DESIGN ANALYSIS OF AN OFFICE VENTILATION SYSTEM
VIA CALIBRATED CFD APPLICATION

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ABSTRACT
This paper presents the results of a case study on the application of Computational Fluid Dynamics (CFD) simulations for assessment of ventilation systems. The case study concerns an office space in Austria equipped with combined Displacement Ventilation (DV) and Personalized Ventilation (PV). Monitored data provide a basis to document the indoor conditions and user behavior. Calibrated CFD-based air flow simulations were performed to support a better understanding of the airflow phenomena as well as modelling different design alternatives. Moreover, the implications of alternative design configurations for indoor environmental variables could be computationally investigated.

INTRODUCTION
Air flow in ventilated spaces has been categorized in two groups of mixing and displacement ventilation (Hamilton et al. 2004). In the traditional mixing ventilation, the injected fresh air fully mixes with the stale room air, while Displacement Ventilation (DV) introduces cool air to the zone with low velocity and minimal mixing (Magnier et al. 2012). Typically, in DV system the air suppliers are installed close to the floor level. As cool air comes into contact with indoor heat sources (e.g., occupants, equipment), it warms up and exits the space from the air extract grilles near the ceiling. The desired result is a temperature and contamination stratification in space with cool and clean air at lower levels and warm and polluted air at the upper levels. However, if the system is not well designed, there is the possibility of local discomfort due to the air draught or inadequate vertical temperature differences (Melikov et al. 2002). A number of issues need to be considered for the proper operation of DV systems. For instance, the minimum height of the ventilated room should be about 2.7 m (EDR 2002). The supply air temperature has been suggested to range between 16 to 21°C (Melikov 2004b). The combination of DV system with Personalized Ventilations (DPV) aims at improving the quality of air by delivering clean and cool air to occupants' breathing zone. Moreover, PV systems are meant to facilitate individual adjustments (Schiavon & Melikov 2009). However, the air quality improvement provided by PV depends on the air flow rate, direction and temperature (Faulkner et al. 1999, Melikov et al. 2002, Russo 2011).

Experimental and computational thermal and air flow studies can contribute to progress in this area (Wiercinski & Skotnicka-Siepsiak 2008). There have been many studies on the potential of Computational Fluid Dynamics (CFD) to assist building performance analysis and indoor air quality assessments (Chen & Zhai 2004, Meroney 2009).

Given this background, the present paper explores the results of a field study concerning indoor conditions in an office space. First, performance data and occupants’ responses to the existing ventilation system were collected. Moreover, CFD-based air flow simulations were performed to support a better understanding of the complex nature of airflow phenomena in the space. In order to validate the CFD predictions, simulated air flow velocities and temperatures were compared with measured data at multiple locations in the space. The calibration process (i.e., error minimization) mainly involved the specification of the discharge angle of the air diffusers. Assisted by the calibrated model, potential alternative design improvements were investigated, whereby the geometry and location of the air supply diffusers as well as the air flow rate were considered.
METHODOLOGY

Case study

The case study concerns an open plan office space equipped with a combination of DV and PV systems (see Figure 1). The studied space (width = 7.50 m, length = 17.30 m, height = 3.10 m) is located in the ground floor of a building in Grieskirchen, Upper Austria. The space is used as a call center. Work stations are organized in terms of five star-shaped hubs, each accommodating up to five workers. One hub is provided with ducted PV, whereas the other four have ductless PVs. Seven supply diffusers are installed at the height of 38 cm from the floor level. Six return outlets (0.04 by 0.19 m) are positioned 11 cm below the ceiling.

The monitoring system

For the purpose of the study, a monitoring system was installed to continuously capture indoor environmental parameters (air temperature, relative humidity, CO$_2$ concentration). Conditions near occupants were monitored at eleven locations (four workstations at the ducted hub and seven at the ductless hubs). Moreover, the state of occupancy and windows was monitored as well. The air flow volume out of the PV system units can be modulated by occupants using a valve (from zero to 100 %). Hence, the state of valve was also monitored for the entire period of the study (Figure 1 and Table 1). For a detailed recording of the outdoor conditions a weather station was also installed in close proximity of the building. To obtain necessary input information for the CFD simulation, air flow in/out (1.s$^{-1}$) through the air suppliers and extract grilles as well as the supply air temperature (°C) were measured. The monitoring stretched over a period of eleven months (from July 2012 to May 2013).

The building energy and CFD simulations

The building was modeled in the building energy simulation program DesignBuilder (DesignBuilder 2013, Webb 2013). Boundary conditions play a crucial role in CFD analysis. Internal boundary conditions for an internal analysis relate to the wall and window surface temperatures, surface boundary conditions of supply diffusers and extract grilles, component blocks and assemblies, etc. Part of these boundary conditions such as the airflow rate in/out from supply diffusers and extract grilles are defined by user. Others such as wall and window temperature could be very conveniently imported from the building simulation results (DesignBuilder 2013). The automatic provision of the required geometry and boundary conditions for CFD simulations in DesignBuilder considerably simplifies this procedure (Chowdhury et al. 2010).

Table 1: Monitored indoor data points

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor climate</td>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ concentration</td>
<td>ppm</td>
</tr>
<tr>
<td>User behavior</td>
<td>Presence/absence</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>State of PV valve</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>State of doors/windows</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 1: Floor plan of the office space
Note that, due to the involved assumptions and simplifications CFD simulation results are not always reliable. A conventional method to evaluate the credibility of predictions is comparing the CFD outcomes with actual measurements (Chen & Srebric 2002). The appropriate room model was generated and all the required information for the energy simulation was imported (e.g., construction details and thermal properties, internal loads, HVAC system, weather data). Parallel to building energy simulation, a CFD model was generated. The initial CFD model was calibrated to minimize the difference between the measured and simulated indoor air temperature and velocity. The calibration process involved a single design day (i.e., January 12, 2012). Thermal simulation provided the external and internal surface temperatures as well as zone mean temperature. These were used as the boundary conditions for the CFD simulations. Measurement results were used to set the supply air flow rate 82.2 l.s\(^{-1}\) and the supply air temperature 19.7 °C in CFD analysis. The k-\(\varepsilon\) turbulence model, upwind discretization method and maximum dependent variable residual (iterative convergence error) of \(10^{-5}\) represent the calculation parameters. Subsequently, CFD predictions of air flow speed and air temperature were compared with measurements at multiple locations in the space (12 locations for air flow speed and 8 locations for air temperature). Figure 2 presents the section B-B of the space (see Figure 1) with location of the air flow speed and air temperature measurements (point \(a_1\) to \(a_{12}\) and \(b_1\) to \(b_3\), respectively). In addition, measured temperature at workstations 1, 4, 6, 9 and 10 were also compared with the corresponding simulation predictions.

The initial model was calibrated mainly by modifying the definition of the discharge angle of the air diffusers. Calibration process was continued until an acceptable accordance between the measurement and CFD results was achieved.

The calibrated CFD model (modeled for January 12th, 2013, 12:00) was run for an instance of time in a summer day as well (August 7th, 2012, 12:00). In this case too, boundary condition were imported from the thermal simulation and measurements (supply air flow rate = 82.2 l.s\(^{-1}\), supply air temperature = 21 °C). Afterwards, the temperature and velocity distribution as well as Predicted Mean Vote (PMV) in summer and winter models were studied. PMV was calculated for a metabolic rate of 1.2 met and a thermal clothing resistance of 0.5 clo (summer) and 0.8 clo (winter). Finally, an alternative supply diffuser design with regard to supply diffusers' position (i.e., height above the floor level), geometry, supply air flow rate, and temperature was considered.

RESULTS AND DISCUSSIONS

User behavior evaluations

As noted before, the office workers have the possibility to control air flow volume from the PV diffusers using a valve. Figure 3 summarizes the related results in terms of monthly mean values of valve use frequency (actions per day) over the observation period. Thereby, both the total numbers as well as the fraction of intermediate actions (i.e., actions occurring at least 20 minutes after occupying the workstation or 20 minutes before leaving the workstation) are shown. Note that the data in this Figure is already normalized with regard to occupancy. These results suggest that 70% of the adjustments can be categorized as intermediate actions. Note that adjustments entail – in equal numbers – both actions toward increasing and decreasing the PV volume flow.

A further question relates to PV valve manipulation frequency in the context of the PV type (ducted versus ductless). To address this question, Figure 4 compares the PV actuator adjustment frequency (actions per day averaged over the entire observation period) for ducted and ductless units. These results suggest that ductless PV units are rarely operated.
Ducted workstations show a mean valve manipulation frequency of 2.5 actions per day. For ductless units, the mean value drops to 0.29 actions per day. Five out of seven ductless workstations display zero action frequency. The latter result may also help explain the higher frequency of PV usage in the months of August and September (see Figure 3). In these warmer months, the capacity of ducted PV stations to supply cooler and fresh air could render them more attractive for the occupants.

The monitored results can support the analysis of indoor conditions and the relevant role of ventilation options. For instance, Figure 5 shows the frequency distribution of indoor air temperature and CO₂ concentration levels (measured at workstations) averaged over all workstations for two time periods, namely July to December and January to May. The data in this Figure generally suggest that the maintained indoor temperature in the office was consistently rather high. Moreover, the results also appear to suggest the air quality (as represented via CO₂ concentration monitoring) was somewhat better in the July to December period, when the PV systems were more frequently operated.

**CFD simulations**

Figures 6 and 7 compare the calibrated CFD model predictions of air flow velocities and air temperature with measurements at multiple locations (Figure 2) in the space.
Following the CFD simulations, temperature and velocity were plotted in terms of planar slices through the space. The chromatic temperature legend for these plots (and the following ones) is provided in Table 2. According to the previous studies, the locations in the space with air velocity higher than 0.25 (m.s\(^{-1}\)) should not be occupied. Therefore, the maximum value for the velocity illustration has been set to 0.25.

Figures 8 and 9 illustrate the simulated air temperature and velocity distribution across a vertical plane perpendicular to a supply diffuser (section C-C, Figure 1), for winter and summer. The temperature stratification between the floor level and the occupants breathing zone is not considerable. In fact, the temperature difference is not enough to encourage the users to use the PVs in order to transfer the cool and fresh air to their breathing zone (the workstations are mostly equipped with ductless-PVs). This result may explain the lower rate of ductless-PV usage by the occupants. The plots presenting the velocity distribution illustrate that the area close to the supply diffuser should not be occupied. This condition is already met in the actual office layout.

In this study, occupied locations with PMV ranging from -0.5 to +0.5 have been considered satisfactory. CFD-based PMV calculations suggest that the DV operation can provide a thermally comfortable environment (PMV around 0.14 in winter and 0.23 in summer). The PMV results in summer present a slightly warmer indoor environment. The indoor temperature and PMV results may help explain the higher frequency of PV usage in the months of August and September (see Figure 3). The capacity of ducted PV stations to supply cooler and fresh air in warmer months would encourage higher usage rates.

### Table 2:
Chromatic temperature legend for CFD plots

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Velocity m.s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.00</td>
<td>0.25</td>
</tr>
<tr>
<td>24.73</td>
<td>0.23</td>
</tr>
<tr>
<td>24.45</td>
<td>0.20</td>
</tr>
<tr>
<td>24.18</td>
<td>0.18</td>
</tr>
<tr>
<td>29.91</td>
<td>0.16</td>
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<tr>
<td>23.64</td>
<td>0.14</td>
</tr>
<tr>
<td>23.36</td>
<td>0.11</td>
</tr>
<tr>
<td>23.09</td>
<td>0.09</td>
</tr>
<tr>
<td>22.82</td>
<td>0.07</td>
</tr>
<tr>
<td>22.55</td>
<td>0.05</td>
</tr>
<tr>
<td>22.27</td>
<td>0.02</td>
</tr>
<tr>
<td>22.00</td>
<td>0</td>
</tr>
</tbody>
</table>
Design improvement suggestion

These results imply a couple of conclusions regarding the present ventilation system design:

- The supply airflow rate and temperature cannot provide the temperature stratification level required for ductless-PV application.
- The temperature distribution across the workstations (considering their distance and location relative to the supply diffusers) is rather non-uniform.

In the light of these observations, an alternative supply diffuser design was considered. The aim was to provide a more uniform temperature and velocity distribution across the workstations. Therefore, one linear supply diffuser along the western outside wall of the office at the height of 0.05 m from the floor level was modeled (width = 0.04 m) (Figure 11). In the first set of simulations, the supply air flow rate and temperature are equal to the actual model, 82.2 L.s\(^{-1}\) and 21 °C (summer case).

Figure 12 presents the air temperature and velocity results obtained from the CFD simulation (at section C-C, Figure 1). In this case too, the temperature stratification does not meet the PV application requirements. Hence, we considered higher air flow rates and lower supply temperatures. Assuming a ventilation rate equal to 4 air change per hour, the supply flow would be 480 L.s\(^{-1}\). In addition, the supply air temperature was set to 18 °C. The corresponding results are displayed in Figure 13, indicating a more uniform temperature and velocity distribution throughout the space. In addition, this most recent configuration yields a more pronounced vertical temperature distribution. Note that in both cases the calculated PMV values in the occupied locations were in the defined acceptable range (-0.5 < PMV < +0.5).

As past research has shown, achievable air quality improvement via PV systems depends on different parameters including the PV air flow rate and direction as well as the temperature difference between the PV air jet and the room air temperature. For instance, it has been recommended to condition supply air temperature is 3 to 4 degrees cooler than the room air (Melikov 2004b, Melikov 2004a). This corresponds to conditions as in ducted PVs of our case, and is consistent with their more frequent operation by the occupants (as compared to the ductless PVs).
CONCLUSION

We described a field study concerning the indoor air conditions in an office space, equipped with displacement (DV) and personal ventilation (PV) systems. Data obtained via the monitoring system suggests that the frequency of the PV operation (modulation of volume air flow by the users) was rather low, especially in the case of ductless PVs. PV usage frequency was found to be somewhat higher in the warmer months of the year, when PV stations supply cooler air to the occupants’ breathing zone.

This study also illustrated the utility of calibrated CFD models toward estimation of the air flow velocity and temperature field as well as PMV values. The results suggest generally acceptable indoor environmental conditions provided by the combined operation of the above mentioned systems. However, studying the temperature stratification illustrates that the supply airflow rate and temperature cannot provide the temperature stratification level required for ductless PV application. Therefore, based on the observations an alternative supply diffuser configuration was explored. The CFD simulation outcome suggests that higher difference between the room and supply air temperature as well as higher supply air flow rate could provide the required temperature stratification for ductless PVs. In addition, the modified configuration resulted in a more uniform temperature and velocity distribution across the space.

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REFERENCES


