Diffuse Ceiling Ventilation

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- Design Guide for Wood Wool Cement Panel

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CONTENTS

1. PURPOSE OF THIS GUIDE

Diffuse ceiling ventilation is a novel air distribution concept, where the space above a suspended ceiling is used as a plenum and fresh air is supplied into the occupied zone through perforations in the suspended ceiling panels. Due to the large supply area, air is delivered into the occupied zone with very low velocity and with no fixed air direction, hence the name 'diffuse'. This ventilation system can reach a high cooling capacity by making full use of outdoor air, which has a great potential to apply in the cold climates. Moreover, this ventilation system uses a ceiling plenum to deliver air, which requires much lower pressure drop than the full-ducted systems. Recently, there has been a growing focus on the application of diffuse ceiling ventilation in offices and classrooms, where have intense heat loads and high ventilation demands.

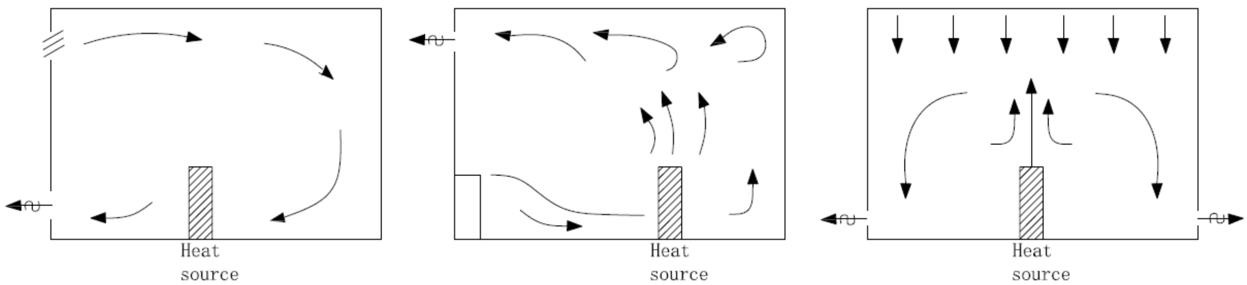
The purpose of this design guide is to provide a technical support and assistance in the design of diffuse ceiling ventilation, especially using wood wool cement panel as air inlet. The principles of air distribution and the benefits and limitation of the system are introduced. In addition, the crucial design parameters are summarized and their effects on the system performance are discussed. In addition to the stand-alone ventilation system, the integrations of diffuse ceiling ventilation with heating/ cooling systems are also addressed. Finally, a case study demonstrates the application and deign procedure of the ventilation concept.

This design guide is intended to be used by design engineers, architects and manufacturers of diffuse ceiling ventilation system.

2. SYSTEM DESCRIPTION

2.1 Principles

The main purpose of ventilation systems in buildings is to supply fresh air to the occupants and remove heat, gases, and particles from the building. Besides these basic requirements, special attentions have been paid to the design of ventilation systems to be more energy efficient and with a high level of thermal comfort. The most widely used ventilation systems in non-residential buildings are mixing ventilation and displacement ventilation, as shown in Figure 1 (a), (b).



(a) (b) (c)

Figure 1: Three different types of air distribution systems. (a) Mixing ventilation, (b) Displacement ventilation, (c) Diffuse ceiling ventilation [1]

In the mixing ventilation, the air is supplied to the room with high initial velocity and generates high turbulence, which promotes a good mixing and uniform temperature and pollution distribution throughout the occupied zone. On the contrary, the principle of displacement ventilation is to replace but not to mix the room air with fresh air, where the fresh and cold air is supplied close to the floor. This system utilizes buoyancy forces in the room generated by heat sources to remove contaminants and heat from the occupied zone. By doing so, the air quality in the occupied zone is generally superior to that achieved with mixing ventilation. However, the highest velocity and the lowest temperature occur near the floor and vertical temperature gradient exists in the room. In the case of large ventilation demand and cold supply air, draught would probably occur by using these two ventilation systems due to their highly concentrated air inlets.

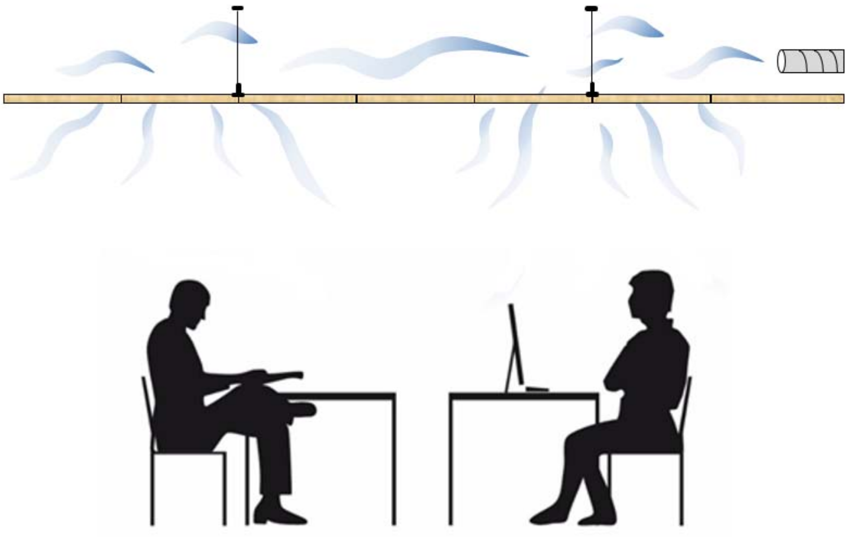
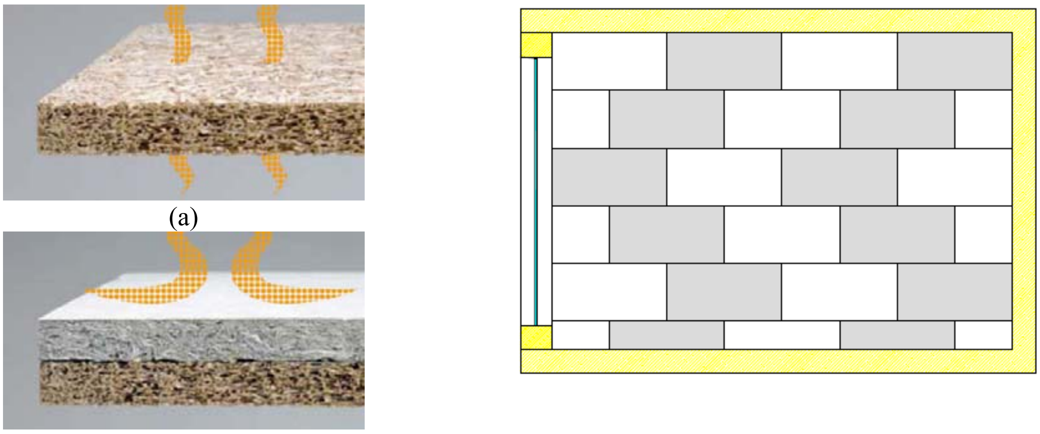


Figure 2: Diffuse ceiling ventilation system

Diffuse ceiling ventilation uses an open space between ceiling slab and suspended ceiling as a plenum to deliver conditioned air, as illustrated in Figure 2. The air penetrates through the suspended ceiling into the occupied zone driven by the pressure difference between the plenum and the conditioned space. This concept is characterized by the large suspended ceiling used as an air diffuser. The air is delivered into the occupied zone with very low velocity and no fixed air direction. Therefore, the ventilation system does not generate significant draught even by directly supplying outdoor air with extremely low temperature. The buoyancy force generated by the heat sources is the dominant force for the air distribution in the room with this system. The uprising buoyancy flow interacts with the downward supply flow through the diffuse ceiling and generates an air recirculation in the room level. The buoyancy flow determines the mixing level in the room. Another feature of diffuse ceiling ventilation is that the plenum employs to distribute air instead of running ducted system. Pressure losses for air distribution are much smaller compared with the ducted system. In addition, suspended ceiling as air diffuser required much lower pressure drop than conventional diffusers, due to its large opening area. The low-pressure drop of the system reduces the energy consumption of fan and makes the use of natural ventilation possible.

2.2 Diffuse ceiling inlet

The designs of diffuse ceiling inlet such as shape and material of ceiling panels, perforation degree, and ceiling suspensions, etc. have significant influences on the performance of ventilation system. Figure 4 demonstrates an example, where the suspended ceiling is made of passive and active wood wool cement panel. The technical detail is shown in Table 1. The active panels are air permeable and typically comprise 10% - 20% of the entire ceiling. The passive panels have a layer of impenetrable mineral wood glued to the backside layer. The combination of the active and passive panels improves the acoustic properties and permits control of the supply air distribution in the room. The further investigation on the impact of the active area on the system performance can be seen in Section 6.1.



(a)

(b) (c)

Figure 3: A combination of passive and active diffuse ceiling panels (a) Active wood wool cement panel (b) Passive wood wool cement panel with impenetrable mineral wool layer (c) Placement of diffuse ceiling panel (grey present active panels, white present passive panels) [2]

Table 1 Properties of active and passive panels

Properties	Active panel	Passive panel
Thickness [mm]	25 - 35	50 - 60
Width [mm]	600	600
Length [mm]	600 -1200	600 -1200
Weight [kg/m^2]	9.7 – 12.0	11.7 – 14.0

2.3 Benefits and limitations

Benefits

- High thermal comfort

Diffuse ceiling panels as an air terminal device could provide a draught free environment, even by directly using outdoor air in winter. Experimental results indicated that no significant draught is experienced even with supply air temperature down to -6 ºC [3][4]. In addition, diffuse ceiling ventilation creates a uniform temperature distribution in the occupied zone. A small vertical temperature gradient ranging from 0.2 K/m to 1 K/m have been observed in the cases of cooling while values are up to 2.5 K/m in the cases of heating [5][6][7]. More information regarding thermal comfort level can be seen in Chapter 4.

- Energy saving

Diffuse ceiling ventilation presents many opportunities for energy saving. First of all, the low-pressure drop, associated with diffuse ceiling diffusers and air distributions by plenum, allows a reduction in fan power and even makes the system could be driven by natural ventilation. Secondly, diffuse ceiling ventilation presents a high possibility to work together with night cooling. Because the ceiling slabs are typically exposed to the supply air pathways in this system, increases the efficiency of the thermal storage and improves the pre-cooling effect. Finally, the energy consumption of the heat recovery unit and the preheating unit can be eliminated, because the system can provide a draught free environment even by directly supply cold outdoor air directly. Detail description regarding energy use refers to Chapter 5.

- High cooling capacity

Compared with conventional ventilation systems, the comfort requirements do not have strong limits on the diffuse ceiling ventilation in term of supply air temperature and ventilation rate. This feature enables the system to handle a high heat load. By comparing different ventilation systems in the same office room [8], it was observed that diffuse ceiling ventilation has the highest cooling capacity of 72 W/m^2, while the cooling capacity of mixing and displacement ventilation are 53 W/m^2 and 40 W/m^2, respectively. However, the system capacity is influenced by a number of parameters. In addition to the plenum and diffuse ceiling configurations, it is also affected by the heat source condition and room geometry. The crucial design parameters and their effects refer to Chapter 6.

- Low investment cost

Compared with conventional mixing or displacement ventilations, diffuse ceiling ventilation requires low initial investment cost, based on the following reasons. First, the suspended ceiling panels are applied as air diffusers, which are originally for the acoustic purpose. Therefore, the ventilation system eliminates the additional cost on the air diffusers. Second, conventional ventilation designs normally require large amounts of ductworks. However, diffuse ceiling ventilation uses a plenum to distribute air, which partly or even totally removes the cost on the duct system. In addition, the plenum height can be reduced, since the ductwork is not required in the plenum. Consequently, it could also reduce the total height of the building and give substantial saving in some case. Finally, the low draught risk of the diffuse ceiling ventilation enables cold outdoor air to be directly supplied to the room without preheating process. The cost saving on the preheating unit or heat recovery unit is significant. It is estimated that a cost saving of 5-10% by using diffuse ceiling ventilation system compared with a conventional ventilation system and a traditional acoustic ceiling.

- Low noise level

In Danish legislation, there are requirements on the acoustic level. For instance, in open plan offices, there is a requirement stated that 80% of the ceiling surface should be covered by acoustic ceilings; while in the classroom, most often requires of 100% covering of the ceiling to limit the reverberation time. In diffuse ceiling ventilation system, the suspended ceiling, combined the functions of acoustic control and air diffuser, covers a large part or even entire ceiling area. On the other hand, due to the minimal use of ductwork, the noise generated from the ventilation system is substantially less than that from a conventional ducted system. This reduction of background "HVAC" noise may create a better working or study environment for the occupants.

- Easy installation

The installation of ductwork and air diffusers will be significantly reduced by using diffuse ceiling ventilation. In addition, due to the elimination or minimal use of ductwork and other equipment in the plenum, the installation becomes easier and simpler.

Limitations

- Condensation risk

According to the previous studies, if the ceiling panels are made of a material with high thermal conductivity (for example aluminum), the diffuse ceiling will present a lower surface temperature than the rest of room surfaces. Thus, condensation issue is a problem faced by this technology. Condensation of moisture will affect visual perception and function, also, the surface of the ceiling grows wet dirty and microorganism so that disease breeds heavily and drop water from the ceilings forming the so-called "Office Rain". Condensation risk can be aggravated by reverse-flow, where high-humidity and high-temperature air flow from conditioned space is forced back to condense on the back-side of suspended ceiling panels. The condensation can cause early failure of the suspended ceiling panels.

The risk could be minimized by choosing proper diffuse ceiling panel and suspension profile. For example, when using the system with wood wool cement panels and a concealed grid system, either T or C-profiles, the condensation risk will be minimized as the panels work as thermal insulation between the plenum and the conditioned space. In addition, the panels are made by high absorbing material and could serve as a humidity buffer and give a substantial stability to the indoor relative humidity, where the moisture capacity is as high as 3 kg/m^2.

- Room geometry

The system performance of diffuse ceiling ventilation depends on the room geometry. It is recommended to use this ventilation concept in the room with a typical room height (less than 3 m), in order to reduce the draught risk in the occupied zone, detail refers to Section 6.4.

On the other hand, the area of the room is another crucial parameter. The increase in the room area could exacerbate any uneven air distribution through the diffuse ceiling and lead to problems on the thermal comfort and air quality. If the area of the room is more than 150-200 m^2, it is recommended to even out the air distribution by using diffuse ceiling panels with a higher pressure resistance, or/and optimize plenum inlet configuration (e.g. provide more inlets over the plenum, or use a perforated duct to distribute air in the plenum).

Finally, a minimum plenum height should be specified in the design phase, at which acceptable air distribution through the plenum could be expected. In the case driven by natural ventilation or plenum inlet only in one edge of the room, a minimum plenum height of 20 cm is required. Detail description regarding plenum configuration can be found in Section 6.2.

3. CHARACTERISTICS OF DIFFUSE CEILING VENTILATION

3.1 Room air flow pattern

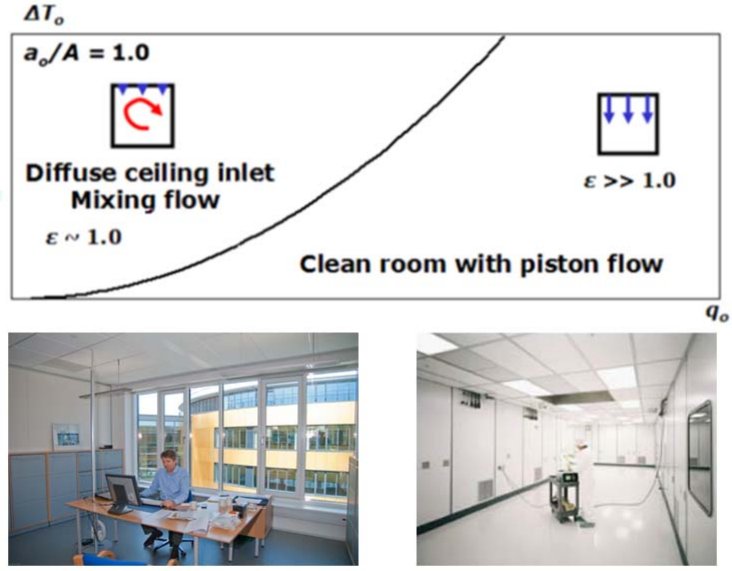


Figure 4: Diffuse ceiling ventilation presented on a q-ΔT graph, and two examples of diffuse ceiling ventilation application: office and clean room [9]

Diffuse ceiling ventilation is also named as downward ventilation. The air distribution patterns in rooms with diffuse ceiling inlet might be controlled either by buoyancy flows from heat sources or by momentum flow from the air supply depending on air change rate, see Figure 4.

In the case of air distribution pattern controlled by momentum flow, the high air change rate is needed (50-100 h^{-1}), where the piston-flow takes place. This air distribution concept is specially applied in a clean room where very high ventilation effectiveness is expected. Low return openings are required in this case.

When the air change rate ranges from 1 to 5 h^{-1}, the air distribution pattern in the room is controlled by buoyancy flows, and the ventilation effectiveness is close to 1, which could regard as a mixing flow. This air distribution concept is suitable for buildings requiring high cooling demand and high thermal comfort level, like offices or classrooms. There is no strict requirement on the location of return opening in this pattern. In this design guide, special attentions have been paid on buoyancy controlled air distribution pattern, due to its wide application potential.

3.2 Ventilation system solutions and characteristics

A ventilation system solution is often a comprehensive decision based on outdoor and indoor climate, energy use, total costs, building design, building function and user requirements. In this section, different system solutions with diffuse ceiling inlet are described and their characteristics are evaluated.

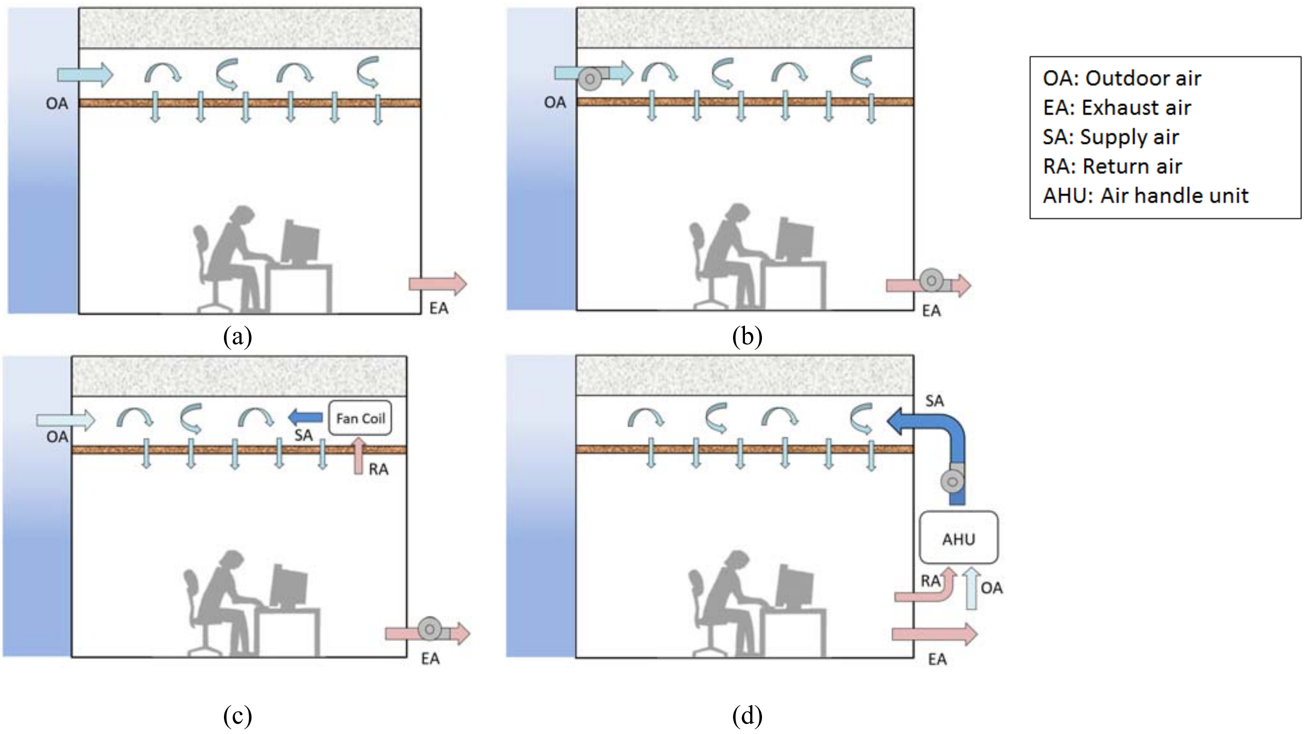


Figure 5: Schematic diagram of different ventilation strategies (a) Natural ventilation (b) Mechanical ventilation (c) Hybrid ventilation with fan coil unit (d) Full air conditioning

- **Natural ventilation:** Natural ventilation can provide fresh air to achieve air quality requirement and to provide cooling when needed. However, the implement of natural ventilation is limited in winter or part of the transient season, due to thermal comfort becomes a major concern. This problem can be solved by using diffuse ceiling ventilation since the system can provide a draught free environment even by directly cool outdoor air. Another advantage of diffuse ceiling ventilation is that it has low pressure drop, which makes it possible to be driven by natural driving force.
  The most important issues of natural ventilation are to optimize using of driving forces and to minimize pressure loss of the system. For example, maximum use of wind conditions at the building site, optimal design of inlet size and location, careful evaluation of room geometry (avoid a narrow plan). Normally, the pressure loss of natural ventilation system should keep less than 10 Pa.
  Heat gain is another critical factor in the success of natural ventilation strategy. When the heat gain is above 30-40 W/m^2, careful evaluation should be made before using natural ventilation (e.g. solar control, exposed thermal mass, night cooling ventilation). A hybrid ventilation (mixing mode) could be appropriate.

- **Mechanical ventilation:** Mechanical ventilation resolves a number of problems associated with natural ventilation. It requires much smaller inlet opening and does not have a strict limit on the room geometry. In addition, it is easier to control and provide the possibility of sound absorption and air filtration.
  But using mechanical ventilation for cooling requires careful consideration, whether the energy use for transport the air sometimes is greater than the delivered cooling energy. The Even worse situation is that the work energy may raise the temperature of the outdoor air, results in warming of the building [10]. Therefore, the relation between outdoor air temperature and the COP of the fan should be considered in the design stage.

- **Hybrid ventilation (mixed mode ventilation):** Hybrid ventilation systems use both natural driving forces and mechanical systems to provide a comfortable indoor environment. In the hybrid ventilation,

mechanical and natural forces are combined in a two-mode system where the operating mode varies according to the season and within individual days. Thus, the active mode depends on the outdoor environment and takes maximum advantage of ambient conditions at any point in time. The main difference between a conventional ventilation system and a hybrid system is that hybrid system requires an intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption.
Mechanical cooling is only used when natural resource is inadequate. The cooling terminal can be classified into two categories based on their heat exchange mechanism: air-based and radiant terminal. The typical air-based terminal is fan coil unit Figure 5 (c).

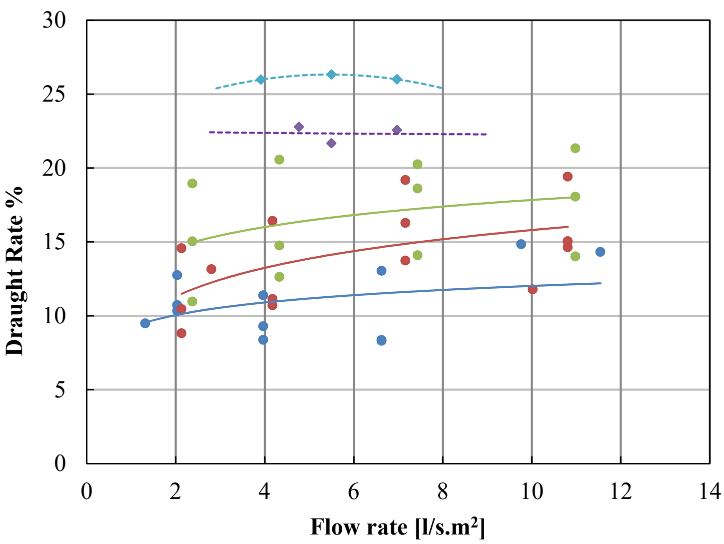
- **Fully air-conditioning:** Fully air-conditioning system uses a central air-handling unit to treat the air to a desired temperature and humidity, and then transports the conditioned air to each room by means of a fan. The room temperature can be controlled by varying the supply air temperature with a constant air flow rate (CAV) or by varying the air flow rate at a constant supply air temperature (VAV). Using fully air-conditioning system into a design can often add approximate 50% of running cost of the building[11]. At the same time, the environmental emissions and maintenance cost significantly increase. It should be avoided where possible.

It should be noticed that not all parts of a building have to be treated in exactly the same way. Different ventilation solutions may be applied to different parts of a building, or at different times.

4. THERMAL COMFORT AND INDOOR AIR QUALITY

4.1 Draught rate

Draught is an unwanted local cooling of the body caused by air movement, which is one of the most common causes of complaint in ventilated or air conditioned buildings. Diffuse ceiling as air terminal devices is able to provide a draught free indoor environment even with low supply air temperature [8][6][12].



Description	Parameter	Reference
● 2.5 m	Room height	[13]
● 4.1 m		
● 4.4 m		
◆ Even	Heat load distribution	[14]
◆ One side		

Figure 6: Draught rate vs flow rate with different design parameters.

Although diffuse ceiling ventilation has lower draught risk compared with the conventional ventilation system, some critical parameters should be careful analyzed in the design phase to avoid the draught problem. Figure 6 indicates the relation between draught rate and two design parameters: room height and heat load distribution. By comparing the draught rate in the rooms with three heights (2.5 m, 4.1 m and 4.4 m), it can be concluded that the increase of room height results in an increase of the draught rate. On the other hand, the heat loads located on one side of the room gives a higher draught rate than those evenly distributed. It is needed to notice that the draught rates presented in Ref. [14] are higher than the practical cases, due to the extreme high heat load of 72 W/m^2. The draught rate also depends on the diffuse ceiling and plenum configurations, etc. Detail discussion on the impact of different design parameters refers to Chapter 6.

4.2 Temperature gradient

Temperature stratification that results in the air temperature at the head level being higher than at the ankle level may cause thermal discomfort. In order to avoid discomfort, the limitation of the temperature difference between the head level and ankle level (0.1 – 1.1 m above floor) less than 3 ºC for Category B [15].

Diffuse ceiling ventilation can provide a good mixing of supply air and room air and creates a low vertical temperature gradient in the cooling conditions, where the temperature gradient is less than 1 ºC/m. While a temperature stratification may occur in the heating case, where the temperature gradient may above 2 ºC/m. However, the heating is normally required during the unoccupied period, or use for preheating the space 1-2 hours before occupants show up. Therefore, discomfort caused by temperature gradient may not be the major concern in this scenario.

4.3 Indoor air quality

The parameters to evaluate the indoor air quality include ventilation effectiveness and air exchange efficiency. If there is complete mixing of air and pollutants, the ventilation effectiveness is 1. The ventilation effectiveness of diffuse ceiling ventilation can be analyzed by means of tracer gas measurements [6], and it is found that the ventilation effectiveness by diffuse ceiling ventilation is 0.9 ~ 1 in the breathing zone. This means diffuse ceiling as the air terminal device can generate good mixing in the occupied zone.

Another index of the indoor air quality is air exchange efficiency, which shows how fast the air is exchanged in a ventilated room. It is dependent on the air distribution system in the room, the geometry of the room and location of heat source, but it is not dependent on the location of the contaminant sources. The investigation on the air exchange efficiency supports that good mixing in the occupied zone by diffuse ceiling ventilation [12]. On the other hand, no evidence indicated there is any stagnant zone or short-circuiting ventilation in the room.

5. ENERGY USE

One of the benefits of diffuse ceiling ventilation system is the large energy saving potential. This section explains the factors that affect energy use in the system.

5.1 Air distribution energy

The air distribution energy is determined by the pressure drop of the system. Normally, it is preferable to reduce the pressure drop, which is possible to avoid noise problem and at the same time save the power consumption of the fan. One advantage of the diffuse ceiling as air terminal device is the low-pressure drop.

The low-pressure drop of the diffuse ceiling system is attributed to two reasons. First of all, the plenum is a primary air distribution route. The use of the plenum reduces or even eliminates the need for ductwork and the large size of the plenum creates a little restriction to the flow of air. Consequently, the amount of pressure required to deliver air by diffuse ceiling is much lower than that required by the conventional ventilation system. Secondly, suspended ceiling panels are used as air inlet in this system. Compared with conventional air inlets, the diffuse ceiling panels requires low-pressure drop due to its large inlet area.

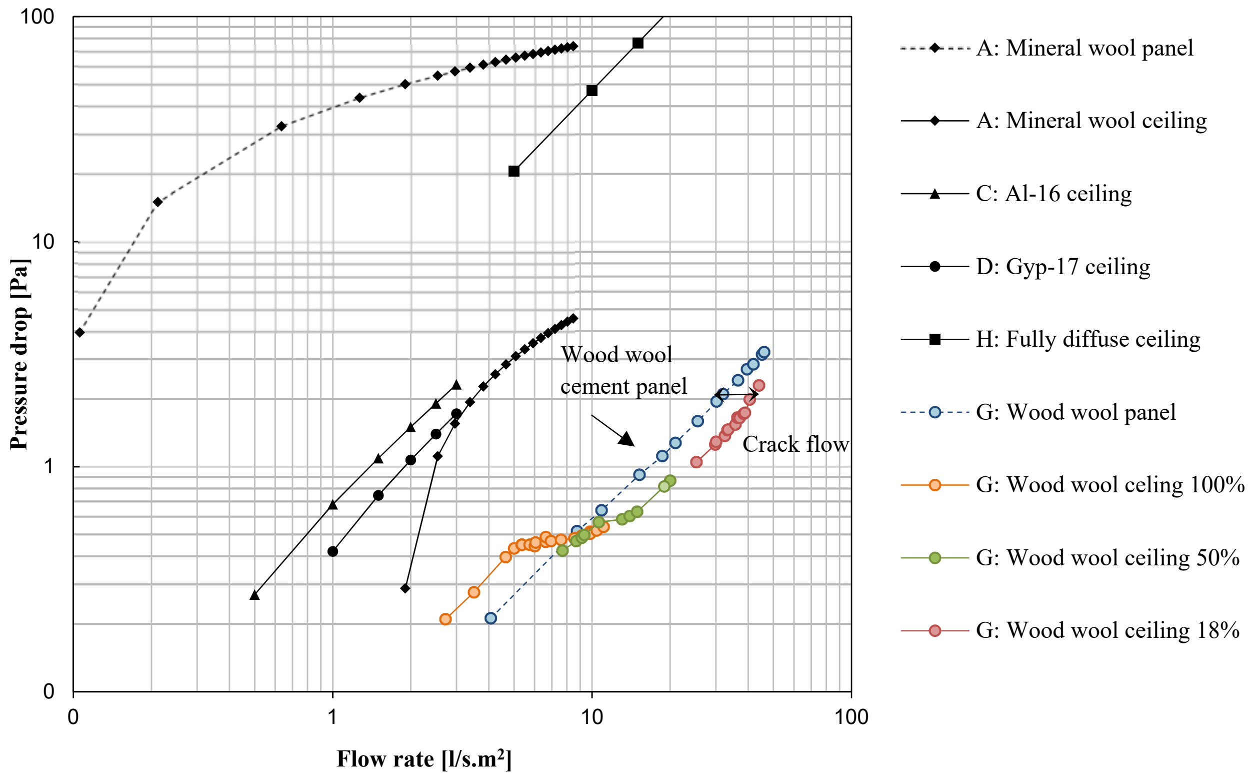


Figure 7: Relation between pressure drop and flow rate for different diffuse ceiling inlets, and comparison with single panel

Figure 7 illustrates the pressure drops across different types of diffuse ceiling designs, as a function of air flow rate. Compared with the other diffuse ceiling designs, wood wool cement ceiling gives the lowest pressure drop, which is less than 4 pa for the air flow rate ranging from 1- 40 l/s.m^2.

For the wood wool cement ceiling, panel flow takes 75% and crack flow takes only 25%, when the pressure drop is 2 Pa. The crack flow can reduce the pressure drop of the system, but may influence the air distribution by introducing micro-jets. These results also indicate that the pressure drop depends on the types of diffuse ceiling panel and connection profile.

On the other hand, the pressure drop strongly depends on the diffuse ceiling opening area. The measurements on the pressure drop were conducted under three diffuse ceiling opening ratios: 100%, 50% and 18%. The results indicated that air is mainly supplied through the perforated panels in the case with 100% DF. The crack flow becomes more significant while reducing the diffuse ceiling opening area. Therefore, it can be concluded that major factors influencing pressure drop are diffuse ceiling inlet type, opening area, air tightness of connections as well as a suspension system.

The pressure loss through the air distribution system is a dominant parameter of fan's energy consumption. P Jacobs et al. [4] described two field studies of the classroom with diffuse ceiling ventilation systems, Sliedrecht primary school and Tilburg primary school. By comparing with traditional and modern ventilation systems for schools in Netherlands [16], they found out the specific fan power (SPF) and energy cost of diffuse ceiling systems was considerably lower than other ventilation systems, as shown in Table 2. In Holland, the average electricity use of a classroom is 18 kWh/m^2. This costs about 200 € per year per classroom. The implementation of diffuse ceiling ventilation reduced the electricity cost even to 20-2€/a, due to the absence of preheating unit and reduction on fan's consumption.

Table 2: Comparison of specific fan power (SPF) and electricity consumption of different ventilation systems. Occupancy 1040 h/year, flow rate 200 dm3/s, electricity costs 0.2 euro/kWh [16]

Systems	**SPF [kW/m^3]**	**Electricity costs [€/year]**
Traditional system	5 - 10	290
Modern system	2 – 2.5	90
Primary school Sliedrecht	0.04	2
Primary school Tilburg	0.5	20

5.2 Extended free-cooling period

Natural ventilation is one of the most effective techniques for passive cooling. However, in winter or part of transient seasons, if the outdoor air is used directly for cooling, it could generate draught in the occupied zone. A common approach is to preheat the outdoor air before sending into the room, which results in a remarkable decrease of the ventilation cooling capacity and increases the investment cost.

As mentioned in Section 4.1, low draught rate is the main characteristic of diffuse ceiling ventilation. The large inlet area enables the air delivered into the occupied zone with very low velocity, and the preheating effect of the plenum ensures the air into the room with moderate temperature. According to the experimental study [3], even with an extremely low supply air temperature down to -7°C, occupants still do not experience draught in the room with diffuse ceiling ventilation. This makes it possible to directly use outdoor air for cooling even in winter, which reduces or eliminates the need for the pre-heating unit and extends the free-cooling period by ventilation.

5.3 Night cooling strategy

Due to an overall trend towards less heating and more cooling demands in buildings in many European countries over the last few decades, passive cooling by night-time ventilation is seen as a promising technique, particularly for commercial buildings in the moderate or cold climate. The basic concept involves cooling the building structure overnight in order to provide a heat sink that is available during the occupancy period. Such a strategy could guarantee the daytime thermal comfort of building occupants without mechanical cooling or, at least, with a lower daytime cooling energy requirement. Based on the analyzing on the climatic data [17], it is found out there is a high potential for night-time ventilation cooling over the whole of Northern Europe and still significant potential in Central, Eastern and even some regions of Southern Europe.

Diffuse ceiling ventilation presents a high potential to combine with the night cooling strategy, because the ceiling slabs are typically exposed to the supply air pathways in this system, which increase the efficiency of the thermal storage and improve the pre-cooling effect. The diffuse ceiling ventilation can circulate cool air throughout of the building, effectively removing stored heat from the building and pre-cooling the building constructions for the next day.

Although this ventilation concept offers a significant potential for energy saving and lower cooling peak loads, it requires a proper and complete control strategy. Sometimes, one weakness of this system is that there is a period of warm up required on the morning following the night cooling. Then the thermal mass would have a negative impact on the heating system and more heating energy would be required.

6. DESIGN PARAMETERS

6.1 Diffuse ceiling opening area

Unlike the momentum driven ventilation systems, the inlet area of diffuse ceiling ventilation is more flexible. The inlet can either occupy the whole ceiling area or a part of the ceiling. The impacts of the diffuse ceiling opening area on the thermal comfort and system performance have been studied through experimental study [4]. The tests were carried out with three diffuse ceiling opening ratios: 100%, 50% and 18%, as shown in Figure 8.

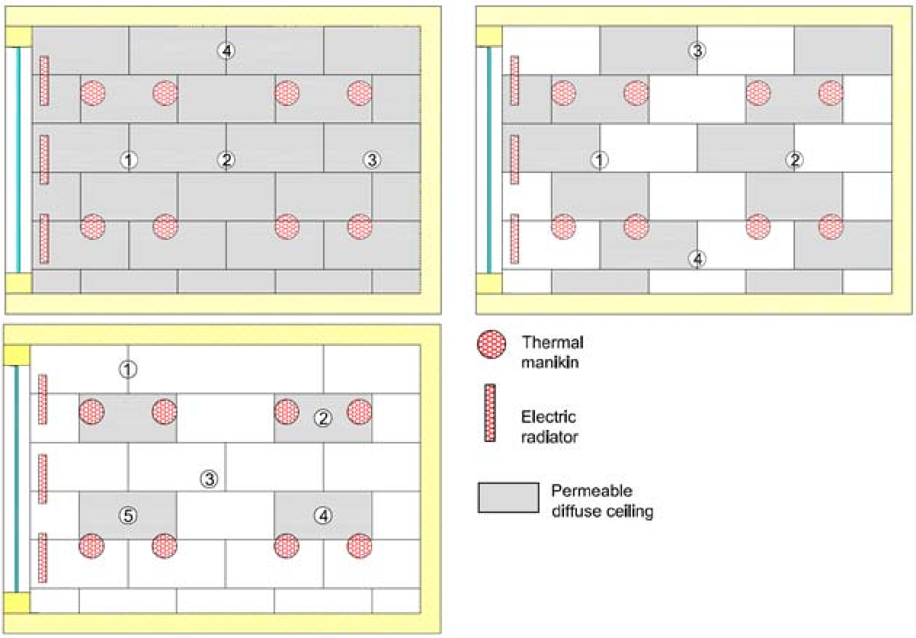


Figure 8: The layout of diffuse ceiling with different opening areas[4]

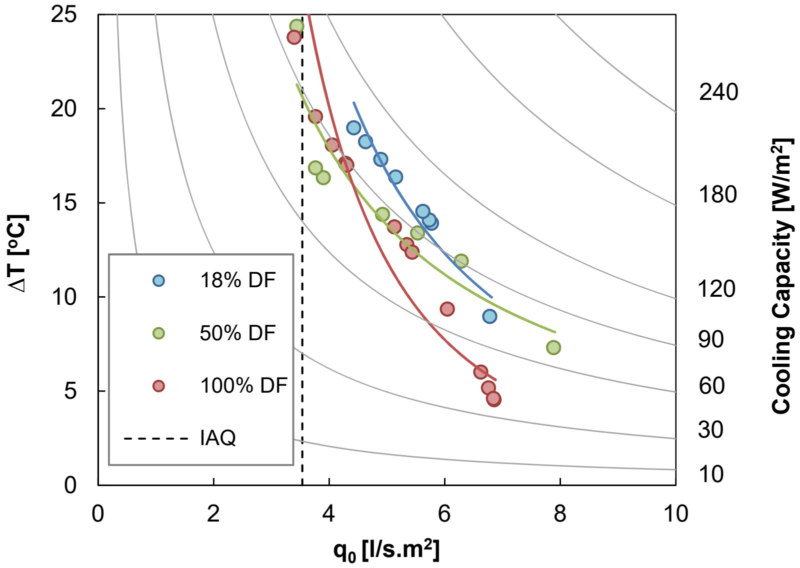


Figure 9: Design chart for different diffuse ceiling opening areas [4]

A design chart method was implemented to compare the system with different diffuse ceiling configurations, and the enclosed area of the design chart satisfied both the thermal comfort and indoor air quality requirements. Figure 9 indicates that the cooling capacity of diffuse ceiling ventilation ranged from 40 W/m^2 to 100 W/m^2 depending on the diffuse ceiling configurations. The system with 18% opening area was able to handle the highest heat load without draught. This could be explained by the heat sources being located below the perforated diffuse ceiling panels in the 18% case. Consequently, the cold supply air can directly deal with the thermal plume from the heat sources. On the other hand, 18% of the opening area can produce relatively higher momentum flow than the other two configurations, which to some extent influences the flow pattern of the room. On the contrary, the system with 100% opening area had the lowest cooling capacity. However, it is too early to draw the conclusion that smaller the opening area will lead to a higher cooling capacity. The relative location of heat sources and the diffuse ceiling opening plays an important role and need further investigation.

6.2 Plenum design

(a) (b)

Figure 10: Overhead plenum and diffuse ceiling setup [4]

The use of a plenum to distribute air is one of the key features that distinguish diffuse ceiling ventilation from conventional ducted ventilation systems. The plenum is the space between the ceiling slabs and the suspended ceiling panels. Figure 10 presents an example of an overhead plenum. The ceiling panels are installed 0.35 m below concrete slabs with a specific suspension system. The inlet openings face to the plenum and supply outdoor air to the plenum directly.

The thermal process in the plenum differs from that with the fully ducted system. As supplied air travels through the plenum, it has directly contacted with the thermal mass of ceiling slabs and diffuse ceiling panels. This will transfer heat from TABS and the occupied space to the air and results in a thermal decay on the supply air. In the design of the plenum, the main objective is to ensure a uniform distribution through the diffuse ceiling on both air quantity and air conditions. A large number of design parameters encounter in practice, for example, plenum geometry, plenum inlet configuration, obstruction within the plenum and so on. These design parameters and their effects on the energy and airflow performance will be discussed in this section.

6.2.1 Plenum inlet

The plenum inlet location and configuration determine the air flow pattern within the plenum and further influence the temperature variation within the plenum. Figure 11 presents an example of temperature distributions in the plenum with single jet inlet and with inlet vanes [18]. The dimension of the plenum was 14.6 × 4.7× 0.254 m^3. It is found that inlet vanes provide more evenly distributed temperature throughout the plenum. In addition, the results indicated that the area closest to the plenum inlet do not essentially have the lowest temperatures, which depends on the direction of airflow.

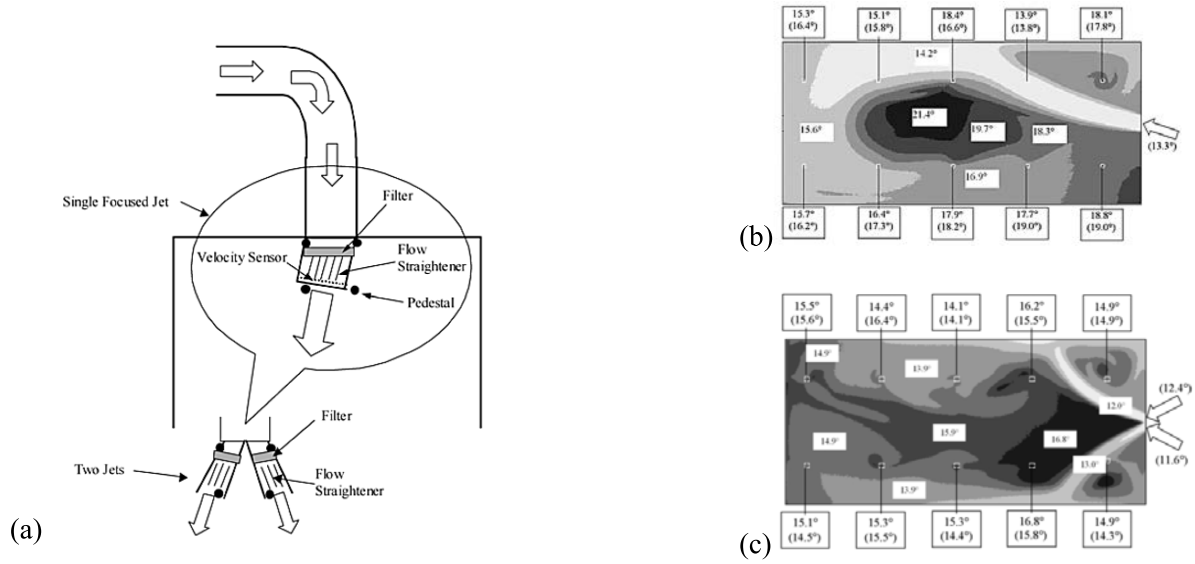


Figure 11: Comparison of plenum air temperature for different inlet configurations; Predicted temperature (Measured temperature) ºC (a) Schematic of plenum inlet (b) Single jet inlet (b) Inlet vans [18]

If the size of the plenum is more than 150- 200 m^2 or depth of the room is larger than 10 m, the inlet placed on one edge cannot guarantee that the supply air reaches the entire space with required quantity and conditions. An alternative solution is to place additional inlet on different edges of the plenum to uniform the air distribution. Another solution is to use ductwork to distribute air through parts of the plenum [19]. The inlets can be placed along the length of the duct and balance dampers should be considered to avoid variances of distribution within the plenum. However, fan units are required to drive the airflow through the duct and additional investment and running cost is expected.

6.2.2 Plenum geometry

From an architectural standpoint, it is preferable to reduce plenum height in order to maintain sufficient headroom. However, low plenum height may also result in uneven air distribution. It is important to identify the minimum plenum height at which an acceptable air distribution within the plenum could be achieved. Studies were performed on plenums varying from 5cm to 35 cm in height under the boundary condition of a winter case (supply air temperature at -7 °C), and TABS was activated as a heating mode [20]. Figure 12 presents the air temperature distribution through the diffuse ceiling (1cm above ceiling panel). It is clear that the distribution variances dramatically increased when the plenum is lower than 10 cm. This is because the supply air could not mix well with the plenum air when the plenum height was low. Therefore, cold air was delivered to the room at a short distance from the plenum inlet, and warm air was delivered at the far end of the room.

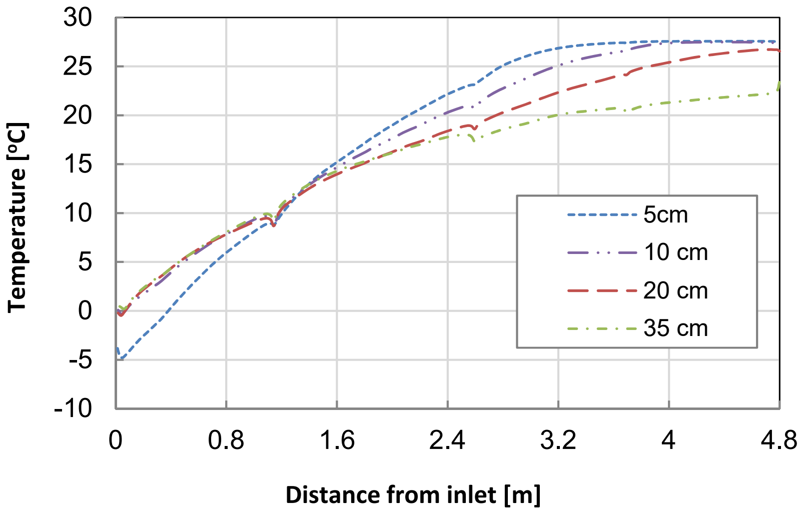
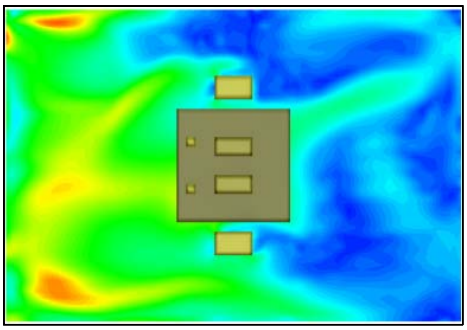
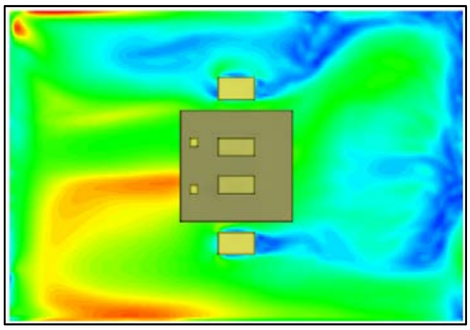


Figure 12: Temperature distribution through diffuse ceiling [20]

Plenum height influences the uniformity of air distribution through the diffuse ceiling, and further impacts the airflow performance in the occupied zone. The velocity distributions at 0.1 m height were analyzed and compared by different plenum heights, as illustrated in Figure 13. While decreased the plenum height from 35 cm to 5cm, reverse flow with high velocity penetrated from front side of the room to the entire room and the magnitude of air velocity increased significantly. The high air velocity at the floor level consequently resulted in a high draught risk for the occupants, especially those seated close to the plenum inlet. A minimum plenum height of 20 cm is recommended to enable an even air distribution and low draught risk in the occupied zone.



(a)



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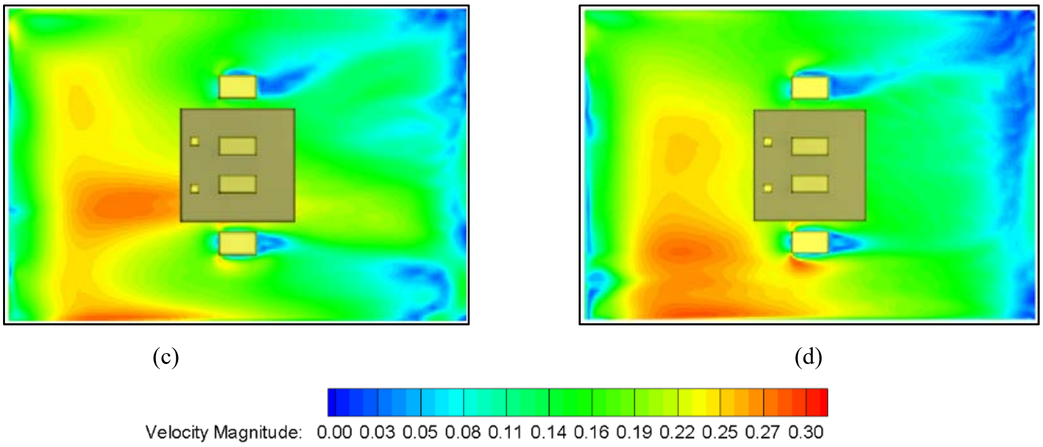

Figure 13: Velocity distribution at 0.1 m height with different plenum heights (a) 35 cm (b) 20 cm (c) 10 cm (d) 5 cm [20]

Plenum depth is another important parameter effected the air distribution through the diffuse ceiling. Figure 14 presents the velocity distribution at 0.1 m height in the room with two plenum lengths (4.8 m and 9.6 m). The intensity of air velocity and the region with high velocity increased dramatically when the length was doubled. The maximum velocity in the occupied zone reached 0.32 m/s in the room with 9.6 m length. The occupants located near the façade will experience significantly higher draught risk than the ones located near the back wall. Therefore, if the room depth is larger than 10m, additional plenum inlets over the plenum or ductwork within the plenum are recommended to even up the air distribution.

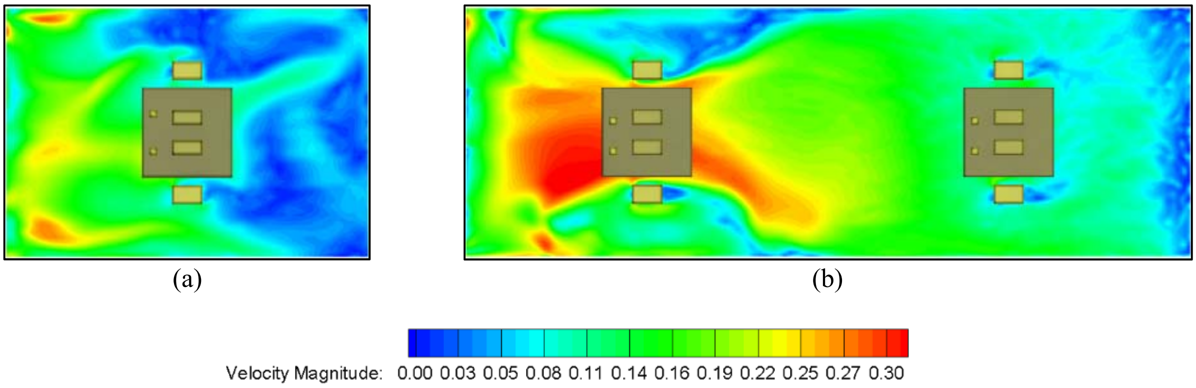

Figure 14: Velocity distribution at 0.1 m height with two plenum depths (a) Plenum depth of 4.8 m (b) Plenum depth of 9.6 m [20]

6.3 Heat sources

As mentioned in Section 3.1, convection flow generated by the heat sources is the dominant flow and determines the flow pattern in the room with diffuse ceiling ventilation. Therefore, the heat source, such as location and type, have a significant impact on the ventilation system performance.

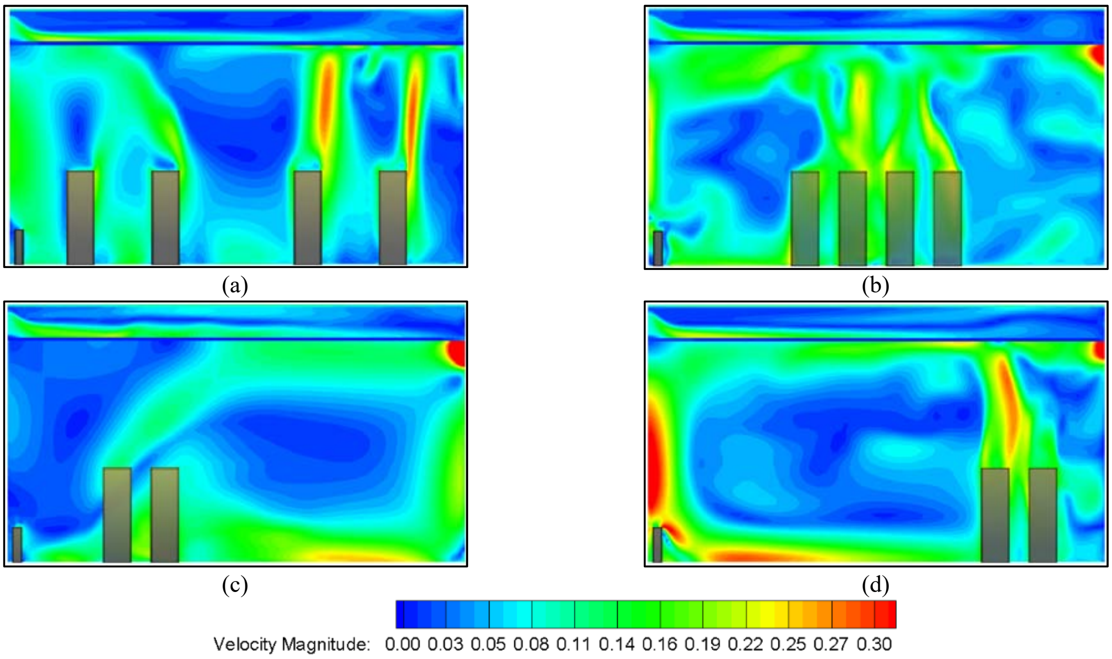

Figure 15: Velocity distribution for different heat load layout (a) evenly distributed, (b) centered, (c) front side and (d) back side. [4]

An investigation of heat load distributions was conducted by the numerical study [4]. It was obvious that different heat load locations generated very different flow patterns and further affected the comfort level in the occupied zone. A strong air recirculation occurred when the heat sources were placed on one side of the room and generated high draught risk at the floor level. The draught rate with back side located heat sources reached 20%. While, in the case with evenly distributed heat sources, no clear air recirculation was observed and the draught risk was only 12%. It has to be taken into consideration that for very unevenly distributed heat sources in a room the cooling capacity of the system will be reduced.

6.4 Room height

The impact of room height was investigated under three scenarios: 2.335 m, 3.0 m and 4.0 m, as shown in Figure 16 [4]. The air flow patterns showed a similar tendency. However, the intensity of the recirculation increased dramatically with the increase of the room height. This can be explained by the fact that the engine of the recirculation is the convective flow and the amount of air involved in the recirculation increases with room height due to the entrainment of ambient air. Therefore, the draught rate showed a proportional relationship with the room height. The diffuse ceiling ventilation is preferable to apply in the room with ceiling height lower than 3 m.

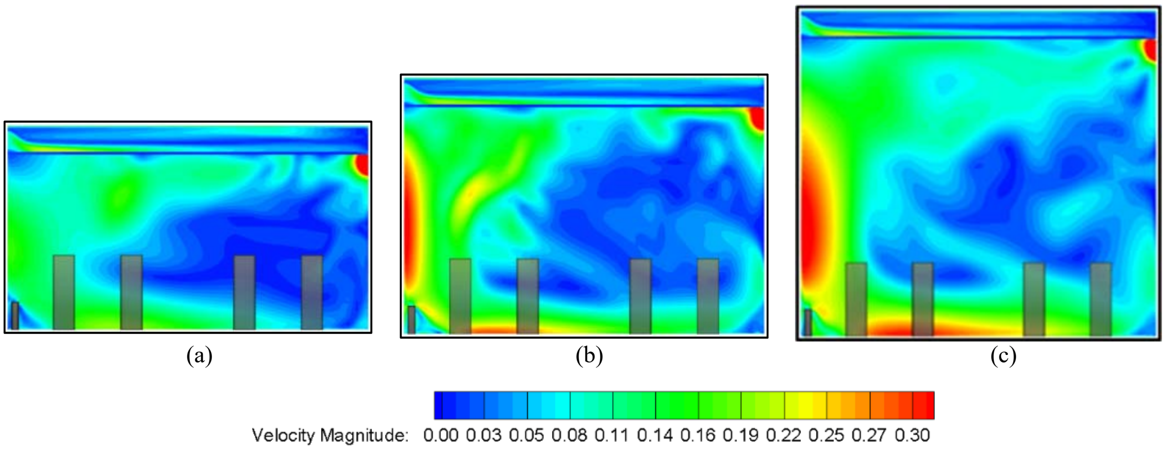

Figure 16: Velocity distribution across the central plane of the room at different room height (a) 2.335 m, (b) 3.0 m and (c) 4.0 m. [4]

7. SYSTEM CAPACITY AND COMPARISON WITH THE OTHER AIR SUPPLY SYSTEMS

As mentioned in Chapter 4, diffuse ceiling ventilation has superior performance on the indoor thermal comfort. The comfort requirements such as draught and vertical temperature gradient do not have strong limits on the system ventilation rate and supply air temperature, which enable the system to have a higher cooling capacity compared the other ventilation systems.

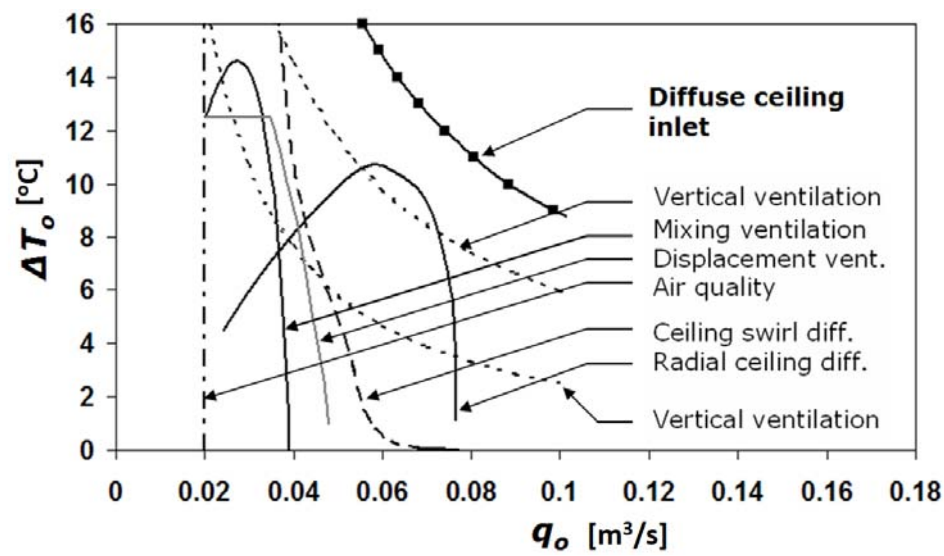

Figure 17: Design chart for a diffuse ceiling inlet and five other air supply systems [21]

The performance of diffuse ceiling ventilation and five other air supply systems were tested in the same room under the same heat load condition [21]. The five other supply systems included mixing ventilation from a wall-mounted terminal, mixing ventilation from a ceiling-mounted diffuser, mixing ventilation from a ceiling-mounted diffuser with a swirling flow, displacement ventilation from a wall-mounted low-velocity diffuser and vertical ventilation from a ceiling-mounted textile inlet. A design chart method was applied as a tool to make a direct comparison of the capacity of different ventilation systems, as shown in Figure 17. A minimum ventilation rate of 0.02 m^3/s was required by all systems for the air quality consideration (10 l/s per person for

Category A). The results indicated that diffuse ceiling inlet was able to handle the highest heat load of 72 W/m^2. While the cooling capacity of five other ventilation systems were between 36~53 W/m^2. The tolerance of high ventilation rate is because the large ceiling inlet area generates the supply flow with low velocity and no fix direction. The tolerance of the high air temperature difference is because the cool supply air mixed with the room air before entering the occupied zone. Therefore, diffuse ceiling ventilation is able to handle the highest heat load compared with the other air supply systems.

It is necessary to emphasize that system capacity of diffuse ceiling ventilation is determined by many parameters, such as diffuse ceiling types, opening area, plenum configurations, room geometry and heat load conditions. It is necessary to evaluate the cooling capacity of systems based on the given condition and select the optimal solution. The effects of different design parameter are discussed in Chapter 6.

8. INTEGRATED WITH HEATING/COOLING SYSTEM

Ventilation as a passive cooling strategy strongly depends on the outdoor climatic conditions. When natural resource is insufficient to maintain an acceptable indoor environment, a supplementary heating or cooling system is required. This chapter will discuss the diffuse ceiling ventilation integrated with different heating and/or cooling system.

8.1 VAV system

Variable Air Volume (VAV) is one of the most commonly used HVAC systems for the non-residential building. Unlike constant air volume (CAV) systems, which supply a constant airflow at a variable temperature, VAV systems vary the air flow rate at a constant temperature. In cooling mode, the system distributes supply air at a constant temperature of approximately 13 °C. Because the supply air temperature is constant, the air flow rate must vary to meet the demand caused by the changing of heat load in the conditioned space.

The basic components of a VAV air conditioning system include: a central air handling unit (AHU) with a variable speed supply fan, controls, filters, mixing box, ducts, VAV terminal unit connected to thermostats and supply diffusers, and sometimes exhaust fan also be used[22]. Figure 18 presents the schematic diagram of the VAV air conditioning system with diffuse ceiling diffuser. Instead of directly supply outdoor air to the plenum, the outdoor air is handled by AHU system to a certain temperature and then driven by supply fan to each room. The VAV terminal unit is controlled by the thermostats located in the occupied space. If the conditioned space requires more cooling, the mechanical damper will open wider to increase the air flow rate until the required temperature is reached. On the other hand, if an area is too cold and requires temperature rise, the damper is gradually closed to reduce the inflow volume of cold air. In order to reduce the energy consumption, some VAV systems recirculate exhaust air and mix it with outdoor fresh air when outdoor air temperature is too high.

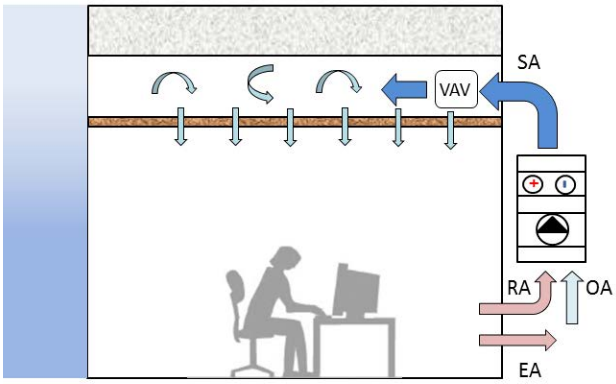

Figure 18: Schematic diagram of the VAV air conditioning system with diffuse ceiling diffuser

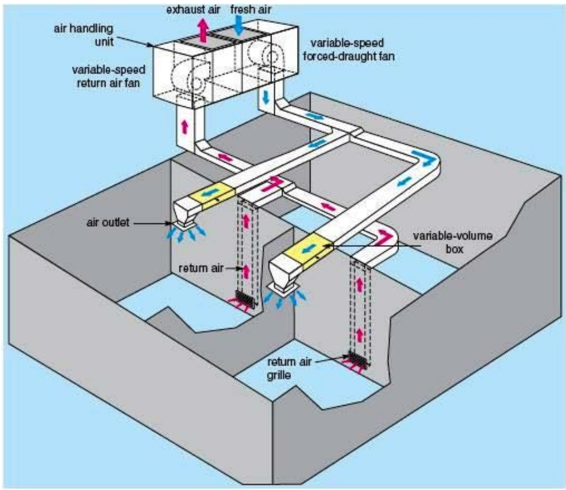

Figure 19: Schematic diagram of multiple-zone VAV system [23]

The VAV terminal unit enables the zone level flow control. Therefore, this system is suitable for multiple zone air conditioning. Each end of a supply duct contains variable air volume dampers which control the volume of air delivered to the zone, as shown in Figure 19. Control of the system's fan capacity is critical in VAV systems. Without proper and rapid flow rate control, the system's ductwork can easily be damaged by over -pressurization. A constant pressure should be maintained at the outlet of the fan. As the dampers close, the fan slows down or restricts the amount of air going into the supply duct. As the dampers open, the fan speeds up and allows more air flow into the duct, maintaining a constant static pressure[24].

This system offers a greater flexibility with respect to varying heat load and a quick response than the radiant system. In addition, VAV system provides a passive dehumidification effect due to the fact that outdoor air exposes to the cooling coil and condenses on the coil. Therefore, the air is supplied to the room with low humidity. However, this system does not take advantage of the plenum as a low-pressure air distribution pathway, where the ductwork and the VAV terminal unit increase the pressure loss of the system and consequently increase the energy consumption of the fan. On the other hand, the equipment and pipes placed in the plenum will limit the open space in the plenum and influence the air distribution in the plenum.

8.2 Fan coil unit

Fan coil is a typical air-based heating/cooling system. Fan coil units can be used to introduce outdoor air into space, circulate and filter air within space, and provide heating and/or cooling within space. The basic components of fan coil unit are heating/cooling coil, fan section, and a filter[25]. Units may stand alone within a single space or be ducted to serve multiple spaces and can be controlled by a manual switch, thermostat, or building management system. Compared with VAV system or central heating system with air handling units, fan coil unit is reputed by its simplicity and flexibility. It has significantly smaller ventilation plant and ductwork than the all-air system. Fan coil units are typically selected and sized to heat and cool a small zone with specific load requirements.

Fan coil units are divided into two types: two pipe fan coil unit and four-pipe fan coil unit. A two-pipe system includes two pipes: one for supply and one for return. The supply is switched between chilled water and hot water depending on the season. Although they have the advantage of lower initial costs associated with piping and installation, two-pipe systems offer less flexibility with heating and cooling demand as it will not allow heating in one unit and cooling in another. This can sometimes be problematic, such as when seasonal or occupancy loads change. Four-pipe systems consist of two supply pipes and two return pipes, which can supply chilled water and hot water at the same time. A three-way valve with chilled and hot water supply entering can be controlled by a room thermostat or return air sensor and signal either the hot or chilled water supply side to open or close. In contrast to two-pipe systems, four-pipe systems often require higher piping and installation costs but are capable of maintaining higher levels of occupant comfort in all seasons.

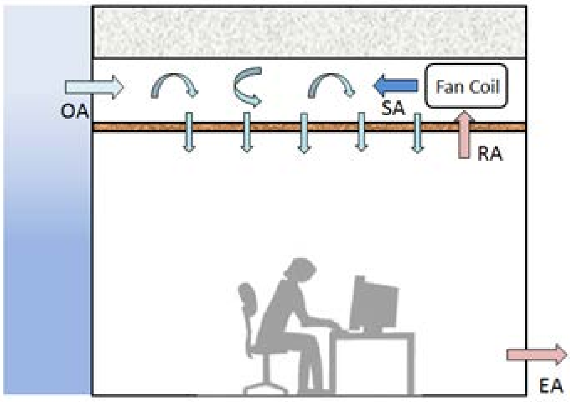

Figure 20: Schematic diagram of the fan coil system with diffuse ceiling diffuser

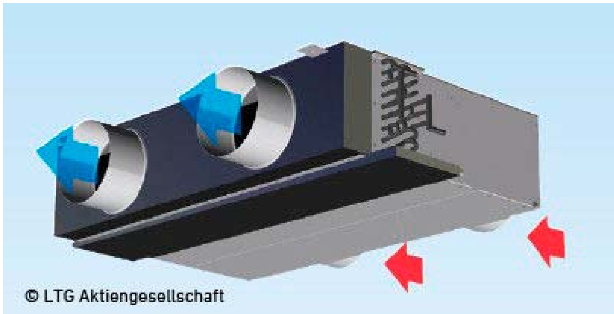

Figure 21: Ceiling-mount fan coil unit[26]

Fan coil unit can be installed either in the plenum or in the occupied space. However, the draught risk can be a significant problem when fan coil located in the occupied space. Figure 20 shows a schematic diagram of the fan coil system with diffuse ceiling diffuser, where the fan coil unit is placed in the plenum. The fresh air from outdoor will be conditioned by the fan coil unit and supplied into the plenum. In the season outdoor air temperature is too high or heating is required, the exhaust air from the room can also be recirculated and be drawn into the unit for re-conditioning. Therefore, the airflow into the unit can be either 100% fresh air or a mix between return air and fresh air.

Fan coil unit typically operate with a supply chilled water temperature of 6 ºC and 12 ºC return, and the other temperature such as 7/13 ºC or 8/14 ºC are also encountered in practice [27]. Condensation will form on the cooling coil at such temperatures when used in Danish climate. The condensate water should be proper collected and disposed. Otherwise, it will result in the damage of diffuse ceiling panels and further lead to the 'office rain'. Normally, a condensate drainage system can be used, which can be either gravity assisted system or pumped system. On the other hand, noise is a particularly sensitive issue for the fan coil system. Because the fan located in the plenum and closer to occupants compared with other systems, the noise associated with the fan must be considered in the design stage and limited to the level permitted in the room. Finally, similar to the VAV system, a large amount of equipment and ductwork located in the plenum restrict the height of plenum and also have an impact on the air distribution in the plenum.

9. CONTROL STRATEGIES

9.1 Supply air temperature

When ventilation air is used as a carrier medium for cooling, the cooling capacity is a function of the temperature difference between the supply air and the room air (exhaust air). Therefore, the lower the supply air temperature, the higher the cooling capacity. Normally, displacement ventilation is limited to a minimum floor inlet temperature of approximate 19 ºC, whereas a mixing type floor diffuser can supply air at a temperature of 16 ºC without causing draughts. Mixing ventilation with a diffuser on side-wall can supply air at a temperature as low as 12 ºC.

Diffuse ceiling ventilation allows a low inlet air temperature into the plenum. The plenum has a pre-heating function, where the supply air will be warmed up by the heat transfer from the thermal mass (both ceiling slabs and diffuse ceiling panels) before delivering into occupied space. The pre-heating effect is influenced by the plenum configuration, diffuse ceiling types, air flow rate etc. For example, a warm-up up to 5 ºC was observed in the plenum by using 50% air permeable diffuse ceiling, while the value for the plenum with 100 % air permeable diffuse ceiling was only 2 ºC [28].

On the other hand, the low momentum supply by diffuse ceiling ventilation ensures a low draught risk in the occupied zone even with a very low inlet air temperature. An inlet air temperature down to -4 to -6 ºC was tested in the experimental study [4][12], and the results indicated that it was still able to maintain a comfort indoor environment if the air flow rate was properly controlled. However, further decrease of inlet air temperature will reduce the possible air flow rate and will result in poor indoor air quality.

9.2 Air flow rate

When designs a ventilation system, the ventilation rate should satisfy two considerations: healthy and thermal comfort.

For the healthy point of view, occupant exposure to pollutants in the air may cause some risk to health. In the office or classroom, exposure to any individual pollutant is much lower than in industry. However, occupants still expose to a wide range of pollutants, such as building materials, furniture, office equipment, human metabolism, etc. The required ventilation rate from the health aspect is 7 l/s per person and 0.7 $l/s.m^2$ for low polluting building, based on EN 15251 categories B [29].

From the thermal comfort point of view, ventilation rate should be restricted to avoid draught risk in the occupied zone. Based on the previous studies (Figure 6), it is observed that the draught rate in the occupied zone does not show a strong relation to the air flow rate, due to the fact the air distribution in the room is not dominated by the supply flow. Therefore, the thermal comfort requirement doesn't have a restriction on the air flow rate. However, while increases the air flow rate to a certain level (10 h^{-1}), the flow pattern in the room will turn from buoyancy control to momentum control, where draught will become a major concern in this case.

9.3 Pressure

In order to maintain a unidirectional air supply through the diffuse ceiling panels, the plenum should keep a positive pressure compared with the conditioned space. The pressure difference can either be provided by the wind or buoyancy force by natural ventilation or maintained by a fan. For the typical climate in Denmark, the annual average wind speed is about 4.4 m/s, resulting in a pressure difference of above 3.5 Pa in buildings with natural ventilation. However, natural ventilation strongly depends on weather conditions and varies from time to time. It is recommended to have a supply fan or exhaust fan in the system to maintain a sufficient pressure of the plenum.

9.4 Humidity control

As mentioned in Section 2.2, condensation risk needs to be considered when designs a diffuse ceiling ventilation system. The inlet temperature and air flow rate should be carefully controlled to maintain the suspended ceiling surface temperature above the dewpoint of the ambient air. In addition, proper control of the static pressure of the plenum and choose connection profile with good airtightness may avoid reverse flow from room side, and reduces the associated condensation problems. The wood wool cement panel with a moisture absorbing property should serve as a humidity buffer to keep a stable indoor relative humidity.

10. CASE STUDY: CLASSROOM WITH DIFFUSE CEILING VENTILATION

This chapter presents a summary of recommended design procedures for diffuse ceiling ventilations. A classroom in a school building is planned to be mechanically ventilated by diffuse ceiling supply, the extra heating/cooling load will be handled by fan-coil unit.

Description

- Function: Classroom
- Location: Copenhagen, Denmark
- Dimension: 6 m× 10 m ×2.5 m, window area: 35% of external wall
- Occupant: 27 students and 1 teacher
- Heat load: Internal heat sources (Person, lighting, equipment) 45 W/m^2, solar radiation based on weather condition (Table 3)
- The building is occupied from 8:00 to 16:00 during weekdays.
- Infiltration rate: 0.1 h^{-1}
- One external wall facing to the south: U-value =0.2 W/m^2.K; Window: U-value=1.3 W/m^2.K, g-value=0.65. Heat transmission through the internal wall is neglected.
- The classroom is used for ordinary class work inside the occupied zone.
- The activity of the occupants is mainly sedentary office work, 1.2 met and the clothing insulation is 1.0 clo in winter and 0.5 clo in summer.
- The building is suited in an area with excellent outdoor air quality and the level of outdoor air pollutants are of no health concern.

Design conditions:

Table 3: Monthly mean weather conditions based on DRY

Climate	Outdoor temperature (°C)	Solar radiation facing south (Wh/m^2.day)
Winter (Jan)	-1.0 ± 2.5	4142
Transient (April)	6 ± 4.5	5466
Summer (July)	16 ± 6	4965

Design criteria:

Table 4: Thermal design criteria (Category B) [29][15]

	Summer	Winter
Operative temperature	24.5 ± 1.5 ºC	22 ± 2 ºC
Mean air velocity	0.22 m/s	0.18 m/s
Vertical temperature difference	< 3 ºC	

Table 5: Indoor air quality criteria [30]

	Airflow per person q_p	For building emissions q_B (very low-polluted building)
Ventilation rate	5 l/s/pers	0.35 l/s.m^2

Design procedure:

a) A simplified method is applied to estimate the ventilation rate and cooling/heating load of the fan coil unit. This calculation method is based on the energy balance of the room during 24 hour period and the heat accumulation in the room is also taken into account [31]. A modification has been done on this method to divide the 24 hours into the occupied period and unoccupied period. The room is ventilated by a constant air flow rate during each period (could be different between occupied and unoccupied period) and room temperature should fulfill the thermal design criteria only during the occupied period. The inlet air temperature of the ventilation system equals to the outdoor air temperature.

Minimum ventilation rate is calculated based on the air quality requirement, as expressed by the equation below:

$$q_{tot} = n \cdot q_p + A \cdot q_B = 28 \times 5 + 0.35 \times (6 \times 10) = 161 \text{ l/s} = 3.45 \text{ h}^{-1}$$

Maximum ventilation rate is 6 h^{-1}, which is the most efficient for night cooling.

Table 6: Required ventilation rate and heating/cooling load of fan coil unit

Case	Climate	Ventilation rate occupied period [h^{-1}]	Ventilation rate occupied period [h^{-1}]	Shading factor	Heating/cooling load of fan coil unit [kWh/day]	Calculated T_{room} occupied period [ºC]	Calculated T_{room} unoccupied period [ºC]
1	Winter	3.45	0	1 (No shading)	+ 2.4	22 ± 1.5	14 ± 0.2
2	Transient	4.8	2	1 (No shading)	0	23 ± 1.6	10.2 ± 0.6
3	Summer	6	6	1 (No shading)	-17.5	24 ± 1.8	16.4 ± 1.2
4	Summer	6	6	0.3 (External blind)	-5.8	24 ± 1.1	15.4 ± 1.2

The ventilation rates and heating/cooling load of the fan-coil unit are specified in Table 6 for each season. The indoor air temperature during occupied hours is within the comfortable range. It needs to notice that shading becomes an important parameter in summer or transient season. Introducing a shading device can significantly reduce the solar heat gain and reduce half of the cooling load of the fan coil unit.

b) Design of diffuse ceiling ventilation

- Selection of diffuse ceiling panel:
  The floor area of the classroom is 60 m^2 and the depth is 10 m. In order to avoid the uneven air distribution through the diffuse ceiling supply. It is recommended to use ceiling panel with a higher pressure drop or combine active ceiling panel with the passive one (as indicated in Figure 3) to even the air distribution. In this case, both the active wood-cement panels and the passive panels with an extra layer of mineral wood are employed as the diffuse ceiling. The mineral wool layer could improve acoustic properties and permits control of the supply air distribution in the room.

- Diffuse ceiling opening area and location of opening

  The active panels should be evenly placed and take at least 10% of the ceiling area.

- Plenum height:

  A minimum plenum height of 20 cm is required to keep a uniform air distribution through diffuse ceiling supply. In this case, fan coil unit is employed as a heating/cooling system. Therefore, the plenum needs to keep sufficient height for installation and placement of the fan-coil unit.

- Plenum inlet

  Due to the large ventilation rate and large room size, this system is designed to be mechanically ventilated. In order to uniform the air distribution within the plenum, ductwork is used to distribute air through part of the plenum, and several inlets are connected to the duct and discharge to different directions in the plenum.

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