Integrated ventilation and night cooling in classrooms with diffuse ceiling ventilation

Hviid, Christian Anker; Petersen, Steffen

Published in:
Proceedings

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hviid, C. A., & Petersen, S. (2011). Integrated ventilation and night cooling in classrooms with diffuse ceiling ventilation. In *Proceedings*

INTEGRATED VENTILATION AND NIGHT COOLING IN CLASSROOMS WITH DIFFUSE CEILING VENTILATION

Dr. Christian Anker Hviid
Department of Civil Engineering, Technical University of Denmark
Brovej bygn. 118, DK-2800 Lyngby
Tel.: +45 45 25 18 86
E-mail: cah@byg.dtu.dk

Dr. Steffen Petersen
Aarhus School of Engineering
Dalgas Avenue 2, DK-8000 Aarhus
Tel.: +45 41 89 33 47
E-mail: stp@iha.dk

1 Introduction

The purpose of ventilation in a room is to supply fresh air to the occupants and to remove heat, gases, particulate matter emitted from the building and its use. Two major principles of room air distribution in non-industrial premises are displacement and mixing. In these systems fresh air is typically supplied by diffusors placed at discrete points in the room. This concentration of air sources produces imminent risk of draught in the vicinity of the diffusors which means that the ventilation design requires specific attention to inlet zones and comfort zones. An alternative ventilation principle is known as diffuse ceiling ventilation. In such systems the space above a suspended ceiling (plenum) is used as a pressure chamber and fresh air is supplied to the occupancy zone through perforations in the acoustic suspended ceiling. Because of the low-impulse supply from the ceiling area the system does not produce draught by itself. This makes the concept especially suitable for premises with high concurrent ventilation and cooling demand like in class rooms.

Different types of ceiling tiles, perforation patterns and ceiling suspensions have been documented in laboratory experiments imitating office spaces (Honglu 2011, Nielsen 2010) and class rooms (Hviid 2010). In comparison with conventional mixing ventilation the experimental results have proven satisfactory with regard to ventilation effectiveness and draght risk. Similar findings were reported in a field-study of a classroom with two different types of perforations (Jacobs 2008, Jacobs 2009).

Distributing the supplied air via the plenum allows for a continuous direct contact between the room air and the thermal mass of the concrete slab in the (internal) ceiling. The effect of more exposed concrete on excessive temperatures and free night cooling have been quantified by a large number of simulations and experiments (Kolokotroni 1998, Kolokotroni 1999, Høseggen 2009, Wang 2009). Also experimental investigations into the exact heat transfer of a room with free night cooling have been performed (Artmann 2010). However, in practice the thermal mass of the concrete slab in the (internal) ceiling is often encapsulated by a suspended ceiling. This inhibits a significant free cooling potential of the room. Høseggen (2009) demonstrated this potential by removing the suspended ceiling but this solution does not address the issue of acoustics – especially in class rooms.

The solution presented in this paper combines ventilation and free cooling without compromising acoustics. The paper numerically investigates the free cooling potential of diffuse ceiling ventilation when the cooling air is supplied above the suspended ceiling. A dynamic building simulation tool is employed to quantify the potential as the consequence on thermal indoor environment quality. In order to model the heat transfer at the internal surfaces in the plenum correctly, a computational fluid dynamics tool is employed. Finally we discuss the optimal control strategy with regard to heating and cooling of the concrete slab.

2 Method

The free cooling potential of diffuse ceiling ventilation is investigated with the commercial building simulation software tool IESVE 6.2 (IESVE 2011). The potential is illustrated by comparing the simulated thermal indoor environment quality of two ventilation scenarios for a class room where scenario 1 is conventional mixing ventilation, and scenario 2 is diffuse ceiling ventilation. For scenario 2, the local convective heat transfer coefficient in the plenum is found by computational fluid dynamics (CFD).

2.1 Building simulation model

The building simulation model of the classroom and plenum is made from two rooms with one common surface, the suspended ceiling. Occupancy, lighting, and heating system controls are applied in the lower room. Ventilation air supply is applied to the upper room, then transferred to the lower room before extraction. The resulting convective and radiant heat transfer coefficients of plenum and airflow rate then determines the interaction between supplied air, concrete slab and suspended gypsum ceiling. The convective and radiant heat transfer coefficients of the class room surfaces adds to 8 W/m^2 K. A screenshot of the simulation model is shown in Figure 1 and detailed data assumptions for the model are given in Table 1.

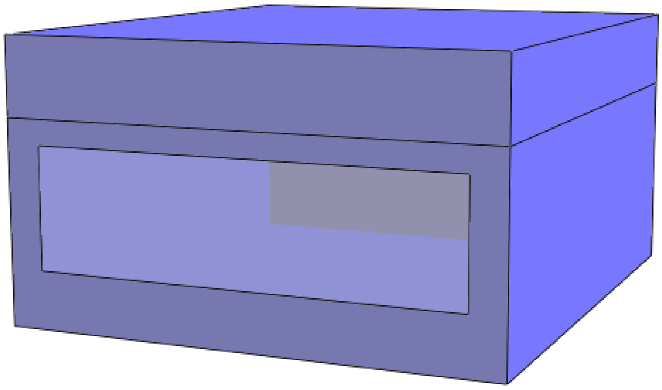


Figure 1 Building simulation model from IESVE with classroom and plenum on top

Table 1 Data assumptions for the simulation model

Room dimensions	Height × width × depth	3 m × 7.25 m × 7.85 m (internal measures)
	Plenum height	0.74 m
Window	Height × width	1.8 m × 6.4 m
	Offset	Symmetrical, 0.85 m from floor.
	Orientation	South
	Glazing type	Triple glazing with solar and low-E coating (U/g/LT = 0.6/0.3/0.54)
	Frame	Aluminium frame, U=1.0 W/m^2 K, width=0.05 m, ψ=0.03 W/m K
Constructions	Façade	Emalit glass/mineral wool/plaster (U=0.11 W/m^2 K)
	Internal partitions	Plaster/mineral wool/plaster
	Internal ceiling	Concrete/cavity/plaster
Systems	Infiltration	0.04 l/s m^2, always active.
	Mechanical ventilation during	Max. ventilation rate (V_{max}) is 7.5 h-1. Air flow is controlled by a ramp function where the air flow is 0.2

	occupancy (7-16)	of V_{max} at 20 ºC and 1 at 24 ºC constrained by a maximum CO_2 level of 860 ppm. Inlet temperature is outdoor temperature +1K but minimum 16 ºC. No mechanical cooling available.
	Mechanical ventilation during unoccupied hours	Max. ventilation rate (V_{max}) is 7.5 h^{-1}. Air flow is controlled with respect to a minimum air temperature of 20 ºC. Inlet temperature is outdoor temperature +1K but minimum 5 ºC.
	General lighting	Max. power (W_{max}) 4.6 W/m^2. Dimming control by ramp function where lighting power is 1 of W_{max} when 0 lux from daylight and 0.1 of W_{max} when 500 lux from daylight. Only active in occupied hours.
	Internal load	People load: constant sensible heat gain of 100 W/person, 1.25 m^2/person. Equipment: 1.189 W. Load pattern: 100 % 8-12 and 13-15, 50 % 12-13 and 15-16, weekdays (except week 24-31 of the year). Diversity factor of 0.8.
External conditions	External obstructions	None
	Weather data	Danish design reference year (Jensen 1995)

2.2 CFD simulation

Figure 2 shows the CFD model (including streamlines) which was implemented in the commercial software package Ansys CFX version 13. The dimensions of plenum correspond to the final plenum. The classroom below plenum does not influence the heat transfer and is reduced in size due to grid size limitations. The pressure drop of the real suspended ceiling causes the airflow to penetrate it uni-directionally. The pressure drop is approx. 2 Pa as found by Hviid (2010) and is modelled with a momentum loss model in the CFD program. This causes the plenum to act as a pressure chamber and allows for calculation of the surface heat transfer coefficient of the upper concrete slap.

The mesh consists of a mix of tetrahedrons and hexahedrons. Special inflation mesh was applied close to the surfaces in the plenum to properly capture the heat transfer. Together with the Shear Stress Turbulence model and automatic adaptive logarithmic wall-laws, which are a special feature of CFX, the boundary layer can be resolved accurately and thus accurate convective heat transfer can be modelled (Vieser 2007). This is documented on Figure 3 which shows that the boundary layer has been sufficiently resolved.

The wall heat transfer coefficient as reported by CFX is documented in Table 2 and compared to standard values. It is clear that the difference is quite small which is due to the mixing of air in the plenum where only a fraction of the air is in direct contact with the concrete slab before it returns and mixes with the inlet jet before eventually crossing the diffuse ceiling barrier into the classroom below.

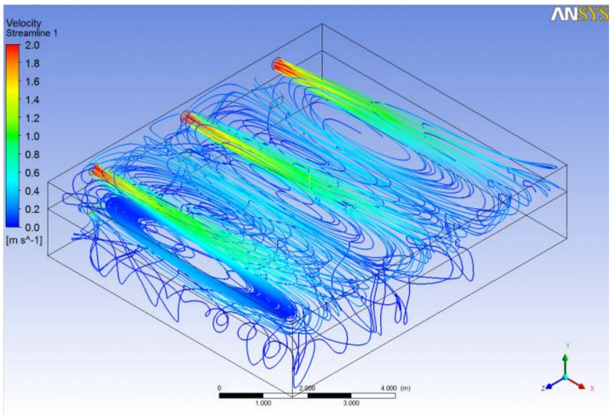


Figure 2 Streamline jets from inlets in the plenum

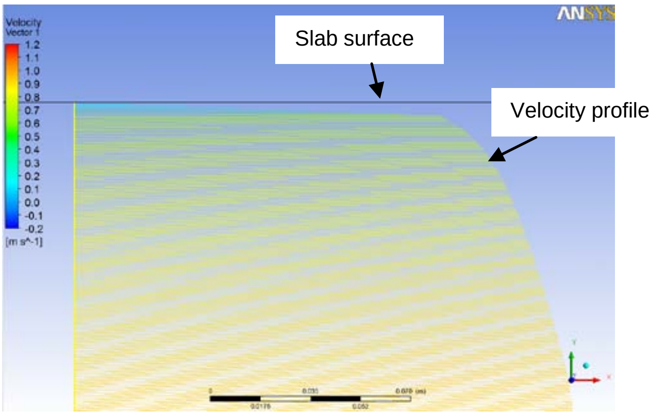


Figure 3 Logarithmic velocity profile of jet near concrete slab surface

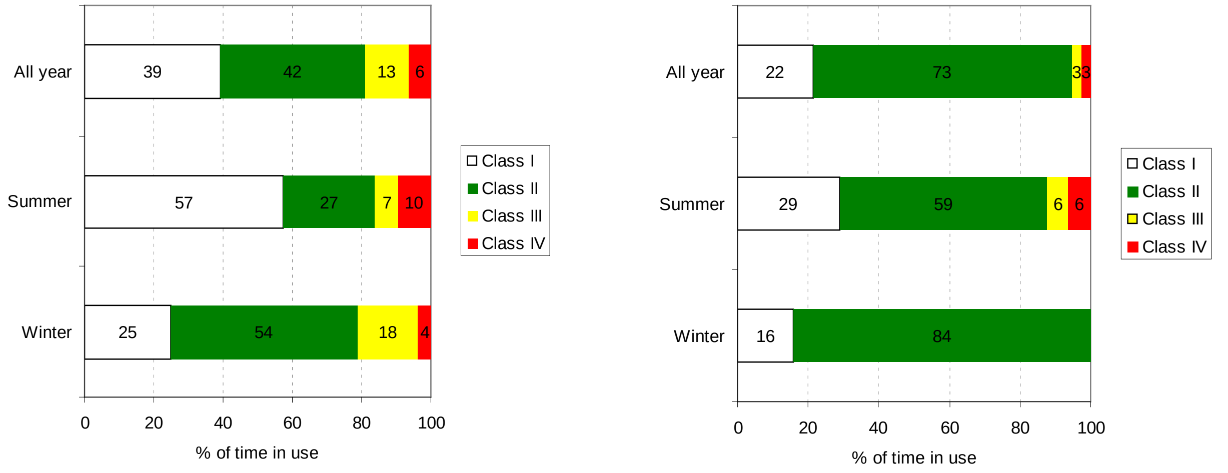
Table 2 Convective and radiant heat transfer coefficients for concrete slab in the plenum

	Convective	Radiant	Combined
Danish ceiling standard (DS-418 2011)			10 W/m^2 K
CFD convective	6,8 W/m^2 K	4,2 W/m^2 K	11 W/m^2 K

3 Results

In the results we show the free cooling potential of supplying ventilation air via the plenum. The potential is illustrated by comparing the simulated thermal indoor environment of the two ventilation scenarios for a class room, 1) mixing ventilation and 2) diffuse ceiling ventilation. In Figure 4 the thermal environments are depicted as footprints. The thermal indoor classes I-IV introduced with EN15251 (EN15251 2007) are designated with the colors white, green, yellow and red and show the amount of time the operative temperature is within a certain comfort range. It is clear from the figure that the percentage of time with overheating (class III and IV) is significantly reduced from 19% to 6% on a yearly basis. However, it is notable that excess overheating occurs even in winter. This is due to the high internal heat gain in the classroom which creates overheating even in winter. This period in particular gains from the extra free cooling potential as overheating is reduced from 22% to 0%.

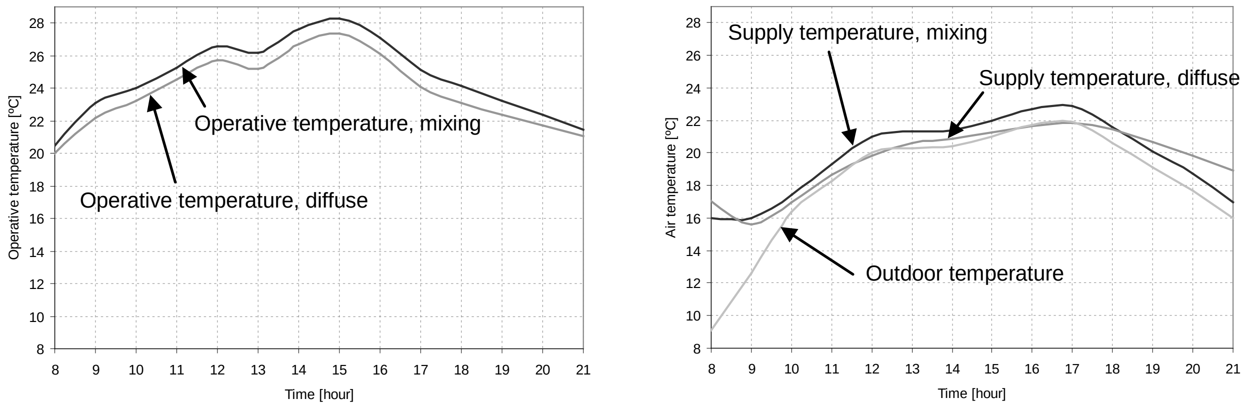
The number of hours in comfort range I and II shifts from I to II going from mixing to diffuse ventilation. This is because the overall indoor temperature is lower in the diffuse situation and temperatures below the lower comfort limit in class I are more prevalent.



(1) (2)

Figure 4 Thermal comfort during occupancy with mixing ventilation (1) and diffuse ceiling ventilation (2). Green and white color are within normal comfort range.

Figure 5 shows the detailed temperatures of the classroom and the plenum. In (a) the operative temperature of the class room with diffuse ceiling system is consequently 1K lower. This is due to the lower temperature of the inlet air (b) because it is cooled in the plenum prior to being supplied.



(a) (b)

Figure 5 Operative temperatures in classroom (a) and ventilation supply temperatures (b) on May 3 with mixing and diffuse ceiling ventilation

The heat transfer coefficient is calculated to be 11 W/m^2 K at an air change of 7.5 h^{-1} at full internal load (Table 1). In the winter situation the ventilation rate can be lower meaning that the heat transfer coefficient decreases. This effect is not included in the model, but does not influence the overall conclusion as it is based on the extreme case with maximum heat load and maximum flow rate.

4 Optimal control strategy

The concept sketched here raises some issues regarding the optimal control strategy. Ideally the concrete slab is cooled at night by outside air to a temperature where the cooling capacity is sufficient for the entire next day. However, if the slab is cooled too much, the supply air from the plenum will be too cold the next day thus requiring heating energy. Furthermore, the inlet air should be controlled with respect to outdoor humidity to prevent condensation in air ducts and plenum. An optimal control of temperature as well as humidity might include the use of weather forecasts and other predictions together with building simulations.

It is also important to ensure a sufficient cooling capacity of the concrete slab and room constructions because mechanical cooling, in the event that free cooling is insufficient, can become particularly energy expensive with this concept as the concrete in the plenum must be cooled first. Also the penetration depth of low temperatures within the concrete slab, and consequently the surface temperature on the upper floor, should be given consideration in the control strategy, particularly during winter season.

5 Conclusion

The paper presented the concept of low-impulse diffuse ventilation via the suspended acoustic ceiling. Literature sources have stated sufficient ventilation air distribution but have not made an attempt to quantify the concurrent free cooling potential of supplying ventilation air via the plenum. Here we have simulated the extra free cooling potential made available by activating the thermal mass of the concrete slab in the plenum. The simulations included investigations of two scenarios with a building simulation tool with CFD-derived surface heat transfer coefficients of the concrete slab. The results showed clearly the effect of the extra exposed thermal mass by overall lower operative temperatures in the classroom in both summer and winter situations. Also peak temperatures were lower. Lastly critical issues regarding the optimal control strategy which should be addressed in future research activities were identified.

6 Literature

Artmann N., Jensen R.L., Manz H., Heiselberg P., (2010), Experimental investigation of heat transfer during night-time ventilation, Energy and Buildings, Vol. 42, No. 3, 366-374

CFX, (2011), ANSYS, version 13

DS-418, (2011), Calculation of heat loss from buildings, Dansk Standard

EN15251, (2007), Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, European Standard

Honglu Y., (2011), Experimental and numerical analysis of diffuse ceiling ventilation, M.Sc. thesis, Department of Civil Engineering, Technical University of Denmark

Hviid C.A., (2010), Building integrated passive ventilation systems, Ph.D. thesis, Department of Civil Engineering, Technical University of Denmark

Høseggen R., Mathisen H.M, Hanssen S.O., (2009), The effect of suspended ceilings on energy performance and thermal comfort, Energy and Buildings, Vol. 41, No. 2, 234-245.

IESVE, (2011), Integrated Energy Solutions, Virtual Environment, version 6.2

Jacobs P., van Oeffelen E.C., Knoll B., (2008), Diffuse ceiling ventilation , a new concept for healthy and productive classrooms, in: Proceedings of Indoor Air, paperID #3, Copenhagen

Jacobs P., Knoll B., (2009), Diffuse ceiling ventilation for fresh classrooms, in: Proceedings of 30th AIVC Conference, Berlin

Jensen T., Lund H., (1995), Design reference year – a new Danish reference year (in Danish). Technical University of Denmark, LFV announcement no. 281

Kolokotroni M., (1998), Summer cooling with night ventilation for office buildings in moderate climates, Energy and Buildings, Vol. 27, No. 3, 231-237

Kolokotroni M., Aronis A., (1999), Cooling-energy reduction in air-conditioned offices by using night ventilation, Applied Energy, Vol. 63, No. 4, 241-253

Nielsen P.V., Jensen R.L., Rong L., (2010), Diffuse ceiling inlet systems and the room air distribution, in: Proceedings of Clima, 10th REHVA World Congress, Antalya

Vieser, W., Esch, T., Menter, F., Smirnov, P., (2007), Heat transfer predictions using advanced two-equation turbulence models, CFX validation report, ANSYS Germany

Wang Z., Yi L., Gao F., (2009), Night ventilation control strategies in office buildings, Solar Energy, Vol. 83, No. 10, 1902-1913