents an extract of some preliminary results for different ventilation concepts concerning perceived air quality [21,22]. Comparison of the hybrid ventilation system with and without filter is especially interesting. The schools with hybrid ventilation have much in common. They are situated in the countryside with probably good quality of the outdoor air. The room volumes and ceiling heights are well above the minimum requirements in the Norwegian Building Code. And they have demand-controlled displacement ventilation. The perceived indoor air quality seems to be best in the schools without filters in the air supply path.

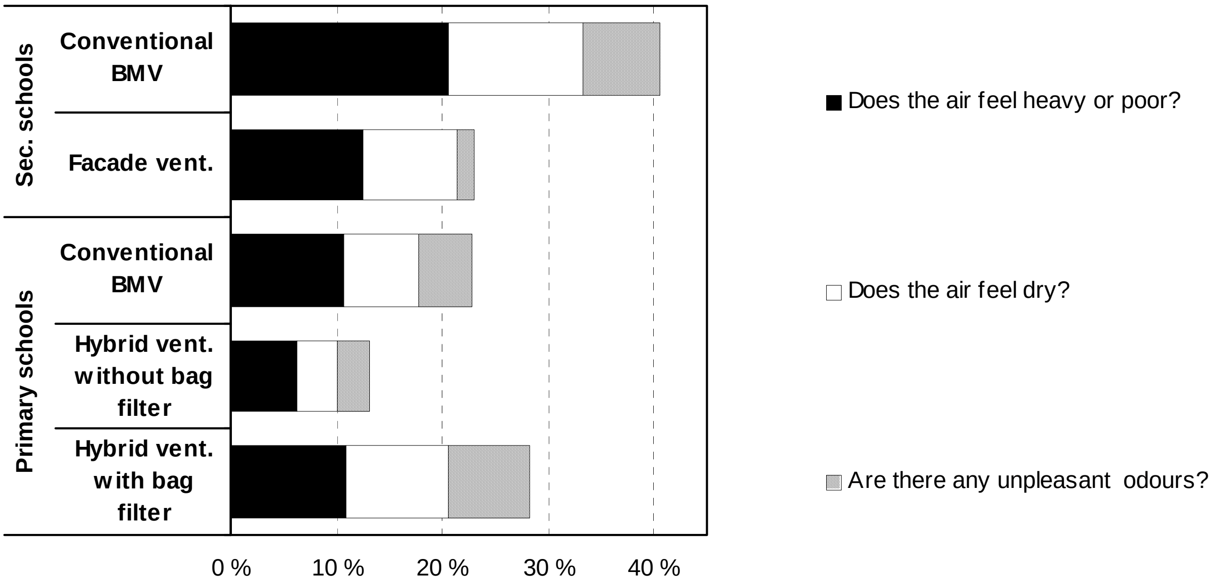

Figure 2. Responses to questions on perceived air quality in schools with different ventilation systems. The total length of the bar for a school is the sum of the relative contribution of the question prevalence used. 100% (worst) means all pupils always answer 'yes' for all questions.

Another interesting reflection derived from the preliminary studies, is that the energy use in schools with alternative ventilation systems is not necessarily above average even though they have less efficient systems for heat recovery from the exhaust air than conventional systems [21].

1.7 Problems addressed in this dissertation

The results of the preliminary studies indicate that there might be relevant associations not yet fully understood between ventilation system, indoor climate and energy use. With this as a starting point, I have conducted several different studies, to find proof of such associations, and hopefully the major cause of this difference. Conclusive studies are reported in seven different papers. The conclusive studies address the following main issues:

1) Effect of conventional filtration techniques on perceived air quality and indoor-air related symptoms (Paper I, II and III)
2) Benefits of demand-controlled ventilation (Paper IV and V).
3) Air supply through the façade in a cold climate (Paper VI)
4) Cooling performance of ground-coupled ducts (Paper VII)

The studies are described in detail in the corresponding and enclosed papers. A summary of the studies with the main results for the four main issues mentioned above, are presented in chapter 7.

Finally, the thesis closes with overall discussions on air filters and ventilation control. This discussion is founded on the knowledge derived in 7 papers documenting my work. Details of the discussions in these papers that do not enlighten this overall perspective are not repeated in this closing section. This also means that chapter 8 only covers some limited aspects of air filters and ventilation control.

2 STUDY SUMMARIES WITH MAIN RESULTS

The studies documented in this thesis employ an array of different approaches including use of pupils as measurement instruments by means of questionnaires, physical measurements, field interventions, laboratory experiments and theoretical considerations. The used methods and the main results are presented together in this chapter to avoid unnecessary confusion, even though it is normal to separate these two topics.

The used methods are described in detail in separate Method chapters in the enclosed Papers (except for Paper V which is based on a purely theoretical approach). Table 1 gives a thematic overview of the papers and the corresponding methods used.

Table 1. Thematic overview of the papers and the corresponding methods used

Theme	Paper	Method
Studies of air filter and indoor climate	I	Cross-sectional study of the influence of filter on PAQ- and SBS symptoms. Based questionnaire surveys among 59o pupils from 26 classes in 13 schools
	II	Reversed and blind filter intervention study in a primary school based on PAQ-assessments and questionnaire survey among the pupils in 5th , 6th and 7th grade.
	III	PAQ-assessments by an untrained test panel of filter samples simulating different AHU-operating conditions. The assessments were done in controlled laboratory environment.
Studies of ventilation control, energy use and indoor climate	IV	Empirical and theoretical study of energy use with different ventilation control strategies based on an investigation of real use of 157 primary school classrooms in Oslo.
	V	Theoretical study of the energy use and profitability with demand controlled ventilation in office cubicles.
	VI	Case study of indoor environment in a school with air supply through the facade during cold and warm weather. The study is based on a questionnaire survey among 50 pupils in two different classrooms together with physical and microbiological measurements. The questionnaire responses were compared with corresponding responses in classrooms with supply air served by other types of ventilation systems.
	VII	Empirical and theoretical study of the cooling performance of ground coupled ducts. The study is based on measurements of temperatures, airflow rates and ground-coupled duct surface area in two schools.

2.1 Air filters and indoor climate

2.1.1 Questionnaire survey in schools with different ventilation concepts

The first study (Paper I) is based on a questionnaire survey conducted in several recently built or retrofitted schools in Norway with or without a filter in the supply air path, to see if there are any indications of differences regarding Perceived Air Quality (PAQ) and Sick Building Syndrome (SBS)-symptoms. None of the schools had a previously known indoor air quality problem.

Six of the schools have a balanced mechanical ventilation (BMV) system providing 100% fresh air (i.e. no recirculation). Five of the schools have hybrid ventilation providing 100% fresh air (i.e. no recirculation). Two of the systems were equipped with bag filters in the supply air path and three of the systems had no filtration beyond precipitation of particles due to low air velocity in the ground-coupled duct [28]. Two of the schools have façade ventilation with no filtration of the supply air.

The age and the standard of the bag filters were not examined, but they are assumed to be bag filters (typically F7) in accordance with the normal understanding of the existing building code [19,17]. The age is likely to be representative for filters in BMV-systems.

In all, 590 pupils from 26 classes in 13 schools answered the same questionnaire. The questionnaire was repeated three times for each class over a period of two weeks. The questionnaire was answered near the end of school days with normal school activities in the classroom. All surveys were conducted during winter, before the main pollen season.

The questionnaire consisted of 45 simple yes/no questions regarding health symptoms, the indoor environment, and personal background information. The questionnaire was a Norwegian application of the Örebro questionnaire [31, 32], but which had been simplified to be suitable for intervention studies among children. The main difference was that the questions asked how the person was feeling at the present moment in time, instead of how the person had generally felt in the previous 3 months.

The questions *Are you tired?, Does your head feel heavy?, Do you have a headache?, Do you feel faint or dizzy?, Do you have problems concentrating?, Does your eyes itch or sting?, Are* *you horse, or is your throat dry?, Do you have a stuffy or runny nose?, Do you have a cough?, Do you have a cold?, Does your hands or face itch?, Are you nauseous or unwell in any other way?* are about SBS symptoms. These are analysed separately and grouped together in an index denoted ‘BS-index’ (Building Symptom Index) in this paper.

BS-index is defined as:

$$BS-index = \frac{\sum_{i=1}^{n}\left(\overline{S}_i\right)}{12} \qquad (1)$$

Where $\overline{S}_i$ is the schools average score (%) for question *i*, and 12 is the number of questions used in the index. A BS-index of 1 means that all pupils have answered yes to the question on all three occasions that the questionnarie is held.

The three questions *Does the air feel heavy or poor?, Does the air feel dry?* and *Are there any unpleasant odours?* concerns perceived air quality (PAQ). These are analysed separately and grouped together in an index denoted ‘PAQ-index’ in this paper. The PAQ-index is calculated in a similar manner as the BS-index.

The mean PAQ-index was calculated for each class. Figure 5 shows the crude PAQ-index values with its 95% confidence interval for the two groups of classes, with used bag filter (16 classes) and without used bag filter (10 classes).

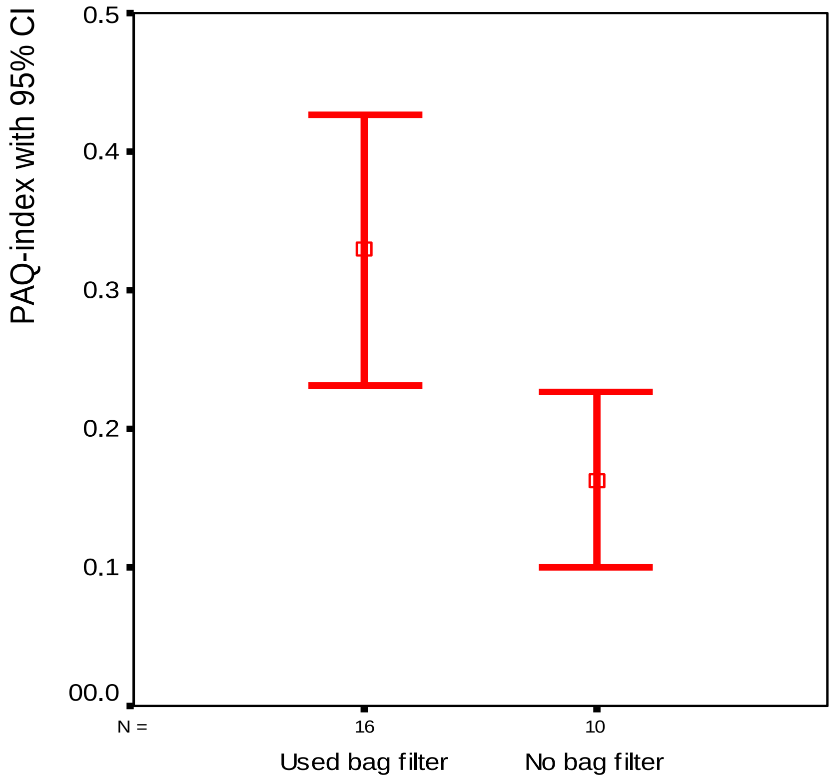

Figure 5. PAQ-index based on the mean PAQ-index for each class. N is the number of classes.

The confidence intervals do not overlap, indicating that the difference between the two groups did not occur by chance.

SBS- and PAQ-related questionnaire responses and resulting BS- & PAQ-indices are used as dependent variables in a GLM Multivariate test to analyse influence of the ventilation systems (BMV, Hybrid ventilation and Facade ventilation). This analyse is done in two steps. The first step controls for pupils’ sex, class-level (age) and ventilation system, together with the responses to questions about personal background (*Do you share your bedroom with any brothers or sisters?, Do you have wall-to-wall carpet in your bedroom?, Are your bedroom well ventilated at nights?, Does anyone smoke at home?, Do you have a pet at home?, Do you have frequent contact with other pets?)* and the responses to the question *Have you eaten anything today?*.

The second step is in addition controlled for the influence of conventional air filtration.

The Multivariate test is then repeated to analyze influence of conventional air filtration controlled for the influence of ventilation system together with all the confounders mentioned in step 1 and all noise and light-related responses, since they are assumed to be independent of PAQ.

The first adjustment for confounders (step 1) indicate that indoor air quality is perceived to be best in the schools with Hybrid ventilation and Facade ventilation (Table 2).

Table 2. PAQ and BS-index adjusted for age, sex and personal background.

				95% Confidence Interval	
Dependent Variable	Ventilation system	Mean	Std. Error	Lower Bound	Upper Bound
PAQ-index	BMV	.337[a]	.018	.301	.373
	Hybrid ventilation	.209[a]	.020	.170	.248
	Facade ventilation	.191[a]	.032	.129	.254
BS-index	BMV	.233[a]	.011	.211	.254
	Hybrid ventilation	.210[a]	.012	.187	.233
	Facade ventilation	.256[a]	.019	.218	.293

[a] Evaluated at covariates appeared in the model: Class level = 7.51, Sex (quota girls) = .49, Do you have frequent contact with other pets? = .6315, Do you have a pet at home? = .6449, Does anyone smoke at home? = .3794, Are your bedroom well ventilated at nights? = .6950, Do you have wall-to-wall carpet in your bedroom? = .2124, Do you share your bedroom with any brothers or sisters? = .0889, Have you eaten anything today? = .8634.

This difference almost vanished when the PAQ-index was adjusted for the influence of filter (Table 6 in Paper I).

A reanalyse of data with respect to whether the supply air was filtered or not (Table 3), indicates that use of filter can be a risk factor for PAQ and some SBS-symptoms.

Table 3. Adjusted prevalence means of the influence of filter on the PAQ- index and some PAQ- and SBS-responses.

				95% Confidence Interval	
Dependent Variable	Filter	Mean	Std. Error	Lower Bound	Upper Bound
PAQ-index	Filtered supply air	.314[a]	.017	.280	.348
	No filter	.183[a]	.022	.141	.226
Does the air feel heavy or poor?	Filtered supply air	.440[a]	.025	.391	.489
	No filter	.218[a]	.031	.158	.279
Does the air feel dry?	Filtered supply air	.321[a]	.024	.273	.368
	No filter	.197[a]	.030	.138	.256
Do you have a cough?	Filtered supply air	.260[a]	.024	.213	.306
	No filter	.150[a]	.029	9.256E-02	.208
Do you have a runny or stuffy nose?	Filtered supply air	.373[a]	.027	.321	.426
	No filter	.257[a]	.033	.192	.322
Does your eyes itch or sting?	Filtered supply air	.154[a]	.018	.119	.189
	No filter	8.476E-02[a]	.022	4.146E-02	.128

[a] Evaluated at covariates appeared in the model: Ventilation system = 1.91, Class level = 7.50, Sex (quota girls) = .49, Do you have frequent contact with other pets? = .6309, Do you have a pet at home? = .6453, Does anyone smoke at home? = .3775, Are your bedroom well ventilated at nights? = .6958, Do you have wall-to-wall carpet in your bedroom? = .2142, Do you share your bedroom with any brothers or sisters? = .0897, Have you eaten anything today? = .8622, Are you bothered by the sun light? = .1298, Is it reflections on the blacboard? = .1251, Is the light sufficient? = .8636, Are you bothered by noise from the ventilation system? = .1384, Are you bothered by noise from outside? = .0871, Are you bothered by noise from other classes? = .3195, Are you bothered by noise from other pupils in the class? = .3838, Is it difficult to hear what is said in the classroom? = .0980, Is it diffucult to see the wrighting on the blackboard? = .0758.

2.1.2 Reversed filter intervention study in a Primary School

The objective of this study (Paper II) was to conduct a conceptual replication of the study in Paper I utilizing a refined experimental design, to see if pupils in a school environment without a used bag-filter in the supply air path experienced fewer SBS-symptoms and perceived the air quality to be better than with a used bag filter in the supply air stream. The study was conducted at Tredal Primary School. The school is located on the west coast of Norway and opened in August 2000.

The effect of used bag-filters on SBS-symptoms and PAQ were examined by the following 3-step field intervention with one week intervals between each step:

Step 1: Before the intervention, SBS-symptoms and PAQ were assessed while the used bag-filters were present in the air supply path, i.e. normal operation conditions (Condition 1). The filter bank was then removed from the air supply path and carefully stored in a nearby plant room with normal humidity and temperature conditions.

Step 2: SBS-symptoms and PAQ were assessed without any bag filters in the supply air path (Condition 2). The assessment took place approximately one week after the removal of the filters. The used filter bank was then carefully put back in the supply air path.

Step 3: SBS-symptoms and PAQ were assessed one week after the filters had been refitted (Condition 3).

The participating pupils were blind to the intervention.

The same questionnaire as in Paper I was used for evaluation of SBS-symptoms.

Perceived air quality assessment votes were marked on the DTU split-scale of air quality acceptability (Chapter 8 Appendices, DTU split scale). The votes have been assigned values between –1 (clearly unacceptable) and +1 (clearly acceptable) for statistical analysis.

The supply air filter bank consisted of 3-year old F7 bag-filters. The bag-filter bank was designed with a very large cross-sectional area in order to achieve a low-pressure drop for hybrid ventilation. The nominal face velocity over the filter bank was 0.17 m/s.
This means that their ‘real age’ based on filtered air volume, corresponded with filters used for approximately 12 weeks at a face velocity of 2.5 m/s, which is a normal face velocity for air-handling units.

Figure 6 shows the average assessment score for each of the three conditions, together with their 95% confidence intervals, for the classes that were tested for all three conditions (5th and 7th grade pupils). The confidence intervals overlap, so there is no immediate significant difference in the assessment score values. The results indicate, however, that PAQ improved when the used filter was removed, and deteriorated back to the original level when the used filter was refitted.

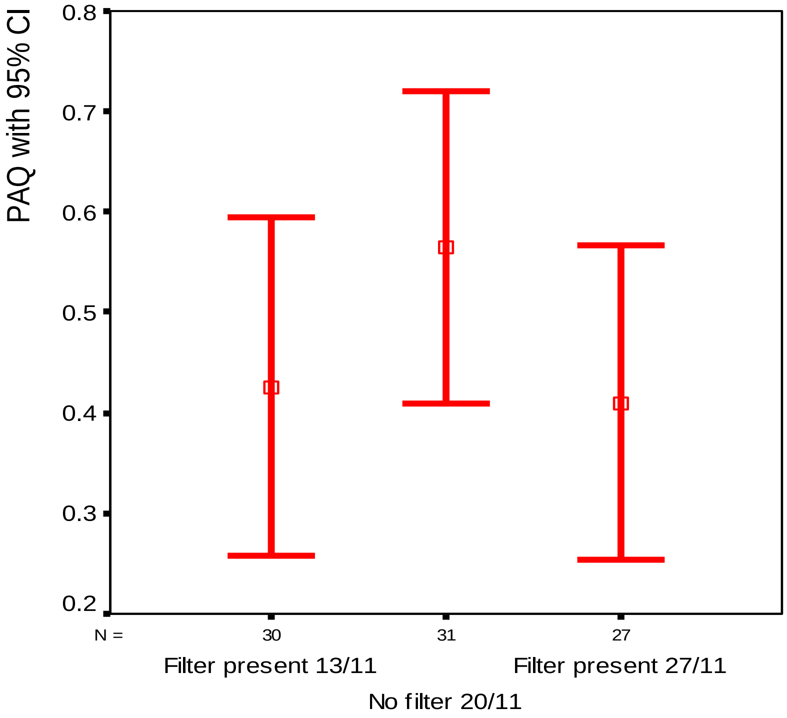

Figure 6. Air quality assessments with and without filter present. *N* is the number of pupils making assessments.

If the majority of the subjects assess the difference between two conditions in the same direction, there can be a significant difference between the samples even though the aforementioned confidence intervals from the basic statistical test overlap. Such a repeated test comparison is examined by using Student's Paired-Samples T-Test. There was a significant improvement in PAQ when the filter was removed (Condition 1&2, t(27)=2.18, $p = .04$). Refitting the filter reduced PAQ in a similar way (Condition 2&3, t(25)=1.94, $p = .06$). As a control, the assessment scores before the intervention and after the removal of the treatment were paired. The result showed no indication of a real difference in PAQ during the two conditions with filter present (Condition 1&3, t(24)=.71, $p = .48$).

The effect of each of the intervention steps was analyzed using General Linear Model (GLM) Repeated Measures. An SBS-index was used as the dependent variable. The SBS-index is defined as:

$$SBS - index = \frac{\sum_{i=1}^{12}(S_i)}{12} \tag{1}$$

Where S_i is the score for question i, and 12 is the number of questions used in the index. (The difference between the SBS-index and the BS-index in Paper I is that the BS-index was based on the average score of three repeated questionnaires).

The intervention between condition 2 and 3 had a significant adverse effect on the SBS-index among the allergic subjects ($F(1,35)=5.7$, $p= .02$), but not for all the pupils as a whole group ($F(1,35)=0.45$, $p= .51$).

2.1.3 Influence of typical ways of operating an air-handling unit

To reduce energy consumption, it is normal to turn off or reduce the ventilation air volume delivered by the air-handling units (AHU) outside regular working hours. The unanswered question is: *will this lead to an accumulation of chemicals in the air enveloping the filter, causing an increase in the sensory pollution emitted from the bag filter after the AHU is switched back on for normal operation?*

An experiment was performed to determine whether the sensory pollution emitted from a bag filter that had been used for 3 months in a typical suburban area in Denmark was influenced by different ways of operating the air-handling unit (AHU). Samples from the same used filter were pre-conditioned to simulate three operating conditions: 1) switched off overnight; 2) airflow reduced to 10% overnight; and 3) continuous 100% operation.

The study was based on blind assessments of perceived air quality in a controlled laboratory environment. Five identical test rigs were constructed for the experiment. Samples from one used filter were put in three of the test rigs. As references for evaluation of the results, a sample from a new unused EU7 filter was put in one test rig and the last test rig was left empty, meaning that the air did not pass through a filter before being assessed. In addition, an odour reference generated by releasing a known concentration of acetone was used.

An untrained panel of about 15 subjects made the assessments 30 minutes and two hours after the AHU was switched back to normal operation. This was a blind test for the test panel. The assessment order was randomised. The assessment votes were marked on the DTU split scale of air quality acceptability. The votes have been assigned values between –1 (clearly unacceptable) and +1 (clearly acceptable) for statistical analysis and calculation of decipol values.

The perceived air pollution from the used filter samples was calculated from the difference between perceived air quality of exhaust air from the used filter samples and perceived air quality of exhaust air from the reference without filter (Figure 7).

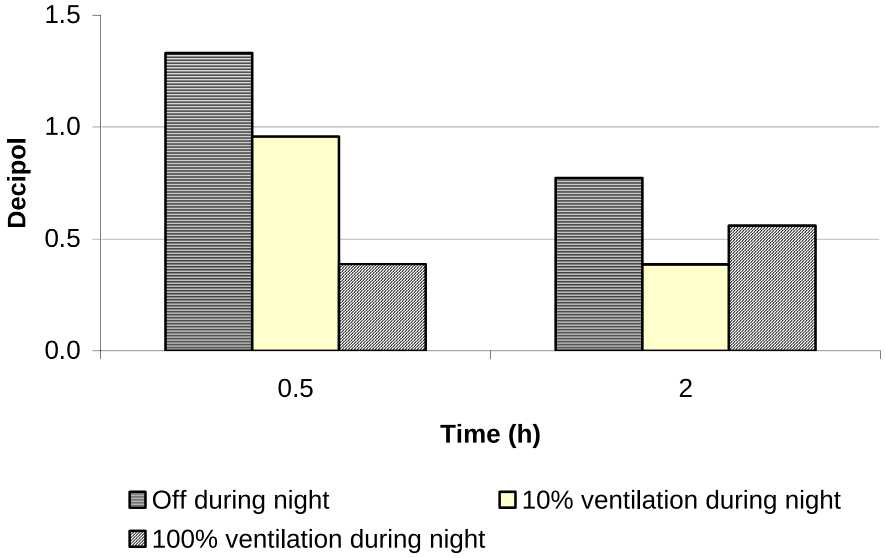

Figure 7. Development of perceived air pollution half an hour and two hours after the air-handling unit was switched on for normal operation. The following typical ways of operating an AHU were tested: 1) switched off overnight; 2) airflow reduced to 10% overnight; and 3) continuous 100% operation.

The acceptability of the“Used-10%” sample (airflow reduced to 10% overnight) was significantly lower than that of the “Used-full” sample (continuous 100% operation) after ½ an hour of full ventilation (t(13)=2.6, *p=.02*, 2-tailed). After two hours there were no significant differences between the samples. This shows that different ways of operating an AHU resulted in a real difference in the pollution load from a used bag filter immediately after the AHU was turned on, but this difference was greatly reduced some time after the ventilation system had been turned on again. This indicates that there was a continuous emission of odorous compounds from the particulate matter associated with the filter surfaces. These emissions accumulated during periods with no or reduced airflow through the filter. Since it was statistically proven that the “Used-10%” sample smelled worse than the “Used-full” sample after ½ an hour, it should be valid to assume that even the “Used-off“ sample would smell worse than the "Used-full" sample. This means that the results can be analyzed for 1-tail significance. Such an assumption leads to a significant difference between the Used-off and the Used-full sample (t(13)=2.1, *p=.03*, 1-tailed).

2.2 Ventilation control, energy use and indoor climate

2.2.1 Occupancy density and benefits of demand-controlled ventilation

Modern Norwegian schools usually have a constant air volume (CAV) ventilation system. The ventilation rate is dimensioned for the maximum pollutant load expected in the ventilated space. This implies that, for much of the time, energy is wasted due to over-ventilation when the occupancy and pollutant loads are below maximum. The concept of demand-controlled ventilation (DCV), in which a space is variably ventilated according to the pollutant load, addresses this problem. The unanswered question is: *What is the energy use with DCV-strategies compared to CAV*?

The corresponding ventilating air volume and energy use is analyzed for three ventilation strategies: (*a*) constant air volume mixed ventilation (CAV), (*b*) CO_2-sensor based demand-controlled mixed ventilation (DCV-CO_2), and (*c*) infrared occupancy-sensor based demand-controlled mixed ventilation (DCV-IR).

This issue is addressed in Paper IV "Occupancy density and benefits of demand controlled ventilation in Norwegian primary schools". A practicable method for calculating profitability with demand-controlled ventilation (DCV) compared to constant air volume (CAV) is shown in Paper V. This method was applied for office cubicles in Paper V, but the theory is also applicable for school buildings.

Two factors of vital importance when analyzing the potential energy savings and profitability of DCV compared to CAV are the *actual occupancy density* and the *actual hours of use* of the ventilated areas. These factors were investigated as a part of a health survey of Oslo children born in 1992. 157 classrooms for 4th grade pupils (born 1992) were inspected at 81 randomly selected schools in Oslo, Norway. The results are shown in table 2.

Table 4. Results from inspection of 157 classrooms in Oslo. All the classrooms are probably designed for 28 pupils.

	Average	**Min.**	**Max.**	**Standard deviation**
Pupils attached to the class	22.3	13.0	28.0	3.5
Pupils present during inspection	20.9	13.0	28.0	3.6
Teachers present during inspection	1.3	1.0	3.0	0.5
Floor area of classroom [m²]	61.5	43.0	93.0	8.2
Volume of classroom [m³]	190.0	150.0	285.0	31.0
t_{use} – Use of classroom during inspection day [h]	4.0	3.0	5.0	0.4

Primary school classrooms in Oslo have an average of 22 occupants present, while ventilation airflow rates are normally designed for 30 persons. Thus, typically only 74% of the classroom's design occupancy capacity is utilized. The average occupancy density in classrooms is 0.37 pupils/m². The average classroom is used 4 hours each weekday with normal school activities.

Figure 8 shows the percentage reduction in daily volume of ventilation air for the DCV strategies relative to CAV with different operation time of the air-handling unit. This figure applies to an average sized classroom designed for 30 occupants, and with 22 of them present for four hours.

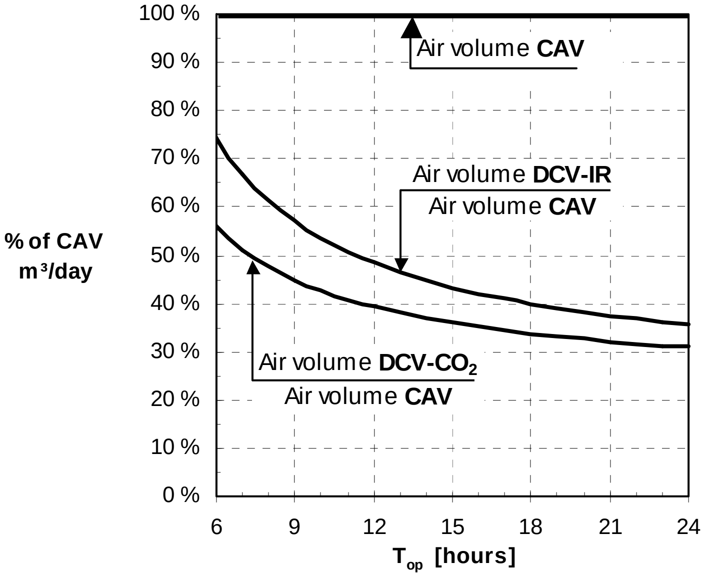

Figure 8. Influence of operation time on the reduction of daily volume of ventilation air with DCV-strategies compared to CAV.

DCV-CO_2 and DCV-IR reduce the daily volume of ventilation air for an average classroom to respectively 43% and 54% of the air volume with CAV, presupposed that the CAV-system operates with full airflow from 7 AM to 5 PM. DCV-CO_2 and DCV-IR reduce the daily volume of ventilation air for an average classroom to respectively 31% and 36% of the air volume with CAV in the case of 24-hour operation (Figure 8). The impact of (i) infiltration, (ii) breaks between lessons, (iii) window opening, and (iv) displacement ventilation will in practice further increase the energy saving potential of DCV-CO_2, but is ignored in the calculations.

Figure 9 shows the percentage reduction in energy use for ventilation purposes for the DCV strategies relative to CAV.

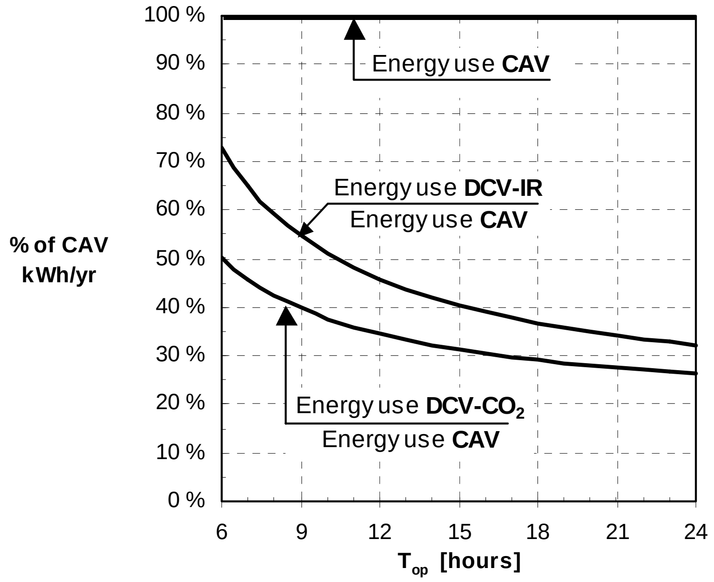

Figure 9. Influence of operation period on relative energy use with DCV-strategies compared to CAV.

Both of the studied DCV strategies have a considerable potential for reducing the daily volume of ventilation air. DCV-CO_2 can reduce the energy use for ventilation purposes to 38% relative to CAV with a 10 hour operation period, whilst DCV-IR can reduce the energy use to 51% (Figure 9). The relative reduction of energy use compared with CAV, slightly exceeds the reduction of ventilating air volume.

2.2.2 Air supply through the façade in a school in a cold climate

Retrofitting a school building with a new mechanical balanced ventilation system is expensive, and it can be problematic to integrate in a building due to lack of space for central air handling units and ducts. This has motivated the application of simplified ventilation systems. Revetal Secondary School in Norway has recently been refurbished with a simplified ventilation system where unconditioned air is taken in from the façade and distributed directly to classrooms at ceiling level via an insulated air-distribution duct with air-supply nozzles. This issue is addressed in Paper VI "Evaluation of a simplified ventilation system with direct air supply through the facade in a school in a cold climate".

Extract ducts from each classroom are collected at a central fan at roof level. The fan generates a negative pressure in each classroom relative to outside. The supplied airflow rate is controlled by a combined CO_2- and temperature-sensor in each classroom, which adjusts the position of a damper in the extract duct from each classroom. The sensor is located on the inner wall of the classroom about 1.6 meters above the floor. During the measurements, the supplied airflow rate was controlled to prevent the CO_2 concentration from exceeding 800 ppmv. Moreover, the extract damper closes if the sensor measures a temperature below 19°C.

According to the Headmaster, the indoor climate is satisfactory, and the energy use has not increased after the refurbishment even though the building probably has a considerably higher ventilation rate than before. In addition, it is possible to implement exhaust air heat recovery to reduce the energy use even further. Such systems can represent a significantly lower Life-Cycle-Cost than BMV-system [25].

The scope of this study was to examine the following issues:

1. Are the pupils really satisfied with the indoor climate compared to other schools?
2. Is there a problem with unpleasant draughtiness on cold days?
3. Is there a risk of pollution of the supply air due to accumulated particles and microbiological growth in the supply air duct?
4. Is the supply of unfiltered outdoor air satisfactory?
5. Is there a problem for people with allergy?

This analysis is based on measurements of draft and air temperatures during cold weather, responses of questionnaires (see Paper I – identical questionnaire), microbiological assays, dust measurements in the air-distribution duct and the classroom and particle measurements in outdoor and indoor air.

The pupils seem to be generally satisfied with the indoor climate compared to other schools, except for the indoor thermal climate during extreme cold weather. Air quality is perceived to be best when the supply air temperature is low, leading to a relatively low indoor air temperature. Perceived air quality gradually deteriorates when the supply air and indoor air temperature increase.

There is a problem with unpleasant draughtiness on cold days. The indoor thermal climate is unsatisfactory during days with low outdoor air temperature [16].

There is a risk of pollution of the supply air due to accumulated particles and microbiological growth in the supply air duct. Microbiological growth was found, and the dust coverage area percentage was higher than what is recommended for IAQ reasons [26, 27].

The supply of unfiltered outdoor air seems satisfactory for the pupils. They seem generally satisfied with the air quality and have a “normal” prevalence of indoor-air related symptoms compared to the other schools. However, sedimentation of organic material in the air supply duct, in combination with the presence of moisture, provides fertile conditions for microbiological growth that are potentially harmful.

There might be a problem for people with allergy. There are more pupils with reported allergy problems at Revetal School than the comparable BMV schools. The pupils at Revetal School are probably more exposed to pollen indoors. However, there were too few allergic subjects to draw any firm conclusions, and all kinds of allergy were included. We can therefore neither confirm nor rule out that this ventilation system is a contributory factor.

In general, the application of a simplified ventilation system with direct air supply through the façade requires demand-controlled ventilation (DCV) with a much higher CO_2 set point than 800 ppmv to achieve satisfactorily thermal comfort during cold weather. This could be achieved by a ventilation control strategy with a temperature-compensated CO_2 set-point.

Such a strategy could improve thermal comfort and reduce energy use for heating without compromising PAQ during cold weather. In addition, it could improve thermal comfort and IAQ during warm weather with only a slight increase of energy use. An example of such a strategy is shown in Figure 10.

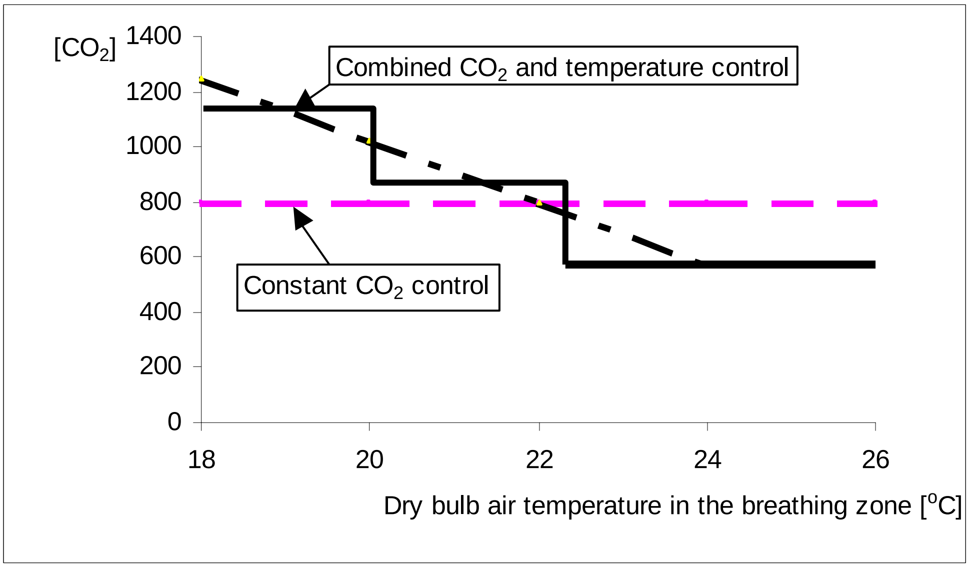

Figure 10. Three different control strategies for DCV. The conventional constant CO$_2$ control and the suggested improved control strategy with linear or stepwise temperature compensated CO$_2$ set-point.

The risk posed by fertile conditions for microbiological growth can be further reduced by better air inlet design, improved access to the supply air duct, and regular inspection and cleaning.

Further evaluation of an improved solution is needed before such a ventilation concept can be recommended in cold climates.

2.2.3 Cooling performance of ground-coupled air intake ducts

Hybrid or natural ventilation with ground-coupled fresh air intake ducts (or culverts) has become an increasingly popular way of conditioning air in Norway and Sweden. Cooling of air is probably the most valuable property of ground-coupled ducts, but *what cooling performance is it possible to achieve with ground-coupled ducts?* An answer, or indication of an answer, has been found by analyzing the data from Jaer School in the municipality of Nesodden [28] and Mediaa School in the municipality of Grong [29], both of which have been evaluated through the Norwegian HybVent-project underlying IEA ECBCS Annex 35 (International Energy Agency) [30]. This issue is addressed in Paper VII “Cooling performance of ground-coupled air intake ducts”.

Warm periods are analysed to find how much the ground-coupled ducts are cooled at night, and how much cooling they provide during daytime. Temperatures during a warm period at Jaer School are shown in Figure 11. The cooling potential is derived from the measured outdoor air temperatures, supply air temperatures and airflow rates. The supply airflow is about 700 ℓ/s during daytime and drops to about 500-600 ℓ/s during night in the examined warm period.

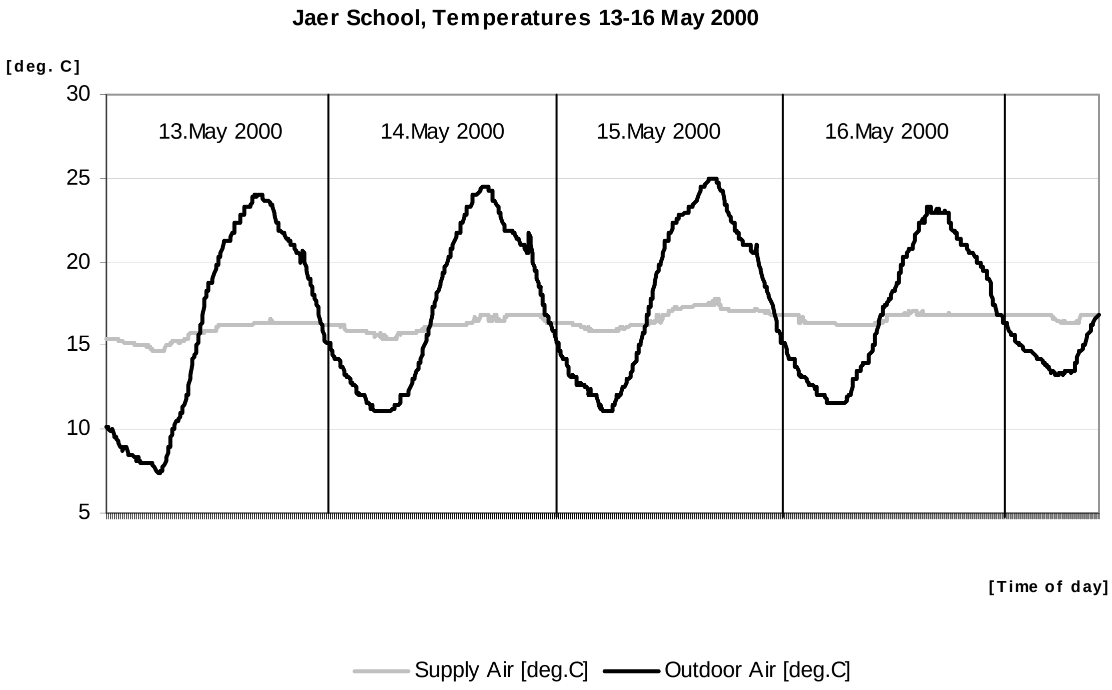

Figure 11. Outdoor- and supply air temperatures at Jaer School.

The measurements at Jaer and Mediaa School show that a culvert has a significant cooling effect. The main mechanism of cooling in these ducts is exploiting thermal storage with night-time precooling, exploiting the diurnal swing in outdoor temperature. In cold climates with cool night temperatures, the available daily cooling energy from the culvert surfaces at Jaer School stabilizes at around 100 Wh/m^2 after a long warm period. By increasing the nighttime airflow rate, it should be possible to increase this to at least 200 Wh/m^2. Sufficient cooling with this method requires a culvert surface area of 1-2 m^2/pupil presupposed demand controlled displacement ventilation for buildings situated in cold climates. Active mixing of the air in the ground-coupled duct can further increase the cooling potential [43].

The maximum recorded peak loads led only to a negligible increase in the supply air temperature after the culvert, which indicates that culvert cooling is well suited for handling considerable peak loads.

3 OVERALL DISCUSSION

3.1 Air filters

3.1.1 Interpretation of statistical analysis

Several results in Paper I, II and III are derived from statistical analysis. Only some of these results qualify as valid statistical proofs alone.

Significant differences in perceived air quality (PAQ), based on the DTU split scale of acceptability in Paper II and III should be considered as valid statistical proof of impact of different filter conditions. The intervention in Paper II was reversed making conditions 1 and 3 as identical as possible, in a real field study. The PAQ-assessment scores during condition 1 were almost exactly recreated during condition 3, indicating good internal validity of the experiment. Measured environment factors do not indicate any alternative explanation of the results. The PAQ-assessments in Paper III were done in a controlled laboratory environment, with different filter conditions as the only varying factor.

Significant differences in the PAQ-index based on questionnaire responses in Paper I cannot be considered as valid statistical proof of general impact of filters alone. Perceived air quality is influenced by innumerable factors at the different schools, acting and interacting in a way beyond the control of the experimental design. But the significant association between filter and PAQ-symptoms, resulting from a confounder-controlled GLM multivariate test, strongly indicate that presence of a used filter is one of the dominating factors influencing PAQ. This assumption is confirmed by the corresponding results in Paper II.

The Mann-Whitney test is used in Paper II for analyzing for significant differences between the groups asthmatic-/allergic subjects and non-asthmatic-/allergic subjects during each of the three conditions caused by the intervention. Some significant differences appeared throughout the intervention, but it is not known to which degree they were caused by the intervention.

The effect of the intervention in Paper II on the two groups asthmatic-/allergic subjects and non-asthmatic-/allergic subjects was tested with GLM Repeated Measures, with the SBS-index as the dependent variable. Presence of the supply air filter had a significant adverse effect on the SBS-index between Condition 2 and 3 for the asthmatic-/allergic subjects. However, we cannot rule out the possibility that the intervention was not the only cause of this significant effect, since the change in the SBS-index between Condition 1 and 2 and for all three conditions was not found significant for any of the groups. Unfortunately, an open hatch in the ground-coupled duct probably caused some filter bypass prior to step 1 (Condition 1).

3.1.2 Impact of used bag filters on PAQ and SBS-symptoms

Comparisons of perceived indoor air quality in schools with different ventilation systems indicates that today's conventional filtration solutions with bag filters has a significant adverse impact on the perceived air quality in schools (Paper I). The results also indicate that presence of used bag filters has an adverse impact on some SBS-symptoms. The cross-sectional study in Paper I is however not infallible, because it is not controlled for several alternative explanations to the observed results. Physical parameters such as temperature, humidity, CO_2-level and particles were not measured during the surveys. The real condition of the AHUs with filters were not evaluated and described. However, Skyberg et al. [60] found no association between risk of SBS-symptoms and last change of air filters, when ventilation systems were divided into two groups whether the air filters had been used for more or less than two years. This indicates no additional adverse impact of very "old" filters.

Other confounders such as outdoor air quality, displacement ventilation, height of ceiling (room volume) might lead to a biased response, explaining to some extent differences in the PAQ-index. The hybrid-ventilated schools should be quite comparable regarding the area where the school was situated (outdoor air quality), ceiling height, ventilation efficiency (all of them utilize displacement ventilation) and air flow rates. The PAQ-index of the hybrid-ventilated schools with used bag filter was quite similar to the PAQ-index in schools with BMV and used bag filter (Table 2 in Paper I). This indicates that these factors did not have a considerable influence on the PAQ-index, but the low number of hybrid ventilated schools (with or without filtration) limited the possibility of drawing firm conclusions.

Based on the suggestive results of the questionnaire survey (Paper I) a reversed intervention study was conducted (Paper II) to hopefully confirm or reject the hypotheses that the used filter contributed to the PAQ-differences between the schools. Removing the used bag-filter from the supply air stream significantly improved the pupils' PAQ. PAQ fell again to its original level when the filter was put back (Paper II). Measured indoor air temperature and

CO_2 concentration do not indicate an alternative explanation of the results (Table 2, Paper II). Although the bag filters were over 3 years old, they were comparable to filters used for approximately 12 weeks in a conventionally designed AHU, with respect to total air volume during the filter's lifetime.

There are few field studies of the impact of bag filters on perceived air quality and health consequences in schools. Marie Hult [61] evaluated different school concepts in Sweden. She found that some concepts without filtration had a relatively low prevalence of SBS-symptoms compared with other schools. Wålinder et al. [62,63] conducted nasal investigations among school personnel in 12 schools (Uppsala, Sweden) with different ventilation systems. He observed that personnel in schools with mechanical ventilation had more symptoms and signs of reduced nasal patency and higher concentration of some biomarkers for inflammatory mucosal reaction in nasal lavage fluid, although schools with natural ventilation had a lower air exchange rate than mechanically ventilated schools. Smedje et al. [64] conducted a double-blind cross-over design study with old and new filters in a school building. She found, by objective clinical methods, that presence of a used supply air filter reduced the nasal patency and increased adverse eye- and throat symptoms among the pupils, which is in good agreement with significant associations in Paper I (Table 3, page 27).

The observed adverse impact of used bag filter on PAQ is further consistent with results from field studies in other type of buildings and studies conducted in controlled laboratory environment. Fanger et al. [58] documented already in the 1980s that a HVAC system can degrade the quality of the supply air even before it reaches the space to be ventilated. Dirty bag filters have later been identified as a main source of pollution in a HVAC system [59], and numerous studies have documented that used bag-filters can be a significant source of indoor air pollution [24,36,37].

Teijonsalo et al. [34] have tested the odour intensity of filters with various operation times in the center of Helsinki. They found the odour intensity of a fine filter without prefilter to be about 3.3 decipol after 13 weeks' operation time when tested with facial exposure. The sensory source strength increases proportionally with the air flow rate, making the odour intensity (in terms of decipol) after the filter independent of the airflow rate [35].

Clausen et al. [38] showed that facial exposure overestimates the sensory strength of the filter compared to full body exposure. The sensory pollution load of filter determined from full body exposure was on average 6.6 times lower than with facial exposure, but the used filter is still considered to be a substantial source of sensory pollution.

Clausen et al. [39] also showed that the presence of used bag-filters in a ventilation system has a significant effect on several indicators of SBS and Indoor Environmental Quality (IEQ). They studied comfort and health of 30 women during 4 hours exposure in an experimental room with either a used or a new filter present in the ventilation system. All environmental parameters were kept constant. Presence of the used filter in the ventilation system had a significant impact on several perceptions and symptoms. PAQ and perceived freshness of air was lower. Furthermore, the ability to concentrate was significantly lower. None of the data showed any improvement of the perceptions or symptoms when the used filter was in the system.

Wargocki et al. [40] conducted a 2x2 replicated field intervention study in a call-centre. They found that replacing a used filter with a new one increased PAQ and reduced the intensity of SBS-symptoms at low outdoor air supply rates. They also found that increasing the air supply rates through a used bag filter significantly decreased the performance of the occupants [73].

The pollution load from used filters is probably caused by sensory offending chemicals associated with particles captured by the filter [44]. As the mass of particles collected on a filter increases, the surface area associated with the collected particles increases. A common 0,6x0,6 m^2 filter with an air flow rate of 0.94 m^3/s will after 4 months use have a surface area of collected particles of about 200 m^2 [46]. The filter captures various organic compounds, and some of these, especially those with unsaturated carbon-carbon bonds, can react with ozone in the air stream passing through the filters [47]. This includes organics like unsaturated fatty acids, terpenes and sesquiterpenes commonly found in plant waxes, pollen and vegetative detritus. It has been shown that the concentration of ozone in the supply air is reduced after passing a used filter [45,48]. The organic compounds that react with ozone on the surface of the loaded filter are transformed to more highly oxidized species. Such oxidized chemicals can influence PAQ downstream of the filter if they are odorous enough and released fast enough [44]. Others have shown that microorganisms may proliferate on air filters with subsequent release into the filtered air [49,50].

3.1.3 Impact of used bag filters on asthmatic and allergic children

Bag filters are assumed to be a relief measure, especially for asthmatic and allergic children. The used bag filters in the supply air path at Tredal School were removed for a week and then put back (Paper II). Putting them back led to a significant increase of the indoor air related symptoms among asthmatic/allergic pupils compared to the rest of the pupils. This result questions the conventional assumption of bag filters as a relief measure, especially for asthmatic and allergic children. However, given the importance of the consequences, this needs confirmation by a more appropriately designed experiment before this result is given general validity, and remedial actions are taken. This intervention was conducted in early winter (November), probably with little pollen in the outside air.

No known published studies have shown that presence of a used filter can lead to an elevated adverse impact of SBS-symptoms among asthmatic-/allergic subjects compared to the rest of the subjects, but Andersson et al. [65] have demonstrated that allergic students have a higher prevalence of general symptoms, skin symptoms and membrane irritations than other students.

3.1.4 Influence of typical ways of operating an air-handling unit

Turning the air-handling unit (AHU) off, or reducing the airflow outside school hours, implies a further elevation of the pollution load from a used bag filter immediately after the AHU is turned on compared with continuous airflow through the AHU (Paper III). The consequence is that the IAQ deteriorates in the initial period after the AHU is switched on. Based on these findings, an AHU with used bag filters should be switched on at least two hours before the workers enter the office to minimize the sensory pollution emitted from the bag filter. A more energy-efficient strategy would be to modify the AHU with an additional timer-controlled damper to permit outside air to be passed through the bag filter and rejected for two or more hours, bypassing the building to avoid the energy cost of conditioning this cleansing air and distributing it in the building.

No known earlier published study have shown that typical ways of operating an AHU can influence the sensory pollution load from used bag filters. Cox and Bluyssen [66] compared the pollution load from filters with continuous and intermittent airflow without finding any significant difference, but they did not look at the development of the pollution load over time during the first period after the ventilation had been switched on. The findings are however consistent with the observations of Bekö et. al [45] presupposed that the increased emission load is somehow connected to ozone consuming chemical reactions on the loaded filter surface. Bekö et. al found that ozone removal efficiency drops from about 50% to about 8% after one hour of ventilation through the filter. Bekö et. al suggests that organics within the “filter cake” diffuse to the surface of the filter, re-generating the filter’s ability to remove ozone. These organics can accumulate on the loaded filter surface during static conditions like having no airflow passing through the filter.

3.1.5 Closing perspectives on air filters for comfort ventilation

The questionnaire survey (Paper I) and the intervention study (Paper II) demonstrate that the air filter in well functioning ventilation systems, can contribute with a significant pollution load to the indoor air. This result is valid for bag filters (typically F7) used in 90-95% of the comfort ventilation systems in Norway [17]. This conclusion is consistent with results from field studies in other types of buildings and studies conducted in controlled laboratory environment. The results also demonstrate that schools with a well functioning ventilation system without bag air filters in the air supply path can be expected to have better perceived indoor air quality than schools with a supply air filter assuming normal frequency of filter replacement. Conventional practice on documenting filter performance (arrestance and retention) is insufficient because it does not take into account emissions from particles trapped in supply air bag-filters [71,72]. These emissions constitute an IAQ problem. Two independent studies performed in office-like environment demonstrate negative impact of used filter on performance [73] and the ability to concentrate [39]. This should be of particular concern in schools made for education of children with greater susceptibility to pollutants and higher allergy prevalence than the rest of the population [7,8,9].

These results do not challenge the benefits of air filtration with respect to removing particles from the supply air, but it demonstrates that normal use of bag-filters are associated with negative by-effects influencing the quality of supply air. This implicates an urgent need to improve filtration products for comfort ventilation. Lacks of knowledge among HVAC-consultants and inadequate practice on documenting filter performance are probably the main reason why improved filtration technology is not demanded in HVAC-applications even though there exists promising filtration products on the market. These results will hopefully contribute to such a demand for improved technology and thereby intensified development of air filtration products suitable for comfort applications. It should however be emphasized that removal of the air filters from AHUs are not a practical measure for improving PAQ. Particle filtration is an absolute necessity in conventional ventilation systems to protect the HVAC components from sedimentation of particles. This is crucial for maintaining long-term functionality. We can also assume that ventilation systems with no particle filtration beyond precipitation of large particles have a larger degree of penetration of particles into the ventilation system and the indoor atmosphere. The long-term effect of this penetration is not addressed in this dissertation.

These results do not challenge the demonstrated positive association between outdoor air supply rates and indoor climate [23], but this association has reduced validity in practice as long as the outdoor air is polluted through the HVAC-system with used bag air filters as the main pollution source [24,37,59]. This is a paradox since conventional use of air filters is assumed to improve the supply air quality. This assumption is violated in practice with normal filter replacement. Conventional use of air filters is an example of a technique with low robustness. Robust HVAC-systems should be especially addressed in schools having high risk of inadequate maintenance of facilities [4,5,6]

Differences in robustness can explain why mechanically ventilated building have an increased risk of SBS-symptoms relative to naturally ventilated buildings assumed to less complex and have a more direct inlet of outdoor air [74]. This further implies that the system's robustness and air quality reliability are not properly addressed when designing ventilation systems. Reliability towards maintaining good supply air quality should be a basic design need for a ventilation system (Figure 1, page 14).

3.2 Ventilation control

3.2.1 Air flow rates and energy use

Use of demand-controlled ventilation reduces ventilating airflow rates considerably compared to CAV (Paper IV). On average only 74% of the maximum capacity is utilized in school classrooms in the region of Oslo, meaning that a CAV system ventilates with considerably more supply air than required by the actual number of users. In addition, a CAV system will in practice use a great deal of energy to over-ventilate empty areas, as a classroom is only used for three to five hours during days with normal school activity. DCV-CO_2 can reduce the ventilation air volume to 43% relative to CAV with 10 hours operation period (Figure 8, page 33). The impact of (i) infiltration, (ii) breaks between lessons, (iii) window opening, and (iv) displacement ventilation will in practice further reduce the ventilation rate with DCV-CO_2. Measured airflow rates at Jaer School shows that the average airflow rate with DCV displacement ventilation can be about 1/3 of the corresponding airflow rate with CAV [28]. Comparison of perceived indoor climate in schools with CAV-systems and DCV-systems does not indicate that CAV-systems add extra quality to the indoor climate. The purpose of extra ventilation with CAV-systems is therefore questionable as it leads to additional energy use.

Infrared occupancy sensors are a cheap alternative to CO_2-monitoring for controlling the ventilation rate. This strategy is bimodal: The ventilation rate is reduced to a minimum when the room is unoccupied, and is increased to the design ventilation rate whenever the room is occupied. The occupancy sensor can also control artificial lighting and solar shading. IR-sensor based demand-controlled ventilation reduces the energy use for ventilation purposes in the average classroom to about 51% of the corresponding air volume for a CAV system operating with full airflow from 7 AM to 5 PM (Figure 9, page 34).

The decision as to which of IR-sensor based DCV, or CO_2-sensor based DCV, is the most profitable depends on absenteeism and utilization of class capacity together with the operation time. If a school is expected to have full classes and negligible absenteeism, then IR-sensor based DCV will be more profitable. An advantage of CO_2-sensor based DCV is that it reduces the risk of under-ventilating overcrowded rooms compared to CAV and IR-sensor based DCV, depending of course on the capacity of the ventilation system. The energy saving potential for ventilation purposes is at least proportional to the airflow reduction, but probably even more. This is because internal gains (solar & occupants) cover a larger fraction of the ventilation heat loss in DCV systems than in CAV systems, and because the reduction of fan energy might be more than proportional than the corresponding reduction of airflow rates. The latter depends on how the airflow rates are controlled by the system (Paper V) [41].

The actual CO_2-production rate has a strong influence on the air flow rates and energy use with DCV-CO_2. All calculations are based on a CO_2-production of 9 mg/s per person [51]. This production rate is valid for adults. Children in primary school with normal activity (1.2 MET) will have a CO_2-production of about 7 mg/s per person [69,70]. DCV-CO_2 with this CO_2-production rate can theoretically reduce the energy use for ventilation purposes to roughly 31% relative to CAV with 10 hours operation period. Since CO_2 is only an indicator for the pollution load caused by occupants, it is an open question whether the actual ventilation rate should depend on the CO_2-production of the occupants, or the number of occupants. If the latter is true, then the CO_2-target for ventilation control should be harmonized with pupil's age and expected activity and reduced in primary school classrooms.

Several studies have shown that DCV is a cost- and energy-efficient alternative to CAV [51], but few studies are specifically directed towards primary school buildings and classrooms. Case studies in Swedish schools have shown that IR-sensor based DCV can reduce the ventilation energy requirements by approximately 50% [52]. Persily et al. [67] has found that DCV-CO_2 can reduce the energy use for ventilation purposes from about 50 to 75% in a lecture hall. Both of these results are in good agreement with the results of Paper IV.

Indirect, but still consistent with Paper IV are the results of Sørensen [41] and Drangsholt [68]. Sørensen has estimated the energy savings to be between 30 and 55% with DCV relative to a comparable CAV-system without being specific about the type of building. Drangsholt found that the average occupant load in a university auditorium during the working period was about 36% of maximum allowed occupancy load.

3.2.2 DCV with temperature-compensated CO_2 control

The energy use in schools with alternative ventilation systems is not necessarily above average even though they probably have less efficient systems for heat recovery from the exhaust air than conventional systems [21]. All the investigated alternative ventilation systems have some sort of demand-controlled ventilation. Some report, in addition, seasonally adapted airflow rates. Meaning that the airflow rates are deliberately reduced during low outdoor air temperatures.

The impact of seasonal adaptation on indoor climate is not investigated in depth, but the results do not indicate that such seasonal adaptation reduces PAQ or increases indoor-air related symptoms (Table 2, page 26). This is demonstrated in Paper VI where a simplified ventilation system with direct air supply has been investigated. An increase of outdoor air temperature correlates significantly with an increased prevalence of all PAQ-related questions and some SBS-symptoms like: “Are you tired?”, “Does your head feel heavy?”, “Do you have a headache?”. The reduction in SBS-symptoms in winter cannot be caused by an increase in the airflow rate, since this rate can be assumed to be about the same or less in January than June. Instead, it is probably caused by a lower room air temperature (due to a lower supply air temperature and increased transmission losses).
The studies of Fang et al. [42] support this assumption. They studied PAQ, SBS-symptoms and performance of office work at three levels of air temperature and humidity and two levels of ventilation rate (20°C/50% RH, 23°C/50% RH, 26°C/60% RH at 10 ℓ/s per person outside air, and 20°C/40% RH at 3.5 ℓ/s per person outside air). This study shows that the impact of PAQ of decreasing the ventilation rate from 10 to 3.5 ℓ/s per person could be counteracted by a decrement of temperature and humidity from 23°C/50% RH to 20°C/40% RH. Several SBS symptoms were alleviated at low levels of temperature and humidity despite a coincident reduction of ventilation rates. This is consistent with several other studies demonstrating that that warm humid air is perceived as less fresh and less acceptable, and that SBS symptoms such as fatigue and headache may be caused by exposure to air at slightly raised temperature and humidity [53, 54, 55, 56].

This implies that PAQ can be maintained at a high level despite a reduction of airflow rates if this appears coincident in time with a relatively low indoor air temperature. A control strategy for façade ventilation in cold climates must be based on this association to reduce problems with unpleasant draught during cold weather. This can be achieved by DCV with temperature-compensated CO_2 control (Figure 10, page 37). Such a control strategy could improve thermal comfort, and reduce energy use for heating, without compromising PAQ during cold weather. In addition, it could improve IAQ during warm weather with only a slight increase in energy use. Such a strategy might lead to negative consequences for IAQ related symptoms if the pollution load is considerably influenced by factors such as cleaning standard, emissions from building materials, and pollution caused by moisture problems. Such solutions presuppose that the total pollution load is always dominated by pollution from the occupants, when occupants are present in the room. This strategy can make it possible to achieve good indoor climate with low-cost ventilation systems in cold climates. There is a need for this in Norway because of shortage of funding [6, Paper VI], but such solutions should be even more relevant in the less wealthier part of the world.

3.2.3 Temperature control with ground-coupled ducts

Sufficient temperature control during hot periods can be achieved with ground-coupled fresh air intake ducts in climates with cool night temperatures (Paper VII). Air-cooling with this method is based on forced ventilation at nights to cool down the thermal mass in the ground-coupled duct and the surfaces enclosing the occupied zones. Sufficient air-cooling requires a culvert surface area of 1-2 m^2/pupil in typical Norwegian climate presupposed demand controlled displacement ventilation. This cooling method is well suited for handling considerable peak loads. This conclusion is consistent with the results of Wachenfeldt [43] who also found that the cooling potential could be further increased by active mixing of the air in the ground-coupled duct.

The use of such concrete culverts will, together with suitable airflow control, ensure that the supply air is colder than room air, which is crucial for functional displacement ventilation. Another interesting issue is that humans adapt to a higher temperature after a period of exposure, meaning that we adapt to or even appreciate a higher indoor air temperature after a long warm period [75,76]. This indicates that culvert cooling might be in a good balance with human levels of acceptance, since this will give a slight increase in indoor temperature after several hot days.

3.2.4 Closing perspectives on ventilation control

Environmental threats such as climate change and severe inequalities in wealth and resource use are grave global challenges [77]. Mankind must strive towards a more energy efficient and sustainable built environment since building and construction activities account for about one third of global resource consumption [77,78]. Buildings in Norway account for 40% of the total annual energy use and about 50% of the electrical energy use [79]. The use of electricity has increased with 1.5% per year during the 1990s [80]. Showing a substantial need to improve the energy efficiency of buildings.

One step forward is to utilize the potential of DCV to reduce the energy use for ventilation purposes without compromising the indoor environment. There are many possibilities for the application of DCV and new knowledge about the importance of outdoor air supply, because of awareness of its positive effect on sick leave and productivity [23,81], should lead to a wish to increase the outdoor air supply in comfort ventilation applications. This will further increase the necessity and profitability of DCV-systems.

Another interesting reflection is that the ventilation rates prescribed in existing ventilation standards do not include the impact of air temperature and humidity [16,57]. These standards are in practice a barrier towards a pragmatic ventilation control with temperature-compensated CO_2-set point (Figure 10, page 37) and the rational basis for this seems dubious. This should be investigated further because it might lead to an unnecessary use of energy during cold weather.

In existing buildings with an unacceptable outdoor air supply, simple retrofitting with DCV can exploit ventilation air paths and the outdoor air supply better. In some cases this could be a profitable alternative to an extensive refurbishment.

The challenge goes to the manufactures to develop equipment that provides profitability for the building owners when completely installed. There is a growing interest in more environmentally favorable technical equipment. Products that contribute to both a better environment and increased profitability will probably have a bright future. There is a rapid technological development towards cheap, reliable multi-sensors with wireless communication with a building management system [82]. This development will probably make DCV a more attractive option in the near future and hopefully improve the reliability of ventilation systems by better monitoring of real performance, making it possible to detect, diagnose and repair faults before it leads to adverse health consequences.

4 MAIN CONCLUSIONS

4.1 Impact of air filters on indoor climate in schools

Conventional use of bag air filter can contribute with a significant pollution load to the indoor air even in well functioning ventilation systems. Schools with a well functioning ventilation system without bag air filters in the air supply path can be expected to have better perceived indoor air quality than schools with a supply air filter assuming normal frequency of filter replacement. These results do not challenge the benefits of air filtration with respect to removing particles from the supply air, but it demonstrates that normal use of bag-filters are associated with negative by-effects influencing the quality of supply air and the perceived indoor climate. Conventional practice on documenting filter performance is insufficient because it does not take into account emissions from particles trapped in supply air bag-filters. There is an urgent need to improve filtration products for comfort ventilation.

Turning the AHU off, or reducing the airflow outside working or school hours, would further increase the sensory pollution emitted by a used bag filter immediately after the AHU is turned on, compared with continuous airflow through the AHU. No significant differences between operating conditions was found after outside air had been passed through the filter for 2 hours.

4.2 Effect of ventilation control on energy use

Primary school classrooms in Oslo have on average 22 occupants present, while airflow rates are normally designed for 30 occupants. Thus, typically only 74% of the classroom's maximum occupancy capacity is being utilized. The average occupancy density in classrooms is 0.37 pupils/m^2. The classroom is typically used 4 hours each weekday for normal school activities.

DCV-CO$_2$ and DCV-IR reduce the energy use for ventilation purposes in the average classroom to respectively 38% and 51% of the corresponding energy use for a CAV-system operating with full airflow from 7 AM to 5 PM. These are conservative estimates of the energy saving potential of DCV, compared with a well-functioning CAV-system.

5 SUGGESTIONS FOR FURTHER STUDIES

5.1 Adequate documentation for filtration products

Systems with conventional filtration techniques have a limited ability to continuously maintain the intended quality of the supply air. Conventional practice on documenting filter performance (arrestance and retention) is misleading since emissions from particles trapped in supply air bag-filters constitute an IAQ problem. There is therefore a need for further R&D on air filtration products and their overall impact on air quality and to develop more adequate standards for documentation of filtration products for comfort ventilation.

5.2 Impact of used bag filters on asthmatic and allergic children

Results derived from two different studies question the conventional assumption of filters as a relief measure, especially for asthmatic and allergic children. This should be investigated further with an increased sample of allergic subjects, and a more rigorous registration of the allergic and asthmatic diagnoses.

5.3 Impact of passive filtration

Some new schools use only passive filtration techniques based on precipitation of large particles (above 10 μm) due to low air velocity in a ground-coupled duct. The consequences of this technique should be evaluated especially regarding:

- Long term effect of penetration of small particles further into the ventilation system (dust accumulation) and the indoor environment.
- Impact on pupils with pollen allergy in the pollen season

5.4 Evaluation of indoor-air-temperature-controlled airflow rates

A strategy for controlling the ventilating airflow rate with an indoor temperature-compensated CO_2 set point is suggested (Figure 10, page 37). Such a control strategy could improve thermal comfort and reduce energy use for heating without compromising PAQ during cold weather. In addition it could improve thermal comfort and IAQ during warm weather with only a slight increase in energy use.

This seasonally adapted ventilation strategy should be implemented in a building and evaluated regarding functionality, indoor climate and Life Cycle Costs.

6 REFERENCES

1. Kreiss K. The epidemiology of building related complaints and illness. Ocup. Med. **4**, 1989, pp 575-592.
2. Mendell MJ, Heath GA. Do indoor pollutants and thermal conditions in school influence student performance? A critical review of the litterature. Indoor Air **15**, 2005, pp 27-52.
3. Fisk WJ. Estimates of potential nationwide productivity and health benefits from better indoor environments: an update. In: Spengler J. Samet JM and McCarthy FJ (eds), Indoor Air Quality Handbook, New York, McGraw-Hill, 4-1-4-36, 2000.
4. U.S. General Accounting Office. School Facilities: Conditions of America´s Schools. Washington, DC U.S. GAO. 1995.
5. Aftenposten Aften. Skremmende om skoleluft (Frightening quality of indoor air in schools). Leader 4.Nov 1997. http://tux1.aftenposten.no/bakgr/971104/aftleder.htm (in Norwegian).
6. Skjelmerud V. Inneklima i skolene: Mangler politisk vilje og økonomisk satsing (Indoor climate in schools: Lack of political will and economical funding). Norsk VVS (Norwegian HVAC magazine) 10/2002 (in Norwegian).
7. Faustman EM, Silbernagel SM, Fenske RA, Burbacher TM and Ponce RA. Mechanisms underlying children susceptibility to environmental toxicants. Environ. Health Perspect. **108** (Suppl. 1) 2000, pp 13-21.
8. Landrigan PJ. Environmental hazards for children in USA. Int. J. Occup. Med. Environ. Health. **11** 1998, pp 189-194.
9. Lambrecht BN, Hoogsteden HC, Diamant Z. The immunological Basis of Asthma. Inc. New York and Basel 2003.
10. Flatheim G. Bastardventilasjon, en farsott over Norden (Bastard ventilation, an epidemic disease in the Nordic countries). Norsk VVS (Norwegian HVAC magazine) 11/2000 (in Norwegian).
11. Fanger PO. Providing indoor air of high quality: challenges and opportunities. In: *Proceedings of the Healthy Buildings 2003*, Keynotes, pp. 1-9.
12. Swaller DL. Hierarchy Of HVAC Design Needs. ASHRAE Journal, August 2003, pp 41-43.
13. Maslow AH. Motivation and Personality. Harper & Row Publishers, Inc. 1954.

14. Leyten JL, Stanley RK. Robustness of buildings and HVAC systems as a hypothetical construct explaining differences in building complaint rates. In: *Proceedings of the Healthy Buildings 2000*, Vol. 2, pp. 469-474.
15. Myrefelt S. The reliability and availabilty of heating, ventilation and air conditions systems. Energy and Buildings, **36** (2004), pp.1035-1048.
16. CR 1752, Ventilation for Buildings: Design criteria for the indoor environment, CEN, Brussels, 1998
17. Smith A. Verbal communication with Aksel Smith, Managing Director of Kaare A. Rustad as. 2004.
18. Norwegian Health Department, Forskrift om miljørettet helsevern i skoler og barnehager (Regulations for environmental health protection in schools and day-care centers), Norway, 2003.
19. National Office of Building Technology and Administration, Norway, Guildelines to the Technical Regulations under the Planning and Building Act 1997 (in Norwegian), http://www.be.no, 3rd ed. April 2003.
20. Enova SF, Manual for Enøk normtall, Enova håndbok 2004:2 (in Norwegian) http://www.enova.no.
21. Schild PG (ed.), Dokka TH, Mysen M, Tjelflaat PO (2003), Bygningsintegrert ventilasjon – en veileder (Building-integrated ventilation – a guide), Økobygg, (in Norwegian) http://www.byggforsk.no/hybvent/
22. Ulriksen CI, Investigation and comparison of indoor environment quality (IEQ) and use of energy in buildings using hybrid ventilation systems vs. buildings with traditional Mechanical Ventilation Systems, Norwegian University of Science and Technology, Trondheim, 2002.
23. Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome, symptoms and productivity. Indoor Air **10,** 2000, pp. 222-236.
24. Clausen G. Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy, Indoor Air **14,** 2004, (s7), pp. 202-207.
25. Vik TA. Life Cycle Cost Assessment of Natural Ventilations Systems, Norwegian University of Science and Technology, Trondheim. Dr. ingeniøravhandling 2003:14.
26. NS-INSTA-800, Cleaning quality – measurement system for evaluation of cleanliness, 1.ed. Oct. 2000.

27. Scneider T, Løbner T, Nilsen SK, Petersen OH. Quality of Cleaning Quantified, Building and Environment, **29**, No.3, 1994, pp.363-367.
28. Schild PG. Pilot study – Jaer School, IEA ECBCS Annex 35 technical report, In: Principles of Hybrid Ventilation CD-ROM. http://www.byggforsk.no/hybvent/ 2002.
29. Tjelflaat, PO, Pilot Study Report for Mediå School, IEA ECBCS Annex 35, "Principles of Hybrid Ventilation" CD-ROM. http://www.byggforsk.no/prosjekter/hybvent/A04-grong_PSreport.pdf 2002.
30. Heiselberg PK (ed.). Principles of Hybrid Ventilation. IEA ECBCS Annex 35: Hybrid ventilation in new and retrofitted office and educational buildings, Aalborg University, Denmark, 2002.
31. Andersson K, Fagerlund I, Bodin L, Ydreborg B (1988). Questionnaire as an instrument when evaluating indoor climate. In: *Proceedings of Healthy Buildings 1988*, Vol. 1, pp. 139-145.
32. Andersson K. The MM-Questionnaires – A tool when solving Indoor Climate Problems. Örebro Medical Center Hospital. Sweden. 1993.
33. Cohen B. Explaining Psychological Statistics. Second Edition. John Wiley & Sons, Inc. New York. 2000.
34. Teijonsalo J, Pasanen P, Seppänen O. Filters of air supply units as sources of contaminants. In: *Proceedings of the 6th International Conference on Quality and Climate*, Vol. 6, 1993, pp. 533-538.
35. Strøm-Tejsen P, Clausen G, Toftum J (2003). Sensory pollution load from a used ventilation filter at different airflow rates. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, 257-261.
36. Pasananen P, Tejonsalo J, Seppänen O. Increase in perceived odour emissions with loading of ventilation filters, Indoor Air, **4**, 1994, 106-113.
37. Alm O, Clausen G, Fanger PO. Exposure-response relationship of emmisions from used ventilation filters. In: *Proceedings of Healthy Buildings* 2000, Vol. 2, 2000, pp. 245-250.
38. Clausen G, Alm O, Fanger PO. Sensory strength of used ventilation filters. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, 2002, pp. 344-349.
39. Clausen G, Alm O, Fanger PO. The impact of air pollution from used ventilation filters on human comfort and health. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, 2002, pp. 338-343.

40. Wargocki P, Wyon DP, Nielsen JB, Fanger PO. Call-centre occupant response to new and used filter at two outdoor air supply rates. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 3, 2002, pp. 449-454.
41. Sørensen B. Applications and Energy Consumption of Demand Controlled Ventilation Systems. Modelling, Simulations and Implementation of Modular Built Dynamical VAV Systems and Control Strategies. Narvik Institute of Technology. Norwegian University of Science and Technology, Trondheim. Doktor ingeniøravhandling 2002:34.
42. Fang L, Wyon DP, Clausen G, Fanger PO. Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance, Indoor Air **14,** 2004**,** (s7), pp. 74-81.
43. Wachenfeldt BJ (2003). Natural Ventilation in Buildings. Detailed Prediction of Energy Performance, in Department of Energy and Process Engineering. NTNU – Norwegian University of Science and Technology, Trondheim. Doktor ingeniøravhandling 2003:72.
44. Weschler CJ. Chemical reactions among indoor pollutants: what we've learned in the new millennium. Indoor Air **14,** 2004, (s7), pp. 184-194.
45. Bekö G, Halás O, Clausen G, Weschler CJ, Toftum J. Initial studies of oxidation processes on filter surfaces and their impact on perceived air quality. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, pp. 156-162.
46. Weschler CJ. Connections: Particles, sensory offending filters, the "sink" effect and nasal pungency treshold. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, 2002, pp. 1-11.
47. Weschler CJ. Ozone in the indoor environments: concentration and chemistry. Indoor Air **10**, 2000, pp 269-288.
48. Hyttinen M, Pasanen P, Salo J, Björkroth M, Vartiainen M, Kalliokoski P. Reactions of Ozone on Ventilation Filters, Indoor Built Environ, **12**, 2003, pp. 151-158.
49. Möritz M, Peters H, Nipko B, Rüden H. Capability of filters to retain airborne bacteria and moulds in heating, ventilating and air-conditioning (HVAC) systems. Int J Hyg Environ Health. **203**. pp. 401-409. 2001.
50. Simmons RB, Price DL, Noble JA, Crow SA, Ahearn DG. Fungal colonization of air filters from hospitals. Am Ind Hyg Assoc. **58**. pp 900-904. 1997.
51. Fisk WJ, De Almeida AT, Sensor-based demand-controlled ventilation: A review, Energy and Buildings, **29** (1998), pp.35-45.

52. International Energy Agency, in: Mansson L.-G (Ed.), Demand-controlled ventilating systems: case studies, Swedish Council for Building Research, Stockholm, 1993.
53. Wyon DP, Fanger PO, Olesen BW, The mental performance of subjects clothed for comfort at two different air temperatures, Ergonomics, Vol. 18, 1975, pp. 359-374.
54. Berglund L, Cains WS. Perceived air quality and the thermal environment. In: *Proceedings of IAQ '89*, San Diego1989, pp. 345-350.
55. Fang L, Clausen G, Fanger PO, Impact of temperature and humidity on the perception of indoor air quality, In: *Proceedings of the 7th International Conference on Indoor Air Quality and Climate*, Vol. 8 (2), 1998, pp. 80-90.
56. Toftum J, Jørgensen AS, Fanger PO. Effect of humidity and temperature of inspired air on perceived comfort, Energy and Buildings, **28**, (1), 1998, pp.15-23.
57. ASHRAE. ASHRAE Standard 62-2001: Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2001.
58. Fanger PO, Lauridsen J, Bluyssen P, Clausen G. Air pollution sources in offices and assembly halls, quantified by the olf unit. Energy and Buildings, **129**, 1988, pp. 7-19.
59. Pejtersen J, Bluyssen P, Kondo H, Clausen G, Fanger PO. Air pollution sources in ventilation systems, In: *Proceedings of CLIMA 2000*, 1989, Sarajevo, Vol. 3, pp. 139-144.
60. Skyberg K, Skulberg KR, Eduard W, Skåret E, Levy F, Kjuus H (2003). Symptoms prevalence among office employees and associations to building characteristics, Indoor Air, **13**, 2003, pp. 246-252.
61. Hult M. Schools with ventilation utilizing natural driving forces (Skolor med ventilation där självdräg används) Byggforskningsrådet Stockholm, A11:1997, ISBN 91-540-5805-8 (In Swedish).
62. Wålinder R, Norbäck D, Wieslander G, Smedje G, Erwall C, Venge P. Nasal patency and biomarkers in nasal lavage – the significance of air exchange rate and type of ventilation in schools. Int. Arch Occup Environ Health. **71**, pp. 479-486. 1998.
63. Wålinder R. Nasal Reactions and School Environment. Nasal Patency and Lavage Biomarkers in Relation to Ventilation, Cleaning and Some Indoor Air Pollutants. Uppsala University Library. 1999.
64. Smedje G, Norbäck D, Wieslander G, Wålinder R. Effects of contaminated supply air filters on symptoms from the eyes and nose – a double-blind experimental study, In:

Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Vol. 2, 2002, pp. 1032-1037.

65. Andersson K, Stridh G, Fagerlund I, Aslaksen W, Rudblad S. Comparison of the perceived indoor climate and symptoms reported by students and personnel in 16 senior high schools in Sweden. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol. 3, 2002, pp. 399-403.
66. Cox C and Bluyssen PM. Pollution by air filters: continuous vs intermittent air flow, In: *Proceedings of Healthy Buildings 2000*, Vol 2, pp 257-262
67. Persily A, Musse A, Emmerich S, Taylor M. Simulations of indoor air quality and ventilations impacts of demand controlled ventilation in commercial and institutional buildings. National Institute of Standards and Technology, Gaithersburg, USA 2003.
68. Drangsholt F. The applicability of demand controlled ventilating systems for assembly halls. Norwegian University of Science and Technology, Trondheim. Dr. ingeniøravhandling 1992:37.
69. K. Diem and C. Lentner (eds.). Documenta Geigy : scientific tables. 7th ed., Ciba-Geigy, Basel, Switzerland, 1975.
70. Comis ver. 3.1. Multizone airflow simulation program, EMPA, Switzerland.
71. EN 779:2002. Particulate air filters for general ventilation – Determination of filter performance. CEN – European committee for standardization. 2002.
72. NORDTEST Method NT VVS 128. Ventilation filters: Field test of efficiency. Nordtest Finland. 2001:11.
73. Wargocki P, Wyon DP, Nielsen JB, Fanger PO. Call-centre operator performance with new and used filters at two outdoor air supply rates. In: *Proceedings of Healthy Buildings 2003*, Vol. 3, pp. 213-218. 2003.
74. Seppänen O, Fisk WJ. Association of ventilation system type with SBS symptoms in office workers. Indoor Air, **12**, 98-112. 2002.
75. R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings, **34**, 2002, pp.549–561.
76. R.J. de Dear, G. Brager, D. Cooper, Developing an adaptive model of thermal comfort and preference, Final Report on RP-884, Macquarie Research Ltd. Australia, 1997.
77. The Worldwatch Institute. State of the World, Annual report 1984 through 2005. A Worldwatch Institute Report on Progress Toward a Sustainable Society. W.W. Norton&Companay New York London. 1984-2005.

78. Schmid P. The Challenge: Proposals for Strategies and Targets Toward Building. Special Issue article in: *The Future of Sustainable Construction*. ISBN 1-886431-09-4. 2003.
79. BAE-rådet. Forskning og utvikling i bygg-, anleggs- og eiendomsnæringen. Utfordringer og samfunnsgevinster. BNL, Oslo, 2002.
80. Myhre L, Pettersen TD, Sustainable Construction In Norway: Climate Changes and Energy Challenges. Special Issue article in: *The Future of Sustainable Construction*. ISBN 1-886431-09-4. 2003.
81. Milton DK, Glencross PM, Walters MD. Risk of sick leave associated with outdoor air supply rate, humidifications, and indoor complaints. Indoor Air, **10**, pp. 212-221. 2000.
82. Drysdale A, Olesen B, Toftum J, Hök B, Gløersen PG, Østbø NP, Jensen GU, Jensen JM, Friis MS. Multi-Sensors for Indoor Environment Control – A feasibility study carried out for the Nordic Innovation Center - Final report. Danish Technological Institute, March 2004.

7 GLOSSARY

7.1 Definitions

Air-handling unit

Standard packaged unit with HVAC-components like air filters, fans, heating-/cooling batteries.

Air quality reliability of ventilation system

The ability of the ventilation system to maintain the intended quality of the supply air throughout its lifetime.

Carbon dioxide

Human exhalation gas with no smell or colour.

Constant air volume

Ventilation system with constant airflow rates

Demand-controlled ventilation

Variably ventilating according to the pollutant load (ventilation by demand).

DTU split scale

Scale from clearly unacceptable to clearly acceptable used for perceived air quality assessments. The scale is splitted in the middle, making it impossible to score in the middle of the scale. The scale was developed at Denmark Technical University (DTU).

Façade ventilation:

Façade ventilation is defined as mechanical exhaust ventilation with supply air taken in through the façade and distributed unheated to classrooms at ceiling level via an insulated air-distribution duct with air-supply nozzles

GLM Repeated Measures

The GLM Repeated Measures procedure provides analysis of variance when the same measurement is made several times on each subject or case. If between-subjects factors are specified, they divide the population into groups. Using this general linear model procedure, you can test null hypotheses about the effects of both the between-subjects factors and the within-subjects factors. You can investigate interactions between factors as well as the effects of individual factors. In addition, the effects of constant covariates and covariate interactions with the between-subjects factors can be included.

GLM Mulitvariate method

The GLM Multivariate procedure provides regression analysis and analysis of variance for several dependent variables by one or more factors and/or variables. The factor variables divide the population into groups.

Hybrid ventilation

Hybrid ventilation is here defined as a balanced mechanical ventilation system designed for extremely low-pressure losses enabling a degree of exploitation of natural driving forces.

Infrared sensor

Sensor for detecting room movements by occupants by infrared beams.

Life Cycle Cost (LCC)

All costs from project inception to disposal of equipment. LCC applies to equipment, systems and projects. LCC costs are found by an analytical study of total costs experienced during the life of equipment or projects.

Mann-Whitney test

A nonparametric test equivalent to the t-test. Tests whether two independent samples are from the same population. It is more powerful than the median test since it uses the ranks of the cases. Also called Wilcoxon-Mann-Whitney test.

Mechanical reliability of ventilation systems

The ability of the ventilation system to maintain the intended airflow rates throughout its lifetime.

Odds Ratio

Odds Ratio or Cross-Product Ratio is a measure of strength of association between different factors/covariates. The measure consists of the ratio between the products of the diagonally opposite cells in the 2 x 2 table.

Paired-Samples T Test

The Paired-Samples T Test procedure compares the means of two variables for a single group. It computes the differences between values of the two variables for each case and tests whether the average differs from 0.

Ventilation

Process of supplying or removing air by natural or mechanical means to or from any space.

7.2 Abbreviations

DCV-CO_2: Demand-controlled ventilation – controlled by a CO_2-sensor
DCV-IR: Demand-controlled ventilation – controlled by a Infrared occupancy-senor
IAQ: Indoor Air Quality
MET: Metabolic rate, 1 MET (=58.2 W/m^2) is the metabolic rate of a sedentary person at rest
OR: Odds Ratio
PAQ: Perceived Air Quality
ppmv Parts per million of a gas in air [volume/volume x 10^6]
SBS: Sick Building Syndrome

8 APPENDICES

Paper I	Mysen M, Fostervold KI, Schild PG. A questionnaire survey of the impact of used supply air filter on health symptoms and perceived air quality in schools.
Paper II	Mysen M, Fostervold KI, Schild PG. An intervention study of the impact of supply air filters on perceived air quality and health symptoms in a primary school.
Paper III	Mysen M, Clausen G, Bekö G, Halás O. The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters.
Paper IV	Mysen M, Berntsen S, Nafstad P, Schild PG (2005). Occupancy density and benefits of demand controlled ventilation in Norwegian primary schools.
Paper V	Mysen M, Rydock JP, Tjelflaat PO. Demand controlled ventilation for office cubicles – can it be profitable?
Paper VI	Mysen M, Schild PG, Hellstrand V, Thunshelle K (2005). Evaluation of simplified ventilation system with direct air supply through the facade in a school in a cold climate.
Paper VII	Mysen M, Schild PG, Tjelflaat PO. Cooling performance of ground-coupled air intake ducts.
Questionnaire	Used in Paper I, II and VI (In Norwegian)
DTU split scale	Used in Paper II and III (In Norwegian)

Paper I Mysen M, Fostervold KI, Schild PG. **A questionnaire survey of the impact of used supply air filter on health symptoms and perceived air quality in schools.**

A questionnaire survey of the impact of used supply air filter on health symptoms and perceived air quality in schools

M. Mysen[1,2], K.I. Fostervold[3], P.G. Schild[1]

[1]*Norwegian Building Research Institute, P.O.Box 123 Blindern, NO-0314 Oslo, Norway*

[2]*Norwegian University Of Science And Technology (NTNU), Department of Energy and Process Technology, NO-7491 Trondheim, Norway*

[3] *Lillehammer University College (HIL), Faculty of Health and Social Work, N-2626 Lillehammer, Norway.*

Abstract

Several schools in Norway and Sweden have ventilation systems without a traditional bag filter in the supply air path. The consequences of this, regarding indoor air quality and associated health symptoms, are disputed. We have analysed data from a questionnaire survey conducted in several recently build or retrofitted schools in Norway with and without bag filters in the supply air path, to see if there are any indications of real differences regarding perceived air quality and SBS-symptoms (Sick Building Syndrome). In total 590 pupils from 26 classes in 13 schools have participated.

Pupils in the examined schools without filtered supply air, perceived the air quality to be better and had less SBS-related symptoms than pupils in the examined schools with filtered supply air. The results implicate a need to improve filtration products for comfort ventilation. However, given the importance of the consequences and the weaknesses of the experimental design, there is a need for conceptual replications of this study utilizing refined experimental design to confirm if conventional air filtration with bag filters is truly detrimental to PAQ- and SBS-symptoms in schools.

Keywords: Schools; Bag filter; Hybrid ventilation; Perceived air quality; Sick Building Syndrome; Allergy

1. Introduction

Several schools in Norway and Sweden have ventilation systems without conventional bag air filter in the supply air path. The consequences of this, regarding indoor air quality and associated health symptoms, is disputed. We have therefore analysed data from a Norwegian questionnaire survey conducted in several recently build or retrofitted schools with and without bag filters in the supply air path, to see if there are any indications of real differences regarding perceived air quality and SBS-symptoms.

2. Methods

2.1 Description of the schools, ventilation system and filtration

In total 590 pupils from 26 classes in 13 schools have answered in the same questionnaire. All the questionnaire surveys were conducted in the winter, before the main pollen season. Some information of schools and classes are listed in Table 1.

Table 1. Description of the schools. Primary schools includes up to 7th grade (age 13), while secondary schools comprise grades 8, 9 and 10.

School	Grade & group	Period for surveys	Number of participating pupils	Ventilation system	Building taken into use [year]	Filtration
Munkerud	5	Mar. 03	26	BMV	2002	Bag filter
	7		21			
Bratsberg	6	Mar. 02	14	BMV	1999	Bag filter
	7		13			
Løkkeberg	6	Mar. 02	25	BMV	1998	Bag filter
	7		19			
Hvalstad	6	Mar. 02	28	BMV	1999	Bag filter
	7		29			
Tredal	6	Mar. 02	25	Hybrid	2000	Bag filter
	7		23			
Grong primary	5	Mar. 02	19	Hybrid	1998	Bag filter
	6		21			
Grong secondary	9	Apr. 02	15	BMV	1997	Bag filter
	10		14			
Nordberg	10-1	Mar. 02	27	BMV	1997	Bag filter
	10-2		23			
Gjerde	6	Mar. 02	20	Hybrid	1998	No filter
	7		25			
Jaer	6	Mar. 02	19	Hybrid	1999	No filter
	7-1		14			
	7-2		14			
Bakkeløkka	9	Jan. 04	58	Hybrid	2002	No filter
Presterød	9-1	Mar. 02	25	Facade	2000	No filter
	9-2		24			
Revetal	9-1	Jan. 03	25	Facade	2000	No filter
	9-2		24			

Six of the schools have a balanced mechanical ventilation (BMV) system providing 100% fresh air (i.e. no recirculation). All BMV systems are equipped with at least one stage of bag air filtration, a heat exchanger and a heating battery along the supply air path. All these components are arranged in a standard packaged air-handling unit. The ventilation systems are operated with Constant Air Volume (CAV) and designed for diluting (mixed) ventilation of the occupied areas. The airflow rates were not measured, but it can be assumed that they comply with the existing Norwegian building code requiring a minimum airflow of 9 to 11 ℓ/s per pupil depending on the chosen building materials (National Office of Building Technology and Administration, 1997 - 3ed 2003). This gives at least 270 ℓ/s supply air in a classroom designed for 30 persons.

Five of the schools have a ventilation system denoted hybrid ventilation in this paper (Figure 1) providing 100% fresh air (i.e. no recirculation).

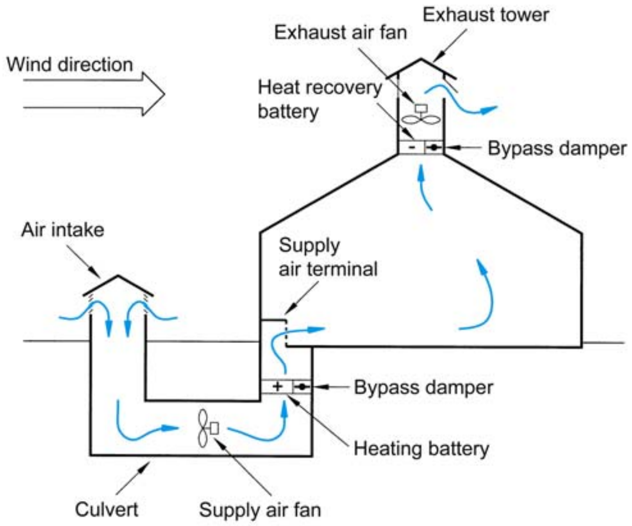

Figure 1. Hybrid ventilation with ground coupled duct - principle solution.

This is a balanced mechanical ventilation system designed for extremely low pressure losses enabling a degree of exploitation of natural driving forces. They all have a ground-coupled concrete duct were the supply air passes with very low air velocity. This leads to a significant precipitation of particles above 10 μm (Schild, 2002). The air is conditioned by a heat exchanger or preheat battery. Two of the systems are equipped with bag filters in the supply air path, the other three have no filtration beyond precipitation effect. All are controlled by some sort of Demand Controlled Ventilation (DCV) and designed for displacement ventilation of the occupied areas. The air flow rates are controlled by a CO_2- or a combined CO_2-/temperature-sensor. The airflow rate varies according to differences in occupancy and time of use, but measurements at two of the schools indicate that the average air flow during a day with normal school activity flow is about half (or less) the of corresponding airflow with CAV (Schild 2002, Wachenfeldt 2003). This is probably due to the following three factors: (i) The real time of use is in practise considerably less than the operation time of the air-handling unit with CAV, (ii) Average occupancy density is less than the design maximum, (iii) Displacement ventilation gives better ventilation efficiency than mixed ventilation (Awbi, 1991). In at least three of the schools the CO_2-sensors are mounted at a height of about 1.1 meter to exploit this effect.

Figure 2. Principle solution with facade ventilation. Source: White Arkitekter AB.

Two of the schools have a ventilation system denoted façade ventilation in this paper. Unconditioned air is taken in from the façade (Figure 2) and distributed directly to classrooms at ceiling level via short insulated short air-distribution duct with air-supply nozzles. Extract ducts from each classroom are collected at a central fan at roof level. This exhaust fan generates a negative pressure in each classroom relative to the outside. The supplied airflow rate is controlled by a temperature- or combined temperature/CO_2-sensor in each classroom, which controls the position of a damper in the extract duct from each classroom. The extract damper closes if the sensor measures a critically low temperature in the classroom. Mysen (2004) has described and analysed the functionality of the system at Revetal secondary school. There is no filtration of the supply air.

2.2 The bag air filters

The age and the standard of the bag filters were not examined, but it can be assumed to be at least EU7 in accordance with the normal understanding of the existing building code. Bag filters (typically EU7) are used in 90 to 95% of HVAC-applications for comfort ventilation (Smith 2005). The age is likely to be representative for filters in BMV-systems. It is normal to change the filters once or twice a year. An earlier study has shown that the pollution load from used bag filters increases during the first 13 weeks of use, and then stabilizes around a maximum pollution load of about 3-4 decipol (Tejonsalo et al., 1993). It has been shown that the reduction of ozone in the air passing a used filter is less during winter than summer in Finland (Hyttinen et al., 2003), indicating that the pollution load from used filters is somehow decreased during winter. The odour intensity (in terms of decipol) is independent of the airflow rate (Strøm-Tejsen et al, 2003). It can be assumed that the vast majority of the bag filters have been in use for so long that the average pollution load from the filters is close to the maximum expected pollution load from used bag filters during typical winter conditions.

2.3 Questionnaires

The questionnaire is repeated three times for each class during a period of two weeks. The class teacher has in most of the cases administrated the questionnaire. The class teacher has been told to avoid Mondays and days with considerable outdoor school activities. The questionnaire is answered in late during a day with normal school activities in the classroom.

The questionnaire consists of 45 simple yes/no questions regarding health symptoms, the indoor environment, and personal background information. The questionnaire is a Norwegian application of the Örebro questionnaire (Andersson et. al., 1988, Andersson, 1993), but which has been simplified to be suitable for intervention studies among children. The main difference is that the questions ask how the person is feeling at the present moment in time, instead of how the person has generally felt in the previous 3 months. All yes-answers are given the value of 1 (meaning they have a problem) and all no-answers are given the value 0. The mean score for each SBS-related question then yields the prevalence of the corresponding symptom at the school.

The questions *Are you tired?, Does your head feel heavy?, Do you have a headache?, Do you feel faint or dizzy?, Do you have problems concentrating?, Does your eyes itch or sting?, Are you horse, or is your throat dry?, Do you have a runny or stuffy nose?, Do you have a cough?, Do you have a cold?, Does your hands or face itch?, Are you nauseous or unwell in any other way?* are about SBS symptoms. These are analysed separately and grouped together in an index denoted 'BS-index' (Building Symptom Index) in this paper.

BS-index is defined as:

$$BS-index = \frac{\sum_{i=1}^{n}\left(\overline{S}_i\right)}{12} \tag{1}$$

Where $\overline{S}_i$ is the schools average score (%) for question *i*, and 12 is the number of questions used in the index. A BS-index of 1 means that all pupils have answered yes to the question on all three occasions that the questionnarie is held. The three questions

Does the air feel heavy or poor?, Does the air feel dry? and *Are there any unpleasant odours?* concerns Perceived air quality (PAQ). These are analysed separately and grouped together in an index denoted 'PAQ-index' in this paper. The PAQ-index is calculated in a similar manner as the BS-index.

2.4 Statistical analysis

All SBS and PAQ related questionnaire responses and resulting BS- & PAQ-indices are used as dependent variables in a GLM Multivariate test to analyse influence of the ventilation systems (BMV, Hybrid ventilation and Facade ventilation). This analyse is done in two steps. The first step is controlled for pupils' sex, class-level (age) and ventilation system, together with the responses to questions about personal background (*Do you share your bedroom with any brothers or sisters?, Do you have wall-to-wall carpet in your bedroom?, Are your bedroom well ventilated at nights?, Does anyone smoke at home?, Do you have a pet at home?, Do you have frequent contact with other pets?)* and the responses to the question *Have you eaten anything today?*.

The second step is in addition controlled for the influence of conventional air filtration.

The Multivariate test is then repeated to analyse influence of conventional air filtration controlled for the influence of ventilation system together with all the confounders mentioned in step 1 and all noise and light-related responses, since they are assumed to be independent of PAQ.

3 Results

3.1 General results

The mean scores for each class are shown in Table 2.

Table 2. Results from the examined schools. The first 16 classes have filtered supply air.

School	Grade & group	PAQ-index (all pupils)	BS-index (all pupils)	Number of not allergic/ asthmatic pupils	Number of allergic/ asthmatic pupils	BS-index (not allergic/ asthmatic pupils)	BS-index (allergic/ asthmatic pupils)
Munkerud	5	.26	.19	19	7	.17	.23
	7	.57	.27	15	6	.26	.32
Bratsberg	6	.27	.22	9	5	.13	.36
	7	.25	.20	10	3	.19	.22
Løkkeberg	6	.37	.22	16	9	.22	.23
	7	.04	.09	10	9	.07	.10
Hvalstad	6	.13	.20	22	6	.15	.38
	7	.34	.18	23	6	.18	.17
Tredal	6	.08	.12	19	6	.13	.10
	7	.45	.22	15	8	.18	.29
Grong primary	5	.23	.34	12	7	.29	.40
	6	.41	.24	13	8	.24	.22
Grong secondary	9	.66	.33	11	4	.32	.35
	10	.65	.24	9	5	.20	.31
Nordberg	10-1	.37	.35	19	7	.31	.45
	10-2	.26	.27	18	5	.23	.41
Gjerde	6	.09	.16	18	2	.17	.08
	7	.05	.19	19	5	.21	.13
Jaer	6	.22	.20	13	6	.16	.30
	7-1	.01	.10	7	7	.11	.08
	7-2	.12	.09	11	3	.08	.12
Bakkelokka	9	.27	.26	41	17	.25	.29
Presteroed	9-1	.24	.29	17	8	.28	.32
	9-2	.20	.30	20	4	.30	.24
Revetal	9-1	.22	.26	17	8	.24	.32
	9-2	.26	.39	15	9	.25	.38
Mean/total		**.27**	**.23**	**418**	**170**	**.21**	**.27**

Table 3 shows the PAQ- and BS-indices for the different types of ventilation system in primary and secondary schools.

Table 3. PAQ- and BS-indices for different types of ventilation system.

Type of schools and ventilation system	PAQ-index	BS-index
All schools with BMV	.33	.23
All schools with hybrid ventilation	.20	.21
All schools with facade ventilation	.23	.29
All schools with filter	.32	.23
All schools without filter	.18	.23
Primary schools with BMV	.28	.20
Primary schools with hybrid ventilation without filter	.10	.16
Primary schools with hybrid ventilation with bag filter	.29	.22
Secondary schools with BMV	.43	.30
Secondary school with hybrid ventilation without filter	.23	.26

Figure 3 shows the PAQ-index value based on class' means scores with its 95% confidence interval for the two groups of classes, with used bag filters (16 classes) and without used bag filters (10 classes).

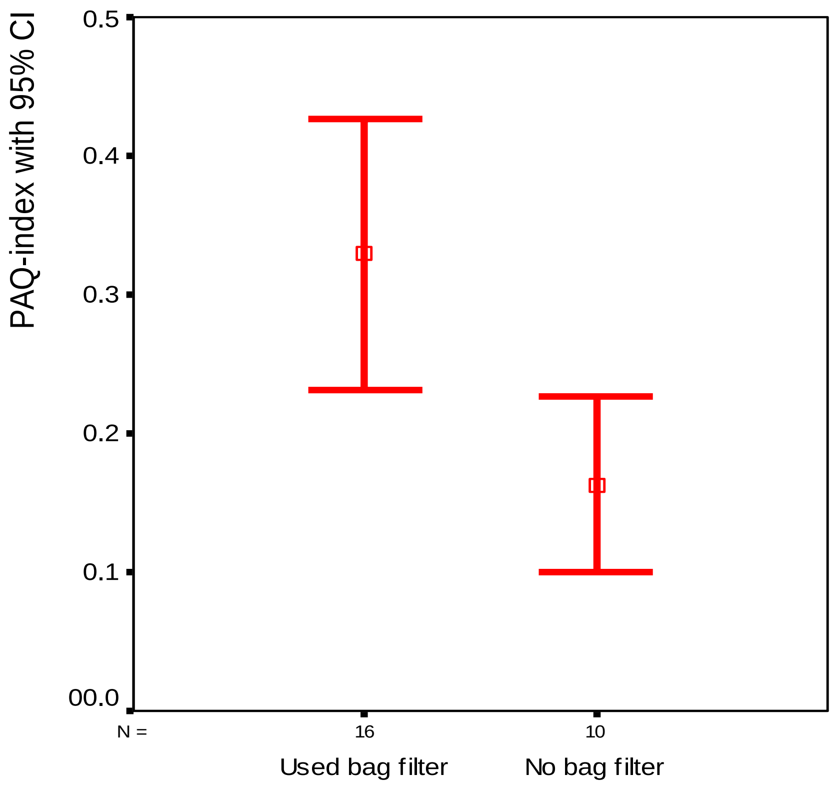

Figure 3. PAQ-index based on the mean PAQ-index for each class. N is the number of classes.

Table 4 shows crude values of the mean PAQ and BS-index for the two groups non-allergic/asthmatic pupils and allergic/asthmatic pupils, and the result of an independent sample t-test between these two groups.

Table 4. PAQ- and BS-indices for different types of ventilation system.

Use of filter	Allergy or asthma?	Number of pupils	Mean PAQ-index	PAQ-index T-test statistics	Mean BS-index	BS-index T-test statistics
Filtered supply air	No	241	.28	t=3.0, p=.014	.20	t=3.4, *p=.001*
	Yes	101	.39		.28	
Not filtered supply air	No	178	.17	t=1.0, p=.25	.22	t=1.6, *p=.12*
	Yes	70	.20		.26	

3.2 Confounder-controlled results

Table 5 shows the means of the PAQ and BS-index adjusted for age (class-level), sex and personal background. The values in Table 6 are in addition adjusted for the influence of filter.

Table 5. PAQ and BS-index adjusted for age, sex and personal background.

				95% Confidence Interval	
Dependent Variable	Ventilation system	Mean	Std. Error	Lower Bound	Upper Bound
PAQ-index	BMV	.337[a]	.018	.301	.373
	Hybrid ventilation	.209[a]	.020	.170	.248
	Facade ventilation	.191[a]	.032	.129	.254
BS-index	BMV	.233[a]	.011	.211	.254
	Hybrid ventilation	.210[a]	.012	.187	.233
	Facade ventilation	.256[a]	.019	.218	.293

a. Evaluated at covariates appeared in the model: Class level = 7.51, Sex (quota girls) = .49, Do you have frequent contact with other pets? = .6315, Do you have a pet at home? = .6449, Does anyone smoke at home? = .3794, Are your bedroom well ventilated at nights? = .6950, Do you have wall-to-wall carpet in your bedroom? = .2124, Do you share your bedroom with any brothers or sisters? = .0889, Have you eaten anything today? = .8634.

Table 6. PAQ and BS-index adjusted for the influence of filter together with age, sex and personal background.

				95% Confidence Interval	
Dependent Variable	Ventilation system	Mean	Std. Error	Lower Bound	Upper Bound
PAQ-index	BMV	.253[a]	.025	.205	.302
	Hybrid ventilation	.260[a]	.022	.217	.303
	Facade ventilation	.284[a]	.037	.212	.356
BS-index	BMV	.210[a]	.015	.181	.240
	Hybrid ventilation	.223[a]	.013	.197	.249
	Facade ventilation	.280[a]	.022	.237	.324

a. Evaluated at covariates appeared in the model: Class level = 7.51, Sex (quota girls) = .49, Do you have frequent contact with other pets? = .6315, Do you have a pet at home? = .6449, Does anyone smoke at home? = .3794, Are your bedroom well ventilated at nights? = .6950, Do you have wall-to-wall carpet in your bedroom? = .2124, Do you share your bedroom with any brothers or sisters? = .0889, Have you eaten anything today? = .8634, Filter = 1.42.

Table 7 shows the influence of filter on the PAQ index adjusted for confounders. This table also includes adjusted responses of the significant influenced PAQ- and SBS-responses.

Table 7. Adjusted prevalence means of the PAQ- index and some PAQ and SBS-responses.

				95% Confidence Interval	
Dependent Variable	Filter	Mean	Std. Error	Lower Bound	Upper Bound
PAQ-index	Filtered supply air	.314[a]	.017	.280	.348
	No filter	.183[a]	.022	.141	.226
Does the air feel heavy or poor?	Filtered supply air	.440[a]	.025	.391	.489
	No filter	.218[a]	.031	.158	.279
Does the air feel dry?	Filtered supply air	.321[a]	.024	.273	.368
	No filter	.197[a]	.030	.138	.256
Do you have a cough?	Filtered supply air	.260[a]	.024	.213	.306
	No filter	.150[a]	.029	9.256E-02	.208
Do you have a runny or stuffy nose?	Filtered supply air	.373[a]	.027	.321	.426
	No filter	.257[a]	.033	.192	.322
Does your eyes itch or sting?	Filtered supply air	.154[a]	.018	.119	.189
	No filter	8.476E-02[a]	.022	4.146E-02	.128

a. Evaluated at covariates appeared in the model: Ventilation system = 1.91, Class level = 7.50, Sex (quota girls) = .49, Do you have frequent contact with other pets? = .6309, Do you have a pet at home? = .6453, Does anyone smoke at home? = .3775, Are your bedroom well ventilated at nights? = .6958, Do you have wall-to-wall carpet in your bedroom? = .2142, Do you share your bedroom with any brothers or sisters? = .0897, Have you eaten anything today? = .8622, Are you bothered by the sun light? = .1298, Is it reflections on the blacboard? = .1251, Is the light sufficient? = .8636, Are you bothered by noise from the ventilation system? = .1384, Are you bothered by noise from outside? = .0871, Are you bothered by noise from other classes? = .3195, Are you bothered by noise from other pupils in the class? = .3838, Is it difficult to hear what is said in the classroom? = .0980, Is it diffucult to see the wrighting on the blackboard? = .0758.

With all pupils included in the sample, there was a significant association between filter and the PAQ-index after adjustment for confounders, F(1,557)=15.9, *p=.000* (observed power = .98, partial eta squared=0.028).

4 Discussion

There seem to be an influence of the ventilation system on PAQ and some SBS-symptoms (Table 2, Table 3) and conventional use of air filtration seems to be a contributory cause of the difference (Table 3, Figure 3). Filters are assumed to be a relief measure especially for asthmatic and allergic children. The comparison between non-allergic/asthmatic pupils and allergic/asthmatic pupils does not indicate that the latter group is relatively relieved (Table 2, Table 4). The surveys are conducted outside main pollen season (Table 1).

After adjustment for confounders, where age had a significant influence, indoor air quality is perceived to be best in the schools with Hybrid ventilation and Facade ventilation (Table 5). Surprisingly this difference almost vanished when the PAQ-index was adjusted for the influence of filter (table 6). A reanalyse of data with respect to whether the supply air was filtered or not, highlights the conventional use of air filter as a risk factor for PAQ (Table 7). It also seems like use of bag air filtration is a risk factor for several SBS-symptoms like, *, Do you have a cough?, Do you have a runny or stuffy nose?* and *Does your eyes itch or sting?.*

This is consistent with the results of Smedje et al. (2002). She conducted a double-blind cross over design study with old and new filters in a school building. She found by objective clinical methods, that presence of a used supply air filter reduced the volume of the nose and increased adverse eye and throat symptoms among the pupils. Wålinder et al (1998) conducted nasal investigations among school personnel in 12 schools (Uppsala, Sweden) with different ventilation systems. He observed that personnel in schools with mechanical ventilation had more symptoms and signs of reduced nasal patency and higher concentration of some biomarkers for inflammatory mucosal reaction in nasal lavage fluid, although schools with natural ventilation had a lower air exchange rate than mechanically ventilated schools.

Marie Hult (1997) has evaluated different school ventilations concepts in Sweden. She found that some concepts without filtration had a relatively low prevalence of SBS-symptoms compared with other schools with filtration.
Numerous studies not performed in a school environment, have documented that used bag filters can be a significant source of indoor air pollution with a negative impact on perceived air quality and indoor-air related health symptoms (Clausen et. al, 2002) (Clausen 2004). It is also shown that presence of a used filter can have a negative impact on human performance (Wargocki et al., 2003). It is believed that organic compounds captured by a filter somehow causes a net pollution load from used filter because these compounds react with ozone creating oxidised products that might be odorous (Weschler, 2004).

Seppänen and Fisk (2002) analysed several independent field studies in order to compare mechanically and naturally ventilated buildings. They found a lower prevalence of SBS-symptoms in naturally ventilated buildings, which are assumed to have no supply air filtration.

However, significant differences based on questionnaire responses in the present study cannot be considered as valid statistical proof of a general adverse impact of filters on PAQ and SBS-symptoms. PAQ and especially SBS-symptoms, is influenced by innumerable factors at the different schools, acting and interacting in a way beyond control of the experimental design. Physical parameters such as temperature, humidity, CO_2-level and particles were not measured during the surveys. The real condition of the AHUs with filters were not thoroughly evaluated and described. However, Skyberg et al. (2003) found no association between risk of SBS-symptoms and last change of air filters. The ventilation systems were divided into two groups whether the air filters had been used for more or less than two years, which indicate no additional adverse impact of very old filters. This is consistent with the results of Tejonsalo et al. (1993). They showed that the odour intensity caused by a used bag filter stabilizes around 3-4 decipol after 13 weeks of use.

Other confounders such as outdoor air quality, displacement ventilation, height of ceiling (room volume) might lead to a biased response, explaining to some extent differences in the PAQ-index. The hybrid-ventilated schools should be quite comparable regarding the area where the school was situated (outdoor air quality), ceiling height, ventilation efficiency (they all have displacement ventilation) and air flow rates. The PAQ-index of the hybrid-ventilated schools with used bag filter was quite similar to the PAQ-index in schools with BMV and used bag filter. This indicates that these factors did not have much influence on the PAQ-index, but the low number of hybrid ventilated schools (with or without filtration) limits the possibility of drawing firm conclusions.

The analysis is also based on all the participating pupils. Pupils in the same class might influence each other’s scores, making the sample independency dubious (Cohen, 2000).

Although this cross-sectional study is not infallible, it is strengthen by its considerable size and by the fact that it was conducted in real field environments. The statistical strength of the results, especially towards PAQ, is convincing. Considering its consistency with other studies, the results seem plausible. This indicates that practical use of conventional filtration technique can be a more important risk factor for the indoor climate than earlier believed. These results do not challenge the benefits of air filtration with respect to removing particles from the supply air, but it demonstrates that conventional air filtration with bag-filters is associated with negative by-effects influencing the quality of supply air. Conventional practice on documenting filter performance (arrestance and retention) seems insufficient because it does not take into account emissions from particles trapped in supply air bag-filters (EN 779:2002). These emissions constitute an IAQ problem. This indicates a need to improve filtration products for comfort ventilation. However, given the importance of the consequences, there is a need for conceptual replications of this study utilizing refined experimental design too confirm if used bag filters have a real “field” impact on PAQ and SBS-symptoms in schools.

5 Conclusions

Pupils in the examined Norwegian schools without filtered supply air, perceived the air quality to be better and had less SBS-related symptoms than pupils in the examined schools with filtered supply air. The results implicate a need to improve filtration products for comfort ventilation. However, given the importance of the consequences and the weaknesses of the experimental design, there is a need for conceptual replications of this study utilizing refined experimental design to confirm if conventional air filtration with bag filters is truly detrimental to PAQ and SBS-symptoms in schools.

6. Acknowledgement

This work has been supported by the Norwegian Research Council as a part of the research program “Environmentally favourable energy use in buildings”. Christian Ulriksen conducted the questionnaire surveys in 10 of the examined schools.

7. References

Andersson K, Fagerlund I, Bodin L, Ydreborg B (1988). Questionnaire as an instrument when evaluating indoor climate. In: *Proceedings of Healthy Buildings* 1988, Vol. 1, pp. 139-145.

Andersson K (1993). The MM-Questionnaires – A tool when solving Indoor Climate Problems, Örebro Medical Center Hospital. Sweden.

Awbi, HB (1991) Ventilation of buildings, New York, E & FN Spon.

Clausen G (2004). Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy, Indoor Air, **14** (s7), 202-207.

Clausen G, Alm O, Fanger PO (2002). The impact of air pollution from used ventilation filters on human comfort and health. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, pp. 338-343.

Cohen, B (2000) Explaining Psychological Statistics, John Wiley & Sons, Inc. New York.

EN 779:2002. Particulate air filters for general ventilation – Determination of filter performance. CEN – European committee for standardization. 2002.

Hult, M (1997) Schools with ventilation utilizing natural driving forces (Skolor med ventilation där självdräg används), Byggforskningsrådet Stockholm, A11:1997, ISBN 91-540-5805-8 (In Swedish).

Hyttinen M, Pasanen P, Salo J, Björkroth M, Vartiainen M, Kalliokoski P (2003). Reactions of Ozone on Ventilation Filters, Indoor Built Environ, **12**, 151-158.

Mysen M, Schild PG, Hellstrand V, Thunshelle K (2005). Evaluation of simplified ventilation system with direct air supply through the facade in a school in a cold climate, Energy and Buildings, **37** Vol. 2, pp. 157-166.

National Office of Building Technology and Administration, Norway (3rd ed. April 2003). Guildelines to the Technical Regulations under the Planning and Building Act 1997 (in Norwegian), http://www.be.no/..

Schild PG (2002). Pilot study – Jaer School, IEA ECBCS Annex 35 technical report, In: *Principles of Hybrid Ventilation CD-ROM.* http://www.byggforsk.no/hybvent/

Seppänen O, Fisk WJ (2002). Association of ventilation system type with SBS symptoms in office workers, Indoor Air, **12**, 98-112.

Skyberg K, Skulberg KR, Eduard W, Skåret E, Levy F, Kjuus H (2003). Symptoms prevalence among office employees and associations to building characteristics, Indoor Air, **13**, 246-252.

Smedje G, Norbäck D, Wieslander G, Wålinder R (2002). Effects of contaminated supply air filters on symptoms from the eyes and nose – a double-blind experimental study. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 2, pp. 1032-1037.

Smedje G, Norbäck D (2000). New ventilation systems at selected schools in sweden – effects on asthma and exposure, Arch Environ Health. **55** (1), pp. 18-25.

Smith A. Verbal communication with Aksel Smith, Managing Director of Kaare A. Rustad as. 2005.

Strøm-Tejsen P, Clausen G, Toftum J (2003). Sensory pollution load from a used ventilation filter at different airflow rates. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, 257-261.

Teijonsalo J, Pasanen P, Seppänen O (1993). Filters of air supply units as sources of contaminants. In: *Proceedings of the 6th International Conference on Quality and Climate*, Vol. 6, pp. 533-538.

Wachenfeldt, BJ (2003) Natural ventilation in Buildings. Detailed Prediction of Energy Performance, Doktor Ingeniør Thesis at Norwegian University of Science and Technology, Department of Energy and Process Engineering.

Wargocki P, Wyon DP, Nielsen JB, Fanger PO (2003). Call-centre operator performance with new and used filters at two outdoor air supply rates. In: *Proceedings of Healthy Buildings* 2003*,* Vol. 3, pp. 213-218.

Weschler CJ (2004). Chemical reactions among indoor pollutants: what we've learned in the new millenium, Indoor Air, **14** (s7), 184-194.

Wålinder R, Norbäck D, Wieslander G, Smedje G, Erwall C, Venge P. Nasal patency and biomarkers in nasal lavage – the significance of air exchange rate and type of ventilation in schools. Int. Arch Occup Environ Health. **71**, pp. 479-486. 1998

Paper II Mysen M, Fostervold KI, Schild PG. **An intervention study of the impact of supply air filters on perceived air quality and health symptoms in a primary school.**

An intervention study of the impact of supply air filters on perceived air quality and health symptoms in a primary school

M. Mysen[1,2], K.I. Fostervold[3], P.G. Schild[1]

[1]*Norwegian Building Research Institute, P.O.Box 123 Blindern, NO-0314 Oslo, Norway*

[2]*Norwegian University Of Science And Technology (NTNU), Department of Energy and Process Technology, NO-7491 Trondheim, Norway*

[3] *Lillehammer University College (HIL), Faculty of Health and Social Work, N-2626 Lillehammer, Norway.*

Abstract

A reversed intervention field-study was conducted in a modern Norwegian primary school with balanced ventilation with very low pressure-drop and ground-coupled supply air duct. The supply air filter bank (3-year old F7 bag-filters, equivalent to approx. 12-week old bag filters in a conventional air-handling unit) was removed for one week to investigate the effect on health and perception of indoor air quality. The pupils were blind to the intervention.

Removing the filters significantly improved perceived air quality (PAQ). PAQ returned to its original level when the filters were put back one week later.

The subgroup of pupils who reported having an asthma-/allergy problem experienced a significant increase in SBS-symptoms relative to the rest of the pupils, when the filter was put back into the supply air path. The results challenge the conventional assumption of filters as a relief measure, especially for asthmatic and allergic children. However given the importance of its consequences, the results should be investigated further before remedial actions are taken. The intervention was conducted in early winter (November), probably with little pollen in the outdoor air.

Keywords: Schools; Intervention study; Bag filter; Hybrid ventilation; Perceived air quality; Sick Building Syndrome; Allergy

Practical implications

Conventional practice on documenting filter performance (arrestance and retention) is misleading. Emissions from particles trapped in supply air bag-filters constitute an IAQ problem, and this problem is possibly elevated among asthmatic/allergic subjects. There is therefore a need for further R&D on air filtration products and their use, and especially on the practical impact of filtration systems on asthmatic/allergic subjects.

1. Introduction

Previous studies have lead us to believe that used bag-type supply air filters can worsen perceived air quality (PAQ) and contribute to SBS (sick building syndrome) symptoms in schools.

Fanger et al. (1988) documented already in the 1980s that a HVAC system can degrade the quality of the supply air even before it reaches the space to be ventilated. Dirty bag filters have later been identified as a main source of pollution in a HVAC system (Pejtersen et al., 1989), and numerous studies have documented that used bag-filters can be a significant source of indoor air pollution (Tejonsalo et al. 1993, Pasanen et al. 1994, Alm et al. 2000, Clausen et al. 2002a). Turning off the air-handling unit (AHU) gives a significant additional increase in the sensory pollution emitted by a used bag-filter immediately after the AHU is turned back on (Mysen et al., 2003).

A field intervention in a central-London office showed that replacing well-used supply-air pre-filters with new ones caused several significant improvements such as: humidity seemed lower, eyes ached less, head felt clearer; subjects felt better, less tired and more positive, and they found it easier to concentrate (Wyon et al., 2000). Clausen (2002b) showed, in controlled laboratory conditions, that the presence of used bag-filters in a ventilation system has a significant effect on several indicators of SBS and Indoor Environmental Quality (IEQ).

Wargocki et al. (2002) conducted a 2x2 replicated field intervention study in a call-centre. They found that replacing a used filter with a new one increased PAQ and reduced the intensity of SBS-symptoms at low outdoor air supply rates. They also found that increasing the air supply rates through a used bag filter significantly decreased the performance of the occupants (Wargocki et. al., 2003). The sensory pollution load from used bag filters are probably caused by sensory offending chemicals associated with particles captured by the filter (Weschler 2002, Bekö et al., 2003).

Smedje et al. (2002) conducted a double-blind crossover design study with old and new filters in a school building. They found by objective clinical methods, that presence of a used supply air filter reduced the volume of the nose, and increased adverse eye and throat symptoms among the pupils.

Schild et al. (2003) have recently published a study investigating the relation between the presence of supply air filter, SBS-related symptoms, and IEQ (indoor environment quality) in Norwegian schools. The study was conducted by means of a questionnaire consisting of 45 simple yes/no questions about health, the indoor environment, and personal background information. Figure 1 is an excerpt of the results, showing SBS symptoms among pupils in five modern primary schools, all with demand-controlled hybrid ventilation with ground-coupled fresh air ducts. The schools are divided into two groups, according to whether or not there are air filters in the supply air path. The main physical difference between these two groups of schools is the presence/absence of used bag-filters.

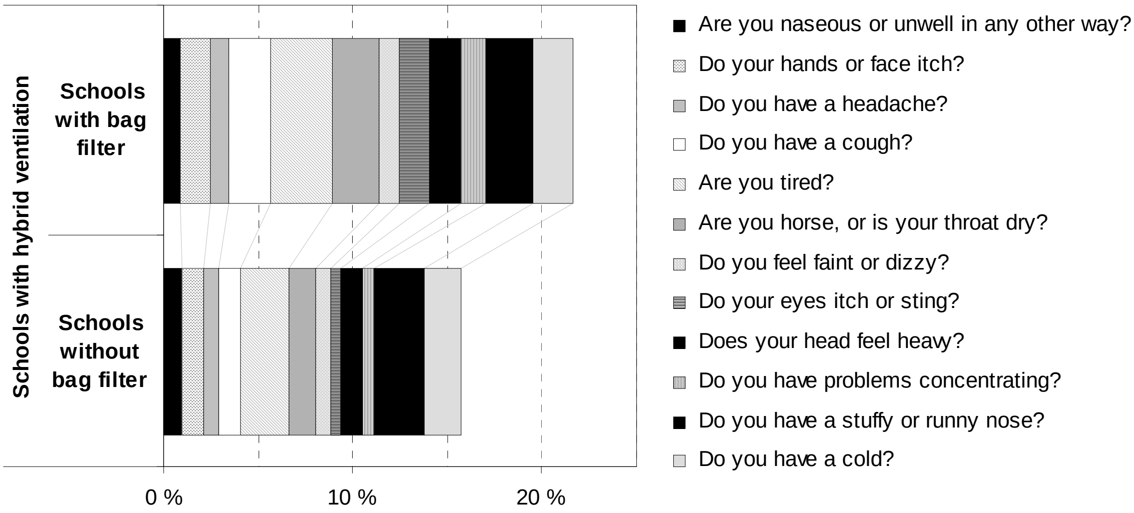

Figure 1. Prevalence of SBS-symptoms in schools with or without supply air bag-filters. The length of the bar for a school-group is the sum of the relative contributions of the questions used in the index. 0% (best) means all pupils always answer 'no' to all questions, 100% (worst) means all pupils always answer 'yes' to all questions. The relative contribution of each of the 12 questions is indicated by different shaded stripes along each bar.

The study indicated that pupils in schools without a used bag-filter in the supply air path experience fewer SBS-symptoms, and perceive the air quality to be better, compared to schools with a used bag filter in the supply air stream. However, the internal validity of this study can be questioned since the behaviour and perceptions of pupils from different schools can be influenced by numerous other factors not controlled by the experimental design.

Given the importance of this finding, the aim of the present study was to conduct a conceptual replication of the Schild et al. (2003) study, utilising a refined experimental design.

2. Methods

2.1 Description of Tredal Primary School

The study was conducted at Tredal Primary School. The School is located on the west coast of Norway and opened in August 2000. Figure 2 shows the school with its exhaust tower.

Figure 2. Tredal Primary School with its exhaust tower.

The single storey building has a floor area of approx. 1700 m². It has 165 pupils divided into seven classes, all of which occupy the same large elongated enclosure. The education area enclosure is divided into seven zones by partition walls, one for each year level. It has a balanced mechanical ventilation system with very low pressure-drop (hybrid ventilation) and run-around heat recovery. Fresh air is distributed via a ground-coupled concrete duct in the basement. The bag-filter bank is located between the subterranean air-intake duct and the air-distribution duct. The system operates with 100% fresh air, i.e.

no recirculation. The education area has demand-controlled displacement ventilation, controlled by a CO_2 sensor located about 1.7 m above floor level.

The duct is of rectangular cross-section with a sufficient size to allow easy access for inspection & cleaning. No cleaning was conducted during, or in the days before, the intervention.

Laser particle-counter measurements in a similar duct in another Norwegian school (Schild, 2002) has shown significant precipitation in the duct of particles above 10 µm.

2.2 The bag filters

The fibreglass F7 bag-filter bank was designed with a very large cross-sectional area (4.32 m^2, i.e.12 cassettes of size 600×600 mm) in order to achieve a low-pressure drop for hybrid ventilation. The pressure drop across the filter was measured to be about 1 Pa with a micromanometer. The measured air flow rate was 0.73 m^3/s on 13th November 2003 at 11:30 AM whilst the education area was in normal use. This flow rate is based on the average of 8 air velocity measurements at different points across a narrow passage in front of the supply fan. These measurements have a large margin of error due to the extremely low air velocity. The resultant nominal face velocity over the filter bank was 0.17 m/s.

The filters had not been changed since the school opened in August 2000, i.e. 3.3 years up to 13th November 2003. However, their 'age', with respect to total filtered air volume, corresponded with filters used for only approx. 12 weeks at a face velocity of 2.5 m/s, which is a normal face velocity for air-handling units (AHUs). This is based on the following assumptions:

- The odour intensity from a filter is proportional to the mass of dust accumulated in it, which again is proportional to the air volume that has passed the filter. This may be a conservative assumption because sedimentation of large particles (e.g. pollen) at low velocity in the ground-coupled duct, before the filter, probably reduces the mass of dust accumulated on this filter relative to a filter in a conventional AHU (Schild, 2002).
- Odour intensity from filters seems to be approximately independent of ventilation rate (i.e. face velocity) for used filters of equivalent age (Strøm-Tejsen et al., 2003).
- The same daily operating hours in both cases. The ventilation rate at Tredal School drops outside school hours, due to demand-control.

2.3 Experimental design

The study was a field experiment applying a pre-test, post-test design with an added removed treatment control. The effect of used bag-filters on SBS-symptoms and PAQ were examined by the following practicable 3-step intervention with one week interval between each step:

Step 1: Before the intervention, SBS-symptoms and PAQ were assessed while the used bag-filters were present in the air supply path, i.e. normal operation conditions (Condition 1). The filter bank was then removed from the air supply path and carefully stored in a nearby plant room with normal humidity and temperature conditions.

Step 2: SBS-symptoms and PAQ were assessed without any bag filters in the supply air path (Condition 2). The assessment took place approximately one week after the removal of the filters. The used filter bank was then carefully put back in the supply air path.

Step 3: SBS-symptoms and PAQ were assessed one week after the filters had been refitted (Condition 3).

The participating pupils were blind to the intervention. The class teachers administered the questionnaires late during the school day, when the classroom had been in use by the pupils for some hours. Mysen (1st author) inspected the execution of the questionnaires on 13th November.

2.4 Questionnaires and measurements

All present pupils in the 5th , 6th and 7th grade filled in the following two types of questionnaire:

(1) Perceived air quality: The assessment votes were marked on the DTU split-scale of air quality acceptability. The votes have been assigned values between –1 (clearly unacceptable) and +1 (clearly acceptable) for statistical analysis.

(2) Örebro-type questionnaire: This has 45 simple yes/no questions regarding health symptoms, the indoor environment, and personal background information. The questionnaire is a Norwegian application of the Örebro questionnaire (Andersson et al. 1988, Andersson 1993), but which has been simplified to be suitable for intervention studies among children. The main difference is that the questionnaire asks how the person is feeling at the present moment, instead of how the person has generally felt in the previous 3 months. The questionnaire responses were analysed with the statistical tool SPSS. All yes-answers are given the value of 1 (meaning they have a problem) and all no-answers are given the value 0. The mean score for each SBS-related question then yields the prevalence of the corresponding symptom at the school. Twelve of the questions are about SBS-symptoms. These are analysed separately and grouped together in an index denoted 'SBS-index' in this paper.

SBS-index is defined as:

$$SBS - index = \frac{\sum_{i=1}^{12} (S_i)}{12} \tag{1}$$

Where S_i is the score for question *i*, and 12 is the number of questions used in the index.

This SBS-index was used as the dependent variable when analysing the results with GLM Repeated Measures and Independent Samples t-test.

Throughout the experiment, the Building Management System (BMS) logged indoor CO_2 concentration and the temperatures of the outdoor air, indoor air, and supply air. The logged values were checked against calibrated instruments on the 13th November.
Table 1 summarises the experimental design.

Table 1. Overview of questionnaires conducted in each class, together with the number of pupils in the class who filled out the questionnaires.

Test condition:	**(1) With filter**	**(2) Without filter**		**(3) With filter again**	
Date:	13th Nov.	19th Nov.	20th Nov.	26th Nov.	27th Nov.
5th grade	Questionnaire & PAQ (17 pupils)	Questionnaire & PAQ (18 pupils)	PAQ only (17 pupils)	PAQ only (16 pupils)	Questionnaire & PAQ (14 pupils)
6th grade	-	Questionnaire & PAQ (14 pupils)	-	Questionnaire & PAQ (14 pupils)	-
7th grade	Questionnaire & PAQ (13 pupils)	-	Questionnaire & PAQ (14 pupils)	-	Questionnaire & PAQ (13 pupils)

The questionnaires and the DTU-split scale were also used on 12th November, but an inspection of the air supply path in the morning of 13th November revealed that a hatch (1.20 × 0.60 m) between the air-intake duct and the air-distribution duct was open. An unknown share of the supply air therefore bypassed the filter. This hatch had presumably been open for 2 days (since a regular fire inspection). The bypass fraction has been estimated to be somewhere in the range 20% ~ 80% during this time. The hatch was immediately closed, and the questionnaires conducted on the 12th November were excluded from the experiment. The consequence of this is that only 5th and 7th grade pupils were tested during all three conditions.

3 Results

3.1 Physical data

Table 2 shows air temperatures and CO_2 concentrations logged by the BMS, when the questionnaires were conducted (at approx. 2 PM).

Table 2. Temperatures and CO_2-concentration logged by the BMS at 2 PM, roughly the same time as questionnaire surveys.

Test condition:	**(1) With filter**	**(2) Without filter**		**(3) With filter again**	
Date:	13th Nov.	19th Nov.	20th Nov.	26th Nov.	27th Nov.
Outdoor air temperature [°C]	4.4	3.8	2.2	4.9	6.5
Supply air temperature [°C]	17.5	18.0	17.3	18.4	18.0
Indoor air temperature [°C]	20.9	22.4	21.8	22.2	21.6
CO_2 concentration [ppm]	412	529	495	581	553

The measured mean CO_2-concentration between 12 am and 2 pm during the weekdays without filter was 492 ppm while the corresponding value during the weekdays with filter was 512 ppm. The measured CO_2-concentration stabilizes around 330 ppm during nights and weekends.

3.2 PAQ expressed by the acceptability scale

Figure 3 shows the average assessment score for each of the three conditions, together with their 95% confidence intervals, for the classes that were tested for all three conditions (5th and 7th grade pupils). The confidence intervals overlap, so there is no immediate significant difference in the assessment score values. The results indicate, however, that PAQ improved when the used filter was removed, and deteriorated back to the original level when the used filter was refitted.

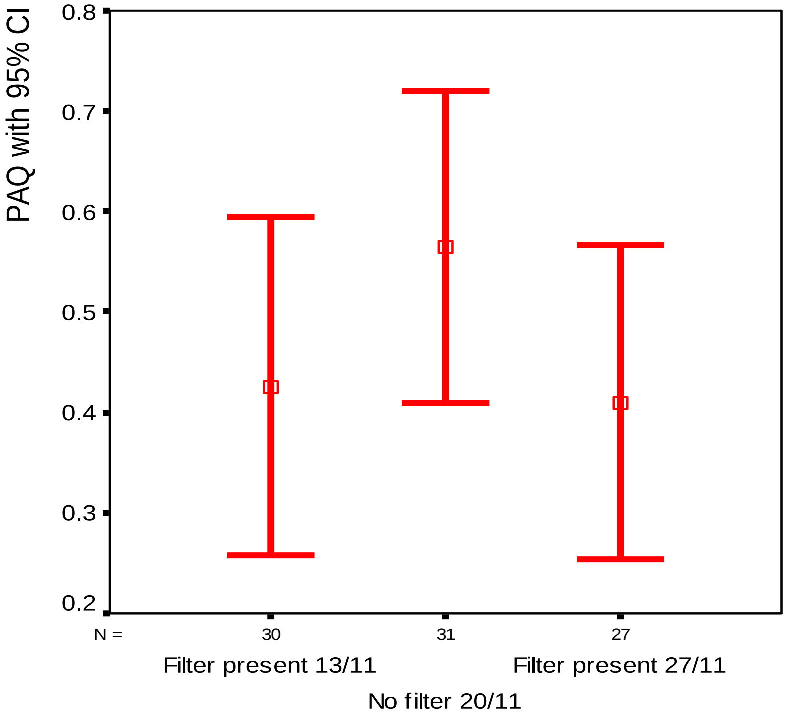

Figure 3. Air quality assessments with and without filter present. N is the number of pupils making assessments.

If the majority of the subjects assess the difference between two conditions in the same direction, there can be a significant difference between the samples even though the aforementioned confidence intervals from the basic statistical test overlap. Such a repeated test comparison is examined by using Student’s Paired-Samples T-Test (Table 3).

Table 3. Paired differences achieved with a paired samples t-test.

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Dev.	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Filter present 13/11 - No filter 20/11	-,12	,29	,06	-,23	-,01	-2,18	27	,04
Pair 2	No filter 20/11 - Filter present 27/11	,13	,34	,07	-,01	,27	1,94	25	,06
Pair 3	Filter present 13/11 - Filter present 27/11	-,05	,34	,07	-,19	,09	-,71	24	,48

There was a significant improvement in PAQ when the filter is removed (t(27)=2.18, *p = .04*). Refitting the filter reduced PAQ in a similar way (t(25)=1.94, *p=.06*). As a control, the assessment scores before the intervention and after the removal of the treatment were paired. The result showed no indication of a real difference in PAQ during the two conditions with filter present (t(27)=2.18, *p = .48*).

Figure 4 shows the calculated odour intensity (decipol) based on the mean PAQ scores.

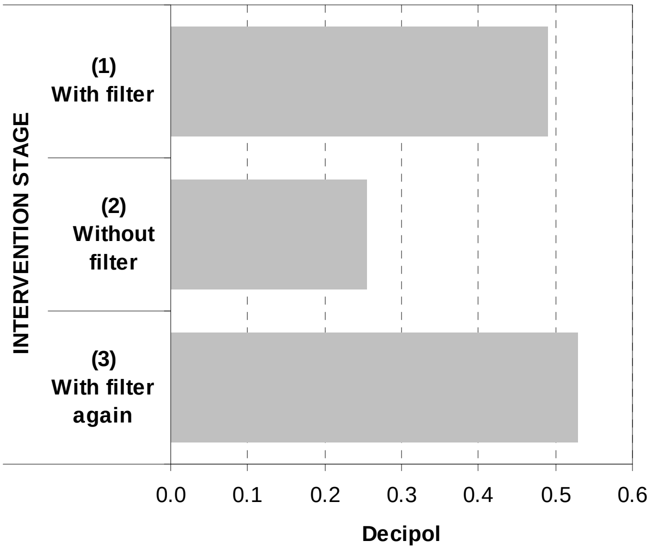

Figure 4. Approximate odour intensity [decipol] derived from the PAQ questionnaire.

3.3 SBS-related symptoms

Figure 5 summarizes the SBS-index results from the questionnaires of all participating pupils.

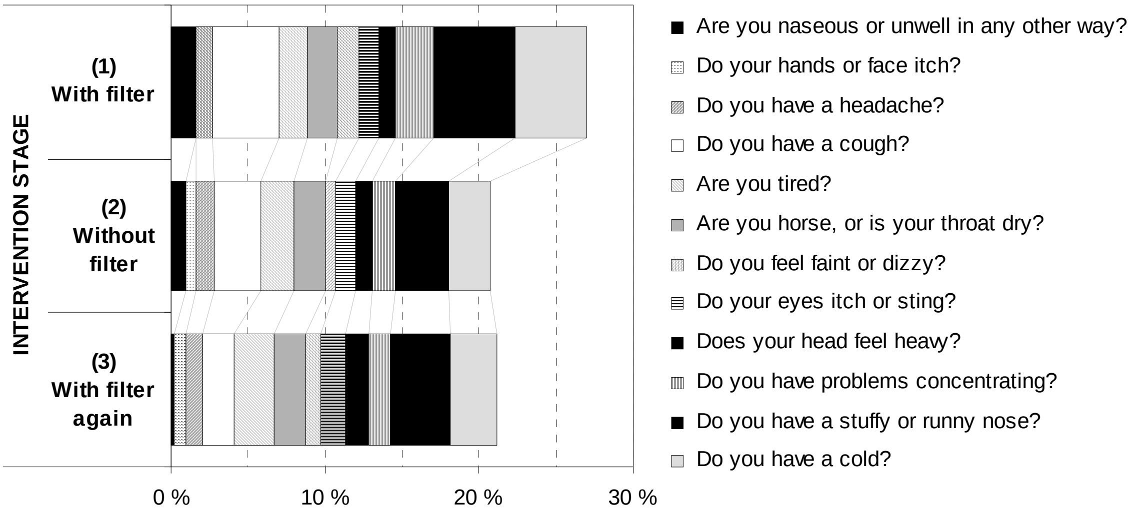

Figure 5. SBS-index before intervention (Condition 1), during intervention (Condition 2) and after intervention (Condition 3) for all participating pupils. The total length of the bar for a school is the sum of the relative contributions of the questions used in the index. 0% (best) means all pupils always answer 'no' to all questions, 100% (worst) means all pupils always answer 'yes' to all questions. The relative contribution of each question is indicated by different shaded stripes along each bar.

Figure 6 shows the SBS-index among the subset of pupils who report having asthma and/or allergy, i.e. the 12 pupils who answered 'yes' to the questions '*Do you have asthma?*' or '*Do you have an allergy problem?*'. Only one of these pupils reported having asthma without also reporting an allergy problem. These 12 pupils are denoted in this paper as 'allergic subjects'.

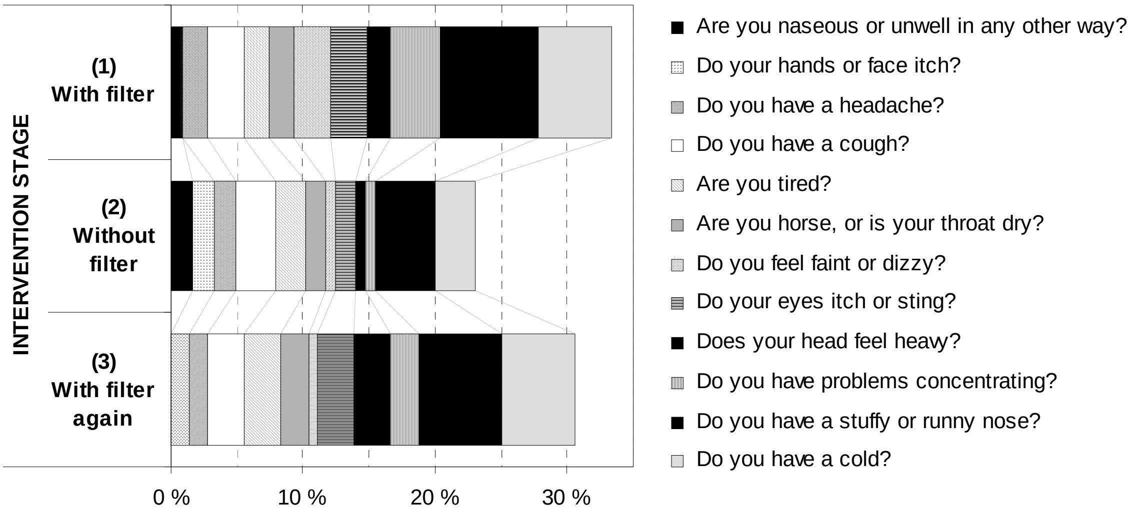

Figure 6. SBS-index for the allergic subjects.

Table 4 summarizes some additional statistical data for the SBS-index, such as the number of pupils in each group (*N*). Note that the 6th-grade pupils did not participate during Condition no. 1.

Table 4. Statisics for the SBS-index during the different conditions.

	Test condition:	**(1) With filter**	**(2) Without filter**	**(3) With filter again**
Allergic subjects	Number of pupils	9	11	12
	Mean SBS-index	33 %	23 %	31 %
	Std. deviation	27 %	15 %	20 %
Non-allergic subjects	Number of pupils	22	35	29
	Mean SBS-index	24 %	20 %	17 %
	Std. deviation	16 %	19 %	18 %
All subjects	Number of pupils	31	46	41
	Mean SBS-index	27 %	21 %	21 %
	Std. deviation	20 %	18 %	19 %

Table 5 shows the prevalence of each SBS symptom at each of the 3 stages of the intervention, both for allergic and non-allergic participants. The difference in prevalence between the allergic participants and non-allergic participants during each condition was tested for significance using the Mann-Whitney test.

Table 5. Prevalence of the 12 separate SBS symptoms. Significant differences (p<0.05) between allergic and non-allergic subjects are marked with footnotes. Corresponding p-values are listed below the table.

Mean

		Prevalences		
		1-With filter	2 - Without filter	3 - With filter
Are you tired?	Not allergic subjects	,23	,26	,31
	Allergic subjects	,22	,27	,33
Does your head feel heavy?	Not allergic subjects	,09	,14	,10
	Allergic subjects	,22	,09	,33
Do you have a headache?	Not allergic subjects	,09	,11	,10
	Allergic subjects	,22	,18	,17
Do you feel faint or dizzy?	Not allergic subjects	,09	,09	,14
	Allergic subjects	,33	,09	,08
Do you have problems concentrating?	Not allergic subjects	,23	,20	,14
	Allergic subjects	,44	,09	,25
Do your eyes itch or sting?	Not allergic subjects	,09	,14	,14
	Allergic subjects	,33	,18	,33
Are you horse, or is your throat dry?	Not allergic subjects	,24	,26	,24
	Allergic subjects	,22	,18	,25
Do you have a stuffy or runny nose?	Not allergic subjects	,55	,37	,34
	Allergic subjects	,89	,55	,75[b]
Do you have a cough?	Not allergic subjects	,59	,37	,21
	Allergic subjects	,33	,36	,33
Do you have a cold?	Not allergic subjects	,50	,31	,24
	Allergic subjects	,67	,36	,67[a]
Do your hands or face itch?	Not allergic subjects	,00	,06	,07
	Allergic subjects	,00	,20	,17
Are you naseous or unwell in any other way?	Not allergic subjects	,23	,09	,03
	Allergic subjects	,11	,20	,00

a. p<0.011

b. p<0.019

The effect of each of the intervention steps were analysed using General Linear Model (GLM) Repeated Measures. The SBS-index is used as the dependent variable. The intervention between condition 2 and 3 had a significant effect on the SBS-index among the allergic subjects (F(1,35)=5.7, *p=.02*), but not for all the pupils as a whole group (F(1,35)=0.45, *p= .51*).

The difference in SBS-scores between the two groups (allergic/non-allergic subjects) was tested for significance with independent samples t-test. The allergic subjects had a significantly higher SBS-index when the used filter was present (condition 3, t(39)=2.1, *p=.04*), whilst there is no indication of a real difference between the two groups when no filter was present (condition 2, t(43)= .45, *p=.65*).

4 Discussion

4.1 Perceived air quality

Removing the filter significantly improved PAQ (Table 3). Putting the filter back in the air stream reduced PAQ by a similar magnitude, indicating good internal validity of the experiment.

It is demonstrated that differences in temperature and ventilation rate can influence PAQ in schools (Mendell & Heath, 2005). Slight increase in enthalpy (temperature and relative humidity) or increase of the CO_2-level is associated with reduced PAQ. Measured indoor air temperature was highest during condition 2 (Table 2), implying that PAQ should be relatively reduced during this condition without filter, which is opposite the observed effect. The CO_2-level was lowest during condition 1 (with filter). The CO_2-levels measured 1.7 above floor, were only about 100-200 ppm above outdoor air level during all three conditions, indicating well-functioning displacement ventilation with little mixing of supply air and used air in the pupils breathing zone (about 1 m above floor). This means that measured indoor air temperature and CO_2 concentration do not indicate any alternative explanation of the observed intervention effect.

The negative impact of used bag-filters on PAQ can explain why pupils in schools with a HVAC-system without air supply filter perceived the air quality to be better than in schools with a HVAC-system with bag-filters (Schild et al., 2003). This presupposes that the HVAC design and maintenance is considered thoroughly to eliminate the need for supply air filtration to protect the HVAC components.

Although the bag filters were over 3 years old, they were comparable to filters used for approximately 12 weeks in a conventionally designed AHU, with respect to total air volume during the filter’s lifetime. Teijonsalo et al. (1993) tested the odour intensity of filters with various operation times in the centre of Helsinki. They found the odour intensity of a fine filter without prefilter to be about 3.3 decipol after 13 weeks’ operation time when tested with facial exposure. The sensory pollution load of filter determined from full exposure is approximately 7 times lower (Clausen et. al., 2002a). This is still considerably more than the odour intensity from the tested filter at Tredal School (about 0.25 decipol based on full exposure assessment, see Figure 4). The PAQ-scores for the pupils at the Tredal School have not been calibrated against a reference smell, so this comparison with earlier studies is just informative, but it indicates that the filter at Tredal is quite low-polluting relative to filters used for 13 weeks in standard AHUs. The reason is probably that the ground-coupled duct acts as a prefilter due to sedimentation of heavier particles (Schild et al. 2003), reducing the particle load on the filter. It is shown that the odour intensity of the first filter is relatively much higher than of the second filter when prefilter and fine filters are used together (Teijonsalo et al. 1993).

4.2 SBS-related symptoms

Removal of the used bag-filters does not seem to have affected the pupils as a whole group, with regard to reported SBS symptoms (Figure 5). Despite some reduction of SBS symptoms when the filter was removed, there was no sign of a corresponding increase when the used filter was put back. Tamblyn et al. (1992) have shown that prevalence of symptoms can gradually diminish regardless of environmental changes when humans are repeatedly used as test-objects. This can explain the result for the whole group but not for the allergic subjects. These subjects experienced fewer SBS symptoms when the filter was not present (Figure 6). This tendency seems consistent for the symptoms related to the following questions (Table 5): *'Do you have a cold?', 'Do you have a stuffy or runny nose?', 'Does your head feel heavy?', 'Do you have a problem concentrating?', 'Do your eyes itch or sting?', and 'Are you horse, or is your throat dry?'*. These observations are consistent with earlier observations by Smedje et al. (2002) and Anderson et al. (2002). Smedje et al. clinically showed that contaminated air supply filters reduce nose volume and increase adverse throat and eye symptoms among pupils in general. Andersson et al. documented that allergic students have a higher prevalence of general symptoms, skin symptoms and membrane irritations, than other students.

The effect of our intervention was tested with GLM Repeated Measures, with the SBS-index as the dependent variable. Presence of the supply air filter had a significant adverse effect on the SBS-index between Condition 2 and 3 for the allergic subjects, but there was no significant effect on the pupils regarded as a whole group. The change in the SBS-index between Condition 1 and 2 or for all three conditions, was not found significant for any of the groups. The open hatch in the ground-coupled duct, which caused some filter bypass, probably reduced the influence of the filter on SBS-symptoms during Condition 1.

The difference in SBS-index between allergic and non-allergic subjects was compared for Condition 2 (no filter present), and Condition 3 (filter present). The allergic subjects reported a significantly higher SBS-index than the non-allergic subjects when the used filter was present. There is no indication of a difference between the two groups when the filter is not present. This however, does not prove that there is no difference between the two groups when the filter is not present.

The allergic participants in this experiment had an increased prevalence of SBS-related symptoms when the supply air passed a used filter. This can be due to a hypersensitive response or by a hyper reactive response of the allergic group, or a combination of these two responses:

(i) A hypersensitive response means that the allergic group is more sensitive to the *increase* in pollutants from the used bag-filter, leading to an earlier response to pollutants from the filter than the non-allergic group. This implies that the difference between the allergic and non-allergic group will be reduced after some time. This explanation is in accordance with earlier studies (Smedje et al. 2002).

(ii) A hyper reactive response means that the allergic group has an abnormal response to the pollutants caused by the used filter. This implies an enduring difference between the allergic and non-allergic group. This is consistent with the observations of Andersson et al. (2002).

Having a cold might influence the results in a biased way for the relatively small group of allergic subjects. The percentage of allergic subjects reporting a cold at each intervention stage was 67% → 36% → 67% whilst the corresponding development among the non-allergic subjects was 50% → 31% → 24%. The difference between the groups was significant for Condition 3 (Table 5). It is possible that allergic subjects have an increased risk of catching a cold when the supply air is polluted by a used bag-filter, or that a sense of having a cold is somehow triggered by allergens or other pollutants released from the used filter into the supply airflow. Smedje et al. (2002) showed that such connections exists. This explains the tendency throughout our experiment. However, we cannot rule out the possibility that the intervention was not the only cause of the increased prevalence of cold symptoms among allergic subjects from Condition 2 to Condition 3. Having a cold could well influence symptoms such as a heavy head, concentration difficulties, and stuffy or runny nose.

The significant effect of the intervention on the allergic subjects was not anticipated. This result questions the conventional assumption of filters as a relief measure, especially for asthmatic and allergic children. However, given the importance of the consequences, this needs confirmation by a more appropriately designed experiment before this result is given general validity, and remedial actions are taken. Such an experiment should have an increased sample of allergic/asthmatic subjects, and a more rigorous registration of the allergic and asthmatic diagnoses.

It is feasible that the experimental treatment of the filter (removing it from the supply air path, storing it for one week, and then putting it back) might somehow unrealistically affect the reported SBS symptoms among the allergic subjects. However, the PAQ data shows that the sensed pollution in the classroom is quite similar during Conditions 1 and 3, both cases with the filters present in the supply air path. This indicates that the experimental treatment did not influence the sensory pollution load from the filters.

5 Conclusions

Removing the used bag-filter from the supply air flow at Tredal School significantly improved the pupils' Perceived Air Quality (PAQ). PAQ fell again to its original level when the filter was put back after a week.

Presence of the filter had an adverse impact on the SBS-symptoms of the subgroup of pupils who reported having an asthma/allergy problem. This intervention thus contradicts the common belief that air filters have a positive impact on the health of allergic subjects. However given the importance of its consequences, the results should be investigated further before actions are taken.

6. Acknowledgement

This work has been supported by the Norwegian Research Council as a part of the research program “Environmentally favourable energy use in buildings”.

7. References

Alm O, Clausen G, Fanger PO (2000). Exposure-response relationship of emmisions from used ventilation filters. In: *Proceedings of Healthy Buildings* 2000, Vol. 2, pp. 245-250.

Andersson K, Stridh G, Fagerlund I, Aslaksen W, Rudblad S (2002). Comparison of the perceived indoor climate and symptoms reported by students and personnel in 16 senior high schools in Sweden. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 3, pp. 399-403.

Andersson K, Fagerlund I, Bodin L, Ydreborg B (1988). Questionnaire as an instrument when evaluating indoor climate. In: *Proceedings of Healthy Buildings* 1988, Vol. 1, pp. 139-145.

Andersson K (1993). The MM-Questionnaires – A tool when solving Indoor Climate Problems, Örebro Medical Center Hospital. Sweden.

Bekö G, Halás O, Clausen G, Weschler CJ, Toftum J (2003). Initial studies of oxidation processes on filter surfaces and their impact on perceived air quality. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, pp. 156-162.

Clausen G, Alm O, Fanger PO (2002a). Sensory strength of used ventilation filters. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, pp. 344-349.

Clausen G, Alm O, Fanger PO (2002b). The impact of air pollution from used ventilation filters on human comfort and health. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 1, pp. 338-343.

Fanger PO, Lauridsen J, Bluyssen P, Clausen G (1988). Air pollution sources in offices and assembly halls, quantified by the olf unit, Energy and Buildings, **129**, 7-19.

Mendell MJ, Heath GA. Do indoor pollutants and thermal conditions in school influence student performance? A critical review of the litterature. Indoor Air **15**, 2005, pp 27-52.

Mysen M, Clausen G, Bekö G, Halás O (2003). The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, pp. 267-272.

Pasananen P, Tejonsalo J, Seppänen O (1994). Increase in perceived odour emissions with loading of ventilation filters, Indoor Air, **4**, 106-113.

Pejtersen J, Bluyssen P, Kondo H, Clausen G, Fanger PO (1989). Air pollution sources in ventilation systems. In: *Proceedings of CLIMA* 2000, Sarajevo, Vol. 3, pp. 139-144.

Schild PG (ed.), Dokka TH, Mysen M, Tjelflaat PO (2003), Bygningsintegrert ventilasjon – en veileder (Building-integrated ventilation – a guide), Økobygg, (in Norwegian) http://www.byggforsk.no/hybvent/

Schild PG (2002). Pilot study – Jaer School, IEA ECBCS Annex 35 technical report, In: *Principles of Hybrid Ventilation CD-ROM*. http://www.byggforsk.no/hybvent/

Smedje G, Norbäck D, Wieslander G, Wålinder R (2002). Effects of contaminated supply air filters on symptoms from the eyes and nose – a double-blind experimental stud. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate,* Vol. 2, pp. 1032-1037.

Strøm-Tejsen P, Clausen G, Toftum J (2003). Sensory pollution load from a used ventilation filter at different airflow rates. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, 257-261.

Tamblyn RM, Menzies RI, Tamblyn RT, Farant JP, Hanley J (1992). The feasibility of using a double blind experimental cross-over design to study interventions for sick building syndrome. J Clin Epidemiol. Jun; 45 (6). pp 603-612.

Teijonsalo J, Pasanen P, Seppänen O (1993). Filters of air supply units as sources of contaminants. In: *Proceedings of the 6th International Conference on Quality and Climate*, Vol. 6, pp. 533-538.

Wargocki P, Wyon DP, Nielsen JB, Fanger PO (2002). Call-centre occupant response to new and used filter at two outdoor air supply rates. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol. 3, pp. 449-454.

Wargocki P, Wyon DP, Nielsen JB, Fanger PO (2003). Call-centre operator performance with new and used filters at two outdoor air supply rates. In: *Proceedings of Healthy Buildings* 2003, Vol. 3, pp. 213-218.

Weschler CJ (2002). Connections: Particles, sensory offending filters, the “sink” effect and nasal pungency thresholds. In: *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol. 1, pp. 1-11.

Wyon DP, Tham KW, Croxford B, Young A, Oreszczyn T (2000). The effects on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises. In: *Proceedings of Healthy Buildings* 2000, Vol. 1, pp. 641-646.

Paper III Mysen M, Clausen G, Bekö G, Halás O. **The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters.**

The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters

M. Mysen[a,b,]*, G. Clausen[a], G. Beko[a], O. Halas[a]

[a]*International Centre for Indoor Environment and Energy, Technical University of Denmark, Denmark;* [b]*Norwegian Building Research Institute, Norway*

ABSTRACT

An experiment was performed to determine whether the sensory pollution emitted from a bag filter that had been used for 3 months in a suburban area in Denmark was influenced by different ways of operating the air-handling unit (AHU). Samples of the used filter were pre-conditioned to simulate three operating conditions: (1) switched off overnight; (2) airflow reduced to 10% overnight; and (3) continuous 100% operation. Outside air passed through the samples and the acceptability of the air after the filter was assessed by a panel of subjects. The results indicate that turning off the AHU or reducing the airflow outside working hours would significantly increase the sensory pollution emitted by a used bag filter immediately after the AHU is turned on, in comparison with continuous airflow through the AHU ($P < 0.05$). After outside air had been passed through the filter for 2 h, no significant differences were found.

INDEX TERMS

Air filter; Perceived air quality; Ventilation system; Air pollution

INTRODUCTION

Used bag filters may pollute the supply air from the HVAC system considerably (Clausen *et al.*, 2002a). This sensory pollution increases in strength during the first 3 months of operation before it stabilizes at a level of about 2.5 decipol (Teijonsalo *et al.*, 1993). A field intervention in a central-London office showed that replacing well-used supply-air pre-filters with new ones caused several significant improvements such as: humidity seemed lower, eyes ached less, head felt clearer; subjects felt better, less tired and more positive and they found it easier to concentrate (Wyon *et al.*, 2000). A field intervention in a call-centre in Denmark showed that changing from used to new supply air filters at low outdoor air supply rate significantly alleviated many Sick Building Syndrome (SBS) symptoms (Wargocki *et al.*, 2002). This indicates that sensory offending chemicals are associated with the particles captured by the filter (Weschsler, 2002).

To reduce energy consumption, it is normal to turn off or reduce the ventilation air volume delivered by the air-handling units (AHUs) outside regular working hours. The unanswered question is: will this lead to an accumulation of chemicals in the air enveloping the filter, causing an increase in the sensory pollution emitted from the bag filter after the AHU is switched back on for normal operation?

Cox and Bluyssen (2000) compared the pollution load from filters with continuous and intermittent airflow without finding any significant difference, but they did not look at the development of the pollution load over time during the first period after the ventilation had been switched on.

An experiment was performed to determine whether the sensory pollution emitted from a bag filter that had been used for 3 months in a typical suburban area in Denmark was

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[*] Corresponding author. E-mail: mads.mysen@byggforsk.no

influenced by different ways of operating the AHU. Samples of used filter were pre-conditioned to simulate three operating conditions: (1) switched off overnight; (2) airflow reduced to 10% overnight; and (3) continuous 100% operation.

METHODS

The measurements took place in Chamber one at the International Centre for Indoor Environment and Energy at DTU in Denmark. The room was supplied with outside air corresponding to 60 air changes per hour. The temperature in the room was kept constant at 24.5°C throughout the experiment. The relative humidity was kept above 40%.

Five identical test rigs were constructed for the experiment (Picture 1). Each consisted of 1 m of 100 mm diameter inlet duct before the sample. After the sample a flexible Teflon coated plastic duct was connected to a fan. After the fan a plastic valve for adjusting the airflow and 1 m of glass tube led up to the assessment point. The filter samples have an area of 79 cm^2. The airflow rate out of the glass tubes was adjusted to 1 l/s. The air velocity through the sample was 12.7 cm/s, which is approximately the same as through a filter in a normally designed AHU with 2.5 m/s face velocity.

Picture 1 One of the test rigs constructed for the experiment.

All the parts except the fans were thoroughly cleaned with a strong detergent and afterwards rinsed first in fresh tap water and then with distilled water. Initial assessments of the empty test rigs showed that the perceived air quality at the assessment point was the same for all the test rigs.

Samples from one used filter were put in three of the test rigs. The filter was a EU7 filter that had been used in an office building 30 km north of Copenhagen near the east coast of Zeeland. The filter had been used from 31 January 2003 to 6 May 2003 with continuous airflow of 3500 m^3/h throughout this period. This yielded an air velocity of 13.7 cm/s through the filter material and a total air volume of about 8 million m^3.

As references for evaluation of the results, a sample from a new unused EU7 filter was put in one test rig and the last test rig was left empty meaning that the air did not pass through a filter before being assessed. In addition, an odour reference generated by releasing a known concentration of acetone was used.

An untrained panel made the assessments. The assessment order was randomized and the assessment subjects were told to wait 1 min between each assessment. People connected to the International Centre for Indoor Environment and Energy, mostly students, did the assessments. This was a blind test for the subjects and the construction of the test rigs ensured that the samples are completely hidden from the subjects who assessed.

The assessment votes were marked on the DTU split scale of air quality acceptability. The votes have been assigned values between –1 (clearly unacceptable) and +1 (clearly acceptable) for statistical analysis and calculation of decipol values.

A listing of airflows in test rigs throughout the experiment is shown in Table 1. Assessments were made three times on 11 June: After 0.5 h (between 9.30 and 10 a.m.), after 2 h (between 11.00 and 11.30 a.m.) and after 6 h.

Table 1 Airflows in test rigs throughout the experiment with simulated day and night operation

Test rig	Simulates	Preconditioning (100 h)	Night (16 h)	Day (8 h)
1 Used-off	Switched off overnight	Full	Off	Full
2 New	Reference—new filter	Full	Off	Full
3 Used-10%	Airflow reduced to 10% overnight	Full	10% of full	Full
4 None	Reference—no filter	Full	Off	Full
5 Used-full	Continuous 100% operation	Full	Full	Full

The samples were assessed at the beginning and at the end of the preconditioning phase. This confirmed that all three samples from the used bag filter had approximately the same sensory source strength.

RESULTS

The assessment scores were analysed statistically with SPSS release 11.00. The distribution of the assessments scores was tested for normality with the Shapiro–Wilks test and a general skewness test and this showed that all the relevant data could be treated as normally distributed.

Figures 1 and 2 show the means of the assessments scores with their 95% confidence interval after 30 min and after 2 h. The confidence interval for the three used filter samples (denoted Used-off, Used-10% and Used-full) overlap, meaning that there is no significant difference in the assessments score values between these samples.

The perceived air pollution from the used filter samples were calculated from the difference between perceived air quality of exhaust air from the used filter samples and perceived air quality of exhaust air from the reference without filter (Figure 3). The sample that had not been ventilated during the night improved most from 0.5 to 2 h after the fan was switched on.

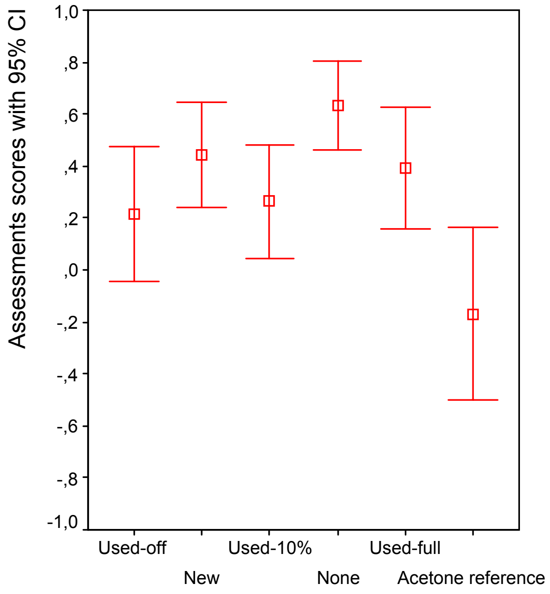

Figure 1 Assessments scores with 95% confidence interval after a night and after 30 min with full airflow through the samples; 14 subjects assessed the samples

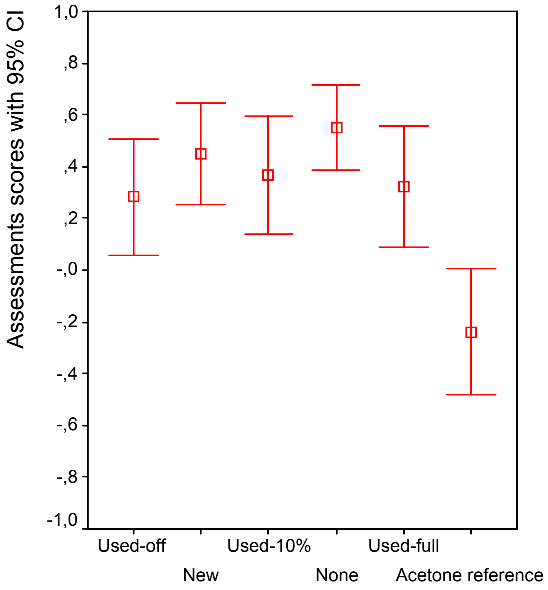

Figure 2 Assessments scores after a night and after 2 h with full airflow through the samples; 17 subjects assessed the samples

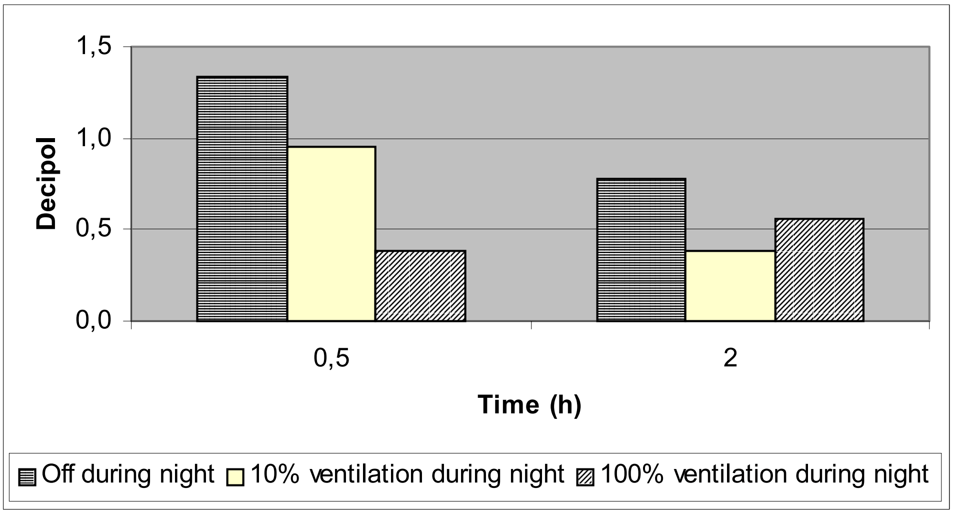

Figure 3 Development of perceived air pollution after a night.

If the vast majority of the subjects assess the difference between two samples in the same direction, there might be a significant difference between the samples even if the mean differences are small. Such a comparison is often called a repeated-measures comparison and was examined by using Student's Paired-Samples *t*-Test procedure. Here the two cases with reduced or no airflow were compared with the sample with continuous airflow. The results are shown in Table 2. There was a significant difference between the 'Used-10%' sample and 'Used-full' sample after 0.5 h of ventilation (pair 2, $P < 0.021$, 2-tailed).

Table 2 Paired differences achieved with a paired samples *t*-test

		Paired Differences of acceptability				
				95% Confidence Interval of the Difference		
		Mean	Std. Deviation	Lower	Upper	Sig. (2-tailed)
Pair 1	Used-off 1/2h - Used-full 1/2h	-,1779	,32048	-,3629	,0072	,058
Pair 2	Used-10% 1/2h - Used-full 1/2h	-,1279	,18297	-,2335	-,0222	,021
Pair 3	Used-off 2h - Used-full 2h	-,0418	,50600	-,3019	,2184	,738
Pair 4	Used-10% 2h - Used-full 2h	,0441	,47603	-,2006	,2889	,707
Pair 5	Used-off 1/2h - Used-off 2h	,0442	,52493	-,2894	,3777	,776

There are no significant differences after 2 h (pairs 3 and 4), and there was no significant improvement in the ‘Used-off ‘ sample between 0.5 and 2 h of ventilation (pair 5), but in this case only the12 subjects who took part in both assessments were used in the statistical analysis, i.e. considerably fewer subjects.

DISCUSSION

The acceptability of the’Used-10%’ sample (airflow reduced to 10% overnight) was significantly lower than that of the ‘Used-full’ sample (continuous 100% operation) after 0.5 h of full ventilation (Table 2, pair 2, $P < 0.021$, 2-tailed). After 2 h there were no significant differences between the samples (Table 2, pairs 3 and 4). This shows that different ways of operating an AHU resulted in a real difference in the pollution load from a used bag filter immediately after the AHU was turned on, but this difference is greatly reduced after ventilation has continued for some time. This indicates that there is a continuous emission of odorous products on particulate matter associated with the filter surfaces and that these products accumulate during periods with no or reduced airflow through the filter.

Since it is statistically proven that the ‘Used-10%’ sample smelled worse than ‘Used-full’ sample after 0.5 h it should be valid to assume that even the ‘Used-off’ sample will smell worse than the ‘Used-full’ sample which means that the results can be analysed for 1-tail significance. Such an assumption leads to a significant difference between the Used-off and the Used-full sample ($P < 0.029$, 1-tailed).

The increased pollution load caused by this bag filter used during the months of February, March and April is about 0.6 decipol or about 8 olf/m^2 filter. This is less than expected from other experiments (Teijonsalo *et al.*, 1993; Clausen *et al.*, 2002b). This indicates that the pollution load from a used filter can be strongly influenced by the amount and the composition of the particulate matter associated with the filter surfaces, as one would expect. This again is affected by parameters such as: when it has been used (time of year), placement of the air intake, where the building is situated together with the total filtered air volume.

Similar assessments were made after a simulated weekend with 11 subjects who assessed the samples. No significant differences were found in this experiment. This may be explained by the relatively small size of panel used.

CONCLUSIONS AND IMPLICATIONS

Turning the AHU off or reducing the airflow outside working hours would increase the sensory pollution emitted by a used bag filter immediately after the AHU is turned on compared with continuous airflow through the AHU ($P < 0.05$). The consequence is that the

IAQ deteriorates or more outside air is required. After outside air had been passed through the filter for 2 h, no significant difference between operating conditions was found in terms of the sensory pollution emitted from the filter.

Based on these findings an AHU with used bag filters should be switched on several hours before the workers enter the office to minimize the sensory pollution emitted from the bag filter. A more energy-efficient strategy would be to modify the AHU with an additional timer-controlled damper to permit outside air to be passed through the bag filter and rejected for 2 or more hours, bypassing the building to avoid the energy cost of conditioning this cleansing air and distributing it in the building.

ACKNOWLEDGEMENTS

This work has been supported by the Danish Technical Research Council (STVF) as part of the research programme of the International Centre for Indoor Environment and Energy established at the Technical University of Denmark for the period 1998–2007, The Norwegian Research Council, Nordic Academy of Advanced Study (NorFA). Norsk VVS stiftelse for forskning and Fondet for Dansk-Norsk Samarbejde.

I would like to thank David Wyon for helping me with the statistical analysis and the English grammar, and the subjects who repeatedly contributed with their assessments.

REFERENCES

Clausen, G., Alm, O. and Fanger, P.O. (2002a). The impact of air pollution from used ventilation filters and health. *Proceedings: Indoor Air 2002*, pp. 338–343.

Clausen, G., Alm, O. and Fanger, P.O. (2002b). Sensory source strength of used ventilation filters. *Proceedings: Indoor Air 2002*, pp. 344–349.

Cox, C. and Bluyssen, P.M. (2000). Pollution by air filters: continuous vs intermittent air flow. *Proceedings of Healthy Buildings 2000*, Vol. 2, pp. 257–262.

Teijonsalo, J., Pasanen, P. and Seppänen, O. (1993). Filters of air supply units as sources of contaminants. *Proceedings of Indoor Air 1993*, Vol. 6, pp. 533–538.

Wargocki, P., Wyon, D.P., Nielsen, J.B. and Fanger, P.O. (2002). Call-centre occupant response to new and used filters at two outdoor air supply rates. *Proceedings of Indoor Air 2002*, Monterey, CA, USA, Vol. 3, pp. 449–454.

Weschler, C.J. (2002). Connections: particles, sensory offending filters, the ‘sink’ effect and nasal pungency thresholds. *Proceedings: Indoor Air 2002*, pp. 338–343.

Wyon, D.P., Tham, K.W., Croxford, B., Young, A. and Oreszczyn, T. (2000). The effects on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises. *Proceedings of Healthy Buildings 2000*, 6–10 August, Helsinki, Vol. 1, pp. 641–646. Helsinki, Finland: SIY Indoor Air Information.

Paper IV Mysen M, Berntsen S, Nafstad P, Schild PG (2005). **Occupancy density and benefits of demand controlled ventilation in Norwegian primary schools.**

Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools

[1]Mads Mysen[4], [2]Sveinung Berntsen, [3,2]Per Nafstad , [1]Peter G. Schild

[1]Norwegian Building Research Institute, P.O. Box 123 Blindern, NO-0314 Oslo, Norway

[2] Division of Epidemiology, Norwegian Institute of Public Health, P.O. Box 4404 Nydalen, NO-0403 Oslo, Norway

[3] Department of General Practice and Community Medicine, The Medical Faculty, University of Oslo, P.O.Box 1130 Blindern, NO-0318 Oslo, Norway

Abstract

157 classrooms for 4th form pupils were inspected at 81 randomly selected schools in Oslo, Norway. Primary school classrooms in Oslo have on average 22 occupants present, while the maximum capacity is 30. Classrooms are typically used 4 hours daily for normal school activities. The corresponding ventilating air volume and energy use has been analysed for three ventilation strategies: (*a*) constant air volume [CAV], (*b*) CO_2-sensor based demand-controlled ventilation [DCV-CO_2], and (*c*) infrared occupancy-sensor based demand-controlled ventilation [DCV-IR].

DCV-CO_2 and DCV-IR reduce the energy use due to ventilation in the average classroom to 38% and 51% respectively, compared to the corresponding energy use for a CAV system operating with full airflow from 7 AM to 5 PM.

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[4] Corresponding author. Tel.: +47-2296-5582; fax: +47-2296-5725.

E-mail address: mads.mysen@byggforsk.no

URL: http://www.byggforsk.no

Keywords: Schools; Constant air volume (CAV); Demand-controlled ventilation (DCV); Occupancy; Airflow rates; Energy use

1. Introduction

A healthy indoor environment with sufficient fresh air is a prerequisite for the well-being and high productivity of building occupants [1]. Modern Norwegian schools usually have a constant air volume (CAV) ventilation system, for which the ventilation rate is dimensioned for the maximum pollutant load expected in the ventilated space. The Norwegian building regulations require at least 2 m² for each occupant, or a maximum occupancy density of 0.5 persons/m² [2]. Classrooms in Norway are traditionally sized for a maximum of 28 pupils and two teachers, which implies a required area of 60 m². Further, the building regulations suggest a fresh (outdoor) air ventilation rate of 7 ℓ/s for each occupant, with an additional 0.7 to 2.0 ℓ/s·m² depending on the expected emissions from the building materials and fittings [3]. Normal practice for CAV is to provide a classroom with 270 ℓ/s or 330 ℓ/s fresh air, depending on the pollution load from building materials. This airflow rate is kept constant during the operational hours of the air-handling unit. There are no official guidelines on the operation period of air-handling units, but the practice ranges anywhere from the school's opening hours up to 24-hour continuous operation. This implies that, for much of the time, energy is wasted due to over-ventilation when the occupancy and pollutant loads are below maximum.

Demand-controlled ventilation (DCV) has proved to be a cost- and energy-efficient alternative to CAV [4,5]. DCV is especially suitable in schools with large open areas with varying occupancy density and times of use. At present, most DCV systems are based on monitoring and control of carbon dioxide (CO_2) concentration [denoted **DCV-CO_2** in this paper]. Humans are the main indoor source of CO_2 in schools, leading to a higher concentration indoors than outdoors. The outdoor concentration is approximately

350 ppmv. Norwegian regulations require a CO_2 concentration of less than 1000 ppmv in the breathing zone in schools [2]. CO_2 is not harmful at such a level, but it is regarded as an easily measured surrogate indicator for other occupant-generated pollutants such as odour. The ventilating airflow can thus be matched at all times with the actual number of occupants in a classroom with DCV-CO_2.

Infrared occupancy sensors are a cheap alternative to CO_2-monitoring for controlling the ventilation rate. This ventilation strategy is denoted **DCV-IR** in this paper. This strategy is bimodal: The ventilation rate is reduced to a minimum when the room is unoccupied, and is increased to the design maximum ventilation rate whenever the room is occupied. The occupancy sensor can also control artificial lighting and solar shading. It has been shown in Swedish schools that DCV-IR can reduce the ventilation energy requirements by approximately 50% [6]. The disadvantage with DCV-IR compared to DCV-CO_2, is that the room is over-ventilated when the actual number of occupants is less than the room is dimensioned for. This might lead to uncomfortable draught and low temperature, in addition to unnecessary use of energy. One possible solution for this is recently developed IR-sensors that are intended to give an approximate measure of the number of people in the room, according to the amount of motion registered by the sensor.

Two factors of vital importance when analyzing the potential energy savings and profitability of DCV compared to CAV are the *actual* occupancy density and the *actual* hours of use of the ventilated areas. These factors were investigated as a part of a health survey of Oslo children born in 1992. The study was carried out from autumn 2001 to autumn 2002. As part of the survey, classrooms for children born in 1992 were inspected, and indicators of the quality of the indoor environment (IAQ etc.) were registered and measured.

The data on actual occupancy density and time-of-use allowed us to estimate the ventilated air volume per day for the different ventilating strategies and corresponding energy savings with DCV compared to CAV.

It should be mentioned that Norwegian schools are in rapid development because of a national school reform decree in 1997. This has led to a more open-plan layout in new schools, and the traditional terminology *class* and the *classroom* could eventually disappear in the future. Since almost every inspected school had a traditional classroom organization, the terms *class* and *classroom* are used in this paper.

2. Methods

2.1 Occupancy factor and time of use

157 classrooms for 4th form of pupils (born 1992) were inspected in the period March 5th to June 17th 2002 at 81 randomly selected schools in Oslo. For those schools with more than two parallel 4th form classes, two classrooms were chosen at random. The following were noted during inspection:

- Number of pupils assigned to the classroom
- Number of people present in the classroom
- Use of the classroom during inspection day
- Floor area of the classroom
- Volume of the classroom

Two different occupancy factors were calculated based on the results from the inspection. The first one (**OF1**) is occupancy factor due to sick leave or other reasons for absence among the pupils. The second one (**OF2**) is occupancy factor relative to the design maximum, which is assumed to be 30 people (28 pupils + 2 teachers).

2.2 Ventilating air volumes with different ventilation strategies

The required fresh (outdoor) air volumes per day with normal school activity were calculated for the 3 ventilation strategies: CAV, DCV-CO_2, and DCV-IR. The following assumptions were made:

CAV: Designed for 30 occupants (7 ℓ/s·person) and an additional 1 ℓ/s·m² due to pollution load from materials. This airflow is maintained during the entire operating time of the air-handling unit.

DCV-CO_2: Designed for the actual number of occupants present and a minimum airflow of 1 ℓ/s·m² when the CO_2-level is less than 700 ppmv. The minimum airflow is maintained until the CO_2-level rises to 900 ppmv after the start of the lesson. The ventilation rate is then increased and regulated to keep the CO_2 concentration at a steady state level of 900 ppmv. At the end of the lesson this ventilation rate is maintained until the CO_2-level drops below 700 ppmv when the ventilation rate is reduced to minimum (1 ℓ/s·m²). The CO_2-level of 900 ppmv was chosen because the Norwegian regulations recommend a maximum of 1000 ppmv, combined with the fact that mixing ventilation has an overall relative ventilation efficiency of less than 1.0 in practice compared to *perfect* mixing [7]. Another consequence of the choice of 900 ppmv is that the resultant ventilation rate is approximately the same as CAV & DCV-IR for a full classroom with 30 occupants during steady state conditions.

DCV-IR: Designed for 30 occupants (7 ℓ/s·person) plus an additional 1 ℓ/s·m² for the pollution load from the building materials. An infrared occupancy-sensor controls the ventilation rate between minimum airflow (when the classroom is unoccupied) and the design airflow (when the classroom is in use). The minimum airflow is 1 ℓ/s·m².

In each case, the air supply distribution principle in the classroom is fully mixed. The total air volume for CAV is calculated as follows:

$$Q_{CAV} = \frac{\left(N \cdot q_{CAV} + Area \cdot q_{area}\right) \cdot t_{op}}{1000} \qquad [\mathrm{m^3/day}] \qquad (1)$$

Where N is the maximum number of occupants that the classroom is designed for (30 persons), q_{CAV} is the design ventilation rate per person [7 ℓ/s·person]. *Area* is the classroom floor area [m²], q_{area} is the ventilation airflow [ℓ/s] per m², and t_{op} is the length of time of operation of the air-handling unit [sec./day].

The total air volume for DCV-CO_2 is calculated as follows:

$$Q_{DCV-CO_2} = \frac{Occupants \cdot q_{DCV} \cdot t_{DCV-MAX} + Area \cdot q_{area} \cdot \left(t_{op} - t_{DCV-MAX}\right)}{1000} \qquad [\mathrm{m^3/day}] \qquad (2)$$

Where *Occupants* is the number of occupants present, q_{DCV} is the steady state ventilation rate per person with a CO_2-level of 900 ppmv and $t_{DCV\text{-}MAX}$ is the actual length of time with maximum ventilation of the classroom [sec./day].

A DCV system responds to changes in indoor pollution generation by appropriate adjustment of the ventilation rate. When the pollutant production rate or ventilation rate changes, the indoor pollutant concentration changes and eventually attains a new equilibrium level. This makes $t_{DCV\text{-}MAX}$ different from the time of use (t_{use}) of the classroom. Equation 3 gives the equilibrium concentration, presupposed perfect mixing of the indoor air, equal CO_2-generation from all the occupants, and no absorption of CO_2 in the room [4]:

$$C_{eq} = C_{out} + \frac{g_{CO_2} \cdot 1000}{q_{DCV}} \qquad [\mathrm{mg/m^3}] \qquad (3)$$

Where C_{eq} is the equilibrium concentration [mg/m³], C_{out} is the outdoor concentration and g_{CO2} is CO_2 production rate per person in the room [mg/s] and q_{DCV} is the steady state ventilation airflow to the room [ℓ/s·person]. Solved for q_{DCV}, Equation 3 gives:

$$q_{DCV} = \frac{g_{CO_2} \cdot 1000}{C_{eq} - C_{out}} \qquad [\ell/\text{s}\cdot\text{person}] \qquad (4)$$

With a known initial condition $C(0)$ and equilibrium concentration, the development of the CO_2 concentration over time (C) follows:

$$C = C_{eq} + \left(C(0) - C_{eq}\right) \cdot e^{-nt} \qquad [\text{mg/m}^3] \qquad (5)$$

Where n is the air exchange rate (outside airflow divided by indoor air volume) [h^{-1}] and t is the time after the initial condition [h].

The total air volume for DCV-IR is calculated as follows:

$$Q_{DCV-IR} = \frac{N \cdot q_{CAV} \cdot t_{use} + Area \cdot q_{area} \cdot t_{op}}{1000} \qquad [\text{m}^3/\text{day}] \qquad (6)$$

Where t_{use} is the length of time of occupancy of the classroom [hrs/day].

2.3 Energy use with different ventilating strategies

In this study, energy use for ventilation purposes includes fan energy and energy for space heating due to ventilation heat loss, minus useful energy recovered by ventilation heat recovery. Normal Norwegian schools do not have air-conditioning (cooling or (de)humidification).

Energy used by the fan motors can be calculated using the Specific Fan Power (SFP) of the ventilation system [8]. In Norway, SFP is defined as [9]:

$$SFP = \frac{P_{CAV}}{Q_{CAV}} \qquad [\text{kWs/m}^3] \qquad (7)$$

Where P_{CAV} is the total power input to the fan motors [kW], and Q_{CAV} is the mechanical airflow rate [m^3/s]. The energy use [kWh] is the necessary fan power multiplied with its corresponding time [hours/day or hours/year].

Norwegian CAV-systems typically have a SFP of between 2 and 5, with an average of about 3.5 kWs/m³, but an SFP of 2 is recommend as a target value for new ventilation systems [9]. Assuming a well-designed ventilation system with SFP of 2 with a known mechanical airflow rate (Q_{CAV}), the necessary fan power for the CAV-system (P_{CAV}) can be found. P_{CAV} follows the cubic fan law, and can be expressed as follows [10].

$$P_{CAV} = \frac{k_1 \cdot Q_{CAV}^3}{\eta_{tot}} = \frac{Q_{CAV} \cdot \Delta p_{tot}}{\eta_{tot}} = \frac{Q_{CAV}}{\eta_{tot}} \cdot (\Delta p_c + \Delta p_d) = P_{CAV-c} + P_{CAV-d} \qquad \text{[kW]} \qquad (8)$$

Where Δp_{tot} is the total pressure drop (sum of pressure drop for supply air and extract air) in the system [kPa], η_{tot} is the total efficiency of the fan system [%], k_1 is a constant, Δp_c is the pressure drop through central components i.e. air-intake, air-exhaust and air handling unit [kPa], and Δp_d is the pressure drop through the distribution ductwork [kPa]. $P_{\text{CAV-c}}$ plus $P_{\text{CAV-d}}$ is the necessary fan power for transporting air through central components and distribution ducts [kW].

DCV systems have variable airflow rate. Assuming an air temperature of 293 K, and turbulent airflow through the entire ventilation system, the power demand for transporting air through central components for a DCV system relative to a CAV system will vary with the ventilation flow according to [5]:

$$P_{DCV-c} = P_{CAV-c} \cdot \left(\frac{Q_{DCV}}{Q_{CAV}} \right)^3 \qquad \text{[kW]} \qquad (9)$$

It is not possible to achieve ideal DCV whilst obeying the cubic fan law in complex distribution systems, because this requires that all ventilated zones in the building simultaneously have an equal proportional ventilation demand, i.e. not individual zonal control. In practice, one tries to keep the duct static pressure (Δp_d) constant by means of some sort of throttling in the ducts (e.g. motorized VAV damper), combined with fan speed control. The extra fan energy consumed by throttling can only be utilized if a heating demand exists, otherwise it is wasted [11] and it might even give an extra cooling load. The power demand for transporting air through distribution ducts for a DCV-system relative to a CAV-system will vary with the ventilation flow according to [5]:

$$P_{DCV-d} = P_{CAV-d} \cdot \left(\frac{Q_{DCV}}{Q_{CAV}} \right) \qquad \text{[kW]} \qquad (10)$$

The energy use for space heating due to ventilation (E_h) for a DCV system relative to a CAV-system will vary with the ventilation flow according to [5]:

$$E_{H-DCV} = E_{H-CAV} \cdot \left(\frac{Q_{DCV}}{Q_{CAV}} \right) \qquad \text{[kWh/m}^2\text{year]} \qquad (11)$$

The above equation gives a conservative estimate of the energy saving potential of DCV systems. This is because $E_{H\text{-}DCV}$ will be further reduced by the fact that internal gains (solar & occupants) cover a larger fraction of the ventilation heat loss in DCV systems than in CAV systems [11].

3. Results

3.1 Occupancy factor and time of use

The inspection reveals that the average number of occupants in a typical classroom is about 22 (Table 1). The classroom is used for about four hours. The average occupancy density is about 0.37 pupils/m^2 (Table 2).

Table 1. Results from inspection of 157 classrooms in Oslo. All the classrooms are designed for 28 pupils.

	Mean	Min.	Max.	Standard deviation
Pupils assigned to the class	22.3	13.0	28.0	3.5
Pupils present during inspection	20.9	13.0	28.0	3.6
Teachers present during inspection	1.3	1.0	3.0	0.5
Floor area of classroom [m²]	61.5	43.0	93.0	8.2
Volume of classroom [m³]	190.0	150.0	285.0	31.0
t_{use} - Use of classroom during inspection day [h]	4.0	3.0	5.0	0.4

Table 2. Occupancy density in classrooms in Oslo and occupancy factors relative to the number of pupils assigned to the classroom (OF1), and relative to the expected design maximum (OF2).

	Mean	Min.	Max.	Standard deviation
Occupancy density [pupils/m²]	0.37	0.21	0.62	0.07
OF1 - Number of pupils present divided by the number of pupils assigned to the classroom	0.94	0.70	1.00	0.06
OF2 - Number of occupants (pupils + teachers) present divided by 30 (which is assumed to be design maximum)	0.74	0.47	1.00	0.12

Only two classrooms had a floor area smaller than 50 m². The smallest (43 m²) was the main classroom for 26 pupils, indicating that it in practise will be used as a classroom for up to 28 pupils if necessary. Six of the classrooms had an occupancy density above 0.5 pers/m². The maximum number of 28 pupils was found in 8 classrooms (5% of the classrooms).

3.2 Ventilating air volumes with different ventilating strategies

DCV-CO_2 involves ventilating the classroom with the minimum rate until the CO_2-level reaches 900 ppmv, at which point the ventilation increases to 9 ℓ/s·person (Equation 4) presupposed a CO_2-production rate of 9 mg/s per occupant [4] and an outdoor CO_2-level of 350 ppmv. The average classroom has a volume of 190 m³, an area of 61.5 m² and 22 occupants present. It thus takes approximately 12 minutes for the average classroom to reach 900 ppmv CO_2 after being occupied (Equations 4 & 5). Maximum ventilation is maintained until the CO_2-level drops below 700 ppmv, after the room has been vacated — this takes approximately 6 minutes for the average classroom (Equations 4 & 5). This indicates that a DCV system will typically operate with maximum airflow rate for 6 minutes less than the period of use. The period $t_{DCV\text{-}MAX}$ is decreased even further as a result of brakes and periods with reduced occupancy, during the school day. This has been neglected in this analysis even though it is likely to happen.

Table 3 shows the resulting daily volume of ventilation air for the different control strategies. The mean values are valid for the average classroom.

Table 3. Total ventilation air volumes with different ventilation strategies, and the corresponding reduction factors compared to CAV. This table assumes that the air-handling unit operates 10 hours per day (t_{op}).

	Mean	Min.	Max.	Standard deviation
Total air volume with CAV [m³/day]	9773	9123	10895	295
Total air volume with DCV-CO_2 [m³/day]	4164	2904	5767	561
Total air volume with DCV-IR [m³/day]	5242	4058	6900	448
Air volume DCV-CO_2 / Air volume CAV	0.43	0.32	0.53	-
Air volume DCV-IR / Air volume CAV	0.54	0.44	0.63	-

Figure 1 shows the influence of operation period on the daily volume of ventilation air for the different control strategies. This figure applies to an average sized classroom with 22 occupants present during hours of use.

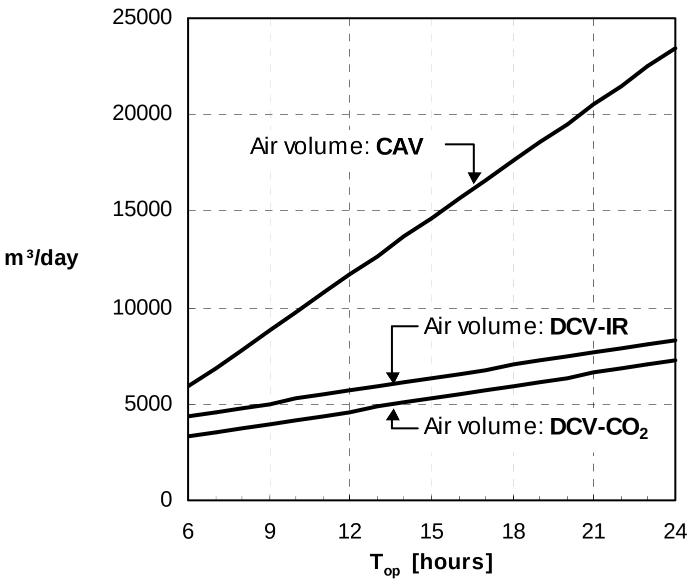

Fig. 1. Influence of AHUs operation period on ventilating air volume with different ventilation control strategies.

Figure 2 shows the percentage reduction in daily volume of ventilation air for the DCV strategies relative to CAV.

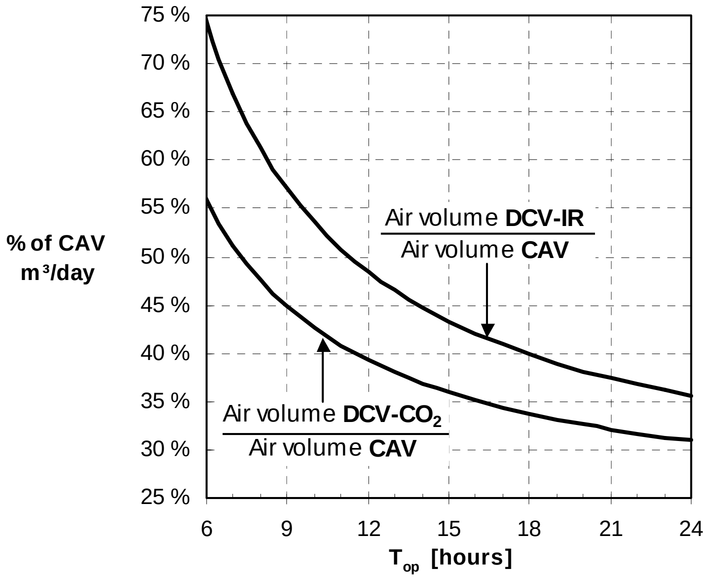

Fig. 2. Influence of operation period on the reduction of daily volume of ventilation air with DCV-strategies compared to CAV.

3.3 Energy use with different ventilating strategies

The energy use for a CAV system has been calculated with the following assumptions, which represent good design practice in Norway: (i) SFP of 2 [9], (ii) the pressure drop through the distribution ducts represents half of the total pressure drop (i.e. $P_{CAV\text{-}c} = P_{CAV\text{-}d}$) [5], (iii) the CAV system operates for 10 hours per day, 188 days per year [12], (iv) the space heating requirement due to ventilation heat loss is 27 kWh/m^{2}year assuming ventilation heat recovery (typical for Norwegian schools [12]).

The corresponding energy use for DCV-CO_2 and DCV-IR system are calculated according to Equations 8, 9, 10 and 11.

Figure 3 shows the influence of operation period on the energy use for ventilation purposes with different ventilation strategies. This figure applies to an average sized classroom (61.5 m^2) with 22 occupants present.

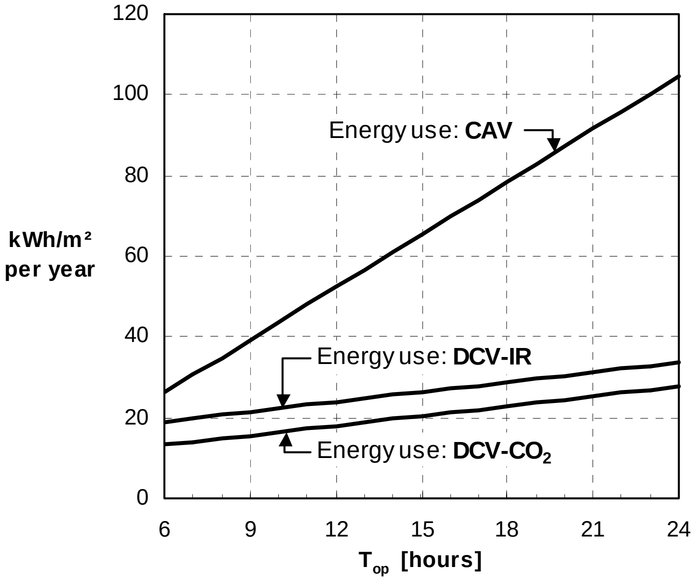

Fig. 3. Annual specific energy use for ventilation purposes for with different ventilation control strategies. The values are based on an average sized classroom of 61.5 m^2 with 22 occupants present.

Figure 4 shows the percentage reduction in energy use for ventilation purposes for the DCV strategies relative to CAV.

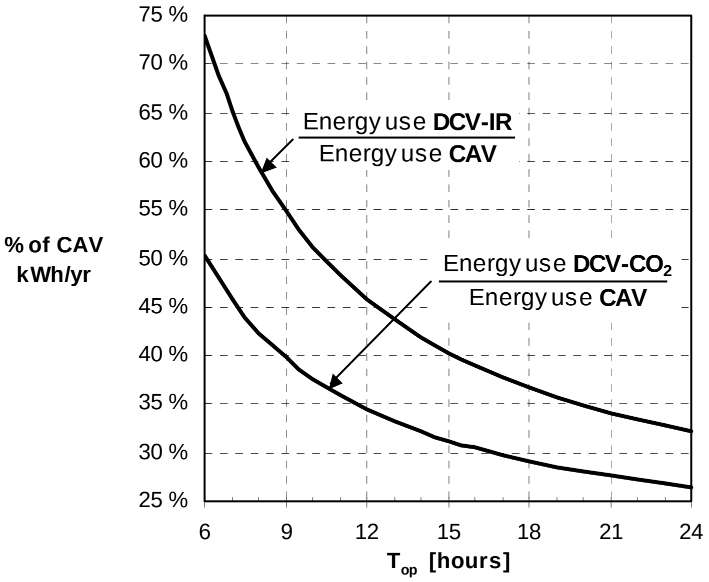

Fig. 4. Influence of operation period on relative energy use with DCV-strategies compared to CAV.

4. Discussion

4.1 Occupancy density in Norwegian primary schools

The inspection of 81 schools and 157 classrooms shows that classrooms typically have a considerably lower occupancy density than they are designed for. The average number of occupants was 22.2, while the expected design maximum is 30 (Table 1). The average classroom occupancy density was 0.37 pers/m² (Table 2). Only 8 of the 157 classrooms exploited the design capacity of the classroom. On average 1.4 pupils (6% of the class) are absent due to sickness or other errands. 74% of the maximum capacity of the average classroom is utilized when it is used, and the classrooms are used for school activities from 3 to 5 hours per day.

4.2 Energy use with different ventilating strategies

Both of the studied DCV strategies have a considerable potential for reducing the daily volume of ventilation air. DCV-CO_2 can reduce the energy use for ventilation purposes to 38% relative to CAV with 10 hours operation period, whilst DCV-IR can reduce the energy use to 51% (Figure 4). This corresponds well with the results from the Swedish case-study [6].

The pattern of use of the classrooms is a key factor influencing the potential energy savings with DCV compared to CAV. The average use of a classroom for school activities was 4 hours daily; the maximum recorded length of use was 5 hours.
A classroom is typically in use for only 30%~50% of the air-handling unit's operation period of usually 10~11 hours [12]. Many schools are used for other activities after normal school hours, so it is very difficult to restrict the operation period of the air-handling unit without risking insufficient ventilation for these activities.

DCV-IR reduces the daily volume of ventilation air to 74% relative to CAV, in case of 6-hour operation, and to 36% for 24-hour operation (Figure 2). The corresponding reduction of energy use is 73% in case of 6-hour operation, and 32% for 24-hour operation (Figure 4). The reduction of energy use exceeds slightly the reduction of ventilating air volume because of the cubic fan law (Equation 9).

DCV-CO_2 has a significant potential to reduce the daily volume of ventilation air, even with a very short operation period. It reduces the daily volume of ventilation air to 56% relative to CAV, in the case of 6-hour operation, and to 31% for 24-hour operation in a classroom with an average occupancy density (Figure 2). The corresponding reduction of energy use is 50% in the case of 6-hour operation, and 26% for 24-hour operation (Figure 4).

The energy saving potential is very sensitive to differences in the CAV operation period (Figure 4), and this shows that much energy can be wasted with CAV, due to ventilating empty classrooms. It is possible to reduce CAV operation period by having several small CAV-systems. It is sensible that each small CAV system supplies parts of the school that have a coincident pattern of use — however it is almost impossible to predict the pattern of use of the different areas throughout the lifetime of the school. Another advantage of DCV-CO_2 is that it reduces the risk of under-ventilating overcrowded rooms compared to CAV or DCV-IR, depending on the ventilation system's capacity.

The impact of (i) infiltration, (ii) breaks between lessons, (iii) window opening, and (iv) displacement ventilation, will in practice further increase the energy saving potential of DCV-CO_2, but have been ignored in our calculations.

4.3 Influence of the CO_2-production rate

The actual CO_2-production rate can have a vital influence on the air flow rates and energy use with DCV-CO_2. All calculations are based on a CO_2-production of 9 mg/s per person [4]. This production rate is valid for adults. Children in primary school with normal activity (1.2 MET) will have a CO_2-production of 7 mg/s per person [13,14]. DCV-CO_2 with this CO_2-production rate can theoretically reduce the energy use for ventilation purposes to roughly 31% relative to CAV with 10 hours operation period. However, since CO_2 is only an indicator for the pollution load caused by occupants, it is an open question whether the actual ventilation rate should depend on the CO_2-production of the occupants, or the number of occupants. If the latter is true, then the CO_2-target for ventilation control should be reduced from 900 ppmv to about 800 ppmv in primary school classrooms.

4.4 Overall design issues

The aforementioned differences in both energy-saving and risk of insufficient ventilation, must be balanced against differences in investment- and maintenance costs. For example, infrared occupancy-sensors are considerably cheaper than CO_2-sensors, and probably more robust and longer lasting because of simpler technology [15]. If they fail, they are cheap to replace, which might reduce the risk of malfunctioning sensors not being replaced for a long time due to budget restrictions.

The decision as to which of DCV-IR or DCV-CO_2 is the most profitable depends on absenteeism & utilization of class capacity (factor *OF2* in Table 2) together with the operation period. If a school has full classes and negligible absenteeism then DVC-IR will be more profitable, and vise versa for DCV-CO_2.

The growing architectural trend of opening up school areas, in line with modern pedagogic practice, will probably increase the variability in time of use, occupancy density and resulting pollution loads — hence the energy saving potential of DCV will increase (relative to CAV). Future new schools will probably have a larger volume per pupil, leading to a further reduction in $t_{DCV\text{-}MAX}$ relative to the time of use (t_{use}), especially if DCV-CO_2 is combined with displacement ventilation and the CO_2-sensor is located in the breathing air height (approx. 0.9~1.1 m above floor level).

5. Conclusions

Primary school classrooms in Oslo have an average of 22 occupants present. CAV ventilation systems are normally designed for 30. Thus typically only 74% of the classroom’s design capacity is being utilized. The average occupancy density in classrooms is 0.37 pupils/m². The average classroom is used 4 hours each weekday for normal school activities.

DCV-CO_2 and DCV-IR reduce the energy use for ventilation purposes in the average classroom to respectively 38% and 51% of the corresponding energy use for a CAV system operating with full airflow from 7 AM to 5 PM. These are conservative estimates of the energy saving potential of DCV in a well-functioning ventilation system in a typical modern Nordic primary school.

Acknowledgements

The Norwegian Research Council has supported this work as a part of the research programs “Environmentally favourable energy use in buildings” and “Asthma and allergy among school children”.

References

[1] P. Wargocki, D.P. Wyon, J. Sundell, G. Clausen and P.O. Fanger, The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome, symptoms and productivity, Indoor Air, Vol.10 (2000), No.4, pp.222-236.

[2] Norwegian Health Department, Forskrift om miljørettet helsevern i skoler og barnehager (Regulations for environmental health protection in schools and day-care centers), Norway, 2003 (in Norwegian).

[3] National Office of Building Technology and Administration, Norway, Guildelines to the Technical Regulations under the Planning and Building Act 1997 (in Norwegian), http://www.be.no/, 3rd ed. April 2003 (in Norwegian).

[4] W.J. Fisk and A.T. De Almeida, Sensor-based demand-controlled ventilation: A review, Energy and Buildings, Vol.29 (1998), pp.35-45.

[5] M. Mysen, J.P. Rydock and P.O. Tjelflaat, Demand controlled ventilation for office cubicles – can it be profitable?, Energy and Buildings, Vol.35 (2003), pp.657-662.

[6] International Energy Agency, in: L.-G. Mansson (Ed.), Demand-controlled ventilating systems: case studies, Swedish Council for Building Research, Stockholm, 1993.

[7] H.B. Awbi, Ventilation of Buildings, E & FN Spon, London, 1995.

[8] L. Jagemar, Design of energy efficient buildings: applied on HVAC systems in commercial buildings, Department of Building Services Engineering, Chalmers University of Technology, Goteborg, Sweden, 1996.

[9] M. Mysen and K. Polak, Energieffektiv viftedrift – Prosjekteringsveiledning (Fan-energy efficient ventilation systems – Design guidelines), Norwegian Building Research Institute, Project report 303, Oslo, Norway, 2001 (in Norwegian).

[10] ASHRAE, ASHRAE Handbook: Systems and Equipment, Refrigerating and Air-Conditioning Engineers, Inc., American Society of Heating, Atlanta, 1996.

[11] B. R. Soerensen, Application and Energy Consumption of Demand Controlled Ventilation Systems, Norwegian University for Science and Technology, Trondheim, Norway, 2002.

[12] Enova SF, Manual for Enøk normtall, Enova håndbok 2004:2 (in Norwegian).

[13] K. Diem and C. Lentner (eds.). Documenta Geigy : scientific tables. 7th ed., Ciba-Geigy, Basel, Switzerland, 1975.

[14] Comis ver. 3.1. Multizone airflow simulation program, EMPA, Switzerland.

[15] Heiselberg P.K. (ed.). *Principles of Hybrid Ventilation*. IEA ECBCS Annex 35: Hybrid ventilation in new and retrofitted office and educational buildings, Aalborg University, Denmark, 2002.

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Energy and Buildings 35 (2003) 657–662

ENERGY and BUILDINGS

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Demand controlled ventilation for office cubicles—can it be profitable?

M. Mysen[a,*], J.P. Rydock[a,1], P.O. Tjelflaat[b,2]

[a]Norwegian Building Research Institute, Forskningsveien 3b, P.O. Box 123, Blindern, NO-0314 Oslo, Norway
[b]Department of Refrigeration and Air Condition, Norwegian University for Science and Technology, Kolbjoern Hejes Vei 1b, 7491 Trondheim, Norway

Received 28 August 2002; received in revised form 13 October 2002; accepted 13 October 2002

Abstract

In an office building fresh air is normally provided by ventilation systems designed for a constant air volume (CAV). This implies that for much of the time, considerable amounts of energy can be wasted on ventilating empty offices. We have performed a simple analysis of the potential profitability of demand controlled ventilation (DCV) on a reference office building in Norway. Our calculations suggest that the maximum profitable investment in DCV equipment is about 400 EURO per cellular office if central installations and technical areas can be reduced as a consequence of DCV. Reduced energy costs alone will cover an investment of about 300 EURO per cellular office. If the electrical energy price in Norway increases to the same level as in Denmark, reduced energy costs alone will cover an extra investment of about 700 EURO per cellular office.

Keywords: Office building; Demand controlled ventilation; Profitability; Simplified calculation methods

1. Introduction

A good office environment with sufficient fresh air is a necessary condition for high productivity and good health among workers [1]. Fresh air is normally provided by ventilation systems designed for a constant air volume (CAV) determined by the maximum pollutant load expected in the ventilated space. This implies that for much of the time, considerable energy can be wasted on ventilating empty offices because of the variable use rates and pollutant loads.

The concept of demand controlled ventilation (DCV), in which a space is variably ventilated according to the pollutant load or occupancy at any given time, addresses this problem. Demand controlled ventilation relies on a sensor in the space to give feedback to adjust air supply and extraction to the level appropriate for the ventilation needs of the space. The requirements for an occupancy sensor and an adjustable air supply make DCV-systems initially more expensive than constant-flow ventilation arrangements. For DCV to be a attractive alternative, the extra initial costs must be recouped from lower operating costs because of less energy to fans, heating and cooling and reduced installation and area costs for central installations like air-handling units, air intakes and outlets.

Large spaces with widely varying occupancy rates have large variability in ventilation demand. In such spaces like movie theatres, auditoriums, classrooms, etc. demand controlled ventilation has been proven to be a money- and energy-saving alternative to constant-flow systems [2]. For smaller spaces designed to be occupied by one person or several people, however, the economics are much more stringent. This has limited the application of DCV in office buildings. This article analysis the possible profitability of DCV in office cubicles and introduces a method to determine whether DCV is profitable or not in an office building.

2. Power and energy use of fans

Energy use of fans can be calculated using the specific fan power (SFP) of the ventilation system [3]. In Norway, SFP is defined as [4],

$$\mathrm{SFP}\ (\mathrm{kWs/m^3}) = \frac{\sum P}{Q} \tag{1}$$

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* Corresponding author. Tel.: +47-2296-5582; fax: +47-2296-5725.
E-mail addresses: mads.mysen@byggforsk.no (M. Mysen), james.rydock@byggforsk.no (J.P. Rydock), per.o.tjelflaat@kkt.ntnu.no (P.O. Tjelflaat). *URL:* http://www.byggforsk.no
[1] Tel.: +47-2296-5544; fax: +47-2296-5725.
[2] Tel.: +47-7359-5000; fax: +47-2259-5310.

where $\sum P$ is the total of all fan power measured as power input to the fan engine (kW) and Q is the total mechanical airflow (m^3/s).

The mechanical airflow should be corrected for other temperatures than 293 K, but this can normally be neglected for HVAC plants.

For CAV-systems, the SFP in office buildings in Norway is between 2 and 5 with and average of about 3.5 kWs/m^3 [4].

Specific energy use of fans per year is,

$$E_{\mathrm{fa}}\,(\mathrm{kWh/m^2\ per\ year}) = \mathrm{SFP}\,Q_{\mathrm{s}}T_{\mathrm{u}} \tag{2}$$

where Q_{s} is the specific airflow (m^3/(m^2 s)) and T_{u} is the time of use of mechanical ventilation (h per year).

A DCV-system will have variable airflow. Assuming demand control at about 293 K air temperature and turbulent airflow through the entire ventilation system, the power demand will vary with the ventilation flow according to the cube fan law [5]:

$$P\,(\mathrm{kW}) = \frac{Q_{\mathrm{DCV}}\,\Delta p_{\mathrm{tot}}}{\eta_{\mathrm{tot}}} = \frac{Q_{\mathrm{DCV}}k_1Q_{\mathrm{DCV}}^2}{\eta_{\mathrm{tot}}} = \frac{k_1Q_{\mathrm{DCV}}^3}{\eta_{\mathrm{tot}}} \tag{3}$$

where P is the power use measured as power input to the fan engine (kW), Δp_{tot} the total pressure drop (sum of pressure drop for supply air and extract air) in the system (kPa), η_{tot} the total efficiency of the fan system (%), k_1 a constant and Q_{DCV} is the mechanical ventilation flow in a DCV-system (m^3/s).

The fan efficiency varies with ventilation flow divided by fan speed [6]. If we reduce the fan speed within the normal limits of how a DCV-system operates, we will have a corresponding reduction of the ventilation flow so that the fan efficiency will remain approximately constant, even though it will have some variation due to how the fans and dampers are modulated to sustain a constant duct static pressure. This means that we can take the fan efficiency as constant in rough calculations of the profitability of DCV in office cubicles [7]. Since fan efficiency is by far the largest contributor to the total efficiency of the fan system, we can treat the total efficiency for the fan system η_{tot} as a constant as well.

With many ventilated zones it is not possible to achieve ideal DCV because the ventilation demand in one ventilated zone will influence the ventilation rates in the other zones. In practice, one tries to keep the duct static pressure constant with some sort of throttling in the ducts in combination with fan speed control. The extra energy consumed by throttling can only be utilized if a demand for heating exists, otherwise it is wasted [7] and it might even give an extra cooling load. The fan power demand in the duct system will then vary roughly as follows:

$$P_{\mathrm{d}}\,(\mathrm{kW}) = \frac{Q_{\mathrm{DCV}}\,\Delta p_{\mathrm{duct}}}{\eta_{\mathrm{tot}}} = \frac{Q_{\mathrm{DCV}}k_2}{\eta_{\mathrm{tot}}} \tag{4}$$

where k_2 is a constant because of constant pressure difference between main duct and room.

The occupancy factor o in an office building is the actual number of occupied offices divided by the total number of offices in the building. If an office is unoccupied there is still a need for maintaining minimum ventilation so that a visitor is met with reasonably fresh air when entering the room. The base rate b is the minimum ventilation rate factor, or the ventilation rate used for an unoccupied office divided by the corresponding ventilation rate for an occupied office. If all the offices in the building are occupied at the same time, we will have the same airflow with DCV and CAV. If we denote the air flow through a CAV-plant by Q_{CAV}, the corresponding air flow through a DCV-plant will be

$$Q_{\mathrm{DCV}}\,(\mathrm{m/s}) = Q_{\mathrm{CAV}}o + Q_{\mathrm{CAV}}b(1-o) = Q_{\mathrm{CAV}}(o+b-bo) \tag{5}$$

The simultaneous air flow at a given occupancy and base rate can be expressed with a simultaneous factor s:

$$s = o + b - bo \tag{6}$$

Kukla [8] has found that DCV fans runs at about 60% of full load on average for a typical office building during occupancy if the building. This indicates that the simultaneous factor is about 0.6 and that the occupancy factor is around 0.5. In Norway, it is normal to operate the ventilation plant for about 12 h, while the building has about 8 h of normal occupancy. This means that the occupancy factor is probably less than 0.5 during the operating hours of the ventilation plant.

Eqs. (3), (5) and (6) give the necessary fan power for transporting air through central components like air-intake, air-outlet and air-handling unit:

$$P_{\mathrm{c}}\,(\mathrm{kW}) = k_3Q_{\mathrm{DCV}}^3 = k_3(Q_{\mathrm{CAV}}s)^3 \tag{7}$$

while Eqs. (4)–(6) give the necessary fan power for transporting air through the duct system:

$$P_{\mathrm{d}}\,(\mathrm{kW}) = k_4Q_{\mathrm{DCV}} = k_4Q_{\mathrm{CAV}}s \tag{8}$$

where $k_3 = k_1/\eta_{\mathrm{tot}}$ and $k_4 = k_2/\eta_{\mathrm{tot}}$ are approximately constant.

If we assume that the instantaneous simultaneous factor generally deviates only slightly from the average simultaneous value (except for short peak loads which have small energy impact), the specific energy use will vary as follows:

$$E_{\mathrm{fa-DCV}}\,(\mathrm{kWh/m^2\ per\ year}) \approx E_{\mathrm{fac-CAV}}s_{\mathrm{avg}}^3 + E_{\mathrm{fad-CAV}}s_{\mathrm{avg}} \tag{9}$$

where $E_{\mathrm{fa-DCV}}$ is the specific energy use of fans with a DCV-system, $E_{\mathrm{fac-CAV}}$ the specific energy use to transport air through central components like air-intake, air-outlet and air-handling unit with a corresponding CAV-system and $E_{\mathrm{fad-CAV}}$ is the specific energy use to transport air through the duct system with a corresponding CAV-system, and

$$E_{\text{fa-CAV}}\,(\text{kWh/m}^2\text{ per year}) = E_{\text{fac-CAV}} + E_{\text{fad-CAV}} \tag{10}$$

where $E_{\text{fa-CAV}}$ is the specific energy use of fans with a CAV-system.

3. Power and energy use for central heating and central cooling

Power demand for central heating or cooling can be determined as follows when humidity is regarded [9]:

$$P_{\text{ch/cc}}\,(\text{kW}) = Q_{\text{DCV}}\rho c_p\,\Delta T \approx Q_{\text{CAV}}s_{\text{avg}}k_5\,\Delta T \tag{11}$$

where r is the density of air (kg/m^3), c_p the specific heat capacity for air (kJ/(kg K)), ΔT the change of temperature (K) and k_5 is a approximately constant for air at about 293 K.

We see that the power demand will vary with the simultaneous factor to the first power.

Energy demand for central heating and central cooling will then vary with the simultaneous factor as follows:

$$E_{\text{ch}}\,(\text{kWh/m}^2\text{ per year}) = E_{\text{ch-CAV}}s_{\text{avg}} \tag{12}$$

$$E_{\text{cc}}\,(\text{kWh/m}^2\text{ per year}) = E_{\text{cc-CAV}}s_{\text{avg}} \tag{13}$$

where E_{ch} is the specific energy for central heating, $E_{\text{ch-CAV}}$ the specific energy for central heating for a corresponding CAV-system, E_{cc} the specific energy for central cooling and $E_{\text{cc-CAV}}$ is the specific energy for central cooling for a corresponding CAV-system.

4. Profitable investment for DCV because of reduced use of energy

When a measure results in a reduction in the energy demand we can accept a higher investment cost. The maximum profitable investment can be calculated if we know the approximate annual energy reduction, energy costs, the functional lifetime of the measure and the claim for profit (real interest).

Maximum profitable investment is the difference between the present worth of the savings and the present worth of the expenses resulting from the measure. If we expect the same development of energy costs and other expenses we can normally simplify the maximum profitable investment to be the present worth of the net annual savings during the functional lifetime of the measure [10].

$$\text{MPI (chosen currency)} = \Delta C_{\text{m}}\,PV_{i,L} \tag{14}$$

where MPI is the maximum profitable investment (chosen currency), ΔC_{m} the net annual savings due to DCV (chosen currency) and $PV_{i,\,L}$ is the present worth factor based on real interest (i) and functional lifetime (L).

4.1. *Profitable investment for DCV because of reduced use of energy and reduced installations—and area costs*

Installation costs for constant air volume vary between different countries. A good way of making a fast and quite accurate prediction of the costs is to use the most recent local investment cost for a conditioned cubic meter of air (chosen currency/(m^3/h)). In Norway, this cost was about 7.5 EURO/(m^3/h) for treated air with cooling around the Oslo area in 2002. A major share of this cost lies in components like: air intake, central unit, main ducts that can to a certain degree be reduced with regard to the occupancy factor. Local components like room vents, secondary ducts and so on, must still have dimensions like they had been a part of a CAV-system.

With regard to the occupancy factor, we can reduce the dimensions of the central ventilation installations and the technical floorage with DCV. Kukla [8] suggests a diversity factor of 70–80% while the simultaneous factor is 0.6. This means that the central components in a DCV-system can be scaled down to about 0.75 of a CAV-system for a simultaneous factor of 0.6. In rough calculations, we can assume that the following relation between the diversity factor d_{f} and the average simultaneous factor is valid when the diversity factor is less than unity:

$$d_{\text{f}} = \frac{0.75}{0.6}s_{\text{avg}} = 1.25s_{\text{avg}} \tag{15}$$

The difference between the diversity factor and the simultaneous factor will give a reduction in fan power energy needed for DCV compared to CAV because of reduced pressure drops through central components. This reduction is expressed with the term $(s_{\text{avg}}/d_{\text{f}})^2$ which is about 0.64 when the s_{avg} is less than 0.8. This means that the necessary fan power for transporting air through central components like air-intake, air-outlet and air-handling unit will approximately vary with the simultaneous factor to the first power according to Eqs. (16) and (17):

$$P_{\text{fa}}\,(\text{kW}) = k_6Q_{\text{CAV}}s_{\text{avg}}\left(\frac{s_{\text{avg}}}{d_{\text{f}}}\right)^2 \approx k_6Q_{\text{CAV}}s_{\text{avg}} \times 0.64 \tag{16}$$

$$E_{\text{fa}}\,(\text{kWh/m}^2\text{ per year}) = E_{\text{fa-ref}}s_{\text{avg}}\left(\frac{s_{\text{avg}}}{d_{\text{f}}}\right)^2 \approx E_{\text{fa-ref}}s_{\text{avg}} \times 0.64 \tag{17}$$

where k_6 is a approximately constant.

Necessary fan power for transporting air through the duct system and energy demand for central heating and cooling will vary with the simultaneous factor to the first power as before, according to Eqs. (8), (12) and (13).

Installation costs for CAV vary between different countries. A good way of making a fast and quite accurate prediction of the costs is to use the most recent local investment cost for a conditioned cubic meter of air (chosen currency/(m^3/h)). In Norway, this cost was about 7.5 EURO/(m^3/h) for treated air with cooling around the Oslo area in 2002. A major share of this cost lies in components like: air intake, central unit, main ducts that can to a certain degree be reduced with regard to the occupancy factor. Local components like room vents, secondary ducts and so on, must still have dimensions like they had been a part of a CAV-system.

Saved investments because of reduced equipment sizes can be calculated according to Eq. (18):

$$\mathrm{SI_E}\ (\text{chosen currency}) = C_{\mathrm{AIR}}\frac{Q_{\mathrm{CAV}}}{3600}xd_{\mathrm{f}} + C_{\mathrm{AIR}}\frac{Q_{\mathrm{CAV}}}{3600}(1-x) \tag{18}$$

Saved investments because of reduced cost of technical floorage can be calculated according to Eq. (19):

$$\mathrm{SI_A}\ (\text{chosen currency}) = \frac{Q_{\mathrm{CAV}}}{3600}f(1-d_{\mathrm{f}})C_{\mathrm{A}} \tag{19}$$

where C_{AIR} is the specific ventilation cost for a conditioned cubic meter of air (chosen currency/(m^3/h)), x the share of the ventilation system that can be reduced with DCV, f the relationship between necessary area for the air-handling unit and the corresponding conditioned airflow in m^3/h (m^2/(m^3/h)); in Norway, f varies between 0.3 and 1% [11], this means that a very simple ventilation system demands about 3 m^2/(1000 m^3/h) (275 l/s) conditioned air and a complex ventilation system demand about 10 m^2/(1000 m^3/h) conditioned air and C_{A} is the calculation cost for technical area (chosen currency/m^2).

A possible decrease in area for components like shafts is neglected.

5. Reference building

The annual energy demand for a typical office building in Norway with a CAV-system is shown in Table 1 broken down into uses [12,13]. The system includes a heat exchanger with 70% efficiency and a total pressure drop over the whole system of about 2000 Pa. The air-handling system is assumed to be on for 3000 h per year and supplies 10 m^3/(m^2 h). Ventilation related costs are central heating, fans and central cooling. Energy to fans will always be electric energy, while energy to heating and cooling can be either thermal or electric energy. Total ventilation related energy use is 51 kWh/m^2 per year, which is 22% of the building's total energy use.

Table 1
Simulated yearly energy demand for a typical office building in Norway with ventilation heat recovery

Number	Category	Energy demand (kWh/m^2 per year)
1	Local heating	65
2	Central heating = $E_{\mathrm{ch\text{-}CAV}}$	**12**
3	Hot water	12
4a	Fans = $E_{\mathrm{fa\text{-}CAV}}$	33
4b	Pumps	15
5	Lightning	45
6	Equipment	27
7	Local cooling	20
8	Central cooling = $E_{\mathrm{cc\text{-}CAV}}$	**6**
Sum		235

Reference values used in later calculations are given in boldface.

5.1. Case 1: Maximum profitable investment because of reduced energy demand (Norway)

Case 1 is based on the following assumptions, which are quite common in Norway:

Specific ventilation rate m^3/(m^2 h)	10
Minimum ventilation rate factor	0.2
Specific fan power kW/(m^3/s)	4
Hours of use (h)	3000
Real interest (%)	5
Predicted lifetime (years)	20
Electrical energy cost (EURO/kWh)	0.083
Thermal energy cost (EURO/kWh)	0.064

Because of regulation needs the pressure in the duct system is kept constant. We assume that this represents half the total pressure drop in a corresponding CAV-system.

Fig. 1 presents maximum profitable investment for one 10 m^2 cellular office because of reduced need of energy.

In this case, the maximum profitable investment is about 300 EURO for a cellular office with an occupancy factor of 0.5 or a corresponding simultaneous factor of 0.6.

In Denmark and Germany, the electrical energy cost is about tree times higher than in Norway. If we use an electrical energy cost of 0.25 EURO/kWh in Case 1, the maximum profitable investment is about 700 EURO for a cellular office with an occupancy factor of 0.5.

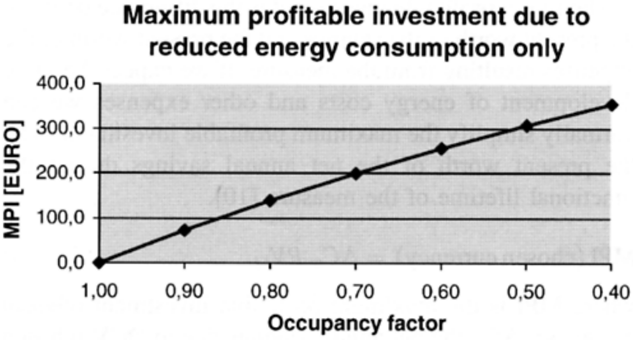

Fig. 1. Maximum profitable investment per cellular office vs. occupancy factor, exclusively because of reduced need of energy.

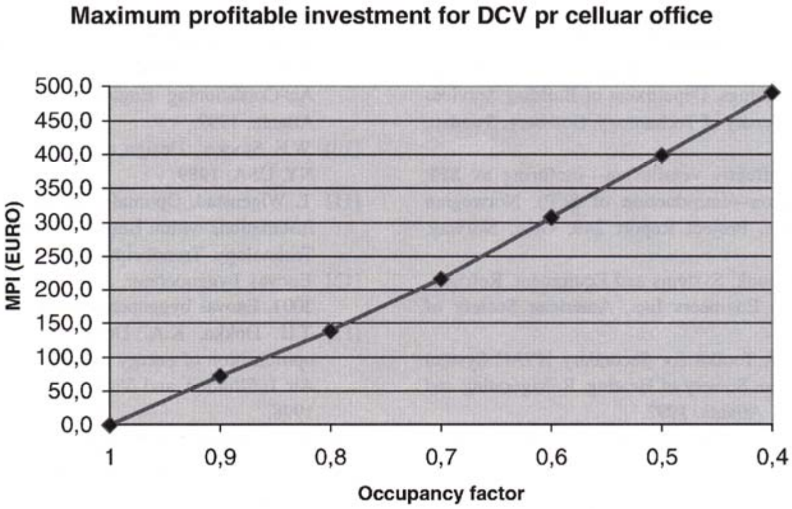

Fig. 2. Maximum profitable investment and occupancy factor per celluar office when we take into consideration the savings because of energy use, installation costs and reduction of technical area.

5.2. *Case 2: Maximum profitable investment due to reduced energy consumption and reduced installation—and technical area costs (Norway)*

Case 2 is based on the following assumptions, which are quite common in Norway:

Specific ventilation rate ($m^3/(m^2$ h))	10
Minimum ventilation rate factor	0.2
Specific fan power ($kW/(m^3/s)$)	4
Hours of use (h)	3000
Real interest (%)	5
Predicted lifetime (20 years)	
Electrical energy cost (EURO/kWh)	0.083
Thermal energy cost (EURO/kWh)	0.064
Specific ventilation cost (EURO/(m^3/h))	7.75
Share of the ventilation system which can be reduced with DCV (%)	60
Relationship between necessary area for the air-handling unit and the corresponding conditioned airflow in m^3/h (%)	0.8
Total building cost for technical area (EURO/m^2)	1200

Fig. 2 shows the connection between maximum profitable investment per cellular office and the occupancy factor. In this case, maximum profitable investment increases to about 400 EURO per cellular office with an occupancy factor of 0.50.

6. Conclusion

The profitability of DCV depends on ventilation demand, hours of use, assumed occupancy factor, future energy prices, actual claim for profitability in the project, and extra investment costs associated with a DCV-system.

We have performed a simple analysis of the potential profitability of DCV-system on a reference office building in Norway. Our calculations suggest that investment in DCV equipment must not exceed 400 EURO per cellular office if central installations and technical areas can be reduced as a consequence of DCV. This investment in DCV must cover all extra costs attributable to DCV, such as equipment for fan speed regulation, pressure regulation, management facility equipment and maintenance costs for this equipment. Reduced energy costs alone will cover an extra investment of about 300 EURO per cellular office. If the electrical energy price in Norway increases to the same level as in Denmark, reduced energy costs alone will cover an extra investment of about 700 EURO per cellular office.

The potential use of DCV is enormous and new knowledge about the importance of outdoor air supply, because of its positive effect on sick leave and productivity [1,14], will probably increase the outdoor air supply in office buildings. The challenge goes to the producers who must develop equipment that provides profitability for the building owners when completely installed. There is a growing interest in more environmentally favourable technical equipment. Products that contribute to both a better environment and increased profitability will probably have a bright future. In existing buildings with an unacceptable outdoor air supply, simple retrofitting with DCV will exploit the outdoor air supply better. In some cases, this could be a profitable alternative to an extensive refurbishment.

References

[1] P. Wargocki et al., The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome, symptoms and productivity, Indoor Air 10 (2000) 222–236.

[2] W.J. Fisk, A.T. De Almeida, Sensor-based demand-controlled ventilation: a review, Energy and Buildings 29 (1998) 35–45.

[3] L. Jagemar, Design of Energy Efficient Buildings: Applied on HVAC Systems in Commercial Buildings, Department of Building Services Engineering, Chalmers University of Technology, Goteborg, Sweden, 1996.

[4] M. Mysen, et al., Energieffektiv ventilasjon—innføring av SFP (Energy Efficient Ventilation—Introduction of SFP), Norwegian Building Research Institute, Project Report 249, Oslo, Norway, 1999.

[5] ASHRAE, ASHRAE Handbook: Systems and Equipment, Refrigerating and Air-Conditioning Engineers Inc., American Society of Heating, Atlanta, 1996.

[6] M.J. Brandemuehl, et al., A Toolkit for Secondary HVAC System Energy Calculation, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1992.

[7] B.R. Soerensen, Application and Energy Consumption of Demand Controlled Ventilation Systems, Norwegian University for Science and Technology, Trondheim, Norway, 2002.

[8] M.D. Kukla, Situations to consider when variable air volume is an option, ASHRAE Trans. 103 (2) 1997.

[9] ASHRAE, ASHRAE Handbook: Fundamentals, Refrigerating and Air-Conditioning Engineers Inc., American Society of Heating, Atlanta, 1997.

[10] W.F. Stocker, Design of Thermal Systems, 3rd ed., McGraw-Hill, NY, USA, 1989.

[11] T. Wigenstad, Optimal Pathway for the Mechanical and Electrical Installations within Building, Norwegian University for Science and Technology, Trondheim, Norway, 2000.

[12] Enovas byggoperatør, Energy Statistics for Buildings in Norway 2001, Enovas byggoperatør, Norway, 2002.

[13] T.H. Dokka, K.A. Dokka, A software approach for economic optimization of energy use in buildings, in: Proceedings of the 19th Air Infiltration and Ventilation Center Conference, Oslo, Norway, 1998.

[14] D.K. Milton, Risk of sick leave associated with outdoor air supply rate, humidification and occupants complaints, Indoor Air 10 (2000) 212–221.

Paper VI Mysen M, Schild PG, Hellstrand V, Thunshelle K (2005).

Evaluation of simplified ventilation system with direct air supply through the facade in a school in a cold climate.

Evaluation of simplified ventilation system with direct air supply through the facade in a school in a cold climate

Mads Mysen* [1,2], Peter G. Schild[1], Vidar Hellstrand[1], Kari Thunshelle[1]

[1]*Norwegian Building Research Institute, Forskningsveien 3b, P.O. Box 123, Blindern, NO-0314 Oslo, Norway*

[2] *Norwegian University Of Science And Technology (NTNU), Department of Energy and Process Technology, NO-7491 Trondheim, Norway*

Abstract

Many educational buildings in industrialised countries have poor indoor climate, according to today's knowledge about the impact of indoor climate on well-being and productivity. Budget restrictions and practical limitations such as lack of space for central air handling units and ventilation ducts, have motivated the application of simplified ventilation systems in some schools, such as taking unconditioned supply air directly from the facade. One such school was recently evaluated in Norway.

On cold days, thermal comfort in the classroom deteriorated due to cold downdraught from the supply outlet. In addition, moist and fertile conditions for microbiological growth were observed in the air-supply ductwork. On the other hand the same pupils are more satisfied with the school and have less Sick Building Syndrome (SBS) symptoms during winter than summer. An improved control strategy with a temperature-

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* Corresponding author.

E-mail address: Mads.Mysen@byggforsk.no

compensated CO_2 set-point for controlling the airflow is suggested. This could improve thermal comfort and reduce energy use without compromising Perceived Air Quality (PAQ) during cold weather. Furthermore it could improve Indoor Air Quality (IAQ) during warm weather with only a slight increase of energy use. Further evaluation of an improved solution is needed before such a ventilation concept can be recommended in cold climates.

Keywords: Schools; Demand-controlled ventilation; Indoor air quality; Thermal comfort; Sick Building Syndrome (SBS).

1. Introduction

Retrofitting school buildings with a new mechanical balanced ventilation system is expensive, and it can be problematic to integrate in the building due to lack of space for central air handling units (AHUs) and ducts. This has motivated the application of simplified ventilation systems. Revetal Secondary School in Norway has recently been refurbished. The building area is 5882 m^2. The budget limit for refurbishing the ventilation system was approx. € 0.5 million, but a new balanced mechanical ventilation system would have cost approx. € 1 million. The design team was therefore forced to look for alternatives, and ended up with a simplified ventilation system where unconditioned air is taken in from the façade (Figure 1) and distributed directly to classrooms at ceiling level via an insulated short air-distribution duct with air-supply nozzles (Figure 2).

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Figure 1. Separate air intake in the façade at ceiling level for each classroom.

Figure 2. Thermally insulated air supply ductwork with integrated diffuser nozzles.

Extract ducts from each classroom are collected at a central fan at roof level. This generates a negative pressure in each classroom relative to outside. The supplied airflow rate is controlled by a combined CO_2- and temperature-sensor in each classroom, which controls the position of a damper in the extract duct from each classroom. The sensor is located on the inner wall of the classroom about 1.6 meters above the floor. During the measurements, the supplied airflow rate was controlled to prevent the CO_2 concentration exceeding 800 ppm. Moreover, the extract damper closes if the sensor measures temperature below 19°C.

According to the Headmaster the indoor climate is satisfactory and the energy consumption has not increased after the refurbishment, even though the building probably has a considerably higher ventilation rate than before. The school has a pool and the specific energy consumption was 218 kWh/m^2 in 2002. The corresponding average for comparable schools was 237 kWh/m^2 [1]. It would be possible to further reduce the energy consumption by recovering heat from the exhaust air with a heat pump. This possibility has not yet been exploited.

The ventilation system is very interesting. Apart from the reported satisfied users, it has a low investment cost, and potentially low running costs presupposed that exhaust air heat-recovery is implemented. However, the following issues need to be examined before such a solution can be recommended for other schools:

1. Are the pupils really satisfied with the indoor climate compared to other schools?
2. Is there a problem with unpleasant draughtiness on cold days?
3. Is there a risk of pollution of the supply air due to accumulated particles and microbiological growth in the supply air duct?
4. Is the supply of unfiltered outdoor air satisfactory?
5. Is there a problem for people with allergy?

2. Method

2.1 Measurements of thermal comfort in the classrooms

Firstly, smoke ampoules were used to reveal the general air distribution pattern and to localize spots with a potentially elevated draught problem. Further measurements were done near these spots. Air velocity, air temperature and turbulence intensity were measured at different heights: 3 cm above the floor, 3 cm above the desk, and 1.2 meters above the floor (head/neck). These measurements were taken at different desks in classrooms 201 and 210 on two days in January 2003 (Figure 3).

Figure 3. Measurement of air velocity and temperature in a classroom (two researchers).

Each measurement period was 3 minutes. Maximum, minimum, time-averaged, and standard deviation values were logged. Draught Rating was calculated according to CR-1752 [2] in terms of the percentage of people dissatisfied (PPD) due to draught.

2.2 Questionnaire

Pupils in two same classrooms (201 and 210) answered 45 simple yes/no questions regarding their health, the indoor environment, and background information. The questionnaire is a Norwegian application of the Örebro questionnaire [3], but which has been simplified and modified to provide more accurate results for children. The main improvement is that the questions ask how the person is feeling at the present moment in time, instead of how the person has generally felt in the previous 3 months. The questionnaire is applied to the same group of children three times during a period of two weeks and an average value is calculated for each question and individual. At Revetal Secondary School, each pupil filled the questionnaire 3 times in January 2003 and an additional 2 or 3 times in June 2003, usually at the end of the day at school. This same questionnaire has so far been used in surveys of approximately 24 Norwegian schools [4,5,6], providing a growing set of useful reference data. Pupils in secondary schools have more problems like tiredness and heavy heads and they complain more about stuffy air than pupils in primary schools [5]. The questionnaire results are therefore compared with three other quite new or recently retrofitted secondary schools, with the same age group of pupils. One of these schools has a similar supply-air system, and the other two have a balanced mechanical ventilation system (BMV). Key facts about the schools are given in Table 1.

Table 1 **Key facts about Revetal School and 3 other comparable schools that have had the same questionnaire survey. Note that Revetal has had two separate questionnaire surveys with the same pupils, one during winter and one during summer.**

Type of ventilation	***School no.***	***Location***	***Built or retrofitted***	***Class***	***No. of pupils***	***Time of questionnaires***
Simplified supply direct from facade	***1***	*Revetal – South East Norway. Inland climate*	*2000*	*9b & 9d*	*50*	*20th to 29th January 2003*
						5th to 11th June 2003
	2	*Presterød – South-East Norway. Coastal*	*2000*	*9b & 9c*	*48*	*12th to 20th March 2002*
Mechanical balanced ventilation (BMV) with Central AHU	***3***	*Oslo – South East Norway. Coast/inland climate*	*1997*	*10a & 10f*	*48*	*13th to 20th March 2002*
	4	*Grong – Middle of Norway. Inland climate*	*1997*	*9a & 10b*	*28*	*3th to 17th April 2002*

All “no” answers, which normally mean ‘not a problem’, are given the value 0, while “yes” answers are given the value 1. This means that the average score corresponds with the relative share that have answered yes on the question. Questions that have not been answered in are ignored.

The answers of the questionnaire are analysed statistically with SPSS. The average of each pupil’s scores is analysed with a one-way ANOVA to find possible significance differences between the schools. This is in principle a dubious way of treating dichotomous variables, but the procedure is justified in this case since the purpose of the analysis is merely to find tendencies for further analysis.

2.3 Other measurements

Microbiological assays (Air-O-Cell and Mycotape) were taken of airborne particles in the outside air, the air-distribution duct, the classroom and the corridor.

The quantity of sedimented dust in the air-distribution duct and in the classroom was measured with a BM Dust-detector.

A particle counter was used to measure the concentration of airborne particles of size 0.3 µm to 20 µm in outside air, in the supply air and in the classroom.

Outdoor air temperature was measured. The combined CO_2- and temperature-sensor was checked against calibrated equipment. The damper's response on elevated CO_2 concentration was checked. The air-distribution duct was visually inspected.

Finally, the behaviour of the pupils was observed during the measurement period.

Mysen [4] has described the measurements and observations in detail.

3. Results

3.1 Measurements of air-velocities and temperature

The air velocities and temperatures varied during the measuring periods, as expected with this type of ventilation system. Table 2 and Table 3 show some of the results from the measurements. Draught Rating exceeded 25% at neck height several times during January 23rd. Draught Rating above 70% was not uncommon near the floor on January 31st.

Table 2 **Some typical time-averaged temperatures, velocities and Draught Rating at Revetal School on January 23rd.**

Class-room #	Persons in room	Time of day	Outdoor air temp.	Measuring point	Local air temp.	Local air velocity	Draught Rating
201	21	12:00	2,5 °C	Floor	19,3 °C	0,204 m/s	21,4 %
				Neck	17,9 °C	0,233 m/s	27,3 %
210	22	09:30	2,5 °C	Floor	19,4 °C	0,183 m/s	18,8 %
				Desk	19,2 °C	0,181 m/s	18,8 %
				Neck	19,3 °C	0,227 m/s	24,2 %
		11:00	2,5 °C	Floor	18,9 °C	0,140 m/s	14,3 %
		10:30	2,5 °C	Neck	19,4 °C	0,245 m/s	26,2 %

Table 3 **Some typical time-averaged air temperatures, velocities and Draught Rating at Revetal School on January 31st.**

Class-room #	Persons in room	Time of day	Outdoor air temp.	Measuring point	Local air temp.	Local air velocity	Draught Rating
201	27	09:30	-14,0 °C	Floor	14,5 °C	0,421 m/s	77,3 %
				Desk	14,8 °C	0,330 m/s	65,1 %
				Neck	15,6 °C	0,227 m/s	50,5 %
210	25	10:30	-12,5 °C	Floor	14,0 °C	0,335 m/s	68,1 %
				Desk	14,5 °C	0,180 m/s	37,5 %
				Neck	14,8 °C	0,235 m/s	48,2 %

3.2 Questionnaires

Figure 4 shows the average scores expressed in percent, of some relevant factors for Revetal Secondary School in winter and summer and the comparable schools.

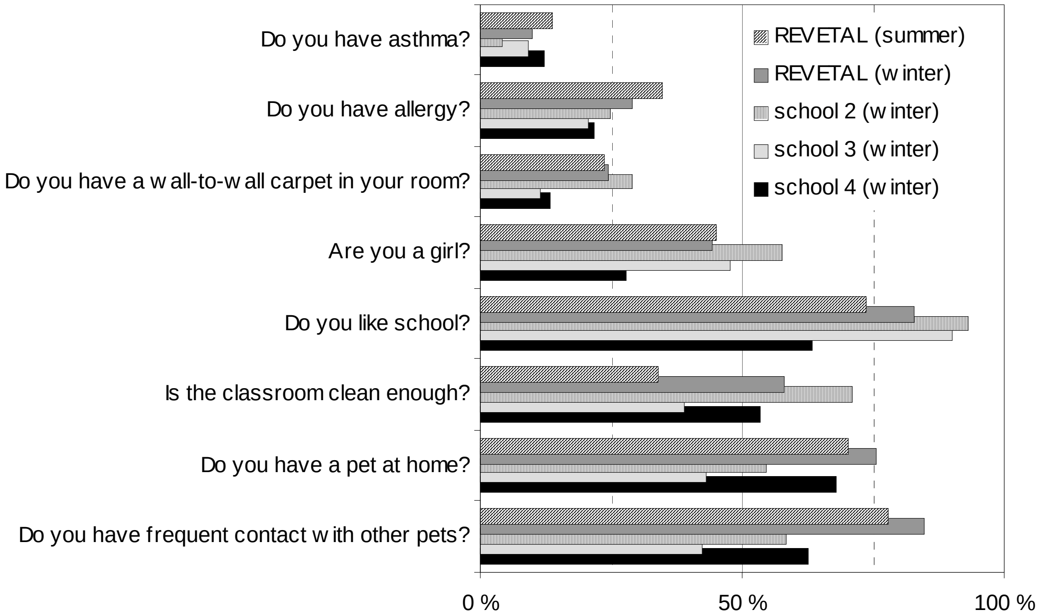


Figure 4. Average score (%) for some relevant factors for Revetal School in winter and summer and three comparable schools. 100% means that all pupils have answered yes on the question on all repeated questionaries.

The prevalence of SBS-related symptoms is shown in Figure 5. The total length of the bar for a school is the sum of the relative contribution of 10 questions in the questionnaire, and is called the Building Symptom Index (BSI). BSI is defined as:

$$BSI = \frac{\sum_{i=1}^{n} AS_i}{n} \qquad (1)$$

where AS_i is the average score (%) for question i, and n is the total number of questions used in the index.

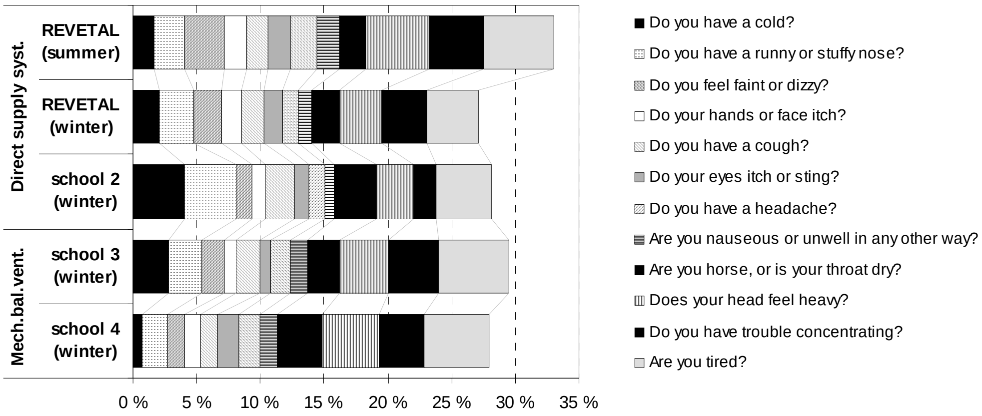


Figure 5. Prevalence of SBS-related symptoms at Revetal School in winter and summer, compared with two schools with balanced mechanical ventilation (school 3 & 4), and one school with a similar ventilation system to Revetal (school 2). The total length of the bar for a school is the sum of the relative contributions of the questions used in the index. 0% (best) means all pupils always answer 'no' for all questions, 100% (worst) means all pupils always answer 'yes' for all questions. The relative contribution of each questions is indicated with different coloured stripes along each bar.

The prevalence of indoor environment complaints is shown in Figure 6. The total length of the bar for a school is the sum of the relative contribution of 10 questions in the questionnaire, and is called the indoor environment index (IEI).

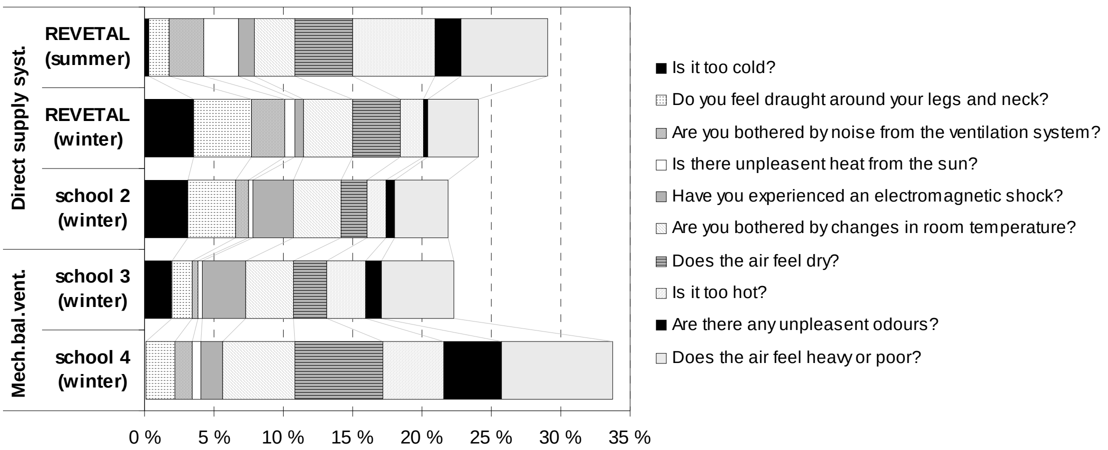


Figure 6. Prevalence for indoor environment complaints (IEI) for Revetal School in winter and summer, compared with two schools with balanced mechanical ventilation (school 3 & 4), and one school with a similar ventilation system to Revetal (school 2). The total length of the bar for a school is sum of the relative contribution of the questions used in the index.

During winter the pupils at Revetal were significantly more dissatisfied than pupils at the BMV schools (regarded as a joint sample) for the following questions: "*Is it too cold?*" and "*Do you feel draught around head or neck?*" (Figure 6).

Moreover, during summer, the pupils at Revetal also were significantly more dissatisfied than pupils at the BMV-schools (regarded as a joint sample) for the following questions: "*Do you feel faint or dizzy?*" (Figure 5), "*Is it too hot?*", "*Is there unpleasent heat from the sun?*" (Figure 6), and "*Do you have allergy?*" (Figure 4).

However, during winter, the Revetal pupils were significant more satisfied than BMV schools for the following questions: "*Are you tired?*" (Figure 5), "*Is it too hot?*", "*Does the air feel heavy or poor?*", "*Are there any unpleasent odours?*" and "*Have you experienced any electromagnetic shock?*" (Figure 6).

When comparing seasons, the pupils at Revetal were significant more satisfied in Januray than June for the following questions: "*Are you tired?*", "*Does your head feel heavy?*", "*Do you have a headache?*", "*Is it too hot?*", "*Is there unpleasent heat from the sun?*", "*Does the air feel heavy or poor?*" and "*Are there any unpleasent odours?*".

The Revetal questionnaires were filled in on seven different occasions, each with different outdoor air temperatures. The supply air temperature is quite similar to the outdoor air temperature since the air is delivered unconditioned directly to the room. Figure 7 shows the correlation between the outdoor air temperature and the average score for some questions.

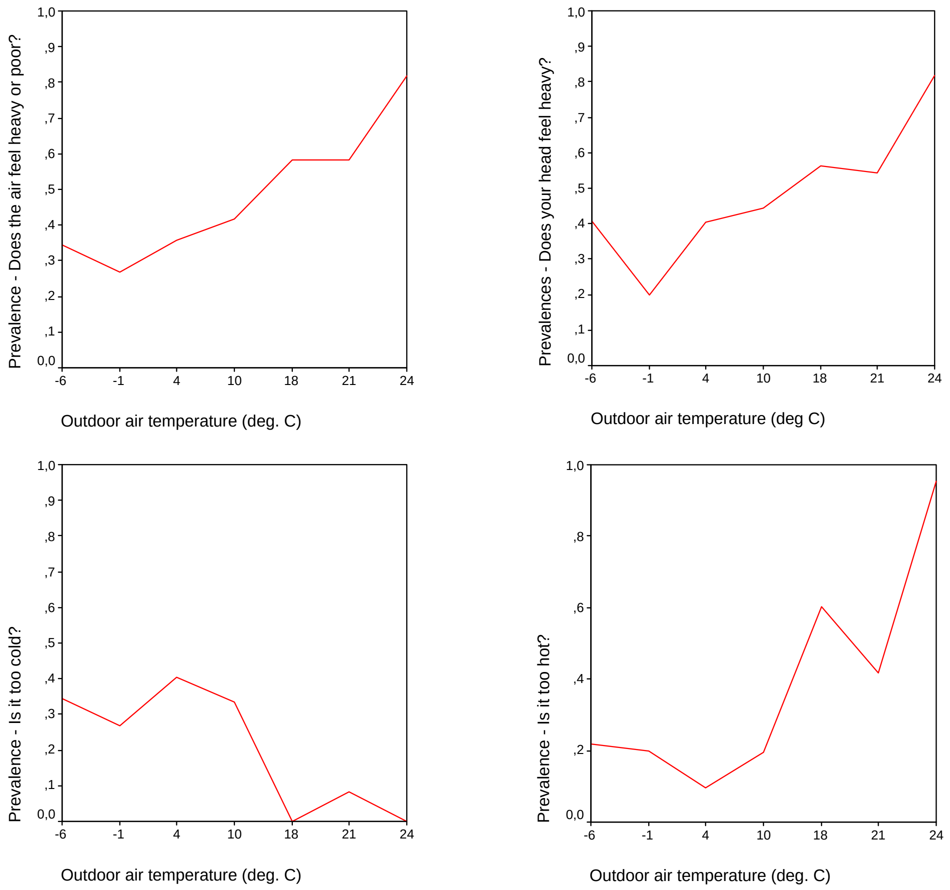


Figure 7. Prevalence of some of the answers in relation to outdoor air temperature.

The jump between 18°C and 21°C is probably caused by differences in solar gain.

The correlation between outdoor air temperature and the prevalence’s are significant for the questions in Table 4.

Table 4 **Prevalence's with significant correlations with outdoor air temperatures. Note that the Pearson's r and p-values are based on scores from dichotomous variables**.

Question	*Pearson's r*	*p-value (2-tailed)*
Are you tired?	*0.182*	*0.004*
Is your head heavy?	*0.220*	*0.001*
Do you have a headache?	*0.131*	*0.041*
Is it too hot?	*0.402*	*0.000*
Is there unpleasant heat from the sun?	*0.316*	*0.000*
Is it too cold?	*-0.349*	*0.000*
Do you feel draft around your legs or neck?	*-0.275*	*0.000*
Does the air feel heavy or poor?	*0.273*	*0.000*
Do you smell any unpleasant odours?	*0.251*	*0.000*
Are you bothered from noise from outside?	*0.160*	*0.012*
Is it clean enough?	*-0.233*	*0.000*
Do you like it at school?	*-0.221*	*0.001*
Is your bedroom well ventilated at night?	*0.182*	*0.004*

The answers of pupils with allergy were analyzed. In general these pupils had a higher prevalence of SBS-symptoms than the average pupil, but there were no significant differences between the schools. The total number of subjects who reports allergy varies between 6 and 15 depending on the school (Figure 4).

3.3 Fungi’s, particles and dust

The air-distribution duct in Classroom 210 was visually inspected. It appeared clean after four years of use without cleaning according to the headmaster. But the microbiological assays revealed an elevated level of fungi growth compared to outdoor air, and a considerable amount of sedimented pollen in the duct. *Ciliata* were found in the air-distribution duct. This is single-celled organism that lives in almost every environment with liquid water, especially germ-enriched water with abundant nutrients.

The concentration of airborne particles was about twice as high in the outdoor air 1.5 meter above ground level compared to supply air.

The average dust-coverage area percentage in the air-distribution duct was 11.2% on the bottom and 6.3% on the sides.

3.4 Observations

The behavior and level of activity of the pupils was observed during the measurements. When entering Classroom 201 on January 23rd, the indoor air seemed a little stale. The indoor air became fresh after the pupils had entered the room, as this caused the demand-controlled ventilation system to increase the ventilation rate. There was no obvious sign that the thermal environment disturbed the lesson.

On January 31st, the thermal conditions seemed satisfactory when we entered Classroom 201, but after a while, it became very cool with an unpleasant draught. After 20 minutes, three girls put on their outdoor jackets, and some pupils put on a scarf and cap as well. The measured indoor air temperature dropped from +17°C to below +15°C before it started rising again. Several pupils complained about the thermal conditions and disturbed the lesson.

4. Discussion

4.1 Thermal climate

In January 2003, air temperatures and air velocities were measured on two different occasions. The thermal comfort parameters differed a lot between the two measurement periods in January (Table 2, Table 3). At outdoor temperatures between 2°C and 3°C, the air velocity in the classroom varied from 10 to 25 cm/s while the local air temperature was between 18°C and 20°C. The upper range of the corresponding Draught Rating was around 20% to 25%. This means that the thermal climate hardly complied with category C according to design criteria's for the indoor environment in CR-1752 [2].

At outdoor temperatures between -12°C and -14°C the Draught Rating was from 50% to 75%, indicating that the majority of pupils would find the conditions unpleasant. The ventilation rate is restricted when the room sensor (which is located on the inner wall) registers a temperature below 19°C. The measurements show that there were spots with air temperature as low as 14°C before the ventilation rate was reduced. This proves that the local air temperature is not uniform throughout the classroom. The sensor placed on the inner wall measures probably a considerably higher temperature than the average local air temperature, during very cold weather. It should also be mentioned that the indoor Draught Rating during very cold weather is influenced by cold draught from windows and thermal bridges. Leakage through the window frames was observed. Such leakages will be increased by this ventilation system compared to BMV, since it increases the relative negative pressure in the building.

4.2 Questionnaires

Pupils in schools with different types of ventilation system have filled in the same questionnaire. The degree of satisfaction, and the significant differences, has already been described above in Section 3. When comparing the different schools, one should bear in mind that the answers are affected by numerous factors independent of the ventilation system. Such a comparison is therefore only suited for finding tendencies for closer analysis. Some important differences like gender, wall-wall carpet in the bedroom, contact with pets, well-being and perceived cleanliness at school are shown in Figure 4.

At Revetal School the same pupils answered the questionnaires several times during January and June. This makes it likely that the significant differences in responses are a consequence of real differences in the indoor environment.

Not surprisingly, pupils at Revetal School are more afflicted by draught problems than pupils at BMV-schools during cold weather. Pupils at Revetal have in general few SBS-related symptoms in January, but the prevalence of some symptoms increases from January to June. Outdoor air temperature correlates significantly with the prevalence of SBS-symptoms like: “Are you tired?”, “Does your head feel heavy?”, “Do you have a headache?” together with perceived air quality (PAQ) (Figure 7). The reduction in SBS-symptoms in winter cannot be caused by an increase in the airflow rate, since this rate can be assumed to be about the same or less in January than June. Instead, it is probably caused by lower room air temperature (due to lower supply air temperature and transmission losses). Several studies have shown that warm air is perceived as less fresh and less acceptable, and that SBS symptoms such as fatigue and headache may be caused by exposure to air at slightly raised temperature and humidity [7,8,9,10,11]. It is also shown [12,13] that people adapt to a lower indoor air temperature during cold weather in naturally ventilated buildings with sufficient opportunities for behavioural adaptation so that thermal comfort might be achieved at indoor operative temperatures around 18°C for 90% of the occupants.

Other factors that might contribute to the correlations between outdoor air temperature and SBS-symptoms are:

- Quality of the cleaning might have changed. This assumption is based on the answers of the question “Is the classroom clean enough” (Figure 4).
- Gravity forces of cold supply air contribute to increased thermal stratification leading to improved air quality in the breathing zone.
- Increased amount of pollutants like pollen in the supply air from January to June.

In general there are more people reporting allergy problems at Revetal School compared to the BMV schools and the allergy prevalence increases from January to June. The supply of unfiltered air might be a contributory cause of this together with wall-to-wall carpets in bedrooms and contact with pets (Figure 4). This ventilation system without filter should have more penetration of allergens like pollen into the classroom than BMV-systems, leading to an increase in SBS-related symptoms among the pollen allergic subjects. The pupils who answered yes on the allergy question at Revetal School did not report significantly more SBS-related symptoms than corresponding pupils at BMV schools. However there were too few allergic subjects to draw any firm conclusions and all kinds of allergy are included.

4.3 Other results

The presence of *Ciliata* in the air supply duct indicates periods with high humidity and patches of free water inside the duct. Microbiological growth in the supply air duct might reduce the quality of the indoor air and could potentially be detrimental to the indoor environment.

The considerable amount of pollen in the air-distribution duct might cause discomfort to pupils with pollen allergy.

The difference in the concentration of airborne particles in outdoor air and supply air may well be because there is a higher concentration of particles near the ground where the measurement were taken than at the air inlet near roof level (Figure 1), but sedimentation in the ducts can be an additional cause.

The average dust-coverage area percentage was 11.2% on the bottom of the air supply duct. The recommended maximum value for interior surfaces is 5% [14] (Cleanliness Quality 4) for indoor air quality reasons [15]. At least the same requirement should apply for the inner surfaces of air-supply ductwork.

4.4 Potential improvement and evaluation of the concept in general

The results are strictly valid for Revetal Secondary School. The ventilation system at Revetal can hopefully be improved. The problems with draughtiness and too low temperatures could be mitigated with better tuning of the control system. Use of a combined CO_2- and temperature target seems more appropriate for such ventilation concepts. This is supported by the fact that PAQ is better in January than June, which we can assume is mainly caused by a lower indoor air temperature in the breathing zone. This assumption is confirmed by the field laboratory study of Fang [7], showing that PAQ and Indoor Air Quality (IAQ) related symptoms are strongly influenced by indoor air temperature. Increasing the airflow from 3.5 l/s per person to 10 l/s per person did not seem to influence perceived air freshness and difficulty in thinking clearly at constant temperature of 20^{o}C and relative humidity of 40% [7]. This indicates strongly that the CO_2-level alone is a poorer measure of IAQ. Figure 8 shows examples of different control strategies. The figure illustrates our suggested improved control strategy with temperature compensation of the CO_2 set-point. The control can be either linear or stepwise. Both are illustrated.

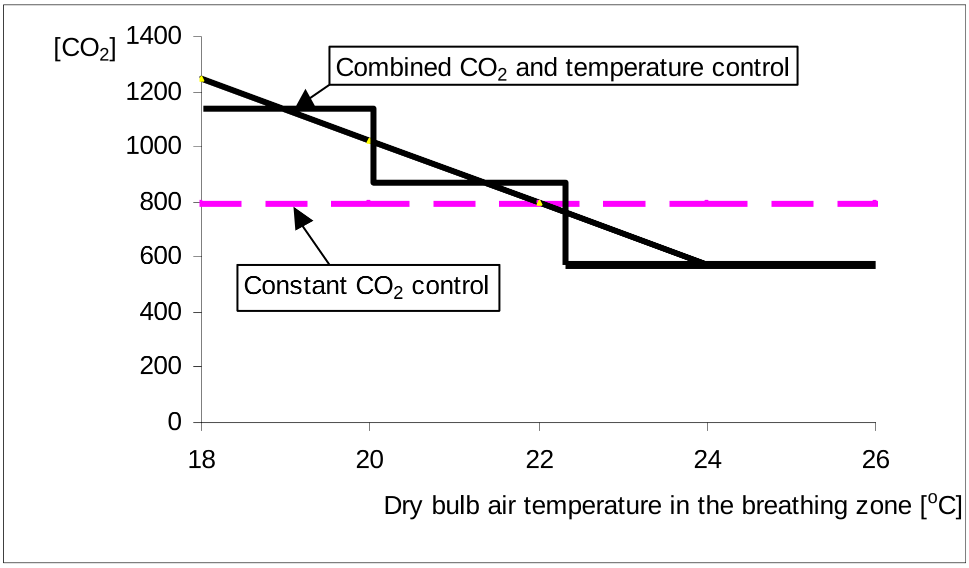


Figure 8. Three different control strategies for DCV. The conventional constant CO_2 control and the suggested improved control strategy with linear or stepwise temperature compensated CO_2 set-point.

Implementing such a control strategy could improve thermal comfort and reduce energy use for heating without compromising PAQ during cold weather. In addition it could improve IAQ during warm weather with only a slight increase in energy use.

Assuming an outdoor CO_2 concentration of 350 ppm, the supply air volume could be reduced by 50% with a CO_2 set point of 1250 ppm compared to 800 ppm, leading to a probably significant improvement of the thermal conditions.

Such a strategy might lead to negative consequences for IAQ related symptoms if the pollution load is considerably influenced by factors such as cleaning standard, emissions from building materials and pollution caused by moisture problems. DCV with CO_2- or temperature-compensated CO_2 control, presuppose that the total pollution load is always dominated by pollution from the occupants.

The air supply diffusers at Revetal School consist of 2 rows of 13 small nozzles (Figure 2). A more uniform distribution of the air supply would probably reduce the localized draft problems. This could be achieved with one continuous row of small nozzles or a continuous narrow slit.

The microbiological activity and sedimented dust indicates that the air distribution duct should be regularly inspected and cleaned. Insulated access hatches at the end of each duct, at the T-duct junction, and in the proximity of the air intake, would make the inner surfaces more accessible for inspection and cleaning.

The air intake should be improved to reduce the risk of moisture ingress into the duct.

5. Conclusions and implications

Based on measurements and the questionnaires, the following answers can now be given:

- *Are the pupils really satisfied with the indoor climate compared to other schools?*
  Yes, except for the indoor thermal climate during cold weather.
- *Is there a problem with unpleasant draughtiness on cold days?*
  Yes. The indoor thermal climate is not satisfactory on days with low outdoor air temperature. Even at outdoor temperatures around +2°C, the indoor environment hardly complies with Category C in CR-1752 [2].
- *Is there a risk of pollution of the supply air due to accumulated particles and microbiological growth in the supply air duct?*

Yes. Microbiological growth has been found, and the dust coverage area percentage is higher than that which is recommended for IAQ reasons.

- *Is the supply of unfiltered outdoor air satisfactory?*

  The pupils are generally satisfied with the air quality, but the sedimentation of organic material in the air supply duct, in combination with the presence of moisture, provides fertile conditions for microbiological growth that is potentially harmful.
- *Is there a problem for people with allergy?*

  Maybe. There are more pupils with reported allergy problems at Revetal School than the BMV schools, and the pupils at Revetal School are probably more exposed to pollen indoors. On the other hand, the survey does not prove that the pupils with allergy at Revetal School have more SBS-related symptoms than corresponding pupils at BMV schools — however there were too few allergic subjects to draw any firm conclusions, and all kinds of allergy is included. We can therefore neither confirm nor rule out that this ventilation system is a contributory factor.

In general, the application of simplified ventilation systems with direct air supply through the façade requires demand-controlled ventilation (DCV) with a much higher CO_2 set point than 800 ppm to achieve satisfactorily thermal comfort during cold weather. This could be achieved by a ventilation control strategy with a temperature-compensated CO_2 set-point. Such a strategy could improve thermal comfort and reduce energy use for heating without compromising PAQ during cold weather. In addition it could improve IAQ during warm weather with only a slight increase of energy use.

The risk posed by fertile conditions for microbiological growth must be reduced as far as possible with careful design, good access, and regular inspection and cleaning.

Further evaluation of an improved solution is needed before such a ventilation concept can be recommended in cold climates.

6. Acknowledgements

This work has been supported by the Norwegian Research Council as a part of the research program “Environmentally favourable energy use in buildings”.

7. References

[1] Enova, Energy statistics of Norwegian buildings 2002, Enova, Norway, 2003 (in Norwegian).

[2] CR 1752, Ventilation for Buildings: Design criteria for the indoor environment, CEN, Brussels, 1998.

[3] K. Andersson, The MM-Questionnaires – A tool when solving Indoor Climate Problems, Ørebro Medical Center Hospital, Sweden, 1993.

[4] M. Mysen, Simplified ventilation system at Revetal Secondary School, Norwegian Building Research Institute, Project report N-9797, Oslo, 2003 (in Norwegian).

[5] C.I. Ulriksen, Investigation and comparison of indoor environment quality and use of energy in building using hybrid ventilation systems vs. building with traditional mechanical ventilation systems, M.Eng. Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2002 (in Norwegian).

[6] H. M. Mathisen, F. Frydenlund, Preventive measures and intervention on carpet removal and ventilation improvement in eleven schools, Proceedings of Healthy Buildings 2000, Helsinki, Vol.1, pp.219-224.

[7] L. Fang, D.P. Wyon, G. Clausen, P.O. Fanger, Sick building syndrome symptoms and performance in a field laboratory study at different levels of temperature and humidity, Proceedings: Indoor Air 2002.

[8] D.P Wyon, P.O. Fanger, B.W. Olesen, The mental performance of subjects clothed for comfort at two different air temperatures, Ergonomics, Vol. 18, 1975, pp. 359-374.

[9] L. Berglund, W.S. Cains, Percieved air quality and the thermal environment. Proceedings of IAQ ’89, San Diego1989, pp. 345-350.

[10] L. Fang, G. Clausen, P.O. Fanger, Impact of temperature and humidity on the perception of indoor air quality, Indoor Air, Vol. 8 (2), 1998, pp. 80-90.

[11] J. Toftum, A.S. Jørgensen, P.O Fanger, Effect of humidity and temperature of inspired air on perceived comfort, Energy and Buildings, Vol. 28, (1), 1998, pp.15-23.

[12] R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings Vol. 34, 2002, pp.549–561.

[13] R.J. de Dear, G. Brager, D. Cooper, Developing an adaptive model of thermal comfort and preference, Final Report on RP-884, Macquarie Research Ltd. Australia, 1997.

[14] NS-INSTA-800, Cleaning quality – measurement system for evaluation of cleanliness, 1.ed. Oct. 2000.

[15] T. Scneider, T. Løbner, S.K. Nilsen, O.H. Petersen, Quality of Cleaning Quantified, Building and Environment, Vol.29, No.3, 1994, pp.363-367.

Paper VII Mysen M, Schild PG, Tjelflaat PO. **Cooling performance of ground-coupled air intake ducts.**

COOLING PERFORMANCE OF GROUND-COUPLED AIR INTAKE DUCTS

Mads Mysen[1], Peter Geoffery Schild[1] and Per Olaf Tjelflaat [2]

1. Norwegian Building Research Institute (NBI), Department of Building Services,
P.O.Box 123 Blindern, NO-0314 Oslo, Norway
e-mail: mads.mysen@byggforsk.no; peter.schild@byggforsk.no
2. Norwegian University Of Science And Technology (NTNU),
Department of Energy and Process Technology, NO-7491 Trondheim, Norway
e-mail: pot@maskin.ntnu.no

Keywords: ground-coupled duct, passive cooling, thermal storage, design criteria

ABSTRACT

This paper presents temperature and airflow measurements proving that ground-coupled fresh air intake ducts can have a significant cooling effect. Measurements at two Norwegian schools with such ducts, Jaer School and Mediå School, show that the actual cooling performance after a three-day warm period is about 100 Wh/m^2 of exposed concrete surface in the duct, with air velocity passing the surfaces of about 0.15 m/s. Our calculations indicate that this can rise to at least 200 Wh/m^2 by increasing the air flow rate during the night. This method of passive cooling is well suited for handling considerable peak cooling loads. The main mechanism of cooling in these ducts is exploiting thermal storage with nighttime precooling, exploiting the diurnal swing in outdoor temperature. The paper concludes by giving a number of design criteria.

INTRODUCTION

Hybrid or natural ventilation with ground-coupled fresh air intake ducts (or culverts) has become an increasingly popular way of conditioning air in Norway and Sweden. Cooling of air is probably the most valuable property of ground-coupled ducts, but what cooling performance is it possible to achieve with ground-coupled ducts? An answer, or indication of an answer, has been found by analyzing the data from Jaer School in the municipality of Nesodden and Mediå School in the municipality of Grong, both of which have been evaluated through the Norwegian HybVent-project underlying IEA ECBCS Annex 35 (International Energy Agency). Design summer temperature for Jaer is 25.2^{o}C and for Grong it is 23.0^{o}C.

This paper does not consider humidity and risk for microbiological growth or risk for radon in the air, but this should be considered in planning of culverts.

DESCRIPTION OF THE GROUND-COUPLED DUCTS

Ground-coupled ducts connect an air intake tower with the ventilated building. They are normally made of concrete and they should be easily accessible for inspection and cleaning, which makes it possible to discover and remove dust and mould before it has a negative impact on the indoor environment. A ground-coupled duct often has two parts: the first part transports air from the air-intake to the building (air-intake culvert), the second part is formed to distribute the air to the vertical shafts which lead to different rooms (air-distribution culvert).

Ground-coupled ducts dampen diurnal temperature swings of the supplied fresh air, reducing the need for preheating and mechanical cooling. The cooling effect during summer is considerably larger than the preheating effect in winter. Due to the low air velocity, ground-coupled ducts also have a beneficial filtration effect by sedimentation, for rain, snow, and particles (mostly larger than 10 µm).

EXPERIMENTAL DATA

Jaer School

Air and surface temperatures throughout the culvert, and air flow rate (by means of anemometer), have been logged for extended periods between January 2000 and April 2002. All the data has been analyzed, and we have chosen the four-day period 13–16 May 2000 for calculation of cooling performance since it was a relatively warm period and the measurement uncertainties were at a minimum. Temperatures in the period are shown in Figure 1. Schild [2002a, 2002b] has described the measurements, methods and results.

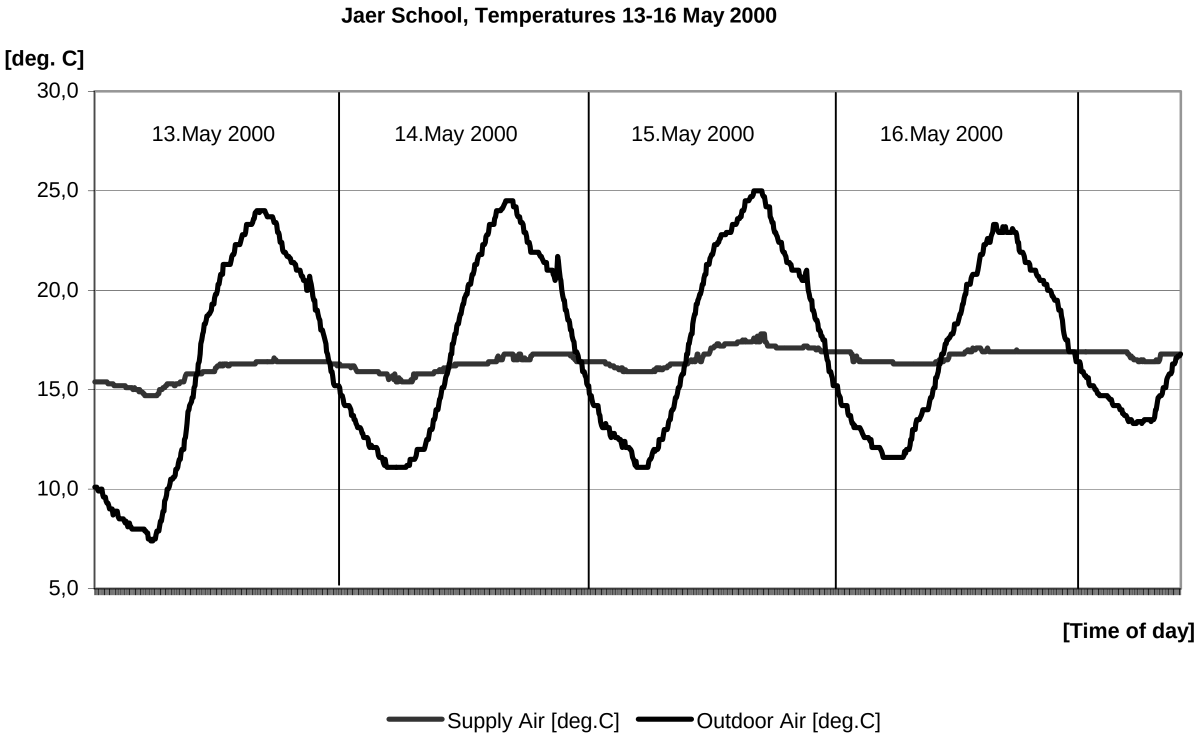


Figure 1. Outside- and supply temperatures at Jaer School.

Mediå School

At this school, the logged measurements included air temperature before and after the culvert, as well as estimated airflow rates (by means of pressure drop over the filter). We have used the four-day period 23–26 August 2001 for further analysis. Temperatures in this period are shown in Figure 2. Tjelflaat [2002a] has described the measurements, methods and results. The airflow rate has been measured to 2890 m³/h when the filter pressure drop (p) is 20.9 Pa [Tjelflaat 2002b]. The air volume (Q) is calculated at other pressure drops from the well-known relationship $Q = k\sqrt{p}$, where k is an empirically derived constant.

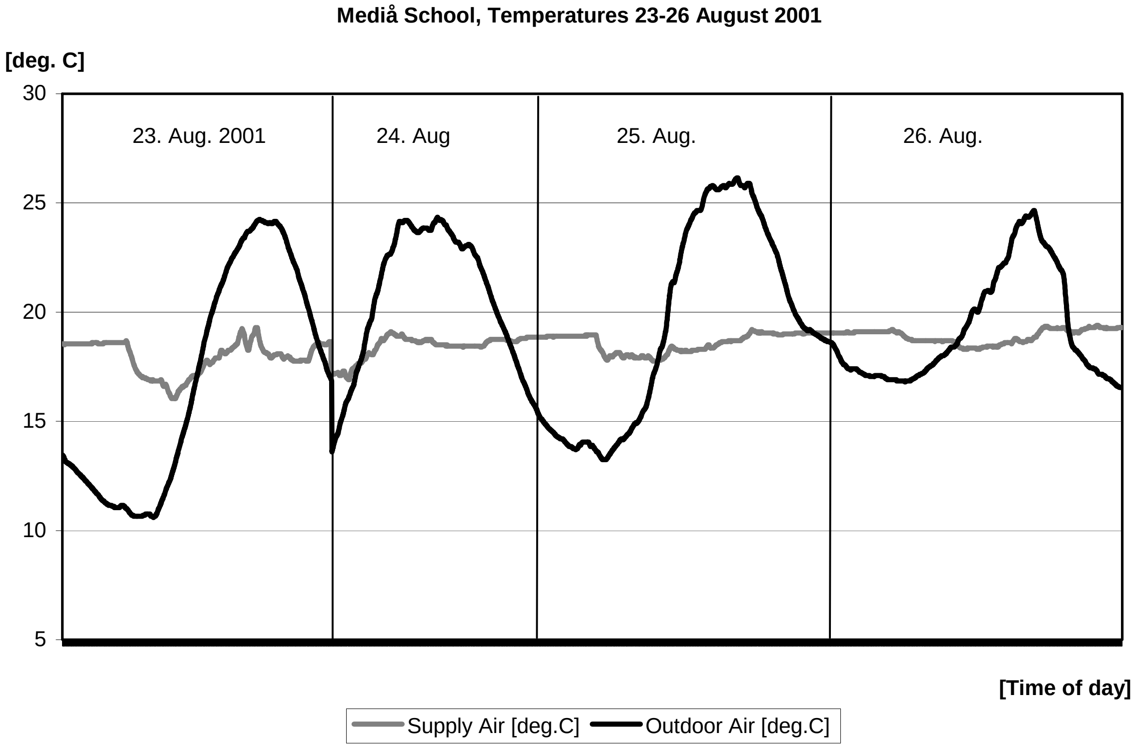


Figure 2. Outside- and supply temperatures at Mediå School

(the first few hours of data on August 24th was not logged it has been reconstructed in the analysis)

METHOD AND RESULTS

Jaer School

Monday the 15 May was the hottest day in the period from 13 to 16 May. The outdoor temperature exceeded 22°C at 11:50 AM and the maximum temperature was 25°C at 3:45 PM. From 11:50 to 16:20 the average cooling effect from the culvert was 5.2 kW, which results in 23.4 kWh cooling. Maximum cooling effect was 6 kW. In this period the supply temperature rose from 17.1°C to 17.5°C. The average airflow rate in the period was 2500 m³/h, which is about $^1/_3$ of the dimensioned airflow rate. Maximum airflow rate in the period was 2850 m³/h with maximum cooling effect of 6.0 kW. The difference between dimensioned and measured airflow rate is probably due to a combination of (i) demand-controlled ventilation with CO_2 sensors in each classroom (there being less pupils present than assumed for dimensioning purposes), (ii) high ventilation efficiency due to displacement ventilation (dimensioning is based on an assumption of fully mixed ventilation), and (iii) some user-controlled ventilation through windows. During most of the time from January 2000 to April 2002, the airflow rates varied between 20 and 50 % of the dimensioned airflow rate.

Jaer School has a 55 m long air intake culvert. The first 20 m consists of a concrete pipe with a net diameter of 1,6 m (Culvert J1). The last 35 m is a 2×3 m² concrete culvert (Culvert J2). This results in a total of about 450 m² concrete surface which can exchange heat with the passing air. On 15th May 2000 between 11:50 and 16:20 the average cooling effect was 11.6 W/m². The average air velocity was 0.35 m/s through Culvert J1, and 0.12 m/s in Culvert J2. The overall weighted mean velocity was 0.17 m/s.

The period was analyzed to find how much the culvert is cooled down at night, and how much cooling it provides during daytime. The results are shown in Table 1.

Table 1. Culvert heat balance for Jaer School

Day of month, May 2000:	*13*	*14*	*15*	*16*	*Sum*
Nighttime precooling of culvert [kWh]	55	36	24	24	139
Daytime cooling provided by culvert [kWh]	-70	-55	-49	-43	-217

Before 13th May it was relatively cold. One can therefore assume that the concrete surfaces were fully charged (i.e. precooled) on 13th May, and this is probably the reason why the culvert provided 78 kWh more cooling during the days than it was cooled down during the nights in the period 13–16 May. It also indicates that this culvert has potential for thermal storage over several days. From Table 1 we see that after 3 hot days the culverts deliver about 43 kWh of cooling per day, whilst the average cooling provided during the period is 54 kWh per day.

Mediå School

Friday 24th August was the hottest day with normal school activity in the period 23–26. August 2001. The outdoor temperature exceeded 22°C at 11:50 AM and the temperature stabilized at around 24°C from 13:00 to late afternoon. From 11:50 to 16:20 the culvert provided a total of 10.2 kWh cooling (2.3 kW on average). In this period, the supply temperature rose from 18.7°C to 19.1°C. The average airflow rate in the period was 1360 m³/h. Maximum airflow rate in this period was 2840 m³/h with maximum cooling effect of 3.4 kW. This maximum airflow rate led only to a small and negligible increase in the supply air temperature after the culvert.

Mediå School has a 20 m long air-intake culvert if one includes the first five vertical meters from the air intake down to the horizontal culvert. This culvert has dimensions of 1.5×2.0 m² (Culvert M1). An air-distribution culvert with dimensions 2.0×2.0 m² follows the air-intake culvert. The supply air temperature was measured at floor level near the intake of an air supply shaft to a classroom, about 5 m into the air distribution culvert (Culvert M2). This results in a total of about 180 m² concrete surface which can exchange heat with the passing air. This gives an average cooling effect from the concrete surface of 12.6 W/m² on 24th August 2001 from 11:50 to 16:20. The average air velocity was 0.13 m/s through Culvert M1, and 0.09 m/s through Culvert M2. The overall weighted mean air velocity was 0.12 m/s.

The period was analyzed to find how much the culvert was cooled down at night compared to how much cooling it provided during daytime. The results are shown in Table 2.

Table 2. Culvert heat balance for Mediå School

Day of month, August 2001:	*22*	*23*	*24*	*25*	*26*	*27*	*Sum*
Nighttime precooling of culvert [kWh]	18	23	2+12[1]	14	7	20	96
Daytime cooling provided by culvert [kWh]	-8	-19	-23	-30	-14	0	-94

[1] Between 23 and 24 August only 2 kWh was recorded because data was not logged between 21:50 and 07:38. In the same period (between 21:50 and 07:38) the day after, 12 kWh of cooling energy was stored in the culvert. 12 kWh is therefore added to the recorded cooling.

There is a good balance between the cooling of the culvert and the cooling from the culvert during the actual period.

AIR VELOCITY AND HEAT-TRANSFER COEFFICIENTS

The influence of air velocity (u) on the convective heat-transfer coefficient (h_c) at the concrete surface, can be estimated from the following relationship for rough surfaces [McAdams 1954]:

$$h_c = 6.2 + 4.3\,u \qquad [\mathrm{W/m^2K}] \qquad (1)$$

Equation (1) presupposes that forced convection is dominating. This might not be the case for very low air velocities, in which case the natural convection heat transfer coefficient will probably be higher than estimated from (1). Moreover the local heat-transfer coefficient depends on the angle of the surface, i.e. if it is a floor, wall or ceiling. If we neglect this in a rough calculation, we can estimate the heat flux (q) from the following known relationship:

$$q = h_c\, dT \qquad [\mathrm{W/m^2}] \qquad (2)$$

Where dT is the average temperature difference between the passing air and the concrete surfaces. This temperature difference has not been measured with sufficient accuracy, but it can be calculated from the heat flux (q). This gives the following results:

Table 3. Air velocity, heat transfer coefficient and temperature difference in the culverts for Jaer School.

Jaer Scool	Mean velocity, u [m/s]	h_c [W/m²K]	Weighted h_c [W/m²K]	Mean dT [°C]
Culvert J1	0.35	7.7	6.9	1.7
Culvert J2	0.12	6.7		

Table 4. Air velocity, heat transfer coefficient and temperature difference in the culverts for Mediå School.

Mediå Scool	Mean velocity, u [m/s]	h_c [W/m²K]	Weighted h_c [W/m²K]	Mean dT [°C]
Culvert M1	0.13	6.7	6.7	1.8
Culvert M2	0.09	6.6		

The two independent measurements at Jaer and Mediå School result in comparable and reasonable calculated heat transfer coefficients and temperature differences. This makes it plausible that Equation (1) can be used for rough estimates of the cooling performance of ground-coupled ducts.

COOLING PERFORMANCE PER UNIT AREA OF GROUND-COUPLED DUCT

The measurements at Jaer and Mediå School show that the concrete ducts have a significant cooling effect on the inlet air during hot days. The amount of cooling depends on the thermal mass of exposed concrete.

Table 5. Jaer School, measured daytime cooling provided by concrete surfaces in culvert.

Date of month, May 2000:	*13*	*14*	*15*	*16*	*Mean*
Cooling per unit area culvert [Wh/m²]	156	122	109	96	121

Jar School's culvert provided 70 kWh cooling on 13th May (Table 1), which is 156 Wh/m² (Table 5). By 15th May, the cooling provided by the culvert had dropped to 49 kWh (109 Wh/m²). The culvert would have provided more cooling the 15th May if the outdoor air temperature or the airflow rate had been higher. In addition the culvert is not being fully 'recharged' during the nights in-between due to low airflow rate (the motorized ventilation control dampers for all rooms are shut at night). In conclusion, by increasing the natural airflow rate at summer nights, it should be possible to get more cooling from the culvert than that which is presently utilized at Jaer School. This will of course depend on the nighttime temperatures. In Norway, which is representative for cold climates, it is rare that the minimum nighttime ambient air temperature is more than 15°C. Increased night cooling will decrease the supply air temperature in the morning. The supply air devices must handle this without giving uncomfortable draft, or the supply air volumes must be decreased.

The culvert at Mediå School had a capacity to produce between 79 and 166 Wh/m² in the period 23-26 August (Table 6). This is similar in magnitude to the corresponding results from Jaer School. The maximum cooling of 166 Wh/m² appears on 25th August after three quite hot days. The night before, the average airflow rate was 980 m³/h, which shows that the airflow had not been forced during the night. The overall weighed mean air velocity during the night was 0.08 m/s which correspond to a heat-transfer coefficient of 6.5 W/m²K. If the mean velocity had been raised to 0.5 m/s, the heat-transfer coefficient should increase to 8.4 W/m²K. This indicates that the storage of cooling energy during nights can be increased 25–30 % by intensive nighttime ventilation. This again will probably increase the cooling performance by 25 to 30 %, which indicates that the cooling potential from culvert surfaces is above 200 W/m² with functional nighttime cooling control. A similar value would be expected for Jaer School.

Table 6. Mediå School, measured daytime cooling provided by concrete surfaces in culvert.

Day of month, August 2001:	*23*	*24*	*25*	*26*	*Mean*
Cooling per unit area culvert [Wh/m²]	107	126	166	79	120

UNCERTAINTY - MEASUREMENT ERRORS

It is very difficult to measure airflow rates at low air velocity through a culvert cross section. The air velocity will vary in the cross section and it will vary over time. In addition, the airflow rate at Mediå School is estimated from the pressure drop across the filter wall. This pressure drop will probably increase due to particles captured by the filter, which creates a possible error when calculating the air flow rates. It will also give an error because the airflow through the filter becomes gradually more laminar at low air velocities. This phenomenon has been neglected when calculating the airflow rates. The uncertainty in airflow rates measurement is hard to estimate due to this variation but we assume that it is within the limits of ± 30 %.

CULVERT DESIGN

The measured cooling performance on 15th May 2000 indicates that Jaer School has a cooling demand of about 49 kWh during a hot day (Table 1). This indicates that the need for concrete surfaces for cooling purposes is about 250 m² based on a cooling potential of 200 Wh/m². This also indicates that the length or the dimensions of the culvert at Jaer School could have been reduced for cooling purposes, making the building less expensive.

The measured cooling performance on 25th August 2001 indicates that Mediå School has a cooling demand of about 30 kWh during a hot day (Table 2). This indicates that the need for concrete surfaces for cooling purposes is about 150 m² based on the cooling potential of 200 Wh/m². This also indicates that the length or the dimensions of the culvert at Mediå School could have been slightly reduced for cooling purposes.

Another design criteria is that the culvert should be at least 1,90 m high for easy inspection and maintenance, and that the air velocity through the culvert should not exceed 0.5 to 1.0 m/s. It is also beneficial for the culvert to have a larger cross sectional area in the proximity of the air-intake, giving an extreme low air velocity for sedimentation of particles, snow and rain at this early stage of the culvert.

The main mechanism of cooling in these ducts is exploiting thermal storage with nighttime precooling, exploiting the diurnal swing in outdoor temperature, so a limited depth of concrete is actively used. Thus the duct need not necessarily be ground-coupled, but can equally be integrated within the building structure, and the surface area of exposed concrete can be increased further by baffle walls within the duct that are exposed on both sides.

Jaer School had about 150 pupils in the school year 2001-2002. This indicates a need for 1.7 m^2/pupil culvert surfaces presupposed demand controlled displacement ventilation for buildings situated in the same environment as in the municipality of Nesodden. Mediå School had about 140 pupils in the school year 2001-2002. This indicates a need for 1.1 m^2/pupil culvert surfaces presupposed demand controlled displacement ventilation for buildings situated in the same environment as in the municipality of Grong.

HUMAN ADAPTATION

Humans will adapt to a higher temperature after a period of exposure [de Dear, 2000]. That means that we adapt to or even appreciate a higher indoor air temperature after a long warm period, for example by adjusting clothing. This indicates that culvert cooling might be in a good balance with human levels of acceptance, since this will give a slight increase in indoor temperature after several hot days.

CONCLUSIONS

The measurements at Jaer and Mediå School show that a culvert has significant cooling effect. In cold climates with cool night temperatures, the cooling flux from the culvert surfaces at Jaer School stabilizes at around 100 Wh/m² after a long warm period. By increasing the at nighttime airflow rate, it should be possible to achieve a cooling effect of at least 200 W/m² of environmentally favorable cooling with no use of electricity and no risk for emission of toxic or harmful greenhouse gases. This correspond to 1.7 m^2/pupil culvert surfaces presupposed demand controlled displacement ventilation for buildings situated in the same environment as in the municipality of Nesodden, or 1.1 m^2/pupil in the same outdoor environment as in the municipality of Grong.

The maximum recorded peak loads led only to a small and negligible increase in the supply air temperature after the culvert, which indicates that culvert cooling is well suited for handling considerable peak loads.

The use of such concrete culverts will, together with suitable airflow regulation, ensure that the supply air is colder than room air, which is crucial for functional displacement ventilation.

The average temperature difference between the air and the concrete surfaces has been estimated to be around 1.5 to 2.0 °C during hot days at both Jaer and Mediå School.

LITERATURE

McAdams, W.H., 1954, Heat transmission, McGraw-Hill Book Company.

de Dear, R., 2000, The Adaptive Model of Thermal Comfort, ASHRAE Project RP-884. http://atmos.es.mq.edu.au/~rdedear/ashrae_rp884_home.html

Schild, P.G., 2002a, Pilot Study Report for Jaer School, IEA ECBCS Annex 35, "Principles of Hybrid Ventilation" CD-ROM. http://www.byggforsk.no/prosjekter/hybvent/A03-jaer_PSreport.pdf

Schild, P.G., 2002b, Hybrid ventilation of Jaer School: Results of monitoring, Hybrid ventilation 2002: 4th International Forum, May 14-15, 2002, Montreal, Canada. http://www.byggforsk.no/prosjekter/hybvent/A03-jaer_paper.pdf

Tjelflaat, P.O., 2002a, Pilot Study Report for Mediå School, IEA ECBCS Annex 35, "Principles of Hybrid Ventilation" CD-ROM. http://www.byggforsk.no/prosjekter/hybvent/A04-grong_PSreport.pdf

Tjelflaat, P.O. 2002b, Verbal communication, Norwegian University of Science & Technology, Trondheim, Norway.

Questionnaire Used in Paper I, II and VI (In Norwegian)

MILJØUNDERSØKELSE VED TREDAL SKOLE

SPØRRESKJEMA

Med dette spørreskjemaet vil vi undersøke innemiljøet i klasserommet ditt. Besvarelsen er anonym. Utfylte skjema sendes til Norges byggforskningsinstitutt, ved Mads Mysen, Postboks 123 Blindern, 0314 OSLO.

Et skjema fylles i *begynnelsen* av siste time på angitte dager

Kontaktperson ved spørsmål:

Mads Mysen – mads.mysen@byggforsk.no - tlf. 22 96 55 82

Kari Thunshelle – kari.thunshelle@byggforsk.no - tlf. 22 96 55 30

Dato for utfylling:

Klasse:

Klasserom:

Kryss av for kjønn:

Jente	**Gutt**

GENERELLE OPPLYSNINGER

		Ja	*Nei*
1	Har du hatt undervisning i klasserommet stort sett i hele dag ?		
2	Sitter du på vindusrad ?		
3	Sitter du i bakre del av klasserommet ?		

HELSE – Hvordan har du det *i dag* ?

		Ja	*Nei*
4	Er du trett ?		
5	Er du tung i hodet ?		
6	Har du hodepine ?		
7	Er du svimmel eller ør i hodet ?		
8	Har du problemer med å konsentrere deg ?		
9	Har du kløe eller svie i øynene ?		
10	Er du hes eller tørr i halsen ?		
11	Har du rennende eller tett nese ?		
12	Har du hoste ?		
13	Er du forkjølet ?		
14	Klør det i ansiktet eller hendene ?		
15	Er du kvalm eller uvel på annen måte ?		

Snu arket!

TRIVSEL – Hvordan er det i klasserommet *i dag* ?

		Ja	Nei
16	Er det for varmt ?	☐	☐
17	Er det plagsom varme fra sola ?	☐	☐
18	Er det for kaldt ?	☐	☐
19	Føler du trekk på føttene eller i nakken ?	☐	☐
20	Er du plaget av skiftende temperatur i rommet ?	☐	☐
21	Er det tung eller dårlig luft ?	☐	☐
22	Kjennes lufta tørr ?	☐	☐
23	Er det ubehagelig lukt ?	☐	☐
24	Er det vanskelig å høre det som blir sagt i klasserommet ?	☐	☐
25	Er det forstyrrende støy eller uro fra elevene i klassen ?	☐	☐
26	Er det forstyrrende støy fra elever eller lærere i andre klasser eller klasserom ?	☐	☐
27	Er det forstyrrende bråk utendørs (fra trafikk/skolegård/ byggevirksomhet eller lignende) ?	☐	☐
28	Er det forstyrrende susing eller dur fra ventilasjon eller andre ting i bygningen ?	☐	☐
29	Er det godt nok lys på arbeidsplassen din ?	☐	☐
30	Er det gjenskinn (refleks) fra tavla ?	☐	☐
31	Er det plagsomt lys fra sola ?	☐	☐
32	Har du fått elektrisk støt ved berøring av noe (statisk elektrisitet) ?	☐	☐
33	Er det rent nok ?	☐	☐
34	Trives du bra på skolen ?	☐	☐

ANDRE FORHOLD

		Ja	Nei
35	Har du problemer med å se det som står på tavla (selv om du bruker briller) ?	☐	☐
36	Har du spist noe i dag ?	☐	☐
37	Har du astma ?	☐	☐
38	Har du allergiplager ?	☐	☐
39	Bruker du faste medisiner mot astma eller allergi?	☐	☐

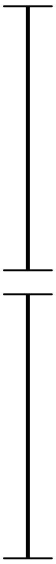
HJEMMEFORHOLD

		Ja	Nei
40	Deler du soverom med noen ?	☐	☐
41	Har du teppe som dekker hele gulvet på soverommet ditt (vegg til vegg-teppe) ?	☐	☐
42	Er soverommet ditt godt luftet om natten (åpent vindu eller tilsvarende god lufting) ?	☐	☐
43	Bor du sammen med noen som røyker ?	☐	☐
44	Har dere dyr hjemme ?	☐	☐
45	Har du jevnlig kontakt med dyr ?	☐	☐

DTU spilt scale Used in Paper II and III (In Norwegian)

MILJØUNDERSØKELSE VED TREDAL SKOLE

Hvordan oppfatter du luftkvaliteten nå? – marker på skalaen:



Veldig bra (klart akseptabelt)

Litt bra (så vidt akseptabelt)
Litt dårlig (så vidt uakseptabelt)

Veldig dårlig (klart uakseptabelt)