EFEKTI KONFIGURACIJE PODNIH DIFUZORA U RAZVOJNOJ FAZI

THE EFFECTS OF FLOOR DIFFUSERS CONFIGURATION IN UNDER FLOOR AIR DISTRIBUTION SYSTEM ON THERMAL COMFORT IN AN EDUCATIONAL SPACE

Mohammad Reza Ganjali BONJAR[*1,2], Hamed MOSLEHI[3], Sevil BERENJI[4], Javad Ganjali BONJAR[5], Norbert HARMATHY[2]

[1] Energia Design Building Technology Research Group, Szentágothai Research Centre, Pécs, Hungary

[2] Budapest University of Technology and Economics, Faculty of Architecture, Department of Building Energetics and Building Service Engineering, Budapest, Hungary

[3] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Khorasan Razavi, Iran

[4] Middle East Technical University, Üniversiteler Mahallesi, Çankaya, Ankara, Turkey

[5] Shiraz Technical University

Sistem za podnu distribuciju vazduha (UFAD) je strategija mehaničke ventilacije koja je bila tema nedavnih studija zbog nekoliko potencijalnih prednosti, kao što je poboljšana toplotna udobnost u zatvorenom prostoru. U sistemu UFAD, zauzeta zona se direktno napaja klimatizovanim hladnim vazduhom, formirajući termičku slojevitost od donje zone prostora do njegove gornje zone. Ova studija predlaže da se obezbede efekti termičke stratifikacije i distribucije brzine vazduha na toplotni komfor u zatvorenom prostoru. S tim u vezi, u obrazovnom prostoru sa 30 osoba, izvedene su četiri različite konfiguracije dovodnih difuzora uključujući tri UFAD sistema i jedan sistem distribucije vazduha za ventilaciju (DVAD). Štaviše, detaljnije se istražuje mogućnost lokalne toplotne nelagodnosti i promaje, koja nastaje usled poremećaja protoka vazduha u UFAD sistemima. Inicijalno generisanje mreže je sprovedeno korišćenjem GAMBIT softvera, a softver OpenFOAM je korišćen za simulaciju UFAD i DVAD sistema protoka vazduha sa različitim konfiguracijama difuzora. Rezultati su pokazali da je detaljno razumevanje vazdušnog transporta i njegovih posledica na toplotni komfor u četiri različita slučaja i pokazali da konfiguracija difuzora ima značajnu ulogu na toplotni komfor u zatvorenom prostoru.

Ključne reči*: podna distribucija vazduha; unutrašnja termalna ugodnost; konfiguracija difuzora; termalna stratifikacija; raspodela brzina vazduha;obrazovni prostor*

Underfloor air distribution (UFAD) system is a mechanical ventilation strategy that has been a topic of recent studies for its several potential benefits, such as improved indoor thermal comfort. In UFAD system, the occupied zone is supplied directly by conditioned cool air, forming thermal stratification from the lower zone of the space to its upper zone. This study proposes to provide the effects of the thermal stratification and air velocity distribution on the indoor thermal comfort. In this regard, in an educational space with 30 occupants, four different configurations of supply diffusers including three UFAD systems and one displacement ventilation air distribution (DVAD) system have been carried out. Moreover, the possibility of having local thermal discomfort and draught, which occurs due to the airflow disturbances in UFAD systems is investigated in more details. Initial mesh generation is conducted using GAMBIT software, and the OpenFOAM software was employed to simulate the UFAD and DVAD airflow systems with different configurations of diffusers. The results showed that the detailed understanding of air transport and its consequence on thermal comfort in four different cases and have shown that the configuration of diffusers has a significant role on indoor thermal comfort of the occupants.

Key words: *Underfloor air distribution; Indoor thermal comfort; Diffuser's configuration; Thermal stratification; Air velocity distribution; Predicted mean vote; Educational space;*

[*] Corresponding author's e-mail: ganjali.mohammadreza@edu.bme.hu

Nomenclatures

F_{cl}	Ratio of fully clothed body surface area to unclothed body surface area
h_c	Convection heat transfer coefficient (W/m^2.K)
P_v	Partial water vapor pressure (Pa)
$T_{0.1}$	Air temperatures at ankle level (°C)
$T_{1.2}$	Air temperatures at seating head level (°C)
$T_{1.8}$	Air temperatures at standing head level (°C)
$t_{a,1}$	Local air temperature (°C)
T_a	Air temperature (˚C)
T_{cl}	Clothing temperature (˚C)
$T_{oz,avg}$	Average temperature at occupied zone (°C)
T_r	Mean radiant temperature (˚C)
$v_{a,1}$	Local mean air velocity (m/s)
C	Centigrade
DR	Draught rate (%)
DVAD	Displacement ventilation air distribution
HVAC	*Heating, ventilation, and air conditioning*
IAQ	*Indoor air quality*
ITC	*Indoor thermal comfort*
M	Metabolism (W/m^2)
m/s	Meter per Second
m^2	Meter Square
OHAD	Overhead air distribution
Pa	Pascal
Tu	Local turbulence intensity (%)
UFAD	Underfloor air distribution
W	External work (W/m^2)
m	Meter

1 Introduction

Due to the rapid growth in human society, economic and human need for social spaces, selecting an appropriate ventilation system to enhance the efficiency of air conditioning systems in addition to meeting the individual thermal needs and preferences of the occupants in different spaces has achieved considerable attention over the last decades (1) The Under Floor Air Distribution (UFAD) system as part of the design of *Heating, Ventilation, and Air Conditioning* (HVAC) system has become an appropriate alternative to conventional Overhead Air Distribution (OHAD) system and has been widely used in new buildings due to many advantages over OHAD systems (2). The only difference between the UFAD and OHAD is in the air supply plenum configuration. While OHAD system typically uses ducts for distributing the conditioned air for its ventilation, UFAD system uses the underfloor plenum which is formed by installation of a raised floor and substantially sits above the structural concrete slab. Also, in cooling mode, due to the closer position of the supply air to the occupants in UFAD systems the supply air temperature is higher (about 3-4 °C) in comparison with traditional OHAD systems (2,3).The air velocity of the supply air in UFAD system is higher than that of the similar systems such as DVAD systems, but this velocity is very low compared to the traditional OHAD systems with the aim of layering the internal air according to relative density for thermal stratification by capitalizing thermal buoyancy to layer high quality supply air at the occupied zone and leave unoccupied zone with unconditioned air (4,5).

In order to emphasize the benefits of UFAD system, knowledge of the features of the system is necessary to help building designers and owners in achieving an optimized energy efficient cooling system with high thermal comfort for occupants (3,6). In UFAD systems as the conditioned air moves upward through the space, it gains heat from existing heat sources such as occupants and lighting, therefore it supports a general floor-to-ceiling air flow pattern which takes benefit of the natural buoyancy introduced by existing heat sources and takes away heat loads and contaminants from the room more efficiently. Webster et al. (7) investigated the effect of supply air temperature and air flow rate on thermal stratification in UFAD systems. They showed that as the air flow rate increases, air stratification in a room decreases. Lin et al. (8) examined the influence of supply air flow rate, its corresponding momentum and buoyancy fluxes on the vertical temperature profile in an indoor environment. Heidarinejad et al. (9) investigated the impacts of return air vent height on thermal comfort conditions, energy consumption, and IAQ in UFAD systems. Choi and Yeom (10) explored the relationship of thermal sensations of local body segments and the whole body for a better understanding of the overall thermal perception.

In this regard, Thermal stratification in UFAD system is defined by the stratification level which divides the space into two zones, upper zone and lower zone. Due to the turbulence created by high velocity jets of the floor supply air diffusers at lower zone of a space, it has a moderately well mixed air, while upper zone has a relatively low average air velocity with warm and contaminated air rising by the thermal plume (11,12). Moreover, UFAD system is one of the best systems in heating mode by considering individual thermal profiles, the heating of the space starts from the lower part of the body toward the upper part. But in cooling mode, temperature, supply air velocity, and the configuration of diffusers should be evaluated carefully to have the best condition for ITC of residents and IAQ in that space. In this regard, one of the most crucial factors that affects the indoor thermal comfort and ventilation effectiveness is the location of UFAD diffusers and comparing the UFAD cases with a similar case in DVAD system will bring a great value to the current study. Kuo and Chung (13) explored the impacts of inlet diffusers and outlet vents placement in UFAD systems on thermal comfort of occupants in the occupied zone. Awad et al. (8) conducted an experimental study and concluded that the location of exhaust vent affects the interface level of the stratified layers. Fathollahzadeh et al. (9) studied ITC, IAQ, and energy consumption of an UFAD system in a dense occupancy space with direct and swirl inlet diffusers. Although there have been various UFAD supply diffusers available in the market since the emerging of UFAD technology in 1990s, literature review reveals that there are a limited number of research works carried out in terms of the airflow pattern in different configurations of UFAD diffusers in various spaces.

The thermal stratification of UFAD system is generally lower compared to the DVAD system. Thus, the ventilation performance of UFAD system could be compared with the DVAD system. Raftery et al. (14) conducted a study on the stratification performance of a floor DVAD diffuser, which delivers air with mostly horizontal air momentum into the space. Lin et al. (15) conducted a study by using a numerical simulation on a typical Hong Kong office and investigated the effect of the location of air supply on the design and performance of the DVAD system under local thermal and boundary conditions.

The main objective of the present study is to examine the occupants' thermal comfort in an educational space supplied by the UFAD system by simulating and investigating thermal stratification and air velocity distribution. Thermal comfort conditions of 30 occupants of the space are evaluated based on the thermal comfort index (PMV and PPD) and local thermal discomfort (temperature difference in the vertical direction) in four different configurations of direct inlet diffusers. Three cases of diffusers configuration in the space supplied by UFAD system and one case supplied by DVAD system were simulated by using finite volume method. Such a study would provide designers and engineers with suitable guidelines for appropriate operation of UFAD systems with respect to the location of supply diffusers and occupants' thermal comfort in a dense occupancy space.

2 Material and Methods

A suitable computational hexahedral mesh is generated using GAMBIT software, while OpenFOAM Ver. 2.2 with *buoyant Boussinesq SimpleFoam* solver is employed for the numerical modeling of the governing equations based on a finite volume technique. We need to mention the governing equations an indoor room in a school surrounded by other rooms with 8 m length, 5.6 m width, and 3.5 m height, which is equipped by an UFAD system has been considered for this study, as illustrated in Figure 1. The existing equipment are thirty diffusers, six supply outlets, eight lights, and thirty occupants. In the simulation of the space, the boundary condition considered for the walls, ceiling and floor are adiabatic to the under-investigated room environment, which means any effects of heat conduction and radiation were ignored. Intake air flow rate for all the simulations is equal to 0.218

m^2/s for the whole space (ACH=5) (ASHRAE Standard 62, 2001) and the intake air temperature from all the diffusers is 18 °C (the increasing of the air temperature between the diffusers is neglected) (16) The clothing coverage ratio, the heat flux of occupants, and the heat flux of lights are assumed to be 0.8, 104.68 W, and 60 W, respectively.

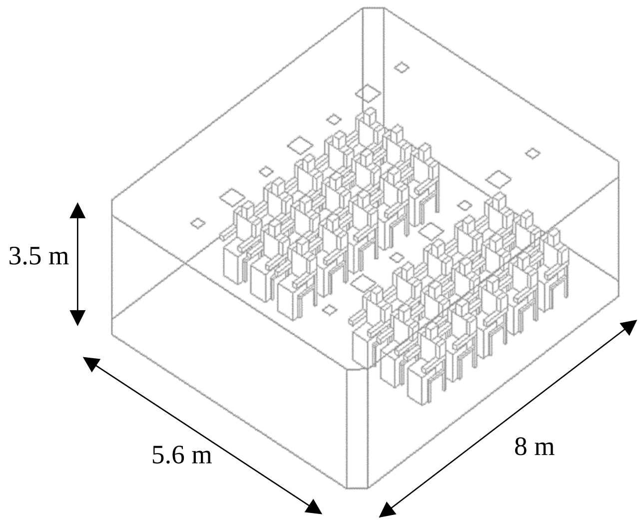

Fig. 1. Schematic representation of the educational space

Due to the geometrical symmetry of the considered space, only half of the space in the width direction is simulated as shown in Figure 2. Therefore, the eastern wall has symmetry boundary condition, while the northern, southern, and western walls have adiabatic boundary conditions. For presenting the cross-sectional velocity and temperature distributions, a plane in the middle section of the simulation domain as shown in Figure 2 is considered. Therefore, all the results will be examined and presented along this mid-plane.

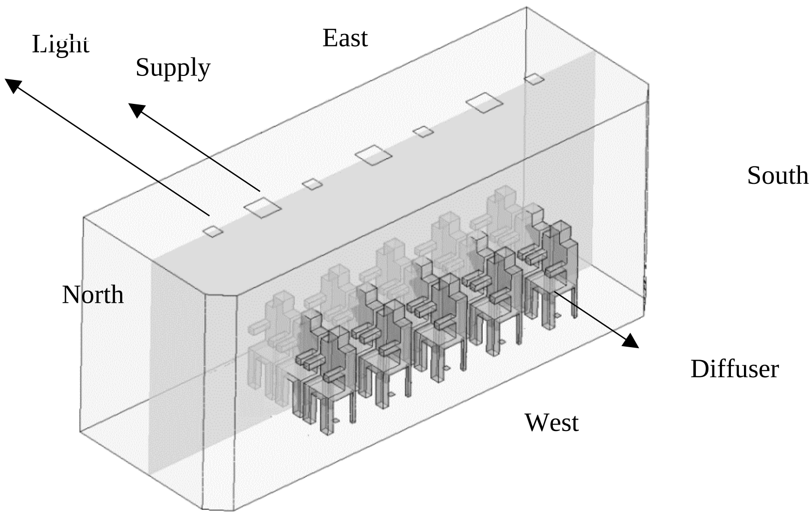

Fig. 2. The view of the mid-plane in the simulation domain

2.1 Study areas

In order to examine the effects of diffusers configuration on the control parameters in UFAD system, four different cases are considered. In all four cases, the number, dimension, and intake air velocity of diffusers were defined by considering the permissible cubic feet per minute (CFM) of the supply air *entering* the *room*. The velocity and temperature of the *air* are calculated in accordance with the standard of ASHRAE Standard 62 for an educational space supplied by UFAD system for the first three cases, and with the guidelines of the usage of displacement ventilation (DVAD) system for the fourth case (17) In the investigated cases, as shown in Table 1, the placements of diffusers are considered to be under the seats, in front of the seats, in the corridors, and on the lower part of the walls.

According to the ASHRAE Standard 62, in order to use the UFAD system for cooling, the speed and air temperature of the supplied *air volume entering* the *room from the diffusers* are considered to be in the range of 0.52- 1. 27 m/s and 16-18°C, respectively, while for DVAD system they are respectively chosen as 0.5 m/s and 17.7-20°C. Note that for the fourth case the diffusers are located on the lower part of the walls in accordance with the specifications of the DVAD ventilation system.

Table 1. The investigated cases

Case No.	Number of diffusers	Dimension of diffuser	Diffuser's locations	Intake air velocity (m/s)	Intake air temperature (°C)
1	30	8.5×8.5	under the seats	1	18
2	30	8.5 × 8.5	in front of the seats	1	18
3	10	5 × 46.6	in the corridors	0.93	18
4	4	50 × 26.1	on lower part of the walls	0.42	18

In the first case, the diffusers are square and placed exactly under the seats as illustrated in Figure 3 (a). In the second case, as shown in Figure 3 (b), the diffusers are square and placed exactly in front of the seats and feet of the occupants. In the third case, the diffusers are rectangle and are located in the corridors of the two sides and hallway in the middle of the class as illustrated in Figure 3 (c). In the fourth case, as shown in Figure 3 (d), four rectangular diffusers are placed on the lower part of the walls as DVAD system to be compared with other diffusers configuration of UFAD system.

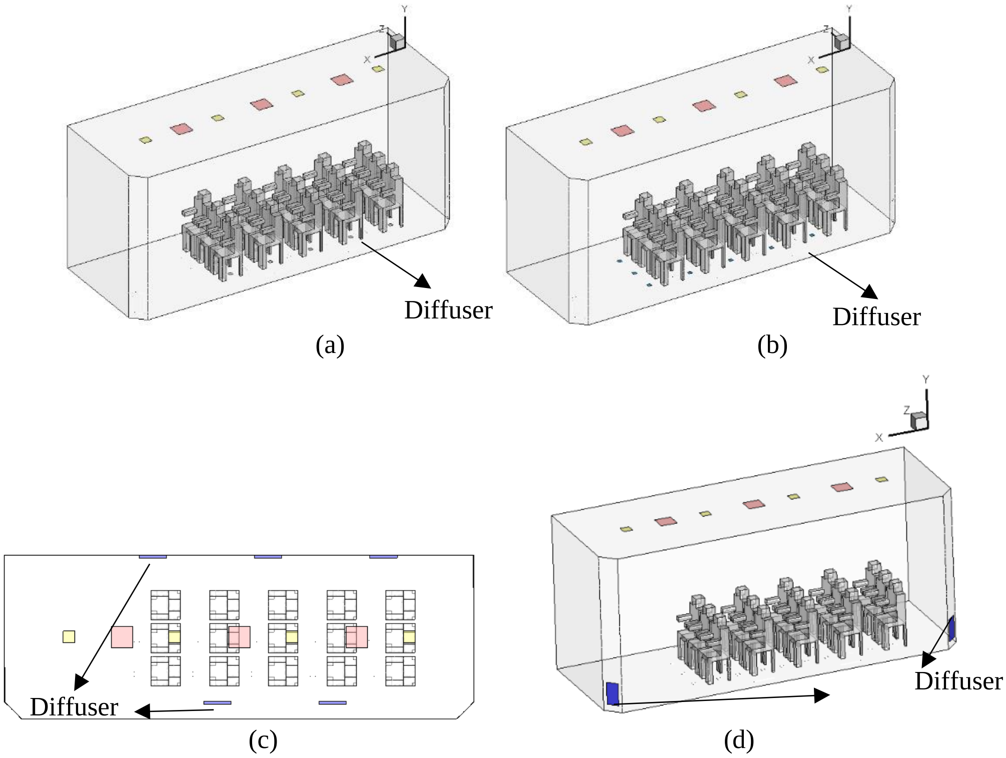

Fig. 3. UFAD system with diffusers: (a) under the seats, (b) in front of the seats, (c) in the corridors (plan view), and DVAD system with diffusers: (d) on lower part of the walls

2.2 Thermal comfort indices (PMV and PPD Scales)

ASHRAE Standadrd 55 (2014) defined thermal comfort as a subjective term and the state of mind, which a body shows satisfaction with its thermal environment. However, there are a number of thermal comforts measuring parameters that could be taken into consideration in order to achieve the minimum requirement of thermal comfort in a space. The most frequently used and probably best-understood parameters are predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). In 1970, Fanger proposed the first and most established method for predicting occupants' thermal comfort conditions. In this model, Fanger combines four physical factors, which are indoor air temperature, air velocity, mean radiant temperature, and the relative humidity with two personal factors which are activity level and clothing insulation to form PMV index as its result.

Predicted mean vote (PMV) is an index developed for quantifying thermal sensation of people. It is a seven-point thermal-sensation scale in which ASHRAE Standard 62 defined each of them with one integer starts from +3 as hot to -3 as cold thermal sensation. ISO7730 standard (1994) defined the proper value of PMV index to be between -0.5 to +0.5. It presented the formulae for calculating PMV which was developed by Fanger (1970) that could be found in Eq. (1), where M is the metabolism (W/m2), W is the external work which is equal to zero for most activity (W/m2), F_{cl} is the ratio of fully clothed body surface area to unclothed body surface area, P_v is the partial water vapor pressure (Pa), T_{cl} is the clothing temperature (˚C), T_r is the mean radiant temperature (˚C), T_a is the air temperature (˚C), and h_c is the convection heat transfer coefficient (W/m^2.K).

$$\begin{aligned} \mathrm{PMV} = {} & (0.028 + 0.3033\exp(-0.036\mathrm{M})) \\ & \times \{(\mathrm{M}-\mathrm{W}) - 0.42\{(\mathrm{M}-\mathrm{W}) - 58.15\} \\ & - 3.05\,\{5.733 - 0.000699(\mathrm{M}-\mathrm{W}) - \mathrm{P_v}\} - 0.0173 \times \mathrm{M}(5.867 - \mathrm{P_v}) \\ & - 0.0014 \times \mathrm{M}(34 - \mathrm{T_a}) - 3.96 \times 10^{8} \times \mathrm{F_{cl}}\{(\mathrm{T_{cl}} + 273)^4 - (\mathrm{T_r} + 273)^4\} \\ & - \mathrm{F_{cl}} \times \mathrm{h_c} \times (\mathrm{T_{cl}} - \mathrm{T_a})\} \end{aligned} \tag{1}$$

Due to Fanger (1972) developed a related index, called predicted percentage dissatisfied (PPD) that is directly determined from PMV in a way that occupants who vote -3, -2, +2, +3 on the PMV scale are considered to be thermally dissatisfied. It is an index used for expressing the thermal comfort level of people as a percentage of them who are prone to be dissatisfied with a certain condition of thermal environment. ISO7730 standard (1994) defined the proper value of PPD index to be 0-10% corresponding to $-0.5 \leq \mathrm{PMV} \leq +0.5$ and presented a formula for calculating it which could be found in Eq. (2).

$$\mathrm{PPD} = 100 \times 95 \times \exp(-0.03353 \times \mathrm{PMV}^4 - 0.2179 \times \mathrm{PMV}^2) \tag{2}$$

2.3 Local thermal discomfort

In UFAD system, the interior space of the building is divided into two parts, occupied zone, which is considered to be from floor up to the height of 1.7 m and unoccupied zone, which is over the 1.7 m height. UFAD system only provides comfort for the occupied zone. Therefore, due to the relatively lower rate of air flow entering to the space, thermal stratification is formed and changes the heat transfer mechanism (17). In UFAD system, unlike the conventional ventilation systems, where the total temperature is roughly uniform, the temperature of the ceiling is higher than the temperature of the floor. As the air is exhausted out of the room through the exhaust air plenum located in the ceiling, it takes away heat loads and contaminants from the room more efficiently (18) The temperature of the air passes through the occupants at the height between 0.2 - 1.7 m is subjected to the temperature variations, although this change in temperature should not exceed the ASHARE (2009) proposed maximum change in the temperature. The average temperature in the occupied zone is calculated by Eq. (3) produced by Schiavon et al. (19) using three benchmark points, where $T_{0.1}$, $T_{1.2}$ and $T_{1.8}$ are the air temperatures at ankle level, seating head level, and standing head level, respectively.

$$\mathrm{T_{oz,avg}} = \left(\frac{1}{71-4}\right)\left[\left(\frac{71-48}{2}\right)(\mathrm{T_{1.8}} + \mathrm{T_{1.2}}) + \left(\frac{48-4}{2}\right)(\mathrm{T_{0.1}} + \mathrm{T_{1.2}})\right] \tag{3}$$

Choi and Yeom's study (10) revealed that there are significant correlations between the local body sensations and the thermal sensation of the whole body. Although occupants could feel thermally neutral in general, one or more parts of their body could be too cold or too warm to cause the localized hot/cold feeling which is called local thermal discomfort (20). Vertical air temperature difference and draught are the most important causes of this phenomenon. In the present study, the air temperature and the amount of entering air flow rate are adjusted according to the standard of ASHRAE Standard 62 so that it can create appropriate thermal comfort conditions in the occupied zone and stay in the average *thermal sensation index* of the occupants in the recommended range. Also, in order to make the percentage of occupants' dissatisfaction remain within the *permissible* range of vertical air temperature difference, ASHRAE (2009) recommends a maximum vertical air temperature difference of 3°C between the height of head (1.1 m at sitting and 1.7 m at stand conditions above the floor) and height of ankles (0.1 m above the floor). It should not be overlooked that there is a high risk of having air draught in UFAD systems, so ASHRAE (2009) advocates the maximum inlet air velocity of 0.8 m/s. The draught rate is calculated by using Eq. (4) where $t_{a,1}$ is the local air temperature (°C), $v_{a,1}$ is the local mean air velocity (m/s), and Tu is the local turbulence intensity (%).

$$\mathbf{DR} = \left(\mathbf{34} - \mathbf{t_{a,1}}\right).\left(\overline{\mathbf{v_{a,1}}} - \mathbf{0.05}\right)^{\mathbf{0.62}}.\left(\mathbf{0.37}.\overline{\mathbf{v_{a,1}}}.\mathbf{Tu} - \mathbf{3.14}\right) \quad (4)$$

Air temperature difference in the vertical direction is considered to be one of the most important factors in thermal comfort conditions of the occupants, and UFAD systems are highly prone to cause an unacceptable value of temperature difference in vertical direction causing local thermal discomfort. Lin et al. (15) and Fanger et al. (21) declared that well designed UFAD systems can supply a good thermal environment for the occupants. The distribution of air temperature inside the room is usually not homogeneous and increases vertically from the floor to the ceiling. This heterogeneous temperature distribution is usually the most important factor for the localized thermal dissatisfaction of the occupants. By increasing the air temperature difference in the vertical direction between the head and ankle ($\Delta t_{a,v}$), the percentage of occupants' predicted percentage of dissatisfied (PPD) increases according to Figure 4. In addition, due to the cooling and overheating of the floor, PPD increases. The relation between the occupants' predicted percentage of dissatisfied (PPD) and the temperature of the floor (t_f) is shown in Figure 5, in which the lowest thermal dissatisfaction of the occupants happens at 24 °C for the floor.

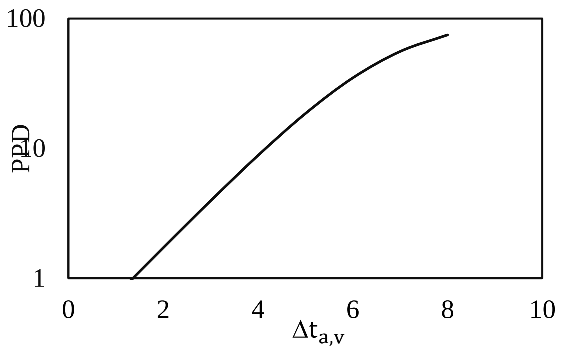

Fig. 4. Predicted Percentage of Dissatisfied (PPD) versus the vertical air temperature difference ($\Delta t_{a,V}$) *(14384 Standard, 2011)*

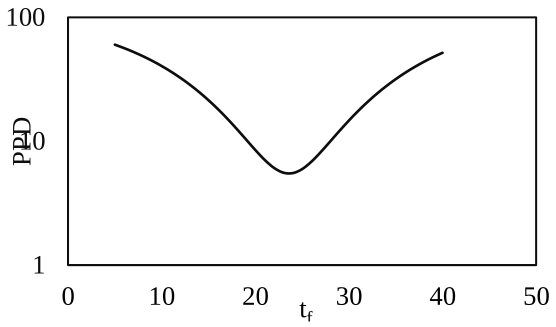

Fig. 5. Predicted Percentage of Dissatisfied (PPD) versus the floor temperature (t_f) (14384 Standard, 2011)

3 Results and discussion

3.1 Mesh independence study

Opting a proper mesh for having the numerical study of the educational room and ensuring the mesh independency of solution is an important step in the simulations. To achieve this, three different mesh systems with increasing number of cells as 475,249, 2,418,307, and 1,145,991 have been examined to obtain mesh independent solutions for the temperature and velocity distribution along some defined lines. The temperatures distribution inside the room were obtained along line 1 (at x=0.7 m and y=1.4 m), line 2 (at x=3.5 m and y=1.4 m), and line 3 (x=6 m and y=1.4 m) and velocity distribution along line 3 (x=6 m and y=1.4 m) for three different cell numbers and presented in Figure 6 (a), (b), (c), and (d), respectively.

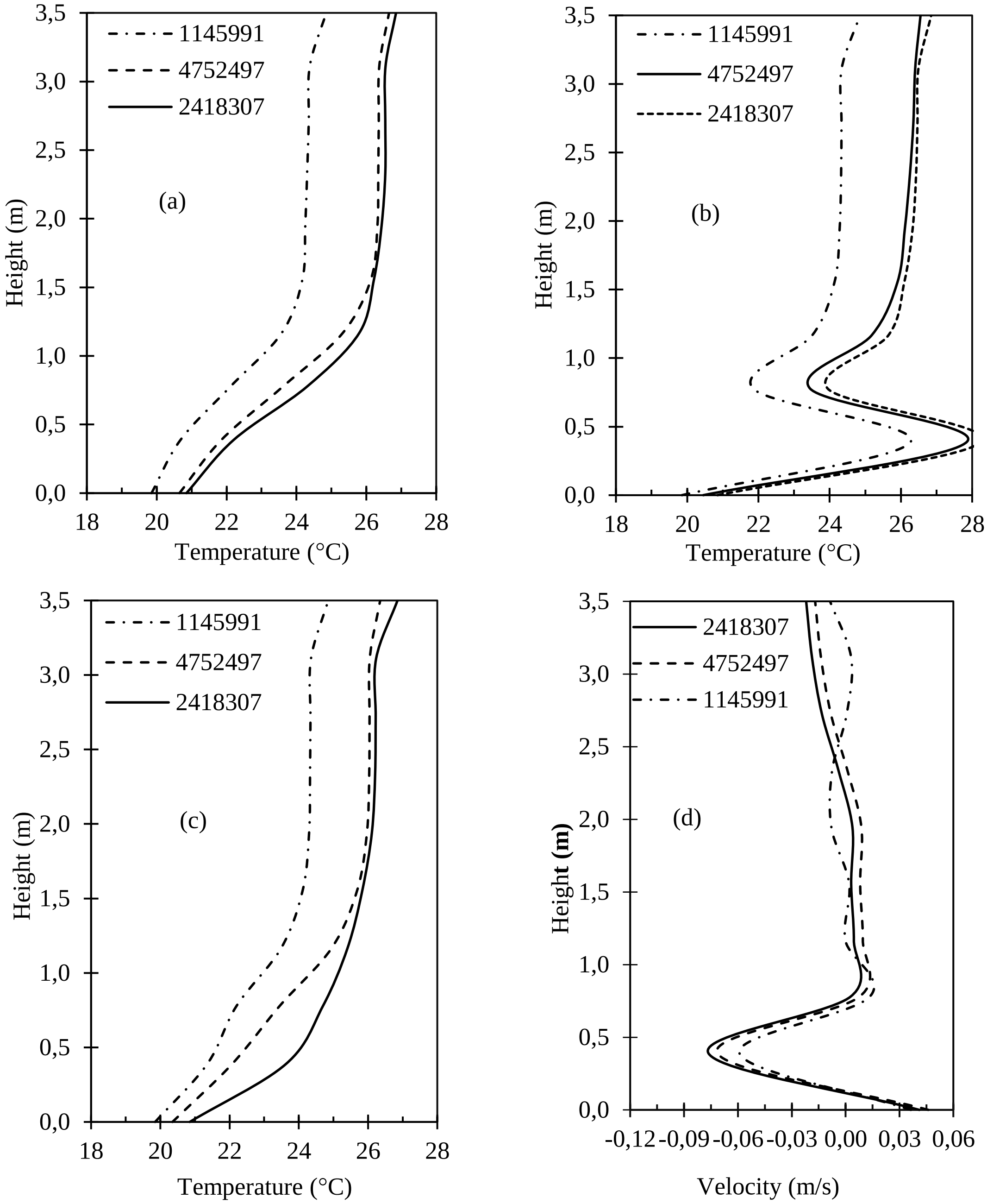

Fig. 6. The mesh independency study for: (a) temperature along: x=0.7 and y=1.4; (b) temperature along: x=3.5 and y=1.4, (c) temperature along: x=6 and y=1.4; (d) velocity along: x=6 and y=1.4

The result has not changed much as the number of cells changed from 2,418,307 to 4,752,497. Therefore, a mesh network with 2,418,307 cells was adopted to carry out the present study as the most appropriate choice for simulations. This network is an irregular network and mesh elements are finer in regions of high load objects like diffusers and supply outlets, walls, inhalation area, and heat sources. This helps capturing of thermal boundary layer in those areas more accurately (16). Mesh network of the space as shown in Figure 7 has been developed for each of considered cases.

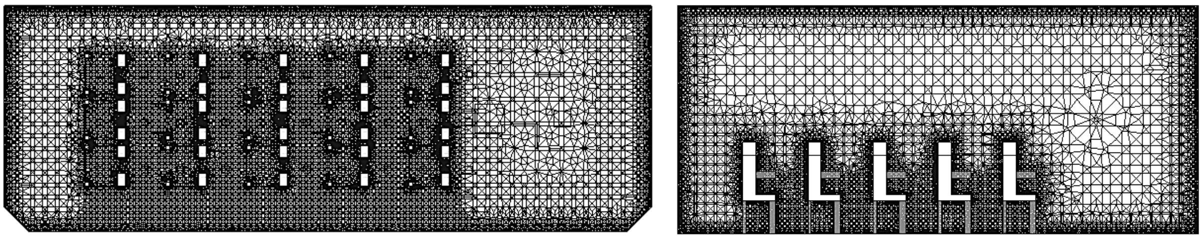
(a) (b)

Fig. 7. Mesh network of the room: (a) plan view; (b) side view

3.2 Thermal comfort evaluation

PMV-PPD indices are used to evaluate the occupants' thermal comfort conditions for each case. These indices were calculated in the occupied zone, which is defined up to the height of 1.7 m from the floor. PMV represents the averaged thermal sensation response of a large number of subjects. In accordance with the thermal sensation scale proposed by the ISO 7730 standard (1994), the PMV should range between -0.5 and +0.5. According to Figure 8, the PMV in the occupied zone is in the range of 0 to -0.5 in all of the cases by considering the fact that case 4 is more suitable for the comfort of people in hot seasons.

As shown in Figure 8 (a) and (b), due to the entrance of the air from the diffusers, which are in front of the occupants' seats and the lack of uniform distribution of air throughout the class, PMV of the occupied zone is higher than the first case. By placing the diffusers on the lower part of the walls in case 4 as shown in Figure 8 (d), PMV of the unoccupied zone has increased strongly. The PMV and PPD results for each of the cases are presented in Table 2. It is concluded that the most dissatisfaction in the occupied zone belongs to the case 4, and the least dissatisfaction belongs to the case 2.

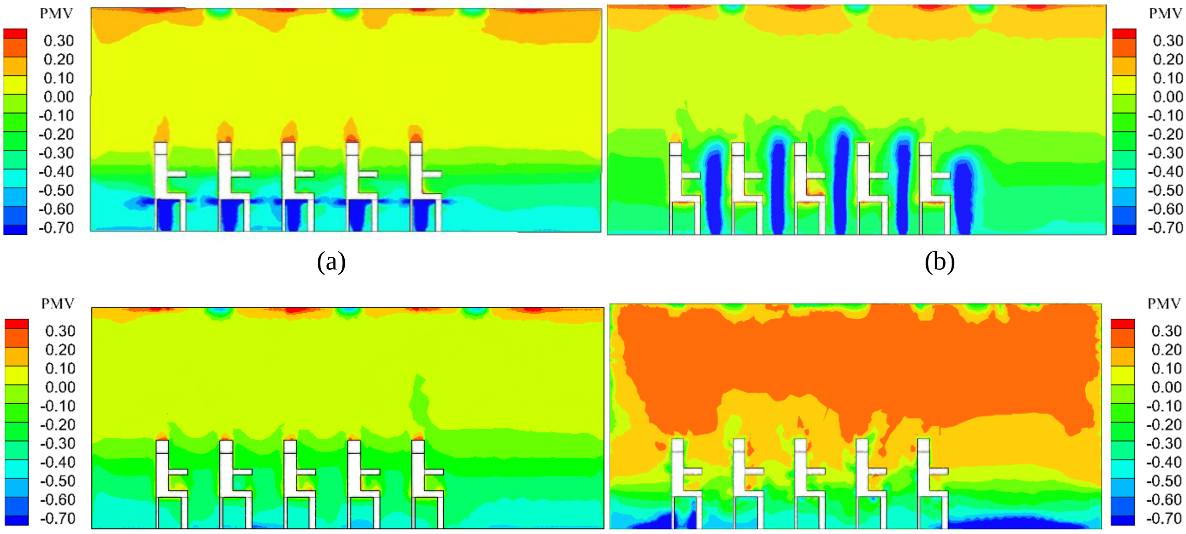

Fig. 8. Distribution of Predicted Mean Vote (PMV) in: (a) case 1, (b) case 2, (c) case 3, (d) case 4

3.3 Local thermal discomfort and stratification evaluation

To determine the distribution of temperature along the room height, simulation results for cases 1 to 4 are examined along the mid-plane. The temperature distribution in the case 1 is illustrated in Figure 9 (a) in which due to the placement of the diffusers under the seats, first the entered supply air hits the seats and causes the air temperature at lower elevations to drop down and to form a thermal stratification. The average temperature difference along the vertical direction, from the floor to the occupants' head is about 2.9 °C, which lies within the permissible range of ISO 7730 standard (temperature difference < 3 °C) (ASHRAE, 2009). In the case 2, as shown in Figure 9 (b), by placing the diffusers in front of the occupants' seats, the supply air could enter the space easily, and therefore the temperature of the occupied zone is lower than that of the first case. Also, the difference in temperature from the floor to head is about 2 °C, which is within the allowable range.

In the case 3, by locating the diffusers in the corridors of two sides and hallway in the middle of the class, a distribution of temperature along the height of the room is illustrated in Figure 9 (c) in which its thermal stratification is similar to the first case. Also, the temperature difference along the height from the floor to the head is about 2.5 °C, which is within the permissible range. In the case 4, as shown in Figure 9 (d), the room temperature is higher due to the diffuser's placement on the lower part of the walls and the number of diffusers is less than the other cases, and the temperature difference between floor and the head is about 4.5 °C and has exceeded the standard ISO 7730. In this case, by spreading cold air over the floor of the room horizontally, the air moves upward along the height of the room as a natural displacement due to warming up by absorbing interior thermal loads.

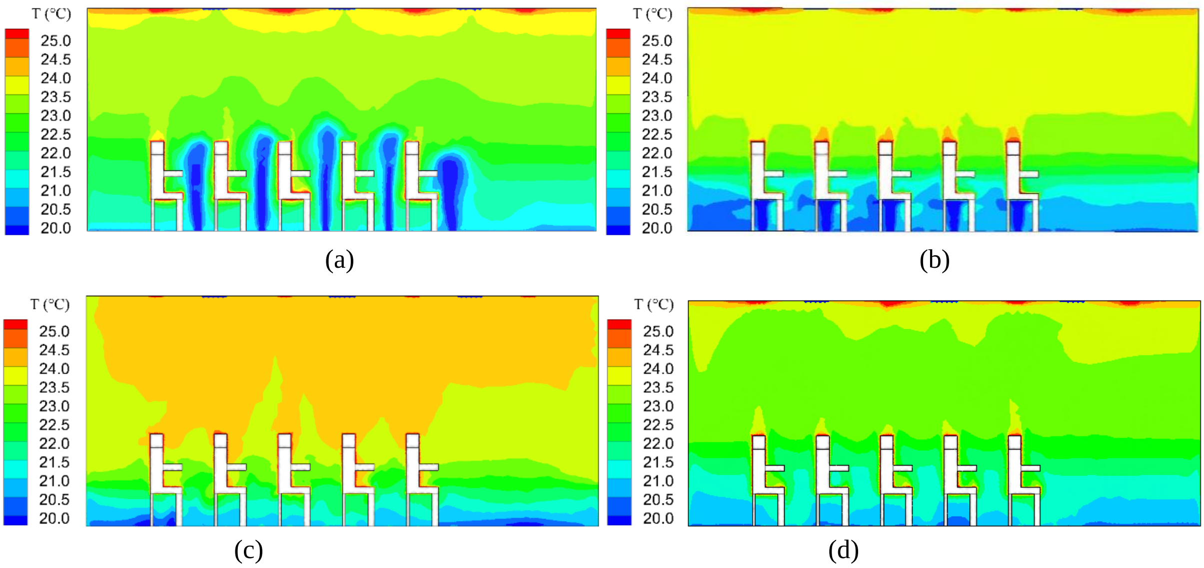

Fig. 9. Distribution of temperature around the occupants in the:
(a) case 1, (b) case 2, (c) case 3, (d) case 4

For clarifying and better comparison of temperature distribution resulting from different configurations of inlet air diffusers, the average temperature along the height of the space is presented in Figure 10. As shown in the figure, the highest temperature variation is for to the case in which the diffusers are on the lower part of the walls and the lowest temperature variation is for the case in which the diffusers are located in the corridors. As mentioned before, ISO 7730 standard is satisfied for the temperature difference between the floor and head in all the cases except for the case 4.

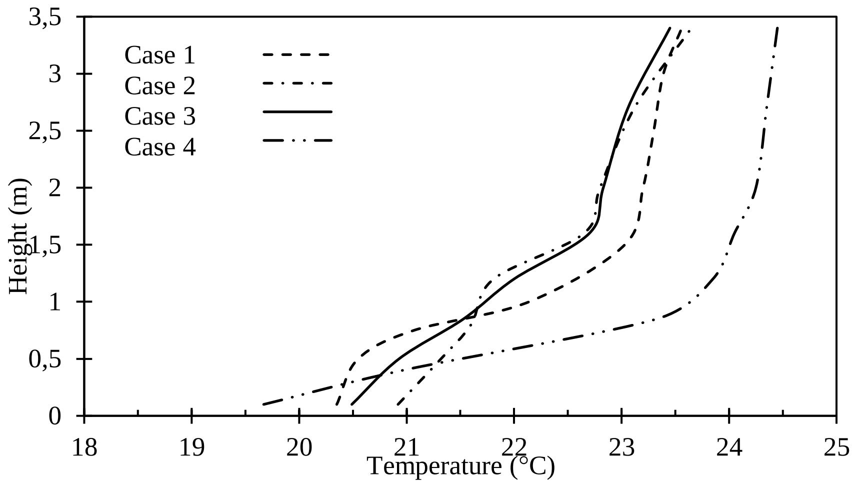

Fig. 10. Average vertical air temperature along the height of the room for each case

The most important advantage of UFAD system, due to placement of the diffusers on the floor, is the maximum use of supply air within the occupied zone. According to the Table 2, the lowest temperature of the occupied zone is related to the case 1 and the highest temperature is related to the case 4. The maximum temperature difference between the occupied zone and unoccupied zone is related to case 1, which indicates the superior energy performance of this case. In the following, the main objective of studying interior air velocity distribution is identifying the possibility of having draught, the local cold sensation that occurs due to disturbances of the airflow which causes thermal dissatisfaction of the occupants. If the draught occurs, one of the ways for reducing its effects is to change the diffusers position. As mentioned earlier, ASHRAE recommends the inlet air velocity of 0.8 m/s as the threshold of local thermal discomfort of occupants.

In order to investigate air circulation patterns and the amount of air velocity around the body, air velocity contours and vector field are presented in Figures 11. In case 1, as shown in Figure 11 (a), the maximum air velocity around the body is 0.25 m/s which is below the maximum permissible velocity (maximum inlet air velocity < 0.8 m/s). In this case, the air hits the seats after passing through the diffusers and then returns downward to form a return flow in the lower part of the room. It is shown in Figure 11 (b) that in case 2, the maximum air velocity near the body is 0.3 m/s which is below the maximum permissible velocity. By placing the diffusers in front of the occupants' seats, the air passes through the diffusers and moves directly to the top, while touching the body. This increases the possibility of having draught.

By examining Figure 11 (c), it is concluded that in case 3, the maximum air velocity near the body is 0.2 m/s, which is below the permissible velocity, and reduces the possibility of having draught. By entering the supply air from the diffusers located in the corridors, the uniform velocity distribution in the occupied zone is formed in this case. According to Figure 11 (d), the maximum air velocity near the body in case 4 is 0.25 m/s. Also, by placing the diffusers in the four corners of the class, the possibility of having draught for the occupants close to the diffusers increases, and consequently because of the low air flow rate, for the occupants who are far from the diffusers, the possibility of having draught decreases.

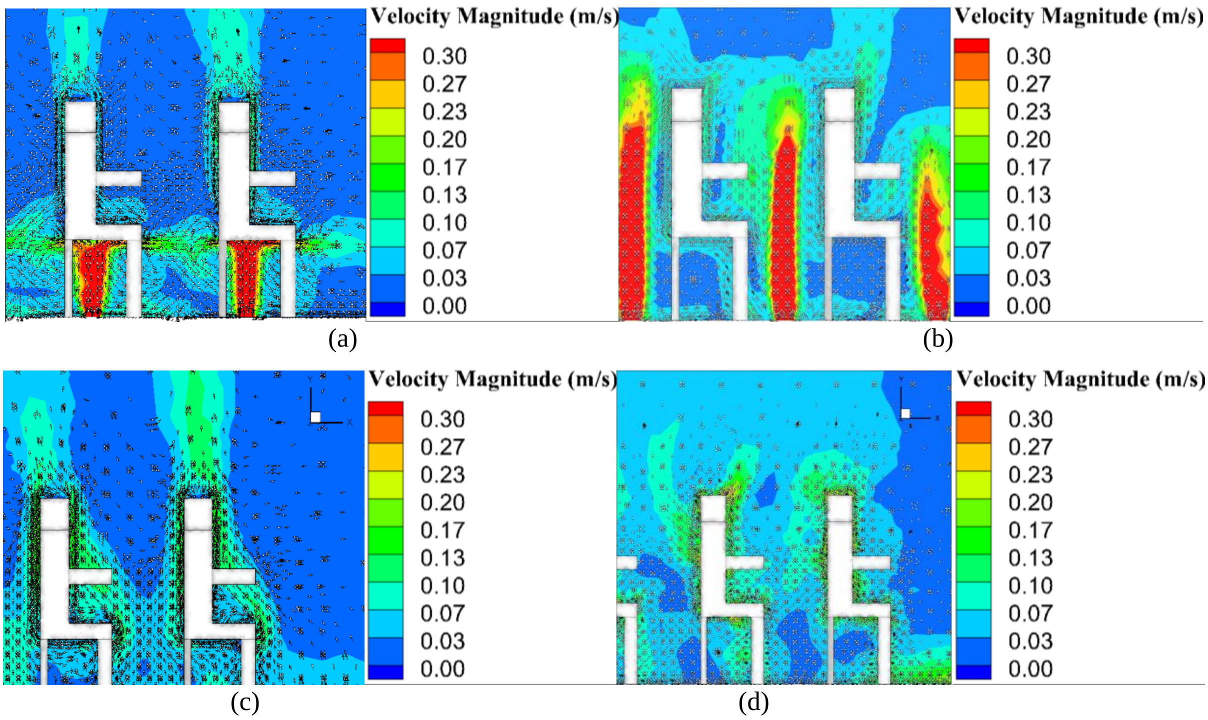

Fig. 11. Distribution of air velocity fields and their magnitude contours (m/s) around seats and occupants in the occupied zone for: (a) case 1, (b) case 2, (c) case 3, (d) case 4

The draught and the fluctuations in the air flow could cause local thermal discomfort for the occupants, therefore by considering the effects of these disturbances, predicted percentage of dissatisfied increases. In other words, occupants tend to increase the air temperature to some extent in order to compensate their chilly feelings (22). According to the results of the study conducted by Fanger et al. (21) the presence of the draught causes the maximum design temperature in the summer conditions to be about 3.2°C higher compared to the Fanger (1972), which would reduce the energy consumption in summers. On the other hand, the results show that the presence of the draught causes the minimum design temperature in the winter conditions to be about 2.5 °C higher than the Fanger (1972), which would increase the energy consumption for heating the space in cold seasons. By reviewing the results and mean values of the draught rate in the occupied zone according to the Table 2, it is obvious that the lowest amount of draught is related to the case 2 and the maximum amount of draught is related to the case 4.

Table 2. Thermal state of the occupants and the room

Case No.	PMV	PPD (%)	DR (%)	Occupied temperature (°C)	Unoccupied temperature (°C)
1	0.30-	9.5	3.5	21.7	23.7
2	.-0.16	6.5	3.3	22.3	23.5
3	-0.21	6.9	3.8	22.2	23.4
4	-0.35	9.7	6.6	22.6	24.4

4 Conclusion

In the present study, the impacts of the placement of floor diffusers in UFAD system in an educational room on the occupants' thermal satisfaction were studied. General thermal comfort indices, thermal stratification, and air velocity distribution in four different cases were investigated to examine the thermal comfort and local thermal discomfort of the occupants. The floor diffusers configurations were considered to be under the seats, in front of the seats, in the corridors, and on the lower part of the walls for the considered cases. The minimum room temperature in the occupied zone were achieved by placing the diffusers under the seats which led to have the most energy efficient ventilation system in terms of providing thermal comfort temperature in the occupied zone. In this case, the temperature difference between the floor and the head is also within the *permissible* range. In the case that the diffusers were located on the lower part of the walls, due to the fact that the middle row occupants of the class are farther away from the diffusers, the most dissatisfaction occurred in this case because of having the highest temperature variation along the height and the unstandardized temperature difference between floor and the head. In this case, the room temperature in both occupied and unoccupied zones were the highest temperature among other cases. The lowest amount of draught rate occurred when diffusers were placed in front of the seats. Placing the diffusers on the bottom part of the walls, doubled the possibility of having draught which would reduce the energy consumption in cold seasons, and increase in hot seasons. All the results of the case in which the diffusers were located in the corridors were within the permissible range. The results of the simulations show that the thermal comfort of the occupants is highly influenced by the diffusers configuration in a space. In conclusion, it was stablished that with a well-designed placement of the ventilation system diffusers, the UFAD system can provide appropriate ventilation within the permissible limits of occupants' thermal comfort and health conditions in crowded places.

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