Air Distribution Performance Inside Office Room with Combined Displacement and Personal Ventilation

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Abstract. The main goal of the paper is to study the effect of adding a new type of ventilation device, which is personal ventilation to displacement ventilation, and know its effect on heat removal and how to reach thermal comfort for humans. Experiments were practically conducted inside a thermally insulated room with full-scale of dimensions (3 × 1.75 × 3) m. The results of the experimental work are used to validate the CFD simulations. The RNG k-ε model is utilized to simulate the cases for predicting indoor airflows. The displacement ventilation supply temperature is close to 18°C and the flow velocity of 0.25 m/s. As for the personal ventilation, the flow rates 5 l/s and 10 l/s were taken with a temperature close to where the air was drawn (at height 0.4 m). It was concluded that adding personal ventilation improved air quality and thermal comfort, and it was also concluded that a flow rate of 10 l/s gave better efficiency for the device to function in terms of air distribution performance index and effectiveness of temperature (εₜ) which about 71% and 1.8 respectively.

Keywords: Displacement combined with personal ventilation; effectiveness temperature; thermal comfort; air quality, air distribution performance index

1. Introduction

Several studies have discussed the importance of air quality in occupied space and the extent of its effect on human breathing and thermal comfort. As it has been proven that poor air quality causes...
symptoms of pathological construction syndrome, such as increased headaches, reduced thinking, increased dizziness, and so on (Wargocki et al., 2000). As it has been demonstrated by and by that the nature of the air breathed in from low warm substance (low temperature and dampness) is superior to the high warm substance (Fang L. et al., 1998).

The most significant explanation behind utilizing ventilation is to give a satisfactory nearby atmosphere inside the space to be ventilated. In this manner, planners and administrators of ventilation frameworks know about the prerequisites of comfort and air quality, which are required to accomplish sound and satisfactory inner conditions, notwithstanding the warm harmony between the body of humans and the conditions encompassing it and the components that influence its temperature. Just as adequate indoor air contamination and the idea of physical movement (H. B. Awbi, 2003).

Personal ventilation (PV) is of great importance in providing clean air to the breathing area in the occupied space, and thus this increases the effectiveness of ventilation, especially when using displacement ventilation (Melikov, A.K., 2004). Providing people with cold and dry air in the respiratory area provides thermal and respiratory comfort, and therefore also increases the quality of air inside the space, as a small flow of air is used for the air provided at temperatures two degrees lower than the temperature of the space etc (Arsen K. Melikov et al., 2002). Experimentally the thermal comfort of thirty women endures to nine different of indoor conditions by supplying cold air at a level near the floor when the lower parts of their legs, ankles, and feet weren’t covered. The foremost sensitive part of these parts was found at the ankle. Also, showed that if designers apply a particular recommendation for thermal comfort for air-conditioning design with displacement ventilation and air distributed underfloor, they created conditions uncomfortable for ladies. An oblong displacement diffuser unit was used with dimensions of (51 cm by 20 cm) and the air was delivered to the three used diffusers from an independently isolated air-handling unit utilizing an insulated duct. The temperature drop between the entering air from the three used diffusers hasn't exceeded the value of (0.2 °C). The used diffusers were placed behind the chair and consequently, the flow of air came from behind the themes (Stefano, 2016). A displacement ventilation concept and reveal more suitable turbulence model were evaluated among four models (standard k-ε, RNG k-ε, realizable k-ε, and SST k-ω) for different case studies under Iraqi climate conditions for two case studies. Case-I at ACH equals 3.5 for Non-Isothermal ventilation office room, and Case-II at ACH equals 4.5 for Isothermal office room ventilation by using a displacement ventilation system (Aedan, 2016).

The main objectives of the present work are comparing thermal performance between two types of ventilation systems; DV only and DV in conjunction with PV to reach the acceptable system which gives suitable Indoor Air Quality (IAQ) and human comfort. Studying the optimum occupant distribution inside the attested chamber to reach the acceptable indoor air quality. Giving recommendations on the strategy of using DV in combined with PV system in a hot climate at different occupant distributions.

2. Experimental method

The experiments were carried out in a thermally insulated wooden room with glass fibers and thermal nylon within the mechanical engineering laboratories at the University of Babylon as shown in Figure 1.

It has been assumed that working conditions are stable in numerical and experimental analyses. The distribution of temperature, speed, and airflow from the displacement with personal ventilation devices was studied inside an office room and under the Iraqi climate and in different locations for the distribution of occupants where the dimensions of the room are (3 × 1.75 × 3) m, where the operation of the ventilation devices was approved on two case studies, the first state Case-I was placed the displacement device only with two situation of occupant distribution as shown in Figure 2.
Figure 1. A photograph of the test chamber room with air conditioning unit and air supply hose, (a) front view (b) side view.

The second state case-II used the personal ventilation device in addition to the displacement ventilation unit also with two situation of occupant distribution as shown in Figures 3. Many types of thermal sources were adopted, the personal computer, the room lights, and the office employee where the calculations were done according to the international ASHRAE standards.
The second case includes the addition of a ductless personal ventilation device that draws air from below and at a height of 0.4m from the floor and is fixed to a table where the bottom part consists of fans at different flow rates. A flow rate of 5l/s and 10l/s is adopted as flow rates are studied to know its effect on comfort. The breathing zone for occupants from the floor level equals 1.1 m at sitting position (Iraqi cooling code, 2012), as shown in Figure 3.

Figure 2. Office room diagram for case-I of occupant distribution, (a)1st situation (b) 2nd situation
3. Mathematical of supply system

There are some procedures adopted to calculate the design temperature of the displacement ventilation device as well as the amount of air flowing from air ventilation terminal (Seppänen, O., 2008).

**a.** The amount of supply air flow rate

Supply air flow rate required for cooling load is:

\[
Q = \frac{0.295q_{\text{in}} + 0.132q_{\text{w}} + 0.185q_{\text{es}}}{0.584Q^2 + 1.208A_fQ_{\text{DV}}}
\]

(1)

\[Q = U \cdot A \cdot \Delta T\]

(2)

**b.** Temperature of ventilation air supply

The following equation represents the design temperature of the displacement ventilation device during the experiment (A. k. Melikov et al., 2007)

\[T_s = T_{sp} - \Delta T_{hr} - [(A_r q_r)/(0.584Q^2 + 1.208A_f Q_{DV})]\]
The air change per hour (ACH) is determined by equation of Nobukazu, 2003. Its value (8.32).

\[ ACH = \frac{Q}{V_{Room}} \times 3600 \]  

Figure 4 represents an illustration of the displacement ventilation device in Solid Work program and represents an illustration of the number and diameter of the holes for the personal ventilation device.

c. Measurement devices

The estimating gadgets are separated into three primary frameworks:

1-Example Units: For all tests, there are three poles, and six nodes in which every node is set at various degrees of height (0.0.4, 0.8, 1.1, 1.4 & 1.8) m and knows about account parameters. The poles were arranged close to the beginning at (X =2m, Y=0m, Z=0.875m), the other poles at (X =0.7m, Y=0m, Z =0.5m) and (X =0.7m, Y=0m, Z =1.25m) for all cases as showed up in Figure 5.

2-Air Speed: by using the thermocouple wire anemometer sensor model YK.2005AH.

3-Temperature assessing instruments: number of K-type thermocouples used to be standard air temperature. Thermocouples measure temperature after each 600s.

\[ \text{Figure 4. The supply devices ventilation, the supply air diffuser (DV) manufacturing(b) air flexibly outlet for PV diffuser} \]
d. Exploratory procedures

The trial was done in two phases relying upon the sort of ventilation gadget utilized, as the examination was in late March and April of 2019. The trial room is thermally protected with a high 3m from the floor. In room, temperatures were estimated an hour after turning on the cooling unit to get warm strength. The tests were rehashed multiple times in the two cases to check the exactness of the estimation.

1. Case-I

Air enters the room through a free-standing one-way supply diffuser which was called displacement ventilation device of the rectangular cross-sectional area located at the center ground of the north wall, occupants were classified in 1st and 2nd situation as shown in Figure 2.

2. Case-II (DV combined with PV)

Air enters the room through a suppling device displacement and personal ventilation. Personal ventilation draws the air from inside the room at a height of 0.4 meters from the ground level. PV system consists of fans at different flow rates 5l/s and 10l/s where the air is flowing from the bottom to the top and through (ATD) to the seating human level (1.1m). Occupants were classified in the 3rd and 4th situations as shown in Figure 3.

PV from 5l/s to 10l/s

(5)

4. ANALYTICAL INVESTIGATION

a. General Governing Conservation Equations

The conservation equations which govern the continuity, momentum and energy at constant density in
a Cartesian coordinate can be presented as follows.

- Preservation of mass:

Preservation of mass is given by the accompanying condition (Wargocki, P. et al., 2000)

\[
\frac{\partial}{\partial x}(u) + \frac{\partial}{\partial y}(v) + \frac{\partial}{\partial z}(w) = 0
\]  

(6)

Preservation of energy (Navier_Stokes equation): The resultant powers affecting a differential control volume are regularly controlled by applying energy protection law in each facilitate bearing to ask three power parts inside the x, y and z headings.

- Protection of warm energy (Fluent Inc., 2006):

\[
\frac{\partial}{\partial x}(\rho uT) + \frac{\partial}{\partial y}(\rho vT) + \frac{\partial}{\partial z}(\rho wT) = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial T}{\partial z} \right)
\]  

(7)

The terms and are the fierce warmth motions, St is a source term considering the pace of warm vitality creation.

- The centralization of species condition:

Condition of species fixation can be composed as:

\[
\frac{\partial}{\partial x}(\rho uc) + \frac{\partial}{\partial y}(\rho vc) + \frac{\partial}{\partial z}(\rho wc) = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial c}{\partial z} \right) + \frac{\partial}{\partial x} \left( -\rho \overline{uc^2} \right) + \frac{\partial}{\partial y} \left( -\rho \overline{vc^2} \right) + \frac{\partial}{\partial z} \left( -\rho \overline{wc^2} \right) + \frac{\partial}{\partial x} \left( -\rho \overline{uc} \right) + \frac{\partial}{\partial y} \left( -\rho \overline{vc} \right) + \frac{\partial}{\partial z} \left( -\rho \overline{wc} \right) + S_c
\]  

(8)

b. Computational Set and Numerical Scheme

This examination incorporates a confined office space for case-I DV just there are two warmth source over tables (PC) and two-man with two places and for case-II DV joined with PV there is one warmth source over a strong table and one individual additionally with two places of inhabitant, other than new numerically study case which was used displacement ventilation only with office person and one PC with two positions which named as case-III.

The effective draft temperature (EDT) was resolved in (100) centers scattered along with ten levels range between \((Y=0 \text{ to } Y=1.8)\) inside the included zone. Similarly, are performed to facilitate utilitarian results with speculative results through pole-1 at \((x=2 \text{ m}, y=0 \text{ m}, z=0.875)\). The reaction to stream field issues (temperature, pressure, speed, and so on) is characterized at nodes for each plane. the number of components for case-I first and second situations were 291707, 289496, for case II third and fourth situations were 255871, 267492, and case-III third and fourth situations were 200073, 199382, individually as appeared in Figure 6. Materials arrangement incorporating material
properties used in recreation like thickness ($\rho$), heat ($C_p$), and warm Conductivity ($k$) at values 1.189, 1005 and 0.0258, individually. The Limit conditions which includes a critical effect on CFD recreation achievement in giving a dependable outcome for the tackled issue. Limit conditions that forced in CFD reenactment executed during this work contain three sorts: speed gulf and outpouring as organized in Figure 7 divider limit included Dividers with consistent temperatures and furthermore steady warmth motions from another inside source like an individual, PC and lightweight are 44.69, 176.47 and 2000 separately.

![Figure 6](image1)

**Figure 6.** Fit model for exploratory space (a)First case (b)Second case (c)Third case.

When taking care of issues numerically it's difficult to encourage a specific arrangement, so acknowledged scaled mistake residuals ought to be determined for different terms like congruity, speed segments, and vitality. during this Appropriation Execution List (ADPI) was assessed to
appraisal dispersion execution of air at different cases during a ventilated space. Effective draft temperature (EDT) is determined from the condition below (M. Ahmed, 2004):

\[ \text{EDT} = (T_x - T_{av}) - 8 \times (V_x - 0.15) \]

A comparison was made between the results of the CFD program from the Humans program and showed the practical results that were conducted in an isolated room during the first and second cases in the case of the presence of two displacement and personal ventilation devices or the presence of the displacement device only where the examination depends on the vertical temperature estimated in a room at six levels which are numerical investigations. General normal mistake computations on account of the resulting condition (10) (Hashimoto, 2005), the run of the mill rate mistake for case-I first and second circumstances were 6.8 % and 10.5% separately and case-II third and fourth circumstances were 7.8%, 12% individually at 5 l/s, and 13%, 13.5% individually at 10 l/s.

\[ (E\%) = \left( \frac{1}{n} \sum_{i=1}^{n} \left| \frac{x_{\text{obs}} - x_{\text{exp}}}{x_{\text{exp}}} \right| \right) \times 100 \]

5. Results and discussion

A. Experimental and Numerical Results

Results of numerical with practical were studied and a comparison was made between them for the first and second cases. It was studied theoretically and practically based on the different positions of the occupants and based on the presence of ventilation devices where the distribution of heat and speed of air was studied on three columns divided within the area designated for human comfort. The numerical prompts this examination for the tried room was received utilizing numerous computational works at different planes for all spaces. Air distribution performance index (ADPI) and reasonability temperature degree were settled. Figure 7 shows the association of air temperature at the space height through pols (1,2,3). Where the change in temperature is evident during the occupied space. This temperature thinking strategy is the addition of a good way to brilliantly air level.
Table 1 and Table 2 speak to numerical consequences of Air Dispersion Execution Record (ADPI) and adequacy temperature(ɛt) for all cases considered. The most extreme estimation of viability and Air Circulation Execution Record (ADPI) was established at case-II for stream rate 10 l/s fourth circumstance.

Figure 7. Estimated temperature dispersions for poles1,2 and 3
Table 1. Numerical estimations for ADPI and effectiveness

| Ventilation Devices | Case-I (DV only) | Case-III (DV only) |
|---------------------|-----------------|-------------------|
|                     | 1st situation   | 2nd situation     | 3rd situation | 4th situation |
| ADPI%               | 0.56            | 0.6               | 0.63          | 0.65          |
| Effectiveness       | 1.3             | 1.32              | 1.33          | 1.34          |

Table 2. Numerical estimations of ADPI and effectiveness

| Ventilation Devices | Case-II DV combined | PV Case-II |
|---------------------|---------------------|------------|
|                     | At flow rate 5l/s   | At flow rate 10l/s |
|                     | 3rd situation       | 4th situation | 3rd situation | 4th situation |
| ADPI%               | 0.54                | 0.64        | 0.46          | 0.71          |
| Effectiveness       | 1.25                | 1.4         | 0.93          | 1.8           |

Figures 8 and 9 demonstrated numerical outcomes as shapes of air temperature dispersion at five designs for the testing room. Additionally, the same figures indicated that the temperature increments from 20°C near the accessibility terminal reach about 30°C close to physical bodies. It found on the off chance that case-I and case-III that the ground district close to the zone of diffuser would show low temperature estimates, as indicated by the cooling impact of the accessibility entering the air. Besides, a ceaseless augmentation of temperature gained as stature increase inside the space beside that case-III shows a little addition of temperature level close to a locale of warmth sources nearness than case-I, as for case-II exhibited that PV drawing the air at low high at 0.4 m to arrange high at 1.1 m (breathing zone) along these lines, so temperature degree at seat level is smaller than case-I and case-III. Moreover, a rising of indoor temperature is as often as possible noted near the individual, PC, lighting for all cases.
Figure 8. Temperature forms plans (1,2,3,4&5), a-Case-I, b-Case-II

Figure 9. Process temperature shapes plans (1,2,3,4&5) for Case-II, (a) at mass stream rate 5l/s, (b) at mass stream rate 10l/s.
For case-II (DV combined with PV), Figure 9 shows the conscious temperature apportionment which is best than two cases (case-I and case-III) gained in Figure 9. For case-I with case-III thermal manikin, PC and light effect on the environment of all room air temperature that reduces ventilation capability, for case-II suitable spread region and air course gained near the three warmth source result from the improvement of cold air from personal ventilation decrease heat transmitted by the thermal manikin, light and PC. In like manner, case-I and case-II in Figures 8 and 9 second and fourth situation showed best air dissemination over first and third condition while case-II at mass stream 10 l/s fourth situation show air movement execution document and effectively better than each and every other case and condition. Numerical results show the speed fields for the three cases are shown in Figures 10 and 11. High estimations of velocity were gotten at the lower territory where the region of air effortlessly diffuser DV exists during this zone. The air move process at this zone is progressively capable of diminishing the temperature of the hot space of warmth sources during this zone.

![Figure 10. velocity contours for planes 1.2,3,4&5 to (a) Case-I (b) Case-III](image-url)
Figure 11. Processed speed shape at planes 1,2,3,4&5 for case-II (a) at mass flow rate 5l/s (b) at mass flow rate 10l/s

The distinction between estimated temperature profile for pole-1 at (1) m from DV air diffuser uprooting ventilation with reenacted temperature profile utilizing (RNG-K-ε) disturbance model. This correlation appeared in Figure 12. the regular deviation between the trial and numerical qualities, for case-I first and second circumstances were about 6.8% and 10.5% separately. For case-II at the mass stream 5 l/s third and fourth circumstances were about 7.8%, 12%, and 13%, 13.5% for mass flow 10 l/s separately.
Figure 12. Comparison between predicted and experimental results using DV and PV ventilation system. (a) Case-I (b) Case-II at mass flow rate 5l/s (c) Case-II at mass flow rate 10l/s
Figure 13. Temperature shape at 1.1m planes (2,5), (a) Case-I (b) Case-III (c) Case-II at mass flow rate 5l/s (d) Case-II at mass flow rate 10l/s
Figure 14. Streamlines flow pattern for (a)Case-I (b)Case-III (c) Case-II at mass flow rate 5l/s (d) Case-II at mass flow rate 10l/s
6. CONCLUSIONS

Experimental and numerical investigations were carried out to evaluate air distribution performance with combined displacement and personal ventilation. In this study, firstly using one-way displacement ventilation only according to two occupants' distribution situations, and secondly using combined displacement and personal ventilation system. It was concluded that the 2nd situation of occupant distribution achieved higher efficiency and good distribution than the 1st situation. Also, using the displacement ventilation combined with personal ventilation systems are more efficient than using displacement ventilation only, taking into consideration the various locations of the occupant distribution, it gives more acceptable agreement. Air mass flow 10 l/s from the personal terminal gives acceptable results for Air Distribution Performance Index (ADPI) equals to about (0.71) and effective temperature equals about (1.4). The results showed that personal ventilation (PV ) system works to provide occupants with thermal and breathable comfort by increasing the ability to individually control air outlets as well as by improving indoor air quality for the purpose of use. Also will have the ability to reduce energy use by reducing the amount of air conditioning that is delivered to the interior.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| A | Surfaces Area for Wall | m² |
| Cₚ | Specific heats of the air at constant pressure | kJ/kg.K |
| C₁ₑ, C₂ₑ | Coefficient in the specific dissipation rates |
| D | Diameters | m |
| dx dy dz | Control volume | m |
| E₀ | The mean rate of deformation tensor |
| G | Gravitational acceleration | m/s² |
| H | Convection heats transfer coefficient | W/m².K |
| K | Color factor correct |
| K₁ | Conduction heats transfer coefficient for first layer of wall | W/m.K |
| Kₐ | Conduction heats transfer coefficient for final layer of wall | W/m.k |
| kᵢ,j,k | Turbulents kinetic energy at cell (i,j,k) | J/s |
| N | Total numbers of draft temperature points measured in occupied |
| N₀ | Number of points of draft temperature measured in occupied zone |
| P | Pressure | N/m² |
| Pz | Zone population person |
| Q | Heats transfer through the wall | W |
| Sᵢ | Source term for the rates of thermal energy Production | J/kg |
| T | Temperature | oC |
| U | Total heats transfer coefficient | W/m².K |
| u,v,w | Velocity components in x,y, and z-directions | m/s |
| uᵢ,j,k | Velocity at cell (i,j,k) | m/s |
Greek Symbols
\( \rho \) Air density \( \text{kg/m}^3 \)
\( \mathcal{E} \) Turbulent energy dissipation rate \( \text{J/kg.s} \)
\( \text{Pr} \) Prandtl or Schmidt number
\( \Sigma k \) Model constant
\( \Sigma \varepsilon \) Model constant
\( \Omega \) Specific dissipation rate \( 1/s \)
\( \Gamma \) Diffusion coefficient (diffusivity) \( \text{m}^2/\text{s} \)
\( \mu_t \) Turbulent viscosity \( \text{N.s/m}^2 \)
\( \Omega \) Rotation velocity \( \text{rad/s} \)
\( \Delta T_{hf} \) Temperatures difference from head to foot level. \( ^\circ\text{C} \)
\( a_k, a_\varepsilon \) Coefficient in the specific dissipation rate
\( \varepsilon_t \) Effectiveness temperature.
\( \mathcal{T}_t \) Turbulent Reynolds stress

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