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Analysis of the indoor climate at Jøa swimming hall

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MASTER THESIS

for

Student Julie Jørgensen

Spring 2018

Analysis of the indoor climate at Jøa swimming hall
Analyse av inneklimaet i Jøa svømmehall

Background and objective

Swimming halls represent a type of building with many challenges. Some of these are: The humidity level is high which gives a risks for condensation and problems related to moisture in the construction, The indoor temperature must be relatively high to maintain thermal comfort, the air quality is influenced from emissions from the water treatment system and the energy use is high.

At Jøa in Fosnes kommune a new swimming hall was opened in January 2017. The swimming hall is part of a multipurpose sport centre and serve as a therapeutic pool for the citizens of Jøa. The innovative and advanced HVAC system is a "state of the art" in Norway and include both innovative air flows distribution system and renewable thermal energy supply system.

The objective of the master thesis is to analyse the actual performance of the ventilation system in the swimming hall in accordance with the expected performance. The analysis should be carried out in regard to indoor climate and thermal comfort.

The work is connected to a PhD work at SIAT, Centre for Sport Facilities and Technology, titled "Optimizing energy and climate system in buildings with swimming facilities".

The following tasks are to be considered:

1. Literature review
2. **Technical part** - Mapping the structure of the ventilation system and analysis of the systems vulnerability both concerning operation and parameters and decisions made in the designing phase. The aim is to establish a base for identifying the rate of success.
3. **Performance with regard to user satisfaction** - Quantify the user satisfaction with a user survey. Both to the "swimmers" and the operators. The aim is to get a picture of how this is actually working due to thermal comfort and operation.
4. **Performance due to air quality** - Investigate the performance of the air flows distribution system by performing a tracer gas experiment. The aim is to establish a picture of how the ventilation system is performing in relation to ventilation effectiveness.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☒ Field work

Department of Energy and Process Engineering, 15. January 2018

Hans Martin Mathisen
Academic Supervisor

Research Advisor:
Ole Øiene Smedegård

Preface

This Master Thesis is carried out at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology, and is the finishing work of my Master in Energy and Environmental engineering. The work has been conducted at the spring semester of 2018.

The thesis is connected to a PhD work at SIAT, Centre for Sport Facilities and Technology, titled "Optimizing energy and climate system in buildings with swimming facilites".

Julie Jørgensen, MSc. student

Trondheim, 11.06.2018

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Abstract

Indoor swimming pools are popular leisure and sports facilities all over the world. Compared to normal buildings, indoor swimming pools have several challenges regarding ventilation, heating and dehumidification. In order to maintain thermal comfort, the air temperature has to be high. In addition, the indoor air quality is influenced by the water treatment system. To keep the energy consumption on an acceptable level, recirculation of air is necessary for indoor swimming pools. Jøa swimming pool in Fosnes kommune was opened in Januar 2017, and is part of a multi-purpose sports hall and serves as a therapeutic pool for the citizens of Jøa. The ventilation system is innovative and advanced and based on the principle of reversed displacement ventilation. The system has a renewable energy supply system, in addition to an innovative airflow distribution.

The objective of this master thesis was to analyse the actual performance of the ventilation system in the swimming pool in accordance with the expected performance. The analysis have been carried out in regard to indoor climate and thermal comfort.

Fieldwork was conducted at the swimming pool at Jøa. Tracer gas experiments to calculate the air change efficiency, in addition to temperature- and velocity measurements were carried out. Three different experiments were conducted, with different operations of the ventilation system. One with a manipulation of the ventilation system to supply a minimum of one air changes per hour with fresh air, a second with normal operations. The third experiment was conducted with a minimum of one air changes per hour with fresh air and with a reduction of the height of the exhaust grille. The height of the exhaust grille was reduced because of an assumption of short-circuiting of air. One smoke experiment was also carried out to get an understanding of the air flow pattern. In addition, a questionnaire was issued to the swimmers and the operators of the swimming pool.

During the field trip to Jøa it was detected that the fresh air supply was controlled by the humidity level measured in the exhaust air, whereby the air flow was not constant. A non-constant air flow and recirculation of air made the results from the tracer gas experiment less reliable. However, the logarithmic presentation of the tracer gas concentration could be utilized to get an understanding of the air change efficiency. The results showed trends to a fully mixed flow in all of the three experiments. The first experiment showed tendencies to short-circuiting of air, while for the third experiment it seemed like there was no short-circuiting of air. The smoke visualization also showed a fully mixed flow. The questionnaire showed that the majority of the people were satisfied with the indoor climate, but that they all perceived the thermal environment differently.

The current ventilation system differs a lot from how it was designed. The supply diffusers below the windows were supposed to work as "security-diffusers", but they are in constant operation. The system is designed on the principle of reversed displacement ventilation, but from the conducted measurements, it looks like the air is fully mixed. However, this does not mean a poor ventilation system. The users' seem to be satisfied with the indoor climate, but due to very few respondents, it is not possible to draw any conclusions about the indoor climate based on the questionnaire.

Sammendrag

Innendørs svømmehaller er populære fritids- og idrettsanlegg over hele verden. Sammenlignet med vanlige bygninger har svømmebasseng flere utfordringer knyttet til ventilasjon, oppvarming og avfukting. For å opprettholde termisk komfort må lufttemperaturen være høy. I tillegg er inneklimaet påvirket av vannbehandlingssystemet. For å holde energiforbruket på et akseptabelt nivå er resirkulering av luft nødvendig i innendørs svømmehaller. Jøa svømmehall i Fosnes kommune ble åpnet i januar 2017, og er en del av en sportshall med flere formål og fungerer som et terapi- og opplæringsbasseng for innbyggerne på Jøa. Ventilasjonssystemet er innovativt og avansert, og er basert på omvendt fortrengningsventilasjon. Systemet har et fornybart energiforsyningssystem, i tillegg til en nyskapende luftstrømfordeling.

Målet med oppgaven var å analysere ytelsen til ventilasjonsanlegget i svømmehallen i forhold til forventet ytelse. Analysen ble gjennomført med fokus på inneklima og termisk komfort.

Feltarbeid ble utført i svømmehallen på Jøa. Sporgassforsøk for å beregne ventilasjonseffektiviten, i tillegg til temperatur- og hastighetsmålinger ble gjennomført. Tre ulike forsøk ble gjennomført, med ulik drift av ventilasjonssystemet. Det første forsøket ble utført ved å tilføre minimum et luftskifte per time med friskluft. Det andre forsøket ble utført med normal drift av anlegget. Det tredje forsøket ble gjennomført med minimum et luftskifte per time med friskluft og redusert høyde på avtrekksristen. Høyden på avtrekksristen ble redusert på bakgrunn av en mistanke om kortslutning av luft. Et røykforsøk ble også utført for å få en forståelse av luftfordelingen i rommet. I tillegg til forsøkene ble en spørreundersøkelse utstedt til brukerne og de som arbeider i svømmehallen.

I løpet av feltarbeidet på Jøa ble det oppdaget at den tilførte friskluftsmengden er kontrollert av fuktighetsnivået målt i avtrekket, og at luftmengden derfor ikke er konstant. En ikke-konstant luftstrøm og resirkulering av luften, førte til at resultatene fra sporgassforsøkene ikke er pålitelige. Derimot, kunne den logaritmiske presentasjonen av sporgasskonsentrasjonen benyttes for å få en forståelse av ventilasjonseffektiviteten. Resultatene viste trender til omrøringsventilasjon i alle forsøkene. Det første forsøket viste tendenser til kortslutning av luft, men det tredje forsøket viste ingen tendenser til kortslustning av luft. For røykforsøket så det også ut som det var fullstendig omrøring i rommet. Spørreundersøkelsen viste at mesteparten av brukerne av svømmehallen var tilfreds med inneklimaet, men at de opplever inneklimaet ulikt.

Det nåværende ventilasjonssystemet avviker mye fra hvordan det er designet. Tilluftsventilene under vinduene skulle i utgangspunktet kun benyttes ved behov, men er per nå i kontinuerlig drift. Systemet er basert på omvendt fortrengningsventilasjon, men fra de utførte målingene ser det ut som at det er omrøring. Dette betyr derimot ikke at ventilasjonssystemet er dårlig. Brukerne av svømmehallen virker å være fornøyd med inneklimaet, men på grunn av svært få besvarelser, er det ikke mulig å trekke noen konklusjoner om inneklimaet basert på undersøkelsen.

Abbreviations

ach	Air Changes per Hour
AH	Absolute Humidity
AHU	Air Handling Unit
clo	Clothing Insulation
CRE	Contaminant Removal Effectiveness
CO_2	Carbone Dioxide
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
N_2O	Nitrous Oxide
RH	Relative Humidity
SF_6	Hexafluoride
PMV	Predicted Mean Vote
PPD	People Percentage Dissatisfied

Nomenclature

c_e	Concentration in the exhaust air	[ppm, mg/m^3, etc.]
$\langle c \rangle$	Mean concentration in the room	[ppm, mg/m^3, etc.]
c_o	Start concentration of the tracer gas	[ppm, mg/m^3, etc.]
c_P	Concentration at point P	[ppm, mg/m^3, etc.]
C_{res}	Heat exchange due to convention in breathing	
ε^a	Air change efficiency	[%]
ε^a_P	Local air change index in a particular point P	[%]
ε^c	Contaminant Removal Efficiency	[CRE]
ε^c_P	Local concentration in a particular point P	
$E(I)$	Evaporative heat loss of the wet body's segment I	[W]
E_c	Heat exchange due to the evaporation on the skin	
E_{res}	Heat exchange due to the evaporation in breathing	
f_{pcl}	Permeation efficiency factor by Nishi	
f_{cl}	Surface area factor of the clothing	
h_c	Convective heat transfer coefficient	[W/m^{2}K]
H	Sensitive heat loss	
I_{cl}	Clothing insulation	[m^{2}K/W]
M	Metabolic rate	[W/m^2]
p_a	Water vapour partial pressure	[Pa]

p_{skin}	Saturated water vapour pressure of the skin's segment I	[Pa]
q_v	Ventilation flow rate	[m^3/h, m^3/s]
$S(I)$	The segment's I surface area	[m^2]
τ_n	Nominal time constant	[s, min, h]
$\overline{\tau}_P$	Local mean age of air	[s, min, h]
$\overline{\tau}_r$	Actual air change time	[s, min, h]
$\langle\overline{\tau}\rangle$	Room mean age of air	[s, min, h]
t_a	Air temperature	[°C]
t_{cl}	Surface temperature of the clothing	[°C]
t_{skin}	Temperature of the skin	[°C]
t_r	Mean radiant temperature	[°C]
t	time	[min]
t_A	Time elapsed for molecule A from entering the room to point P_1	[s, min, h]
t_B	Time elapsed for molecule B from entering the room to point P_1	[s, min, h]
t_C	Time elapsed for molecule B from entering the room to point P_1	[s, min, h]
$\overline{t}_{P1}$	Mean age of air in point P_1	
V	Volume	[m^3]
V_{tg}	Flow rate of tracer gas	[m^3/h]
W	Effective mechanical power	[W/m^2]

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1. Introduction

1.1 Background

Indoor swimming pools are popular leisure and sports facilities all over the world. In 2012 Norway possessed as much as 850 different swimming facilities (Kampel et al., 2013). Compared to normal buildings, indoor swimming pools have several challenges regarding ventilation, heating and dehumidification. In order to maintain the thermal comfort of the swimmers and protect the building structure, several environmental parameters have to be controlled (Sun et al., 2011). Evaporation from the pool leads to very high humidity levels, and good dehumidification solutions are necessary. In addition, the air temperature has to be high to maintain thermal comfort. The air quality is also influenced due to the water treatment system, and efficient ventilation systems are important.

Jøa swimming pool in Fosnes kommune was opened in January 2017. The swimming pool is part of a multi-purpose sports hall and is a therapeutic pool for the citizens of Jøa. The ventilation system is innovative and advanced, and has a renewable thermal energy supply system, in addition to an innovative airflow distribution.

1.2 Objectives

The objective of this master thesis is to analyse the actual performance of the ventilation system in the swimming pool in accordance with the expected performance. The analysis will be carried out in regard to indoor climate and thermal comfort. To evaluate the performance of the ventilation system, tracer gas experiments were conducted. In addition, velocity- and temperature measurements were carried out. A questionnaire was issued to the swimmers and the operators of the pool to evaluate users' perception of the indoor climate.

The objective of the thesis is carried out around the following research questions:

- Is the ventilation system working as expected based on tracer gas experiments? Should there be taken any measures on the ventilation system?
- Is the ventilation system working as expected based on the answers from the user survey, is the indoor climate satisfactory based on the answers from the questionnaire?

The following tasks are to be considered:

1. Literature review
2. Technical part - Mapping the structure of the ventilation system and analysis of the system vulnerability both concerning operation and parameters and decisions made in the designing phase. The aim is to establish a base for identifying the rate of success.
3. Performance with regard to user satisfaction - Quantify the user satisfaction with a user survey. Both to the "swimmers" and the operators. The aim is to get a picture of how this is actually working due to thermal comfort and operation.
4. Performance due to air quality - Investigate the performance of the air flows distribution system by performing a tracer gas experiment. The aim is to establish a picture of how the ventilation system is performing in relation to ventilation effectiveness.

1.3 Approach

In the beginning of the semester, the main focus was on collecting relevant literature on the topic of ventilation, ventilation efficiency and indoor climate, primarily in swimming pools. Several search engines have been used, such as Google Scholar and Science Direct.

Prior to the fieldwork, the tracer gas equipment was tested in the lab. Tracer gas experiments were then conducted in the swimming pool at Jøa. In addition, temperature- and velocity measurements were carried out. One smoke experiment was also conducted to get an understanding of the air flow pattern in the room. A questionnaire created in SelectSurvey was issued to the users' and operators of the pool. As the swimming pool is often used by the pupils of the school, the principal of the school arranged so the pupils could answer the questions during school hours. For other private users of the pool, the operator of the pool distributed the survey through email.

1.4 Limitations

Jøa is located around four hours by car from Trondheim. As it is located so far from Trondheim it was only possible to visit the site once during the semester. The whole experiment was therefore dependent on this one visit. Ideally, several experiments should have been carried out.

During the field trip, it was discovered that the supplied and extracted air were not constant. The outdoor air supply is controlled by the humidity level measured in the exhaust. It was discovered that the humidity could reach a level of 63 % before the damper for fresh air supply was opened. When injecting the tracer gas in the outdoor air supply, the concentration in the step up-method fluctuated until the gas was turned off. It was therefore decided to omit the results from the step up-method and focus on the step down-method.

Regarding the questionnaire, it was very hard to get a proper amount of respondents. A very small percentage of the respondents are operators of the pool, thereby all of the answers are evaluated together. The amount of respondents is a great limitation when evaluating the indoor climate based on the questionnaire.

Regarding the indoor climate, the focus in this thesis will be on the thermal- and atmospheric environment, which is mainly the focus for ventilation systems.

In addition, studies on indoor climate in swimming pools, especially tracer gas experiments are very limited.

2. Indoor climate in swimming pools

This chapter presents the theory for indoor climate in buildings with swimming pools. In addition, it presents studies conducted in swimming pools in regard to indoor climate. Further, it explains the evaporation from the pool and how it may affect the climate and the building construction.

Indoor climate is a term that is composed of several factors. These factors affect various parts of the indoor climate, but person perception of the indoor climate shows an overall picture. (Ingebrigsten, 2016)

Indoor climate is divided in to the following factors (Ingebrigsten, 2016; Novakovic et al., 2007):

- The thermal environment
- The atmospheric environment (Indoor Air Quality (IAQ))
- The acoustic environment
- The actinian environment
- The mechanical environment

In addition are people affected by (Ingebrigsten, 2016):

- The aesthetic environment
- The psychosocial environment

2.1 Thermal environment

The thermal environment comprises all parameters that have an influence on the heat balance of a human body (Ingebrigsten, 2016). These parameters are the air temperature, radiation temperature, air velocity and water vapour pressure (Abel et al., 2003). Perception of the thermal environment is also affected by clothing, activity level and state of mind (Ingebrigsten, 2016).

2.1.1 Thermal comfort

Thermal comfort is when a person is comfortable (Ingebrigsten, 2016), and is defined by Novakovic et al., 2007 as: "Thermal comfort is a state of mind in which a person expresses full satisfaction with their thermal surroundings."

Thermal comfort is not always easy to achieve, and it is necessary to distinguish between the factors that influence and decide the thermal comfort of a human being (Novakovic et al., 2007).

Thermal comfort is influenced by (Novakovic et al., 2007):

- Dry air bulb temperature
- Thermal radiation in the room
- Air movement (velocity) and turbulence
- Air humidity
- The person's activity level
- The person's clothing

Thermal comfort is decided by physiological criteria (Novakovic et al., 2007):

- Skin temperature, 32-34 °C
- Core temperature, 37-38 °C
- Sweat excretion, "skin dampness"<0.25

The activity level of a person is of big importance when defining thermal comfort. The energy that is developed by the oxidation process in the human body is called metabolism [W/m^2]. The largest part of this energy goes into internal heat production. Depending on the activity level, and with higher activity level, the metabolism will increase. The energy is expressed per m^2 body surface, and on average for a grown up this value is 1.75 m^2. For a sedentary relaxed person, the energy developed is equal to 58 W/m^2. This effect is referred to as 1 MET. (Ingebrigsten, 2016)

MET-values for different activity levels are stated in Table 2.1 (Ingebrigsten, 2016):

Table 2.1: MET-values for different activities

Activity	**MET-value**
Laying	0.8
Sitting	1.0
Standing	1.2
Walking (3 km/h)	2.0
Running (5 km/h)	3.0

Clothing is also an important factor when evaluating thermal comfort. The heat conduction resistance of clothing describes the thermal resistance between the skin and the outside surface of the clothing. Clothing insulation is expressed in m^2K/W or in clo. 1 clo equals 0.155 m^2K/W. In swimming pools, the people will have a clothing level equal to almost 0 clo (naked). (Ingebrigsten, 2016)

2.1.2 Draft

According to Novakovic et al. (2007) draft is defined as "an undesired, local, convective cooling of the body". For the people using the swimming pool the sense of draft is extra important because of the wet body surfaces (Øiene Smedegård, 2017). If the relative humidity is lower than 50 % they will experience draft (Bøhlerengen et al., 2004).

Draft is divided into radiant heat draft and convective draft, where radiant heat draft is due to fluctuations of the heat, while convective draft depends on the air temperature, humidity and air velocity (Novakovic et al., 2007).

2.1.3 Predicted mean vote (PMV and Predicted percentage dissatisfied (PPD))

Fanger developed the predicted mean vote (PMV) to determine the correlation between clothing, metabolic activity and physical parameters (Fanger et al., 1970). The PMV is a 7-point scale, formed by the heat balance of the body. The scale goes from -3 to 3, where -3 is cold and 3 is hot. The desired PMV is between -0.5 and 0.5, which is in between neutral and slightly cool, and neutral and slightly warm, respectively. The PMV can be calculated from different equations, with use of air- and mean radiant temperature, metabolic rate, air velocity and humidity. (Norsk Standard NS-EN ISO 7730, 2005)

The predicted percentage dissatisfied (PPD) is used to establish the prediction of people that are thermal dissatisfied, feeling too cold or too warm. People stating dissatisfaction of the thermal environment will vote -3,-2, 2 and 3, which equals cold, cool, warm and hot, respectively. (Norsk Standard NS-EN ISO 7730, 2005)

In Annex E in NS-EN ISO 7730 (Norsk Standard NS-EN ISO 7730, 2005) there are tables for determining the PMV depending on operative temperature, air velocity, activity level and clothing level.

To determine the operative temperature equation 2.1 can be utilized. The equation applies for air velocities below 0.4 m/s and radiation temperatures below 50 °C. (Novakovic et al., 2007)

$$t_o = \frac{t_r + t_a}{2} \tag{2.1}$$

where:

- t_o - Operative temperature
- t_r - Radiation temperature
- t_a - Dry-bulb temperature

Calculation of the PMV

The PMV can be calculated by the following equation (Norsk Standard NS-EN ISO 7730, 2005; Rajagopalan and Jamei, 2015):

$$PMV = (0.303e^{-0.036M} + 0.028)[(M - W) - H - E_c - C_{res} - E_{res}] \tag{2.2}$$

where:

- M - Metabolic rate [W/m^2]
- W - Effective mechanical power [W/m^2]
- H - Sensitive heat loss
- E_c - Heat exchange due to the evaporation on the skin
- C_{res} - Heat exchange due convection in breathing
- E_{res} - Heat exchange due to evaporation in breathing

$$H = 3.96 \cdot 10^{-8} \cdot f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \cdot h_c(t_{cl} - t_a) \tag{2.3}$$

$$E_c = 3.05 \cdot 10^{-3}[5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] \tag{2.4}$$

$$C_{res} = 0.0014 \cdot M(34 - t_a) \tag{2.5}$$

$$E_{res} = 1.7 \cdot 10{-}5 \cdot M(5867 - p_a) \tag{2.6}$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot (3.96 \cdot 10^{-8} \cdot f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)) \tag{2.7}$$

$$\begin{aligned} h_c &= 2.38(t_{cl} - t_a)0.25 \quad \text{for} \quad 2.38|t_{cl-t_a}|0.25 > 12.1(v_{ar})^{1/2} \\ h_c &= 12.1(v_{ar})^{1/2} \quad \text{for} \quad 2.38|t_{cl} - t_a|0.25 < 12.1(v_{ar})^{1/2} \end{aligned} \tag{2.8}$$

$$\begin{aligned} f_c &= 1 + 1.290 I_{cl} \quad \text{for} \quad I_{cl} <= 0.078 \ \ \mathrm{m^2K/W} \\ f_c &= 1.05 + 0.645 I_{cl} \quad \text{for} \quad I_{cl} > 0.078 \ \ \mathrm{m^2K/W} \end{aligned} \tag{2.9}$$

$$p_a = e^{16.6536 - \frac{4030.183}{T + 235}} \tag{2.10}$$

where:

- I_{cl} - Insulation of the cothing [m^2K/W]
- f_{cl} - Surface area factor of the clothing
- t_a - Air temperature [°C]
- t_r - Mean radiant temperature [°C]
- v_{ar} - Relative air velocity [m/s]
- p_a - Water vapour partial pressure [Pa]
- t_{cl} - Surface temperature of the clothing [°C]
- t_{sk} - Skin temperature [°C]

For the wet swimmers the evaporative term has to be added. Revel and Arnesano, 2014 utilized the Stolwijk model (Lammers, 1978) for their study:

$$E(I) = (p_{skin}(I) - p_a) \cdot 2.2 \cdot h_c(I) \cdot (10 \cdot v_{ar})^{1/2} \cdot f_{pcl}(I) \cdot S(I) \quad (2.11)$$

where:

- $E(I)$ - Evaporative heat loss of the wet body's segment I
- p_{skin} - Saturated water vapour pressure of the skin's segment I [Pa]
- p_a - Water vapour pressure of air [Pa]
- h_c - Convective heat transfer coefficient [W/m^2K]
- v_{ar} - Air velocity [m/s]
- f_{pcl}(I) - Permeation efficiency factors of segment I by Nishi
- $S(I)$ - The segment's I surface area [m^2]

E(I) can be found by the following equation (Singleton, 1982)):

$$f_{pcl}(I) = \frac{1}{1 + 0.143 \cdot h_c \cdot I_{cl}} \quad (2.12)$$

Study conducted in Australia

One study conducted in Australia (Rajagopalan and Jamei, 2015) evaluated the thermal comfort of swimmers, spectators, and staff in seven aquatic centres in Australia. The PMV and the thermal sensation of all the groups were evaluated. They observed that the PMV and thermal sensation had a good correlation for both spectators and staff. For the swimmers, however, they concluded that the equation for PMV had to be further developed by adding the evaporative term.

Table 2.2 shows the water-, air- and outdoor temperatures, and the air velocity for three different buildings from the study.

Table 2.2: Temperatures and air velocity for the different buildings

Building	**1**	**3**	**4**
Water temperature [°C]	31	27	29
Mean air temperature [°C]	28.06	29.07	29.16
Outdoor temperatures [°C]	12-17	10-15	8-12
Mean air velocity [m/s]	0.19	0.13	0.12

Figure 2.1 shows the thermal sensation of the swimmers for the three different buildings. As the figure shows the swimmers stated their termal sensation between neutral and hot, and most of them were either slightly warm or warm. Figure 2.2 shows the comparison between the thermal sensation and the calculated PMV. As the figure shows the thermal sensation and the calculated PMV differs between the three buildings, which may be due to the missing evaporation term in the calculation of the PMV.

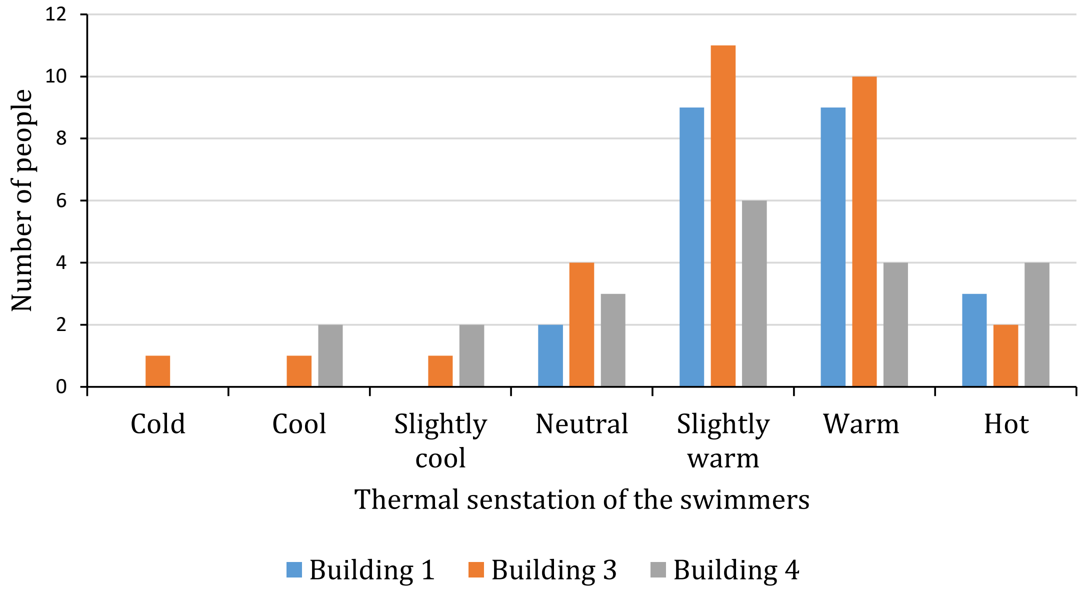


Figure 2.1: PMV of the swimmers in Australia

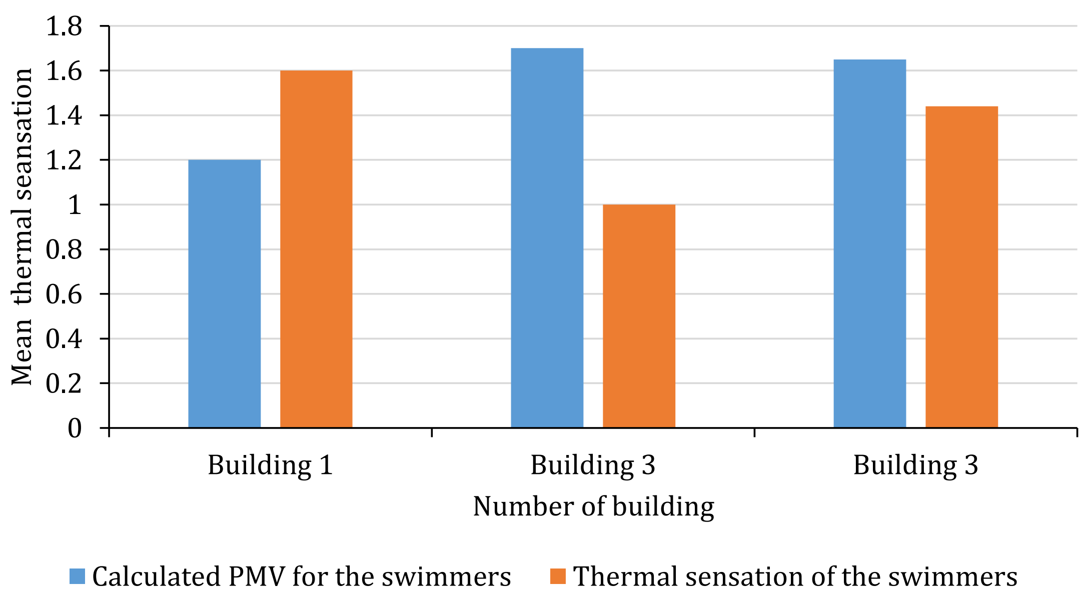


Figure 2.2: PMV and TS of the swimmers in Australia

Study conducted in Italy

A second study conducted in Italy (Revel and Arnesano, 2014) investigated the PMV and thermal sensation of occupants in a gym and swimming pool during four days. For the swimmers, the evaporative term was added. The study concluded that the wet swimmers condition coming out of the pool could be evaluated by the PMV and the thermal sensation of the swimmer.

Table 2.3: Temperatures and air velocity for three days

Day	1	2	3
Water temperature [°C]	30.2	29.9	29.9
Mean air temperature [°C]	30.6	30.3	30.8
Outdoor temperatures [°C]	26	27.2	28.9
Mean air velocity [m/s]	0.02	0.02	0.02

Figure 2.3 shows the correlation between the calculated PMV and the thermal sensation of the wet swimmers for three days. As the figure shows both the calculated PMV and the thermal sensation coincide well, and is between 0 and -0.6, which indicates a thermal sensation between neutral and slightly cool. Compared to the study by Rajagopalan and Jamei (2015), both the calculated PMV and the thermal sensation of the swimmers are lower than for the study conducted in Italy. By comparing the the different parameters from table 2.2 and 2.3, all of the measured parameters from the study in Australia would indicate a worse thermal sensation. The air velocity is higher and the outdoor air temperature is lower. The study from Australia also have higher velocities and lower outdoor air temperatures. The PMV may be explained by the lack of the evaporation term in the equation, but the thermal sensation of the swimmers cannot really be explained other than that people perceive the thermal environment differently.

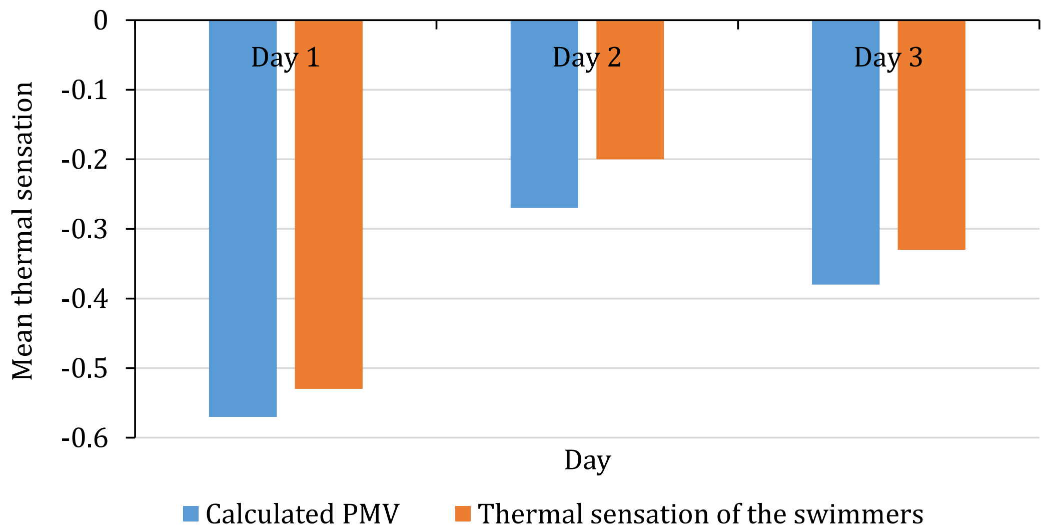


Figure 2.3: PMV and TS of the swimmers in Italy

2.2 Atmospheric environment (Indoor air quality)

The atmospheric environment, also known as indoor air quality is a general description of how clean the indoor air is. A higher amount of pollutants in the air leads to a worsening of the indoor air quality. This may have an impact on people, as well as on products and processes (e.g. laboratories). (Abel et al., 2003)

The atmospheric environment is affected by gases, smells, chemicals, and particles. Compounds generated from people (e.g. CO_2) and volatile compounds from the building and technical products are important factors considering the indoor air quality (Abel et al., 2003). For indoor swimming pools, chlorine used for cleaning the pool will also affect the indoor air quality. (Bøhlerengen et al., 2004). Perception of the atmospheric environment is influenced by the air temperature, humidity and the time spent in a room (Ingebrigsten, 2016).

There are several symptoms that may be due to bad air quality in swimming pools, especially the chlorine used for cleaning the pool. A study by Kaydos-Daniels et al. (2008) interviewed 128 people, where 32 of them stated three or more symptoms due to chloramine exposure, which is ammonia from people and by-products from chlorine used for cleaning the pool. As much as 84 % of the individual stated symptoms of cough, 78 % stated eye irritations, while 34 % had symptoms of rash.

2.3 Requirements for indoor climate in swimming pools

Depending on the building type, there are different laws and requirements for the indoor climate. Both TEK 17 and NS-EN 15251 have requirements that must be followed. However, the standards do not cover swimming pools. There are on the other hand recommendations from "Byggforsk", "Ventøk" and "Retningslinjer for vannbehandling i offentlig bassengbad", which are recommendations based on reasearch. According to Bøhlerengen et al. (2004), different water- and air temperatures are recommended depending on the type of pool. Recreational pools should have water temperatures between 28-34 °C, normal swimming pools 26-29 °C, while training pools should have water temperatures between 26-27 °C. The air temperature should be 2 °C higher than the water temperature to reduce evaporation, but should not exceed 34 °C. This will be discussed further in subsection 2.4.4. There are also different recommendations regarding how the ventilation system should be designed, this will be further discussed in Chapter 3.

2.4 Humid air

The humidity in swimming pools will be very high. Humidity is divided into relative and absolute humidity. This is primarily due to evaporation from the pool which is caused by convection. High relative humidity can cause condensation on the building construction.

2.4.1 Relative humidity

Relative humidity (RH), ϕ, is given as a percentage, and is the ratio of the amount of water in the air and the total amount of water the air can contain in a given temperature (Aaslund (2015)), and can be expressed by the formula under (Moran et al., 2012).

$$\phi = \left(\frac{p_v}{p_q}\right)_{T,p} \tag{2.13}$$

where

- p_v = partial pressure of the water vapour
- p_g = saturation pressure of the water vapour

2.4.2 Absolute humidity

Absolute humidity (AH), ω, is the ratio between the amount of water vapor per amount of dry air and can be expressed by the formula under (Moran et al., 2012).

$$\omega = \left(\frac{m_v}{m_a}\right) = 0,622\left(\frac{p_v}{p - p_v}\right) \tag{2.14}$$

where:

- m_v = mass of the water vapour
- m_a = mass of dry air
- p_v = partial pressure of the water vapour
- p = total pressure of the mixture

2.4.3 Convection

Convection is divided into forced and natural convection. The forced convection mechanism is due to air flows caused by the ventilation system and movement in the pool. Natural convection is due to molecular movements between the air and the water surface. The air right above the water surface becomes saturated. Heavier and drier air replaces the saturated air, and the process continues. If there is no air movement in the pool, this process will be very slow. However, in indoor swimming pools, both the ventilation system and movement due to people using the pool will cause air currents, which will speed up this process. (Shah, 2014)

2.4.4 Evaporation

Evaporation from the pool leads to very high humidity levels in the air, which causes heat loss from the pool and thereby increases the energy consumption.

Both natural and forced convection cause evaporation. In addition, the evaporation depends on the relative humidity in the air and the difference between the water and air temperature. To reduce the evaporation from the pool, the air temperature should be 2 °C higher than the pool water, and the relative humidity of the air should be around 65% in the summer and 50-55% in the winter. The temperature of the air should, however, not exceed 30-31 °C. (Bøhlerengen et al., 2004)

Shah, 2014 measured the evaporation from an unoccupied pool. Figure 2.4 shows the evaporation from the pool with a temperature of 27 °C, with different air temperatures and a relative humidity of 50% and 60%. The figure shows that the evaporation is reduced when the air temperature is increased relative to the pool temperature. The evaporation is also lower with a relative humidity at 60% compared to a relative humidity of 50%.

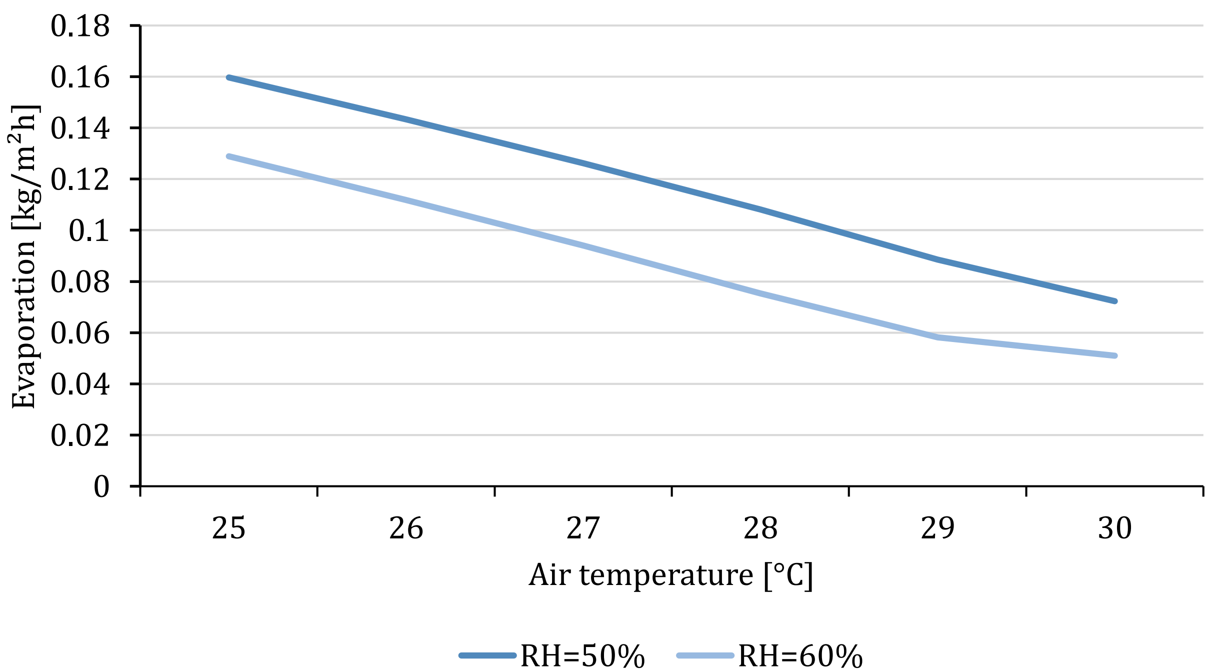


Figure 2.4: Evaporation from an unoccupied pool (Shah, 2014)

2.4.5 Condensation

Condensation can occur on inside surfaces and on windows as well as in the construction of the building and may cause a severe damage to the construction (Bøhlerengen et al., 2004).

Inner surfaces

Dehumidification solutions are important to control the humidity inside the room, but the inner surfaces still have to withstand a high relative humidity. The temperature of the inner surfaces should therefore be higher than the dew point temperature of the air. In this way condensation on the surfaces can be avoided. (Bøhlerengen et al., 2004)

Windows

High U-values and thermal bridges lead to condensation on windows. If the windows do not have sufficiently low U-values it is necessary to install supply diffusers beneath the windows and that the air touches the windows. (Bøhlerengen et al., 2004)

Inside construction

Conduction inside the construction of the building happens because of diffusion or convection (exfiltration) (Bøhlerengen et al., 2004).

Because of the evaporation from the pool, the water vapour pressure inside the swimming pool will usually be higher than the water vapour pressure of adjoining rooms and outside. A difference in the water vapour pressure causes water vapour to move from locations with higher pressure to places with lower pressure. In order to avoid diffusion, it is possible to install a vapour barrier or make sure that the temperature of the wall is less than the water vapour saturated temperature. (Bøhlerengen et al., 2004; Polak, 2008)

Condensation inside the building construction occurs when the humid air exfiltrates through the construction. This happens when humid air travels from a place with a higher air pressure to a place with lower air pressure. Because of higher inside temperatures than outside, an overpressure in the upper parts of the room will be established. To avoid a big pressure difference inside and outside, the air pressure inside the swimming pool should be reduced. This can be solved by extracting 10 % more air than is supplied. (Bøhlerengen et al., 2004)

3. Ventilation

This chapter presents the background theory for ventilation systems in swimming pools. It explains the concept of different ventilation types, and which types that should be utilized in buildings with swimming facilities. Further, this chapter also presents ventilation effectiveness and how to measure it with the use of tracer gas experiments.

3.1 Ventilation

The main purpose of a ventilation system is to supply fresh air and simultaneously remove contaminants as fast as possible (Skåret, 2000).

For buildings containing swimming pools, the humidity is very high due to evaporation from the pool. Chlorine is used for cleaning the pool and will be presented in the air. In addition, compounds generated from people will affects the atmospheric environment. Sufficiently ventilation is therefore necessary to control the humidity level and make sure that the air is sufficiently clean. (Bøhlerengen et al., 2004)

In the earlier years, the most common solution for dehumidification was to ventilate the moist air out and then supply the same amount of heated air. This is very energy consuming, as the latent heat from the evaporation gets lost. (Bøhlerengen et al., 2004)

Nowadays the most common solutions are to use heat exchangers or heat pumps. Swimming pools that are of a larger size than private pools, are normally build with air handling units (AHU) that ventilates, heats and dehumidifies the room air. (Bøhlerengen et al., 2004)

3.2 Requirements for swimming halls

When designing ventilation systems for normal buildings, requirements from TEK17 is normally used, where different factors of contaminants are considered. Buildings containing swimming pools have a very different climate than other buildings, and the requirements from TEK17 is therefore not suited for swimming pools. According to Bøhlerengen et al. (2004) recommended requirements for swimming pools are:

- 4-7 air changes per hour
- 1,4 l/s per m^2 (water surface and floor)
- 2,8 l/s per m^2 (water surface)

Recirculation of air in swimming pools is recommended because of very high energy consumption if only supplying fresh air. As long as the contaminants not are spread to adjoining rooms, recirculation of air is recommended. (Bøhlerengen et al., 2004)

3.3 Ventilation types

3.3.1 Mixing ventilation

Mixing ventilation is based on supplying air to the room with high velocity. The air is supplied in a distance from the occupied zone to avoid draft and simultaneously dilute contaminants. This ventilation type is the most common type, and can also be used for heating and cooling. (Novakovic et al., 2007)

Figure 3.1 illustrates mixing ventilation where V_S is the supplied air, C_a is the amount of allowed contaminants and S is supplied contaminants. t_s and t_a is supplied and extracted air, respectively.

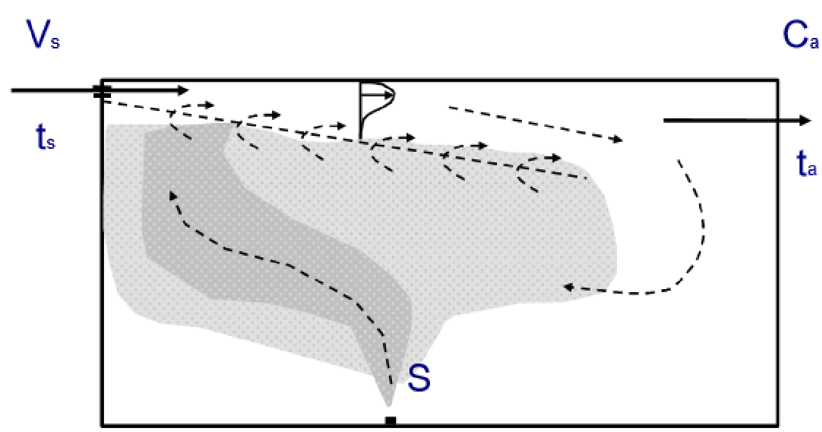


Figure 3.1: Principle sketch of mixing ventilation. Reused with permission from Hans Martin Mathisen

For indoor swimming pools mixing ventilation is the most common type. With mixing ventilation the temperature and the relative humidity will be relatively even throughout the whole room, which gives a risk of condensation in the ceiling. This can only be avoided if the ventilation system establishes an under pressure in the upper part of the room compared to the outdoors. (Tjelflaat, 1998)

To maintain a sufficiently under-pressure, infiltration of outdoor air will occur. Infiltration of outdoor air will increase the risk of draft, and the heating demand will therefore increase. (Tjelflaat, 1998)

To avoid this, an alternative solution is to utilize reversed displacement ventilation. This will be introduced in subsection 3.3.3.

3.3.2 Displacement ventilation

Displacement ventilation is when air with a lower temperature than the room air is supplied directly to the occupied zone. The exhaust is placed in the upper parts of the room. The supplied air gets heated up by the internal gains in the room and rises due to buoyancy effects. A stratification layer is established with the contaminated air in the upper parts and fresh and clean air in the occupied zone. (Skåret, 2000)

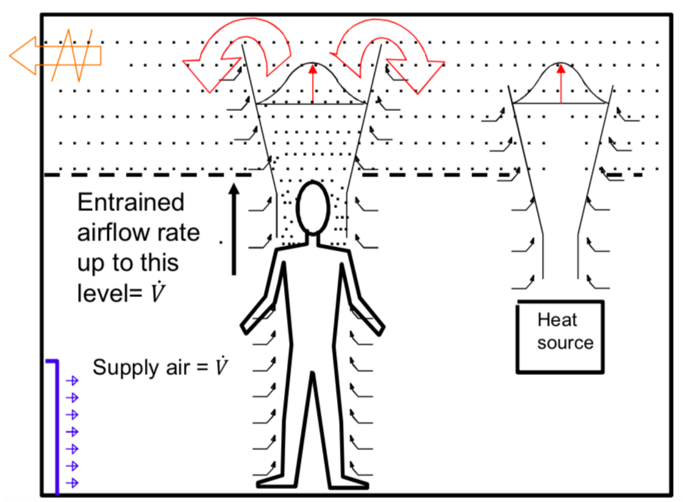


Figure 3.2: Principle sketch of displacement ventilation. Reused with permission from Hans Martin Mathisen

3.3.3 Reversed displacement ventilation

For swimming pools displacement ventilation is not a valid option as the environment is very humid, and the heated air that rises will contribute to an overpressure in the room. As mixing ventilation gives a risk of condensation in the ceiling, an alternative solution can be reversed displacement ventilation. By supplying hot dry air beneath the ceiling with exhaust valves placed in the lower parts of the room, the risk of condensation can be reduced. (Tjelflaat, 1998)

The dry hot air supplied will be cooled down by the cold surfaces inside the building, and gets heavier while it seeps downwards. As the air is dry there will not be any condensation on the inside surfaces. The "cold" air that enters the lower parts of the room has a lower temperature than the air in the room and works on the same principle as displacement ventilation. The air blends with the humid air over the pool so the air in the occupied zone gets an acceptable humidity level. The exhaust diffusers are placed in the lower parts of the room so the water vapour is extracted before it blends with the room air. (Tjelflaat, 1998)

A study by Per Olaf Tjelflaat (Tjelflaat, 1998) investigated this concept in 1998 to see if it was possible to utilize displacement ventilation at Pirbadet swimming pool in Trondheim. By CFD-simulations of the pool, he concluded that this could be a good solution for Pirbadet.

Buffer zone

With reversed displacement ventilation, overheated air is supplied below the ceiling while the exhaust diffusers are placed in the lower parts of the room. The strategy with reversed displacement ventilation is that the overheated air forms a buffer zone under the roof with dry light air. The humid air from the pool will be colder and more humid than the air supplied beneath the roof. It is crucial that the air from the pool is heavier so it does not "break through" the buffer zone. If some of the air exfiltrates through the ceiling, it will be dry and condensation in the ceiling will not occur. (Tjelflaat, 1998)

To achieve this it is essential that the supplied air has adequatly low RH to avoid exfiltration which can lead to condensation inside the walls. It is also important that the supplied air has sufficiently low density, as the temperature is very high. In this way the humid air above the pool will not be able to "break through" the dry air, and a buffer zone is established under the roof. (Øiene Smedegård, 2017)

Figure 3.3 shows the correlation between density and temperature. The temperature difference between the overheated supplied air and the humid air above the water surface should be minimum 5 °C (Øiene Smedegård, 2017).

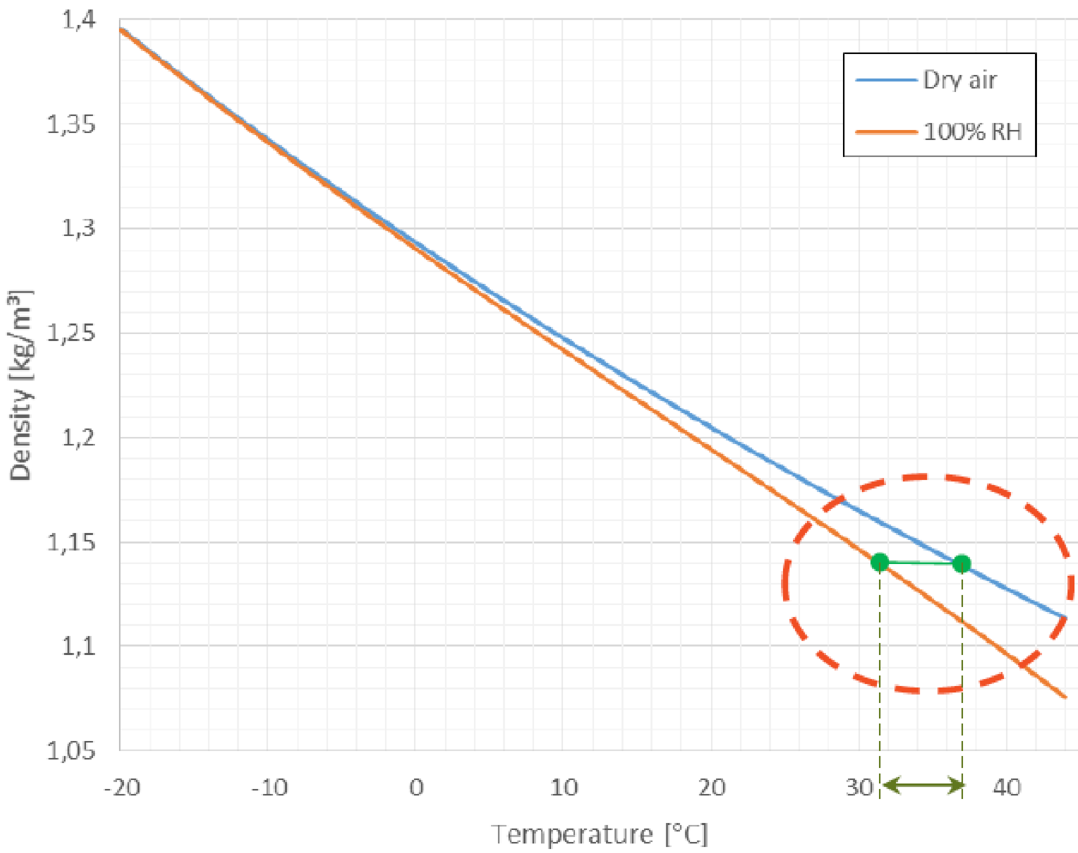


Figure 3.3: Correlation between temperature and density og air. Reused with permission from Ole Øiene Smedegård

Short-circuiting of ventilation air

When utilizing the principle of reversed displacement ventilation there might be a risk of short-circuiting of air. Short-circuiting of air is when the supplied air goes straight to the exhaust (Ingebrigsten, 2016). If the stratification layer, which is the layer between the humid air above the pool and the hot air supplied, is below the exhaust, a short circuit of air will occur (Øiene Smedegård, 2017). This is not beneficial as this will reduce the ventilation efficiency (Ingebrigsten, 2016). This can be avoided by reducing the height of the exhaust grille.

3.4 Ventilation effectiveness

The purpose of a ventilation system is to remove contaminants from the air, and to supply new fresh air into the room (Mundt et al., 2004). As ventilation systems are expensive to build and run, it is important to ensure that the ventilation system is working properly (Grieve, 1989).

To determine the effectiveness of the ventilation system, there are to ways (Mundt et al., 2004):

- Contaminant Removal Efficiency (CRE), ε^c, is used to determine how fast the contaminants in the room are removed
- Air Change Efficiency, ε^a, is used to determine how fast the air is changed

There are also local values (Mundt et al., 2004):

- Local air quality index, ε_P^c, is used to determine the local concentration in a particular point P
- Local air change index, ε_P^a, is used to determine the characterisation of the air change rate in a point P

3.4.1 Age of air

To determine the ventilation effectiveness, tracer gas measurements must be conducted, and the concentration of the tracer gas must therefore be in relation to the age of air (Ingebrigsten, 2016). Figure 3.4 illustrates the age of air. Tracer gas measurements will be introduced in section 3.5.

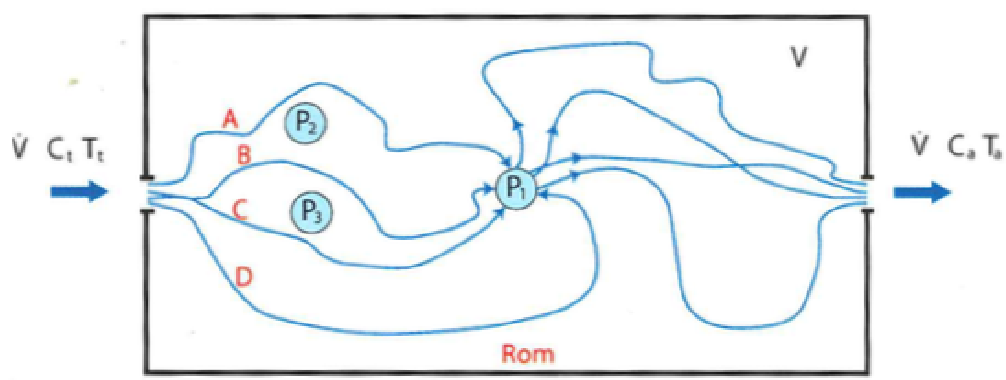


Figure 3.4: The age of air. Reused with permission from Skarland Press (Ingebrigsten, 2016)

The mean age of air in point P_1 is given by (Ingebrigsten, 2016):

$$\bar{t}_{P1} = \frac{t_A + t_B + t_C + ...}{\text{number of molecules}} \tag{3.1}$$

where:

- t_A = time elapsed for molecule A from entering the room to point P_1
- t_B = time elapsed for molecule B from entering the room to point P_1
- t_C = time elapsed for molecule C from entering the room to point P_1

For a fully mixed flow, the age of air will be equal in the entire room (Mundt et al., 2004).

Local mean age of air

The local mean age of air, $\overline{\tau}_P$, is the mean time elapsed for the air from entering the room to reach a specific point (Mundt et al., 2004).

Room average age of air

The room average age of air, $\langle\overline{\tau}\rangle$, is the mean age of the air in the whole room (Mundt et al., 2004).

Nominal time constant

The average age of the exhaust air, also known as the nominal time constant, is given by (Mundt et al., 2004):

$$\tau_n = \frac{V}{q_v} \tag{3.2}$$

where:

- V = Room volume [m^3]
- q_v = Airflow [m^3/s]

3.4.2 Contaminant removal effectiveness (CRE)

The contaminant removal effectiveness (CRE), ε^{c}, is one way to evaluate the efficiency of the ventilation system. The CRE tells how fast the air-borne contaminants are removed. The efficiency is measured by how long it takes to remove all the contaminants in the room. The CRE is defined as the ratio of the concentration of contaminants in the exhaust air and the mean concentration in the room. (Mundt et al., 2004)

The CRE can be expressed by the formula below (Mundt et al., 2004):

$$\varepsilon^{\mathrm{c}} = \frac{c_{\mathrm{e}}}{\langle c \rangle} \tag{3.3}$$

where

- c_e = concentration in the exhaust air
- $\langle c \rangle$ = mean concentration in the room

The local air quality index indices the local concentration of contaminants in a given point, and is given by (Mundt et al., 2004):

$$\varepsilon_P^c = \frac{c_{\mathrm{e}}}{c_{\mathrm{P}}} \tag{3.4}$$

where:

- c_e = steady state concentration of contaminant at the exhaust air
- c_P = steady state concentration of contaminant in point P

3.4.3 Air Change Efficiency

Another way to evaluate the ventilation effectiveness is the air change efficiency. The air change efficiency, ε^{a}, tells how fast the air in the room is replaced according to what is theoretically conceivable. It is defined as the ratio between the shortest air change time that is achievable (the nominal time constant) and the real air change time. (Mundt et al., 2004)

The air change efficiency can be determined by the formula below (Mundt et al., 2004):

$$\varepsilon^a = \frac{\tau_\mathrm{n}}{\overline{\tau}_\mathrm{r}} \cdot 100 = \frac{\tau_\mathrm{n}}{2\langle\overline{\tau}\rangle} \cdot 100[\%] \tag{3.5}$$

where:

- ε^a = air change efficiency
- τ_n = nominal time constant
- $\overline{\tau}_\mathrm{r}$ = actual air change time
- $\langle\overline{\tau}\rangle$ = room mean age of air

The local air change rate indices the concentration of contaminants in a given point P, and can be expressed by (Mundt et al., 2004):

$$\varepsilon^a_P = \frac{\tau_\mathrm{n}}{\overline{\tau}_P} \tag{3.6}$$

where:

- $\overline{\tau}_\mathrm{P}$ = local mean age of air at point P

The air change efficiency is dependent on the type of flow. The highest value that can be reached is 100 %, and can only be attained with ideal piston flow. For fully mixed flow the air change efficiency is 50%, while for displacement it is between 50 % and 100 %. However, if the air change efficiency is below 50%, there might be short-circuiting of air. (Mundt et al., 2004).

3.4.4 What measures to utilize

If the position of the contaminant sources is known, the CRE should be utilized and the focus should be on removing the contaminants locally (Mundt et al., 2004).

Otherwise, the aim should be on the air chance efficiency, which also provides the most knowledge about the efficiency of the ventilation system. For larger spaces, the focus should be on local values for air exchange. (Mundt et al., 2004)

3.5 Tracer gas method

By performing tracer gas measurements, the ages of air and the nominal time constant can be determined (Ingebrigsten, 2016; Mundt et al., 2004).

The tracer gas used has to be non-toxic and should not be presented in the room as it can influence the measurements (Mundt et al., 2004). Gases normally used are hexaflouride (SF_6), carbon dioxide (CO_2) or nitrous oxide (N_2O) (Ingebrigsten, 2016).

Common tracer gas methods are: (Mundt et al., 2004; Ingebrigsten, 2016):

- Tracer step-down (Decay) method: A constant concentration of tracer gas in injected into the room until it reaches a constant concentration C_1 at time t_0. The time until the tracer gas decays to a concentration C_2 is measured.
- Tracer step-up method: The measurements starts without a concentration C_1. The time is measured until a concentration C_2 is reached.
- Pulse method: A known amount of tracer gas is injected into the room in pulses. The amount of tracer gas is measured in either a point in the room or in the exhaust air.
- Homogeneous constant emission method (Active or passive methods): A known amount of tracer gas is injected in to the room until a constant concentration is attained in the exhaust air.

3.5.1 Tracer step-down (Decay) method

For the step-down method, the tracer gas is spread into the room until it is thoroughly mixed with the air. The concentration of tracer gas should equal the concentration c_e in the exhaust air at time t=0. Due to the air flow from the ventilation system the tracer gas decays, and the age of air can be measured either in a point or in the exhaust. (Mundt et al., 2004)

The step-down method is not suitable for small air changes rates.

3.5.2 Tracer step-up method

For the tracer step-up method the tracer concentration is injected into the room at time t=0 in a constant and continuous flow, and as the tracer gas increases the air change efficiency or the contaminant removal effectiveness can be evaluated. Depending if the air change efficiency or the contaminant removal effectiveness is measured, the gas should be injected in the supply duct or in a point in the room, respectively. (Mundt et al., 2004)

3.5.3 Analysers

To measure the ventilation effectiveness, measurement devices are needed. Several devices are possible to use, and the most common ones are (Mundt et al., 2004):

- Infrared absorption (IR)
- Electron capture detector
- Mass spectrometer (MS)
- Thermal conductivity detectors (TCD)
- Photo ionisation detectors (PID)

3.5.4 Calculating ventilation effectiveness from measured concentrations

Mundt et al. (2004) presents a procedure to calculate the air change efficiency by measuring the concentrations:

1. Draft a logarithmic plot as a function of time with the use of the measured concentrations. If the concentration of the contaminants is fully mixed, it will start with a straight line, if there is a delay there will be a inital elapse before the straight line. With lower concentrations the line will be irregular because of disturbances from the analysers. The irregular part should not be part of the analysis. Indicate the last concentration c_n that can be used.
2. Calculate the slope of the curve where the line is "straigth". The slope is utilized for extrapolation from measurement n to infinity, which is referred to as the tail of the curve.

3. The ventilation efficiency can be calculated by the following equations.

Figure 3.5 shows an illustration of the step-up and step-down method.

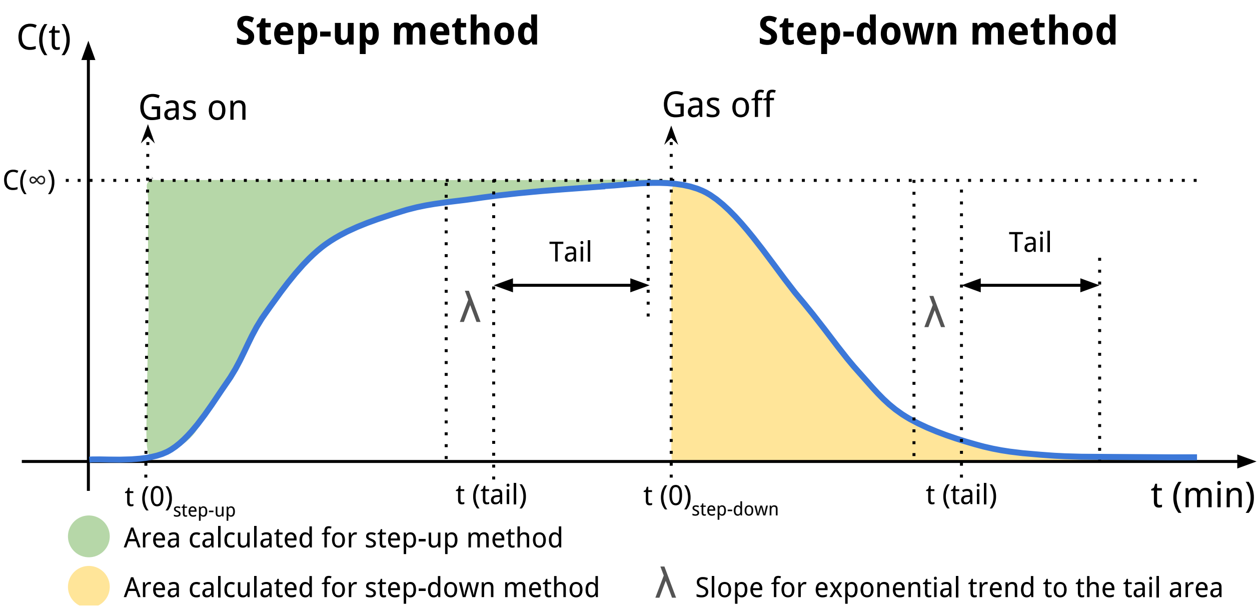


Figure 3.5: Illustration of the step-up and step-down method. Reused with permission from Odin Budal Søgnen (Søgnen, 2015)

Equations for the step down method

The room mean age of air is equivalent to the weighted area under the graph, and can be calculated with the following equation (Mundt et al., 2004):

$$\langle \overline{\tau} \rangle = \frac{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \cdot \frac{t_i + t_{i-1}}{2} \right] + \frac{c_n}{\lambda} \cdot \left[\frac{1}{\lambda} + t_n \right]}{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c_n}{\lambda}} \tag{3.7}$$

where:

- c = concentration of the tracer gas in a given point
- λ = absolute value of the slope
- t = time

The nominal time constant can be expressed as (Mundt et al. (2004)):

$$\tau_n = \frac{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c_n}{\lambda}}{c_0} \tag{3.8}$$

where:

- c_0 = start concentration of the tracer gas

The air change efficiency can then be calculated with the use of equation 3.7 and 3.8:

$$\varepsilon^a = \frac{\tau_n}{2 \cdot \langle \overline{\tau} \rangle} \cdot 100\% \tag{3.9}$$

The local mean age of air can be calculated with the following equations (Mundt et al., 2004):

$$\overline{\tau}_p = \frac{\sum_{i=1}^{i=n} \left[\frac{c_i + c_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c_n}{\lambda}}{c_0} \tag{3.10}$$

where c indicates a concentration at a point P in the room.

Equations for the step up method

For the step up method, the room mean age of air is equivalent to the area over the graph and can be calculated with the use of the same equations as for the step down method, but by introducing the concentration c', defined as c'=[c(∞)-c]. By substituting this into Equation 3.7 and 3.8, the equations for the step up method will become:

$$\langle \overline{\tau} \rangle = \frac{\sum_{i=1}^{i=n} \left[\frac{c'_i + c'_{i-1}}{2} \cdot (t_i - t_{i-1}) \cdot \frac{t_i + t_{i-1}}{2} \right] + \frac{c'_n}{\lambda} \cdot \left[\frac{1}{\lambda} + t_n \right]}{\sum_{i=1}^{i=n} \left[\frac{c'_i + c'_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c'_n}{\lambda}} \tag{3.11}$$

$$\tau_n = \frac{\sum_{i=1}^{i=n} \left[\frac{c'_i + c'_{i-1}}{2} \cdot (t_i - t_{i-1}) \right] + \frac{c'_n}{\lambda}}{c_\infty} \tag{3.12}$$

where:

- $c(\infty)$ = constant concentration at infinite time

The local mean age of air is calculated the same was as Equation 3.10 for the step down method.

3.6 Field experiments in swimming pools

As introduced in Section 3.2, recirculation of air in swimming pools is necessary to supply enough air and on the same time keep the energy consumption at an acceptable level. When doing a tracer gas experiment in a building where some of the air is recycled, a big part of the tracer gas that is extracted will be supplied back into the pool. Most studies done on ventilation effectiveness are done in buildings without recirculation of air.

Mathisen et al. (1990) conducted fields experiments in a swimming pool in Trondheim in 1990. The swimming pool had an area of 72 m^2, with measures 12 m x 6 m. The volume of the room including the pool was 365 m^3. The ventilation air was supplied by diffusers below the windows, and the exhaust was located beneath the ceiling. The air handling unit recycled air and included a filter and an electric heating coil. The heating coil ensured a constant air temperature, while the damper for air recycling ensured a constant relative humidity in the room. It is, however, important to state that this is a swimming pool built in 1977, and the dehumidification was only based on supplying outdoor air.

One tracer gas experiment and one air velocity measurement was conducted at the site. The air velocity was measured at different points above the pool by making a grid of 21 measuring points. The air velocity varied from 0.086 m/s to 0.266 m/s, with an average value of 0.16 m/s. The tracer gas experiment showed by injecting the gas in the supply air and measure the concentration in the exhaust, that the ventilation system had a displacement effect, and thereby the ventilation air was exploited efficiently.

4. Jøa swimming pool

Jøa swimming pool is located at Jøa in Fosnes kommune in Trøndelag. It is a multipurpose sports hall that consists of among other things a swimming pool, sports hall, library, café, and gym. The swimming pool is designed to be a recreational facility for the population of Jøa. The swimming pool was opened in January 2017, and has an innovative and advanced HVAC system.

This chapter presents the building, how the HVAC-system is designed, and how the system actually is working compared to how it is designed.

4.1 Climate and location of Jøa

Jøa is located 64.6°N, 11.2°E, 65 meter above mean sea level. Figure 4.1 shows the global location of Jøa.

Figure 4.1: Location of Jøa (Google Maps, 2018)

As Jøa is located at the coast, the weather is both cold and windy. The design temperatures are:

- Winter condition -18 °C
- Summer condition 22.5 °C @ 60% RH

Besides the low temperatures during the winter, the wind has a big impact on both indoor climate and energy consumption. The façade of the building is facing the north. Both the north and west façades are exposed to wind.

4.2 Design of the swimming pool

The swimming hall is designed after the Norwegian passive house standard NS 3701 (Norsk Standard NS 3701, 2012), and thereby the construction has very low U-vales, and low infiltration and exfiltration.

- Windows 0.8 W/m^2K
- Façade 0.2 W/m^2K
- Roof 0.09 W/m^2K
- Leakage 0.6 ach (50 Pa)

At design conditions the dew point temperature is approximately 20 °C (Øiene Smedegård, 2017). If surfaces have a lower temperature than the dew point, there might be a risk of condensation.

The volume and area of the room containing the swimming pool is 1090 m^3 and 266 m^2, respectively. The pool has an area of 100 m^2, with measures of 12.5 m x 8 m.

Table 4.1: Design parameters

	Temperature [°C]	**Relative humidity [%]**
Water	34	
Indoor air	31	60
Supply air	36	40

Because of different users of the pool, both grown-ups and children, the pool is constructed with an adjustable floor. During the time when the pool is unused, the floor works as a pool cover. This reduces the evaporation, and thereby the energy consumption. The lifeguard is placed in a separate room with a window facing the swimming pool. From this room, the floor can be adjusted to the desired height.

4.3 The HVAC-system

The heating of both the pool water and the air, ventilation, and dehumidification are all combined in one air handling unit.

4.3.1 Heating

Heating of both the pool water and the air is covered by heat that is recovered from the exhaust air by an integrated heat pump. For the pool water, the temperature is maintained by a closed heating circuit where the heat is supplied by the recovered heat.

The integrated heat pump also dehumidifies the air when the humid air gets in contact with the evaporator of the heat pump.

For additional heating, a ground-source heat pump utilizing CO_2 as working fluid heats up water in a heat distribution system. A heat exchanger connected to the heat distribution system serves as peak load for the pool water.

4.3.2 Ventilation system

The ventilation system is designed on the principle of reversed displacement. The air is supplied beneath the ceiling with textile diffusers. Supply diffusers are placed below the windows, and was supposed to serve as "security-diffusers" in case of condensation on the windows, but as the system is operated today they are in constant use. The exhaust grille is placed 0.7-2.7 metres above the floor.

Figure 4.2 illustrates how the ventilation system is designed. The purple duct is the outdoor air supply, while the orange duct is the return air. The blue ducts are the supply air into the pool, where both fresh- and recirculated air supplied. The green box is the exhaust air from the pool. The grey box is the air handling unit delivered from Menerga, where heat from the exhaust is recovered by an integrated heat pump. This is also where the air is dehumidified. The unit is delivered by Menerga, which is a well know manufacturer for AHU- and HVAC units of swimming pools. Figure 4.3 shows the swimming pool and the supply textile diffusers beneath the ceiling.

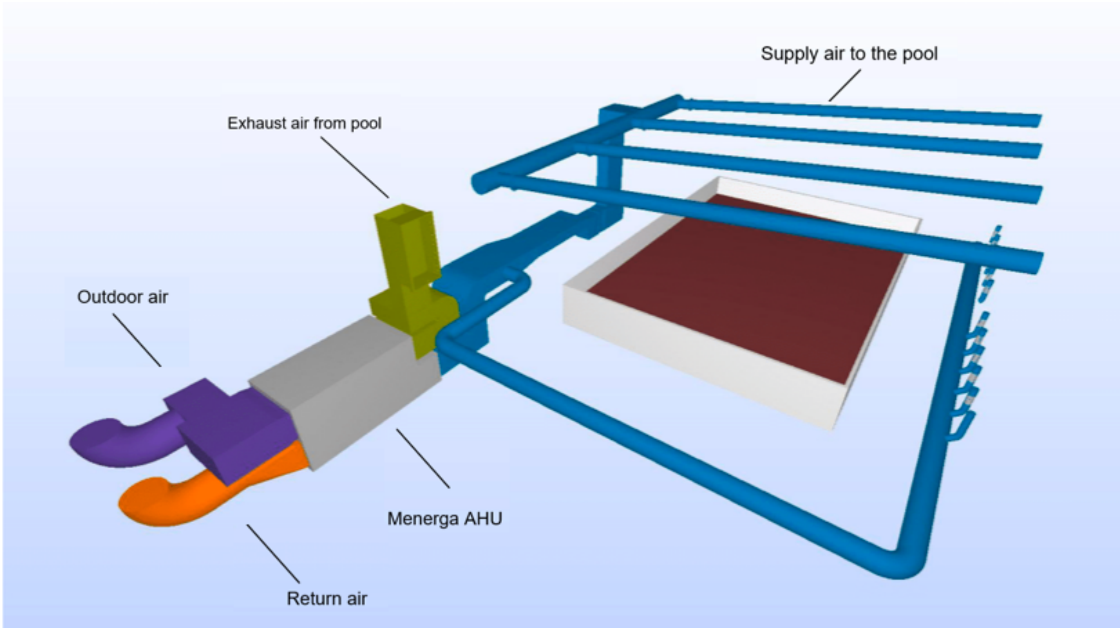


Figure 4.2: 3D-picture of the ventilation system

Figure 4.3: Jøa swimming pool. Photo: Julie Jørgensen

Table 4.2 shows the initial boundary conditions for the ventilation system.

Table 4.2: Initial boundary conditions

	Supply	**Exhaust**
Air temperature [°C]	36	31
Relative humidity [%]	40	60
Flow rate [m^3/h]	7000	8000

To establish an under-pressure in the room, the air handling unit is designed to extract 1000 m^3/h more than it supplies. However, after observing the central processing system, it was detected that this is not the case. The air handling unit extracts more than it supplies but on average only about 300 m^3/h. The amount of supply and exhaust air also vary a lot during the operation time of the ventilation system. The outdoor air flow also varies a lot depending on the humidity level in the exhaust from the pool. It was detected that the outdoor air supply is controlled by the humidity level in the exhaust. The humidity could reach 63% before the dampers for outdoor air were opened.

4.3.3 Buffer zone

When designing the system, it was desired that the buffer zone should be established to protect the building envelope against condensation. As introduced in subsection 3.3.3 the temperature difference between the overheated supplied air and the humid air above the water surface should be minimum 5 °C.

As the case is now the supplied air temperatures differs a lot during the operation time, with an average value of around 38.6 °C. Measurements conducted during the field trip to Jøa showed temperatures above the pool to be between 30 and 32 °C.

4.3.4 Air flow

The heating, ventilation and air condition (HVAC) system of Jøa is very special. The pattern of the air flow is influenced by many factors, and is important for the indoor climate as well as the risk of condensation in the building structure. The air flow pattern is influenced by the pressure difference caused by extracting more air than supplying. Natural convection due to the temperature difference between surfaces and air, as well as density difference due to evaporation from the pool, are also important factors that influences the air flow pattern. (Øiene Smedegård, 2017)

Figure 4.4 shows the anticipated airflow pattern in the swimming pool.

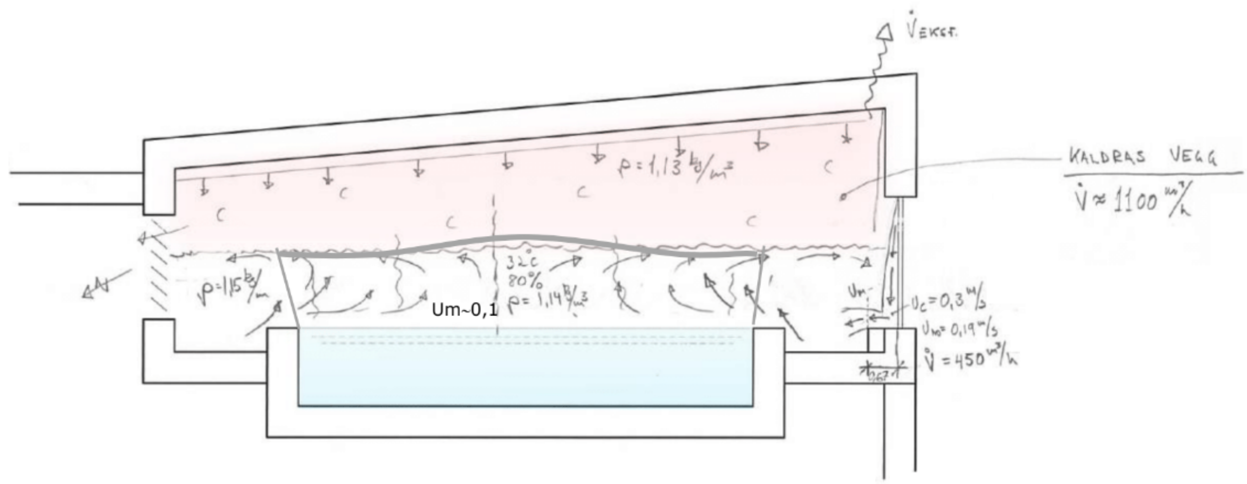


Figure 4.4: Anticipated airflow pattern. Reused with permission from Ole Øiene Smedegård

4.3.5 The current system

A recent evaluation of the performance of the ventilation system was conducted by Ole Øiene Smedegård (Øiene Smedegård, 2017). It was stated that the performance of the ventilation system deviates from how it is designed. The supply diffusers beneath the windows are not only serving as "security-diffusers" as they are in use during the whole operation time.

When the buffer zone is established, there is a possibility of short-circuiting of air between the supply- and exhaust air. If this happens the occupancy zone will not be supplied with a sufficient amount of fresh air. This is one of the main objectives for the field experiments and will be further discussed in Chapter 6.

5. Methodology

The field work was conducted at the swimming pool at Jøa. Three tracer gas experiments were carried out with different operations of the ventilation system. Prior to each experiment, the air velocity and temperature over the swimming pool were measured. To measure the temperature continuously iButtons were placed at different points on the walls of the swimming pool, see Appendix A.2 for futher information about iButtons. In addition, one smoke experiment was carried out in order to analyze the air flow pattern in the room is.

5.1 Tracer gas experiments

Three different tracer gas experiments were carried out at the site:

- Experiment 1: Ventilation system manipulated to supply at least 1 ach of fresh air
- Experiment 2: Normal operation
- Experiment 3: Ventilation system manipulated to supply at least 1 ach of fresh air. The height of exhaust grille was reduced from 2 m to 0.7 m. This was carried out due to a suspicion of short-circuiting of air.

5.1.1 Principle of tracer gas method

As mentioned in subsection 3.4 there are several methods that can be applied when conducting a tracer gas experiment. In this case, a total of six experiments were carried out, three step-up methods followed by the step down-method. The gas was injected into the desired location with a plastic tube connected to a rotameter (Vögtlin V-100) to obtain a constant flow of tracer gas. When the desired concentration was reached, the gas flow was turned off. Figure 5.1 illustrates the set-up of the equipment.

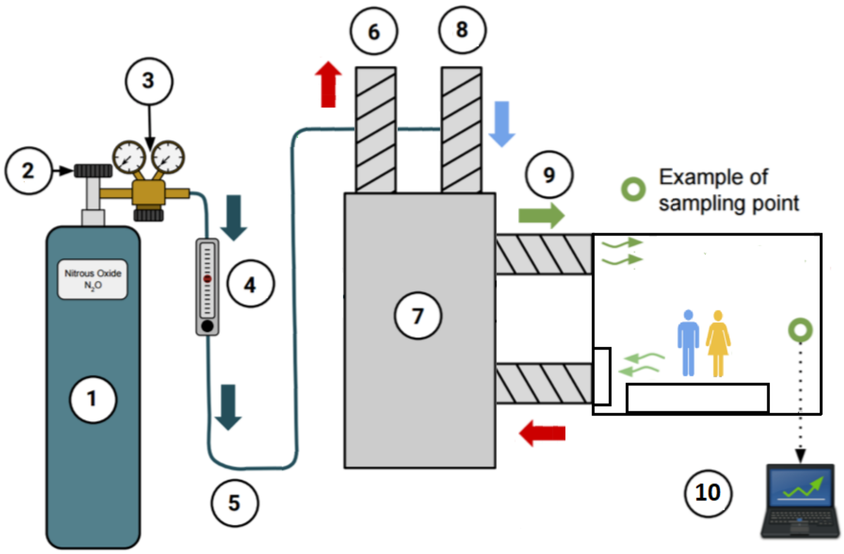


Figure 5.1: Set-up for the tracer gas experiment. Figured based on illustration by Søgnen (2015)

1. Gas bottle with Nitrous Oxide (N_2O)
2. Valve
3. Manometer for pressure control
4. Rotameter for controlling the gas flow rate
5. Plastic tubes for injecting the gas
6. Return air
7. Air Handling Unit - exhaust air from the pool is recirculated back into the supply
8. Outdoor air intake
9. Supply air (both fresh and recirculated air)
10. Computer for analysing the concentration in different sampling points

5.1.2 Method

The tracer gas equipment was placed in the technical room at the floor below the swimming pool. For experiment 1 and 3, the tracer gas was injected into the fresh air supply. For experiment 2 the tracer gas was injected into the supply air to the pool, where both recirculated and fresh air was supplied to the room. Six plastic tubes were stretched from the machine to the desired sampling points, both in the room and in the ducts. Figure 5.2 shows the sampling points (red dots) placed inside the room with the pool, which were the same for all of the three experiments. The height of the two sampling points were 1.2 m above the floor and 30 cm above the pool, for point 1 and 2, respectively. These sampling points were selected on the basis of suspicion of a "dead zone" in the corner of the pool, and that the occupancy zone above the pool was not sufficiently ventilated. The four remaining sampling points were placed in separate places in the duct; the fresh air supply, supply air to the pool, exhaust from the pool and the return air. For experiment 2 one sampling point was placed in the fresh air supply, to investigate if there was a leakage from the exhaust air to the supply air. The tracer gas used was Nitrous Oxide (N_2O), see appendix A.3.2 for properties of the gas.

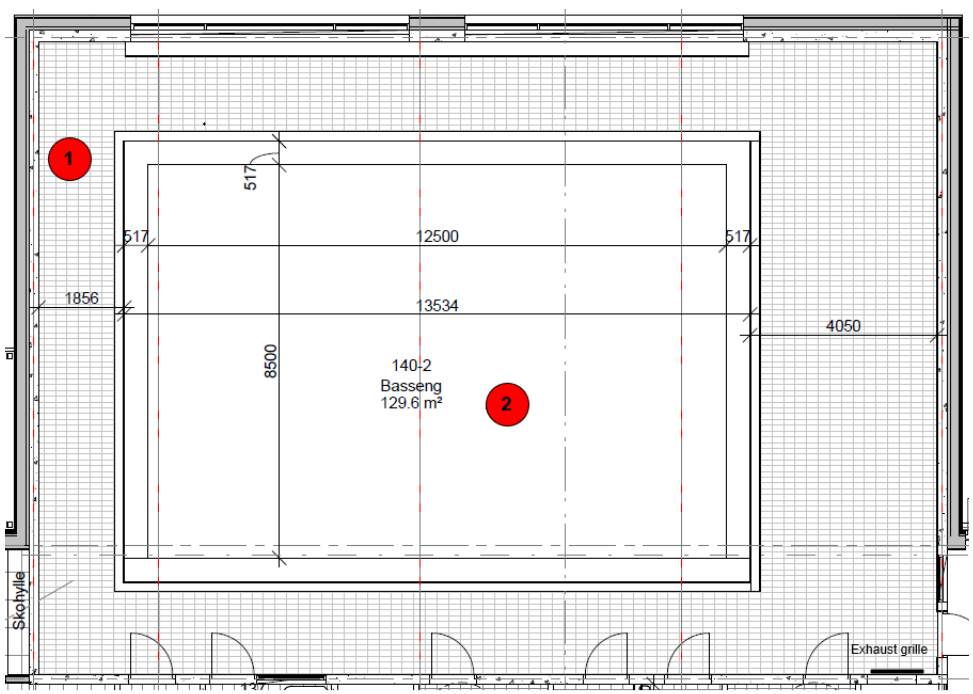


Figure 5.2: Sampling point 1 in the corner of the room and samling point 2 above the pool (red dots)

Figure 5.3 and 5.4 illustrates the placing of the sampling points (red dots) and injection of tracer gas (blue dot) in experiment 1 and 3, and 2, respectively.

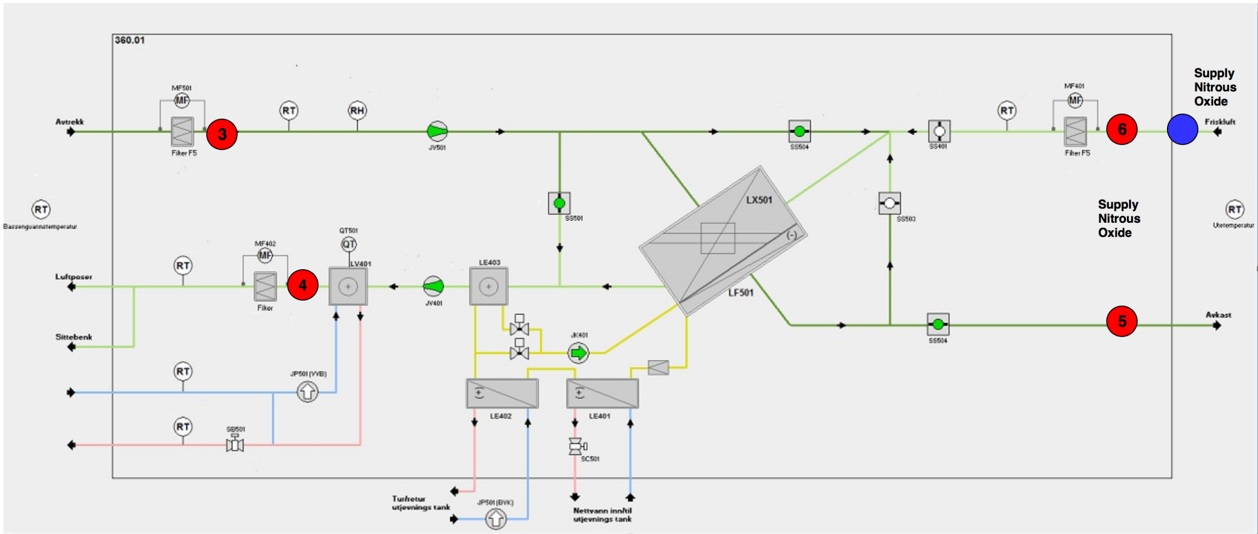


Figure 5.3: Sampling points in the ventilation ducts during experiment 1 and 3

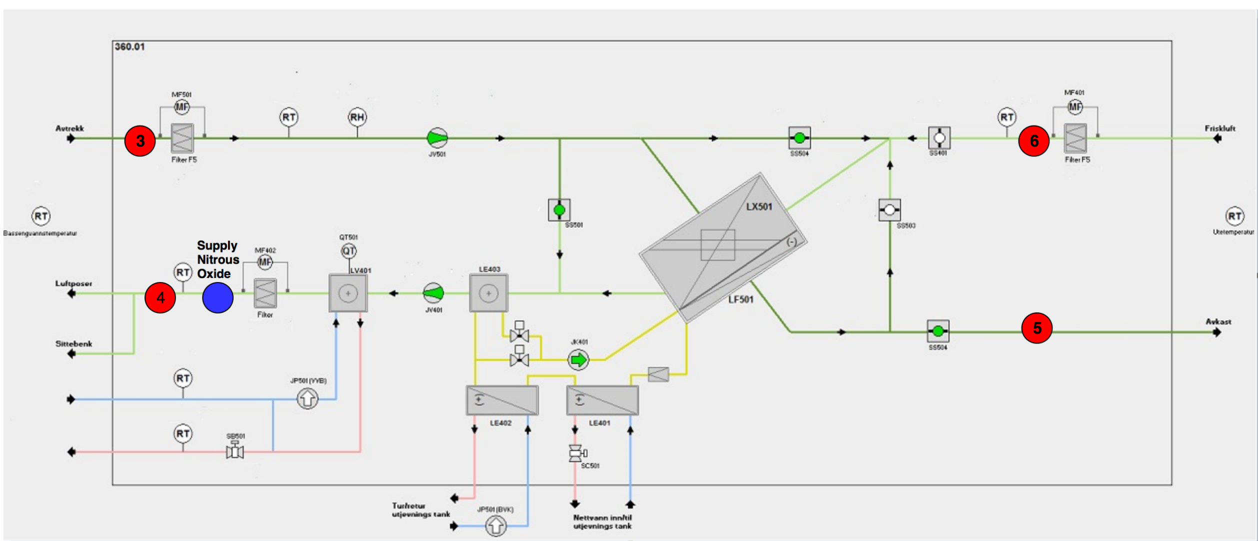


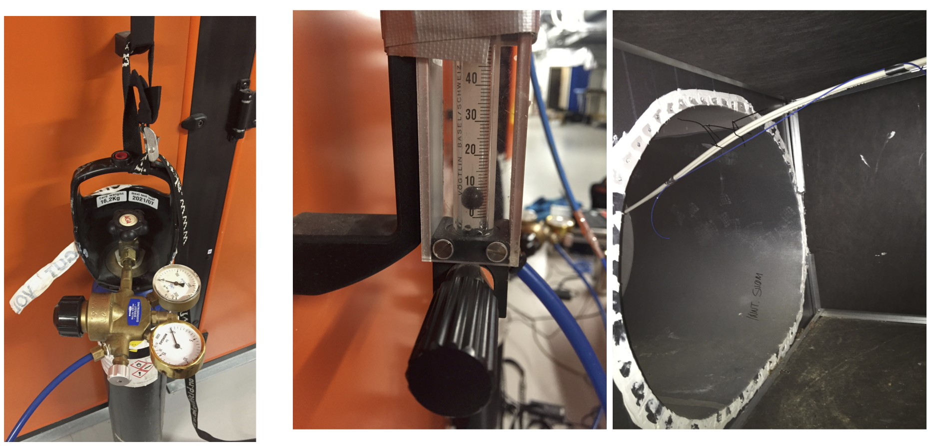
Figure 5.4: Sampling points in the ventilation ducts during experiment 2

Figure 5.5 shows the set up of the tracer gas equipment. The gas bottle was safely secured. The rotameter controlled the flow rate of the gas, to maintain a constant flow. The desired concentration of tracer gas was set to 25 ppm. In order to maintain the desired concentration of 25 ppm, the following equation was used to calculate the flow rate of the gas:

$$\dot{V}_{tg} = c_{tg} \cdot 10^{-6} \cdot q_v \ \ \mathrm{m^3/h} \tag{5.1}$$

where:

- c_{tg} - desired concentration of tracer gas
- q_v - air flow rate



(a) Gas bottle secured **(b)** Rotameter **(c)** Supply of gas

Figure 5.5: Tracer gas set-up

During experiment 1 and 3, the ventilation system was manipulated to supply an amount of minimum 1 ach of fresh air, which equals 1500 m^3/h. With a desired concentration of 25 ppm, the flow rate was calculated to 0.0375 l/min. As the rotameter is designed for air, it was necessary to find the ratio between the molar mass of nitrous oxide and air. The conversion factor was calculated to 1.57, which equals a flow rate of 0.98 l/min of Nitrous Oxide.

For the second experiment, the ventilation system was running under normal conditions, which made it harder to calculate the correct flow rate of gas. The same flow rate was therefore used for this experiment as well.

5.2 Velocity and temperature measurements above the swimming pool

Prior to each of the three tracer gas experiments, the air velocity and temperature were measured at 16 different points over the pool. A grid of 16 points was drawn up over the pool to make it easier to keep track of the different sampling points. A Swema 3000 anemometer was used to measure the air velocity and temperature, see Appendix A.1 for further information about the equipment. As the grid was over the pool, the anemometer had to be attached to a long pole to reach all of the points. For each measurement, the velocity and temperature were stabilized before it was read off the device.

Figure 5.6 shows all the 16 points where the air velocity and temperature were measured. For all of the three measurement sets, point number 7 had the lowest velocity and was therefore the reference point for the sampling of the tracer gas concentration above the pool.

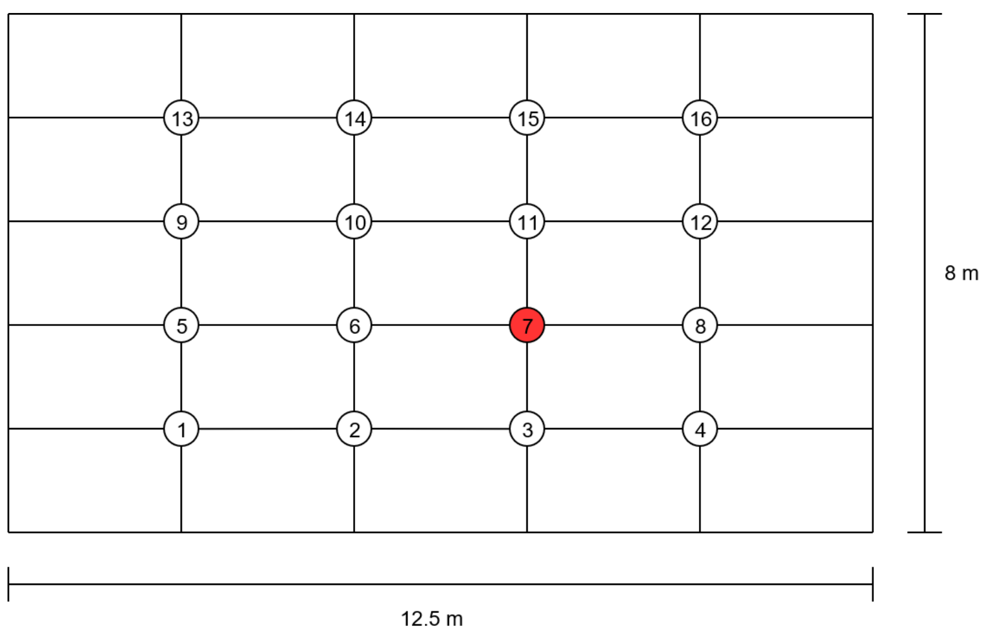


Figure 5.6: Grid over pool

5.3 Temperature measurements

For continuous temperature measurements, iButtons were placed on the walls of the swimming pool. An iButton is a thermometer that measures the temperature digitally, and saves the recorded data (Maxim Integrated, 2018). Each iButton has its own unique address and was marked with a number to keep track of the placement. The temperature range of the iButton is from -40 °C to +85 °C, with an accuracy of ± 0.5 °C (iButtonLink, 2018). See Appendix A.2 for further information. A total of 44 iButtons were placed at a height of 1.7 m for odd numbers and 1.1 m for even numbers. Figure 5.7 shows the placing of all of the iButtons (red dots). The temperature logging started April 19th 14.30 and lasted until April 20th 09.30. The iButtons logged the temperature every ten minutes. After finishing the measurements the iButtons were taken down and the temperature loggings were transmitted to a laptop with the use of an USB adapter.

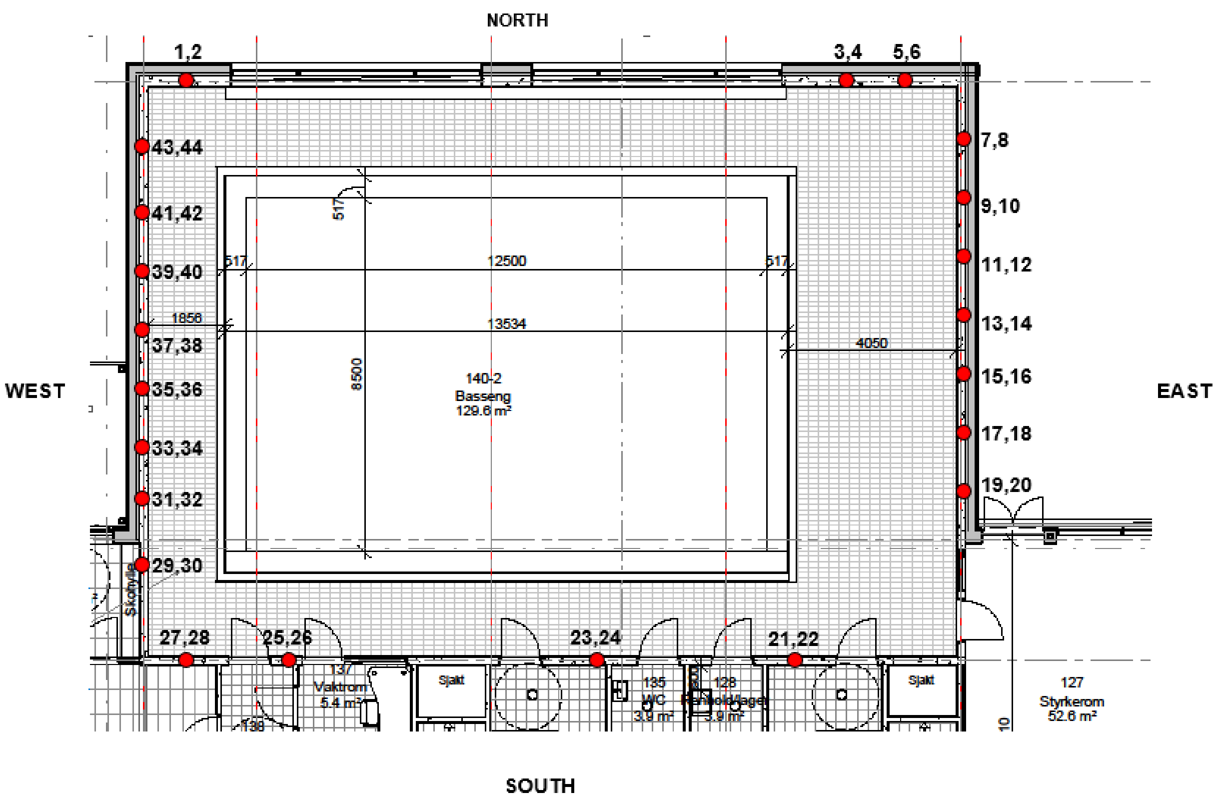


Figure 5.7: Placement of iButtons (red dots)

5.4 Smoke visualization

The smoke experiment was conducted after the tracer gas experiment with a minimum of 1 ach of fresh air and reduced size of the exhaust grilles. For the smoke experiment, a smoke machine was placed in the air handling unit. The smoke utilized for the experiment was Pro Smoke Super, which is a medium density smoke normally used for clubs and theatres (HARMAN, 2018). The smoke was injected into the room by the ventilation system, and by observing the smoke distribution in the room, the air distribution could be analysed.

Figure 5.8 shows hos the smoke is injected into the room through the supply diffusers below the ceiling.

Figure 5.8: Injection of smoke. Photo: Julie Jørgensen

6. Results

This chapter presents and discusses the results of the tracer gas experiments, velocity- and temperature measurements, and the smoke visualization.

During the step-up period, it was observed that the concentration of tracer gas in the supply air was not constant, but fluctuating. By observing the central processing system, it was detected that the supply of fresh air was controlled by the humidity level measured in the exhaust air from the pool. Thus, the amount of supplied air into the pool which is both fresh and recirculated air, was not constant. The relative humidity and temperature of the air were measured in both the outdoor air supply grille and after the heater battery in the supply duct. It was observed that the relative humidity for the outdoor air was very high, but was reduced after the heater battery, see Appendix B for graphical data.

During experiment 2 the central processing system showed that the relative humidity could reach a level of 63 % before the damper for fresh air supply was opened. Due to these observations, it was decided to omit the results from the step up-method, and focus on the step down-method. Unfortunately, it was not possible to get the amount of fresh air supplied from the central processing system. However, the pressure drop through the filter for fresh air supply was given and gives a good indication on how the system is operating by comparing this value to the humidity level measured in the exhaust air from the pool.

For the calculation of the ventilation efficiency, it was discussed if either the exhaust air from the pool or return air would be the correct basis for the calculation of the air change efficiency and the nominal constant. By utilizing the concentration in the exhaust air, it would be necessary to correct for the gas supplied due to the recirculated air. It was therefore decided to utilize the concentrations measured in the return air, and thereby include the return air in the system boundaries.

6.1 Experiment 1

For experiment 1 the ventilation system was manipulated to supply a minimum of 1 ach with outdoor air, which equals a volume flow rate of 1500 m^3/h.

6.1.1 Operation of the ventilation system

Figure 6.1 shows how the relative humidity fluctuated throughout the measuring period, and how the pressure drop over the filter for the fresh air supply followed the same trend. The fluctuation of the supplied tracer gas can therefore be explained by the control of the humidity level inside the pool.

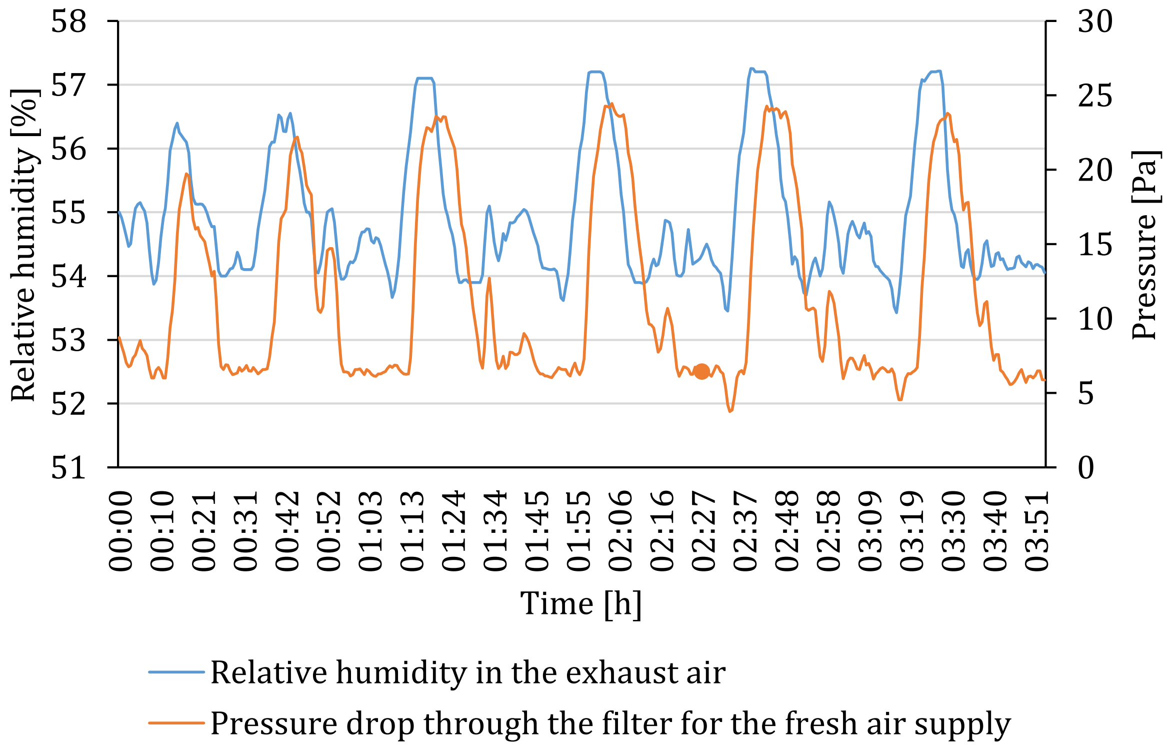


Figure 6.1: Measured pressure drop through the filter for the fresh air supply and the relative humidity in the exhaust air, experiment 1

Figure 6.2 shows the volume flow rate for the supply and exhaust air, and the supply air temperature during the measuring period. It can be seen that they all followed the same trend, and fluctuated during the measuring period. Compared to the initial boundary conditions, the volume flow rate was higher for both the supplied and extracted air. This may be due to the manipulation of the system to supply a minimum of 1 ach with fresh air. The initial boundary condition for the temperature of the supply air was 36 °C, but the figure shows that the temperature was as low as 31 °C occasionally during the measuring period.

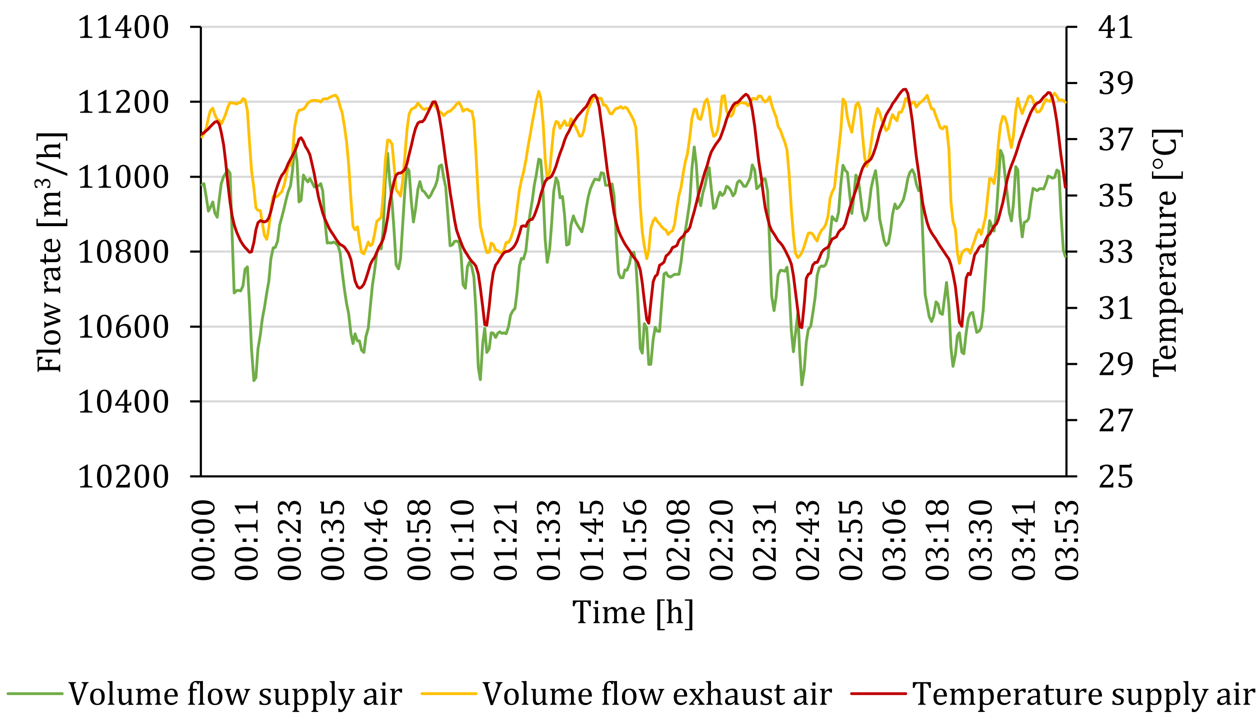


Figure 6.2: Volume flow rate for supplied and extracted air, and temperature of supplied air, experiment 1

6.1.2 Tracer gas experiment 1

Figure 6.3 and 6.4 show the concentration of N_2O in linear and logarithmic scale, respectively. After the gas was turned off, the concentration measured in the outdoor air supply decreased immediately to 13.71 ppm. For the next measuring point, the concentration was down to 0.79 ppm until it fluctuated around 0.5 ppm. The reason for not reaching zero can be due to air leakage from the return air to the fresh air supply. This will be further discussed in subsection 6.2.2. The logarithmic curve shows that the remaining points are mainly presented as a straight line, but are somewhat jagged. This may be due to the recirculation of air, i.e. some of the tracer gas was recirculated back into the supply air. The decay line for the return air is below the other measuring points inside the pool, which may imply a short-circuiting of air. The decay line for the sampling point above the pool is slightly below the sampling point in the corner of the room, which may imply that corner has a faster air exchange than the point above the pool. Because of the jagged decay line, the calculations of the air efficiency and the local values may not be that credible. The evaluation of the ventilation system should therefore be done in regards to the logarithmic decay curve.

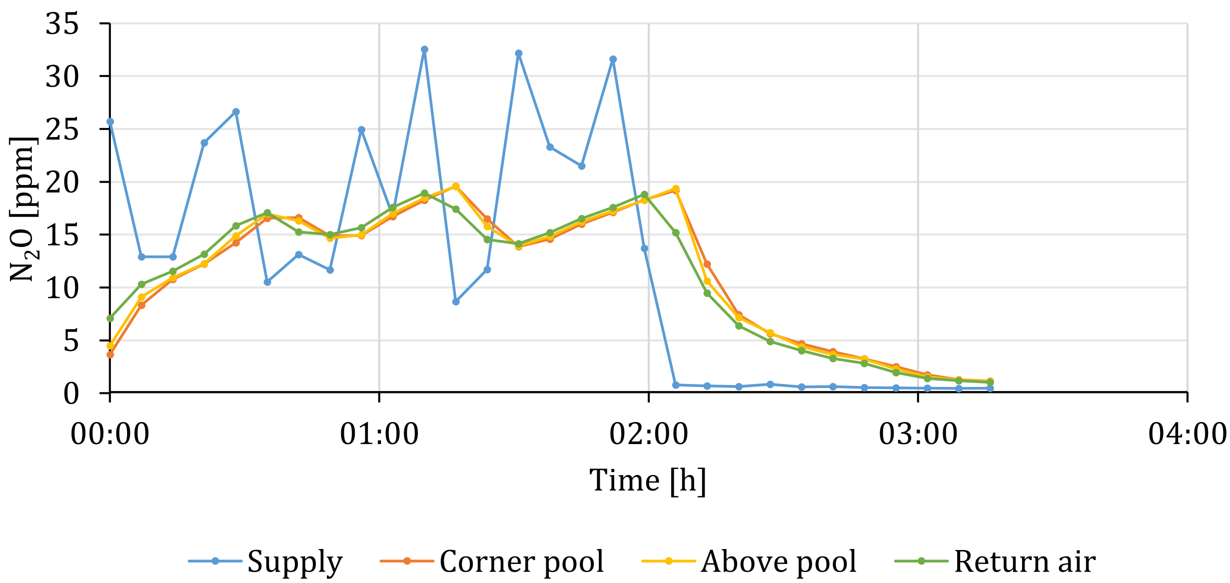


Figure 6.3: Linear presentation of tracer gas, experiment 1

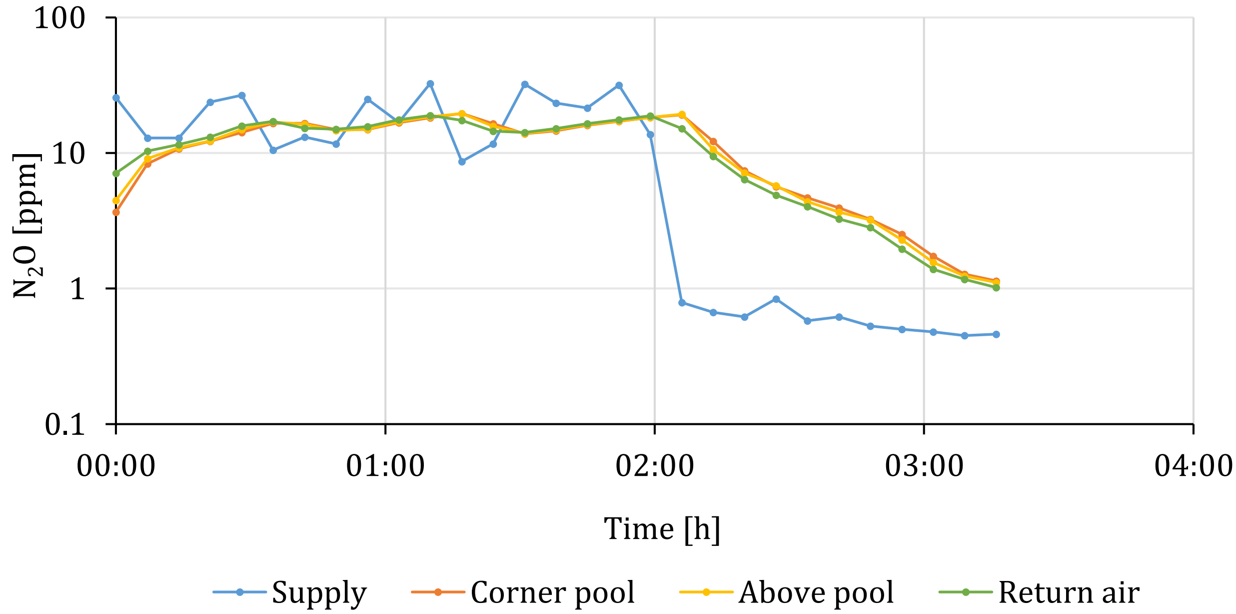


Figure 6.4: Linear presentation of tracer gas, experiment 1

The results from the first tracer gas experiment are shown in Table 6.1. The air change efficiency is 48%, and is lower than expected for displacement ventilation, which normally is between 50% and 100%. An air efficiency around 50% implies a fully mixed flow, while values below 50% may indicate a short-circuit flow. As the room is quite large, the local values are of big interest. The local mean ages of air of the corner and above the pool, are almost equal to the nominal time constant, which indicates a fully mixed flow. This can also bee seen from the local air change indexes, as they all are very close to 100%. Thus, the calculated values correspond to what was observed in the graph. However, the calculations may not be that credible as the decay line of the logarithmic curve is jagged, and the analyse should be done in regards to the logarithmic decay curve.

To verify the tracer gas experiments and the consecutive calculations, equation 3.2 can be utilized to calculate the ventilation flow rate of the outdoor air supply. The flow rate of outdoor air supplied was calculated to 3009.92 m^3/h.

Table 6.1: Results from tracer gas experiment 1, step-down method

Sampling point	Corner pool	Above pool	Return air
Mean age of air			22.65
Local mean age of air [min]	22.86	23.59	
Nominal time constant			21.73
Air change efficiency [%]			47.97
Local air change index [%]	95.04	92.12	100

6.1.3 Velocity and temperature above the swimming experiment 1

Air velocity and temperature measurements for experiment 1 are shown in Figure 6.5 and 6.6, respectively. As shown in the figure, the air velocities were very low, but fluctuated a little between the different points. The lowest air velocity was measured in point 7, with a velocity of 0.3 m/s. However, it should be stated when measuring such low velocities, that there is a big chance of errors due to measuring accuracy and how the measurements were conducted. As the grid was laid over the pool, the device had to be connected to a pole to reach the desired points. The velocity accuracy is ±0.02 m/s, which may have an impact on the measurements. For the temperature measurements, except for measuring points 1, 2, 3 and 4, the temperatures are pretty stable and similar. These points are closest to the doors, which may have an impact on the temperatures. The accuracy of the equipment is ± 0.3 °C for the air temperature.

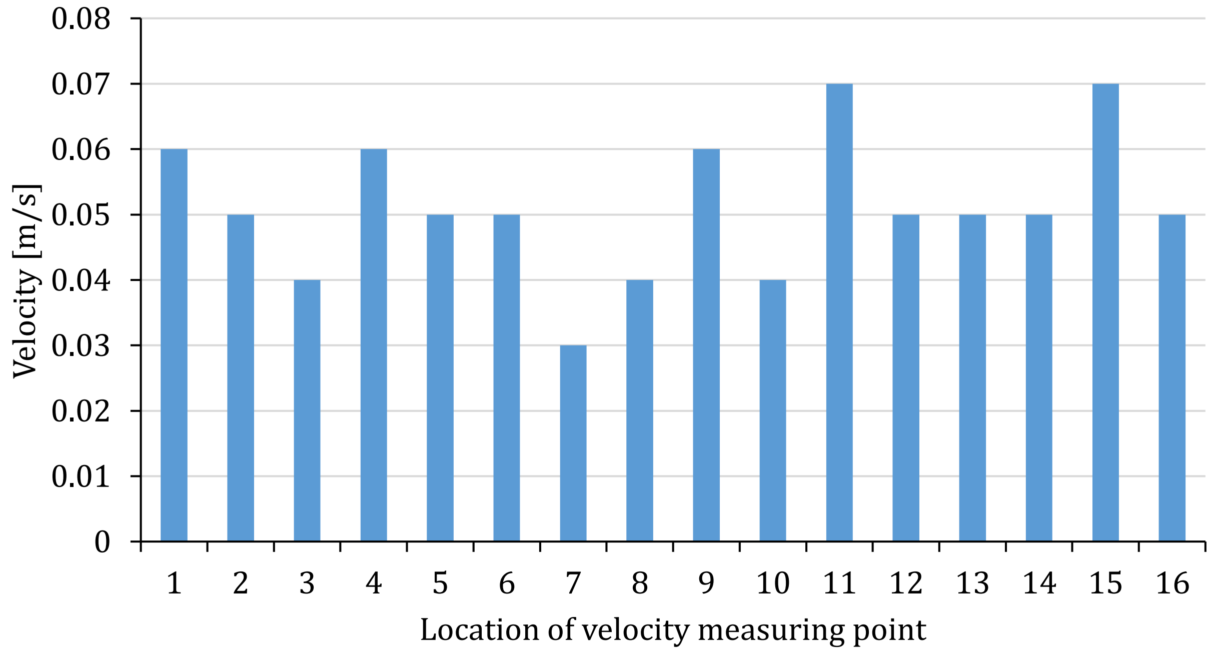


Figure 6.5: Velocity measurements, experiment 1

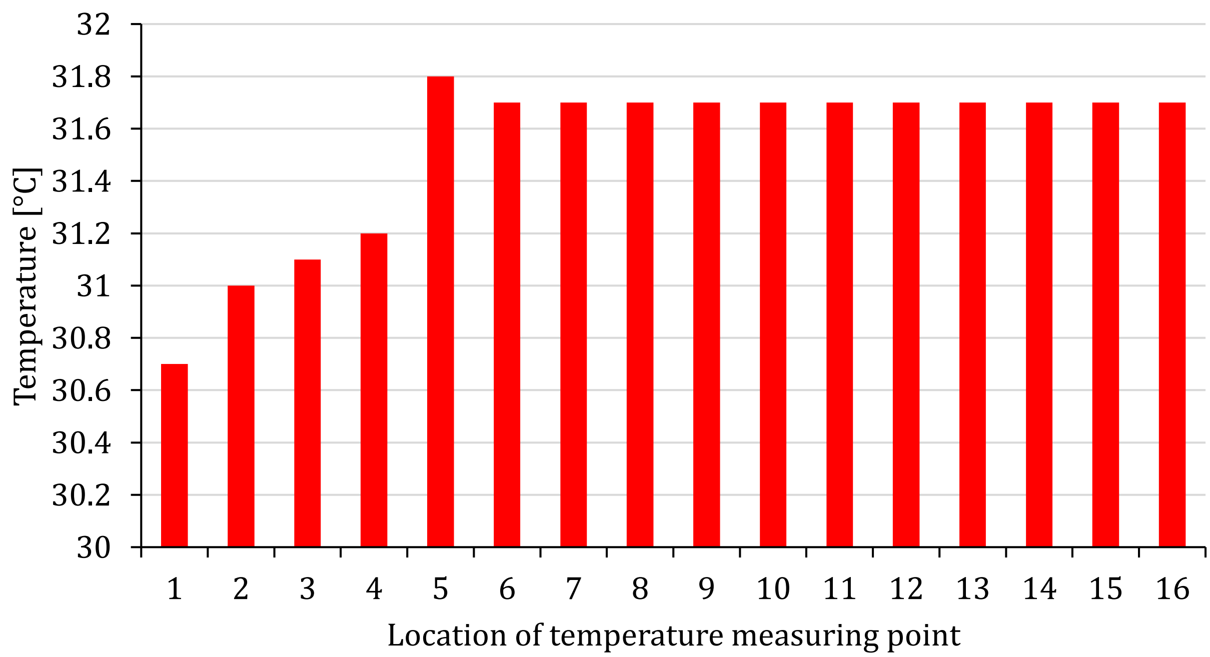


Figure 6.6: Temperature measurements, experiment 1

6.2 Experiment 2

Experiment 2 was conducted with normal operation of the ventilation system.

6.2.1 Operation of the ventilation system

Figure 6.7 shows the relative humidity and pressure drop through the filter for fresh air supply for experiment 2. As for experiment 1, the relative humidity measured in the exhaust air and the pressure drop through the filter for fresh air supply fluctuated during the measuring period. However, they did not coincide in the same way. The humidity level varied between 60 % and 63 %, while for case 1 it varied between 54 % and 57 %. For this case the ventilation system was running on normal conditions with no minimum of fresh air, which may be due to a lower relative humidity. The pressure drop through the filter for the fresh air supply was occasionally during the measuring period down to 0 Pa, while for experiment 1 the lowest value was measured to 5 Pa.

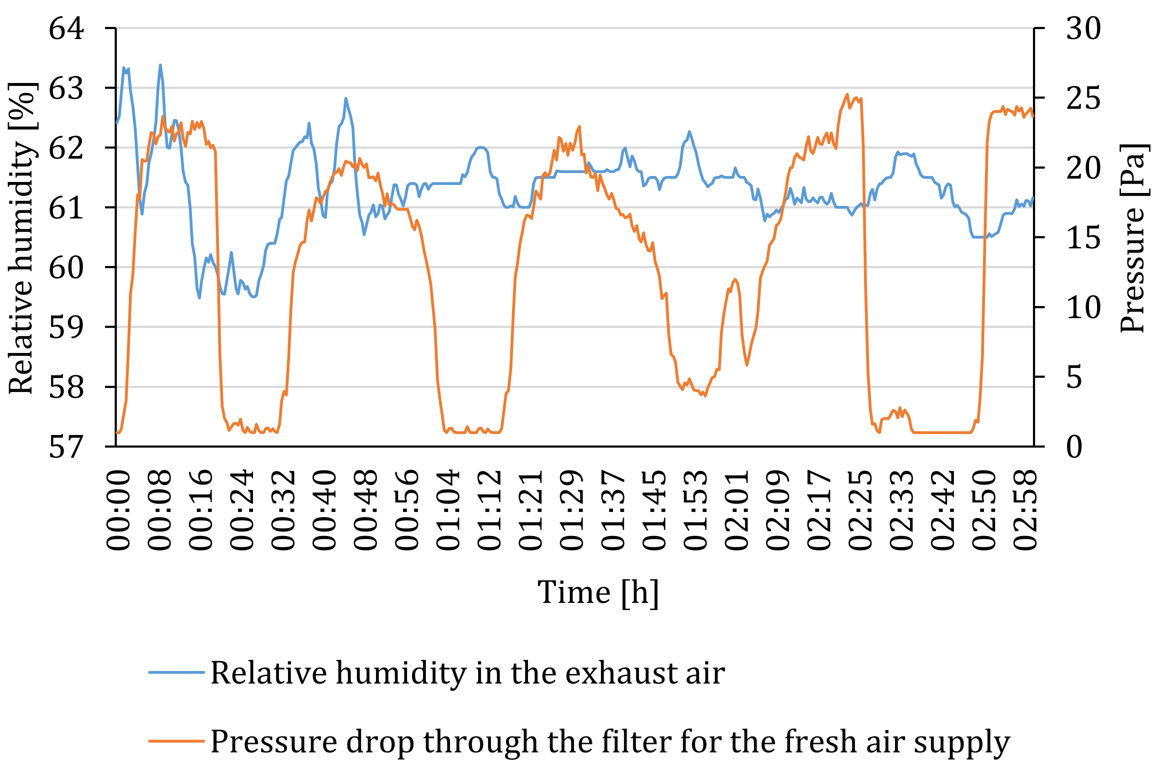


Figure 6.7: Measured pressure drop through the filter for the fresh air supply and the relative humidity in the exhaust air, experiment 2

Figure 6.8 shows the volume flow rate for the supply air and the exhaust air from the pool, and the supply air temperature. As seen from the figure the volume flow rate of the supply and exhaust air are almost equal, and is lower than for experiment 1. Initially, the system was designed to extract 1000 m^3/h than supplied to establish and under-pressure in the room, but this is not the case for the current ventilation system. The temperature does not follow the same trend as the air supplied and extracted as it did in experiment 1, but it is measured to be higher.

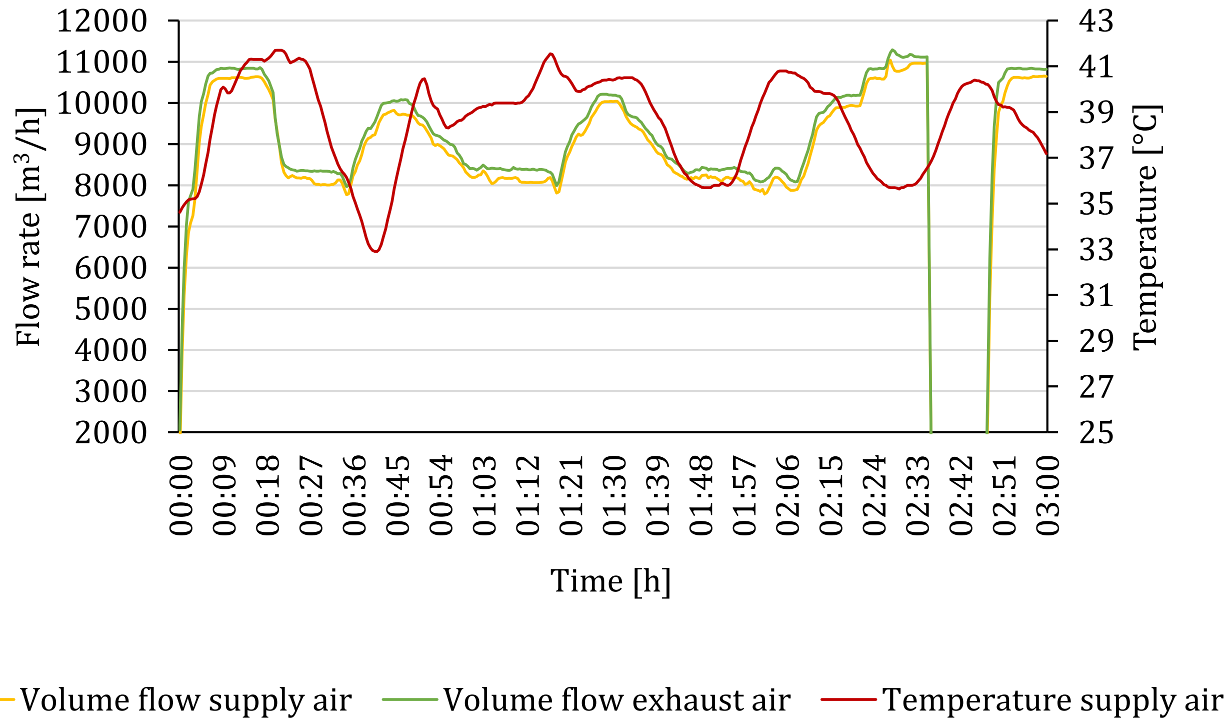


Figure 6.8: Volume flow rate for supplied and exhaust air, and temperature of supplied air, experiment 2

6.2.2 Tracer gas experiment 2

Tracer gas experiment number 2 was conducted with normal operation of the ventilation system with no change in the exhaust grille. The gas was injected in the supply air to the pool, where both recirculated and outdoor air were supplied. Figure 6.9 and 6.10 show the concentration of N_2O in linear and logarithmic scale, respectively. During the step-up method, the concentration was measured to be very high. It fluctuated as for the first measurement, but the values were remarkably higher than the concentrations measured in the remaining points. This is very odd, as it would seem natural that the remaining sampling points would reach a higher concentration with such high concentrations in the supply. This cannot really be explained in any other way than an error in the measuring equipment, and the experiment was therefore terminated before the concentration reached zero. The concentration measured in the remaining points can still be utilized for calculating the ventilation efficiency.

To investigate if there was any leakage from the return air to the outdoor air supply, the concentration in the outdoor air supply was measured. Figure 6.9 shows that there is some leakage from the return air to the outdoor supply, but not so much that is should be taken any measures. This substantiates the allegation from experiment 1.

After the gas supply was turned off, the decay measured in the supply air decreased very slowly. As discussed above, this cannot really be explained in any other way than errors in the measuring equipment. The logarithmic decay in Figure 6.10 shows that the remaining points are mainly presented as a straight line, but are somewhat tagged. This was also the case in experiment 1, and can be explained by the recirculation of air. However, in this case, the decay line for the return air is in between the point in the corner and above the pool, which indicates less short-circuiting of air than for experiment 1. The logarithmic decay line for the corner was below the other two lines, which implies a faster air exchange in this point, while the point above the pool has a longer exchange of air. The reason for a faster exchange in the corner when the system is running under normal conditions, can be due to both the reduced volume flow rate in the supply and the higher temperature of the supply air. As the temperature difference between the wall and the supply air will be greater than in experiment 1 and 3, the air close to the wall will be cooled down faster than the air above the pool, and thereby move faster downwards.

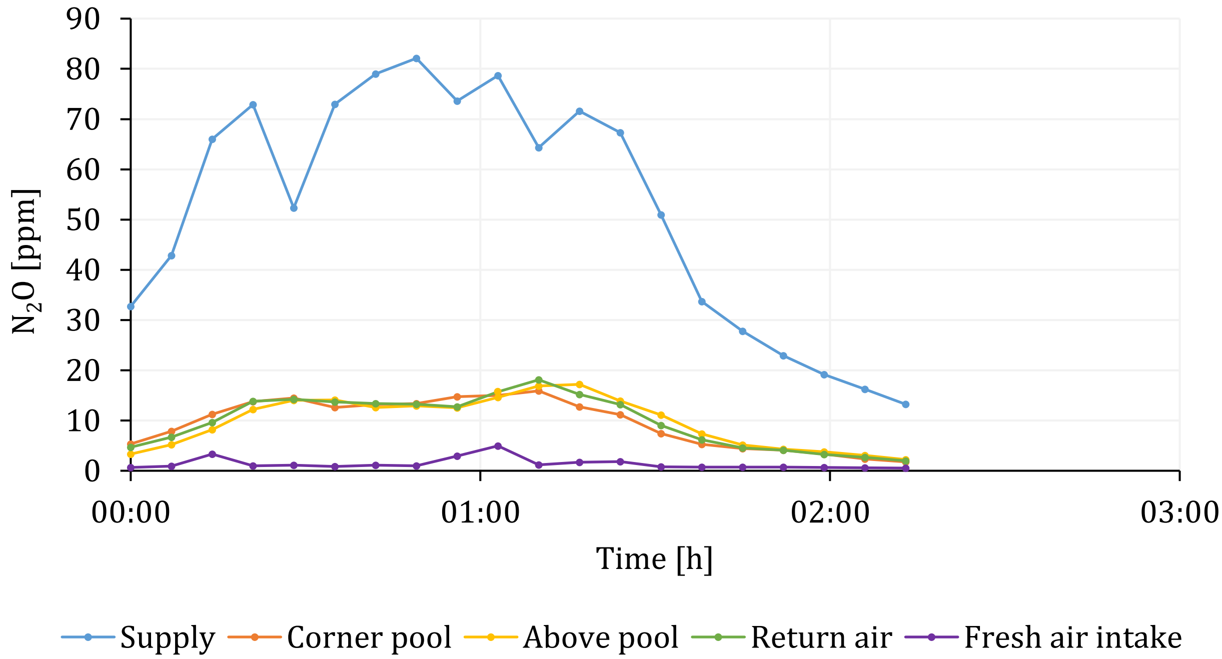


Figure 6.9: Linear presentation of tracer gas, experiment 2

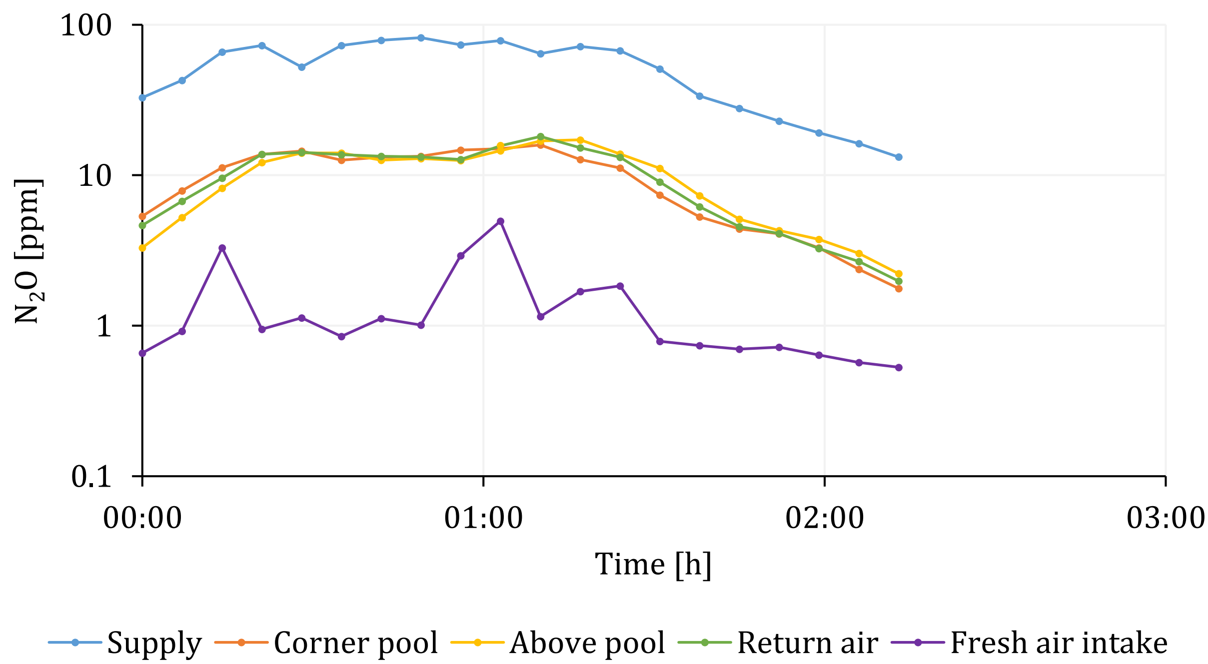


Figure 6.10: Linear presentation of tracer gas, experiment 2

The results from the second tracer gas experiment with normal operation of the ventilation system is shown in Table 6.2. The air change efficiency is 51.54 %, and is the expected efficiency for displacement ventilation. For experiment 1 the local ages of air and the nominal time constant were almost equal, which implied a fully mixed flow. This is however not the case here. The local air change index in the corner is 120.89 %, which implies displacement ventilation. However, above the pool, the local air change index is 88.85 %, which may be due to short-circuiting of air in the occupied zone. As mentioned in 6.1.2, the jagged decay line in the logarithmic curve make the calculated results less reliable, and the focus should be on the logarithmic decay curve.

The flow rate of outdoor air is calculated to 2363.93 m^3/h by using equation 3.2. This is lower than for experiment 1, which was expected as there was no minimum for the fresh air supply.

Table 6.2: Results from tracer gas experiment 2, step-down method

Sampling point	**Corner pool**	**Above pool**	**Return air**
Mean age of air			26.83
Local mean age of air	22.87	31.12	
Nominal time constant			27.65
Air change efficiency			51.54
Local air change index	120.89	88.85	100

6.2.3 Air velocity and temperature measurements above the swimming pool, experiment 2

Figure 6.11 and 6.12 show the velocity and temperature measurements above the pool. As for experiment 1, the velocities are low and similar all over the grid. The measured values are slightly lower than for measurement 1. Point 7 still have the same velocity of 0.3 m/s, but this value is also measured in several other points. However, the values are extremely low, and the difference from measurement 1 can also be explained in errors in the measuring method or device. Regarding the temperatures, they differ more than for experiment 1, but the measuring points 1, 2, 3 and 4 still have the lowest temperatures. However, the difference may be due to inaccuracies in the equipment and the measuring method.

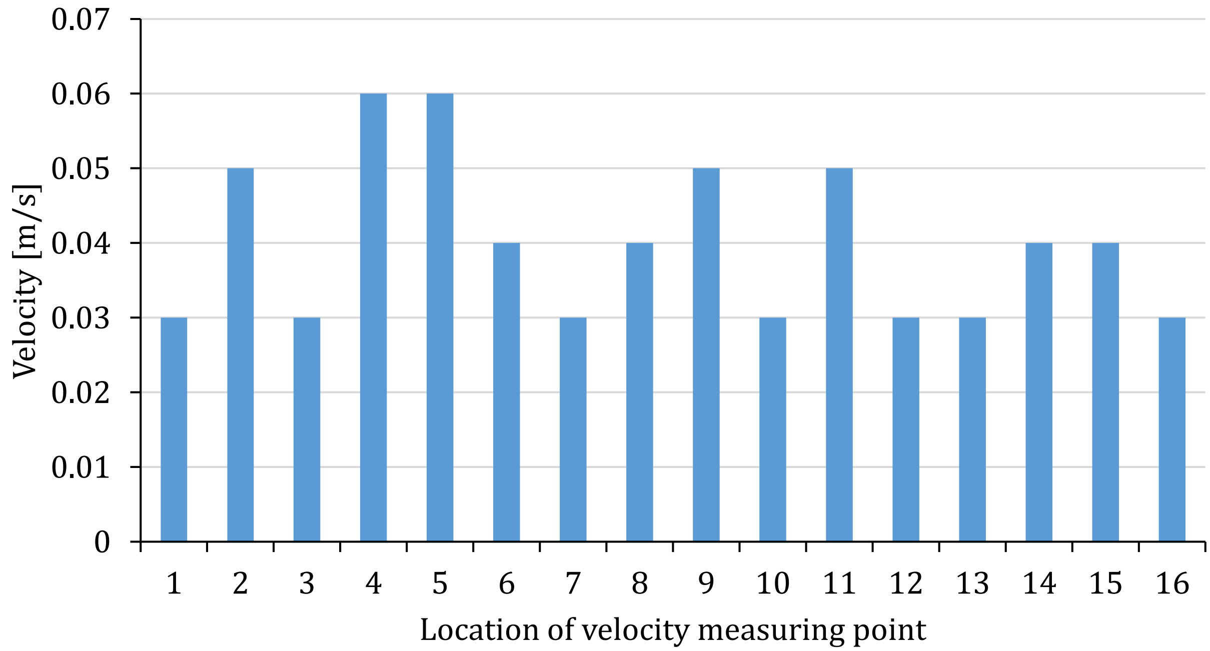


Figure 6.11: Velocity measurements, experiment 2

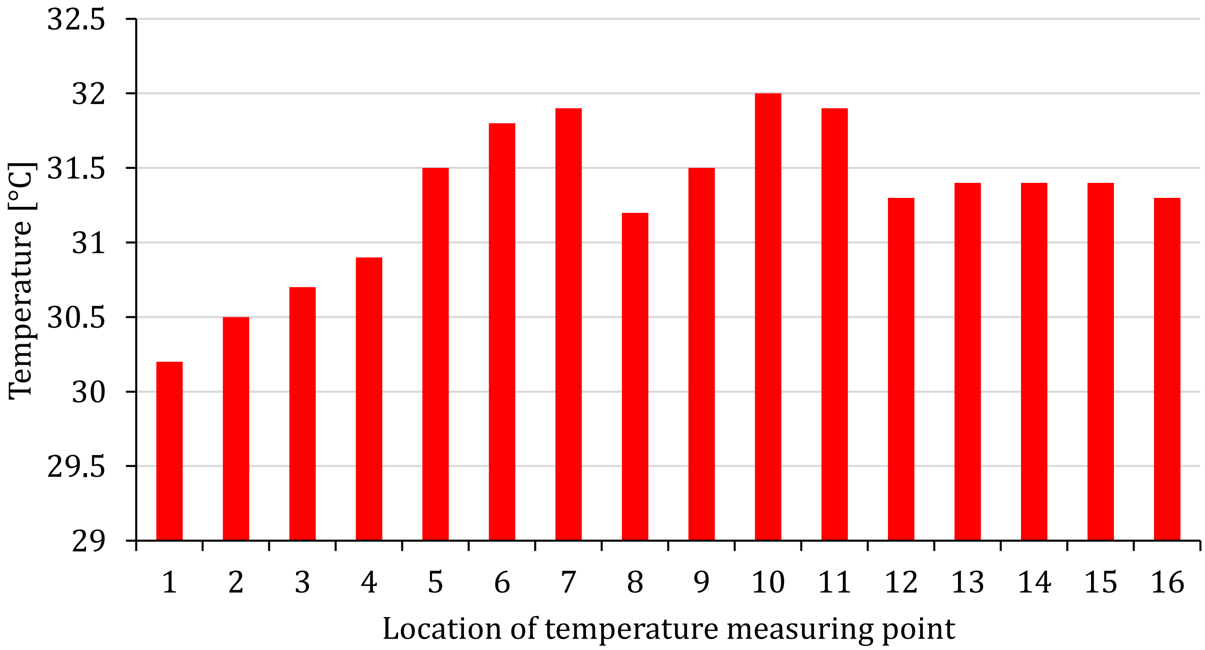


Figure 6.12: Temperature measurements, experiment 2

6.3 Experiment 3

For experiment 3 the ventilation system was manipulated to supply a minimum of 1 ach with fresh air, which equals 1500 m^3/h. The size of the exhaust grille was reduced from 2 m to 0.7 m.

6.3.1 Operation of the ventilation system

Figure 6.13 shows the relative humidity and pressure drop through the filter for the fresh air supply during the measuring period. As for experiment 1 they follow the same trend, but the pressure drop through the filter for the fresh air supply is slightly higher, which indicates a higher amount of fresh air supplied. The relative humidity is on the same level as for experiment 1.

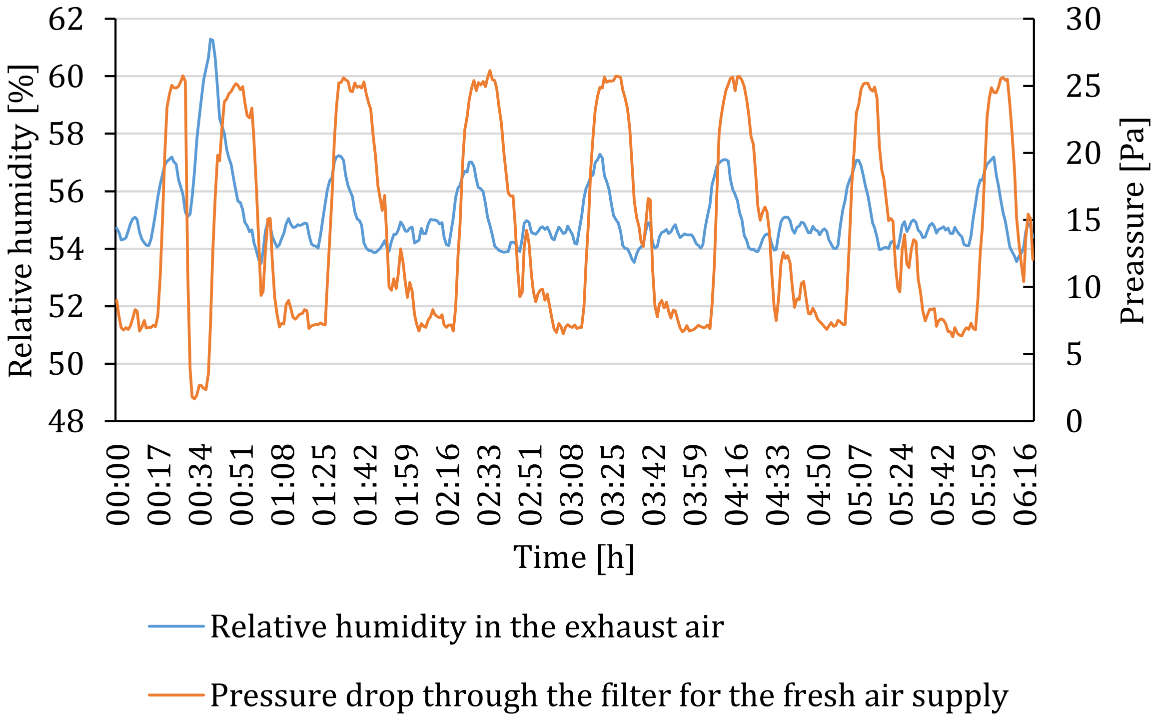


Figure 6.13: Measured pressure drop through the filter for the fresh air supply and the relative humidity in the exhaust air, experiment 3

Figure 6.14 shows the volume flow rate for supply and exhaust air, and the supply air temperature during the measuring period. It can be seen that they all follow the same trend, which also was seen in experiment 1. The amount of air supplied and extracted were almost equal to experiment 1. This applies for the temperature as well.

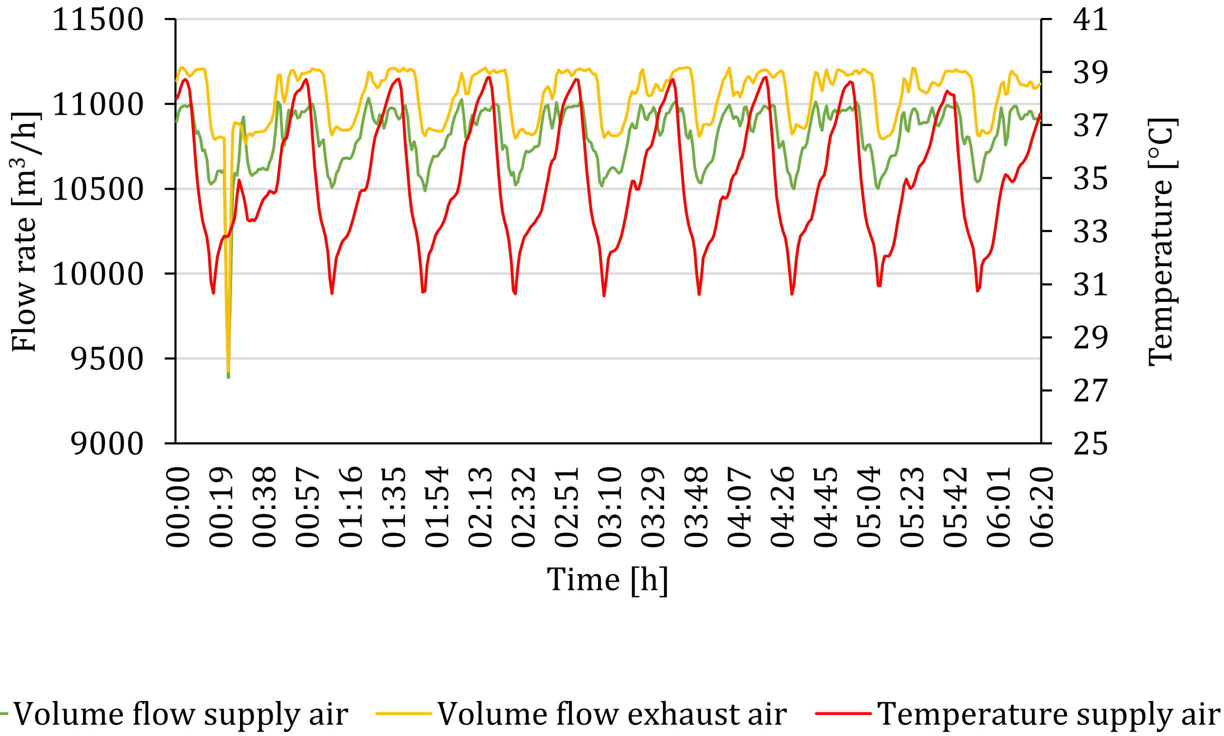


Figure 6.14: Volume flow rate for supplied and extracted air, and temperature of supplied air, experiment 3

6.3.2 Tracer gas experiment 3

Figure 6.15 and 6.16 show the concentration of N_2O in linear and logarithmic scale, respectively. As for experiment 1 the concentration in the outdoor air supply decreases immediately after turning off the gas, in this case from 19.98 ppm to 1.44 pm. It then fluctuated around 0.50 ppm. As for experiment 1 and 2, the logarithmic curve was somewhat jagged, which may be due to the recirculation of air. The logarithmic decay curve also shows that the return air is above the decay line for the sampling points in the corner and above the pool. This indicates less short-circuiting of air than for experiment 1. However, the decay line for the point above the pool is slightly below the point above the pool, which implies a slower air exchange in the point in the corner than above the pool.

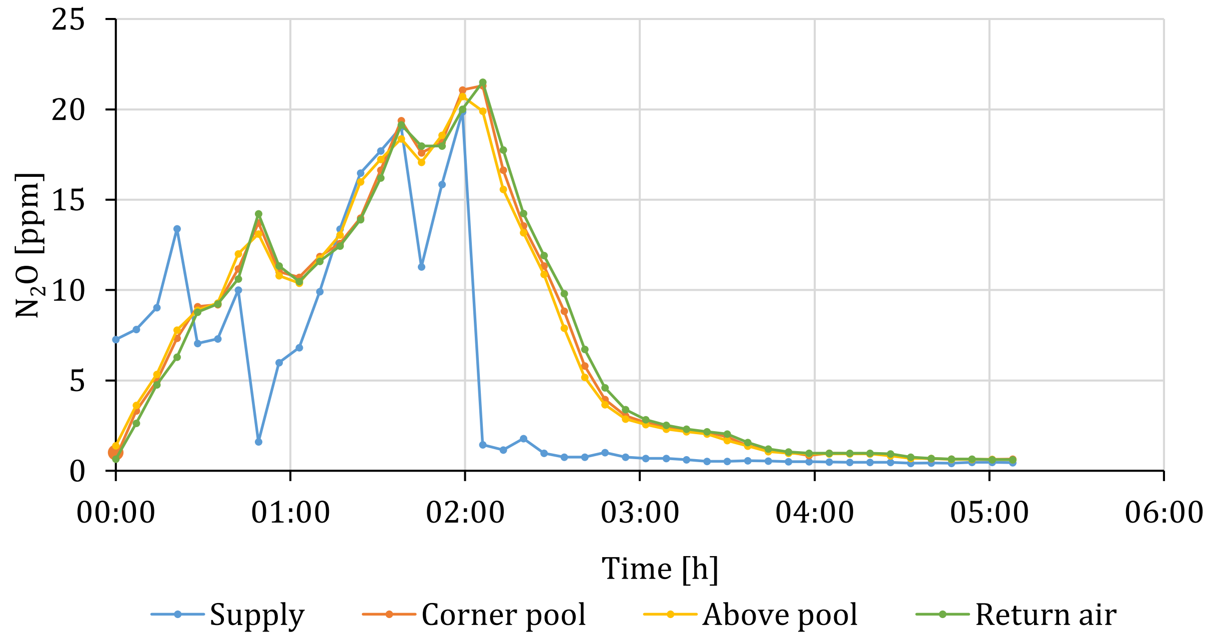


Figure 6.15: Linear presentation of tracer gas, experiment 3

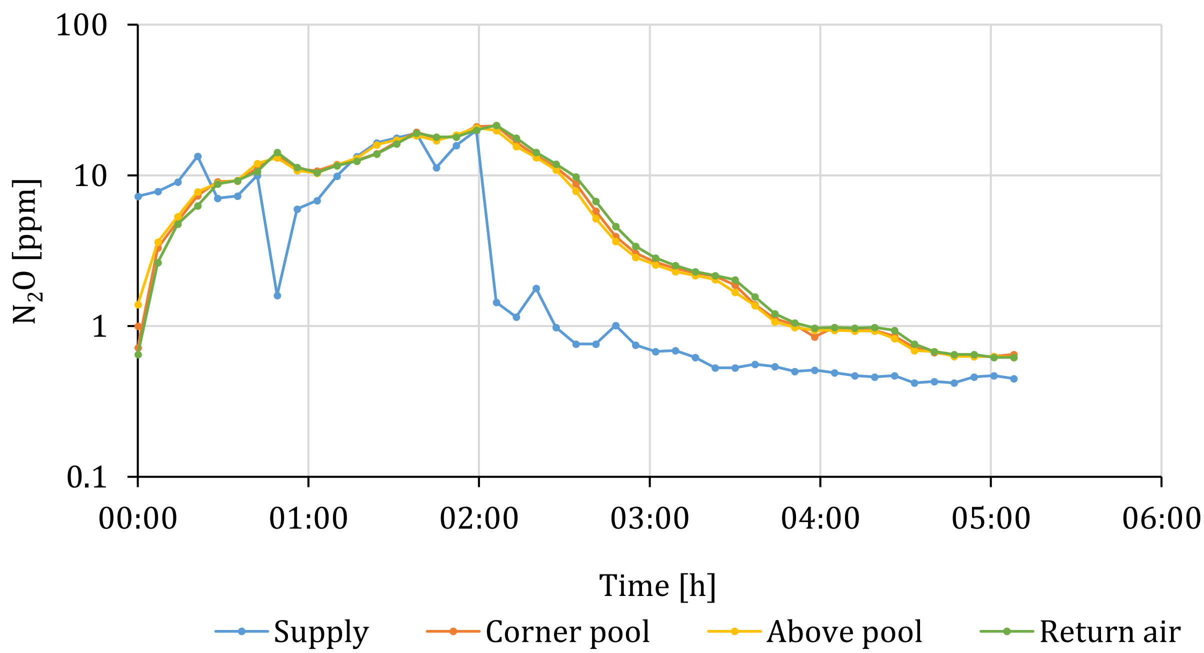


Figure 6.16: Linear presentation of tracer gas, experiment 3

Table 6.3 shows the results of the tracer gas experiment for experiment 3. The air change efficiency is calculated to 43.35 %, and is thereby the lowest efficiency calculated for all the experiments. This may indicate short-circuiting of air. The local age of air in the corner and above the pool are almost equal but differs more from the nominal time constant than for experiment 1. The local air change indexes are lower than for experiment 1. The nominal time constant, as well as the local age of air for both the sampling point above the pool and in the corner of the room, is higher than for both measurement 1 and 2.

The value for the air change efficiency indicates a short circuiting of air, but as the decay line for the return air is above the remaining sampling point, this may not be the case. This substantiates the allegation of using the logarithmic decay curve for the evaluation of the ventilation efficiency.

Table 6.3: Results from tracer gas experiment 3, step-down method

Sampling point	Corner pool	Above pool	Return air
Mean age of air			36.36
Local mean age of air	37.27	36.53	
Nominal time constant			31.53
Air change efficiency			43.35
Local air change index	84.6	86.31	100

The flow rate of outdoor air was calculated to 2364.93 m^3/h by utilizing equation 3.2. Compared to measurement 1 where the flow rate was calculated to 3009.7 m^3/h, the flow rate of outdoor air is lower than for experiment 1. However, figure 6.14 showed a higher pressure drop through the filter for fresh supply than figure 6.8, which implies a higher amount of fresh air for experiment 3 than 1. This is also an indication that the calculated values from the measurements give a wrong impression of the ventilation efficiency.

6.3.3 Velocity and temperature above the swimming pool experiment 3

Figure 6.17 and 6.18 show the velocity and temperature measurements over the pool for experiment 3. The velocities are slightly higher than for experiment 1 and 2. In point 4 the velocity is measured to 0.14 m/s, which is the highest velocity measured in all of the three experiments. This point is closest to the exhaust grille, which may have an impact on the velocities above the pool. On the other hand, there is a big chance that this is just an error, and that this point should be measured again. Regarding the temperatures, measuring point 1, 2, 3 and 4, have as for experiment 2 and 3, expect for point 10, the lowest temperatures.

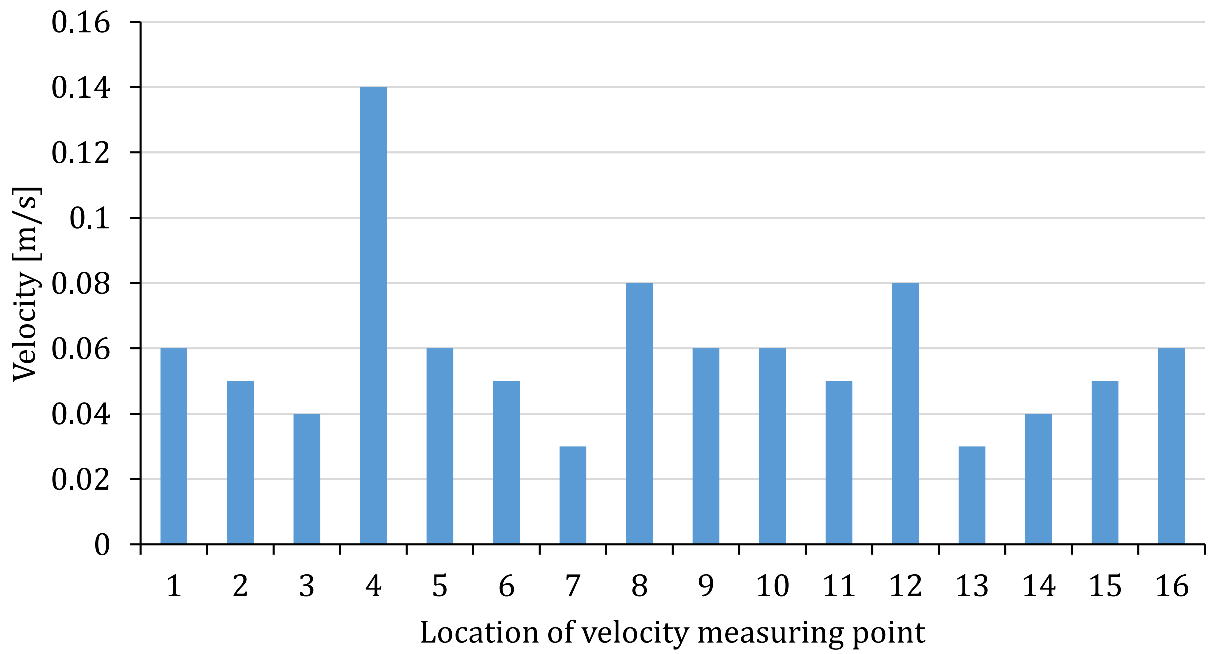


Figure 6.17: Velocity measurements, experiment 3

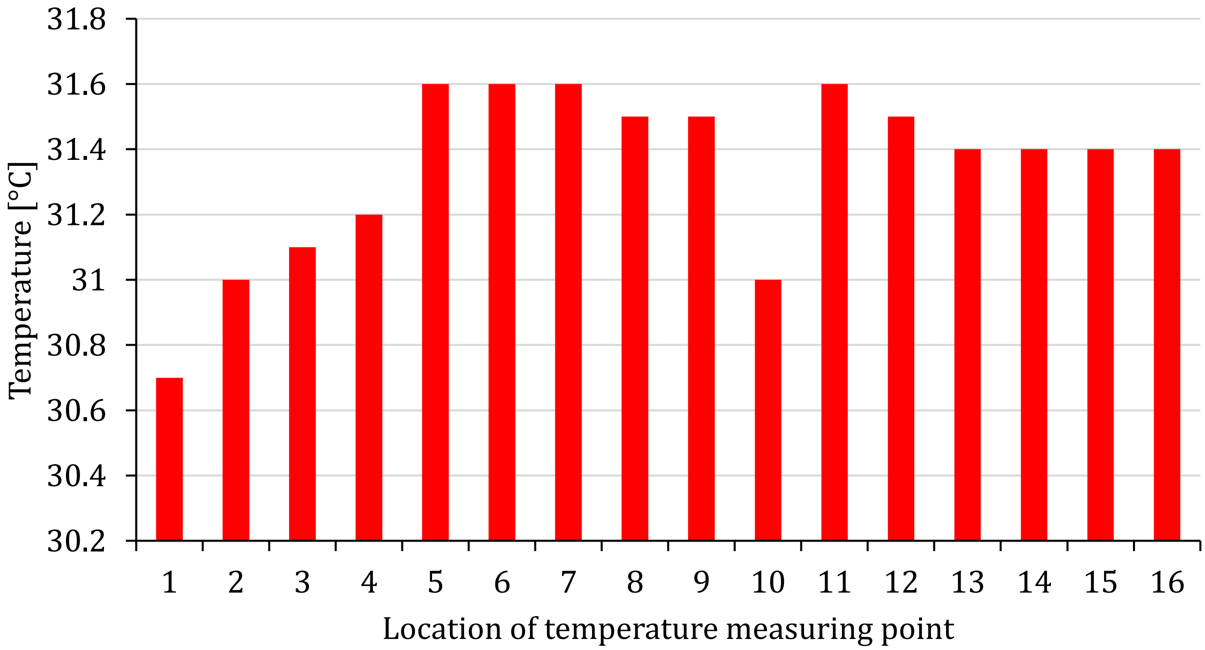


Figure 6.18: Temperature measurements, experiment 3

6.4 Continuous temperature measurements

The results from the continuous temperature measurements are shown below. The iButtons have an accuracy of ± 0.5 °C (iButtonLink, 2018), which may cause uncertainties in the conducted measurements. The lowest temperatures are measured in the points that are close to the entrance doors from the wardrobes and the lifeguard room. This was also detected during the temperature measurements above the pool, and seems accurate as the doors will be opened several times during the day, and may sometimes stay open if not closed. For the remaining sampling points, the temperatures are pretty similar to the temperature measurements conducted above the pool.

Table 6.4: Temperatures north-wall

Sensor location	Min	Max	Mean
1	30.7	31.2	30.7
2	31.1	31.6	31.3
3	31.1	31.6	31.3
4	31.1	31.6	31.2
5	31.1	31.6	31.4
6	30.6	31.1	30.8

Table 6.5: Temperatures east-wall

Sensor location	Min [°C]	Max	Mean
7	31.1	31.6	31.1
8	30.6	31.6	31.1
9	31.1	31.6	31.2
10	31.1	31.6	31.2
11	31.1	31.6	31.2
12	31.1	31.6	31.2
13	30.7	31.7	31.2
14	31.2	31.7	31.3
15	30.6	31.8	31.8
16	31.1	31.6	31.2
17	30.6	31.1	31.0
18	30.6	31.1	31.0
19	31.1	31.6	31.2
20	31.1	31.6	31.3

Table 6.6: Temperatures south-wall

Sensor location	Min	Max	Mean
21	29.6	30.1	30.0
22	29.6	30.6	29.9
23	31.2	32.2	31.6
24	31.1	31.6	31.2
25	30.1	31.6	30.2
26	29.7	31.2	29.9
27	28.6	30.1	28.9
28	28.6	29.1	29.0

Table 6.7: Temperatures west-wall

Sensor location	Min	Max	Mean
29	29.2	30.2	29.5
30	28.7	29.2	28.9
31	30.6	31.1	31.0
32	30.1	30.6	30.4
33	31.2	31.7	31.5
34	31.6	31.7	31.7
35	30.7	31.7	31.2
36	30.6	31.1	31.1
37	31.1	31.6	31.5
38	30.6	31.1	30.9
39	31.1	31.6	31.2
40	31.2	31.7	31.2
41	30.7	31.2	31.2
42	31.6	31.9	31.9
43	30.6	31.1	30.9
44	31.2	31.2	31.2

6.5 Smoke visualization

The smoke was injected into the room after the third tracer gas experiment when the ventilation system was manipulated to supply at least 1 ach of fresh air and with a reduced height of the exhaust grille. Figure 6.19 shows how the smoke was distributed in the room. The smoke was blended very well in the room, and it looks like the air is fully mixed. This was also detected from the calculations from the tracer gas experiment. However, as mentioned, the calculated values may not be that reliable considered the jagged decay line of the logarithmic curve. It should, however, be conducted one smoke experiment with normal operation of the ventilation system. There is also a chance that not enough smoke was injected into the room, and that more smoke would give a different picture of the air flow.

Figure 6.19: Smoke visualization. Photo: Julie Jørgensen

7. Questionnaire

This chapter presents how the questionnaire was developed and how it was distributed. In addition it discusses the results, and the determination of the PMV based on calculation and with the use of tables. It was decided to focus on the thermal- and atmospheric environment, and thereby the questions regarding this are presented and discussed below.

7.1 Method

A user survey can be an adequate way to get an understanding of users' perception of the indoor climate. The questionnaire was made in Select Survey, where different types of questions can be asked. The answers are collected at NTNU's server. See Appendix D for the questions. Before the questionnaire was distributed, an approval of the questionnaire was given from the Norwegian Centre for Research Data.

The questions are based on the Örebro-model (Department of Occupational and Environmental Medicine). In addition, some questions were added to cover the climate in swimming pools.

As the primary users of the swimming pool are pupils at the school, it was desired that as many as possible of them answered the questionnaire. It was decided to set the limit from 5th grade, as it was important that the respondents understood the questions. The questions were formed in an easy and understandable way, taking in consideration that children were answering.

Regarding the questions on evaluating the thermal sensation of the users of the pool, it was decided to formulate the question with respect to the indoor air temperature. This was done because of the biggest part of the respondents were children, and most people will think of the temperature when asked about how their thermal perception is.

As many of the respondents are under 18, it was necessary to get an approval from their parents. An information letter was therefore sent out to the parents by the principal before the survey was conducted during school hours. For the private users' of the pool, the operator of the pool sent the questionnaire by e-mail.

7.1.1 Limitations

A large limitation in the study is the amount of respondents. A total of eleven of a desired selection of 40 people answered the questionnaire. A very small percentage of the eleven respondents are operators of the swimming pool, and it was therefore decided to evaluate all of the answers from the respondents together. Both the floor of the swimming pool and the light in the room are controlled in a separate room, and the operators will not be that affected by the indoor climate in the swimming pool. The small amount of respondents is not really representative for the people that are using the swimming pool, and preferably the amount should be a lot higher. Due to this it cannot be drawn any conclusions regarding peoples general perception of the indoor climate. On the other hand, it shows how eleven individuals perceive the indoor climate.

7.2 Questionnaire

7.2.1 Thermal environment

Regarding the thermal comfort of the swimmers in the swimming pool, the following question was asked:

- When you are in the swimming pool, are you bothered by any of the following factors?

Table 7.1 shows the percentage of the responses to the different questions. As the table shows 9.09 % of the respondents answered that they sometimes are bothered with draft. This is not a lot, and it may be indicate that draft is not a problem in the swimming pool. Regarding the air- and water temperature, most people seem satisfied, but 63.64 % expressed the air temperature to sometimes be too warm, while 45.45 % people stated the water temperature to be too warm. However, people have very different personal preferences regarding temperatures.

Table 7.1: Questions regarding the thermal environment

Factors	Yes often [%]	Yes, sometimes [%]	No, never [%]
Draft	0	9.09	90.91
Air temperature too warm	9.09	63.64	27.27
Air temperature too cold	0	27.27	72.73
Water temperature too cold	18.18	0	81.82
Water temperature too warm	0	45.45	54.55

7.2.2 Atmospheric environment

Regarding the atmospheric environment, the following question was asked:

- After swimming, have you ever experienced any of the following symptoms?

Table 7.2 shows the responses to the different questions regarding symptoms connected to the atmospheric environment. The majority of the people stated that they never experienced any of the following symptoms after swimming. However, 36.36 % stated that they sometimes felt tired, and 27.27 % stated that they often felt tired. This is not unusual due to such high air- and water temperatures. 27.27 % and 36.36 % stated that they often and sometimes, respectively, had itching, sore and irritation in the eyes. As the study conducted by Kaydos-Daniels et al. (2008), irritation in the eyes can come from exposure to chloramine.

Table 7.2: Questions regarding the atmospheric environment

Symptoms	Yes, often [%]	Yes sometimes [%]	No, never [%]	Do not know [%]
Headace	9.09	18.18	72.73	0
Nausea/dizziness	0	27.27	72.73	0
Bad concentration	0	9.09	63.64	27.27
Fatigue	27.27	36.36	36.36	0
Itching, sore and irritation in the eyes	18.18	36.36	45.45	0
Stuffy nose	0	9.09	90.91	0
Dry throat	0	27.27	72.73	0
Cough	0	0	90.91	9.09
Dry or red skin in the face	0	9.09	72.73	18.18
Itching scalp and dandruff	0	9.09	81.82	9.09
Eczema	0	0	81.82	18.18
Asthma	0	0	90.91	9.09

Regarding the users' perception of the air quality, 27 % expressed that the air quality was very good, while 45 % stated good. 18 % stated an acceptable air quality, while 9 % expressed it as very bad.

7.2.3 Thermal sensation of the swimmers

Figure 7.1 shows the thermal sensation of the swimmers coming out of the pool. The average value of the thermal sensation of the respondents is 0.2, which indicates slightly above neutral. This is in between the desired PMV according to NS-EN ISO 7730 (Norsk Standard NS-EN ISO 7730, 2005).

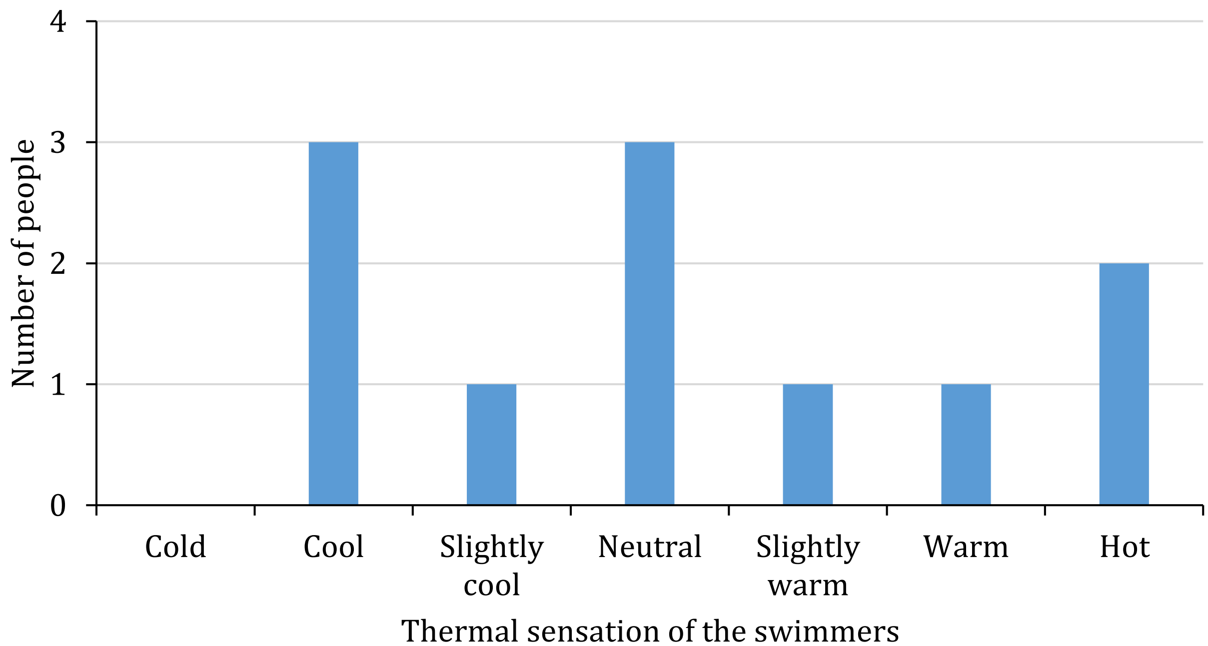


Figure 7.1: Thermal sensation of the wet swimmers

7.3 Calculation of the PMV

For calculation of the PMV the equations from subsection 2.1 can be utilized.

Table 7.3 shows the input values for the calculation of the PMV. The activity factor and clothing isolation are the same values that Rajagopalan and Jamei (2015) utilized in their study. The isolation factor is the same that Revel and Arnesano (2014) used in their study. The remaining values are gathered from the field trip at Jøa and from the central processing system. The clothing surface temperature, t_{cl}, and the convective heat transfer coefficient, h_c, is calculated with the use of iteration in Excel. The water vapour partial pressure is calculated by equation 2.1.3.

Table 7.3: Input-values for calculation of the PMV

Input-values	
M [W/m^2]	104.76
W [W/m^2]	0
I_{cl} [W/m^2]	0.06
f_{cl}	1.0774
t_a [°C]	31.39
t_r [°C]	30.9
v_{ar} [m/s]	0.05
p_a [Pa]	4593.85
h_c[W/(m^{2}K)]	2.83
t_{cl} [°C]	33.4
p_{skin} [Pa]	4600
f_{pcl}	0.978

Due to some errors in the calculations, it was unfortunately not possible to calculate a proper value of the PMV. One reason for the error may be due to the limitations in the PMV index. The water vapour partial pressure should be in the range of 0 to 2700 Pa Norsk Standard NS-EN ISO 7730, 2005, but in this case it was calculated to 4593.85 Pa. This is something that therefore has to further developed.

Instead table E.7 from Annex E i NS-EN ISO 7730 (Norsk Standard NS-EN ISO 7730, 2005) can be utilized to determine the PMV.

The operative temperature is calculated to 31.1 °C by using equation 2.1. By utilizing the operative temperature, the activity factor, the clothing isolation and the air velocity, the determined PMV is 2.03. This is slightly above warm. However, the table does not include PMV-values for activity levels of 2 met with lower velocities than 0.10 m/s. In addition, the PMV-values are based on a relative humidity of 50 %, which is lower than the level in the swimming pool. The swimmers will also be wet, which also probably would decrease the value.

Compared to the thermal sensation of the swimmers, this value is considerably higher. However, the average thermal sensation is based on only eleven users of the pool, and is not enough to draw any conclusions.

8. Discussion

As the volume flow is not constant the measured concentration in the supply fluctuated during the step-up method. The recirculation lead to a somewhat jagged decay line in the logarithmic curve for all of the experiments. This may be due to recirculation of air, i.e. some contaminated air is recirculated back into the room. Because of this, the calculation of the air change efficiency and the local values may not be that reliable. This was clearly shown by comparing the results from experiment 1 and 3. The air change efficiency from experiment 3 showed a stronger tendency of short-circuiting of air than experiment 1. However, the logarithmic decay lined showed the opposite. In addition, the calculated fresh air supplied showed a higher fresh air supply in experiment 1 than 3, but the pressure drop through the filter for the fresh air supply was higher for experiment 3 than 1.

Due to the jagged decay lines in the logarithmic curves, the calculated air change efficiency cannot really be used to establish the ventilation efficiency. The logarithmic decay line for the return air in experiment 1 showed a tendency to short-circuiting of air. When reducing the height of the exhaust grille in experiment 3, the logarithmic decay line for the return air was above the remaining sampling points. This may indicate that a reduction of the height of the exhaust grille will reduce the short-circuiting of air. However, both experiment 1 and 3 were conducted with a manipulation of the ventilation system. Experiment 2 implied a better ventilation efficiency than for the two remaining experiments, and a reduction in the height of the exhaust grille should preferably be conducted under normal conditions as well. Experiment 2 also showed that the corner of the pool had a faster air exchange than above the pool. The reason for this may be due to a greater temperature difference between the wall and the supplied air. The air close to the walls will be cooled down faster than the air in the middle of the room, and will, therefore, move down faster.

The air velocities above the pool were measured to be very low in all of the three experiments. However, inaccuracies in the measuring device, in addition to the measuring method must be taken into consideration when evaluating the results.

The same applies to the temperature measurements above the pool. The continuous measurements on the walls of the room with swimming pool may be more accurate. However, during normal operation with normal occupancy, the temperatures close to the doors will probably be more affected and fluctuate more due to opening of the doors.

Regarding the questionnaire, the majority of the respondents seemed to be satisfied with the indoor climate. The determined PMV did no coincide with the thermal sensation of the swimmers, which may be due to several factors due to the indoor climate in swimming pools. In addition, a small amount of respondents makes it is impossible to draw any conclusion to the indoor climate based on the answers.

9. Conclusion

The objective of the thesis was to evaluate the performance of the ventilation systems in accordance with the expected performance.

Field experiments were conducted in the swimming pool at Jøa, with three different operations of the ventilation system. The calculations for all of the three experiments indicated a fully mixed flow or short-circuiting of air. The smoke visualization did also indicate a fully mixed flow. However, the calculations are not that reliable due to a non-constant air flow, but the logarithmic decay curve could be utilized to get an impression on how the ventilation system works. The logarithmic curve showed that there was short-circuiting of air for experiment 1, but when reducing the height of the exhaust grille in experiment 3, there was no short-circuiting of air. For experiment 2, which was under normal operations, the logarithmic curve showed less tendencies of short-circuiting than experiment 1, but the corner of the pool had a faster air exchange than the point above the pool.

The current system seems to differ a lot from how the system is designed. The supply diffusers that was supposed to work as "security diffusers", are always in operation. The tracer gas experiments and the smoke visualization showed tendencies to a fully mixed flow and short-circuiting of air. However, this does not mean that the ventilation system is bad. A reduction in the height of the exhaust grille showed much less short-circuiting of air. This may be something that could be utilized to improve the ventilation system. However, there are several factors that could have an impact on the measurements, and before taking any measures, further measurements should be conducted.

The questionnaire showed that most of the people were satisfied with the indoor climate. Some people stated that they were feeling cold after leaving the pool, but taking into consideration that people perceive the temperature differently, this is not unusual. The determined PMV did not coincide with the thermal sensation of the users' of the pool, which may be due to that the indoor climate in swimming pools differs a lot from the climate that table E.7 from Annex E i NS-EN ISO 7730 is based on. However, the amount of respondents is a big limitation, which makes it impossible to draw any conclusions in regards to the indoor climate.

10. Further work

Ideally should all measurements be conducted with normal occupancy in the pool. A higher activity in the pool will lead to increased evaporation, which will affect air flow pattern in the room, as well as the indoor climate. This may, however, be hard considering measurements above the water surface. A solution is to simulate activity in the swimming pool.

Regarding the tracer gas experiments, the recirculation of air is a big weakness when analysing the results, and it should be investigated if there are any alternative tracer gas methods that would be better to utilize in swimming pools.

As the tracer gas experiments implied less short-circuiting of air when the height of the exhaust was reduced, this should also be conducted during normal operations of the ventilation system. Further investigations regarding the height of the stratification layer should be carried out to establish the desired height of the exhaust grille to avoid short-circuiting.

More consistent measurements regarding the atmospheric environment could also be done. A cart with different equipment measuring the indoor air quality could get a better understanding of the indoor air quality in different parts of the swimming pool.

Regarding the calculation of the PMV of the users of the pool, more accurate measurements of the different parameters in the equation should be done. A deeper analysis of the swimmers can also be conducted. As it was very hard to get enough respondents to the questionnaire, one solution can be to print it out and deliver it out manually.

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Appendix

A. Equipment

A.1 Air Velocity Equipment

To measure the air velocity a Swema 3000 anemometer was used. The device can measure both air velocity and temperature by connecting it to an air flow probe. The accuracy for velocities between 0.07-0.50 m/s is ±0.02 m/s, while for the temperature the accuracy is ±0.3 °C (SWEMA ABA).

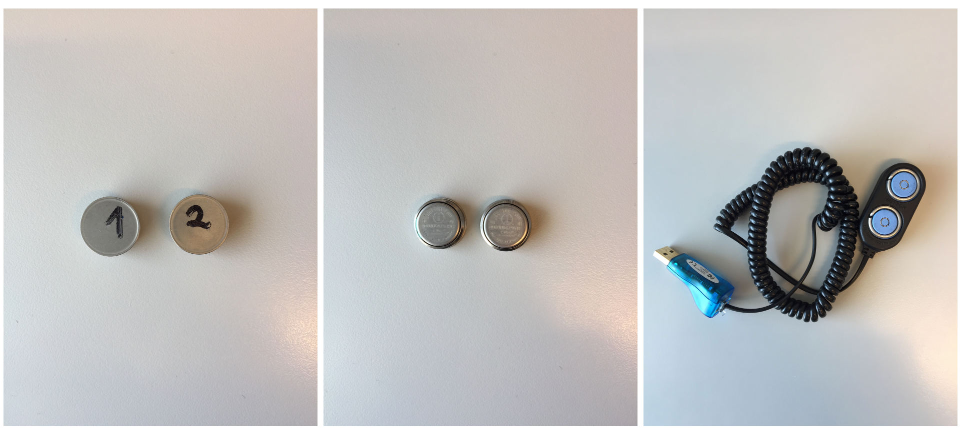
Figure A.1 shows the specifications of the device.

Figure A.1: Swema 3000. Reused with permission from Swema AB (SWEMA ABA)

A.2 Temperature equipment

The Swema 3000 can also measure temperature, which was utilized when the air velocity was measured.

To measure the temperatures in the swimming pool continuously, iButtons were placed on the walls. Each iButton has its own unique address, and can log temperatures for different intervals in longer periods of time. There are several types of iButton, in this case the DS1922L-F5 was used. The temperature range of the DS1922L-F5 is from -40 °C to +85 °C, with an accuracy of ± 0.5 °C (iButtonLink, 2018). An USB adapter is connected to a computer with a Maxim 1-Wire Viewer Software program installed. The iButtons are placed in the adapter, and logging specifications are set. When the temperature logging is finished the iButtons are placed in the adapter and the data can be transported to a computer.



(a) Each iButton was marked with a number **(b)** Each iButton has its own unique address **(c)** USB adapter for transporting data

Figure A.2: iButton equipment

A.3 Tracer gas equipment

For the tracer gas experiment a Multipoint Sampler and Doser and a Multi-gas Monitor from Brüel & Kjær were used. The Multipoint Sampler and Doser Type 1303 has six sampling points. Plastic tubes are connected to these points and stretched to the desired sampling points. The sampling is done for one sampler at time, and it takes around one minute for each sample. The sampler machine is connected to a Multi-gas Monitor type 1302 where the sampled values are analysed. The monitor is connected to a separate computer with a LumaSense Technologies Software installed. Through this software type of gas is chosen, as well as what channels that are activated. Both graphical and numerical data is saved to a database.

Figure A.3: Multipoint Sampler and Doser, Multipoint-gas Monitor

A.3.1 Calibration Multi-gas Monitor

The Multi-gas Monitor from Brüel & Kjær comes with a calibration chart for the filter for N_2O.

LumaSense Technologies

Calibration Chart for Multi-gas Monitor Type 1302

Serial No. : *1846864*

Installed Optical Filter: *UA 0985* to measure: *Dinitrogen oxide* with
Detection Limit: *0.03* ppm.
Filter Installed in Position: *D*
Filter Bank: *1*

Calibration Data for Filter :

Gas name: *Dinitrogen oxide*
Molecular weight: *44.01*

Concentration offset factor[1]: *3.096E-06*
Humidity gain factor[1]: *2.365E-02*
Conc. conversion factor: *1.900E+05*

Cross interference on filter A: *3.667E+08*
Cross interference on filter B: *1.096E+06*
Cross interference on filter C: *1.401E+06*
Cross interference on filter D: */*
Cross interference on filter E: *0.000E+00*

[1] *Coefficients copied to bank 2 to 5.*

Calibration Data :

Average zero level, (Dry zero gas): *-2.19E-03* ppm
Standard deviation, (Dry zero gas): *1.50E-02* ppm
Average zero level, (Wet zero gas): *-1.34E-02* ppm
Standard deviation, (Wet zero gas): *7.89E-03* ppm

Average gas concentration level: *5.14* ppm
Standard deviation: *0.017* ppm

Ambient temperature: *25.6* °C
Ambient pressure: *1000.0* mBar

Nafion tubing used? *Yes*

The Gas Monitor was calibrated mounted on a non-vibrating surface during calibration.

This Calibration is covered by a warranty for a period of 3 months.

Gas used during calibration:

Specific gas: *Dinitrogen oxide*
Substitute gas: */*
Calibration Gas Concentration: *5.05* ppm

Span Gas Specifications :

Span Gas: *Data from the "Analysis Certificate":*
Certificate no.: *040005508995*
Contents: *Dinitrogen oxide*
Concentration: *5.05 ppm ± 2% rel.*
Date of gas analysis: *141014*
Valid after gas analysis date: *60 months*
Manufactured by: *Air Products*

Zero Gas:

Contents: */*
Quality: */* %
Manufactured by: */*
Zero Gas used (Quality > N_2 5.0) : *Yes*

Water Vapour: *(Water Vapour in Zero gas)*

Dewpoint: *18.0* °C

Signature: HmZ Date: 160204

A.3.2 Gas information

The gas used were Nitrous Oxide (N_2O). The gas was delivered from AGA in a pressured 10 liter bottle. The properties of the gas is listed up in the Table A.1 below (AGA, 2016):

Table A.1: Gas properties

Name	Nitrous Oxide
Chemical formula	N_2O
Colour	Colourless
Smell	Weak sweet scented
Boiling point	-88.5 C
Molar mass	44 g/mol
Density	1.98 kg/m^3
Vapour pressure	5.719 kPa

B. Relative humidity and temperature

Figure B.1 and B.2 show the relative humidity and the air temperature measured in the outdoor supply grille and after the heating battery in the ventilation duct. As the figures show the outdoor air has a pretty low temperature and a high relative humidity. After the heater battery the temperature is increased and the relative humidity is decreased.

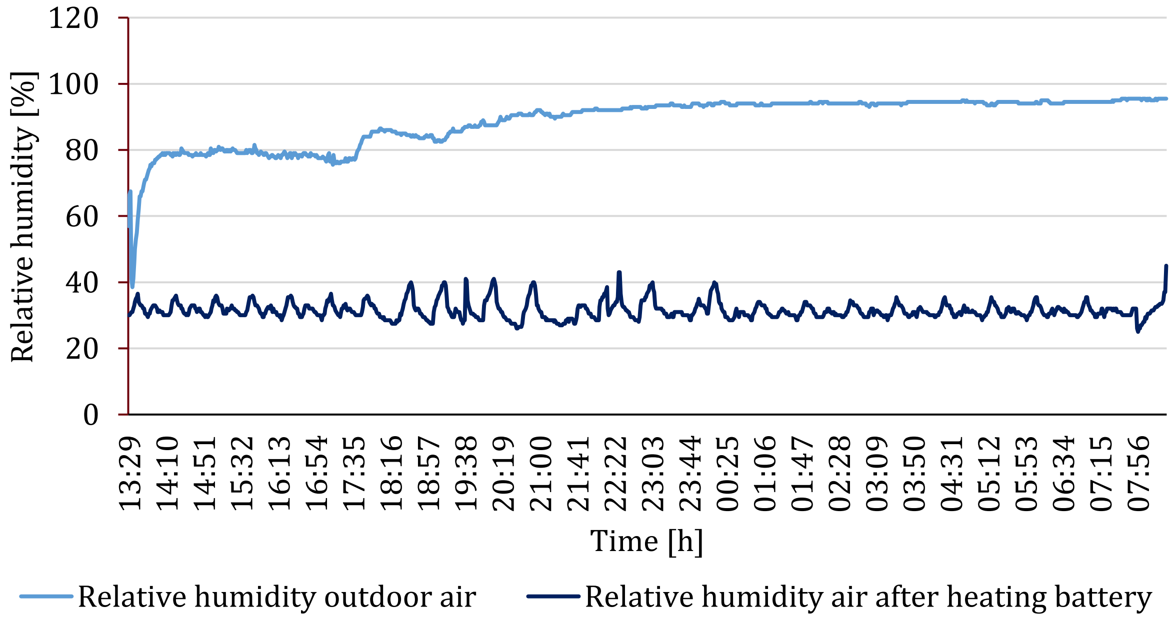


Figure B.1: Relative humidity for the outside air and after heater battery

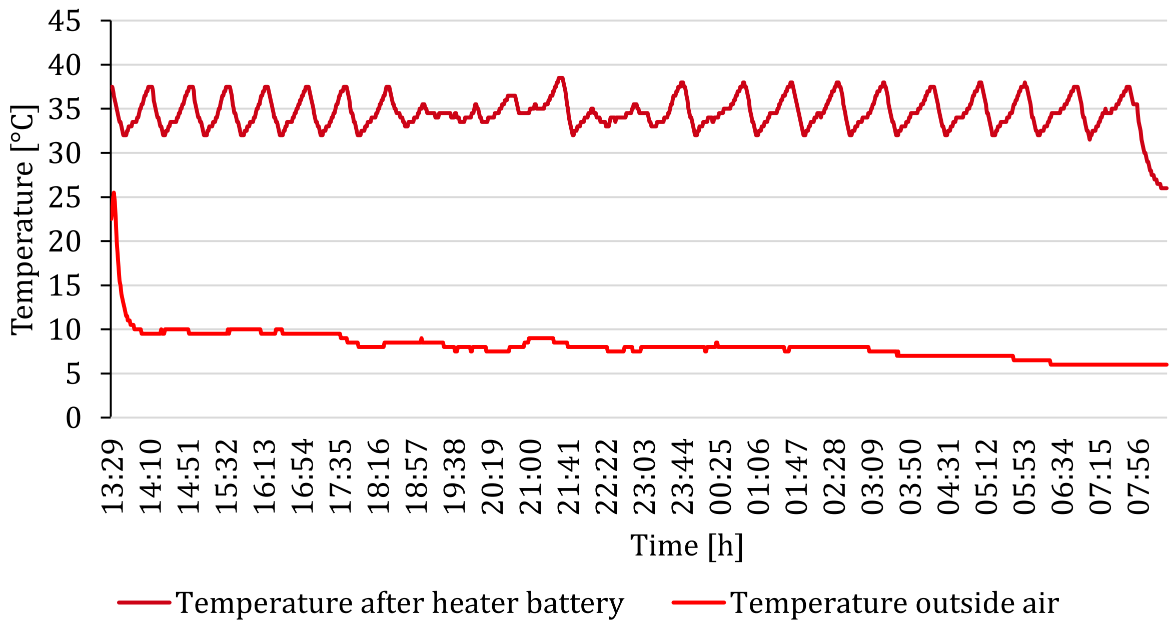


Figure B.2: Temperature air for the outside and after the heater battery

C. Risk assessment

Prior to the field trip the following risk assessment was conducted to reduce and eliminate any risk.

Unit: *Department of Energy and Process Engineering* **Date: 13.04.2018**

Line manager: Therese Løvås

Participants in the identification process: Julie Jørgensen (student), Hans Martin Mathisen (supervisor), Ole Øiene Smedegård (supervisor)

Short description of the main activity/main process: Master thesis for student Julie Jørgensen. Analysis of the indoor climate at Jøa svimming hall.

Is the project work purely theoretical? (YES/NO): NO *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* H. M. Math. *Student:* Julie Jørgensen

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
01	Tracer gas testing in lab	Julie Jørgensen	No	No	No	
02	Tracer gas experiment at Jøa svimming hall	Julie Jørgensen	No	No	No	

NTNU HSE/KS	Risk assessment	Prepared by	Number	Date
		HSE section	HMSRV2603E	04.02.2011
		Approved by		Replaces
		The Rector		01.12.2006

Unit: *Department of Energy and Process Engineering* **Date: 13.04.2018**

Line manager: Therese Løvås

Participants in the identification process : Julie Jørgensen (student), Hans Martin Mathisen (supervisor), Ole Øiene Smedegård (supervisor)

Short description of the main activity/main process: Master project for student Julie Jørgensen. Analysis of the indoor climate at Jøa swimming hall.

Signatures: *Responsible supervisor:* [signature] *Student:* Julie Jørgensen

Activity from the identification process form	Potential undesirable incident/strain	Likelihood:	Consequence:			Risk Value (human)	Comments/status Suggested measures
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
Tracer gas testing in lab	Handling of hazardous gas, N_2O	1	E	D	A	1E	Concentration of gas under work zone levels. Gas bottle secured.
Tracer gas experiment at Jøa svimming hall	Drowning	1	E	A	A	1E	Knows how to swim. Will not be alone.
Tracer gas experiment at Jøa svimming hall	Falling of ladder	1	B	A	A	1B	Will be careful. Will not be alone.
Tracer gas experiment at Jøa svimming hall	Handling of hazardous gas, N_2O	1	E	A	A	1E	Concentration of gas under work zone levels. Gas bottle secured. Will always be two people present under the experiment. Gas bottle placed in technical room that is ventilated. Will wear safety glasses.
Tracer gas experiment at Jøa svimming hall	Traffic accident on the road	1	E	D	A	1E	Have licence. Will wear seat belt.

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

Potential undesirable incident/strain
Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork
Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

Risk = Likelihood x Consequence
Please calculate the risk value for “Human”, “Environment” and, if chosen, “Economy/materiel”, separately.

About the column ”Comments/status, suggested preventative and corrective measures”:
Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE						
	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour	Description
Red	Unacceptable risk. Measures must be taken to reduce the risk.
Yellow	Assessment range. Measures must be considered.
Green	Acceptable risk Measures can be considered based on other considerations.

D. Questionnaire

The following questionnaire was issued to the users and the operators of the swimming pool.

NTNU
Kunnskap for en bedre verden

Inneklima i Jøa svømmehall

Hensikten med denne spørreundersøkelsen er å se nærmere på hvordan temperaturen og luften i Jøa svømmehall oppleves av brukerne. Resultatene fra undersøkelsen vil bli brukt i min mastergradsoppgave ved Norges teknisk-naturvitenskapelige universitet (NTNU).

Det er frivillig å delta, og all informasjon vil bli behandlet konfidensielt. Datamaterialet vil bli anonymisert ved prosjektslutt, senest ved utgangen av juni 2018. Resultatene vil bli presentert slik at ingen enkeltpersoner kan gjenkjennes.

Det tar ca. 5 minutter å svare på undersøkelsen. Vennligst besvar alle spørsmålene i en økt. Bryter du av underveis, vil du ikke kunne komme tilbake til dine svar. Du samtykker i å delta på undersøkelsen ved å svare på spørsmålene og sende dem inn ved å klikke på "Ferdig" på siste side.

Takk for at du er villig til å delta!

Julie Jørgensen
Mastergradsstudent

Hans Martin Mathisen
Professor/veileder

Institutt for energi- og prosessteknikk, NTNU

NTNU
Kunnskap for en bedre verden

Inneklima i Jøa svømmehall

1. Hva er ditt kjønn?
   - ○ Jente
   - ○ Gutt

2. Hva er ditt yrke?
   - ○ Elev
   - ○ Lærer
   - ○ Arbeidende i svømmehallen
   - ○ Annet:

   [ ]

3. Hva er din alder?
   - ○ 9-15

- 15-20
- 20-30
- 30-40
- 40-50
- 50-60
- 60-

4. Hvor ofte er du i svømmehallen?
   - Flere ganger i uken
   - Én gang i uken
   - 2-3 ganger i måneden
   - Én gang i måneden
   - Sjeldnere

NTNU
Kunnskap for en bedre verden

Inneklima i Jøa svømmehall

Plager tilknyttet bruk av svømmehallen

5. Når du er i svømmehallen, er du da plaget av noe av det som er nevnt nedenfor?

	Ja, ofte	Ja, av og til	Nei, aldri
Trekk (Uønsket avkjøling av deler av kroppen som forekommer av luft i bevegelse)?	○	○	○
For varmt i luften	○	○	○
For kaldt i luften	○	○	○
For varmt i vannet	○	○	○
For kaldt i vannet	○	○	○
Ubehagelig lukt	○	○	○
For mye bråk	○	○	○
For svakt lys	○	○	○
For sterkt lys	○	○	○
Støv eller skitt	○	○	○

6. Andre ting du har vært plaget av i svømmehallen:

7. Har du etter å ha vært i svømmehallen opplevd noen av disse plagene som følge av inneklimaet i svømmehallen?

	Ja, ofte	Ja, av og til	Nei	Vet ikke

Vondt i hodet	◯	◯	◯	◯
Kvalm/svimmel	◯	◯	◯	◯
Vanskelig å følge med i timen/Dårlig konsentrasjon	◯	◯	◯	◯
Tretthet	◯	◯	◯	◯
Kløe, svie og irritasjon i øyne	◯	◯	◯	◯
Tett nese	◯	◯	◯	◯
Tørr hals	◯	◯	◯	◯
Hoste	◯	◯	◯	◯
Tørr eller rød hud i ansiktet	◯	◯	◯	◯
Kløe/flass i hodebunn	◯	◯	◯	◯
Eksem	◯	◯	◯	◯
Astma	◯	◯	◯	◯

8. Andre plager/kommentarer til inneklimaet i svømmehallen:

NTNU
Kunnskap for en bedre verden

Inneklima i Jøa svømmehall

Luftkvalitet og lufttemperatur i svømmehallen

9. Hva synes du om luften i svømmehallen?

◯ Veldig god
◯ God
◯ Akseptabel
◯ Dårlig
◯ Veldig dårlig

10. Problemer med luften (Her kan det være flere svar)

☐ Verre med en gang svømmingen starter
☐ Verre når svømmingen er ferdig

11. Andre problemer med luften:

12. Hva synes du om lufttemperaturen i svømmehallen **før** svømmingen?

- Veldig varm
- Varm
- Litt varm
- Nøytral
- Litt kald
- Kald
- Veldig kald

13. Hva synes du om lufttemperaturen i svømmehallen **etter** svømmingen?

- Veldig varm
- Varm
- Litt varm
- Nøytral
- Litt kald
- Kald
- Veldid kald