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Commissioning of the HVAC-plant in a large office building designed with an underfloor ventilation system including input into what should be emphasized when evaluating the total system is to be done.

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Submission date: June 2010
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Problem Description

Background and objective.
In Trondheim, a new bank building complex named Sparebank 1 kvartalet is erected. In the buildings the designers have decided to use an innovative HVAC solution including an underfloor air distribution (UFAD) system. This is done in order to achieve effective ventilation, good indoor air quality and at the same time using the thermal mass of the building construction as an energy storage device.

The office part of the premises is mainly landscaped offices, single person offices as well as meeting rooms and other accommodations typical for bank buildings. The main issue is minimizing the carbon footprint and the need for delivered energy in a multi-functional building where the different functions are time dependent, while at the same time satisfying occupants requirements for indoor climate and cost efficiency.

The plan of progress shows that the testing of the first block is starting in March / April 2010 and that the final and total test is to be finalized in Sept / Oct 2010. It will therefore not be possible for the candidate to evaluate the solutions in full, but it can still focus on the importance of correct planning and what should be evaluated when commissioning of the complete HVAC-plant is to be done.

The following questions should be considered in the project work:

1. Initially, the candidate shall make a brief, but general and satisfactory, description of the building complex including ventilation principle, the HVAC-technical systems and other relevant installations.

2. Then the candidate shall focus on:

Test procedures with a focus on what should be tested
What should be emphasized with respect to measurement and control during testing
What should be evaluated and what should be included in this initial period of testing, including registration and measurement of customer satisfaction?
What is the necessary documentation for the measurement of achievement?

3. Finally, the candidate shall give an assessment of what can be expected with regard to working environment and indoor air quality as well as energy consumption and environmental impact of the new bank building.

Assignment given: 25. January 2010
Supervisor: Vojislav Novakovic, EPT

Norwegian University
of Science and Technology
NTNU

Department of Energy
and Process Engineering

NTNU

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MASTER THESIS

for

Stud.techn.Galina Stankevica
Spring 2010

Commissioning of the HVAC-plant in a large office building designed with an underfloor ventilation system including input into what should be emphasized when evaluating the total system is to be done.

Ferdigstillelse av HVAC-anlegget i et større kontorbygg konstruert med undergulv ventilasjonssystem ("installasjonsgulv") inkludert innspill til hva som bør vektlegges når evaluering av hele systemet skal gjennomføres.

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Within 14 days of receiving the written text on the diploma 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.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

One – 1 complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author's name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).
Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 25 January 2010

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Preface

This Master thesis finalizes the exchange study period at the Norwegian University of Science and Technology (NTNU). Thesis has been performed at the department of Energy and Process Engineering in the faculty of Engineering Science and Technology with Professor Vojislav Novakovic (NTNU) as a main supervisor. The work was carried out between January and June 2010, and has been supported by EEA and Norway Grant scheme.

I would like to express my appreciation to academic supervisors: Prof. Sten Olaf Hanssen, Vojislav Novakovic, and Rasmus Høseggen. Thank you for your advice and positive cooperation. Special thanks to Sten Olaf Hanssen and SpareBank 1 representatives Jørgen Løfaldli and Trygve Leiksett for giving me the opportunity to be part of this interesting project. My gratitude also goes to YIT AS project leader Harald Hasfjord and service technicians Åge and Hermod for their practical on-site assistance.

21.06.2010

Date

Signature

Summary

The following paper presents HVAC system commissioning activities, highlighting the most critical techniques and features to consider when commissioning the underfloor air distribution (UFAD) system. UFAD systems are non-standard and unique and therefore a special attention is needed to some issues and situations specific only for UFAD installations, e.g. coordination of the raised access floor, carpet and furnishings, temperature stratification etc. Some of the most important tests to be performed during commissioning of UFAD systems, are the air leakage, air stratification and thermal decay testing. In order to achieve successful operation of UFAD, the active participation of all involved parties, e.g. architects, interior designers, HVAC designers, contractors etc. is needed since the very beginning of the project. Commissioning of UFAD just requires a discipline, structured approach and commitment from all participants involved.

The practical study involved assessment of expected UFAD performance at the Sparebank kvartalet office building complex in Trondheim, Norway. The underfloor plenum was not properly sealed, creating a significant risk of future energy waste. The openings in the raised access floor construction also lead to the dust and dirt accumulation in the plenum. This in its turn would not only impair indoor air quality, but could also lead to the malfunction of mechanical equipment installed in the plenum. Trying to seal the plenum after laying down the carpet was found to be difficult, costly and time consuming. Even though relatively good air distribution in the entire floor was achieved, some diffusers (automatically controlled) are located too close to the workstations and it will be probably needed to rearrange their layout in order to avoid draught complaints by occupants.

The easier commissioning and better performance of UFAD in Sparebank Kvartalet could actually be achieved in a less time consuming and costly way if the commissioning would start early in the pre-design phase, with a well established commissioning plan.

Abstract

The following paper presents HVAC system commissioning activities, highlighting the most critical techniques and features to consider when commissioning the underfloor air distribution (UFAD) system. Air leakage, room air stratification and thermal decay testing are the most important tests to be carried out in order to achieve successful operation of UFAD, i.e. creating good indoor climate with low energy use.

The practical study involved assessment of expected UFAD performance at the Sparebank kvartalet office building complex in Trondheim, Norway. The underfloor plenum was not properly sealed, creating a significant risk of future energy waste. The openings in the raised access floor construction also lead to the dust and dirt accumulation in the plenum. This in its turn would not only impair indoor air quality, but could also lead to the malfunction of mechanical equipment installed in the plenum. Even though relatively good air distribution in the entire floor was achieved, some diffusers (automatically controlled) are located too close to the workstations and it will be probably needed to rearrange their layout in order to avoid draught complaints by occupants.

Key words: HVAC, Underfloor air distribution (UFAD), Air leakage, Thermal decay, Underfloor plenum, Raised access floor, Indoor air quality

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Nomenclature

AHU	air handling unit
CAV	constant air volume
COH	conventional overhead
HVAC	heating, ventilation and air conditioning
MRT	mean radiant temperature
RAF	raised access floor
SBS	sick building syndrome
UFAD	underfloor air distribution
VAV	variable air volume
VFD	variable flow damper

1 Introduction

For the last few decades underfloor air distribution systems have become very common in a wide variety of projects ranging from offices to schools and data centers. These systems besides being innovative are also effective, i.e. can combine desire for good air quality and comfort with requirements for low energy use and cost efficiency [Bauman 2003]. However, similarly like with any other HVAC project, the success of UFAD project with respect to the energy and operational performance depends greatly on commissioning activities.

According to [ASHRAE 2007] commissioning is defined as *"a quality-oriented process for achieving, verifying, and documenting that the performance of the facilities, systems, and assemblies meets defined objectives and criteria"*. Thus the primary objective of any HVAC commissioning process is to provide documented confirmation that facility's building systems operate as designed, i.e. fulfilling the specified performance requirements for the building owner, occupants and operators.

Generally, UFAD systems do not require specific or unusual steps in the commissioning process, and the traditional commissioning activities can be implemented. However, commissioners should always keep in mind that design of UFAD systems is non-standard and unique. Therefore a special attention is needed to some issues and situations specific only for UFAD installations, e.g. coordination of the raised access floor, carpet and furnishings, temperature stratification etc. Since so far no UFAD commissioning standards are available, commissioning agents based on their previous experience usually set up their own guidelines specified for a particular project. The exact method to be used or the extent of commissioning varies based on the client's personal preferences and experience of the project team. However, usually UFAD systems require a larger scope of commissioning compared to the conventional systems and consequently involve higher commissioning costs. It is well known that the project scope is easier and cheaper to change in the very beginning of the project than fixing errors when the system is already installed and operating. Thus commissioning should be performed as early as possible in order to enhance success of the UFAD and increase the value of the building it is going to serve.

1.1 Objective

The main objectives of this paper are as follows:

- to present HVAC commissioning activities, highlighting the most critical techniques and features to consider when commissioning the underfloor ventilation system
- to give an assessment of expected UFAD performance at the Sparebank kvartalet office building complex in Trondheim, Norway.

2 Methodology

This paper is focused on presentation of most critical techniques and features to consider when commissioning the underfloor ventilation system. Conventional commissioning activities that are used for traditional ducted systems and might be applicable for UFAD systems are also presented in this work. The theory part is organized splitting commissioning activities according to the different commissioning phases, i.e. pre-design, design, construction, and occupancy and operation phases. The literature study of the topic is based on the compilation of available information, including design guidelines, standards and experimental studies.

The on-site work at Sparebank kvartalet building complex was carried out between 12th April and 14th May. Due to the construction delay and problems occurring at the initial commissioning it was impossible to make evaluation of predicted UFAD performance based on measurements. The data to be obtained in this case would not be reliable and not represent the actual operating conditions according to the specified room control. Therefore the assessment is entirely based on observations made during the daily building visits. The only exception are the supply airflow measurements at diffusers that were actually carried out with system operating at the maximum design airflow rate. Obviously for air distribution investigation more interesting results could be obtained while running the system at the minimum airflow rate, but this was unfortunately impossible to perform, since the system had not been programmed for this mode at that period of time. This practical study was therefore limited to the assessment of expected thermal environment, indoor air quality and some issues related to energy consumption.

The registration and measurement of customer satisfaction is expressed as building's occupants' satisfaction.

3 Pre-design phase commissioning

At the very beginning of the project the commissioning team needs to be established in order to supervise and accomplish commissioning. The commissioning team will be consequently responsible for the coordination of all parties involved in UFAD execution, and for personally making all inspections during the execution of the project. The commissioning plan developed by commissioning team members for measurement of the effectiveness of the design and construction should be accepted by the owner.

When considering UFAD systems it is very important to discuss with the owner the spatial considerations, interdisciplinary issues, and the overall quality and performance desired. According to [Beaty 2005] the following issues should be discussed during the pre-design phase:

- *Plenum contents.* This is one of the most important issues affecting future performance of UFAD system. Since the height of the plenum is constant and restricted, the change in the plenum content will directly affect performance of UFAD. For example, putting too much cabling may result in the insufficient air flow rate at air terminal devices. The following questions should be considered:

  - Type of cable routing, i.e. unstructured or structured
  - Plenum occupancy for piping, including plumbing, HVAC, and fire protection
  - Plenum occupancy for cabling, including power, signaling, and voice/data
  - Percentage of vertical obstruction for the piping
  - Percentage of vertical obstruction for the cabling

- *Load characteristics.* It is important to identify zones with different occupancy density that might result in non-uniformly distributed cooling loads throughout the space. For example, there might be a zone where people are more concentrated in one area, and this would consequently lead to the additional cooling requirement in this particular area. Thus the supply of the conditioned air to this area should be coordinated with the underfloor fluid dynamics and plenum content.

- *Frequency and impact of change*. Flexibility in terms of space rearrangement is one of the advantages of UFAD systems. Therefore it is advisable to predict for the future changes, so that the plenum performance and design is not further affected. For example, installing additional equipment in the space will directly affect the cooling capacity that in its turn might have a negative impact on system performance.

- *Air tightness of the raised floor plenum*. The allowable air leakage rate should be discussed and quantified, as well as issues concerning handling of cable openings etc.

4 Design phase commissioning

4.1 Design review

The design phase commissioning is the optimal time to add the extra value to the project without necessarily adding a large cost. The review of the structural details of constructions, e.g. walls, floors and other potential leakage areas, would allow simple, but important changes to be made during design.

According to [Nelson & Stum 2006] the following aspects should be considered during the commissioning design review of UFAD system:

- *Number of AHUs serving the same underfloor plenum.* With numerous AHUs operating in parallel to supply air to the same plenum, attention should be directed towards the control of variable flow dampers (VFDs). VFDs in such cases are typically controlled by a single static pressure sensor, or alternatively by multiple sensors having averaging routine. Another issue to consider is the consequences of possible failure of one of AHUs.

- *Type of sensors.* It is important to choose a sensor that could work in the intended ranges for it. For example, pressure sensors installed in the air highways should be suited for the higher static pressures compared to the general underfloor plenum sensors.

- *Location of temperature and pressure sensors.* The reading of the sensor is directly affected by its location. For example, temperature sensors might show the false reading if placed on the walls subjected to potential leakages from the underfloor plenum. The differential pressure sensors should be located away from corners, supply dampers or other obstructions that could lead to the undesired false results.

- *Air highways.* The farthest non-fan-powered diffusers should be located at the maximum distance of about 15 m from the end of a duct of the supply air highway. In addition, diffusers should not be located in the high pressure areas. Air highways itself should be airtight and not leak.

- *Noise.* The air highways should be insulated in order to reduce the noise. For the same reason diffusers should not be located too close to occupants.

4.2 Drawing details

Drawings of raised access floor with UFAD should include details about sealing the plenum, locations of the underfloor equipment with respect to the floor grid, as well as locations of all floor outlets (e.g. floor diffusers) with respect to the furniture layout etc.

Since UFAD system is structural in nature, it should be generally designed by mechanical engineer together with the architect and structural engineer. In an ideal case commissioner should provide input both on architectural and structural drawing details with respect to wall joints and penetrations etc., as well as on the actual UFAD system installation.

Since air tightness plays a great role in the future performance of UFAD system, especially with respect to the energy savings, commissioner should also address sealing requirements and techniques of the plenum, and explain contractors the importance of sealing the plenum properly, following the stipulated methods. This will allow to perform real sealing activities early in the construction phase with the lowest expenses, since if performed later (e.g. after carpet installed, furniture moved in), it will result in significant increase of relevant expenses and will be more time consuming leading to additional problems to the owner and contractors. The list with sealing requirements is given in Appendix A.

4.3 Specifications

As mentioned before, the design and specification requirements normally need to be addressed by multiple parties. Therefore it is important to clearly state their responsibilities, e.g. responsibilities for sealing the plenum to avoid future failure to maintain underfloor plenum pressure. Only through well coordinated process it will be possible to achieve UFAD project "on budget" and "on schedule". In case one of the parties involved feels unqualified for execution of particular task, commissioning agent needs to assign a consultant.

According to [Nelson & Stum 2006] involved parties should consider the following specification sections:

- Quality control
- Cleaning
- Cutting and patching
- Joint sealers
- Sheet rock
- Access/raised floor
- Structural steel
- Expansion joint cover assemblies
- Basic Mechanical Materials and Methods
- Mechanical Insulation
- Air Handling Equipment
- Air Distribution
- Testing, Adjusting, and Balancing
- Basic Electrical Materials and Methods
- Conductors and Cables

The underfloor construction checklist is given in Appendix B.

5 Construction phase commissioning

Before the construction or installation phase it is suggested to conduct a pre-installation meeting in order to once again stress the importance of proper plenum sealing, coordination of parties involved in placing the systems under the RAF, and emphasize the importance of cleaning.

5.1 Completeness check

Before to start functional performance testing it is first needed to verify that the HVAC system is installed completely and in compliance with relevant technical rules. According to [NS-EN 12599: 2000] the completeness check includes the following main activities:

- Comparison of installed HVAC system's equipment and components with the design specifications (installation list). Attention should be paid to the volume and materials, as well as characteristics and spare parts.
- Compliance with the relevant legal documents, i.e. building codes, standards etc.
- Check of the accessibility of the system with respect to the operation, cleaning and maintenance.
- Check of the cleanliness of the system.
- Check if all documentation necessary for the operation of the system is available.

The completeness check includes basically submission of the relevant documentation to the client and initial testing other than functional, as showed in Figure 5.1.

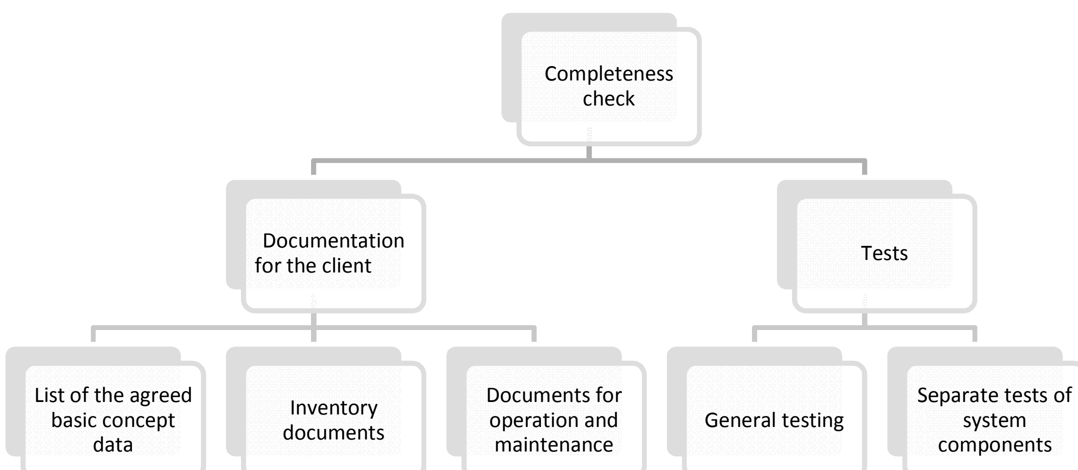


Figure 5.1: Completeness check [NS-EN 12599: 2000].

The list of the agreed basic concept data includes information for performance of system (e.g. information about the building itself, input data in system design and design parameters), and data for checking economic efficiency (e.g. energy cost, return on investment etc.).

Inventory documents include a list with specifications for all components of the ventilation system (e.g. system drawings and diagrams).

Separate tests include testing of ventilation system components such as fans, heat exchangers, air filters, dampers etc.

The detailed list of the documents to be delivered to the owner/developer, as well as initial system tests are given in Annex A of [NS-EN 12599: 2000].

5.2 Functional checks

The main aim is to verify that operational capacity of the system is in compliance with specifications. The testing is performed to document that all system components are correctly installed and operating as intended. The testing should start only after all installation work has been completed and system adjusted. The detailed list with all preliminary works to be done prior functional testing is given in Annex B of [NS-EN 12599: 2000]. In addition, before to start, the checklists for system equipment should be available (usually provided by product manufacturers or contractors).

The functional testing should be performed for any type of installed equipment. The extent of testing should be discussed with the parties involved in advance. The level of functional checks usually corresponds to the level of functional measurements, unless otherwise agreed.

5.3 Functional measurements

The aim is to provide documented proof that the system achieves the design conditions and set points as specified in the design project.

The extent of the functional measurements is based on the particular type of ventilation and air conditioning system. Usually the measurements are performed both at the central system/appliance and room, as showed below [NS-EN 12599: 2000]:

Central system/appliance

- Current drawn by the motor
- Air flow (outdoor, supply, and exhaust air)
- Air temperature (outdoor, supply, and exhaust air)
- Pressure drop at filter

Room

- Supply and exhaust airflow
- Supply air temperature and air temperature in the room
- Air humidity
- Sound pressure level
- Indoor air velocity

The technical documents should include measuring locations, measuring instruments as well as measuring procedures. At least one measuring point is required per room area of up to 20 m^2; larger areas should be subdivided accordingly. The measurements should be carried out in the occupied zone, as well as in the areas where the worst conditions to be expected, e.g. close to the external walls and windows.

The measurement instruments should be chosen with respect to the tolerances given in Table 5.1.

Table 5.1: Allowed uncertainties of measurement parameters [NS-EN 12599: 2000].

Parameter	Uncertainty
Air flow rate, each individual room	± 20%
Air flow rate, each system	± 15%
Supply air temperature	± 2°C
Relative humidity [RH]	± 15% RH
Air velocity in the occupied zone	± 0.05 m/s
Air temperature in the occupied zone	± 1.5°C
A-weighted sound pressure level in the room	± 3 dB(A)

The values specified in Table 5.1 include deviations from the designed values and all measurement mistakes.

The indoor climate factors and airflow rates, as well as other design data should be measured at the design air flow rate of ventilation system.

5.3.1 Measuring methods and devices

5.3.1.1 Air flow rate

According to [NS-EN 12599: 2000] the measurements of air flow rate can be performed:

- In the duct cross section
- With throttle devices
- In the cross section of a chamber or device
- At the air terminal devices

The air flow rate is usually calculated from the measurements of the air velocity and corresponding cross-section. Since the air velocity is rarely uniform, it should be measured at the number of locations in the cross section and then the average value calculated that will be consequently used for determination of the air flow rate.

The results from the airflow measurements as for any other measurements should be clearly presented in a signed protocol. According to [Malmstrom et al. 2002] the following information should be included in the protocol:

- Data describing the plant, project, reference number and date for the measuring.
- System measured and location of the probe or instrument.
- Instruments used (their number or any other designation that will enable their identification in case for example of any disputes.).

- The measured data.
- Notes or factors that might have affected the measured result.
- Calculated probable measurement error (deviation from the stated value).
- Signature of the responsible person for measurements.

5.3.1.2 Air temperature

The air temperature can be measured with various types of thermometers such as expansion thermometers, electrical thermometers and thermomanometers. The principle is to measure the variation of one property (e.g. lengths of solids, volumes of liquids, electrical resistance and electromotive force) that change with temperature.

Precaution should be directed to the following:

- *Reduction of the effect of radiation (coming from hot or cold surfaces)*. Since the environment is almost always inhomogeneous, i.e. with different surface and air temperatures it is needed to shield the temperature sensor from any influences of thermal radiation in order to measure the actual air temperature in order to minimize measuring errors. Otherwise the measurement will reflect the intermediate value between the air and mean radiant temperatures. The reduction of the effect of thermal radiation on the probe can be accomplished by one of the methods mentioned in [NS-EN ISO 7726: 2001]:

    - Reduction of the emission factor of the sensor. This can be achieved by polishing or covering the sensor with the reflective paint.

    - Reduction in the difference in temperature between the sensor and adjacent walls. Since it is impossible to change temperature of walls, the reflective screens (e.g. made of aluminum) might be installed between the sensor and enclosure. In case of reflective screens alone, i.e. without forced ventilation, the gap between screens and sensor should be large enough to allow for air circulation inside [NS-EN ISO 7726: 2001].

    - Increasing the coefficient of heat transfer by convection (between sensor and air). This can be achieved by increasing the air velocity around the sensor, e.g. by means of mechanical or electrical ventilators, and by reduction in the sensor size.

- *Thermal inertial of the sensor.* The air temperature cannot be measured instantaneously, and therefore the measurement should be made after 1.5 times the response time (90%) has elapsed.

The air temperature measuring instruments should be able to measure in the range of 10°C to 40°C. The required accuracy is ± 0.5°C, while desirable is ± 0.2°C [NS-EN ISO 7726: 2001].

5.3.1.3 Mean radiant temperature

"*The mean radiant temperature (MRT) is theoretical uniform temperature of an enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform environment*". The mean radiant temperature is usually used to determine the effect of thermal radiation on person's heat balance.

The MRT can be measured with the black globe thermometer, based on the simultaneous readings of the globe temperature, and the temperature and velocity of air surrounding the globe. However, this method gives only an approximate value of MRT and accuracy varies greatly based on the type of environment being considered (precautions should be taken in heterogeneous environments) and the accuracy of sensors used. It is suggested to use an ellipsoid shaped sensor instead of the spherical shape, since it gives a better approximation to the human body (both standing and seated). According to [NS-EN ISO 7726: 2001] the inaccuracy of measurement of MRT temperature can be as high as ± 5°C for measurements conducted in moderate environments, while the required accuracy by standard is ± 2°C. The desirable accuracy is ± 0.2°C.

The mean radiant temperature is more frequently calculated from the measurements of the surrounding surface temperatures and the size of these surfaces and their position in relation to a person. By this method the MRT can be calculated using equation (5.1).

$$T_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots + T_N^4 F_{p-N} \tag{5.1}$$

Where: T_r – mean radiant temperature [K]
T_N – surface temperature of surface N [K]
$F_{p\text{-}N}$ – angle factor between a person and surface N [-]

The angle factors describe the person's location with respect to the other surfaces and data on angle factors can be found from tables or diagrams given in [NS-EN ISO 7726: 2001].

If there is a small difference between surface temperatures of enclose, equation (5.1) can be simplified to the linear equation (5.2).

$$T_r = T_1 F_{p-1} + T_2 F_{p-2} + \cdots + T_N F_{p-N} \tag{5.2}$$

The descriptions of other, less frequently used, methods for measurement of MRT such as calculation of MRT from plane radiant temperature, measuring method using two sphere radiometer or constant air temperature sensor, are given in [NS-EN ISO 7726: 2001].

5.3.1.4 *The operative temperature*

The operative temperature is defined as the uniform temperature of surrounding air and surfaces, which results in the same heat loss as the actual environment.

When measuring the operative temperature directly, the relation between radiant and convective heat loss coefficient should be the same as for person, i.e. sensors radiation properties should be similar to those of the closed human body. The air velocity is the key parameter affecting the optimal diameter of the sensor that is usually around 0.04 to 0.1 m [NS-EN ISO 7726: 2001]. Similar precautions as for direct measurement of mean radiant temperature with the black globe thermometer should be taken into account, i.e. shape and color of the globe, number of sensors to be used especially in non homogenous environments etc. [NS-EN ISO 7726: 2001].

The operative temperature can be also calculated based on the measurements of the mean radiant temperature and air temperature. It can be calculated according to the equation (5.3).

$$t_o = At_a + (1 - A)t_r \tag{5.3}$$

Where: t_o – the operative temperature [°C]

t_a – the air temperature [°C]

t_r – the mean radiant temperature [°C]

A - Factor in accordance to the relative air velocity [-]. The values for A are given in Table 5.2.

Table 5.2: Determination of “A” values [NS-EN ISO 7726: 2001].

v_{ar} [m/s]	< 0.2	0.2 to 0.6	0.6 to 1.0
A [-]	0.5	0.6	0.7

In many buildings the difference between the air temperature t_a and the mean radiant temperature t_r is small, i.e. < 4°C, and relative air velocity is < 0.2 m/s. Thus the operative temperature can be calculated as the mean value of air and mean radiant temperature.

In addition to equation (5.3) the operative temperature can be also calculated with equation (5.4).

$$t_o = \frac{t_a\sqrt{10v_a} + t_r}{1 + \sqrt{10v_a}} \tag{5.4}$$

Where: v_a – is the air velocity [m/s]

t_r – the mean radiant temperature [°C]

5.3.1.5 *Air velocity*

The air velocity determines the heat transfer by convection and evaporation at the position of a person. The airflow is generally turbulent, and therefore the air velocity is defined by its magnitude and direction at the particular measuring point. Therefore measuring instruments should be not only sensitive to the direction of the airflow and velocity fluctuations, but also be possible to obtain a mean velocity and a standard deviation of the velocity over a certain measuring period.

In order to obtain the accurate air velocity measurements the following issues should be considered [NS-EN ISO 7726: 2001]:

- The calibration of the instrument.
- The response time of the sensor and instrument. The measuring instrument that has a long response time will not be able to measure fast velocity fluctuations.
- The measuring period. The longer measuring period will be required to measure the air velocity in an airflow with a high turbulence intensity and low frequency of the velocity compared to the measurements of the airflow with a low turbulence intensity and a high frequency of the velocity fluctuations.

The air velocity in a space can be measured with different types of anemometers such as vane and cup anemometer, hot wire anemometer, laser-doppler anemometer etc. that might be sensitive or insensitive to the direction of the airflow. The main direction of the airflow can be determined by smoke tests. The air velocity measuring instruments should be able to measure in the range of 0.05 to 1m/s. The required accuracy is ± (0.05 + 0.05 v_a) m/s, while desired ± (0.02 + 0.07 v_a) m/s [NS-EN ISO 7726: 2001].

The most frequently used type of anemometer is the one with the hot sphere sensor. Similarly like all other heated sensors for velocity measurements, it is based on the heat transfer between a hot solid and ambient air. Thus it should typically have two sensors for measurement of temperature of hot element and ambient air. Some instruments have only one temperature sensor for measuring the temperature of the hot solid, and thus they can be used only at the air temperature they have been calibrated.

Since the air velocity at any point fluctuates in time, it is recommended to record these velocity fluctuations. The airflow can be described as the mean velocity, measuring during the certain interval of time, and by standard deviation of the velocity, that can be calculated by equation (5.5).

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_{a_i} - v_a)^2} \tag{5.5}$$

The turbulence intensity has an impact on draft sensations, and can be defined as the standard deviation of the air velocity divided by the mean velocity, and is usually expressed in percentage, as showed in (5.6).

$$TU = \frac{SD}{v_a} \cdot 100 \tag{5.6}$$

Where:TU – turbulence intensity [%]
v_a – mean air velocity [m/s]
SD – standard deviation of air velocity

5.3.1.6 Surface temperature

Surface temperature is temperature of a given surface, and is primarily used to evaluate the radiant heat exchange of the human body. In addition it might be also used for evaluation of the effect of direct contact between human body and given surface. The surface temperatures can be measured with contact thermometers, where sensors are placed in direct contact with the surface of interest. However, since this method is based on the heat exchange between the surface and the sensor, surfaces with low thermal conductivity may lead to the false measurements. Another method is the use of thermal radiation meters (with infrared sensors) by which the radiant heal flux is measured and consequently converted to a temperature [NS-EN ISO 7726: 2001].

According to [NS-EN ISO 7726: 2001] surface temperatures measuring instruments should be able to measure in a range of 0°C to 50°C. The required accuracy is ± 1°C, while desirable is ± 0.5°C.

5.4 Specific UFAD tests

5.4.1 Air leakage test (underfloor plenum)

5.4.1.1 Leakage classes

The air leakage is one of the most common problems related to UFAD systems with pressurized supply air plenums. In some documented cases, where the air leakage tests were performed, the total plenum leakage rates ranged from 30-200% of design airflow rates at plenum static pressures of 17 Pa [Gupta & Woods 2007]. Generally one can distinguish between two primary types of leakage from a pressurized underfloor plenum, i.e. category 1 leaks or general construction leaks, and category 2 leaks or product leaks.

5.4.1.1.1 Category 1 – Construction quality leakage

This type of leakage is referred to leaks from underfloor plenum to the other building cavities (see Figure 5.2).

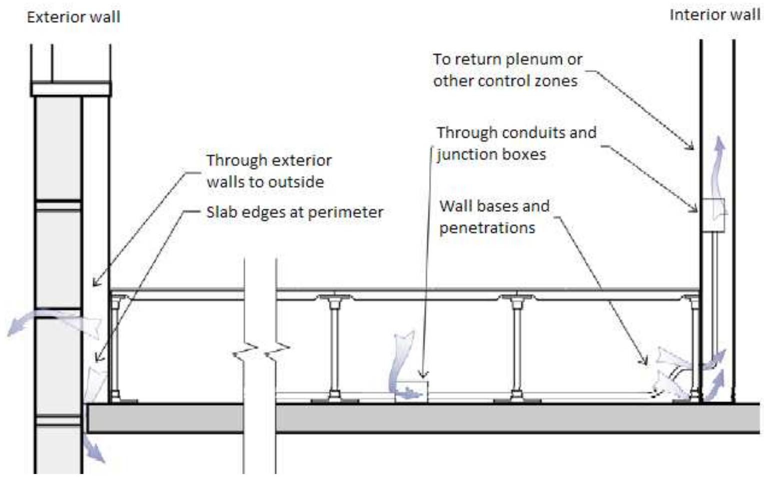


Figure 5.2: Construction quality leakage [Bauman et al. 2008].

This leakage might result in air passing through wall cavities, columns etc. to the return plenum above or below. The air might be also recycled back to the conditioned space, or in the worst case directly to the outside of the building. When this leakage rate is very high it might result in the insufficient amount of air left for space cooling under high load conditions. In any case, in spite of the amount of air leakage, it is causing the waste of energy, including thermodynamic energy used to condition the air, and fan energy to deliver the air through the system. Additionally, if this air leaks to the plenums with surface temperature lower than supply air dew point temperature, condensation occurs, consequently leading to plenum deterioration and mould and bacteria growth on plenum surfaces. Therefore it is very important to ensure that the edge details around the floor plenum, including structural and internal walls, pipe chases, cables etc. are well sealed.

This type of leaks will be most difficult to locate and fix later in the project, and thus the preventive and remedy actions should be taken early at the construction phase. According to [Bauman 2003] the leakage losses of 10-30% can occur in most cases with pressurized plenums, depending on quality of construction, while generally only 3% is considered as acceptable according to GSA guidelines [GSA 2005].

5.4.1.1.2 Category 2 – Floor leakage

This type of leakage is referred as a leakage from the plenum through the raised access floor into the conditioned space. These leaks usually occur at the floor panel seams and edge closures, electric power connection and outlet service units, communications and data service units, as showed in Figure 5.3.

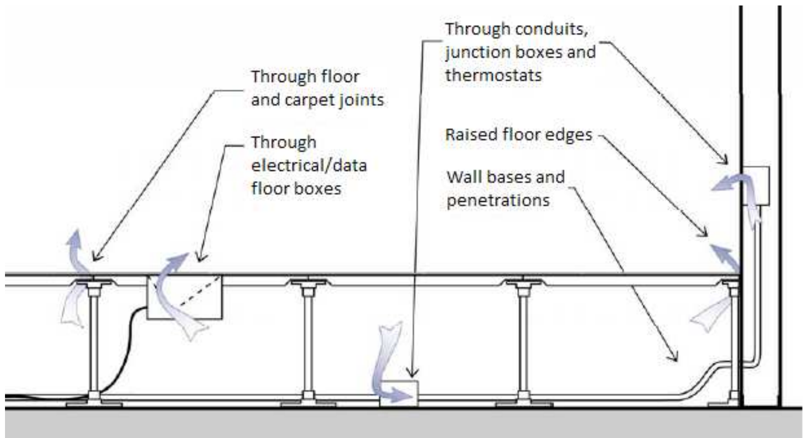
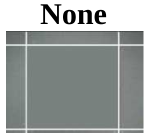
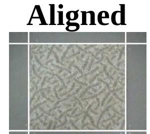


Figure 5.3: Floor leakage [Bauman et al. 2008].

The electrical and data floor boxes are initially designed for RAF applications without UFAD systems and this explains potentially large leakage rate through these devices, i.e. approximately 5-7 l/s per device at 25 Pa [GSA 2005]. The diffusers (even closed) might leak to the similar extent as units for plug-in of power, data and communications. Therefore it is suggested for designer to coordinate with the product manufacturers, requiring maximum acceptable leakage rate in the specifications.

The category 2 leakage rate depends mainly on the raised floor panel type and installation, carpet tile installation and pressure difference across the plenum. Even though pressure in the plenum is usually very low, i.e. in a range of 12.5-25.0 Pa, still the air leakage is an important issue to consider since the surface for leakage is very large. Bauman [Bauman 2003] has performed an experimental study investigating the air leakage through gaps between floor panels with different tile configuration and found out surprisingly high magnitude of air leakage, as indicated in Table 5.3.

Table 5.3: Air leakage between gaps through floor panels [Bauman 2003].

Plenum Pressure [Pa]	**Air leakage [L/(s·m^2)]**		
	None 	**Aligned** 	**Offset** 
12.5 (measured)	3.5	1.5	0.14
25.0 (estimated)	4.9	2.1	0.20

As it can be seen in Table 5.3 the carpet plays an important role in reducing the air leakage between the floor panels. Placing floor tiles as in offset type could reduce the air leakage rate by more than 10 times compared to the aligned carpet tiles.

Compared to the category 1 leakage, the floor leakage is not necessarily detrimental to the system operation. On the opposite, under certain circumstances it might even improve the performance. However, if the leakage rate is high, or it occurs at the undesired place, e.g. close to occupant, it might create comfort problems, especially draught complaints. It may also affect the temperature stratification, reducing the ability of control system to maintain the desired room temperature set point, and consequently occupant comfort.

5.4.1.2 Air leakage criteria

So far the actual impact of the leakages on the energy use and comfort is not documented, and therefore it is hard to establish which leakage rates might be considered as acceptable. However, U.S. General Services Administration (GSA) has addressed this question based on their previous experience of numerous accomplished UFAD projects in US, setting up their own criteria for UFAD plenums, showed in Table 5.4.

Table 5.4: GSA Air Leakage Criteria for UFAD Plenums [GSA 2005].

Test	**Σ Air leakage Category 1 + Category 2**	**Category 1**
Mock-up	0.54 l/s per m^2 floor area	0.11 l/s per m^2 floor area
Building floor plenums	0.54 l/s per m^2 floor area or 10% of the design supply air flow rate, whichever value is smaller	0.11 l/s per m^2 floor area or 3% of the design supply air flow rate, whichever value is smaller

The air leakage values specified in Table 5.4 correspond to the plenum design static pressure of 17.5 Pa.

According to [GSA 2005] it is a good approximation to use maximum 10% of the design supply airflow rate as the reference point for the total plenum leakage. [Nelson & Stum 2007] have reported the air leakage rate of less than 20% as acceptable, emphasizing the importance of taking into consideration the accuracy of air flow measurements, that are typically within ± 10% of the actual value. In some other sources, it is also suggested that air leakage rate should not exceed more than the minimum VAV airflow [Filler 2004].

5.4.1.3 Underfloor leakage test procedures

In order to avoid previously mentioned detrimental effects of air leakage on the system performance, the underfloor plenums should be thoroughly leak tested and approved by commissioning agent and/or other parties assigned for this task.

Before to start testing it is first required to verify that the airflow to the zone is delivered and accurately measured over the range of desired airflow rates. In practice one can distinguish between two primary methods of air delivery:

- *Building's air handling unit (AHU).* In order to accurately record the airflow entering the plenum zone to be tested, the installed airflow sensors must be calibrated (e.g. using a hot wire, pitot tube traverse, calibrated fan method or other relevant methods). In case AHU serves multiple zones, each zone of interest must be isolated, so that accurate airflow measurement can be done [Bauman et al. 2008].

- *Contractor provided blower panel assembly.* In this method the separate fan or few fans are installed to blow air directly to the plenum via one or more floor panels removed or fitted for this purpose. This method requires all plenum inlets from AHU to be tightly sealed. The advantage of this method is that the supply air volume delivered to the particular zone by fans can be more easily controlled and accurately recorded, since usually blower panel assembly has its own high quality sensors [Bauman et al. 2008].

Air leakage testing should be performed in both mockup and permanent construction phase.

5.4.1.3.1 Mockup test – prior to permanent construction

The mockup test should be performed before the construction of any permanent building pressurized plenum systems. The main aim of this test is to determine the air leakage rates at two specific static pressures which are representative of design and operation conditions, i.e. 17.5 and 25 Pa [GSA 2005]. This static pressure test includes procedures to separately determine the Category 1 and Category 2 leakage rates.

The mockup of the system to be tested might be of two types:

- *On-site*, i.e. part of the actual installation. This is the most commonly used way of mockup since it represents the actual construction and there is no need to assign resources for creation of the additional sample. According to [GSA 2005] the size of the on-site mockup should correspond to at least two structural bays of the building. Typically tests are performed for 90 to 360 m^2 of UFAD installation area [Gupta & Woods 2007].

- *Off-site*, i.e. separate structure. According to [GSA 2005] the size of this mockup should not be less than about 90 m^2.

In any case, i.e. whether on-site or off-site, the mockup should include all planned plenum components, penetrations, seams and openings. It is suggested to conduct this mockup test by the same craftsmen, or at least to have the same foreman, that will be further involved in inspecting and testing of the entire building's UFAD installation. Generally the mockup test forms kind of a base of standard for further evaluation and testing of UFAD performance.

As a testing method the fan pressurization test can be used that is basically adapted from the test used to measure the air tightness of building envelope. The test procedure includes the controlled pressurization and depressurization of the finite volume with the use of fans as indicated in the name of this method. The test generally includes the following main steps [GSA 2005]:

- All diffusers and grilles should be fully closed.
- The air is basically blown into an underfloor plenum, increasing the pressure to a preset value (17.5 and 25.0 Pa) in the plenum area. According to [Bauman et al 2008] it is not needed to limit the static pressure values to two, i.e. 17.5 and 25.0 Pa. Since it is quite easy to vary the plenum pressures and airflows, it is possible to develop a characteristic airflow vs pressure equation, from which the air leakage then can be extrapolated to different pressures.
- After steady state condition is achieved, i.e. static pressure do not vary more than ± 1.2 Pa for all measuring locations, the measured static pressure and airflow rate needed to induce this pressure is recorded for six times at uniform intervals of about 10 minutes.
- The average value of these airflow rates is then considered as the total air leakage rate (sum of category 1 and category 2 leakage rates).
- In order to find out category 1 leakage rate the same procedures should be repeated after having properly sealed all floor panel and edge joints, supply air diffusers etc. The difference between the average total and category 1 leakage rates will then represent the category 2 leakage rate.
- The found leakage rates should then be compared with the allowed values (e.g. see Table 5.4). If the uncontrolled leakage is too high, the potential leakage points should be found and corrected, and thus the leakage testing repeated once again.
- The results and lessons learned in this test should be distributed to all trades involved in the UFAD plenum construction, as well to the other parties responsible for project inspection and approval.

Step by step procedures of the mockup testing method developed by GSA are given in Appendix C [GSA 2005].

5.4.1.3.2 Building floor plenum tests during construction

Similarly like with the mockup test, the aim of this test is to verify that UFAD plenum was constructed and sealed in accordance with project specifications and drawings, and meets specified air leakage requirements. However, this test method compared to the mockup test is not intended to measure separately the Category 1 and Category 2 air leakage rates, since it is almost practically impossible to seal completely Category 2 leakage pathways after the construction is completed.

The air leakage test should be carried out before the initial occupancy, but after the substantial construction completion, i.e. after installing all mechanical and electrical devices, equipment, cables etc. in the plenum, but prior to installation of furniture, equipment, etc. that might be damaged from testing activities.

Since the air to the plenum is now supplied with the actual AHU, it is first required to verify that the capacity of AHU will be sufficient to maintain the design air flow rate at design static pressure of plenum. This dynamic air flow test with a minimal effort will allow identifying the potential major problems (e.g. excessive air leakage, undersized AHU). The test generally includes the following main steps [GSA 2005]:

- All diffusers and grilles should be adjusted as specified in design documents.
- The AHU should be adjusted to provide the design (peak) air flow rate. [Bauman et al. 2008] suggests performing this testing under normal operating conditions, since the peak conditions occur only for a very small fraction of time.
- The steady state condition should be achieved. According to [GSA 2005] the static pressure measurements should be carried out for each 90 m^2 with an interval of about 5 minutes. The static pressure should not vary more than ± 1.2 Pa at each measuring location. However, [Bauman et al. 2008] suggests to have an interval of about 15 seconds between pressure readings, since the pressure is varying rapidly in the plenum (within seconds), and it is impractical and unnecessary to wait 5 minutes before to make next measurement. In addition, [Bauman et al. 2008] states that there is no need to measure pressure at each 90 m^2, it is enough to measure at 350 m^2, since static pressure is generally uniformly distributed within the underfloor plenum, unless there are major flow obstructions.
- After steady state condition is achieved the air flow to maintain the specified static pressure in the plenum should be recorded (e.g. by installed flow monitoring device). The measured air flow is then compared with the reading of the airflow rate at the AHU itself. If the difference between measured and design air flow, as well as static pressure values is within 10%, the leakage testing can start following the same procedures as for mockup testing (see step 5 to 7 in Appendix B). Otherwise the sources of discrepancies should be identified and tests procedures repeated until 10% criteria is achieved.

Test step by step procedures suggested by [GSA 2005] are given in Appendix D.

According to [Filler 2004] this leakage test should be conducted every few years, and after space and consequent UFAD reconfiguration.

5.4.1.4 Air leakage detection

The methods used for detecting the air leakage in UFAD systems are basically the same used for air leakage site detection in building envelopes. The most common practices are to use the smoke test and infrared scanning (thermal imaging).

5.4.1.4.1 Smoke Test

The main purpose of the smoke test is to locate air leakage paths, and it can be conducted both during the mockup testing and for permanent system tests. In the latter case it should be conducted during unoccupied periods. Usually the “theatrical” smoke generator (non-toxic) is used, as showed in Figure 5.4.

Figure 5.4: “Theatrical” smoke induction into fan inlet [Gupta & Woods 2007].

This method is based on the pressure differential across the plenum. The plenum is pressurized either by the separate fan or by mechanical system in the building, i.e. AHU. Since the plenum is pressurized, the smoke tracer source is moved over the interior of the plenum, and thus the air exfiltration through the air leakage sites will draw the smoke from tracer source to the site, visually revealing its location [ASTM 2009].

5.4.1.4.2 Thermal imaging

Using thermal imaging for the raised access floor system applications it is possible to find the air leakage pathways in a non destructive way. When using this method, it is possible to obtain documented images of the air leakage paths by creating temperature difference between the plenum and floor above. The thermal imaging testing is best to be performed operating the system in the cooling mode, that is the AHU or separate fan is supplying cool air to the plenum, in order to have larger temperature gradient between the supply and room temperature. After few minutes, the air leakages can be easily found using an infrared camera, as showed in Figure 5.5.

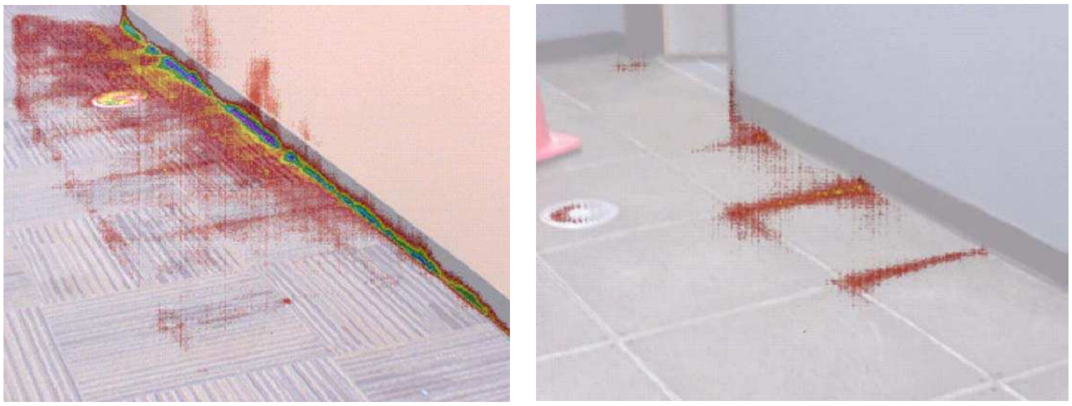


Figure 5.5: Air leakage through RAF construction [Neudorfer Engineers 2010].

In the image on the left, the leakage occurs greatly between the joint of the RAF system and the perimeter wall. On the right, the main air leakage pathways are around the floor tile edge closures.

The images can be ideally used to compare the “before and after” scenarios, i.e. when the leakage paths were identified, the according actions of sealing the construction were taken, and another thermal image would document these corrections and possible improvement or failure achieved. The main advantage of thermal imaging is the rapid surveying capability, covering large areas. The typical specifications for infrared equipment can be found in [ISO 6781: 1983].

5.4.2 Duct air leakage test

Since the air from the AHU to the underfloor plenum is supplied through the ducted air distribution system, it is necessary to perform the air leakage testing of the supply air ducts. The requirements and test methods for leakage assessment are the same as for any other ducted (sheet metal) ventilation system, and are specified in [NS-EN 12237: 2003] for circular sheet metal ducts and in [NS-EN 1507: 2006] for sheet metal air ducts with rectangular section. However, in fact the air leakage testing procedures given in these standards are basically the same for circular and rectangular ducts.

The requirements for air tightness should be specified well before the installation of the ducts and clearly stated in contract documents according to the relevant standards. It is important that these requirements are not only set, but also actually tested in order to ensure that desired quality of ductwork is provided.

5.4.2.1 Requirements

In order to assess air tightness of the ducts, the air leakage factor is used. It is defined as leakage flow rate per unit of duct surface area, as shown in equation (5.7):

$$f = \frac{qV}{A} \tag{5.7}$$

Where: qV – air leakage flow rate of the ductwork at a given test pressure [m^3/s]
A – surface area of the ductwork [m^2]

The maximum permitted air leakage factor for the ductwork is given in Table 5.5 .

Table 5.5: Ductwork classification [NS-EN 1507: 2006].

Air tightness class	Air leakage limit (f_{max}) m^3/s per m^2	Static gauge pressure limits (ps) Pa			
		Negative at all pressure classes	Positive at pressure class		
			1	2	3
A	$0.027 \cdot p_{test}^{0.65} \cdot 10^{-3}$	200	400		
B	$0.009 \cdot p_{test}^{0.65} \cdot 10^{-3}$	500	400	1000	2000
C	$0.003 \cdot p_{test}^{0.65} \cdot 10^{-3}$	750	400	1000	2000
D	$0.001 \cdot p_{test}^{0.65} \cdot 10^{-3}$	750	400	1000	2000

The leakage factor should be lower than the air leakage limit specified for one of the air tightness classes. In case the air leakage rate does not meet any of stipulated values in Table 5.5, depending on its class, ducts will have to be sealed and retested. Additional requirement of retesting is set in [Eurovent 1996], to retest ductwork together with additional 10% of the circular ducts and 20% of the rectangular ductwork, unless the system meets specified air leakage criteria. This will add additional expenses for the contractors and therefore in order to avoid extra retesting costs the work should be carried out correctly from the very beginning.

5.4.2.2 Testing

Before to start testing the section of interest should be sealed off from the rest of the system. The sample of testing should include the representative variety of duct dimensions and fittings, for example, at least 2.5 m of straight ducts. The ductwork surface area should be as large as 10% of the total ductwork surface area, preferably at least 10 m^2 [NS-EN 1507: 2006].

The test pressure should not exceed the design operating pressure, and should be maintained within ± 5% of the specified value for 5 minutes.

If the testing is performed under conditions other than standard (20°C and 101325 Pa) the measured leakage rate should be corrected according to equation (5.8).

$$qV = q_{measured} \cdot \frac{293}{273 + t} \cdot \frac{p}{101325} \tag{5.8}$$

5.4.2.3 Measurement accuracy requirements

All the measuring instruments should be calibrated before to start the measurement. This is usually done in accordance with the manufacturer specifications or relevant standards, if applicable. The requirements for airflow measurements are specified in [ISO 5221: 1984]. The largest allowable uncertainty for measurement of airflow rate is 2.5% of reading or maximum 0.000012 m^3/s.

5.4.2.4 Leakage test report

According to [NS-EN 1507: 2006] the air leakage report should include the following general data:

- Date and place of test
- Test personnel and witnesses
- Test equipment, including pressuring means and measuring instruments
- Air temperature and barometric pressure during the test
- Building or project reference
- Design of installed ductwork
- Required air tightness class and design operating pressure of the installed ductwork
- Installer of ductwork
- Manufacturer of ductwork

The test report should include specific air leakage testing information as showed below [NS-EN 1507: 2006]:

Measured values

- Ductwork surface area
- Total joint length
- Test pressure
- Leakage flow rate corrected for temperature and barometric pressure, if needed

Calculated values

- Leakage factor
- Air leakage limit (see Table 5.5 .
-
- Table 5.5)

5.4.3 Supply air temperature measurements - Thermal decay

Effectiveness of the underfloor air distribution system depends greatly on the following thermal processes occurring within the plenum and surrounding thermal masses [Bauman 2003]:

- Heat transfer between the slab and the plenum air
- Heat transfer between the floor panels and the plenum air
- Variations in plenum air temperature with distance travelled through the plenum
- Thermal storage performance of the slab and floor panels.

In order to achieve effective air distribution in the space and also to avoid the loss of air cooling ability, it is needed to limit the amount of temperature variation usually referred as a thermal decay in the plenum. The schematic of this temperature increase or thermal decay of the underfloor plenum is shown in Figure 5.6.

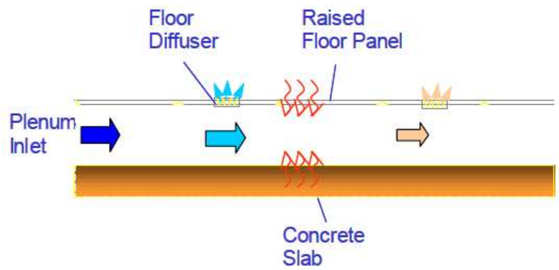


Figure 5.6: Thermal decay in an underfloor plenum [Bauman 2003].

The potential risk zones are diffusers located farthest away from the plenum inlet. Initially supply air entering the plenum is cool, however, by travelling through the plenum it warms up due to the heat transfer between the plenum air and floor panels above and concrete slab below. For typical slab temperatures and airflow rates, the temperature increase is approximately 0.1 to 0.3°C/m. However, it depends greatly on the configuration of the underfloor plenum, e.g. the number and location of plenum inlets, the temperature difference between the plenum air and floor panels and concrete slab etc. [Bauman 2003].

As a rule of thumb, the supply air temperature should not exceed 2°C from the time it enters the underfloor plenum until it is discharged to the space through the furthest diffuser [Filler 2004]. If the greater thermal decay occurs, it should be solved, for example, by adding additional plenum inlets or air highways, however this additional ductwork would greatly increase the system expenses. Therefore this thermal decay factor should be considered early in the design phase in order to prevent further system (plenum) reconfigurations and consequent expenditures.

As a rule of thumb, many experienced UFAD designers are limiting the distance from the plenum inlet to the furthest diffuser to about 15 – 18 m, when having pressurized plenum designs. The temperature increase can be also limited by the system operating in the nighttime pre-cooling mode, i.e. using concrete slab thermal storage properties. In addition, if the measurements at different diffusers indicate the temperature non uniformity, it is very easy to fix it by installing the plenum inlet vanes that would more uniformly spread the airflow across the entire plenum [Bauman 2003].

The supply air temperature can be measured using methods described in chapter 5.3.1.2.

5.5 Operations and maintenance documents

The project closeout phase includes the preparation of the necessary documentation of the performance test results, including also information of what was encountered during the design, construction and functional testing, as well as changes implemented to achieve the design intent. After the project has been completed the owner and/or facility manager should be provided with key documents and guidelines for further operation of the system, as well as complete set of all drawings, including the grid system with location of all UFAD components and controls. It is very important to keep up-to-date record on all system changes implemented. Therefore, it is suggested to keep the drawings in electronic format, so that in case of a change it is much easier to specify modifications.

According to [GSA 2005] the following issues should be considered with respect to operation and maintenance documents:

- *Monitoring and supervision of changes to systems under the floor.* For example, when the wiring has been removed, any consequent openings in the walls or floor of the plenum should be completely sealed.
- *Periodic cleaning of plenum.* The cleaning should be performed on regular basis. Additional cleaning should be done, when panels are removed for maintenance and repair.
- *Training and supervision of O&M personnel.* Responsible persons should be informed about relocation of all floor outlets, appropriate cleaning methods and handling and protecting the floor panels, especially when removed and/or replaced.
- *Relocation of diffusers, grilles and other device outlets in case of space rearrangement.* The original integrity of plenum should be maintained through the whole life cycle of the building.
- *Removal of panels for service or replacement.* The panels to be removed as well as adjacent panels should be examined in terms of any damage, especially at the edges.
- *Maintenance (repair or replacement) of floor panels.* Due to deformation the panels might not meet tightly. In addition the panel edges might be lost, so that openings occur between the panels.
- *Procedures for cutting openings in the floor panels, as well as their corresponding maintenance, e.g. sealing edges, etc.*
- *Leakage tests.* In order to ensure the design pressure, the additional air leakage testing should be carried out, when space reconfiguration area exceeds 230 m^2.

According to [GSA 2005] it is suggested to extend the warranty period of maintaining the system for a minimum of 5 years, after the substantial completion of the project in order to ensure continuous and successful performance of UFAD system. It is also recommended to notify the responsible emergency responders, especially fire fighters about the presence of RAF with UFAD in the building, so that they are aware of proceeding with special caution in these areas, in case of fire event.

5.6 Training of building occupants and O&M personnel

After completion of the commissioning process usually people who performed the commissioning are the only ones familiar with the system operation. Therefore, even if the verification was well documented, it is still needed to ensure communication between commissioning agent and operating and maintaining personnel of the building. The training of the maintenance personnel is very important in achieving the optimal performance and operation of the UFAD system. The operating personnel should have all the applicable service manuals regarding the operation and maintenance of the systems, and it is also suggested that commissioning agent educates them and explains all the details. The special attention should be paid to the control of the room temperature stratification and its impact on comfort [Filler 2004].

The building occupants should be also informed about the special features of UFAD system and its potential benefits, including comfort, indoor air quality, energy efficiency and flexibility. The responsible person should also show the locations of room thermostats and sensors and explain how to use them. Moreover, the contact information of responsible person should be provided in case of occupants comfort complaints and other relevant issues [Filler 2004].

6 Occupancy and operations phase commissioning

6.1 Air temperature stratification test

Promoting and maintaining room air stratification is of critical importance in achieving the successful design and operation of UFAD system. The primary objective is to minimize the energy use, while maintaining high indoor air quality and comfort in the occupied zone. The air stratification in the zone can be described as a function of supply air temperature and flow rate, heat loads, number and type of diffusers installed, and whether the zone environment is interior or perimeter.

Testing of room air distribution should be performed both in winter and summer periods, and during the fully load (or close to it) conditions, i.e. the building should have been already operated for a few weeks. This is done to ensure that all thermal loads are in equilibrium with the daily operation of building. [Montgomery 2009] suggests to perform temperature stratification test also before initial occupancy and before plug loads are active, but this in its turn would lead to not very drastic temperature stratification and in any case there would be need to repeat this test after the full occupancy.

6.1.1 Measurement locations

According to [NS-EN 12599: 2000] at least one measurement point is required per 20 m^2 of floor area. The measurement locations should be chosen in representative areas, i.e. in the occupied zone close to the occupants, and in potentially problematic locations where the worst conditions to be expected (e.g. in perimeter zones). In addition, the locations of measurements should be adjusted to have about 0.6-0.9 m clearance from the nearest diffuser, so that the stratification profiles would represent the conditions in the space outside the direct influence of diffusers [Webster et al. 2002b]. The temperature stratification test is usually done with the stratification-measurement tree that consists of a string with several sensors monitoring the temperature from floor to ceiling. Table 6.1 shows the standard measuring heights for the physical quantities of an environment.

Table 6.1: Measuring heights for the physical quantities [EN ISO 7726: 2001].

Locations of the sensors	Recommended heights [m]	
	Sitting	Standing
Head level	1.1	1.7
Abdomen level	0.6	1.1
Ankle level	0.1	0.1

Values given in Table 6.1 represent some of the most sensitive locations of the human body with respect to the thermal comfort conditions. However, measuring heights can vary widely depending mostly on the height of the room to be tested and extent of information pursued.

Besides direct measurement of occupied zone temperature with thermometers, the temperature stratification can be also studied using infrared thermography method that provides visualization of the temperature in the space. However, a great care should be paid when using this measurement technique at the perimeter zones affected by heating systems, windows etc. In such areas there is an increased risk of measurement inaccuracy due to the rapidly varying thermal loads.

6.1.2 Sensor accuracy

The temperature readings of sensors vary greatly in rooms with different air stratification. In highly stratified rooms the temperature gradient can be to extent of few degrees, while in rooms with more uniform temperature distribution it might be as less as fraction of degree. Therefore in order to examine the room air stratification more accurately, it is necessary to consider even the small differences in sensor calibration.

According to [NS-EN ISO 7726: 2001] the air temperature measuring instruments should be able to measure in a range of 10°C to 40°C, and have an accuracy of at least ± 0.5°C, while ± 0.2°C is considered as desirable.

6.1.3 Criteria

When using conventional air distribution systems zone thermostat set-point temperature is usually kept between 22 to 24°C (cooling applications). Having the same set-point for UFAD system in many cases results in too low temperatures in the occupied zones caused by extensive stratification, especially at the peak loads [Webster et al. 2002a]. In such cases, it is generally suggested to increase the thermostat set point by 1 to 2°C above desired, average occupied zone temperature in order to avoid uncomfortable thermal environment for building occupants. This would also reduce the required airflow rate, consequently leading to fan energy savings.

However, it is important to keep in balance air stratification in the space with comfort considerations. Permissible vertical air temperature gradient, measured between head and ankles (0.1 and 1.1 m above floor level) for three categories of thermal environment is given in Table 6.2).

Table 6.2: Permissible vertical air temperature gradient [NS-EN ISO 7730: 2006].

Category	**Air temperature difference [°C]**
A	<2
B	<3
C	<4

According to Table 6.2 the temperature gradient should not exceed 4°C in order to comply with the standard, corresponding to the last permissible category C.

In case temperature gradient is too high or too low further adjustments should be implemented, for example, adjusting thermostat set-points, plenum pressures, and/or the number of diffusers. Some potential reasons for insufficient stratification might be too high underfloor pressure and/or supply air temperature [Webster & Bauman 2006].

6.2 Subjective evaluation of UFAD system performance

6.2.1 Occupant surveys

Building occupants are a rich source of information on building performance, including information about indoor environmental quality and its effect on comfort, health and productivity. Therefore occupant survey can be actually used as a "tool" to assist in the commissioning and finally in the operation of UFAD system, as well as for diagnostic of problems. Even though occupant surveys increase the commissioning scope by adding extra activities to be carried out during the warranty phase, it still suggested to perform at least the basic survey on general workplace issues and occupant comfort [Nelson & Stum 2006].

There are mainly three types of occupant surveys [Nelson & Stum 2006]:

- *On-line survey*. The most preferable and common one. The main advantage is a minimum effort of collecting and processing the data, especially if statistical software is further used.

- *Hard copy survey*. Through this survey the same results as for the on-line survey might be achieved, but it would require much more effort since it is very time consuming and expensive process to create, distribute and analyze paper questionnaires. In addition, it takes longer time for occupants to complete them.

- *Suggestion box*. This questioning method addresses only small part of all occupants, basically people with the issues.

When carrying out surveys it is important to explain people the importance of their active participation. In addition it should be also mentioned that these surveys are going to be voluntary and anonymous [Webster et al. 2002c].

According to [NS-EN 15251: 2007] the questionnaires should be completed during middle morning or middle afternoon, and not straight after the arrival or lunch break. When processing the data, results need to be presented as average values and/or distributions.

According to [NS-EN ISO 10551: 2001] one can distinguish between five primary types of subjective judgment scales for evaluation of the influence of the thermal environment, listed in Table 6.3.

Table 6.3: Subjective judgments for assessment of thermal environment [NS-EN ISO 10551: 2001].

Type of judgment		Wording/Description	Examples
1	Perceptual	7 or 9 degrees from very (or extremely) COLD to very (or extremely) HOT	Thermal sensation
2	Affective evaluation	4 or 5 degrees, from COMFORTABLE to very (or extremely) UNCOMFORTABLE	Thermal environment
3	Thermal preference	7 (or 3) degrees, from (much) COLDER to (much) WARMER	Preferred temperature change Preferred air movement
4	Personal acceptabilit y	2 degrees, GENERALLY ACCEPTABLE, GENERALLY UNACCEPTABLE	Temperature acceptability
5	Personal tolerance	5 degrees from perfectly TOLERABLE to INTOLERABLE	-

The first three can be referred to the personal thermal state and the latter ones to the thermal ambience, i.e. assessment in terms of acceptance or rejection. Please note that the questions should be posed in the sequence given in Table 6.4

Table 6.4. Examples of possible scales used in questionnaires are given in Appendix E.

Some examples of aspects to be addressed in occupant surveys with respect to UFAD and building are given below:

Workspace and spatial layout

- Personal workspace
- Building itself
- Space for work and storage
- Ease of interaction with co workers
- Furnishings
- Cleanliness and maintenance

Floor diffusers

- Diffuser location and settings
- Individual control
- Cleanliness
- Noise
- Drafts
- Aesthetics/how it looks
- Interferes with the chair rolling or in the way of people walking

Raised floor

- Preference of the UFAD to COH system

Thermal comfort

- Temperature in the workspace

Lighting

- Visual privacy
- Light levels

Acoustics

- Sound privacy

Air quality

In US it is very common to use the 7 point satisfaction scale that ranges from “very satisfied” to “very dissatisfied”, as showed in Figure 6.1.

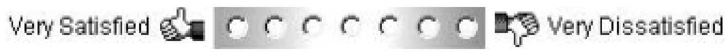


Figure 6.1: Occupant satisfaction rating scale [Webster et al. 2002c].

[Zagreus et al. 2004] has developed occupant satisfaction questionnaire with respect to 7 different environmental categories and 2 questions about overall satisfaction with the building and personal workspace:

Different environmental categories

- Office layout
- Office furnishings
- Thermal comfort
- Air quality
- Lighting
- Acoustics
- Cleaning and maintenance

Overall satisfaction

- Overall satisfaction with the building
- Overall satisfaction with workspace

However, occupants are also provided with the possibility to express the other issues, for example, which were not included in the distributed questionnaire, making comments at a “general comments” section at the end of the survey. The preferred response rate for this questionnaire is at least 40% [Zagreus et al. 2004].

6.2.2 System operator survey

The 7 point satisfaction scale (see Figure 6.1) can be also used to obtain operators feedback about operation of UFAD. The questions can be divided into following two categories, taking into account problematic issues specific for UFAD systems:

- Operators perception as the seriousness to the UFAD issues related to UFAD system operation.
- UFAD comparison to conventional buildings from operators perspective and based on their experience.

[Bauman et al. 2008] have studied operators’ feedback on system performance asking the following questions about different issues related to UFAD:

1. *“Based on your knowledge of how the UFAD system has been operating, how the occupants have been responded on average and your experience in other Non-UFAD/conventional buildings, how much better or worse is this UFAD building than conventional buildings with respect to the following?”*
    - Hot and cold complaints
    - Air quality
    - Energy use
    - Problems with zone equipment

- Automatic temperature controls categories
- Effort and cost in maintenance
- Changing tenant space
- Occupant control
- Overall performance of UFAD system

2. *"Based on your experience with this building, indicate how serious of a problem the following have been in terms of interruptions to operations, cost, occupant comfort, etc."*
    - Dust and dirt in the underfloor plenum
    - Supply air leakage
    - Temperature stratification
    - Moisture related problems
    - Underfloor air distribution and temperature decay

7 Miscellaneous

7.1 Cleaning

7.1.1 Underfloor plenum

Cleaning and maintenance of the UFAD plenum is crucial for indoor air quality and mechanical devices installed in the plenum such as VAV dampers, thermo-regulators etc. According to [SBE 2006] it is recommended to perform cleaning activities of the UFAD plenum in the following sequence:

1. *Cleaning prior to setting RAF panels.* In order to avoid dust and dirt accumulation in the future plenum construction, the RAF panels should not be installed until the space is entirely closed from the outside or from adjacent spaces that might have been affected by external ambient conditions or any building construction works itself. After pedestals are mounted the concrete floor should be cleaned, including some additional area around the floor construction. The cleaning procedures should include sweeping of the concrete slab, scraping it of mud if any, and finally vacuuming it with a pleated filtered vacuum with a brush-ended tool consisting of short, fine and dense bristles. In addition, the floor slab must be treated with an anti-microbial agent prior to floor installation in order to prevent the microbial growth in the underfloor plenum [Bauman 2003]. However, according to [SBE 2006] this recommendation might not be considered necessary, since the underfloor plenum is made of concrete, and even if having the some dirt it is not really food for mold. The area to be cleaned should correspond to the area to be covered with panels not longer than in the following two days.
2. *Cleaning during RAF panel installation.* During this phase, all dust or debris generating work, e.g. cutting the panels etc. should be carried out outside the room where the panels are going to be installed. Workers should vacuum any dust and debris on the floor accumulated when installing the panels. During the panel installation the owner or its representative together with the contractor should make a visual observation of the plenum cleanliness for each 90 m^2, and consequently document its approval or rejection. Observation is usually made from the open end of the floor section, and therefore there is no need to lift the floor panels.
3. *Cleaning after RAF panel installation and before carpet.* Until the carpet is laid, the floor panel joints should be taped, or the floor should be covered with the paper or plastic to avoid dust or dirt transport into the plenum. This covering should be also kept relatively clean. Workers are a potential pollution source and therefore in case they access the plenum, i.e. remove the floor panels; it’s needed to vacuum any dust, dirt etc. before to close the floor. This cleaning should be always applied, whenever the RAF plenum is accessed.

4. *Cleaning after carpet installation.* The owner or its representative together with the contractor once again performs the visual check of the plenum cleanliness. For this reason, up to one panel should be lifted for every 45 m^2. The floor should be as clean as in earlier checkups. If not, the additional cleaning should be performed by contractor.

Even though after the completion of installation of RAF, the plenum is appropriately sealed and cleaned, over the time it may become contaminated with dust, mould or bacteria, moisture, even with vermin and other materials. The major source of dirt in the plenum is the supply air itself and thus a great attention should be paid to the frequent and on time replacement of air filters. The floor plenum can get dirty also because of the workers, who access the floor, e.g. for repairs etc., and through floor diffusers that have poorly fitting or malfunctioning dirt baskets. Therefore the visual inspection of cleanliness of UFAD plenum should be carried out on regular basis in order to ensure good indoor air quality, as well as to verify that materials and devices installed in plenum are not damaged. The cleaning should be carried out by people with relevant knowledge of such "construction" cleaning, since plenum has extensive cabling and different mechanical devices, and thus has some dangers of electricity.

7.1.2 Ventilation ducts

The cleaning of ventilation ducts should be performed due to the following main reasons:

- *Function.* The airflow can be restricted due to the pollutants. This will result in the rise of pressure drop and consequently decreased airflow rate. Attention should be especially paid to the wet rooms, which have small duct dimensions. Since the air removed from such spaces is usually warm and humid, the extract ducts will have wet surfaces that are good place for different particles to accumulate on.
- *Fire risk.* The ducts can become coated with combustible pollutants that might create even fires or explosions. This is especially applicable for specific rooms such as extraction systems in kitchen ranges and different industrial processes. The ducts should be cleaned regularly based on the requirements of national fire prevention regulations.
- *Health.* Pollutants having impact on human health. The dirty ducts can impair the quality of the supplied air that in its turn might lead to the SBS.

The ducts should be cleaned at all steps of installation starting from delivery to the site until the system is put in operation. The ducts should be closed at the ends with tight fitting covers typically made of plastic or cardboard. In case the ducts are not protected and are object to pollution, the system should be cleaned before the first time of its operation.

The need for cleaning is usually determined by the visual inspection. This can be done either by using the TV inspection equipment such as cameras mounted on remotely controlled robots, or manually and visually by using, for example, torches and mirrors, that are inserted in the ducts through the inspection hatches.

The most commonly used methods for duct cleaning are: dry cleaning, wet cleaning, disinfection, encapsulation, and removal of insulation linings.

7.2 Airflow and flow balancing

The airflows to different spaces/zones should be carefully measured, adjusted and controlled to comply with stipulated design values. The balancing of the system is usually accomplished by one of the following methods:

- The proportionality method
- The pre-set method

7.2.1 The proportionality method

In the proportionality method the air dampers and registers in the system are adjusted to deliver the same proportion of the design airflow. This means that relation between the airflow in branch ducts will be the same in spite of the airflow change in the main duct. The measurement of the absolute value of the airflow is not necessary, since this method is based on the relative data, e.g. air velocity and pressure.

The balancing starts with the setting all dampers and registers to fully open position. The reference register R, i.e. register located farthest downstream, is determined. The starting point of balancing is the register that has the lowest ratio between measured and design air flow ($Q_{measured}/Q_{design}$). Any register other than reference register "R" having lower ratio will be assigned as Index register I. The reference register R is then adjusted to have the same ratio as the index register. The damper position of the index register remains fully open after the adjustment. This procedure of adjusting the dampers in registers should be repeated until all registers have the same ratio of measured and design airflow.

This method is used not only to balance the air flow at the registers, but also for adjustment of duct branches and main ducts.

This is the most commonly used method despite being time consuming, costly and requiring skilled personnel.

7.2.2 The pre-set method

According to [Malmstrom et al. 2002] the pre-set method has the following requirements:

- The pressure drop calculation is available and is based on the manufacturer data.
- The set values of all dampers and registers are calculated and specified on the drawings.

- All ductwork components are installed in accordance with the building specification.
- The actual installation of the system corresponds to the design drawing.

After these requirements have been fulfilled the balancing can start, and this method will be fast and accurate. All dampers and registers are set corresponding to the values given in building specifications, and as showed in drawings. The measurement of the airflow at registers should correspond to the design values. Otherwise, the previously mentioned requirements should be rechecked and balancing work restarted.

Even though this method is fast, reliable and cost effective, it is not very commonly used in practice. This can be explained with the fact that usually significant alterations from the initial design exist in the actual installation case.

8 Field study - Sparebank 1 building complex

8.1 Project background

8.1.1 Project description and design intentions

SpareBank kvartalet was designed to be a high performance, environmentally responsible and aesthetically appealing office and commercial building complex in Trondheim, Norway. One of the primary objectives of the design team was to meet the net energy consumption less than 100 and 145 kWh/m^{2}yr for office and commercial spaces respectively. This is significantly less than stipulated in a Norsk Standard 3031, i.e. 165 and 240 kWh/m^{2}yr for typical office and commercial buildings [NS 3031: 2007]. Consequently, SpareBank building's energy performance could comply with the category A in the European energy efficiency certification system [NS-EN 15217: 2007], and it would also become one of the most energy efficient buildings in Norway [Teknisk Ukeblad 2009].

The project scope included a complete renovation of the older bank building and basements (7617 m^2), and a raise of a new adjacent office building (12400 m^2) for SpareBank 1 headquarters and other companies (see Figure 8.1).

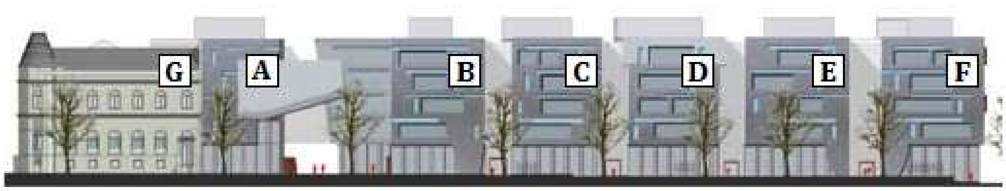


Figure 8.1: SpareBank 1 kvartalet, East exposure [Agraff Arkitekter 2009].

As it can be seen in Figure 8.1 SpareBank 1 building complex consists of new six blocks (A to F), and an older bank building, i.e. block G. New blocks are connected to each other by atriums, with the exception of blocks A and B, which have an overhead bridge above the passage for public between Apotekerveita and Søndre gate.

Project description, including main building characteristics is given in Table 8.1

Table 8.1: Project description.

Items	Contents
Location	City center of Trondheim, Norway
Size	Five stories Total floor area 20017 m^2, from which 7617 m^2 retrofitted
Building use	Corporate offices of SpareBank 1 and other companies Ground floor retail
Occupancy	Designed to be typically occupied Monday-Friday, 8 am to 5 pm Designed to accommodate 25-30 people per floor (in offices)
Completion	October 2010 Occupants moving in November/December 2010

The construction process had started in October 2008 and it is planned to complete the building in October 2010, with employees moving in November/December 2010. The building complex is privately owned by Sparebank 1 that will entirely occupy the older bank building and blocks A to D, and rest of the blocks leasing to other companies. The ground floor is going to accommodate stores and other services aimed for general public.

The main project team members are listed in Table 8.2.

Table 8.2: Development team.

Role	Company
Owner/Developer	SpareBank 1
Architect	Agraff AS
Building engineering consultancy	Myklebust AS
Electro engineering consultancy	COWI AS
Sanitary, heating and ventilation engineering consultancy	COWI AS
Building contractor	Teknobygg Entreprenør AS
Mechanical contractor	YIT AS
Energy consultancy	SINTEF Byggforsk/NTNU

The project team consists of Norway's most revered engineering companies. The energy consultancy services were provided by Sintef Byggforsk/NTNU.

One of the main principles implemented to keep energy consumption low was the well insulated and air tight building envelope. The building is of precast concrete panel construction (external wall overall U-value 0.13 W/m^2K), with the glazing (U-value 0.7 W/m^2K and G-value 0.5) covering 70/50/30/30% of the façade area in floors 1 to 4, respectively. All main windows have an external solar shading system made of solar screen fabrics. Shading system automatically adjusts to changes in daylight based on the data received by the rooftop weather station, which besides solar radiation collects also temperature, humidity, wind speed and wind direction information.

The interior layout in all four floors is analogical for each new block, as indicated in Figure 8.2.

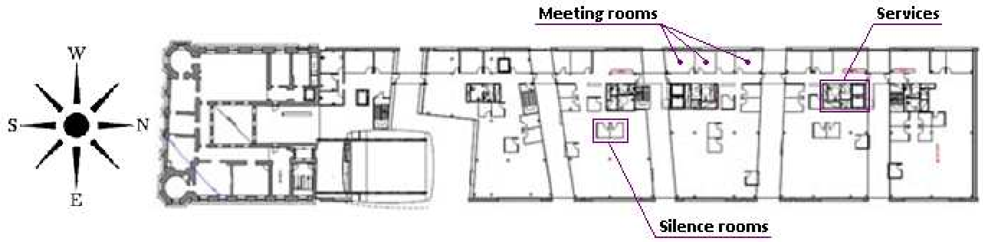


Figure 8.2: 2nd floor plan [Agraff Arkitekter 2009].

Inside, the building is mainly open plan with the meeting rooms on the west perimeter. Services, i.e. hygiene rooms, as well as the technical rooms for mechanical equipment are also concentrated in the western area of the each floor. During the project progress, some changes were made to the 5th floor of block F, which in addition has meeting and private office rooms on the northern perimeter.

The architectural rendering of the main floor interior is given in Figure 8.3.

Figure 8.3: Main floor interior [Agraff Arkitekter 2009].

Walls and ceiling are painted white. Ceiling is open, with the suspended lines of sprinklers and fluorescent lighting fixtures. The general lighting system is controlled by a combination of the daylight and occupancy sensors. Each workstation is also going to be equipped with the task lights that are controlled either by manual switches or automatically by occupancy sensors. The illuminance (lux) level of 500 lx should be maintained in meeting rooms, while 300 lx at the workstations, and 200 lx in corridors. Sound absorbing system consists of acoustic wall and ceiling panels made of fiberglass.

During the mechanical process cooling of the data centrals located in basement U2, large amount of heat is released that is further utilized in the building, as indicated in Figure 8.4.

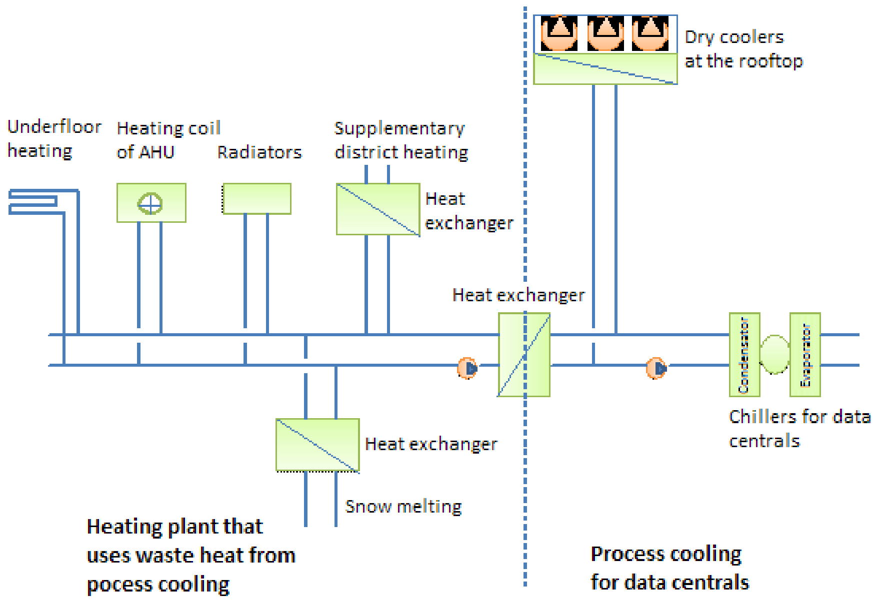


Figure 8.4: Waste heat use [Hasfjord 2008].

Building complex has both the low (50/30°C) and high (80/60°C) temperature heating systems. Building's low-temperature hydronic heating system is installed only in blocks E and F, and primarily uses waste heat from the data rooms as a heat source. The heat is distributed to the space via a two pipe radiator system. The radiators are located along the eastern and western outer walls of all new blocks, and along the northern wall in block F. The waste heat from process cooling of data rooms is also used to heat the ventilation air, as well as for melting the snow on the pavement around the building. If needed, the supplementary heat for the previously mentioned purposes is provided by Trondheim Energi Fjernvarme Company owning the district heating grid in the city. The district heating central was dimensioned in order to cover the entire heating energy need of the building, including also the hot water supply and operation of hydronic air curtains for entrances in blocks A and B (from bank passage) and block G (from Kongens gt).

Since the windows are not openable, the building entirely relies on the operation of balanced mechanical ventilation system that in this case is used to meet both the requirements for good air quality and thermal comfort, i.e. providing also comfort cooling. The installation of the raised access floor (RAF) for cable management also affected the choice of the underfloor air distribution system to be used in the office layout in all four floors, except the technical and hygienic rooms. This type of system has the air distribution principle similar to displacement ventilation, enabling to achieve high ventilation efficiency. The ground floor retail has a conventional overhead air distribution system which is designed to operate as a CAV.

In case of fire the ventilation system will continue to supply sufficient amount of air in order to keep the escape route for people free of smoke. The smoke will be removed through atrium based on so called stack effect by opening the lower (above the entrance doors in atriums) and upper level smoke ventilation openings. The results from building's fire simulation showed that smoke might collect under the ceiling of atrium approximately at the entire level of the last floor. Therefore the air outlets of 4^{th} floor in case of fire are going to be closed in order to prevent smoke penetration inside the floor. In addition, the return air damper to the AHU will be also closed to avoid the mixing of the smoke with the supply air at the AHU.

The control and monitoring of HVAC systems in a building is accomplished by use of an advanced Web based building automation system IWMAC that provides scheduling, trend logging, and energy management capabilities as well as system and maintenance alarms.

The summary of key energy saving strategies implemented in the building is given in Appendix F.

8.1.2 Underfloor air distribution system characteristics

8.1.2.1 Design intent

Sparebank 1 wanted a state of the art solution that would combine the desire for high energy efficiency with the high quality indoor climate. Initially, two solutions, i.e. KlimaTak and UFAD were proposed and further examined using ESP-r, an advanced modeling tool for simulation of building's performance. UFAD was chosen due to the greater energy savings and improved aesthetics, since the need of an overhead plenum was also eliminated. The potential benefit of UFAD regarding possible future space reconfigurations (associated with reduced churn costs) was also discussed; however generally played a minor role in choosing this particular system for space conditioning.

8.1.2.2 Design/configuration

UFAD system is installed in floors 1 to 4 of the new blocks, serving approximately 90% of the entire floor area. The design configuration is analogous for all floors that each has five independently controlled HVAC zones, as indicated in Figure 8.5.

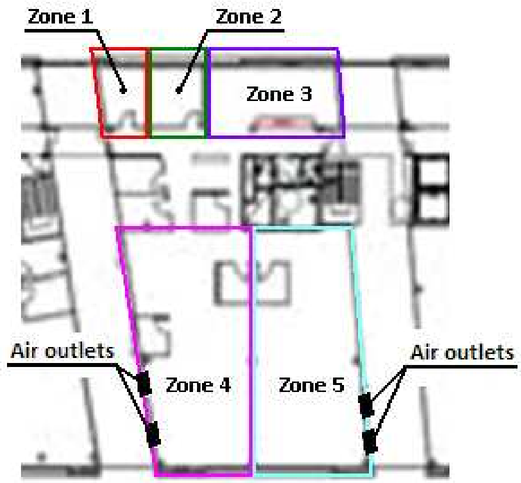


Figure 8.5: HVAC zones on 2nd floor, Block C.

Zoning is achieved by partitioning the underfloor plenum with walls. Zones 1 to 3 serve the west perimeter spaces, mainly the meeting rooms, and zones 4 and 5 – the open plan office layout, including the silence rooms. Due to the space reconfiguration in the 5th floor, it was decided to have 6 separate thermal zones instead of 5.

The underfloor air distribution system details as well as chosen products are given in Table 8.3.

Table 8.3: Underfloor air distribution system details.

Items	Contents
Plenum height	500 mm
Raised access floor	600 mm Interface Gypsum fiber core panel
Structural slab	200 mm
Diffuser type	Trox swirl diffuser, Type FB
System type	Variable Air Volume (VAV)
Supply air temperature	18°C nominal temperature
Air handling unit	Swegon Gold RX (21000 m^3/h) Rotating heat exchanger (temperature efficiency 79%)

The underfloor plenum has a height of 50 cm and is used to route the electrical cabling to the various distribution junction boxes and further to the workstation, and also serving as an air plenum for delivering conditioned air to the occupied zones. The grid of pedestals mounted (glued) to the concrete slab supports the RAF made of gypsum fibers. Pedestals are spaced based on the floor tile size of 0.6 x 0.6 m, supporting four corners of each tile. Floor panels are covered with glued down 0.5 m square carpet tiles aligned in a non-coincident layout with the floor.

In order to minimize possible water damage to cabling, wiring and UFAD devices, UFAD plenums should be protected from water accumulation in the plenum, e.g. caused by leaks from joints in the slabs and walls, floods from sprinkler discharge or other accidents, and also condensation. However, in the present case no moisture detection and drainage system is installed in the underfloor plenum.

Smoke sensors are installed on plenum surfaces and communicate with the BAS that in case of a fire accident in the plenum will shut off the ventilation system. Underfloor plenum does not have its own fire extinguishment (e.g. sprinkler) system.

The swirl type Trox diffusers are used all round the office space, including the kitchenette area. Even though UFAD is unique with its feature of giving occupants some control over their microenvironment, in the present case occupants do not have any individual control, since the floor diffusers are controlled automatically.

The configuration of installed UFAD system is shown in Figure 8.6.

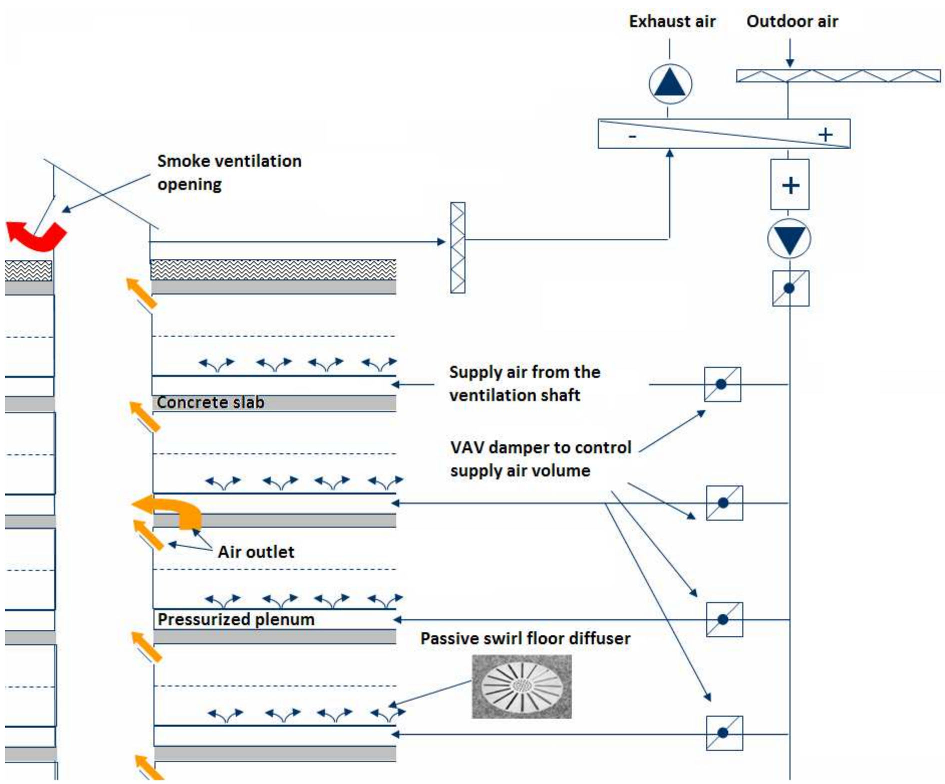


Figure 8.6: UFAD system configuration [Wachenfeldt and Høseggen 2008].

The outdoor air is conditioned at the AHUs located at the technical rooms at the rooftop; each AHU is serving its own block. The ventilation air is heated up to about 16°C using primarily the waste heat from the data rooms (supply/return temperatures at the heating coil are 50/30°C). During the cooling period, chilled water of 9°C is supplied to the cooling coil of an AHU. The conditioned air passing through the ventilation shaft is further delivered to the plenum of each floor by means of five main supply air ducts each serving particular HVAC zone (see Figure 8.5). As mentioned before, block F is slightly different, having 6 thermal zones served by 5 main supply ducts. The supply air volume delivered to each separate zone is controlled by a VAV damper. The air is then supplied to the space through the floor mounted passive swirl diffusers, since UFAD system is configured as having a pressurized plenum.

The polluted air from the meeting rooms is removed first into corridors through its "local" extract system consisting of a sound attenuator and a ventilation grille. The contaminated air from the private offices is removed via the ventilation grilles located above the doors. This extract air (from meeting and private office rooms) together with the contaminated air from the open plan office space is further extracted into atriums through the large slot openings in the walls near the ceiling level (see Figure 8.5 for the location of the air outlets). The extract air is then returned back to the AHU (for the heat recovery purposes) through two return grilles located close to roof level in atriums, with the exception of block F that has only one return grill. The service rooms such as toilets and copy rooms have their own local exhaust system.

During the nighttime ventilation system is operating in a free cooling mode using thermal storage properties of the concrete slab. The cool outdoor air is brought to the underfloor plenum in order to cool the slab overnight, so that lower air flow rates can be used on the following day to meet cooling demand. This strategy allows reducing the demand for mechanical cooling for at least part of the day.

8.1.2.3 Operation

The air is supplied at variable air volume and constant air temperature of about 17-18°C. The balanced mechanical ventilation system has DCV control, i.e. ventilation air flow rate is controlled by the actual needs of the space. As an indicator for DCV system, the CO_2 and temperature sensors are used in conditioned spaces in order to monitor and consequently recognize when the occupied zone is adequately ventilated.

The extract ventilation from copy rooms and toilets is operating as CAV.

The calculation of the building's ventilation airflow rate that is of two components, namely people and building, is given in Table 8.4 .

Table 8.4: The calculated and design ventilation airflow rates [Hasfjord 2008].

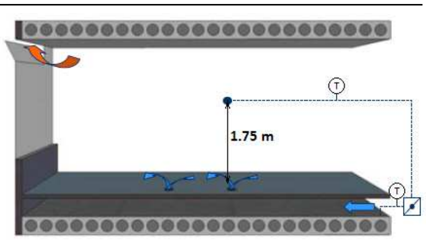
Type of space	Calculated				Designed	
	Floor area [m^2/person]	Ventilation rate for occupancy [l/s per person]	Ventilation rate for emissions from building [l/s per m^2]	Total ventilation rate of the room [m^3/h per m^2]	Minimum air flow rate [m^3/h per m^2]	Maximum air flow rate [m^3/h per m^2]
Open office	8	7.0	1.0	6.75	10	15
Meeting r.	2			16.2	13	20

The calculation of the ventilation rate is based on the methodology given in [NS-EN 15251: 2007]. The new blocks of Sparebank 1 can be considered as low polluting, since the low emitting building materials and equipment are used throughout the building. The total calculated minimum required ventilation air flow rate is 6.75 and 16.2 m^3/h per m^2 of the floor area for the open plan office space and meeting rooms respectively. The designed indoor environmental input parameters for the entire building are given in Appendix G.

Table 8.5 shows the UFAD set point values as well as system operation schematic.

Table 8.5: Desired set point values and underfloor system operation schematic.

Type of space	Operative temperature [°C]				Max CO_2 conc. above the outdoor [ppm]
	Summer		Winter		
	Min	Max	Min	Max	
Open office	21	25	20	24	500
Meeting room	21	25	20	24	500



The ventilation system in each zone can operate in three different modes: night, passive and active ventilation mode.

Night ventilation mode. During the specified hours (based on clients needs) the ventilation system is generally closed. During the summertime when the cooling energy need is high the system operates in the free cooling mode, if the outdoor temperature is low enough. During the nighttime the temperature is allowed to deviate not more than ±4°C from the desired set-point temperature.

Passive ventilation mode. In order to ensure acceptable indoor air quality and desired thermal comfort conditions at the beginning of the working day the system switches from night mode to the passive mode. In this mode the temperature is allowed to fluctuate for ± 2°C of the desired set point temperature.

During the working day meeting rooms are always kept in the passive/awaiting mode. The responsible person manually switches to the desired operation mode.

Active ventilation mode. During the specified hours (based on clients needs) the temperature in the occupancy zone should correspond to the set point temperature. During the normal occupancy hours the sensor measures the operative temperature in the occupied zone and the airflow rate is adjusted, if it is needed. For example, if the temperature in the open plan office area in summer period exceeds 21°C, the airflow rate is gradually increased from 10 m^3/hm^2 (at 21°C) to maximum of 15 m^3/hm^2 (at 25°C and higher).

8.2 Assessment of "expected" UFAD performance

8.2.1 Thermal environment

The location of floor diffusers in the open plan office area is shown in Figure 8.7.

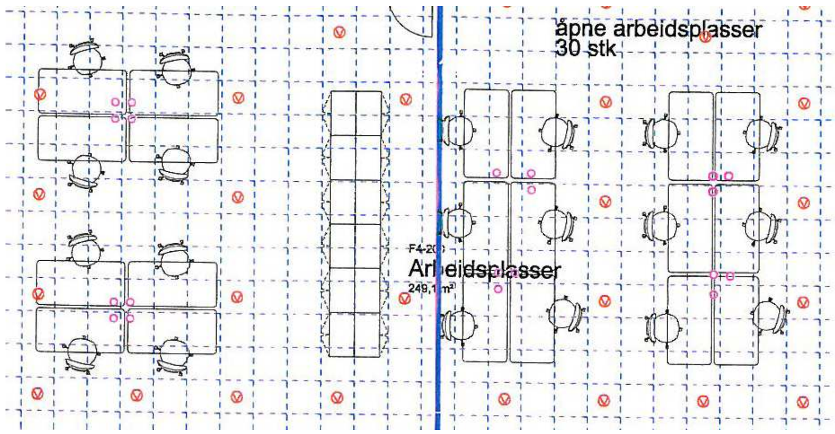


Figure 8.7: Diffuser location on 4th floor in block F.

As it can be seen in Figure 8.7 diffusers are located between furniture in order to avoid additional air obstructions. However, diffusers in the present building are located too close to the workstations. According to [Bauman 2003], it is suggested to have a minimum distance of 1 m between diffuser and a person. In the present building (see Figure 8.7) many diffusers are placed significantly closer than suggested distance of 1 m. As a result it can be expected that building occupants will complain about draughts. This problem could be eliminated if diffusers would be manually adjustable, i.e. if occupants would have some individual control over the airflow direction etc. Since in the present case the system was designed having automatically adjustable diffusers, it will be probably needed to change location of some diffusers taking into consideration occupant preferences. In case no actions regarding relocation of diffusers or workstations will be carried out, occupants might simply block the diffusers with heavier objects, e.g. books, thus not only negatively affecting the air distribution in the space, but possibly creating comfort problems for other nearby occupants having diffusers open, since air will flow where there is a smaller resistance.

The draught risk in this building may also occur due to the air leakage through the raised access floor construction. A potential problem space might be the private office room on 3rd floor in Block F, where the same floor panels as in kitchenette area are installed instead of carpeted floor panels which are used throughout the office space (see Figure 8.8).

Figure 8.8: Private office on 3rd floor.

Person will be most probably seated close to the window. This area will be affected by leakage not only from the panel joints itself, but also due to the improper sealing of joints around the column and radiator pipes. Thus it might be necessary to seal the RAF panels and its joints more properly in order to reduce risk of draught.

Air leakages through the floor panels were observed also in the kitchenette area. However, since this space is going to be occupied only for short time, this might not necessarily have a negative effect on comfort of building occupants.

According to results from energy simulation [Høseggen 2008], Sparebank building did not have energy demand for space heating due to the well insulated building envelope, high heat gains from people, equipment, lighting etc. However, after experiencing cold winter of 2009/2010 it was decided to install the radiators, that actually counter-played with operation of thermostats. There are typically two thermostats installed in the open plan office area: one at the east wall and the other one on the wall of technical rooms. The average value of these two is then further used as a reference point for climate control. Since now the heating radiators are installed also at the east perimeter, they will directly affect the reading of the temperature sensor, giving the false reading (see Figure 8.9).

Figure 8.9: Thermostat location on the east wall.

This however will be a problem only when heating system will be in operation. The "false" reading from thermostat will artificially increase zone average temperature. As a result it will seem that it is more warmer than it actually is. In order to avoid this operation conflict it was decided to switch off thermostat on eastern wall during the heating season. By this heating and ventilation system will be controlled only based on one thermostat located on the wall of technical rooms. This however might lead to another problem: people seated farthest of this thermostat might feel too warm. However, this might not be a big problem, since usually people are more sensitive to cool temperatures than warm, and do not very often complain of feeling too warm.

In addition it should be mentioned that thermostats in meeting rooms were initially placed just under the ceiling, i.e. at about 2.5 m height. Normally room thermostats should be placed in the occupied zone (up to 1.8 m high, depending on the activity to be carried out, i.e. seated or standing position of a person). During the cooling season, having thermostats just under the ceiling will most likely cause too low temperatures in the occupied zone, leading to occupant discomfort. In addition, this will also increase the ventilation airflow rate, and thus the energy consumption.

Since the windows have very low U-value, the risk of having downdraught is small. In addition this risk is reduced by having the radiators just under the windows.

8.2.2 Indoor air quality

Diffusers are located with a spacing of about 1.8-3.6 m (see Figure 8.7). By having more diffusers (smaller spacing distances), it is possible to achieve more even supply air distribution in the entire floor. This was confirmed by results of supply airflow measurements at each diffuser at the 4th floor in block F (see Appendix H for measurements). The average supply airflow rate was 53.5 m^3/h (σ is 2.08) and 45.3 m^3/h (σ is 2.97) for zones 4 and 5 respectively. Almost the same airflow rate was obtained at the diffusers located in potential problematic areas such as close to plenum obstructions, furthest from the air inlet etc.

The temperature sensors in the plenum are installed only in the concrete slab. The supply air temperature is measured only at the AHU and since no temperature sensors are installed to measure it in the plenum itself, it will be hard to verify if supply air temperature is in acceptable limits, i.e. in a range of 18-20°C. It is very important to consider the thermal decay of the plenum, i.e. temperature will increase with the distance from the plenum air inlet. As discussed in chapter 5.4.3. supply air temperature increases by approximately 0.1 to 0.3°C/m. For the present design layout this might result in temperature increase of about 1.5-4.5°C at diffusers located farthest from the plenum air inlets. The higher supply air temperatures at diffusers will directly affect the air stratification in the room, minimizing the advantageous buoyant flow air pattern typical for UFAD. Thus the conditions in the space will be similar to the ones achieved by mixing ventilation, i.e. more or less even temperature and pollution distribution in the space, lowering the ventilation efficiency. Therefore it is very important to actually perform the air stratification testing in the space in order to achieve better indoor climate.

The cleanliness of any ventilation system is of critical importance in achieving good indoor air quality in a space. During the commissioning process it was found that the underfloor plenum was not clean enough, as showed in Figure 8.10.

Figure 8.10: Dust and dirt in the underfloor plenum.

It can be clearly seen in Figure 8.10 that the underfloor plenum contains dust and other construction debris, even though the plenum was initially cleaned after carpet installation. The reason for this extensive dirt might be the unsealed openings in walls through which the dust and other pollutants most probably were blown throughout the entire plenum. Another source of dirt in the plenum was the floor panels opened for accessing the VAV units.

The dirty plenum possesses a great risk of supplying already polluted air into the occupied zone. This would impair the indoor air quality significantly affecting not only health, comfort and well-being of building occupants, but also productivity. Dust in the plenum could also negatively affect operation of mechanical devices in the plenum, e.g. electronics of volume control dampers.

During the inspection of the plenum it was also found that plenum contains the organic matter in a form of pressed wood board, as showed in Figure 8.11.

Figure 8.11: Pressed wood board panels supporting the radiator valves.

Since the plenum does not have any moisture detection system installed, the possible water leaks, e.g. from plumbing, and also condensation, could lead to mould growth on plenum surfaces. In addition, the quality of construction, in this case laying the fire insulation around the supply duct is not very good (see Figure 8.12).

Figure 8.12: Fire insulation of supply ducts on the 5th floor.

As it can be seen in Figure 8.12 ducts are insulated with the mineral wool, but the ends of insulation are not closed. Since the plenum is used for air delivery, with time mineral wool fibers will be aired out, and most likely also reach zone of occupancy. Mineral wool fibers could cause allergenic reactions to some of building occupants. Besides affecting negatively the indoor air quality, this “airing” would also impair the functionality of insulation.

8.2.3 Energy consumption

The measurement of slab temperature is necessary for night cooling operation mode, which uses advantage of slab’s thermal storage properties. However, without measuring the supply air temperature in the plenum, all benefits of night cooling might not be achieved.

During the building visits it was found that underfloor plenum was not sealed properly (see Figure 8.13).

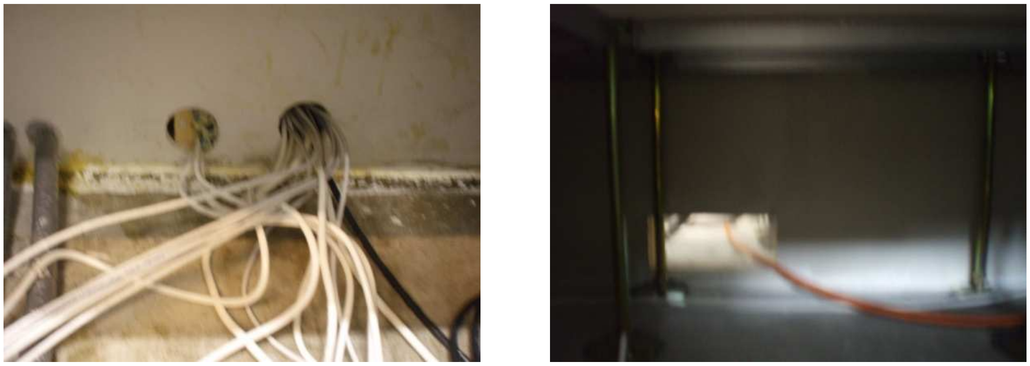


Figure 8.13: Potential air leakage pathways.

The air leaking to the place other than occupied zone is causing waste of energy, including thermodynamic energy used to condition the air, and fan energy to deliver the air through the system. Thus it is very important to ensure that plenum is properly sealed and air leakage rate minimized.

In all office blocks the same AHU is serving both the conventional overhead mixing ventilation system on ground floor retail and UFAD on floors 1 to 4. These two systems have different operating conditions: the supply temperature for COH system is usually in a range of 13-14°C, while UFAD systems require 18-20°C. This might lead to increased energy consumption for cooling. For example, when there is a moderate cooling need, the AHU will have to cool down temperature for conventional overhead system, while UFAD actually does not require such a low supply air temperature. Thus it would be generally better not to have the same AHU serving conventional overhead system and UFAD.

9 Conclusions

UFAD systems are non-standard and unique and therefore a special attention is needed to some issues and situations specific only for UFAD installations, e.g. coordination of the raised access floor, carpet and furnishings, temperature stratification etc. Some of the most critical tests to be performed in commissioning of UFAD systems, are the air leakage and air stratification testing. In order to achieve successful operation of UFAD the active participation of all involved parties, e.g. architects, interior designers, HVAC designers, contractors etc. is needed since the very beginning of the project. Commissioning of UFAD just requires a discipline, structured approach and commitment from all participants involved.

In the Sparebank kvartalet no plenum air leakage testing was performed. During the building visits it was found that plenum was not properly sealed, and therefore there might be a high risk of energy waste. Trying to seal the plenum after laying down the carpet is also very difficult and time consuming.

Generally a relatively uniform air distribution was obtained in the entire floor. However, some of the diffusers were located too close to potential workspaces. This might lead to local discomfort complaints due to draught and therefore it will probably needed to relocate the diffusers after the initial occupancy.

Even though the plenum was initially cleaned, it still remained dirty, possibly because of the unsealed openings in the plenum. This might significantly impair the indoor air quality and have also negative effects on mechanical devices installed in the plenum.

The easier commissioning and better performance of UFAD in Sparebank kvartalet could actually be achieved in a less time consuming and costly way if the commissioning would start early in the pre-design phase, with a well established commissioning plan.

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Appendix A: Sealing requirements [Nelson & Stum 2006]

- Floor area inspected and each opening to wall or floor cavities or to other spaces or zones is verified to be appropriate and all openings that should not be communicating to this floor space are sealed.
- Underfloor perimeter along exterior walls and above unconditioned space sealed absolutely airtight (drywall or sheet metal to concrete deck, vertical and horizontal drywall joints, other penetrations). Overlapping or butting building elements are not acceptable as a seal unless caulked.
- Penetrations from underfloor space into interior walls sealed reasonably airtight, but still caulked (drywall to concrete deck, vertical and horizontal drywall joints, around duct, pipe, conduit, and cabling penetrations).
- Open ends of conduits in underfloor space sealed with caulk.
- Penetrations of ducts and piping and other assemblies through the concrete subfloor or through the raised floor are sealed.
- Floor panels butting walls are *planned* to be gasketed and seal tight.
- The contractor is responsible to make the underfloor area airtight from all interior and exterior spaces, except for penetrating ducts and diffusers.
- The contractor shall follow the intent of the above requirements. The contractor shall follow the drawing details.

Appendix B: Underfloor construction checklist [Nelson & Stum 2006]

PRIOR TO SETTING PEDESTALS:

- Meeting held with drywall, electrical, controls, cabling, mechanical, sheet metal, and general contractors, architect, and commissioning authority to go over raised floor protocols and sealing details.
- Concrete floor sealer applied to subfloor, IF specified.
- Pre-installation adhesive field test completed per specifications (set 3 pedestals in adhesive, let cure for 30 days under 25 lbf, apply lateral load at top of pedestal, measure force to fail adhesive bond).

PRIOR TO SETTING FLOOR PANELS:

-MISC.

- All underfloor utilities and work complete (HVAC, plumbing, electrical, data, etc.).
- Carpet glue type and method of application relative to how much it seals panel joints is mocked up and approved.
- Underfloor air plenum dividers located and installed as designed.
- Zone and fire separations installed. Perimeter of every air handler zone is walked to verify it is in place and sealed.
- Shut off valves, sensors, dampers, actuators, fan coil units, filters booster fans be located so they can be accessed later for service and replacement.
- Record drawings submitted showing location of shut off valves, sensors, dampers, fan coil units, filters booster fans, controllers and other equipment requiring future maintenance or replacement. Submittal required before any panels cover these devices.
- Underfloor temperature sensors in good representative locations away from piping that may affect readings.
- Zone thermostats installed in location to avoid drafts and allow the best available representation of the zone temperature for control.
- Leak and moisture sensors in place, as specified.
- Insulation installed, as specified.
- Floor drains installed, as specified.
- FCU and booster fans mounted to avoid vibration. Duct insulation installed.
- Transfer ducts and extension ducting installed.
- Ducts to terminal devices connected and sealed. Special dampers installed.
- Any piping or other assembly under the floor that is more than 1/ 4 the floor space depth tall and is more than 1/2 the width of a path to an underfloor zone shall be viewed and approved by the designer.
- Electrical conduit and junction boxes and water piping is mounted above the concrete floor to allow for water to flow underneath to a floor drain or at least not backup into electrical equipment in the event of a leak.

- Piping pressure tested and passed and reports submitted.
- Underfloor motorized dampers and valves wired and verified to be functioning properly.

-CLEANING

- The area that panels are to be installed in is closed-in from outside (doors, windows installed and no wall breaches).
- The area that panels are to be installed in is closed-in from other areas in the building that are not closed-in to the outside.
- Prior to applying floor panels, after pedestals are set, sweep the concrete deck, scrape it of mud and vacuum with a pleated filtered vacuum with a brush-ended tool. The area cleaned shall be no more than the area planned to be covered with panels in the following two days.

-AIR SEALING

- Floor area inspected and each opening to wall or floor cavities or to other spaces or zones is verified to be appropriate and all openings that should not be communicating to this floor space are sealed.
- Underfloor perimeter along exterior walls and above unconditioned space sealed absolutely airtight (drywall or sheet metal to concrete deck, vertical and horizontal drywall joints, other penetrations). Overlapping or butting building elements are not acceptable as a seal unless caulked.
- Penetrations from underfloor space into interior walls sealed reasonably airtight (drywall to concrete deck, vertical, and horizontal drywall joints, other penetrations).
- Open ends of conduits in underfloor space sealed.
- Penetrations of ducts and piping and other assemblies through the concrete subfloor or through the raised floor are sealed.
- Floor panels butting walls are planned to be gasketed and seal tight.

DURING SETTING OF CONCRETE OR METAL FLOOR PANELS

- Do not cut and trim floor panels or perform other dust or debris generating work in rooms where floor panels are being installed.
- During installation of the concrete panels, workers have vacuumed any dust and debris on the floor before covering more than four new feet of panel and vacuum any dust and debris that may have accumulated under the panels during installation.
- Within two days of any floor panels being laid, the floor top has been vacuumed and each concrete or metal panel joint taped or covered with overlapping; taped paper or plastic to prevent dirt and dust from falling down the joints between the panels.
- Inspection. During panel installation, the owner or owner representative and the contractor have together made visual observations of approximately every 1,000 square feet during panel installation. Observations will be made from the open end of work (not lifting panels). Owner will approve or reject the cleanliness of that floor

section at that time and make visual note of the cleanliness or perform a “white glove test” for later reference.

BEFORE LAYING CARPET TILES (after setting floor panels)

- When workers access the under-floor after the panels are laid, they shall vacuum up any dust, dirt, or debris they create prior to closing the floor and replace the paper or plastic floor covering.
- When pulling panels, workers shall replace stripped screw heads.
- Floor panels butting walls and pillars are gasketed and sealed tight.
- Each floor box is airtight inside and sealed to floor panel.
- Penetrations into walls above are sealed.
- Plenum dividers located and sealed as designed.
- Junction boxes in exterior or interior walls used for thermostats are sealed to prevent air from space being pushed up past sensor.
- Mark floor panels with a heavy permanent marker indicating location of ALL valves (with ID and tag #), drains, sensors, dampers, control panels, and junction boxes are under the floor.
- Entire floor has been walked and any rocking panels tightened and stripped screw heads replaced.
- Carpet laid so carpet joints are offset from floor panel joints.

AFTER LAYING CARPET TILES

- When workers access the under-floor after the carpet is laid, they shall vacuum up any dust, dirt, or debris they create prior to closing the floor and replacing the carpet tile.
- Inspection. Contractor has walked floor with owner or owner representative and lifted up to one panel per 500 square feet and compared cleanliness to observations made during floor panel installation. The floor should be as clean as the earlier observations.
- Additional required under-floor cleaning complete.

Appendix C: Air leakage test procedure for Mock-up [Bauman et al. 2008]

1. A calibrated test fan or fans should be provided which should have the capability of supplying various airflow quantities from shutoff to 120% of the design airflow quantity required for the zone being tested and should be driven by a variable speed controller.
2. The test fan(s) should be installed together with a calibrated airflow test station. The discharge duct of the test fan(s) should be connected to the plenum through an opening by removing a floor panel and using an adhesive seal to secure a pressure tight connection.
3. A calibrated static pressure sensor-controller should be inserted into the plenum to control the speed of the test fan(s).
4. All floor diffusers and grilles, whether automatically or manually controlled, should be adjusted to their fully closed design positions.
5. The test fan(s) should be operated to hold the test static pressure in the plenum at 0.07 and 0.10 in. wg. (17.5 and 25 Pa).
6. The test fan(s) should be operated for a sufficient time to establish a steady-state static pressure within the zone being tested. Measurements should be taken at five minute intervals in each 1000 ft_2 of floor space within the zone being tested. Steady-state should be defined by at least six contiguous sets of readings of plenum static pressures that do not vary by more than +/- 0.005 in. wg. (1.2 Pa) for all measurement locations.
7. After steady-state has been established, the measured static pressure (in. wg. or Pa) and airflow rate (CFM or l/s) should be recorded for six consecutive times at uniform intervals of approximately 10 minutes. The average value of these airflow rates should be considered the sum of the Category 1 and Category 2 leakage and called the Σ leakage.
8. With the test fan(s) off, the floor panel and edge joints, the supply air diffusers and the cable floor connectors should be tightly sealed by taping, blanking off and other means, and steps 5 - 7 should be repeated. The resultant average value of the airflow rates should represent the Category 1 leakage.
9. Subtracting the Category 1 leakage rate from the Σ leakage rate should represent the Category 2 leakage rate.
10. The leakage rates in steps 8 and 9 should be compared to the allowable rates from the table below. If the rates are found to exceed the table values in either category, procedures should be taken to re-inspect, determine sources or causes of the leakage, repair or correct, and retest - repeating this process until the rates are within the table.
11. The systemic corrections that are required for the mockup to bring it into compliance with the test limits should be incorporated into the construction process and procedures for the remaining pressurized plenums in the building.

Appendix D: Air leakage test procedure during construction [Bauman et al. 2008]

1. The testing should be performed after the concrete surfaces of the plenum have been sealed, and all mechanical and electrical devices, equipment, cables, racks, diffusers, power connectors and voice/data connectors have been installed, but prior to installation of furniture, fixtures, equipment and finishes that may be vulnerable to damage from testing procedures.
2. The permanent air-handling system should have been installed, inspected and successfully tested.
3. The static pressure sensing component of the BAS should have been installed and calibrated before the test. One independent, calibrated static pressure gauge per UFAD zone should be installed adjacent to each permanent sensor (1000 square feet).
4. Prior to conducting the static pressure tests on the UFAD zones for air leakage, a *dynamic airflow test* should be conducted. The purpose of the dynamic airflow test to verify that the capacity of the AHU will maintain the design airflow rate at the design static pressure of the plenum (e.g., 0.07 in. w.g. (17.5 Pa)) shown on the AHU and Diffuser/Grille Mechanical Schedules of the Project Drawings:

a. This test should be conducted with all floor diffusers and grilles within the AHU zone in the positions as adjusted by the TAB contractor.
b. Adjust the AHU to provide the design airflow rate shown on the Mechanical Schedule.
c. Obtain static pressure measurements in the floor plenum at five minute intervals in each 1000 ft^2 of floor space within the zone being tested. Steady-state should be defined by at least six contiguous sets of readings of plenum static pressures that do not vary by more than +/- 0.005 in. wg. (1.2 Pa) *at each* measurement location.
d. When steady-state is achieved, measure the supply air from the AHU to the pressurized plenum. This measurement should be obtained either by recording the calibrated output from the installed flow-monitoring device, or by a standardized pitot-tube traverse method.
e. Compare the measured supply airflow rate and the maintained plenum mean value and range of static pressure with the conditions shown on the AHU and Diffuser/Grille Mechanical Schedules.

1. If the design value of the supply airflow rate for the AHU zone is within 10% of the value shown in the AHU Mechanical Schedule, and the maintained mean value of the plenum static pressure measurements for the zone (see 4c, above) is within 10% of the value shown in the Diffuser/Grille Mechanical Schedule, proceed to Step 5;

Otherwise, procedures should be taken to re-inspect, determine sources or causes of the discrepancies, repair or correct, and retest - repeating this process until compliance with these criteria is achieved.

Appendix E: Examples of questionnaires [NS-EN 15251: 2007]

How do you rate your thermal sensation?

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold

How do you perceive the temperature?

- Clearly acceptable
- Just acceptable
- Just unacceptable
- Clearly unacceptable

Do you want the room temperature?

a) Higher

b) No change

c) Lower

How do you perceive the air quality?

- Clearly acceptable
- Just acceptable
- Just unacceptable
- Clearly unacceptable

How do you perceive the odor intensity?

- No odor
- Weak odor
- Moderate odor
- Strong odor
- Very strong odor
- Overpowering odor

Appendix F: Energy saving strategies [Høseggen 2008]

Energy saving concept	**Description**
Heating	Low U-values of the windows and external walls Air tight building envelope Low temperature waterborne heating system Heat recovery from the process cooling of data centrals
Heating of the ventilation air	High efficiency heat exchange
Hot water supply	Water saving fittings
Fans and pumps	Low pressure ventilation system Demand controlled ventilation Low emitting building materials (reduce required air flow rate) Smoking is not allowed in a building Low SFP (maximum 1.8 kW/m^3s)
Lighting	Occupancy and daylight management lighting control system (reduces the energy need for lighting and cooling in summertime)
Equipment	Energy efficient equipment (reduces energy need for operation of equipment as well as cooling energy need in summer period)
Cooling	Use of thermal storage properties of the floor concrete slabs Solar shading and solar reflecting glass in windows and glass facades
Cooling of the ventilation air	Free cooling mode

Appendix G: Design indoor climate parameters [Hasfjord 2008]

Sparebanken 1 midt-norge - **Nytt hovedkontor**	Operativ temperatur					Lufthastighet		Fuktighet	Min friskluftsmengde		Lydtrykksnivå i rommet fra tekniske installasjoner db(a)	forurensing over utenivå co_2 ppm
	Dag sommer		Dag vinter		Natt	20°c	25°c	Laveste verdi %rf	Total belastning $m^3/h/m^2$	Person-belastning $m^3/h/pers$		
	Min.	Maks.	Min.	Maks.	Min.	Maks	Maks					
	°c	°c	°c	°c	°c	M/s	M/s					
Cellekontor	21	25	20	24	15	0,18	0,20		10	26	35	500
Kontorlandskap	21	25	20	24	15	0,18	0,20		10	26	35	500
Møterom	21	25	20	24	15	0,18	0,20		13	26	35	500
Kantine	21	25	20	24	15	0,18	0,20		13	26	40	500
Forretningslokaler	21	25	20	24	15	0,18	0,20		13	26	40	500
Arkiv/lager	20	26	18	24	15	0,20	0,20		5		40	500
Toalett / garderobe	20	26	20	24	15	0,20	0,20		-100 m^3/h pr.wc		40	500
Datasentral	20	25	20	25				40	5			500
Auditorium	20	26	20	24	15	0,20	0,20		15	26	35	500
Glass-spalte mellom blokker			18		15							
Parkering			15		10				3			

Appendix H: Supply airflow measurement locations