MEASURING AND VISUALIZING THE FLOW SUPPLIED BY PERSONALIZED VENTILATION

Hayder Alsaad, Conrad Voelker
Department of Building Physics, Bauhaus-University Weimar, Weimar, Germany

Abstract

This study investigates the flow supplied by personalized ventilation (PV) by means of anemometer measurements and schlieren visualization. The study was conducted using a thermal manikin to simulate a seated occupant facing a PV outlet. Air velocity was measured at multiple points in the flow field; the collected velocity values were used to calculate the turbulence intensity. Results indicated that PV was supplying air with low turbulence intensity that was able to penetrate the convective boundary layer of the manikin to supply clean air for inhalation. The convective boundary layer, however, obstructed the supplied flow and reduced its velocity by a total of 0.26 m/s. The PV flow preserved its value until about 10 cm from the face where velocity started to drop. Further investigations were conducted to test a PV diffuser with a relatively large outlet diameter (18 cm). This diffuser was developed using 3d-modelling and 3d-printing. The diffuser successfully distributed the flow over the larger outlet area. However, the supplied velocity and turbulence fields were not uniform across the section.

Keywords: Personalized ventilation, schlieren imaging, air quality, thermal manikin

1 Introduction

In order to control the determining factors of thermal comfort and indoor air quality, the so-called 'total volume' ventilation systems are typically used in buildings. In rooms ventilated using total-volume systems, the supplied air mixes with room air before reaching the occupants, i.e. the occupants inhale a mixture of the fresh supplied air and the polluted indoor air (Gao & Niu, 2004). Studies indicate that in many total-volume applications in practice, about only 1% of the supplied fresh air is inhaled by the occupants, while the other 99% is not used for inhalation (O. Fanger, 2006). Furthermore, such systems ignore the individual preferences of the thermal environment. Thus, total-volume systems fail to provide a high level of thermal comfort to all of the occupants with their physiological and psychological differences (Melikov, 2004). Personalized ventilation (PV) is a ventilation strategy that aims to improve the indoor environment by supplying clean air for inhalation and offering individual control over the flow rate and direction of the supplied air (P. Fanger, 2001). Numerous studies report that PV in combination with background total-volume systems can significantly improve the indoor environment (Alsaad & Voelker, 2021). To avoid draught sensation, air should be supplied "gently" with low velocity and turbulence (P. Fanger, 2001). Melikov (2004) recommends that PV should supply air with low turbulence intensity and a uniform velocity field at the opening of PV to avoid mixing of the clean supplied air with the polluted air in the room. This study investigates the PV-flow using anemometer measurements and schlieren visualization. Schlieren imaging is an optical method of visualizing airflow by capitalizing the refraction of light when entering a medium of different density (Settles, 2001). The main component of the schlieren imaging system is the schlieren mirror; which is a single one-meter diameter concave spherical mirror with astronomical quality (Alsaad & Voelker, 2020). Other components of the schlieren system include a light source, a knife edge, and a high resolution camera. Initial investigations implemented a small PV opening to facilitate controlling the velocity fields across the diameter. Thereafter, 3d printing was implemented to develop a round PV diffuser with a larger outlet that can cover the range of occupants' slight movements at the desk.

2 Initial investigations

2.1 Methods

These investigations were conducted by measuring and visualizing the flow supplied by a PV outlet with a diameter of 8 cm. The PV outlet was facing a thermal manikin (Figure 1, a); the manikin was naked and bold; its face was 40 cm from the PV outlet. The manikin was placed about 45 cm in front of the schlieren mirror; it was operated under the 'comfort mode' to simulate the heat generation of a calm seated person. To achieve a calm personalized flow with no large velocity variations across the diameter of the opening, the PV opening was equipped with a round honeycomb that consists of Ø8 mm cells with a 197 mm depth. The flow rate of PV was set to 5 L/s.

To evaluate the supplied flow, air velocity was measured at multiple points in between the personalized system and the face; the spacing between the measurement points was set to 5 cm with a sampling interval of 1 second for 5 minutes at each point. Air velocity was measured using an omnidirectional hot-wire anemometer with an accuracy of ∓1.5% of the measured value and a response time of 2 s. Turbulence intensity was calculated from the fluctuations of the velocity values.

While the supplied flow was isothermal during the anemometer measurements (about 23°C), the flow was heated during the visualization experiments to about 34°C to create a density difference between the supplied flow and the surrounding room air. This density difference was necessary to establish a difference in the refraction index to allow visualizing the flow with the schlieren mirror. The camera settings implemented to capture the schlieren images were an f-stop of f/2, a focal length of 135 mm, and an ISO speed of 800. Further settings included a 50 fps frame rate and a shutter speed of 1/200. Moreover, the test objects were lit using a LED light source with 284 lumens.

2.2 Results

Figure 1 (b) exhibits the captured schlieren image of the air flow consisting of natural convection (heated manikin) and forced convection (personalized flow). The natural convection is remarkably visible over the horizontal body segments such as the thighs and arms, and also along the vertical surfaces such as the chest and back. The image indicates that PV supplied a steady low-turbulence flow that exited the PV opening in a laminar stream. The PV-flow then transitioned to a higher turbulence intensity, becoming visible after about 4 cm from the PV opening. The supplied flow had a relatively high source and target velocity; this enabled the flow to fully penetrate the convective boundary layer to deliver clean air and induce air movement at the targeted body segment; i.e. the face. However, the convective flow was still able to push the PV flow upwards, which caused the supplied flow to slightly curve up towards the upper part of the face. Another reason for this behaviour is that the supplied flow had to be heated to allow visualizing it using the schlieren system.

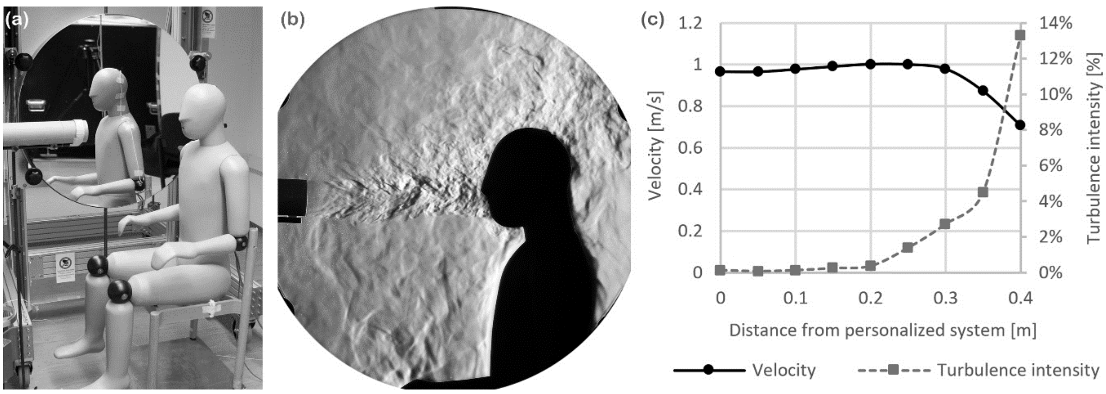

Figure 1. *(a) The setup in front of the schlieren mirror; (b) the captured schlieren image; (c) the measured air velocity and turbulence intensity*

According to the conducted measurements (Figure 1, c), the flow of PV was able to relatively maintain its momentum until reaching the manikin's face. The free convective flow encasing the manikin obstructed the supplied personalized flow; it slowed the supplied flow down by $\Delta v_a = 0.26$ m/s compared to its initial value. The drop in velocity values started at about 10 cm from the manikin's face. However, the PV system still achieved high target velocity of 0.71 m/s at the face. The measurements also confirmed that PV supplied air with a fairly low turbulence intensity due to the honeycomb built inside the system. The turbulence intensity remarkably increased as the supplied air flowed through the manikins's thermal boundary layer. The flow exited PV with a very low turbulence intensity of 0.14%. This value increased gradually until reaching 13% at the manikin's face. However, these values can reflect an underestimation of the actual turbulence intensity due to the relatively long response time of the implemented sensor (2 s). Therefore, in the following section, a new sensor with a short response time of 100 ms was utilized to accurately evaluate turbulence.

3 PV diffuser

3.1 Modelling and setup

While the PV outlet investigated in the previous section achieved good results in supplying air with uniform velocity fields and low turbulence intensity, it does not reflect a realistic PV diffuser due to its small diameter (8 cm). To study the performance of PV, a larger opening is necessary as it gives occupants the flexibility to move their heads while working in their workstations. However, connecting a large opening to a small air duct results in an unequal distribution of supplied air where the clean cool air is concentrated at the centre of the diffuser. Therefore, detailed air diffusers with perforated plates and honeycomb pressure and turbulence controllers were modelled and 3d-printed for this research project. The developed diffuser had an 18 cm diameter according to the round movable panel proposed by Bolashikov et al. (2003). The geometry was created using Rhinoceros 3d modelling environment with Grasshopper parametric design plug-in. The modelled diffuser consisted of three main parts: the conical housing, a perforated curved plate at the diffuser inlet, and a honeycomb structure at the outlet (Figure 2, a). All three components were parametrically defined to optimize the inclination angle of the housing, the distribution and sizing of perforation, and the number and size of the honeycomb cells. Multiple variations were 3d-printed and tested using the schlieren mirror. Air velocity was measured at 9 points at the horizontal diameter (X-axis) and at 9 points at vertical diameter (Y-axis). The spacing between the measurement points was 3 cm, the measurements took place 4 cm in front of the diffuser because of the protection sphere around the tip of the anemometer. Air velocity was recorded for 3 minutes at each point with a time interval of 1 s.

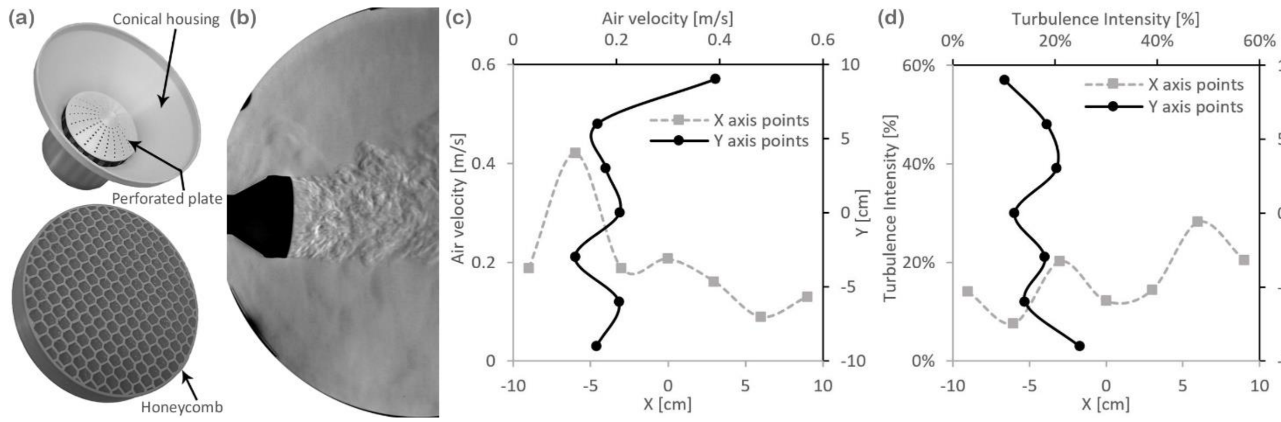

Figure 2. *(a) The components of the diffuser; (b) a schlieren image of the supplied flow; (c) and (d) the measured air velocity and turbulence intensity across the outlet*

3.2 Results

Figure 2 (b, c, and d) exhibits the performance of one of the 3d-printed diffusers. The tested diffuser had a conical geometry with a 45° inclination angle. The perforated plate had ⌀2 mm holes; the displacement of the plate 2 cm from the diffuser inlet. The cells of the honeycomb were 1 cm in diameter. Figure 2 (b) shows the schlieren image of the supplied flow under a flow rate of 4.3 L/s. A qualitative evaluation of the image indicates that the diffuser successfully distributed the flow to the larger outlet area. In other words, the supplied flow did not exit the diffuser from the central region only, but from the whole outlet area. However, when examining the quantitative values in Figure 2 (c), the diffuser failed to supply a uniform profile of velocity at the horizontal diameter (X-axis) as well as in the vertical diameter (Y-axis). While the mean supplied velocity in the X-axis was 0.2 m/s, the supplied velocity was as high as 0.42 m/s at one of the measurement points (i.e. double the mean velocity value). The Y-axis values exhibited a fairly similar pattern, in which the average supplied velocity was 0.21 m/s and the value at the most deviated point was 0.39 m/s. However, in the Y-axis, the largest shift was in one of the points that are located near the rim of the diffuser rather than a middle point, which was the case in the X-axis. Such deviation is difficult to justify since the diffuser was modelled symmetrically. A possible explanation could be the curved perforated plate. Due to the fine perforation, some holes were semi or fully blocked during the printing process, which could have resulted in uneven flow into the diffuser.

Figure 2 (d) exhibits the turbulence intensity at the diffuser outlet, which had a mean value at both axes of 17%. The largest deviation from the average value at the X-axis and the Y-axis were 11% and 8% respectively. The profile of turbulence had smaller fluctuations compared to the velocity profiles. Moreover, unlike the velocity values, no sudden jumps in the turbulence profile were recorded. However, the turbulence distribution was asymmetrical, which was the same case in the velocity profile. Furthermore, it is worth mentioning that the surface of the honeycomb was fairly rough as it was printed on low settings to speed up this process. This contributed to turbulence intensity at the outlet.

4 Conclusion

The flow supplied by PV was measured and visualized in this study. PV supplied air with low turbulence intensity that was able to penetrate the human convective boundary layer to supply air for inhalation. Additionally, the developed diffuser successfully distributed the supplied air over the larger outlet with relatively low turbulence intensity. However, it failed to create uniform velocity profiles. Further investigations are required to optimize the geometry of the diffuser using CFD simulations and to investigate the entrainment of the surrounding air into the jet.

5 Acknowledgements

Our deep gratitude to Th. Möller, A. Gena, and the students of Bauphysikalisches Kolloquium.

6 References

Alsaad, H., & Voelker, C. (2020). Qualitative evaluation of the flow supplied by personalized ventilation using schlieren imaging and thermography. *Building and Environment*, *167*, 106450. https://doi.org/10.1016/j.buildenv.2019.106450

Alsaad, H., & Voelker, C. (2021). Could the ductless personalized ventilation be an alternative to the regular ducted personalized ventilation? *Indoor Air*, *31*(1), 99–111. https://doi.org/10.1111/ina.12720

Bolashikov, Z., Nikolaev, L., Melikov, A. K., Kaczmarczyk, J., & Fanger, P. O. (2003). New air terminal devices with high efficiency for personalized ventilation application. *Proceedings of Healthy Buildings 2003, Singapore*, *2*, 850–855.

Fanger, O. (2006). What is IAQ? *Indoor Air*, *16*(5), 328–334. https://doi.org/10.1111/j.1600-0668.2006.00437.x

Fanger, P. (2001). Human requirements in future air-conditioned environments. *International Journal of Refrigeration*, *24*(2), 148–153. https://doi.org/10.1016/S0140-7007(00)00011-6

Melikov, A. K. (2004). Personalized ventilation. *Indoor Air*, *14*(s7), 157–167.

Settles, G. S. (2001). *Schlieren and shadowgraph techniques: Visualizing phenomena in transparent media / G.S. Settles*. *Experimental fluid mechanics*. Berlin: Springer.