Numerical evaluation of a Ductless Personalized Ventilation (DPV) combined with a radiant HVAC system: thermal comfort

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Abstract. Ductless personalized ventilation (DPV) as a recently developed technique and having the potential to meet the requirement of local thermal comfort and increase a wider thermostat setpoint range. The majority of published studies focused on the performance of DPV combined with convective-dominant HVAC system, while few investigations employed DPV in the radiant heating, ventilation, and air conditioning (HVAC) system. This study conducted the numerical simulation to evaluate the local thermal comfort of a DPV combined with a radiant HVAC system. Flow rate of 2, 4 and 6 l/s were applied as personalized air which is drawn at the sucking height of 0.1 m, and ACH of 1.2 h⁻¹ (0.16 m/s) and 2.4 h⁻¹ (0.32 m/s) were considered for DV system. Different building enclosure temperature of 24, 26 and 28˚C were assumed. Vertical air temperature difference, manikin-based equivalent temperature and draught rate expose to occupant face are mainly used as evaluation criteria. The results remarkably show that DPV can significantly decrease the equivalent temperature in head segment, and slightly increase the equivalent temperature in foot segment as well as calf and thigh segments. Larger draft discomfort with draught rate of about 16% occurred when DPV flow rate of 6 l/s was applied.

1. Introduction

The building sector accounts for energy use up to 40% in the European countries and the United States, in which 50% of the energy use comes from heating, ventilation and air-conditioning (HVAC) systems [1]. Traditionally, the indoor thermal environment is controlled in HVAC system by maintaining the entire zone in a uniform condition, resulting in the thermal discomfort of a certain amount of occupants due to the differences in their physical and mental activity level. Personalized ventilation is promoted to provide a higher potential of energy saving by increasing cooling temperature setpoint or reducing the airflow rate for the whole-space ventilation, as well as improve the breathing air quality [2]. Therefore, an indoor wider thermostat setpoint range can not only benefit a considerable amount of energy saving but also provide a higher level of thermal comfort and satisfaction.

Ductless personalized ventilation (DPV) as a recently developed technique and having the potential to meet the above requirements, which does not require a duct but needs work with background HVAC system. The majority of published studies focused on the performance of DPV combined with convective dominant HVAC system, e.g., mixed ventilation [3], underfloor ventilation [4], displacement ventilation (DV) [5], while few investigations employed DPV in the radiant HVAC system. Considering the advantage of DPV that employs high background temperature and brings fresh air to the breathing zone, the application of DPV might minor the disadvantage of radiant system and present the potential of reducing the low draught risk and more comfortable environment.
Therefore, this study conducted the numerical simulation to evaluate the thermal comfort of a DPV combined with radiant floor system. The main scope of this study is to evaluate the thermal comfort by performing a DPV combined radiant HVAC systems. Results demonstrated that DPV can provide relatively better thermal comfort environment around the occupant compared to non-DPV case.

2. Research method

2.1. Description of simulation model

The simulation model is set up with dimensions of 3.0 m×3.0 m×2.4 m. Figure 1 shows the section view of simulation model for ductless personalized ventilation. The thermal manikin locates in the center of the simulation domain with a stated position and 16 segments. The DPV inlet exposes to the occupant face in a distance of 0.3 m. The intake height of DPV locates at 0.1 m above the floor. Detailed configuration for the simulation model can be found in Table 1.

| Inlet (m×m) | Outlet (m×m) | DPV duct radius (m) | Manikin height (m) | DPV air supply opening height (m) | Intake height (m) |
|-------------|--------------|---------------------|--------------------|----------------------------------|------------------|
| 0.3×0.15    | 0.2×0.2      | 0.04                | 1.25               | 1.15                             | 0.1              |

2.2. Turbulence model and numerical schemes

The commercial CFD software ANSYS Fluent is conducted for modelling the DPV performance combined with radiant floor cooling system. The incompressible flow is assumed with a two-equation realizable k-epsilon model considering the full buoyancy effect [6]. The discrete ordinates (DO) radiation model is selected in this study [7]. Table 2 presents the detailed numerical simulation setup. The CFD model was validated and published in reference [8], by comparing the experimental results in a radiant floor cooling system and displacement ventilation and isolated PV case [9]. Sensitivity analysis is also verified for human body temperature and indoor velocity.

| Turbulence model | Radiation model | Solution methods |
|------------------|-----------------|-----------------|
| Realizable k-epsilon model, enhanced wall treatment, full buoyancy effect | Discrete Ordinates (DO) model with energy iterations per radiation iteration of 10 | SIMPLE scheme, PRESTO! for pressure, Second order upwind for others |

2.3. Grid distribution and boundary conditions

Enhanced wall treatment is chosen to enable the near-wall modeling method that combines a two-layer model with enhanced wall functions. A total number of 3,890,114 is finally used. Figure 2 shows the side view of building domain and the computational grid distribution in the building closure and
around human body. Table 3 shows detailed boundary conditions setup in the CFD simulation. Note a fixed temperature of 34°C for manikin surface is set. The clothes insulation effect is considered in this study with a wall thickness of 5 mm, and thermal conductivity of 0.053 W/mK representing a typical light summer clothing ensemble (0.6 clo). The humidity effect and latent heat effect are not included.

### Table 3. Boundary conditions setup in CFD simulation.

| Boundary  | Simulation setup |
|-----------|------------------|
| DV supply | Velocity 0.16m/s with intensity 6.3%, and 0.32m/s with intensity 5.7%; temperature, 21°C |
| Exhaust   | Outflow, free slip |
| DPV supply| Fan: 2l/s, 4l/s, 6l/s, provided by constant pressure jump |
| Ceiling   | Adiabatic         |
| Walls     | Constant temperature, 24, 26, and 28°C |
|Floor      | Constant temperature, 20°C, internal emissivity 0.9 |
| DPV duct  | Adiabatic wall, internal emissivity 0.9 |

The inlet velocity for DV is assumed as 0.16 and 0.32 m/s, and corresponding normal air change rate (ACH) equals to 1.2 h⁻¹ and 2.4 h⁻¹, respectively. Different DPV flow rates of 3, 5 and 7 l/s are selected. The parameters setup of wall temperature, inlet velocity and DPV flow rate in different cases can be found in Table 4. Note that following section will abbreviate the case description, e.g., Tw24_Vin0.16_DPV2 means the building wall temperature at 24°C, inlet velocity magnitude at 0.16 m/s, and DPV flow rate at 2 l/s.

### Table 4. Parameters setup of wall temperature, inlet velocity and DPV flow rate in different cases.

| T_w (°C) | ACH (h⁻¹) | V_in (m/s) | DPV (l/s) | T_w (°C) | ACH (h⁻¹) | V_in (m/s) | DPV (l/s) |
|----------|-----------|------------|-----------|----------|-----------|------------|-----------|
| 24       | 1.2       | 0.16       | 0         | 24       | 1.2       | 0.16       | 0         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 0         |            | 0         |          | 0         |            | 0         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 0         |            | 0         |          | 0         |            | 0         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |
|          | 2         |            | 2         |          | 2         |            | 2         |
|          | 4         |            | 4         |          | 4         |            | 4         |

2.4. Evaluation criteria of DPV

In order to make the better thermal comfort evaluation, the manikin-based equivalent temperature (\(t_{eq}, °C\)) on each of 16 body segments was first defined [10]:

\[ t_{eq} = t_{sk} - \frac{q}{h_o} \] (1)

where, \(t_{sk}\) is the skin surface temperature (°C), \(q\) is the sensible heat loss (W/m²), \(h_o\) is the heat transfer coefficient of the human body in a standard environment.

The temperature difference (\(\Delta T_{1.1-0.1}\)) specified for a seated person between the head at 1.1m and the feet at 0.1m above the floor is calculated. In addition, convective heat transfer coefficient (CHTC, W/m²K) and radiative heat transfer coefficient (RHTC, W/m²K) are specifically analyzed. In the end, to evaluate the draught effect, the air velocity at the floor level and neck level are monitored. The draught rate (DR) indicating the percentage of people dissatisfied is given as:

\[ DR = (34 - T_a)(V_a - 0.05)^{0.62}(0.37V_aTu + 3.14) \] (2)

\[ Tu = (2/3k)^{0.5}/V_a \] (3)
where $T_a$ is air temperature (˚C), $V_a$ is the mean air velocity (≥0.05m/s), $Tu$ is the turbulent intensity (%) and $k$ is turbulent kinetic (m$^2$/s$^2$).

3. Results and discussion

3.1. Radiative/convective heat transfer coefficients

Table 5 shows the RHTC for different segments of human body. It can be found that with the increase of building wall temperature from 24 to 28˚C, the RHTC increases significantly, e.g., from the 7.3 W/m$^2$K to 9.0 W/m$^2$K for the whole body. However, increased DPV flow rate has little impact on the RHTC, e.g., Case $T_w$28 $V_a$0.16_DPV4 has the almost same RHTC value with Case $T_w$28 $V_a$0.16_DPV0. This is notable that the building wall and floor temperatures keep constant, result in unremarkable change of radiative heat flux.

Figure 3 shows the CHTC distributions for different segments of human body. It can be found that the CHTC at head segment varies a lot with the increase of DPV flow rate. For example, the CHTC is 3.8 W/m$^2$K in Case $T_w$28 $V_a$0.16_DPV0, while the CHTC changes to 12.0 W/m$^2$K in Case $T_w$28 $V_a$0.16_DPV4. Among the cases with the same ACH and DPV flow rate shown in Figure 3(e) and 3(f), with the increase of ambient environment temperature, the CHTC in foot segment increases significantly. This means that DV may play more significant role in offset the convective heat load with its increment. This may also be due to the fact that there is a small gap (0.04m) between foot and floor assumed in the simulation model. This inaccurate setup attribute to proposed finer boundary layers in the adjacent to floor and foot. Further study will pursuit the more realistic cases.

![Figure 3. Convective heat transfer coefficient (W/m²K), (a) Case $T_w$24 $V_a$0.16, (b) Case $T_w$26 $V_a$0.16, (c) Case $T_w$28 $V_a$0.16, (d) Case $T_w$28 $V_a$0.32, (e) Case $V_a$0.16_DPV4, (f) Case $V_a$0.32_DPV4.](image)

Table 5. RHTC (W/m²K) for different segments of human body in the DPV cases.

| Body segments | $T_w$24 $V_a$0.16_DPV4 | $T_w$26 $V_a$0.16_DPV4 | $T_w$28 $V_a$0.16_DPV4 | $T_w$28 $V_a$0.16_DPV0 |
|---------------|------------------------|------------------------|------------------------|------------------------|
| Head          | 6.6                    | 6.8                    | 7.0                    | 7.0                    |
| Chest         | 6.0                    | 6.3                    | 6.7                    | 6.6                    |
| Back          | 7.2                    | 7.5                    | 7.9                    | 7.8                    |
| Upper arm L   | 6.8                    | 7.2                    | 7.8                    | 7.8                    |
Upper arm_R  6.8  7.2  7.8  7.8  
Low arm_L   7.2  7.2  7.7  8.7  
Low arm_R   7.2  7.2  7.8  8.7  
Hand_L      7.0  7.0  7.3  7.8  
Hand_R      7.1  7.1  7.4  7.9  
Pelvis       8.1  8.1  9.0  11.3 
Thigh_L     7.8  7.8  9.0  11.1 
Thigh_R     7.8  7.8  9.0  11.1 
Leg_L       8.2  8.2  9.6  12.0 
Leg_R       8.3  8.3  9.7  12.1 
Foot_L      8.5  8.5  10.5 14.0 
Foot_R      8.6  8.6  10.6 14.2 
Whole body  7.3  7.3  8.0  9.0  

3.2. Vertical air temperature difference
In order better to present the potential that DPV can improve the local thermal environment, Figure 4 and 5 present the indoor air distribution for different cases at middle Z axis section. Results can remarkably show that DPV significantly draws lower temperature air in the lower thermal zone and flows toward to occupant face, with a relatively higher temperature compared to DV air supply temperature. In addition, DPV can decrease the neck and face temperature and remove more heat from the human body. Compared to Figure 4 with Case T_{w28 V_{0.16}}, Case T_{w28 V_{0.32}} in Figure 5 provides more cold air in DV system. Although it may influence air temperature adjacent to the fact at the breathing zone, the draught rate must be paid attention as well as at the ankle level.

Table 6 shows the comparison of local thermal comfort parameters V_{face} and DR_{face} 0.01m away from the face with area of 0.03m². Results show that larger DR about 16% occurs in Case T_{w28 V_{0.32}}. Therefore, draft discomfort adjacent to the occupant face has a slightly larger impact on local thermal comfort. Further study will focus on the air supply opening type and decrease the draft discomfort. In addition, the calculated DRs in Case T_{w28 V_{0.32}} near the ankle equal to about 4.1% and 4.4%, indicating acceptable draft discomfort.

By monitoring the vertical air temperature difference at the horizontal height of 0.1m and 1.1m in different DPV cases as shown in Figure 6, Case Tw28 V_{0.32} and Case Tw28 V_{0.16} present the larger impact on decreasing the temperature difference with about 0.4°C, compared to other cases with

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Figure 4. T_{a} (°C), (a) Case T_{w28 V_{0.16}} (b) Case T_{w28 V_{0.16}} (c) Case T_{w28 V_{0.16}} (d) Case T_{w28 V_{0.16}}

Figure 5. T_{a} (°C), (a) Case T_{w28 V_{0.32}} (b) Case T_{w28 V_{0.32}} (c) Case T_{w28 V_{0.32}} (d) Case T_{w28 V_{0.32}}
about 0.1°C. This phenomena is not remarkable because vertical air temperature difference is calculated in the whole horizontal plane.

### Table 6. Comparison of local thermal comfort parameters $V_{\text{face}}$ and $D_{\text{R,face}}$ exposed to occupant face

| Type         | $T_{w28} \ V_{in0.32}$ | DPV2 | $T_{w28} \ V_{in0.32}$ | DPV4 | $T_{w28} \ V_{in0.32}$ | DPV6 |
|--------------|-------------------------|------|-------------------------|------|-------------------------|------|
| $V_{\text{face}}$ (m/s) | 0.096                   |      | 0.161                   |      | 0.309                   |      |
| $D_{\text{R,face}}$ (%)   | 5.29                    |      | 9.12                    |      | 16.17                   |      |

#### 3.3. Manikin-based equivalent temperature

As shown in Figure 7, the remarkable findings are that the employment of DPV can significantly decrease the equivalent temperature in head segment, and slightly increase the equivalent temperature in foot segment as well as calf and thigh segments. Due to the wider range of comfort zone and more acceptable lower- $t_{eq}$ for head segment, DPV is more suitably applied to this combined radiant HVAC system. As explained in the previous section, the foot segment does not contact the room floor potentially resulting in weak performance in the local thermal comfort. However, we have to notice that human thermal sensation is linked together measured data in convective-dominant HVAC system and comfort zone with specific $t_{eq}$ value is built according to the regression of mean thermal vote (MTV) [10, 11]. Therefore, weak performance in the foot segment and calf segment in Figure 7 does not absolutely negative the potential of DPV applied in radiant HVAC system, especially this case of radiant floor cooling system combined in displacement ventilation system. At least, DPV decrease vertical air temperature difference and slightly increase $t_{eq}$. It should be pointed out that among all cases, Case $T_{w28} \ V_{in0.16}$ DPV4 provides most comprehensively comfortable environment through head segment to foot segment.

![Figure 6. Vertical air temperature difference at the horizontal height of 0.1m and 1.1m in different DPV cases.](image1)

![Figure 7. $t_{eq}(^\circ C)$ for different DPV cases, (a) Case Tw26_Vin0.16, (b) Case Tw26_Vin0.32, (c) Case Tw28_Vin0.16, (d) Case Tw28_Vin0.32](image2)

#### 4. Conclusions

In this study, numerical simulations were conducted to evaluate the performance of DPV combined with a radiant HVAC system on the local thermal comfort around human body. Results showed that increased DPV flow rate had little impact on RHTC, while has significantly affect the CHTC at head segment with a maximum value of 12.0 W/m²K. DPV significantly drawn lower temperature air in the lower thermal zone and flows toward to occupant face, with a relatively higher temperature compared to air supply temperature. Larger draft discomfort with about 16% DR occurred when DPV flow rate of 6 l/s was selected, while less than 5% DR was found in the ankle height level. In the end, the remarkable findings are that the employment of DPV can significantly decrease the equivalent
temperature in head segment, and slightly increase the equivalent temperature in foot segment as well as calf and thigh segments. Due to the wider range of comfort zone and more acceptable lower-\( t_{eq} \) for head segment, DPV is more suitably applied to this combined radiant HVAC system. Further studies will continue to study the impact of DPV on local thermal comfort taking into account more evaluation criteria.

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