Evaluation of Using the Ceiling and Wall Spots Ventilation System on Indoor Thermal Environment

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Abstract. The aim of this paper is to enhance the local comfortable zone for the occupants in a small office room. The ceiling spot ventilation (CSV) system and the wall spot ventilation (WSV) system are proposed and investigated numerically to show the influence of these systems on the local thermal comfort and energy demand. Three different amounts of airflow rate are used in this investigation. A CFD model is employed to explain the behavior of indoor airflow and temperature distribution in each case study. The results show that, when using these systems as a main ventilation system will reduce the demand on fresh air and this will reduce the required load on cooling coil and saving more energy. Also, the results revealed that the wall spot ventilation (WSV) was provided a required local indoor thermal environment air for the occupant zone. Therefore, using this system will provide a comfortable local environment and enhance the air velocity distribution as well as saving more energy.

1. Introduction

The increasing of the energy consumption considers a main issue that need to be solved by decreasing the demand on the energy. According to the recent studies, only buildings sector used about 40% from the total amount of the energy consumption [1]. Half of this percent goes to the Heating, Ventilation and Air conditioning system (HVAC) to provide cooling and heating requirements. For this reasons many strategies are used to supply the required indoor environment at low energy consumption. Many techniques are used to provide a suitable indoor thermal environment at low energy consumption. One of these techniques is to use the personalized ventilation (PV) system. In this new ventilation system the fresh treated air is directed towards the occupied area directly without mixing with the other warm and contaminated room air. This will improve the inhaled air and enhance the amount of the energy consumption. This method consider as the efficient strategy to distribute the treated fresh air to the targeted area at low amount of energy. However, this method has many drawbacks such as difficulty of installation, flexibility and risk of draught.

For this reason many studies are performed to improve the efficiency of using the PV system. Yang et al. [2] investigated the effect of using the personalized exhaust (PE) system on the quality of the inhaled air in area around the occupant. They revealed that using PE system will improve the quality of the inhaled air especially when installed in location near the occupant shoulder level. The combination between the displacement ventilation (DV) system and PV system was examined by Kanaan et al. [3]. They performed an experimental study to show the impact of this system, DV-PV, on the quality of the inhaled air in the occupied zone. They found that up to 20% of the improvement was achieved on inhaled air quality when using the combined DV-PV system in room. Another investigation was performed by Halvonova and Melikove [4] to study the impact of using a DV system combined with ductless personalized ventilation (PCV) system on inhaled air quality in
occupied zone. Their finding revealed that using this system will provide a high air quality comparing with a case study that is not used this system. The new concept of PV system that combined between the personalized ventilation system and personalized exhaust system called (PV-PE) was examined at twelve different levels by Jujing et al. [4]. This system was installed on the chair in level near the occupants shoulder. Their results show that using this proposed ventilation system will improve the microenvironment around the occupant.

Ahmed et al. [5-8] studied the effect of using the local exhaust ventilation (LEV) system combined with DV system on the indoor thermal requirements and energy consumption. They found that using this proposed system will decrease the energy consumption on cooling coil by up to 30% and also using this system will provide a healthy and comfortable zone. Experimental and numerical study was presented by Al Assaad et al. [9] to evaluate the performance of the personalized ventilation system (PVS) coupled with a chilled ceiling to provide a suitable thermal conditions and reduce the percentage of indoor pollution. The results found that, using the PVS coupled with a chilled ceiling will enhance the indoor thermal comfort and achieve energy saving up to 7.52 % compared to a steady system. Another investigation was performed by Al Assaad et al. [10] to investigate the influence of personalized ventilation (PV) coupled with the mixing ventilation (MV) on the human thermal comfort for the occupants and indoor air quality (IAQ). In this study the CFD model was employed to simulate and evaluate the air velocity, air temperature and IAQ inside room. The results showed that, the PV system with air flowrate of 7.5 L/s and frequency of 0.86 Hz gave an optimal solution to reduce indoor contamination with high level of thermal comfort.

Kalmar [11] studied a new method to develop the PV system using equipment have ability to change the direction of air flow during operation. This method showed the high efficiency to provide comfortable thermal environment for occupants. Krajičık et al. [12] performed a model to simulate the effectiveness of various ventilation systems, PV, MV and demand control ventilation. Also, they studied the possibility to improve the occupant’s thermal comfort and energy saving in open space. The results showed that when using the PVS, the percentage of saving energy was about 70% compared to MV system. Another study was presented by Alotaibi et al. [13] to investigate the ability of the ceiling personal ventilation assisted by chair fans and desk fans to reduce of percentage of pollution and provide thermal comfort. The results showed that the proposed system will does not only reduce the contamination but also, it contributes to enhanced the IAQ and provide a thermal comfort environment. The thermal environment and IAQ were studied numerically in an office space equipped with DV system and ductless personalized ventilation (DPV) system by Alsaad and Voelker [14]. The indoor conditions were assessed using the ventilation effectiveness index. The results show that an acceptable enhancement of the IAQ and human thermal comfort was achieved when using the proposed system. Chen et al. [15] studied the influences of using the PV system on the energy consumption and thermal comfort indoor. The results found that, some people prefer increase PV flow rates at higher ambient air temperature. Also, the results showed that, better indoor conditions with low energy consumption was achieved when the PV system supply air temperature at 20 °C and the ambient air temperature at 26 OC.

Yang Junjing et al. [16] investigated the performance of using the PVS which installed in front of occupant face. The PVS was developed by coupled it with two local exhaust fixed with a chair near to a head area. The results showed that, the combined PVS and the personalized exhaust system (PES) provide a more proportion of outdoor air to the breathing zone compared to a PVS alone. In the same line, Lipczynska et al. [17] revealed that the PV system with supply temperature of 25 o C coupled with chilled ceiling system give a good improvement in indoor thermal comfort compared with the MV system. Another study was presented by Yang and Sekhar [18] to explain the effect of using the ceiling personal ventilation (CPV) system on indoor thermal environment in an office. The results show that the high the PVS have a good ability to supply fresh air to the inhaled zone. Makhoul et al. [19] proposed a new CPV system coupled with two coaxial PV systems. They found that this system have an ability to provide a fresh air and create a cover around the person such as a canopy to prevent external thermal effects. In the same line, Makhoul et al. [20] proposed the ceiling personalized ventilation (CPVS) system coupled with fan desk to enhance the indoor thermal comfort in an office. The thermal comfort, concentration of particles and energy consumption were studied numerically.
The results show that, the CPVS provide suitable thermal comfort for occupant with, enhanced IAQ and saving more energy.

Most previous studies were investigated the traditional ventilation system such as DV system, MV system and others main ventilation system aid by or coupled with the PV system. Also, in most researchers study the PV system employed as a secondary system. Insufficient studies were employed the PV system as the main ventilation system. Therefore, in this investigation two types of the PV system, the ceiling spot ventilation (CSV) system and wall spot ventilation (WSV) system, were proposed and studied numerically to show the influences of employing these system as a main ventilation system to improving the amount of energy consumption and enhancing the local indoor thermal environment for the occupants.

2. Method

2.1. Problem Description

The impact of using the spot ventilation system or local ventilation system on indoor air distribution and energy demand was numerically studied in a small room. Two types of the spot ventilation system were used in this study; Ceiling Spot Ventilation (CSV) and Wall Spot Ventilation (WSV). For each system, three different amount of the supplied air flow rate were studied. The length, width and high of the investigated room were 2 m, 3 m and 2.7 m respectively. One occupant with 60 W and one computer with 100 W of heat flux were used as a main internal heat sources. All room walls assume to be adiabatic. Table 1 lists the detailed information of the heat source that used in this investigation.

| Internal heat source | Heat flux amount (W) |
|----------------------|---------------------|
| One occupant         | 60                  |
| One Computer         | 100                 |
| Room walls           | 0 (adiabatic; No heat flux) |
| Total                | 160                 |
| Heat density         | 13.4 (W/m²)         |

In the spot ventilation system, the high quality air supplied directly toward the occupied area. This will provide a suitable local thermal environment. In this study, CSV and WSV system were used to create the local area that thermally comfortable. Therefore, the CSV with diameter of 0.3 m was installed in the center of the room ceiling above the occupant. This location was selected to make sure that the proposed CSV system will supplied the fresh air directly to the occupant. The WSV with diameter of 0.3 m system was positioned on the right side wall above the mid line room. This location was used to provide the supplied treated air directly to the occupant zone. The return opening with dimensions of 1 m × 0.15 m was positioned at 1.3 m from the floor on the side wall. This position was recommended by Cheng et al. [21]. The exhaust outlet was installed on the ceiling level. Figure 1 shows the detailed information on the simulated room. The supply temperature was 20°C. In order to find the optimum amount of the supply flow rate, regarding energy saving and thermal comfort, three different amount of the supply flow rate were used for each type, CSV and WSV, in this study. Table 2 presents the three different amounts for each type and the cases study in this investigation.
2.2. Computational model for the investigated room

2.2.1. Indoor air movement modelling

Choosing a suitable turbulence model will highly enhance the accuracy of the simulated results. For the indoor air movement, there are many turbulence models such as standard k-ε model, Realizable k-ε model, Renormalized group RNG k-ε model and others. All these models can predict the temperature distribution and air velocity at different accuracy and stability [22, 23]. Also, the accuracy, stability and simulation time of these models depend on the application that needs to simulate. In order to get accurate results with high simulation stability, a good turbulence model should be chosen carefully. For this reasons, the RNG k-ε turbulence model was selected among many turbulence model to get an accurate results with high simulation stability. Also this model, RNG k-ε, is highly recommended for such case study [24-27]. This turbulence model can be present as follow [28]:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + P_k + \rho \varepsilon \tag{1}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} P_k + C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{2}
\]
where

\[ C_{2\varepsilon} = C_{2\varepsilon} + \left( C_{\mu} \eta^3 (1 - \eta/\eta_o) \right) / 1 + \beta \eta^3 \]

\[ \eta = (S k / \varepsilon) \]

\[ \eta = (S k / \varepsilon) \]

Also, the constant of the selected turbulence model are listed as:

\[ C_{\mu} = 0.0845, \sigma_k = 0.7194, \sigma_\varepsilon = 0.7194, C_{\varepsilon_1} = 1.42, C_{\varepsilon_2} = 1.68, \eta_o = 4.38, \text{ and } \beta = 0.012 \]

ANSYS FLUENT 15.0 was employed as a Computational Fluid Dynamics (CFD) method to solve the equations of the Navier–Stokes. In order to obtain a good quality of the simulation results, a suitable value of the y+ and enhanced wall treatment was employed in this simulation to calculate the flow properties in region near the solid boundary and near the room heat sources such as occupant and computer. As the change of air density indoor, Boussinesq assumption was used to deal with this change of indoor air. For the pressure and velocity coupling, SIMPLE algorithm was selected in this simulation. Also second order upwind of discretization scheme and PRESTO were employed in this investigation. Radiation heat flux which emitted from the internal room heat sources was taken in the account and the discrete ordinates (DO) model [29] was employed in this simulation. Table 3 presents the details information of the turbulence model that used in this investigation.

### Table 3. Details information of the turbulence model.

| Turbulence   | RNG k – \varepsilon model |
|--------------|----------------------------|
| Radiation    | DO radiation model         |
| Numerical schemes | PRESTO, upwind second order and SIMPLE algorithm |
| Exhaust      | Pressure outlet            |
| Return air   | 75.2 L/s                   |
| Supply Temperature | 20 °C                    |

### 3. Validation of the CFD model

#### 3.1. Validation of temperature and velocity distribution

In order to obtain an excellent simulation results, the selected turbulent model should be validated against a trusted experimental results. For this reason, a validation work is highly important for any simulation work. The current study was a previous experimental study to validate the selected turbulent model. A distribution of the air velocity and temperature were experimentally studied by Xu et al. [30]. In this investigation, the personal displacement ventilation was used to examine the characteristic of the indoor airflow and temperature distribution. Figure 2 shows the experimental chamber. The length, width and height of the simulated room were 6.0 m × 3.9 m × 2.35 m respectively. The room heat sources were one occupant with heat flux of 76 W and one computer with heat flux of 40 W. The supply air diffuser was positioned at the ceiling level with dimension of 0.4 × 0.5 of and the exhaust air outlet was positioned at the ceiling level with dimension of 0.34 × 0.15. The supply temperature and the supply flow rate were 19 °C and 43 m³/sec respectively. Two locations, pole 3 and 4, were used to compare the experimental results of the Xu et al. [30] with simulation results of the current study to make sure the prediction ability of the selected model. A very good agreement was found when comparing the previous experimental results with current simulation results (see Figure 3).
Figure 2. Schematic diagram of the room that used in validation, and (b) the location of the poles 3 and 4 [30]

Figure 3. Comparison between the simulated and experimental results at two position; (circle: experimental results; continuous line: simulation results) (a) air velocity distribution and (b) air temperature distribution.

3.2. Mesh design for the simulated room
The prediction results accuracy and the simulation stability are significantly influenced by the designing mesh such as mesh type, size, and mesh density distribution. There are many tools that used to generate mesh for the different applications and geometries. In this study, ANSYS ICEM software was employed to design the mesh system for the investigated room. As a complexity of the simulated room that used in this investigation, a tetrahedral unstructured mesh was selected because its ability to generate a required mesh for such complex geometry. The density of mesh was carefully distributed in the room domain. The mesh quality was 0.78. As shown in Figure 4, a high density mesh was generated in area, interested area, near the heat sources and outlet opening. Also the mesh was clustered in boundary layer area to verify the y+ requirement. Where the y + value in this investigation was 0.5 < y+ < 8. In order to get an accurate result at low simulation cost, a mesh test was performed in this study. As presents in Table 4, three different size were used in this test. By comparing the
results of the air velocity and temperature for all mesh size, mesh-A, B and C, there are no big difference in results when increasing the size of mesh from mesh B to mesh C. For this reason, mesh B was selected to be the suitable mesh for the simulation of this investigation.

![Image of grid generation for the investigated room](image)

**Figure 4.** Grid generation for the investigated room.

**Table 4.** Mesh test.

| Mesh types | Cells number |
|------------|--------------|
| Mesh_A     | 750,225      |
| Mesh_B     | 1,700,221    |
| Mesh_C     | 2,320,232    |

### 4. Results and discussion

**4.1. Evaluation of the indoor thermal comfort**

The evaluation of the human thermal comfort considers one of the significant evaluating indexes that should be taken carefully when proposed or design any new ventilation system. For this reason, the comfort equations by Fanger [31] are used in this investigation to show the ability of the proposed ventilation system, WSV and CSV, to provide the indoor thermal comfort requirements. In these equations, two indices, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), are used to represent the thermal balance for whole body of the occupant, where the indoor thermal comfort depends on the PMV and PPD values. For the satisfied thermal comfort the PMV should be between -0.5 < PMV < 0.5 and the PPD should be in range less than 10% and the relation between the PMV and human thermal sensation was shown in Figure 5. For an acceptable indoor human thermal comfort, small PPD and PMV values are recommended. The indices of PMV and PPD are represented by the following equations [31]:

\[
\text{PMV} = \left( \frac{1}{2} \right) \sum \text{PMV}_i \quad \text{PPD} = \left( \frac{1}{2} \right) \sum \text{PPD}_i
\]
Where

\[ t_{cl} = 35.7 - 0.028(M - W) \]  

\[ \times c_{cl} \left[ 3.96 \times 10^8 f_{cl} \times \left( t_{cl} + 273 \right)^4 - \left( t_r + 273 \right)^4 \right] + f_{cl} h_c \left( t_{cl} - t_a \right) \]  

and \[ f_{cl}^{1.290(1)} \] for \[ t_{cl} \leq 0.078 \text{ (m}^2\text{C/W)} \]  

and \[ h_c^{2.38(t_{cl} - t_a)^{0.25}} \] for \[ t_{cl} > 0.078 \text{ (m}^2\text{C/W)} \]  

Then

\[ \text{PPD} = 100 - 95 \times e^{-(0.03353 \times \text{PMV}^4 + 0.2179 \times \text{PMV}^2)} \]  

**Figure 5.** The relation between the thermal sensation and the PMV.

Table 5 presents the comparison results of the PMV and the PDD for each case study. From this table, for both system CSV and WSV, it is clear to see that the PMV for the case-1 are approximately the same with small difference. This was because at low supply velocity (0.38 m/sec). The thermal environment is slightly affected by the low velocity that reached to the occupant zone which caused this uncomfortable thermal sensation (slightly cool). Same thing was happened with a high velocity in case-3 where the velocity that reached to the occupant zone was relatively high for both WSV and CSV which causes the high turbulent air flow in the occupied zone. While for the case-2 when the supply velocity was 0.8 m/sec a noticeable difference was found between them. All case studies were with acceptable range of the thermal comfort.

**Table 5.** PMV and PPD evaluation.

| Supply | PMV | PPD |
|--------|-----|-----|
|        |     |     |
4.2. Temperature gradient between foot and head level

In any ventilation system, the gradient temperature evaluation especially between the head level (1.1 m from the floor) and the foot level (0.1 m from the floor) is very necessary factor that have to be taken carefully to assess the comfortable requirements for the occupants. In order to obtain a good thermal comfort for the occupants, the temperature gradient between head level and foot level should not exceed 3 °C [32]. In this investigation, four positions, point 1, 2, 3 and 4, around the occupant (see Figure 6) are used to evaluate the temperature gradient between the head and foot level for each case study.

| velocity (m/sec) | CSV | WSV | CSV | WSV |
|-----------------|-----|-----|-----|-----|
| 0.38            | -0.44 | -0.45 | 12 | 14 |
| 0.8             | -0.52 | -0.75 | 13 | 14.8 |
| 1.2             | -0.74 | -0.77 | 18 | 17 |

**Figure 6.** Measured point positions around the occupant.

Figures 7 a, b and c show the results of the air temperature gradient for case-1, 2 and 3 respectively. From these figures, it is clear to see that the value of the air temperature difference between the head and foot level were in a required range, under 3 °C, for all case studies, case-1, 2 and 3, and for all measured positions. A slight difference was found between case-2 and case-3 for each measured points, while a noticed difference was found in case-1 when compared with case-2 and 3. This was because that the supplied airflow rate in case -1 relatively low compared with case-2 and 3.Where in case-1, the supplied air take relatively long time to reach the foot level compared with case-2 and 3. Figures 8 a, b and c show more detailed information for the velocity distribution in the vertical direction for each case. Three different locations around the occupant which were passing through the measured points, point 1, 2 and 3 shown in Figure 6 were used to see the velocity profile distribution around the occupant. From these figures it is easy to see that the velocity distribution in the occupant zone was highly influenced by the supply airflow rate and the supplied opening type, CSV and WSV. Where a relatively high velocity was found in area around the occupant head when using WSV system compared with CSV system. This was because that the WSV system supplied the air from the side of the occupant and this will create a high turbulent flow in area around the head comparing with relatively smooth and symmetric flow which supplied by CSV system. This will also influenced by the supply flow rate for each case study. Also, for each calculated position, the velocity distribution varied from point to other because of the location of each point from the supply opening.
Figure 7. Temperature difference between the foot and head levels for each case study.
Figure 8. Air velocity distribution in vertical direction at three different locations in occupied area for each case study; x-axis represent air velocity in m/sec; and y-axis represent the measured location in m.
4.3. Temperature and velocity distribution indoor

In order to evaluate the thermal environment indoor, it is very important to assess the temperature and velocity distribution behaviour indoor. This will explain the ability of the proposed ventilation, WSV and CSV, system to provide a healthy and comfortable zone for the occupants.

4.3.1. Temperature distribution

A good indoor thermal comfort need to provide a homogenous temperature distribution for the occupant zone [33-36]. The high gradient of the temperature distribution especially in the area around the occupants will create uncomfortable sensations for the occupants. For this reasons, the temperature distribution especially for the occupant region should be assessed to see the ability of the examined system on providing a homogenous and comfortable environment. In this study the temperature distribution in the investigated room was evaluated for each case study. A vertical section plan, mid plane at x=1.25 m (see Figure 1), were used in this evaluation to explain the air temperature distribution in the most important room domain. Figures 9, 10, and 11 show the temperature distribution at the mid plane (x=1.25 m) for CSV system for the case-1, case-2 and case-3 respectively. While, Figure 9 b, 10 b and 11 b show the temperature distribution at the mid plane (x=1.25 m) for WSV system for the case 1, 2 and 3 respectively.

From these figures, for all case studies, it is clear to see that the air temperature for the WSV system is less warm than CSV system. This was appeared clearly in case-1 compared with case 2 and 3. This was because of that in WSV system the supply opening located in the occupied zone and this will allow providing the supply fresh air directly to the inhaled area. While in the CSV system the supply opening located in place out of occupied zone at ceiling level which was relatively away from the occupant. From these results, it can be say that using the WSV system will provide a better temperature distribution especially in the occupied region compared with the CSV system. This will help to save more energy.

![Figure 9. Temperature distribution for case-1; (a) CSV system and (b); WSV system.](image-url)
4.3.2. Velocity distribution

In order to achieve a required indoor thermal comfort, a velocity distribution should be evaluated carefully. The high velocity especially in area around the human head is highly unwanted. A high velocity will create a discomfort environment for the occupants. In this investigation, the velocity distribution was evaluated for all room domains for each case study. The evaluation of the velocity distribution will provide a details information on the flow behavior for each system, CSV and WSV, and this will also help to explain the quality of the indoor air. Where, directing the fresh supplied air to the inhaled zone, area around the occupant head, will enhanced the inhaled air quality and this will also improve the thermal comfort requirements. To assess and show the air velocity distribution and flow behavior in the important area, near occupant and near the supplied system, for the room domain, A mid plan at x=1.25 m was used in this investigation. Figures 12 a, 13 a, and 14 show the velocity distribution and the air movement at the mid plane (x=1.25 m) for the CSV system for the case-1, case-2 and case-3 respectively. While, Figure 12b, 13 b and 14 b show the velocity distribution and the air movement at the mid plane (x=1.25 m) for WSV system for the case 1, 2 and 3 respectively. From these figures it is easy to see that in all cases of the CSV system, the supplied air create an isolated environment around the occupant. This will improved the quality of the inhaled air because of this canopy work as a cover over the occupant which helps to protect the occupant from unwanted contaminated air. This will appear clearly in case-2 and 3 of the CSV system. While in case-1, the weak canopy appears around the occupant. This was because of that the supply velocity in case-1 was lower than in case-2 and 3. Therefore, the supply velocity plays a significant role in providing a good indoor thermal environment. In addition, for all cases of the WSV system, no canopy created for this type of supplied opening. This was because of that the supplied air directed from the side of the
occupied zone. As thermal comfort required, the air velocity that reached to the occupant head should not be high. Therefore, the air velocity in the occupant zone in case-1 for the WSV system considers the best case among all cases study. This will satisfy the thermal comfort requirement regarding the air velocity distribution.

**Figure 12.** Velocity distribution for case-1; (a) CSV system and (b); WSV system.

**Figure 13.** Velocity distribution for case-2; (a) CSV system and (b); WSV system.
5. Conclusion

A numerical study was performed in this investigation to assess the performance of using the CSV and WSV system on local thermal comfort and demand on energy. Three cases study were used in this investigation. The results show that:

- Using the CSV and WSV system as a main ventilation system will improve the amount of energy consumption by reducing the load on the cooling coil.
- The WSV system with a 0.027 m$^3$/sec of the flow rate, as in case-1, was provided a required air velocity in the occupant zone. Where the temperature gradient between head level and foot level not exceed 3 ℃. This will satisfy the requirement of the thermal comfort regarding the air velocity distribution with low energy consumption.
- Using the WSV system will provide a better temperature distribution especially in the occupied region compared with the CSV system. This will help to save more energy.

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