Diffuse Ceiling Ventilation - Design Guide

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- Design Guide

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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 application potential in cool and dry climates. Moreover, this ventilation system uses a ceiling plenum to deliver air, which requires much lower pressure drop than a ducted system. Diffuse ceiling ventilation is widely used in livestock buildings due to its low investment cost and high thermal comfort level. Recently, there has been a growing focus on the application of diffuse ceiling ventilation in the indoor spaces for humans, especially for offices and classrooms with intense heat loads and high ventilation demands.

The purpose of this design guide is to provide support in the design of diffuse ceiling ventilation systems that will be energy efficient and with a high thermal comfort. The principles of air distribution and the benefits and limitation of the system are introduced. In addition, the critical design parameters are summarized and their effect on the system performance are discussed. In addition to the stand-alone ventilation system, the integration of diffuse ceiling ventilation with other HVAC systems is also addressed. Finally, two case studies demonstrate the application and the deign procedure of the ventilation concept.

Despite that the interest in the diffuse ceiling ventilation has been growing recently, the technical experiences are quite limited. The development of this design guide is mainly based on research and analysis of available information on diffuse ceiling ventilation, including experimental results from laboratory and field studies, as well as numerical simulations. 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 particulates 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).

In 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.

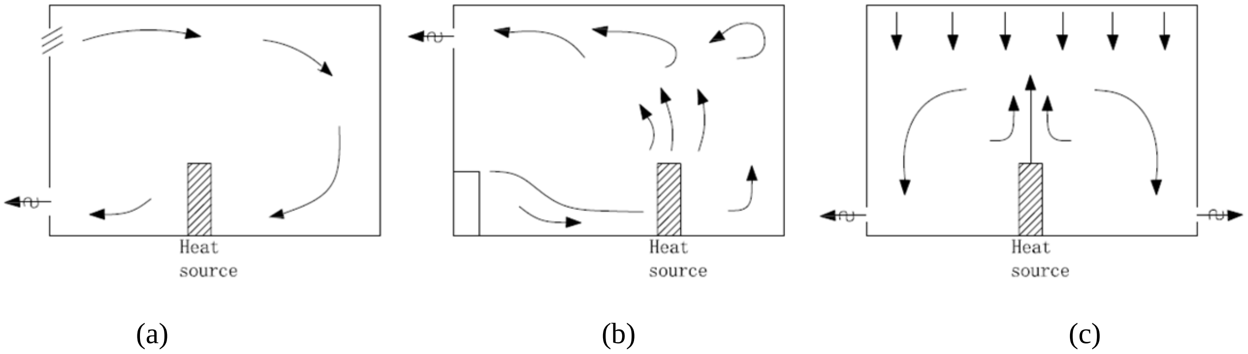


Figure 1: Three different types of air distribution systems. (a) Mixing ventilation, (b) Displacement ventilation, (c) Diffuse ceiling ventilation

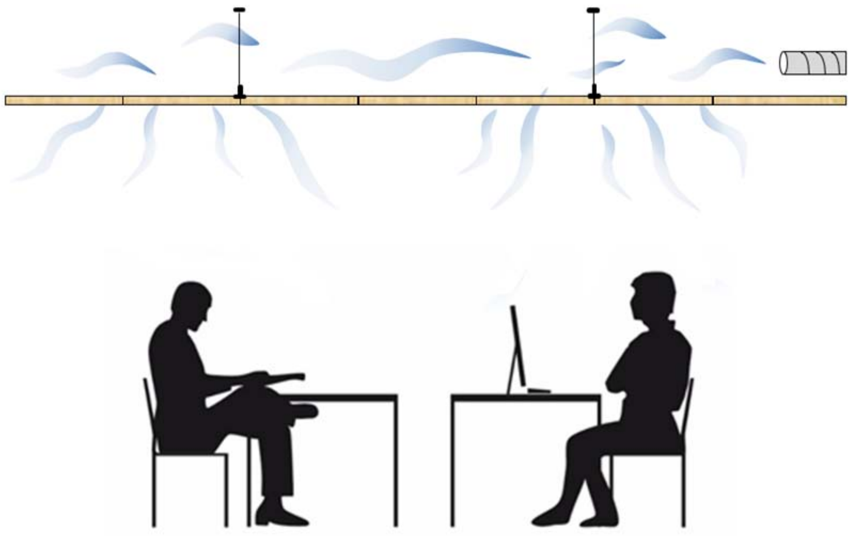


Figure 2: Diffuse ceiling ventilation system

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 doesn't generate significant draught even if outdoor air with extremely low temperature is directly supplied to the room. 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 at the room level. The strength of the buoyancy flow determines the mixing level in the room. Another feature of diffuse ceiling ventilation is that a plenum is used to distribute air instead of a ducted system. Pressure losses for air distribution are much smaller compared with a ducted system. In addition, suspended ceiling as air diffuser require 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 Benefits and limitations

Benefits

- High thermal comfort

Diffuse ceiling panels as an air terminal device can provide a draught free environment, even if outdoor air in winter is supplied directly to the room. Experimental results indicate that no significant draught is experienced even with supply air temperatures down to -6 ^{o}C [1][2]. 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 case of cooling while values are up to 2.5 K/m in the cases of heating [3][4][5]. Discomfort caused by radiant asymmetry of a cool or warm ceiling is negligible. More information regarding the 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 as well as lower air flow rates in winter, allows a reduction in fan power and even allows the system to 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 impose strong limits on the diffuse ceiling ventilation in terms of supply air temperature and ventilation rate. This feature enables the system to handle a high heat load. However, the system capacity is influenced by a number of parameters. In addition to the plenum and diffuse ceiling configuration, it is also affected by the heat source condition and room geometry. The critical 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. Firstly, the suspended ceiling panels are applied as air diffusers, which typically already are present for an acoustic purpose and, therefore, additional cost for air diffusers is avoided. Secondly, 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 at room level. 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

If 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 is a risk to address using this technology. Condensation of moisture will affect visual perception and function, also, the surface of the wet ceiling surface might grow dirty and drop water from the ceilings forming the so-called "Office Rain". Condensation risk can also be aggravated by reverse-flow, where high-humidity and high-temperature air flow from conditioned space is forced back to the plenum condensing on the back-side of the suspended ceiling panels. Such condensation might cause early failure of the suspended ceiling panels.

The risk can 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. For other types of ceiling panels, supply air needs to be preheated to ensure surface temperatures above air dew-point.

- 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.

Room area is another critical parameter as a large room area can exacerbate any uneven air distribution through the diffuse ceiling and lead to problems on both thermal comfort and indoor air quality. If the size of the room is more than 150-200 m^2 or the maximum distance to the plenum inlet is larger than 10 m, 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, divide the plenum in smaller sections 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. If the diffuse ceiling ventilation is combined with a radiant slab system, the plenum height could reduce to 10-15 cm to increase the heat exchange with the radiant surface. Detail description regarding plenum configuration can be found in Section 6.2.

3. CHARACTERISTICS OF DIFFUSE CEILING VENTILATION

3.1 Room air flow pattern

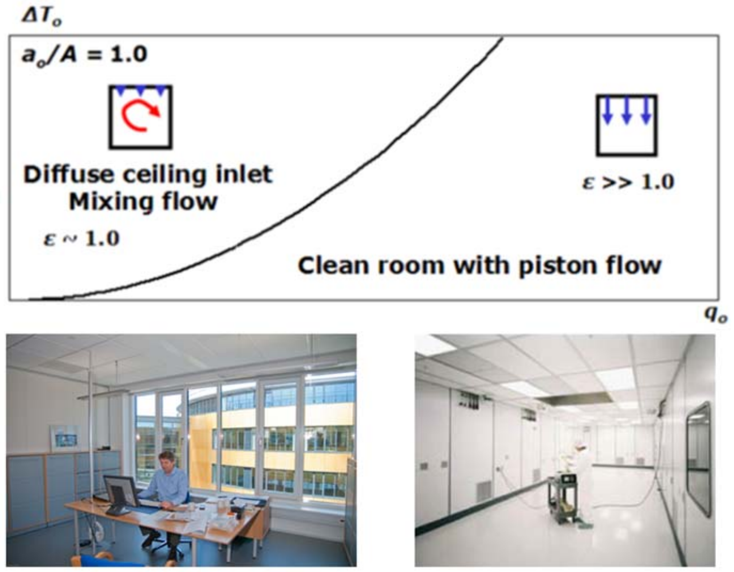


Figure 3: Diffuse ceiling ventilation presented on a *q-ΔT* graph, and two examples of diffuse ceiling ventilation application: office and clean room [6]

Diffuse ceiling ventilation is also named as downward ventilation. The air distribution patterns in rooms with diffuse ceiling inlet might be controlled by either buoyancy flows from heat sources or by momentum flow from the air supply depending on air change rate, see Figure 3.

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 can be regarded 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 case. In this design guide, special attentions have been paid to buoyancy controlled air distribution pattern.

3.2 Category of diffuse ceiling inlet

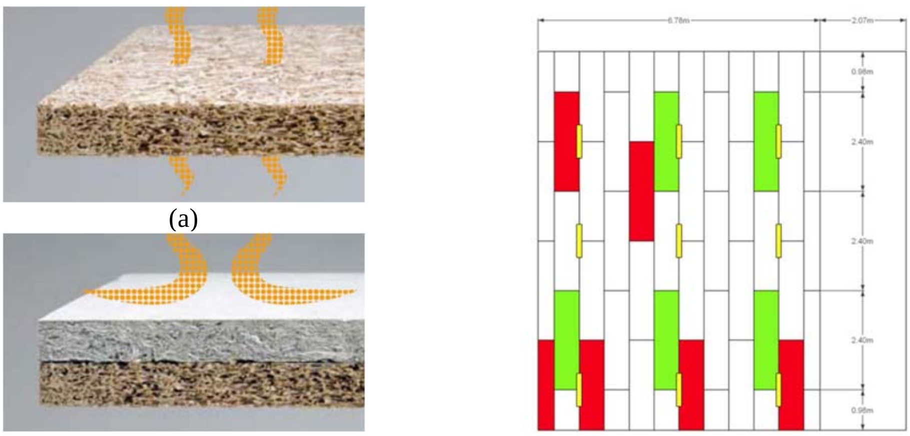
The designs of diffuse ceiling inlet such as shape and material of ceiling panels, perforation degree, and ceiling suspensions, etc. have significant influences on the performance of ventilation system. Generally, diffuse ceiling inlet can be divided into three categories based on the air path, as listed in Table 1.

In the first category, the diffuse ceiling is made of ceiling panels which are impenetrable to air. The air is supplied through the connection slots between panels (crack flow), which may form micro-jets. The micro-jects will generate high local entrainments. Consequently, the connections, their locations, and the micro-jets potentially affect the ventilation performance. High velocity and high entrainment take place near micro-jets and up to 0.25 m below the ceiling. Therefore, it is appropriate to have a distance of at least 0.25 m from the occupied zone to the ceiling surface.

The second category is composed of perforated ceiling panels which are penetrable to air. The air is supplied through both perforations and the connection slots. Similar to the first category, high locate entrainment may occur below the slots. The proportions of crack flow and panel flow strongly depend on the connection profiles and the perforation ratio of ceiling panels.

The third category is called ‘Fully diffuse ceiling’. This category of diffuse ceiling inlet is made of perforated material instead of composing by ceiling panels. Therefore, no connection slot exists. The advantage of this category is the aesthetic aspect without any visible diffusers. The air penetrates through the entire ceiling area, thus, the air velocity is very small and no micro-jet is presented, hence with low local entrainment.

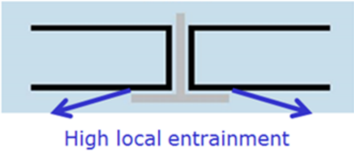
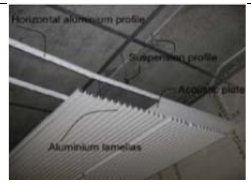
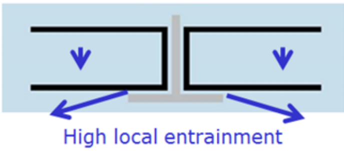
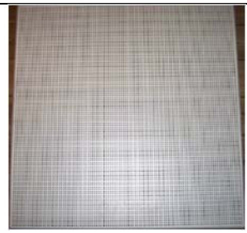
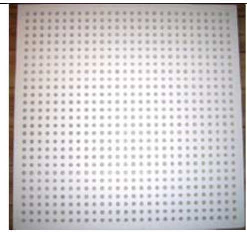
In fact, some diffuse ceiling ventilation systems are designed by combining several inlet categories together. Figure 4 demonstrates an example, where two types of ceiling panels were used: active and passive. The active panels of wood cement board are air permeable and passive panels have a layer of impenetrable mineral wood glued to the backside. The mineral wool layer has been proved that it 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 6.1.1.

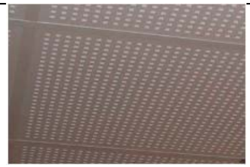
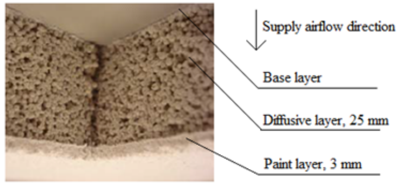


(a) (b) (c)

Figure 4: 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 (red present active panels, white present passive panels and green indicated the intended placement of the active panels) [7]

Table 1: Three categories of diffuse ceiling inlet based on the air path and their examples

Category	Advantages & Disadvantages	Example inlet	Description	Reference
 	Advantage: • Acoustic ceiling panel can be directly used as air inlet • Relatively low energy consumption of fan • Easy installation Disadvantage: • Micro-jet may create draught at the head level • Relatively high risk of uneven air distribution	A) 	• Impermeable mineral wool acoustic tiles • 50 mm thickness	[3][8]
		B)  	• Impermeable aluminum lamellas • 15 mm mineral wool acoustic plates above lamella	[4]
 	Advantage: • Acoustic ceiling panel can be directly used as air inlet • Low energy consumption of fan • Easy installation Disadvantage: • Risk of uneven air distribution	C) 	• Aluminium acoustic tiles • 0.6 mm thickness Circle perforation: Ø =2.5 mm, pitch 5.6 mm • Degree of perforation 16.2%	[9]
		D) 	• Gypsum acoustic tiles • 12.5 mm thickness Hexagon perforation: Ø =11 mm, pitch 20 mm • Degree of perforation 17%	[9]
		E) 	• Large perforations: Ø = 25 mm, pitch 300 mm • Degree of perforation 0.5%	[10]

		F) 	• Small perforations: 12×12 mm^2, pitch 25 mm • Degree of perforation 18%	[10]
		G) 	• Wood wool cement panel • 35 mm thickness • Porosity 65% • Thermal conductivity 0.085 W/m.K	[1][2]
	Advantage: • Aesthetic aspect, without any visible air inlet • Even air distribution Disadvantage: • Relatively high energy consumption of fan • Difficult installation	H) 	• Perforated structure • Three layers: base layer, 25 mm diffusive layer,3 mm paint layer	[11][12]

Note: Test conditions and reference please refer to Appendix A.

3.3 Ventilation system solutions and characteristics

The selection of a ventilation system solution is often 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.

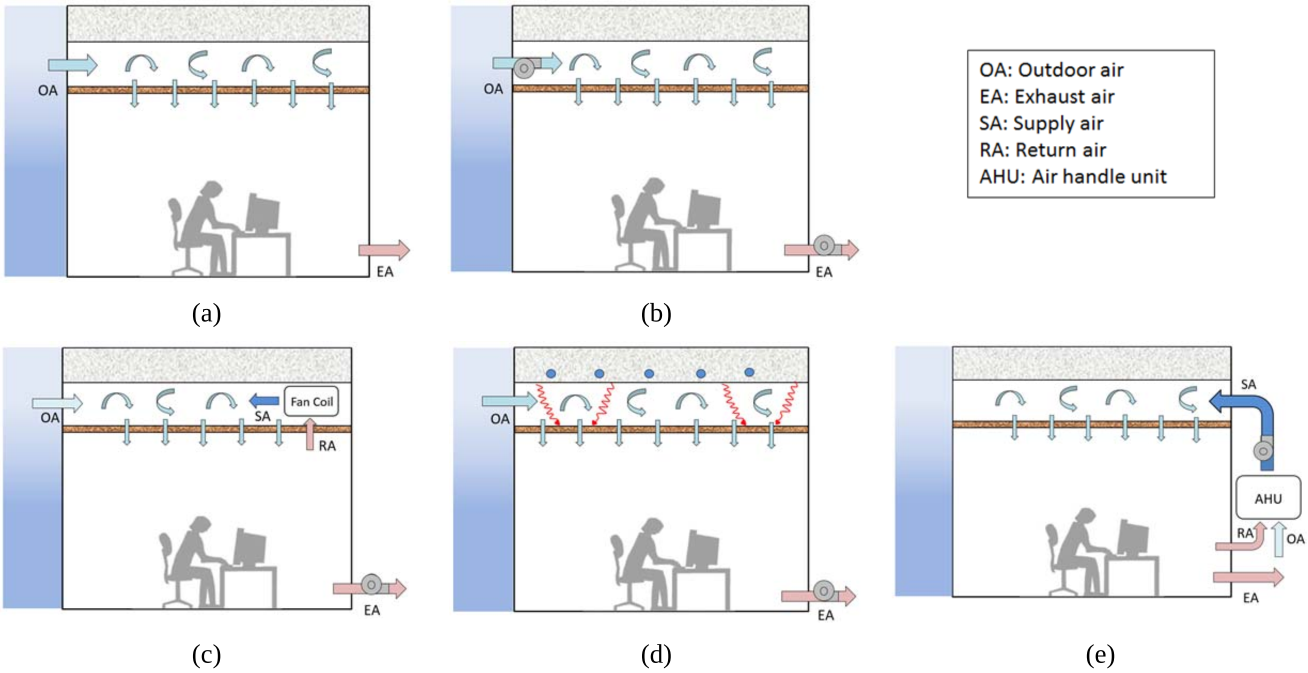


Figure 5: Schematic diagram of different ventilation strategies (a) Natural ventilation (b) Mechanical ventilation (c) Hybrid ventilation with air based terminal (d) Hybrid ventilation with radiant terminal (e) Full air conditioning

- **Natural ventilation:** Natural ventilation can provide fresh air to achieve air quality requirement and to provide cooling when needed. However, the application of natural ventilation is limited in winter and/or part of the transient season, due to high risk of draught with direct intake of outdoor air. This problem can be solved by using diffuse ceiling ventilation since the system can provide a draught free environment even if cool outdoor air is supplied directly. Another advantage of diffuse ceiling ventilation is that it has a low pressure drop, which makes it possible to only rely on natural driving forces.
  The most important issues of natural ventilation are to optimize the 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 be less than 10 Pa.
  Heat gain is another critical factor in the success of a 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) solution 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, while the energy use for transport the air sometimes is larger than the delivered cooling energy. Additionally, the work energy may raise the temperature of the outdoor air, reducing the cooling capacity [13]. Therefore, the relation between outdoor air temperature and the SFP of the fan should be considered carefully 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 a fan coil unit (Figure 5 (c)), while the typical radiant terminal is chilled ceiling (Figure 5 (d)). The key factors to consider when selecting the cooling terminal include [13]: the risk of condensation, the limitation in cooling capacity, the space required by the terminal unit. Detailed description of these two types of systems is in Chapter 8.

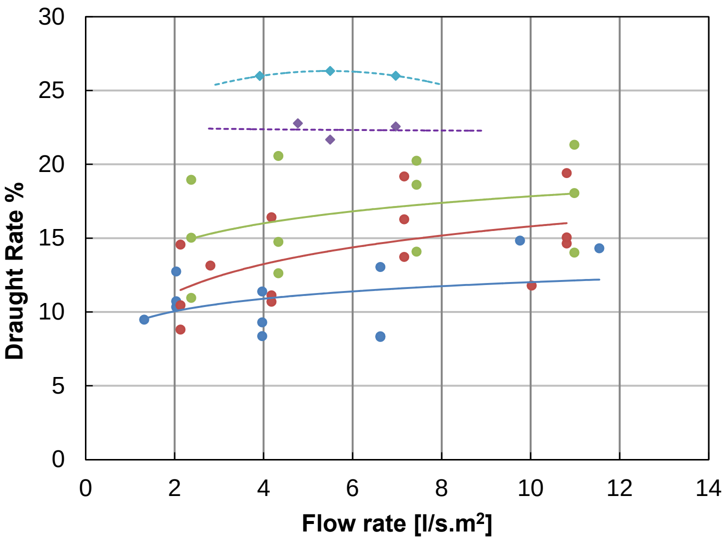
- **Air-conditioning:** An air-conditioning system uses a central air-handling unit to treat the air to a desired temperature and humidity, and then transports the conditioned air to each room by means of a fan. The room temperature can be controlled by varying the supply air temperature with a constant 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 [14]. 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][4][9].



Description	Parameter	Ref.
● 2.5 m ● 4.1 m ● 4.4 m	Room height	[12]
◆ Even ◆ One side	Heat load distribution	[11]

Figure 6: Draught rate vs flow rate with different design parameters. Note: Tests were conducted on Inlet H and test condition refers to Appendix A

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 the example case [11] are higher than the practical cases, due to the high heat load of 72 W/m^2 and large room height of 4.4 m. In the typical office conditions (30-60 W/m^2 and 2.8 m room height), the draught rate is expected to be lower than 15%. 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.

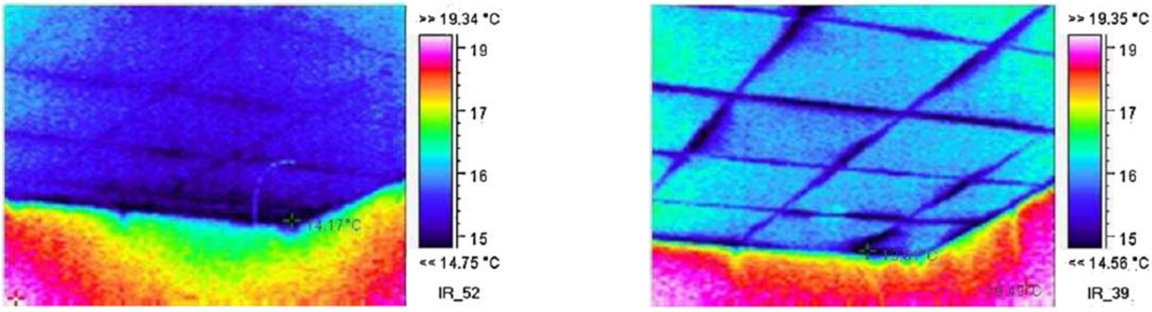
4.2 Temperature gradient

Temperature stratification that results in an air temperature at the head level being higher than at the ankle level may cause thermal discomfort. In order to avoid discomfort, the temperature difference between the head level and ankle level (0.1 – 1.1 m above floor) should be less than 3 ^{o}C for comfort 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 condition, where the temperature gradient is less than 1 ^{o}C/m. While a temperature stratification may occur in the heating case, where the temperature gradient may be above 2 ^{o}C/m. However, the heating is normally required during the unoccupied period, or used for preheating the space 1-2 hours before occupants show up. Therefore, discomfort caused by temperature gradient is not a major concern for a diffuse ceiling solution.

4.3 Radiant temperature asymmetry

Differences in room surface temperatures can lead to thermal discomfort due to radiant asymmetry, even when the mean radiant temperature is within acceptable limits. However, people are less sensitive to radiant asymmetry caused by cool ceilings than warm ceilings or cool walls (windows). The radiant temperature asymmetry for cool ceiling should be less than 14 ^{o}C to fulfill indoor environment category B [15].



(a) Al ceiling (b) Gyp ceiling

Figure 7: Thermographic vision of Al ceiling and Gyp ceiling [9]

The temperature difference between the suspended ceiling and the other surrounding surfaces is determined by the supply air temperature and the ceiling panel material. Ceiling panels with high thermal conductivity may increase the temperature asymmetry. For example, Figure 7 shows a thermographic photo of the aluminum (Al) ceiling system and a gypsum (Gyp) ceiling system [9]. When the supply air temperature was -3 ^{o}C, the Al ceiling had a surface temperature of 14 ^{o}C, while that of the Gyp ceiling was about 16 ^{o}C. Although the low ceiling temperature won't generate discomfort due to radiant asymmetry, there is a condensation risk on the ceiling panels, if the surface temperature is below the dew point temperature of air.

4.4 Indoor air quality

For complete mixing of air and pollutants, the ventilation effectiveness is 1. The ventilation effectiveness of diffuse ceiling ventilation is analyzed by means of tracer gas measurements [4], 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.

The air exchange efficiency 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. Investigations on the air exchange efficiency supports that good mixing in the occupied zone by diffuse ceiling ventilation is achieved, and with no stagnant zones or short-circuiting ventilation [8].

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 air flow rate and the pressure drop of the system. One of the advantages of the diffuse ceiling as air terminal device is potential reduction of air flow rate and the low-pressure drop.

Outdoor air can be used directly for air supply to the building, increasing the cooling capacity of ventilation system during winter and transient seasons, and consequently reducing the needed air flow rate.

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 in the room 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 a 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.

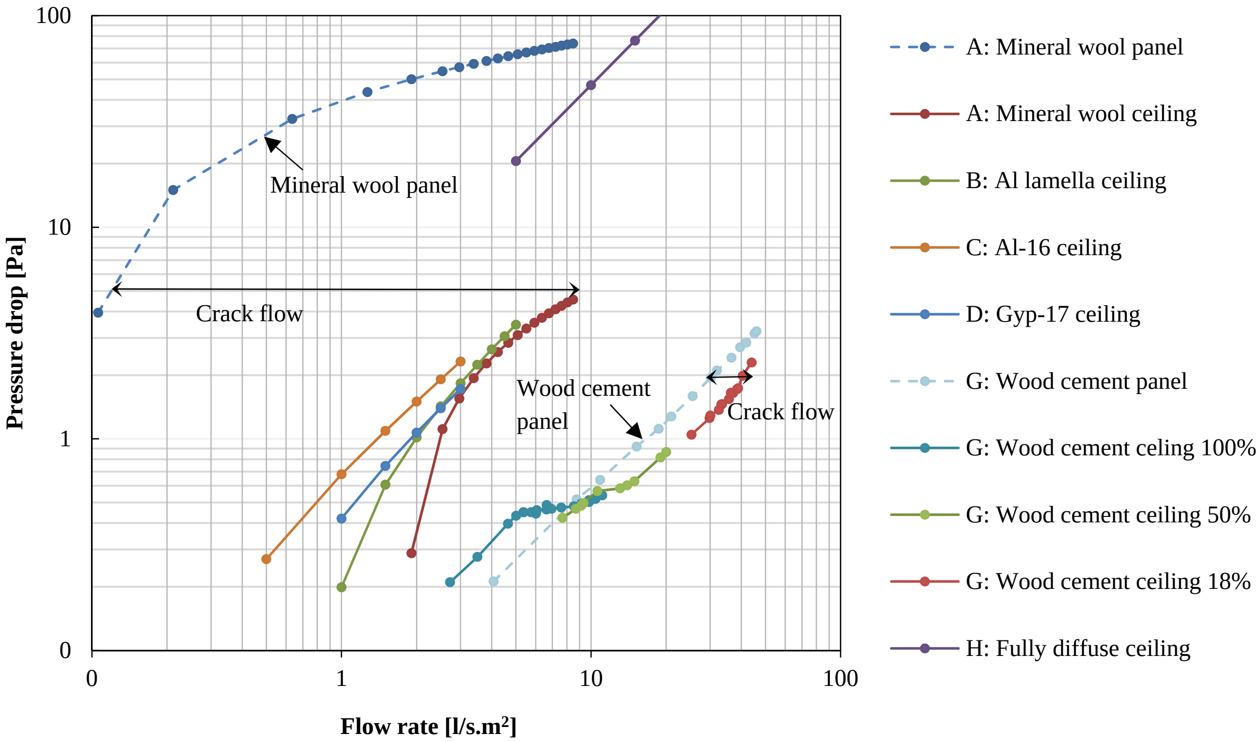


Figure 8: Relation between pressure drop and flow rate for different diffuse ceiling inlets, and comparison with single panel. (Diffuse ceiling inlets refer to Table 1)

Figure 8 illustrates the pressure drop across six different types of diffuse ceiling inlets, as a function of air flow rate. It is obvious that the pressure drop is low for most of the diffuse ceiling constructions, which is less than 5 Pa for the air flow rate ranging from 1-40 l/s.m^2. The only exception is the 'fully diffuse ceiling' made of a perforated material, where the pressure drop varies between 20 to 100 Pa for air flow rate 5-20 l/s.m^2. The special sand structure of the perforated material gives a high resistance to the airflow, and the paint layer further increases the pressure drop.

On the other hand, the air path of diffuse ceiling inlet can be evaluated by comparing the flow rate at the same pressure drop of a single panel and the entire ceiling. Because the mineral wool panel is almost non-permeable to air, almost all the air is discharged through the connection slots (crack flow). However, for wood wool cement ceiling, the panel flow covers 75% and crack flow covers only 25% of the air flow rate, when the pressure drop is 2 Pa. The crack flow reduces the pressure drop of the system, but may influence the air distribution by introducing micro-jets. These results also indicate that the pressure drop of the diffuse ceiling inlet strongly depends on the types of diffuse ceiling panel and connection profile.

Finally, the pressure drop 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 the suspension system.

The pressure loss through the air distribution system is a dominant parameter of fan energy consumption. P Jacobs et al. describes two field studies of classrooms with diffuse ceiling ventilation systems, Sliedrecht primary school and Tilburg primary school [16]. By comparing with traditional and modern ventilation systems for schools in Netherlands, they found that 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 2-20 €/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 the 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 also 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 [1], even with an extremely low supply air temperature down to -7^{o}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 also 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 decade, 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 be combined with a night cooling strategy, as the ceiling slab is directly exposed to the supply air pathways in the plenum, which increases the efficiency of the thermal storage and improve the pre-cooling effect. The diffuse ceiling ventilation can circulate cool air throughout 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, night cooling requires a proper and complete control strategy. If the building is "overcooled" a period of warm up is required in the morning.

6. DESIGN PARAMETERS

6.1 Diffuse ceiling properties

6.1.1 Opening area

The inlet area of diffuse ceiling ventilation is rather 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 experimentally [2]. The tests were carried out with three diffuse ceiling opening ratios: 100%, 50% and 18%, as shown in Figure 9.

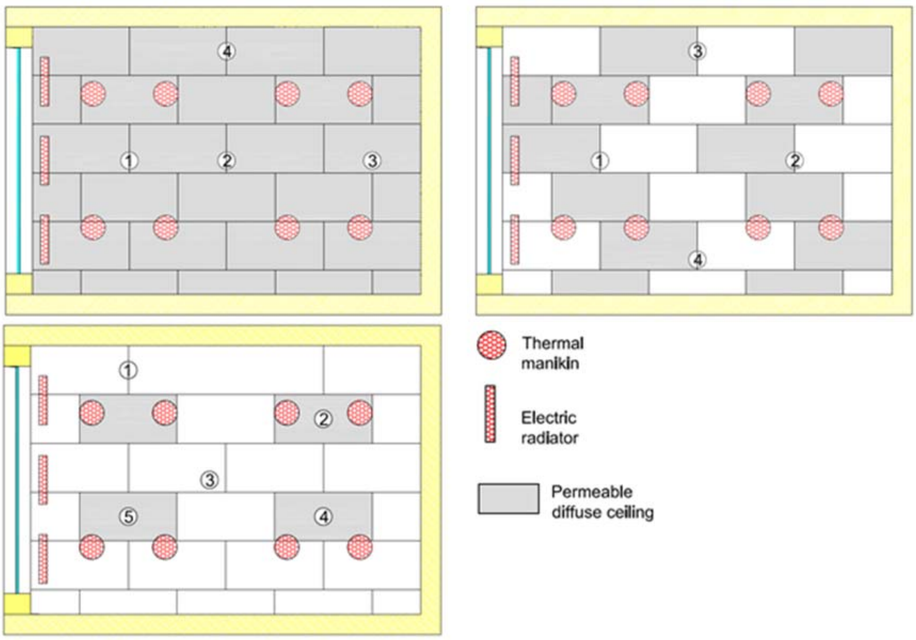


Figure 9: The layout of diffuse ceiling with different opening areas [2]

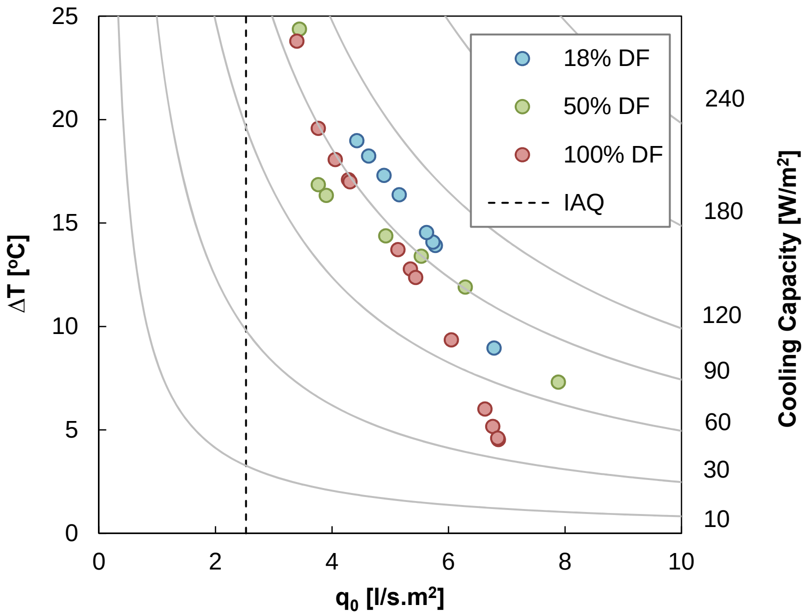


Figure 10: Design chart for different diffuse ceiling opening areas. Left and below the lines inlet air combinations result in comfortable conditions [2]

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. The dashed line limits the minimum air flow rate of 5 l/s per occupant for the indoor air quality purpose required by Building Regulation [18]. The points represent the heat load can be removed by the ventilation system without creating draught (air velocity less than 0.2 m/s). Figure 10 indicates that the cooling capacity of diffuse ceiling ventilation ranges from 40 W/m^2 to 100 W/m^2 depending on the diffuse ceiling configurations. The system with 18% opening area seems to be able to handle the highest heat load without draught. However, the heat sources was located directly below the perforated diffuse ceiling panels in the 18% case. Consequently, the cold supply air could 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, based on the obtained results it is not possible to draw a certain conclusion that smaller opening areas will lead to a higher cooling capacity. The relative location of heat sources and the diffuse ceiling opening area plays an important role and needs further investigation.

6.1.2 Thermal conductivity

Different from other air terminal devices, the diffuse ceiling does not only serve as an air diffuser but also acts as a layer of insulation between the plenum and occupied space. Therefore, the thermal property of the diffuse ceiling panel, such as thermal conductivity, has an impact on the heat transfer between these two zones.

Two types of ceiling panels and their effects were compared in a numerical study [19]. One was wood wool cement panel with a low conductivity of 0.085W/m.K and the other was aluminum panel (Al) which had a very high conductivity of 202.4 W/m.K. It was assumed that both diffuse ceiling panels had the same thickness and porosity and emissivity. The results indicated that the indoor air temperature with Al panels is 1 ^{o}C lower than that with wood wool cement panels.

The effect becomes more significant when diffuse ceiling ventilation couples with radiant ceiling system. The effect of diffuse ceiling thermal conductivity on the TABS' energy performance refers to Section 8.1.2.

6.2 Plenum design

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 11 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.

(a) (b)

Figure 11: Overhead plenum and diffuse ceiling setup [2]

The thermal process in the plenum differs from that with the fully ducted system. As supply air travels through the plenum, it has directly contact with the thermal mass of ceiling slabs and diffuse ceiling panels. This will transfer heat from the slab and the occupied space to the air and results in a temperature increase of the supply air. In the design of the plenum, the main objective is to ensure a uniform distribution of air through the diffuse ceiling both in relation to quantity and thermal conditions. The design parameters encountered in practice, for example, plenum geometry, plenum inlet configuration, obstruction within the plenum and so on 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 12 presents an example of temperature distributions in the plenum with single jet inlet and with inlet vanes [20]. The dimension of the plenum was $14.6 \times 4.7 \times 0.254$ m^3. It is found that inlet vanes provide more evenly distributed temperature throughout the plenum. In addition, the results indicate that the area closest to the plenum inlet do not necessarily have the lowest temperatures, as it depends on the direction of airflow.

If the size of the plenum is more than 150- 200 m^2 or the maximum distance to the plenum inlet 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 [21]. The inlets can be placed along the length of the duct and balance dampers should also 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 required.

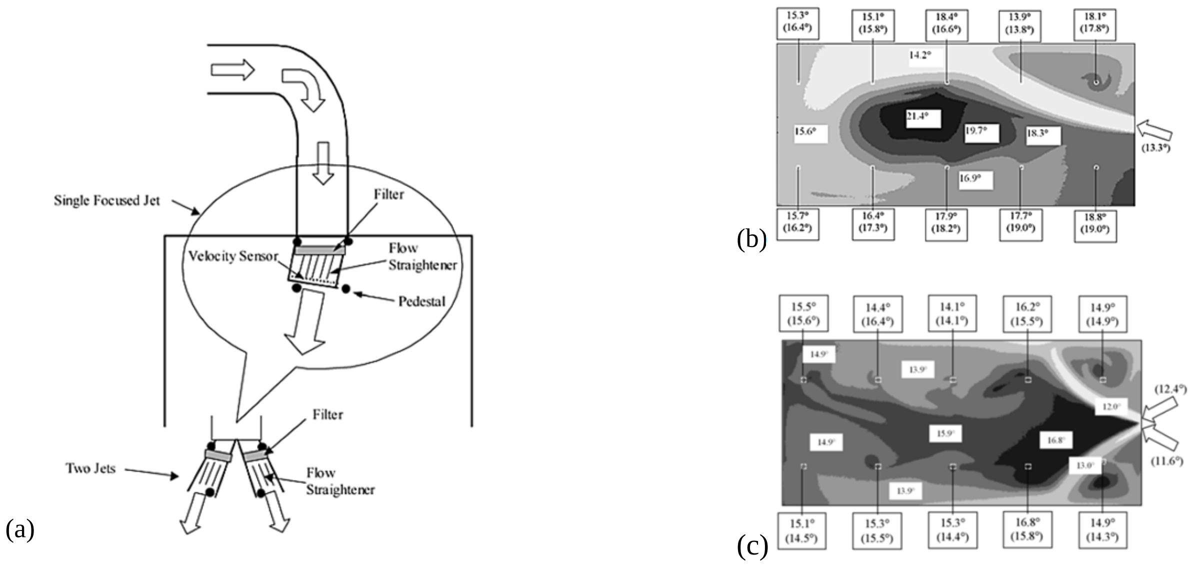


Figure 12: Comparison of plenum air temperature for different inlet configurations; Predicted temperature (Measured temperature) °C (a) Schematic of plenum inlet (b) Single jet inlet (b) Inlet vanes [20]

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 [19]. Figure 13 presents the air temperature distribution through the diffuse ceiling (1cm above ceiling panel). It is clear that the temperature distribution variation is dramatically increased when the plenum is lower than 10 cm. This is because the supply air cannot mix well with the plenum air, when the plenum height is low. Therefore, cold air is delivered to the room at a short distance from the plenum inlet, and warm air is delivered at the far end of the room.

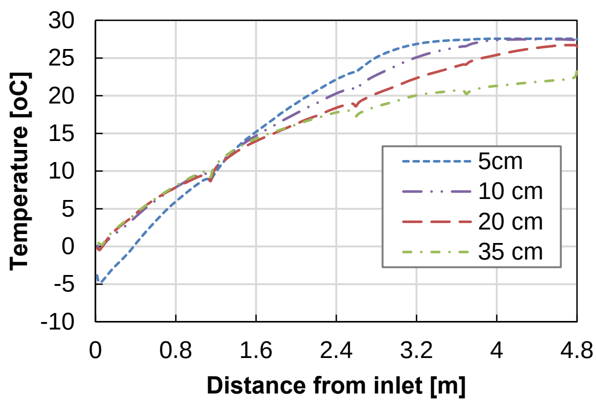


Figure 13: Temperature distribution through diffuse ceiling [19]

Plenum height also influences the uniformity of the air distribution through the diffuse ceiling, and further impacts the airflow performance in the occupied zone. The velocity distributions at 0.1 m height above floor level were analyzed and compared for different plenum heights, as illustrated in Figure 14. Decreasing the plenum height from 35 cm to 5cm, increase air flow with high velocity penetrating through the ceiling in the front side of the 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, which could provide an even air distribution and low draught risk in the occupied zone. If the diffuse ceiling ventilation is combined with a radiant ceiling system, a plenum height of 10-15 cm is possible to enhance the convective heat exchange with the radiant surface.

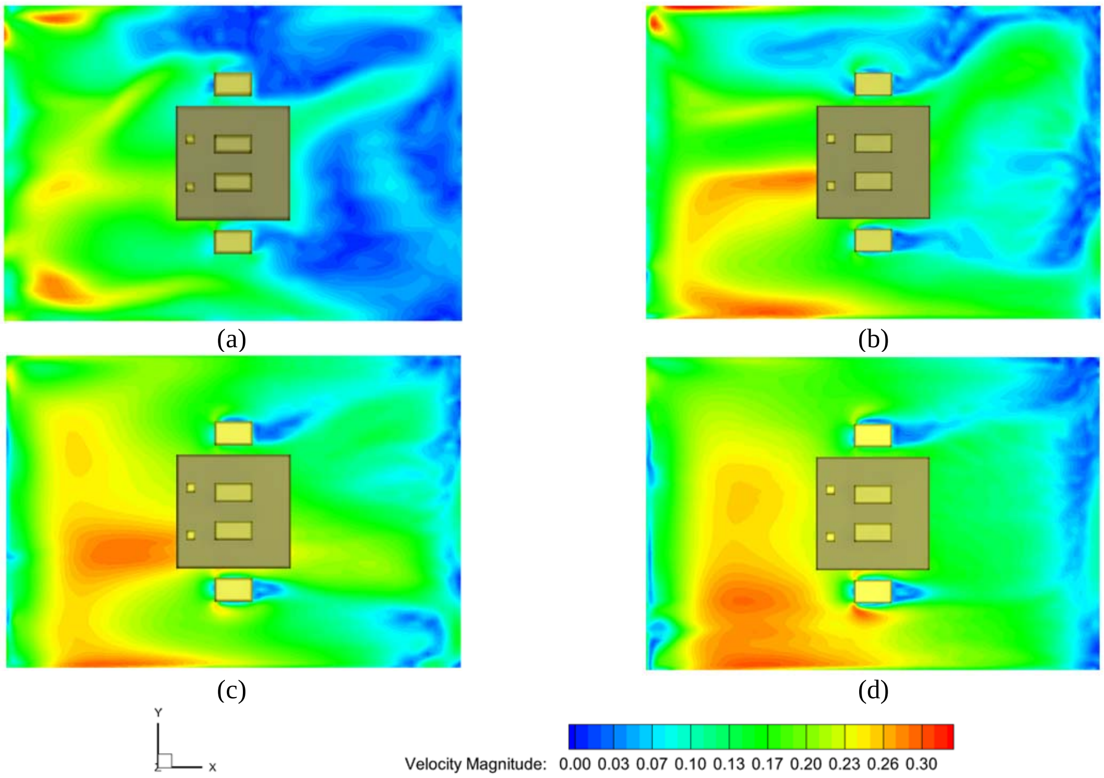


Figure 14: Velocity distribution at 0.1 m height with different plenum heights (a) 35 cm (b) 20 cm (c) 10 cm (d) 5 cm [19]

Beside the plenum height, the effects of plenum depth on the uniformity of delivered air and air flow pattern in the occupied zone are also significant. Figure 15presents the velocity distribution at 0.1 m height in a room with two plenum lengths (4.8 m and 9.6 m). The intensity of air velocity and the region with high velocity increases dramatically when the length is doubled. The maximum velocity in the occupied zone reaches 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, the cooling capacity of diffuse ceiling will be reduced for large room depths and if the room depth is larger than 10m, additional plenum inlets over the plenum or ductwork within the plenum are recommended to even out the air distribution.

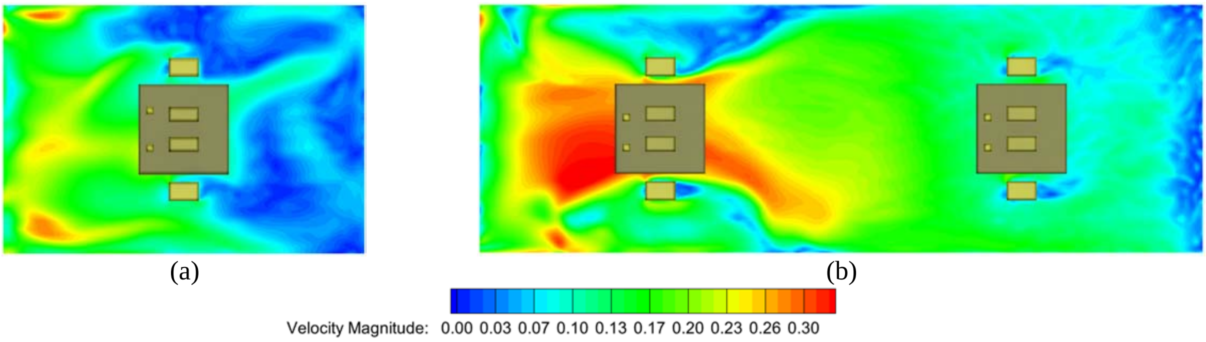


Figure 15: Velocity distribution at 0.1 m height with two plenum depths (a) Plenum depth of 4.8 m (b) Plenum depth of 9.6 m [19]

6.3 Heat sources

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

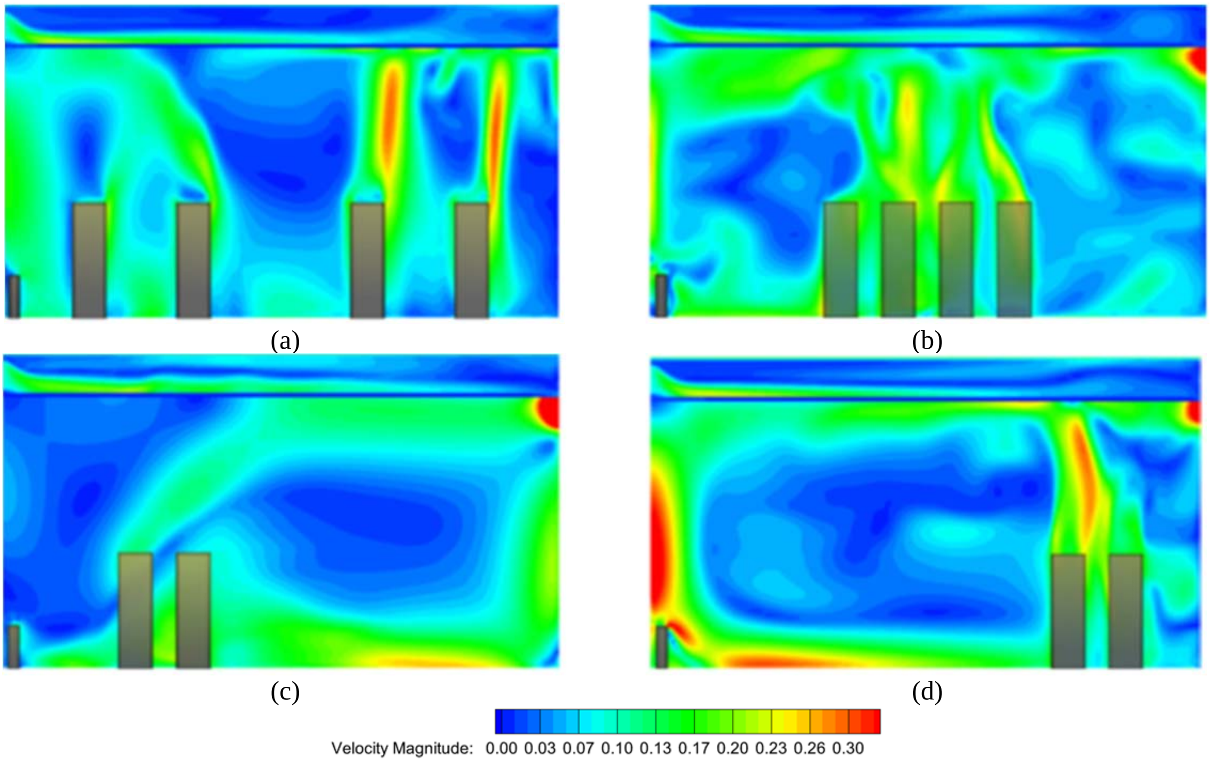
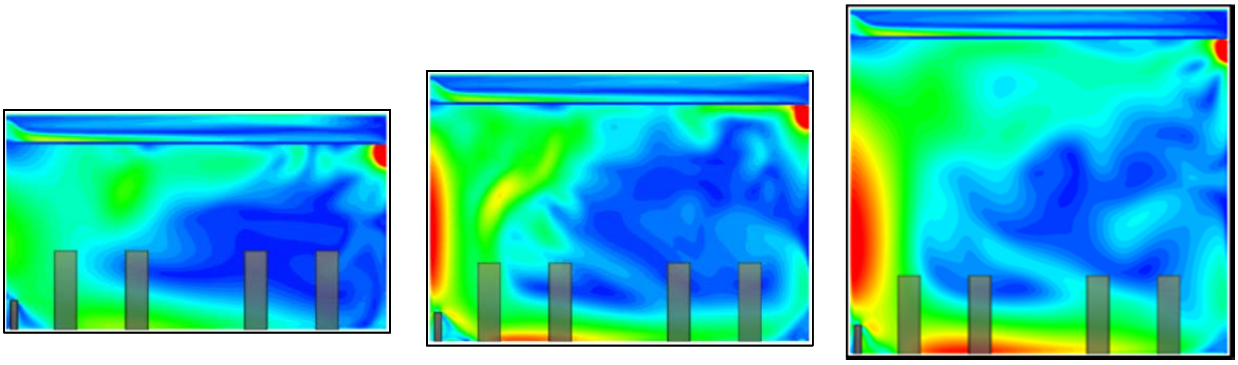


Figure 16: Velocity distribution for different heat load layouts (a) evenly distributed, (b) centered, (c) front side and (d) back side [2]

An investigation of heat load distributions was conducted by the numerical study by Zhang. et.al [2]. It was obvious that different heat load locations generated very different air flow patterns and further had an impact on the comfort level in the occupied zone. A strong air recirculation occurred when the heat sources were placed in one side of the room and a high draught rate at the floor level was generated. The draught rate with heat sources located at the back side of the room reached 20%. While, in the case with evenly distributed heat sources, no clear air recirculation was observed and the draught rate 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: 2.3 m, 3.0 m and 4.0 m, as shown in Figure 17 [2]. 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 system is preferable to be applied in rooms with ceiling height lower than 3 m.



(a) (b) (c)

Figure 17: Velocity distribution across the central plane of the room at different room height (a) 2.3 m, (b) 3.0 m and (c) 4.0 m [2]

7. SYSTEM CAPACITY 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 with other types of ventilation systems.

The performance of diffuse ceiling ventilation and five other air supply systems were tested in the same room under the same heat load conditions [22]. 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 the different air supply systems, as shown in Figure 18. A minimum ventilation rate of 0.02 m^3/s was required by all systems to ensure air quality (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 air supply systems was 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 fixed 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 air supply is able to handle the highest heat load compared with the other air supply systems.

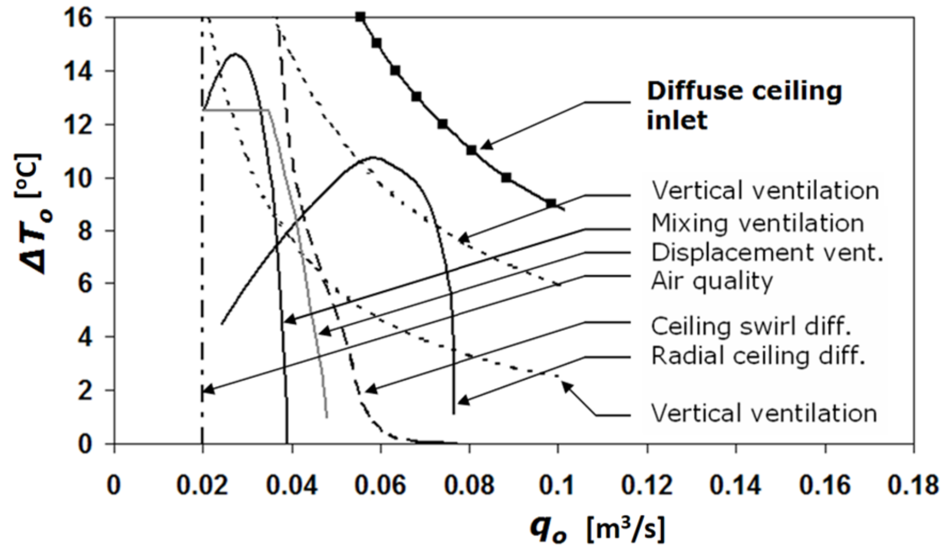


Figure 18: Design chart for a diffuse ceiling inlet and five other air supply systems [22]

It is necessary to emphasize that system capacity of diffuse ceiling ventilation is determined by many parameters, such as diffuse ceiling type, opening area, plenum configuration, 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. INTEGRATION WITH HEATING/COOLING SYSTEMS

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

8.1Thermally activated building system (TABS)

8.1.1 Introduction of the integrated system

TABS is a type of radiant cooling and heating system, where the water carrying pipes are embedded in the building elements. The system exploits the high thermal inertia of the building structure (concrete ceiling or wall) to reduce peak loads and to transfer some of the cooling load beyond the time of occupancy. Therefore, the energy costs can be reduced by using the lower nighttime electricity rate or even free night cooling. At the same time, the size of heating and cooling system can be reduced. Due to the large heat transfer surface, it is possible to heat or cool effectively, even with very slight temperature differences between the concrete slab and the room. This will result in a high efficiency of the energy system and increase application of renewable energy resources such as ground water, heat pump, and/or solar collectors.

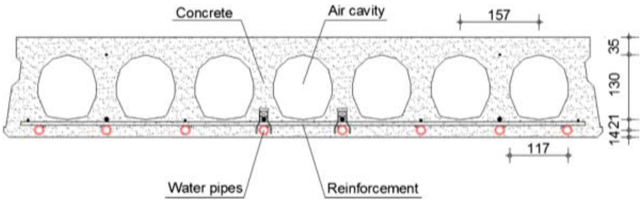


Figure 19: Example of a thermally activated building construction [23]

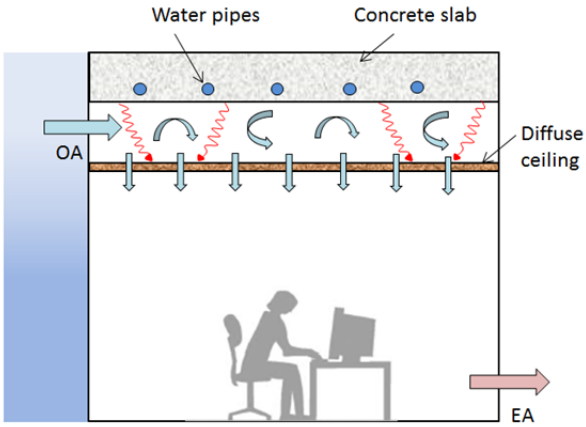


Figure 20: Schematic diagram of the integrated system

Figure 20 shows the schematic diagram of the integrated system combining diffuse ceiling ventilation and TABS. In the system, the space between TABS and the diffuse ceiling is used as a plenum and the fresh air is supplied into the occupied zone through perforations in the diffuse ceiling panels. TABS could work as a passive system to remove peak load by making use of the thermal mass of concrete slabs or it could work as an active system to provide extra heating and cooling need.

8.1.2 The impact of diffuse ceiling on the energy performance of TABS

A key issue of this integrated system is whether these two technics can work in a harmonious manner. Most of the studies regarding TABS have pointed out it is necessary to have a large surface area with exposed concrete. However, in this integrated system, diffuse ceiling acts as an obstacle between TABS and the conditioned space, which definitely influences the energy performance of TABS.

Figure 21 presents the heat transfer coefficients of TABS in the case with and without diffuse ceiling (wood cement panel) under steady-states. The total heat transfer coefficients in the cases without diffuse ceiling are closed to the typical design values, 6 W/m^2.K for ceiling heating and 11 W/m^2.K for ceiling cooling. However, the values in the cases with a diffuse ceiling are in a different manner, which is around 13 W/m^2.K for heating and 2.5 W/m^2.K for cooling. Diffuse ceiling promotes the TABS' heating capacity but reduces its cooling capacity.

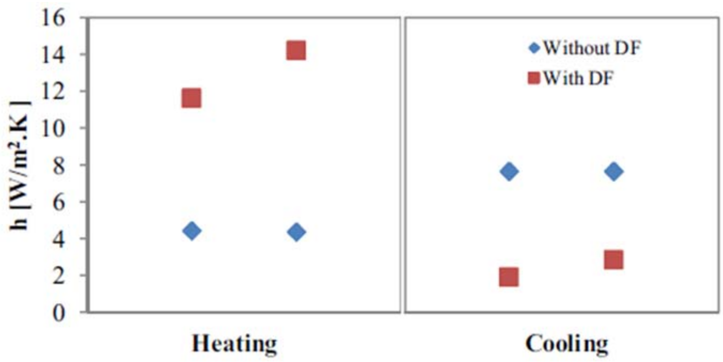


Figure 21: Heat transfer coefficients of TABS under heating and cooling modes, comparison between with and without diffuse ceiling (wood wool cement panel) [1]

The cooling capacity of TABS is significantly reduced after installing the diffuse ceiling, which limits the application of the integrated system in the room with a high cooling demand. This negative effect can be weakened by using diffuse ceiling panel with a high thermal conductivity, for instance, Al panel. Based on the numerical study [24], the cooling capacity in the case with Al panel was 22 % higher than that with wood wool cement panel. It is recommended to use ceiling panel with a high thermal conductivity if additional mechanical cooling is often required during the year.

8.1.3 Control strategy

The steady-state study proved that the diffuse ceiling panel had a significant influence on the cooling/heating capacity of TABS. However, in practical applications, the system is under dynamic operation, which cannot be well presented by the steady-state tests. TABS and natural ventilation can be combined at different periods to remove heat gains and to ensure a comfortable room environment. Therefore, the dynamic control strategy is important both in relation to the energy consumption and the indoor thermal comfort.

Yu et al. [25] developed a control strategy and conducted dynamic tests under three weather conditions: a typical winter day, typical day in the transitional season and a typical summer day. The main control parameters were the operation time of TABS, the ventilation rate and ventilation period. For various climates, different control strategies need to be applied, and the basic control is based on both room air temperature and outside air temperature, as illustrated in Figure 22-25.

In winter, ventilation rate is limited to the minimum, but there is still a heating need in the room outside hours of occupation. TABS acts as a heating system to deal with extra heat loss. In real applications, solar radiation may play a beneficial role in the room heating, which may change the activation of TABS and make it possible to just utilize natural ventilation to ensure the thermal comfort in the mid of the day. However, in the extreme winter with a lower outdoor air temperature, TABS heating time could be extended. Moreover, if extra TABS heating is needed, it is better to activate TABS from the nighttime. This is because plenum temperature drops to the minimum during the night, and low temperature in the plenum can enhance the energy efficiency of TABS heating.

In the transitional season, where the outdoor air has a moderate temperate, but still has a large cooling potential, it is very suitable to use natural ventilation during the occupied period. With a flexible ventilation rate control, it is possible to keep a perfect indoor environment without any mechanical cooling. For real applications, the ventilation time and ventilation rate also should be changed according to the solar heat gain outside the occupied period, in order to eliminate the influence of the extra solar heat gain on the room temperature.

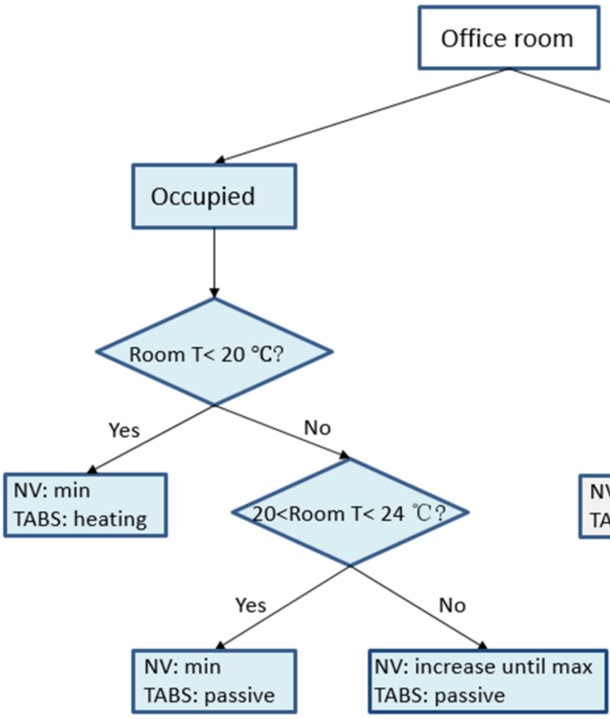


Figure 22: Flow chart of control strategy in winter [25]

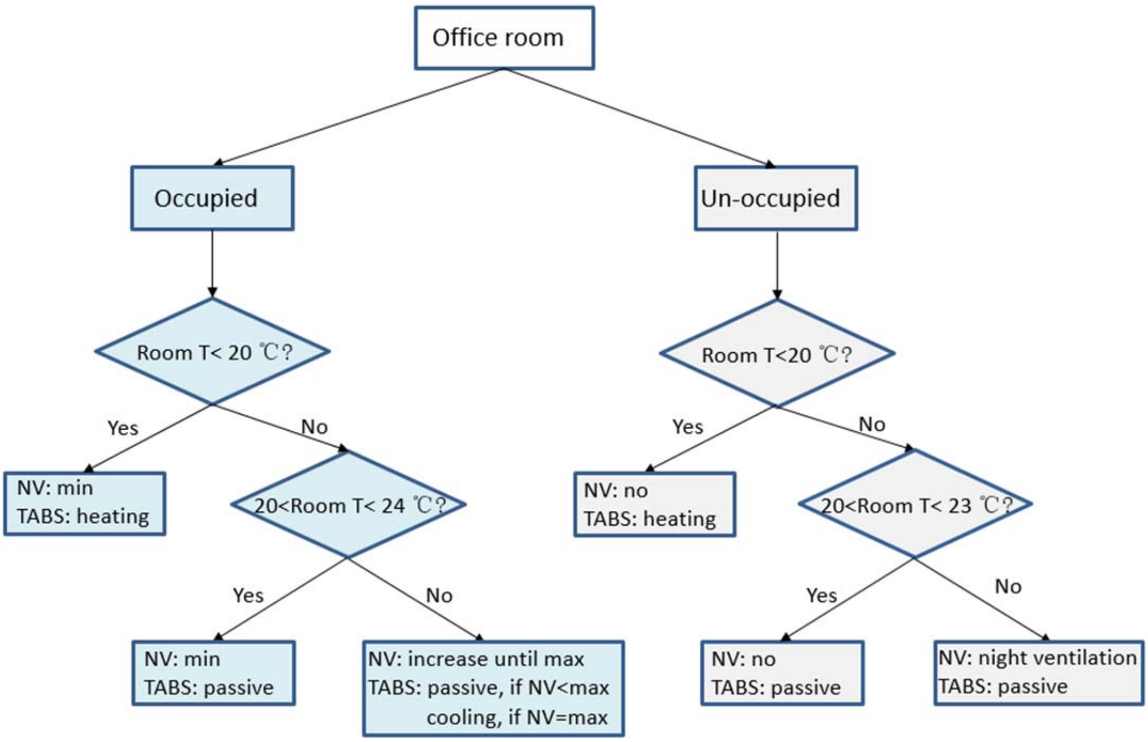


Figure 23: Flow chart of control strategy in transitional season [25]

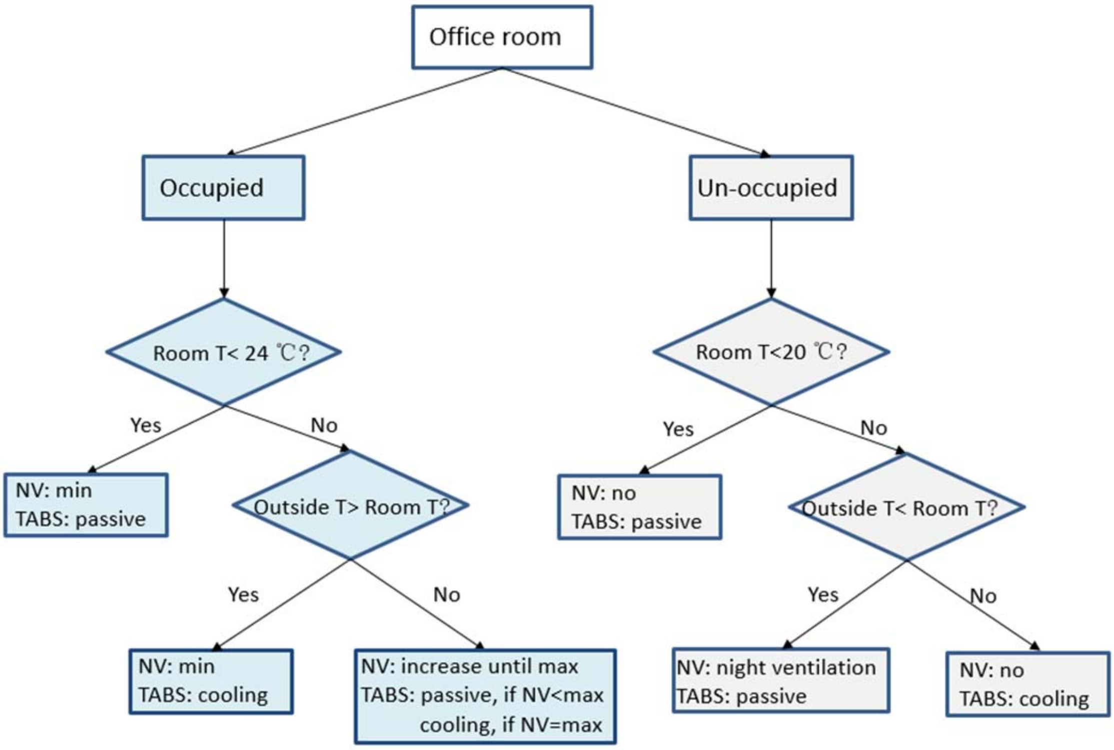


Figure 24: Flow chart of control strategy in summer season [25]

In the summer, outdoor air during the daytime has a relatively high temperature so the daytime free cooling capacity could be insufficient. A night cooling strategy is applied, using free cooling resource during the night to remove the heat stored during the daytime and to store cooling energy in the building thermal mass. But night cooling may result in a cold environment at the beginning of the occupied time and cause thermal comfort problems for a short while. Consequently, night ventilation should be carefully controlled, with an appropriate and flexible set point. The stored cooling in the thermal mass is depleted very fast in the following day, and the heat sources release heat quickly as well. During the daytime, when the free cooling potential disappears, the ventilation rate should be kept at the minimum. TABS should be activated as a cooling system to remove the heat load in the room. The activation time depends on the solar heat gain during the unoccupied time and the stored heat gains in the thermal mass.

8.1.4 Energy performance compared with the other HVAC systems

By means of the energy simulation tool – Bsim, the energy performance of a typical office room with the integrated system is compared with the use of other typical HVAC systems under Danish weather condition (Figure 25) [26]. Case 1 is a traditional air-based heating /cooling system without diffuse ceiling; Case 2 is system with TABS without diffuse ceiling; Case 3 is an air-based heating/cooling system with diffuse ceiling; Case 4 is the integrated system; Case 5 is an air-based heating/cooling system with diffuse ceiling, however, the conditioned air is directly supplied to the occupied space. In Case 1, 3 and 5, the outdoor air is handled by AHU and the systems are considered both with and without heat recovery (HR). The detailed set-up parameters can be found in Appendix B.

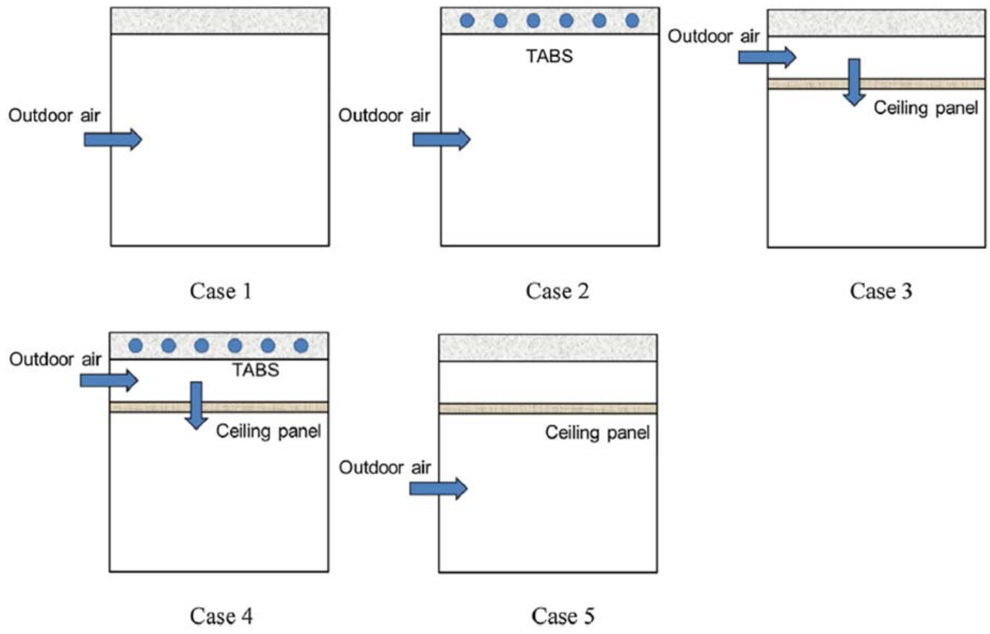


Figure 25: Schematic diagram of different HVAC systems [26]

The simulation results exhibit that the new system solution consumes less primary energy, when the internal heat load is above 30 W/m^2, and that the energy saving potential increases with increasing internal heat load, as shown in Figure 26. In the Danish climate, there is free cooling potential during the entire year. The integrate system maximizes the use of passive cooling resources, like natural ventilation and night cooling. For the typical office room with an internal heat load of 30–40 W/m^2, this energy saving potential can reach up to 50%. Meanwhile, the cooling energy saving of the integrated solution occurs in summer seasons, transitional seasons and part of winter seasons, depending on the internal heat load level.

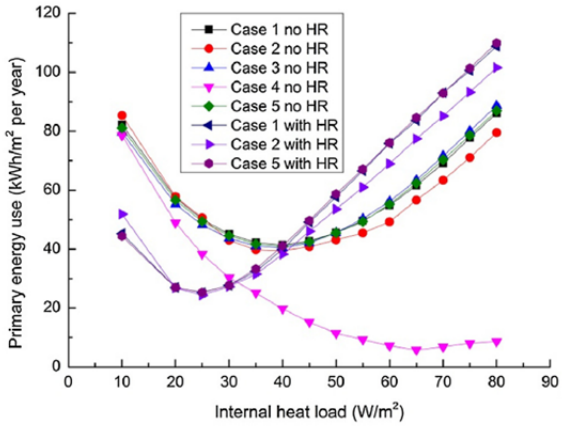


Figure 26: Annual primary energy consumption for different systems [26]

However, some assumptions have been used in the simulation and detailed investigation still need to be conducted in the further studies. First, the maximum natural ventilation rate was assumed to be 5.5 h^{-1} in the simulation. However, the accurate ventilation rate strongly depends on the design factors, such as the outside wind pressure, the plenum inlet configuration, pressure drop of the diffuse ceiling panel, and so on. It is crucial to explore the limit of natural ventilation rate in the early design stage. Second, the air was predicted to be perfectly mixed in the plenum and evenly distributed through entire ceiling area. Actually, the air condition in the plenum is influenced by the heat exchange between supply air and thermal mass and the mixing level is determined by the configuration of plenum and inlet. Although the numerical model shows some limitations, it could employ as a tool for designers or engineers to predict the energy saving potential of the integrated systems in the design stage.

8.2 Air-based systems

8.2.1 VAV system

Figure 27 presents the schematic diagram of the VAV air conditioning system with diffuse ceiling diffuser. Instead of directly supplying 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.

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 28.

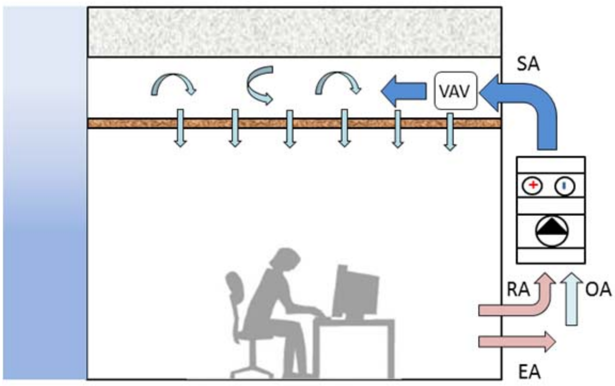


Figure 27: Schematic diagram of the VAV air conditioning system with diffuse ceiling diffuser

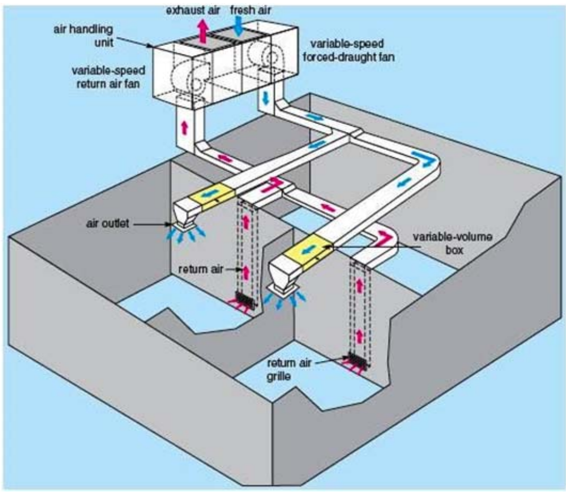


Figure 28: Schematic diagram of multiple-zone VAV system [27]

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.

8.2.2 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.

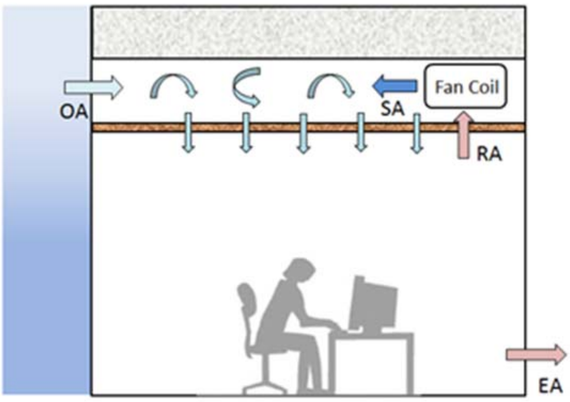


Figure 29: Schematic diagram of the fan coil system with diffuse ceiling diffuser

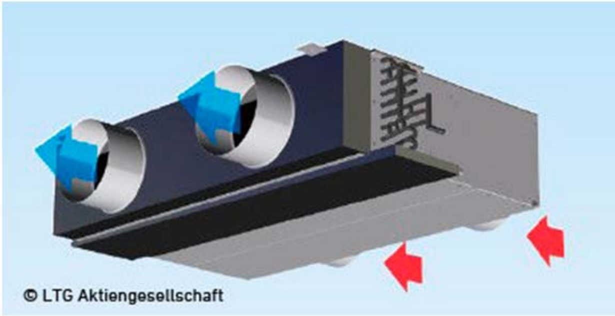


Figure 30: Ceiling-mount fan coil unit[28]

Fan coil unit can be either installed in the plenum or in the occupied space. However, the draught risk can be a significant problem when a fan coil is located in the occupied space. Figure 29 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 where the 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.

A fan coil unit typically operate with a supply chilled water temperature of 6 ^{o}C and 12 ^{o}C return, and the other temperature such as 7/13 ^{o}C or 8/14 ^{o}C are also encountered in practice [29]. 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. 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 AND OPERATION

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 ^{o}C, whereas a mixing type diffuser can supply air at a temperature of 16 ^{o}C without causing draughts.

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 ^{o}C 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 ^{o}C [30].

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 ^{o}C was tested in the experimental study [2][9], and the results indicated that it was still able to maintain a comfortable 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 designing a ventilation system, the ventilation rate should satisfy two considerations: indoor air quality and thermal comfort. 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 [31]. From the thermal comfort point of view, ventilation rate should be restricted to avoid draught 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 air flow. Therefore, the thermal comfort requirement doesn't have a restriction on the air flow rate. However, while increasing 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 concern.

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 through natural ventilation or maintained by a fan. For typical pressure difference required to ensure the necessary flow rate through the diffuse ceiling, se figure 8.

9.4 Humidity control

As mentioned in Section 2.2, condensation risk needs to be considered when designing 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. Special attention needs to be paid, when suspended ceiling is made material with high thermal conductivity, like Al panel. A ceiling panel with a moisture absorbing property can serve as a humidity buffer to keep a stable indoor relative humidity. In addition, proper control of the static pressure of the plenum and the selection of a connection profile with good airtightness may avoid reverse flow from room side, and reduce associated condensation problems. Finally, when diffuse ceiling ventilation is coupled with TABS, the TABS surface temperature needs to above dew-point temperature of the space. One possible way is to keep the lower limit for the supply water temperature equal to the dew-point temperature [32]. The cooling capacity of the TABS could be increased if the outdoor air is dehumidified before entering the plenum.

9.5 Cleaning considerations

Filtration of the fresh air before entering the plenum is recommended, as it eliminates the need of cleaning in the plenum. The regular plenum cleaning can be done by demounting a few panels or through inspection hatches (if installed) and vacuuming.

10. CASE STUDY

This chapter presents a summary of recommended design procedures for diffuse ceiling ventilation. Two case studies are presented. One is a classroom with a stand-alone diffuse ceiling ventilation. The other one is a two-person office with the integrated system.

Case 1: Classroom with diffuse ceiling ventilation

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 ×2.8 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 (^oC)	Solar radiation south facing window, ($Wh/m^2.day$)
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) [15]

	Summer	Winter
Operative temperature	24.5 ± 1.5 ^{o}C	22 ± 2 ^{o}C
Mean air velocity	0.22 m/s	0.18 m/s
Vertical temperature difference	< 3 ^{o}C	

Table 5: Indoor air quality criteria [18]

	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 [33]. 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 unoccupied period [h^{-1}]	Shading factor	Heating/cooling load of fan coil unit [kWh/day]	Calculated T_{room} occupied period [^{o}C]	Calculated T_{room} unoccupied period [^{o}C]
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. 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 width of 10 m and depth of 6 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 4) 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 have a uniform 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,.

Case 2: Two-person office with integrated system

A two-person office is planned to be ventilated by diffuse ceiling supply with hybrid ventilation solution. TABS servers as a supplementary system to deal with extra heating or cooling load in both passive and active ways.

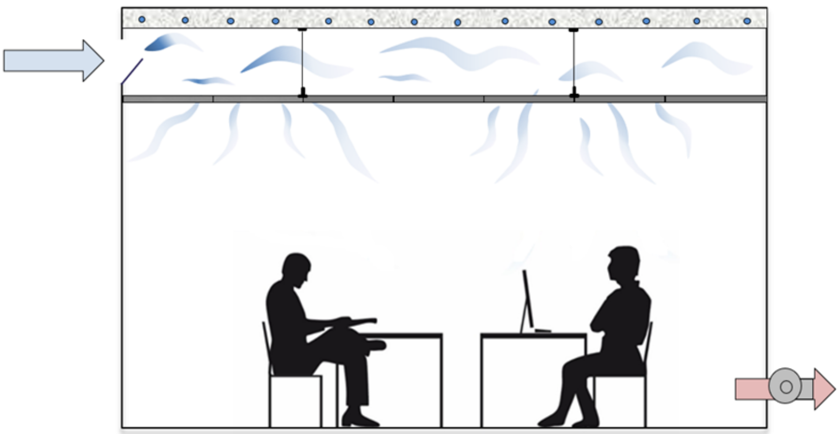


Figure 31: Illustration of integrated system in an office

Description

- Function: Office

- Location: Copenhagen, Denmark
- Dimension: 4.8 m × 3.3m × 2.8 m, window area: 2.4 m × 0.8 m
- Occupant: 2 person
- Heat load: Internal heat sources (person, computer, monitor, desk lamp) 30 W/m^2, solar radiation based on weather condition (Table 7)
- The building is occupied from 9:00 to 17:00 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 spaces in the office building are used for ordinary office 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 7: Monthly mean weather conditions based on DRY

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

Design criteria:

Table 8: Thermal design criteria (Category B) [15]

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

Table 9: Indoor air quality criteria [31]

	Airflow per person q_p	For building emissions q_B (low-polluted building)
Ventilation rate	7 l/s/pers	0.7 $l/s.m^2$

Design procedure:

c) A simplified method is applied to estimate the ventilation rate and additional cooling/heating demand for the TABS system. 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 [33]. 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 equation below:

$$q_{tot} = n \cdot q_p + A \cdot q_B = 2 \times 7 + 0.7 \times (4.8 \times 3.3) = 25 \text{ l/s} = 2 \text{ h}^{-1}$$

Maximum ventilation rate:

Due to the low pressure loss of the diffuse ceiling ventilation, this system is possible to be driven by natural ventilation. However, in order to increase the system reliability, it is recommended to apply a hybrid ventilation concept. An exhaust fan serves as a supplementary option, only when the natural driving force is inadequate. Considering of the maximum available natural ventilation in practice, a maximum ventilation rate of 6 h^{-1} is set in this case.

Table 10: Required ventilation rate and heating/cooling load of TABS in each season

Case	Climate	Ventilation rate occupied period [h^{-1}]	Ventilation rate occupied period [h^{-1}]	Shading factor	Heating/cooling load of TABS [kWh/day]	Calculated T_{room} occupied period [^oC]	Calculated T_{room} unoccupied period [^oC]
1	Winter	2	0	1 (No shading)	0.4	22 ± 1.1	15.7 ± 0.6
2	Transient	4	0	1 (No shading)	0	23 ± 1.5	20.5 ± 0.1
3	Summer	6	6	1 (No shading)	-2.1	24 ± 1.5	15.8 ± 1.2
4	Summer	6	6	0.3 (External blind)	-0.65	24 ± 1.2	15.2 ± 1.2

The ventilation rates and heating/cooling demands of TABS are specified in Table 10 for each season. The indoor air temperature during occupied hours is within the comfortable range. It needs to be noticed that shading becomes an important parameter in summer or transient season. Introducing a shading device can significantly reduce the cooling load of the ventilation system and TABS. For example, in the summer condition, using a shading device with a shading factor of 0.3 can achieve the same indoor air temperature but reduce more than half of the cooling demand from the TABS.

d) Design of diffuse ceiling ventilation

- Selection of diffuse ceiling panel:
  Because the floor area of the two-person office is small, the uneven air distribution through diffuse ceiling supply is not the critical issue in this case. We recommend using diffuse ceiling panel with a low pressure drop, in order to use natural driving forces. (For an open space office, the diffuse ceiling panel with a low pressure drop may result in an uneven air distribution throughout the room, and further lead to a draught problem in the occupied zone. Detail information can be seen in Section 6.2.2.)

  In the integrated system, the energy efficiency of TABS system is also an importation consideration when selecting the diffuse ceiling panel. Based on Table 10, cooling is the primary task of the TABS. It is recommended to choose diffuse ceiling panel with a high thermal conductivity, e.g. Aluminum panel. Compare with wood wool cement panel, aluminum panel enable a higher cooling capacity of

TABS. Therefore, TABS can operate with a higher surface temperature, which reduces the condensation risk and at the same time increases the energy efficiency of chiller. On the contrary, diffuse ceiling panel with a low thermal conductivity is preferable when TABS is mainly used for heating. Detail refers to Section 7.1.2. Therefore, aluminum panel with a low pressure drop is recommended in this case.

- Plenum height:

  A low plenum height will exacerbate any uneven air distribution through diffuse ceiling and results discomfort in the occupied zone. On the other hand, when using the integrated system, low plenum will increase the convective heat exchange with TABS surface and increase TABS' energy efficiency. A balance needs to be reached between thermal comfort and energy efficient. A minimum plenum height of 15-10 cm is recommended in this case. Detail discussion regarding plenum height refers to Section 6.2.2.

- Plenum inlet:
  The plenum inlet is designed to be one or several window openings located on the external wall facing to the plenum. The window opening area could be able to adjust based on the required ventilation rate and weather conditions. In order to ensure sufficient ventilation rate during the whole year, an extract fan serves as a supplementary driving force when natural driving force is insufficient.

e) Design of TABS

- Four pieces of concrete slabs with embedded water pipes are employed as TABS, each piece has a dimension of 3.56 m × 1.2 m× 0.2 m. The pipes are embedded 4 mm above the lower surface of TABS to ensure a quick thermal response. The pipes are connected in series, due to the limited thermal decay along the pipe in a small office. (For the open space office, the pipe is recommended to connect in parallel.)

Table 11: TABS operation in each season

Case	Climate	Running hour	Heating/cooling load of TABS per hour [W]	Heat transfer coefficient of TABS (with Al ceiling panel) [W/m^2.K]	$T_{s,TABS}$-$T_{r,op}$ [k]
1	Winter	7:00 – 9:00	+200	Heating: 7	2
2	Transient	N	N	N	0
3	Summer	7:00 – 17:00	-210	Cooling: 3.5	-3.7
4	Summer	7:00 – 10:00	-166	Cooling: 3.5	-3

- The operative conditions of TABS in each season are presented in Table 11. In winter, TABS heating is activated 2 hour before occupied period, in order to pre-heat the space and provide a comfortable indoor environment for the occupants. The TABS surface temperature needs to keep 2 ^oC higher than the room operative temperature to ensure the sufficient heating capacity. The heat transfer coefficient of TABS is simulated based on that TABS integrates with a diffuse ceiling made by Al panels (refer to Section 8.1.2).
  In transient season, ventilation is enough to remove all the heat load and TABS is not activated. In summer, TABS cooling capacity needs to reach 210 W/h between 7:00-17:00, where TABS surface

temperature keeps 4 ^{o}C lower than the room operative temperature. If a shading device is applied, TABS running hour can reduce to 4 hours per day only.

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APPENDIX

Appendix A: Test conditions of different diffuse ceiling inlets

Inlet type	Description	Flow rate (l/s.m^2)	Heat load (W/m^2)	Supply temp. (^{o}C)	Room dimension (m^3)	Reference
A	Cooling	1.9 – 7.3	32-70	12 – 20	4.2 ×3 .6 × 2.5	[8]
	Cooling	5.4	1 manikin, 1 PC, 1 lamp	N/A	4.1 × 3.2 × 2.45	[3]
	Heating	2.4 – 4.1	0	N/A		
B	Cooling	3.4 – 5.0	31 – 53	16.7 – 17.2	3.6 × 6 × 3.5 (2.9)	[4]
C&D	Cooling	1.9 – 4.9	50	-3.2 – 11.2	3.6 × 6 × 3.5 (2.9)	[9]
E&F	Cooling	3.1 – 6.2	42 W/m2 (person load) + radiator or floor heating	N/A	4.9 × 3.6 × 3 (2.5)	[10]
G	Cooling	2.8 – 11.8	40 – 227	-5 – 15	4.8 × 3.3 × 2.7 (2.335)	[2]
H	Cooling	5.0 – 20.0	72	4.8 – 15.7	6.0 ×4 .65 × 4.5 (4.4)	[11]
	Cooling	1.3 – 11.2	17	8.9 – 20.8	6.0 × 4.65 × 4.5 (2.5, 4.1, 4.4)	[12]

Note: Room dimension = length × width × height (height exclude plenum)

Appendix B: Set-up parameters of BSim model [26]

Room information		
Dimension	8.0 m× 3.6 m×4.8 m	
Envelop	Floor/ceiling	U-value: 0.71 W/m2.K
	Exterior wall	U-value: 0.33
	Interior wall	U-value: 4.77
	Window	U-value: 0.7; g-value 0.25
	Ceiling panel	U-value: 1.03
Total thermal mass	175 Wh/m^2.K, very heavy construction	
System properties		
Air-based system	Specific fan power (SPF): 2.1 kJ/m3 Heat recovery rate: 75%	
TABS	Water temperature: 16-18 oC	
System energy factor		
System	System conversion factor	Primary energy conversion factor
Air-based heating	0.8	1
Air-based cooling	3	2.5
Radiant heating	0.8	1
Radiant cooling	3.5	2.5
Mechanical ventilation	1	2.5

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