7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments

ibpc2018.org | #ibpc2018

Numerical investigation of a diffuse ventilation ceiling system for buildings with natural and hybrid ventilation

Alessandro Nocente[1,*], Francesco Goia[1] and Steinar Grynning[2]

[1]Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[2] Sintef Byggforsk, Trondheim, Norway

[*]*Corresponding email: alessandro.nocente@ntnu.no*

ABSTRACT

The need to meet requirements, both in terms of ventilation and thermal comfort in modern buildings, has led to the development of different concepts for ventilation, among which the so-called Diffuse Ceiling Ventilation (DCV). This system makes use of the space between the ceiling slabs and the suspended ceiling as a plenum for fresh air, while the suspended ceiling itself becomes an air diffuser element. If compared to traditional solutions, this allows a higher amount of ventilation air to be injected in the room at lower speed, and a more even distribution of the fresh air within the room. Furthermore, it allows an easy integration with sound-absorbing perforated ceiling panels, since their typical design makes them particularly fit to be used as air diffusers.

This paper builds upon a previous work by the authors where CFD simulations were used to optimise the dimension and the distribution of the perforation pattern in the panels to achieve an even air speed distribution. In this work, the performance of the perforated ceiling is investigated in a more comprehensive way, evaluating the thermal comfort in the room when varying the outdoor temperature. This solution is in fact meant to work in combination with natural or hybrid ventilation strategies, where the fresh air flow is supplied from the façade.

Numerical simulations were performed on a typical office room, considering both the winter and the summer season, for different inlet air temperatures. This solution demonstrated a positive impact on the indoor conditions and on the thermal comfort inside the room in most of the cases but the most extreme ones. The thermal stratification in the room demonstrated to remain within a satisfactory level.

KEYWORDS

CFD, Diffuse Ceiling Ventilation (DCV), Sound absorbing perforated panels, Natural and hybrid ventilation, Thermal comfort.

INTRODUCTION

Diffuse Ceiling Ventilation (DCV) is a novel air distribution concept for ventilation in low and plus energy buildings. The volume between the ceiling slabs and the suspended ceiling constitutes a plenum where the ventilation air is injected, and the dropped ceiling acts as an air diffuser. This way a large amount of ventilation air can be provided to the room at lower speed, and with a more even distribution compared to conventional inlet solutions realized through ceiling/wall/duct diffusers. According to previous researches, this concepts provides several advantages, such as a low pressure loss, low investment cost and higher thermal comfort if compared to traditional ventilation systems (Zhang et al. 2016).

First proposed in livestock buildings (Van Wagenberg and Smolders 2002), it was presented as a suitable solution to improve the air quality in classrooms by Jacobs et al. (2008). Several scholars investigated the effect of the suspended ceiling characteristics on the ventilation quality (Fan, et al. 2013; Petersen et al. 2014). Zhang et al. (2015) performed hot-box measurements to evaluate the possibility to couple the DCV with water based thermal elements in the plenum while Hviid and Svendsen (2013) evaluated the performances and excluded DCV as source of possible thermal discomfort by means of experiments in a real size test chamber. The last two works both considered the dropped ceiling as realised with sound-absorbing perforated panel. The presence of these panels is quite common, especially in office buildings, and their constructive characteristics make them particularly fit to act as air diffuser without particular design modification, even if their use as air diffuser could slightly affect the sound absorbing capacity – an aspect not herewith investigated, though.

One of the known limitation of the DCV concerns the possible unevenness in the air distribution in the room. In fact, the injection of air ventilation in the plenum typically takes place through a surface of the plenum or via duct works. This creates an uneven pressure distribution in the plenum, therefore the air exiting the diffuser will present a higly non-uniform velocity profile. A proper design of the suspended ceiling considering the use of different panels perforation size and rate in different zones, could partially solve this issue.

In the last years, CFD as a tool to evaluate the performance of DCV appeared in research works (Mikeska and Fan 2015; Zhang et al. 2017). In those cases, the perforated panels were modeled as porous media, not focusing on the different influence that different perforation patterns can have on the fluid dynamics of the ventilation and the air circulation in the room.

In Figure 1, a comparison between injecting the air directly though the façade ((a) and (b)) or through the dropped ceiling plenum is shown. This first illustration previews how a direct inlet leads to potential discomfort (a) due to low air temperature (below 10 °C in most of the room) and an uneven distribution of the fresh air (b), especially if compared to a solution where the air is (much more evenly) distributed through the plenum of the dropped ceiling (c).

The present investigation builds up on a previous work by the authors (Nocente et al. 2018) in which CFD calculations were used to evaluate an optimal panel distribution for a typical office room which ensures a more even velocity distribution out of the perforated ceiling. The previous work focused only on the fluid-mechanical aspects, but neglected the thermal domain of the problem.

The objective of the analysis presented in this paper is instead to take into consideration the thermal environment derived by the direct injection of ventilaiton air from the façade through the dropped ceiling. For this reason, simulations have been carried out parametrizing the inlet temperature (and the airflow rate) with the aim of assessing the performance of DCV in a more comprehensive way, and evaluating the risk of incurring in thermal discomfort conditions in the room under different outdoor air temperature conditions.

The investigation is however limited by the fact that the entire thermal balance of the room is not considered, i.e. the effect of the ventilation air on the heating and cooling load of the room is not assessed in this work.

METHODS

Numerical Model

In a previous work (Nocente et al. 2018) three models (with different perforation size and distribution) of commercially available sound-absorbing panels were taken into account for the suspended ceiling. Two optimal combination were found in that study, and one of those was chosen to realise the numerical analysis presented in this work.

The computational domain, in order to reduce the simulation time, is a room section, which is representative of the entire room geometry. The width is that of one dropped ceiling panel (0.6 m), while all other dimensions are typical of an office room: length 3.6 m and height 3.0 m. The height of the plenum is 0.35 m. The air inlet is the whole surface of the plenum directed towards the façade, while the outlet is placed on the opposite surface and it is modelled as a rectangular opening with dimensions (WxH) 0.6 m x 0.05 m.

The computational mesh is structured hexahedral and counts 22 million cells. The high number of cells was necessary to calculate with sufficient precision the flow conditions past the panel perforation. This also required a high computational effort, which was reduced considering a section of the room, and by setting a non-conformal mesh interface between the suspended ceiling and the room volume. The commercial code Ansys Fluent was used, especially because of the ease of handling of non-conformal interfaces.

Boundary Conditions

Two typical seasonal conditions were taken into account. In both cases the temperature of the plenum ceiling, room floor, and the vertical wall which contains the ventilation outlet, were set constant at the internal room temperature. The wall below the ceiling inlet was considered part of the façade. Therefore, the wall temperature was calculated considering an ideal thermal transmittance in steady state conditions for the façade equal to 0.8 W/m^2K. Both the side walls (3.6 x 3.0 m) are treated as internal air and not as walls.

The calculations were performed in steady state imposing atmospheric pressure at the room outlet and a constant velocity at the plenum inlet. Two conditions were tested, calculated to provide an amount of ventilation air of 1.2 m^3/h and of 2.7 m^3/h per square meter of room floor area. The lowest value is meant to represent a baseline ventilation, while the highest one is representative of a fresh airflow that satisfies the requirements for ventilation in a low-polluting office, reaching an IEQ category III.

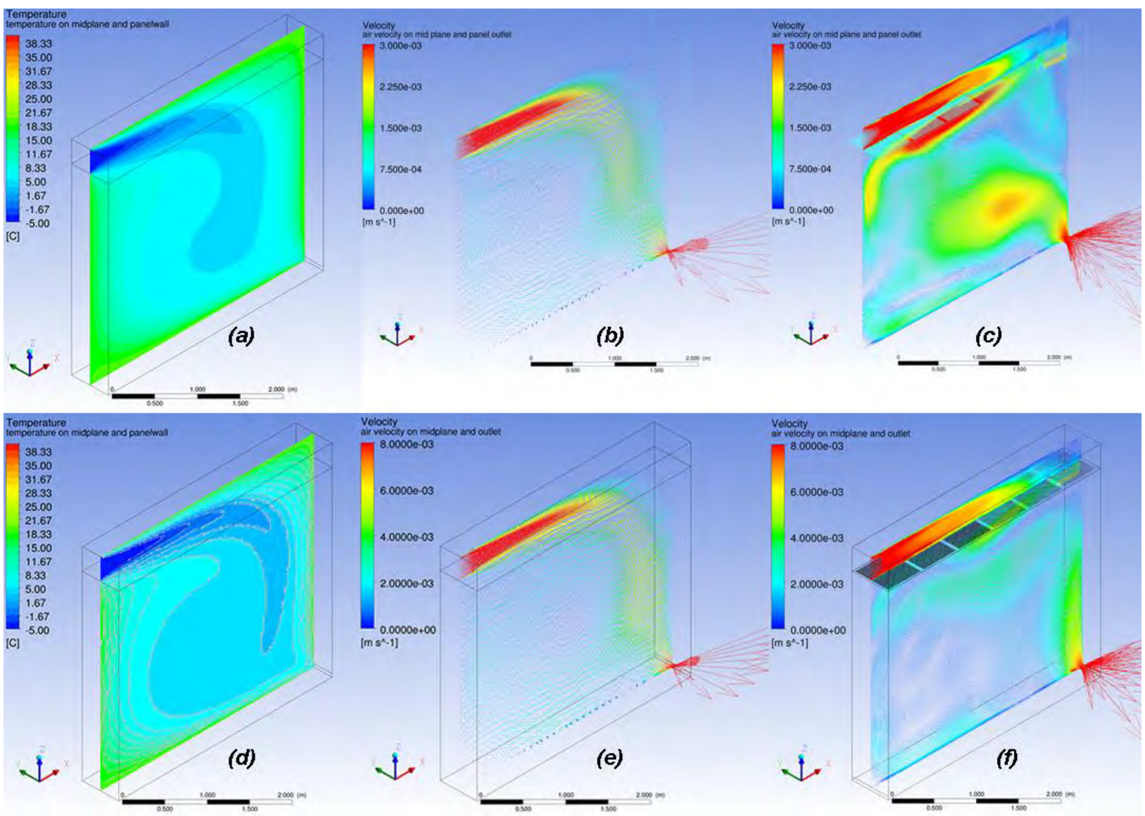

Figure 1. Comparison between inlet design without (a, b and d, e) and with (c, d) a dropped ceiling. (a) temperature profile with inlet temperature equal to -5 °C, airflow: 1.2 $m^3/h\,m^2$; (b) velocity field with airflow: 1.2 $m^3/h\,m^2$; (c) velocity field with airflow: 1.2 $m^3/h\,m^2$; (d) temperature profile with inlet temperature equal to -5 °C, airflow: 2.7 $m^3/h\,m^2$; (e) velocity field with airflow: 2.7 $m^3/h\,m^2$; (f) velocity field with airflow: 2.7 $m^3/h\,m^2$.

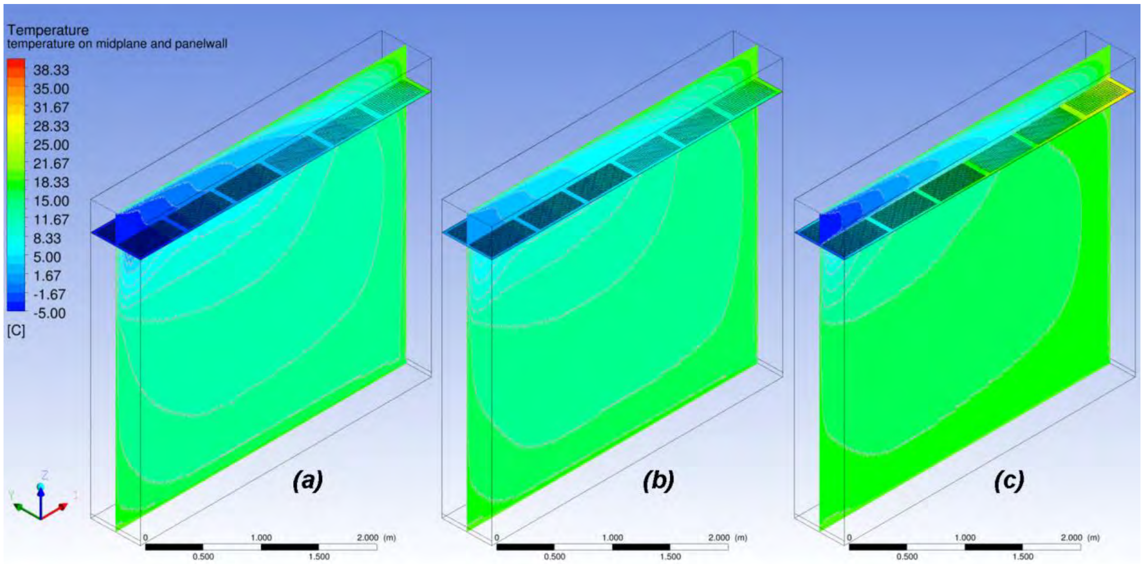

Figure 2. Temperature profile on midplane and dropped ceiling panels for inlet temperature equal to: (a): -5 °C; (b): 0 °C; (c): -5 °C and imposed heat flux 10 W/m^2.

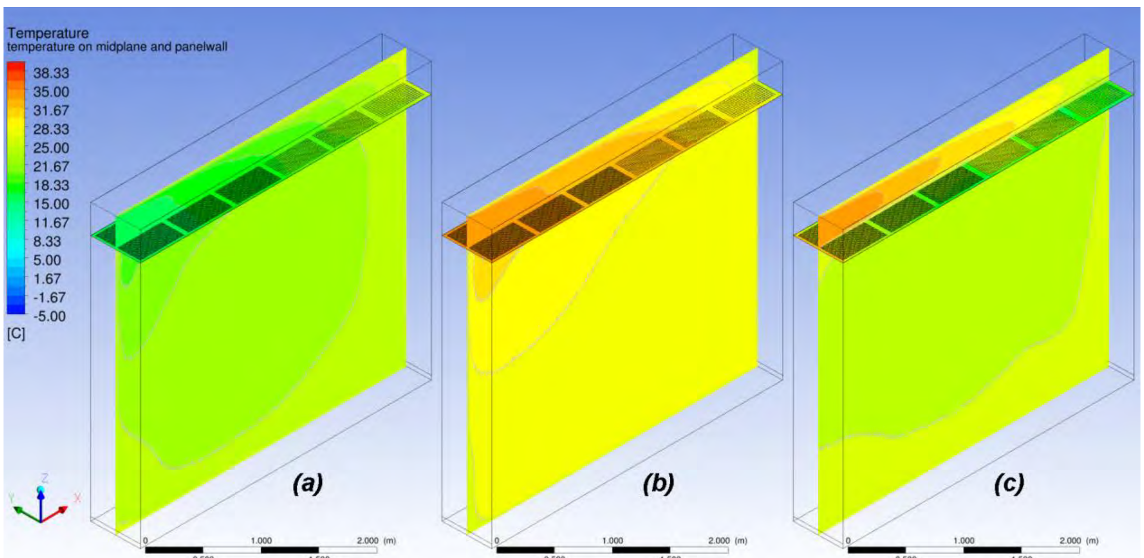

Figure 3. Temperature profile on midplane and dropped ceiling panels for inlet temperature equal to: (a): 15 °C; (b): 35 °C; and (c): 35 °C and imposed heat flux -10 W/m^2).

RESULTS

Winter case

For the winter case, the temperature of the room surfaces (with the exception of the façade and of the dropped ceiling) was considered 20 °C. The outdoor air temperature was set as a variable, and a parametric analysis was carried out to assess the impact of this variable on the system's performance. Simulations were repeated for the following values of the outdoor air temperature: -5, 0, 5 and 10 °C. The ventilation air enters the plenum with conditions equal to that of the outdoor air temperature. Figure 2 reports the temperature distribution in the plenum, the room and the ceiling panel surface for the most extreme cases (-5 °C and 0 °C). In the cases where the inlet temperature is greater that case 0 °C, the injection of air at outdoor temperature does not cause a substantial deviation from the comfort temperature except for the part of volume directly in contact with the ceiling and the façade. Conversely, the internal comfort can be affected in case of an outdoor temperature ≤ -5 °C.

Summer case

In the summer case, the temperature of the room surfaces (with the exception of the façade and of the dropped ceiling) was set at 26 °C. The outdoor air temperature was imposed at 15 °C, 20 °C, 30 °C and 35 °C. The case with outdoor temperature 25°C was not investigated since, as obvious, it does not lead to any significant variation to the internal temperature field being the difference only 1°C.

The case with outdoor air temperature equal to 15°C was instead selected to represent early morning situation with an outdoor air temperature relatively low. The temperature distribution on the mid-plane and the suspended ceiling surface for the summer case is reported in Fig.3, for the most extreme conditions (cold and warm air). Here is it possible to verify that only under the most extreme conditions (inlet air temperature of 35°C, Fig. 3 b)), the indoor air in the room is outside the comfort range.

DISCUSSION

In both winter and summer situation, the use of a DCV coupled with natural or hybrid ventilation, does not entail particular problems for the thermal comfort, both in terms of temperature and air velocity, with the exception of the most extreme conditions.

Under the most extreme (investigated) winter conditions (namely, case (a)), the indoor air reaches a too low temperature in the volume immediately close to the dropped ceiling – i.e. a volume of air that is not usually occupied by the user. However, even under these conditions, the performance of the system is better than a competing solution where the air intake is performed directly through the façade (see Fig. 1). The temperature of the dropped ceiling surface is also low, and this might negatively affect the indoor environment, even if problems related to radiant asymmetry discomfort are probably avoided due to the very small surface at low temperature. The lack of surface condensation was also verified (with the assumption of a relative humidity of the air immediately closed to the surface of 90%.

Under the most extreme (investigated) summer conditions (namely, case (d)), the indoor air reaches a too high temperature in the entire room volume. However, a similar condition would occur also with direct inlet through the façade without the dropped ceiling plenum.

In both the extreme winter and summer conditions, a strategy to minimize discomfort is by locally treating the ventilation air right before it enters the room. An interesting solution could be the use of the dropped ceiling as the terminal of a water based cooling/heating system. Two simulations to assess the performance under this configurations were performed, imposing a constant heat flux of 10 W/m^2 in winter (Fig. 2 c) and of -10 W/m^2 in summer (Fig. 3 c), to the entire dropped ceiling, thus turning it into an active conditioning surface.

The temperature of the suspended ceiling shows in both cases a non-uniform distribution, and this is due both to the temperature distribution in the plenum and the different air velocity through the perforation. In the winter situation, the solution seems to accomplish the objective with no particular problems. In the back section of the dropped ceiling may reach surface temperatures as high as 30 °C, which is still an acceptable surface temperature, even if in the proximity with the head of the users.

In the summer case instead, a more evident thermal stratification in the room is shown, and the temperature of the section of the suspended ceiling at the rear of the room (far away from the façade) reaches values as low as in the range 15-16 °C. Limiting the area of the dropped ceiling's panels equipped with hydronic system to the first two panels next to the façade would probably assure a suitable air temperature and an optimal surface temperature of the dropped ceiling.

CONCLUSIONS

The DCV ventilation system, object of the present work, demonstrates to have a positive impact on the comfort inside a typical office room. A sufficient amount of ventilation air is provided at low velocity and ensuring the absence of draft according to the values recommended by ISO 7730(7730:2005). In case of coupling between DCV and natural and hybrid ventilation, the system ensures the thermal comfort except in case of extremely high or low outdoor temperature. The use of the suspended ceiling as terminal of a water based heating/cooling system can be taken into account. According to preliminary simulations, the water based system should be capable of proving a thermal flux of ± 10 W/m^2, depending on the seasons. This eventuality demonstrated both in the winter and in the summer case a good influence on the comfort conditions. The portion of the dropped ceiling to be equipped with a water based heating/cooling system could be limited to the area closest to the façade and provide an adequate surface temperature of the DCV while conditioning the airflow under the most critical boundary conditions.

ACKNOWLEDGEMENT

This work has been supported by the Research Council of Norway and several partners through the project "Advanced facades with integrated technology – SkinTech" (nr. 255252).

REFERENCES

Fan, J., C. A. Hviid, and H. Yang. 2013. “Performance Analysis of a New Design of Office Diffuse Ceiling Ventilation System.” *Energy and Buildings* 59:73–81

Hviid, C. A. and S. Svendsen. 2013. “Experimental Study of Perforated Suspended Ceilings as Diffuse Ventilation Air Inlets.” *Energy and Buildings* 56:160–68.

ISO-EN 7730:2005 *Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*.

Jacobs, P., E. van Oeffelen, and B. Knoll. 2008. “Diffuse Ceiling Ventilation, a New Concept for Healthy and Productive Classrooms.” in *Proceedings of Indoor Air, paperID*, vol. 3.

Mikeska, T. and J. Fan. 2015. “Full Scale Measurements and CFD Simulations of Diffuse Ceiling Inlet for Ventilation and Cooling of Densely Occupied Rooms.” *Energy and Buildings* 107:59–67.

Nocente, A., S. Grynning, H. M. Mathisen, and F. Goia. 2018. “Computational Fluid Dynamics Study of a Diffuse Ceiling Ventilation System through Perforated Sound Absorbing Ceiling Panels.” in *Roomvent&Ventilation 2018: Excellent Indoor Climate and High Performing Ventilation, p: 899-904*.

Petersen, S., N. Christensen, C. Heinsen, and A. Hansen. 2014. “Investigation of the Displacement Effect of a Diffuse Ceiling Ventilation System.” *Energy and Buildings* 85:265–74.

Van Wagenberg, A. V. and M. Smolders. 2002. “Contaminant and Heat Removal Effectiveness of Three Ventilation Systems in Nursery Rooms for Pigs.” *Transactions of the ASAE* 45(6):1985.

Zhang, C., P. K. Heiselberg, Q. Chen, and M. Pomianowski. 2017. “Numerical Analysis of Diffuse Ceiling Ventilation and Its Integration with a Radiant Ceiling System.” *Building Simulation* 10(2):203–18

Zhang, C., P. K. Heiselberg, M. Pomianowski, T. Yu, and R. L. Jensen. 2015. “Experimental Study of Diffuse Ceiling Ventilation Coupled with a Thermally Activated Building Construction in an Office Room.” *Energy and Buildings* 105:60–70.

Zhang, C., T. Yu, P. K. Heiselberg, M. Z. Pomianowski, and P. V. Nielsen. 2016. “Diffuse Ceiling Ventilation-Design Guide.”