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Authors
Liu, Chonghui
Higuchi, Hiroshi
Arens, Edward
et al.

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Chonghui Liu[1,*], Hiroshi Higuchi[2], Edward Arens[3], Hui Zhang[3]

[1]Facilities Group, C&S Companies, Syracuse, NY
[2]Department of Mechanical & Aerospace Engineering, Syracuse University, NY
[3]Center for Environmental Design Research, University of California, Berkeley, CA

Corresponding email: cliu@cscos.com

SUMMARY

The goal of this joint project is to examine the physical performance of a Personal Environmental Control (PEC) or Personal Ventilation (PV) system that uses opposing airstreams in order to control the microclimate around the human head, and its effect on people's thermal comfort and perceived air quality. Both 4" (10.16 cm) and 2" (5.08 cm) diameter nozzles with respective exit velocity 2.0 m/s and 3.0 m/s (respective Reynolds numbers are 13,000 and 10,000) were studied with particle image velocimetry (PIV), hotwire anemometry and flow visualizations. Parallel human subject tests were conducted to validate their effects on people's perceptions of thermal comfort and indoor air quality. The radial resultant jets generated from the PEC system are able to penetrate the free convection flow at a manikin's face, and possess a fluctuation frequency of 2 ~ 4 Hz. The PEC system can improve thermal comfort and perceived air quality, while no dry eye discomfort was detected.

KEYWORDS

Indoor environmental quality (IEQ), Personal ventilation (PV), Personal environmental control (PEC), Opposing jets, Perceived air quality (PAQ)

INTRODUCTION

PV or PEC systems have been studied extensively (e.g. Kaczmarczyk et al. 2006), and PV systems have been commercially available since late 1980s (e.g. Tuhus-Dubrow, 2010); excellent reviews can be found at "Personalized Ventilation" (Melikov, 2004). Well designed PV can provide improved thermal comfort and indoor air quality (e.g. decrease sick building syndrome, reduce the risk of contagion transmission), increase occupant's productivity, while reducing overall energy use (e.g. Bauman, 1994; Bolashikov, 2009). Nevertheless PV systems haven't been widely applied because of its initial cost (e.g., Dieckmann et al. 2010), its interaction with total volume mechanical ventilation and also with the micro environment of occupant's body.

Existing devices tend to supply air from the front, which may cause little draft sensation (Fanger et al., 1988) but may cause dry-eye discomfort (Wyon and Wyon, 1987; Wolkoff et al., 2005) depending on the velocity. Toftum and Mayer compared air approaching from different directions and found that air directed towards the side of the head was advantageous. In this project, opposing jets of air were used as a PEC system to provide ventilation into the breathing zone from the sides.

Previous work on opposing flows includes visualization of supersonic jets (Thompson 1972), velocity and concentration measurements of two jets with different velocity ratios (Yoda and Fiedler 1996), and the velocity field of two-dimensional jets with different angle of inclination

PV and PEC are used interchangeably in this paper

(Besbes et al. 2003). They showed the general behaviour of the primary jets, but the behaviour of the radial exiting flow remains unclear. This study aims to elucidate this canonical flow field, its application in ventilation, and its effects on human subjects.

METHODS

The Personal Environment Laboratory (PEL) at Syracuse University was used to study the PV system's physical performance. The chamber measures 80" (2.03m) × 104" (2.64m) × 98" (2.49m) high; the exhaust is through a 0.58m × 1.17m perforated ceiling outlet and is connected to the building exhaust. Temperature, humidity and ventilation flow rate is controlled by a software, and all the data is constantly being logged into the control computer.

The opposing round air nozzles are placed in two wooden towers, which are 26" (0.66m) × 14" (0.36m) × 54" (1.37m) high. The height of nozzle centerline is 46.5" (1.18m), and nozzle to nozzle distance is 1.20m for 4" opposing jets; while nozzle to nozzle distance becomes 1.12m for 2" opposing jets because of the two 2" nozzle adaptors (at the length of 1.5" or 3.8cm).

For a typical PIV setup (Figure 1), the pulsed laser light is placed under the raised-floor; and the 8 bit 1280 × 1024 pixels cameras are mounted on a traverse mechanism outside of the chamber.

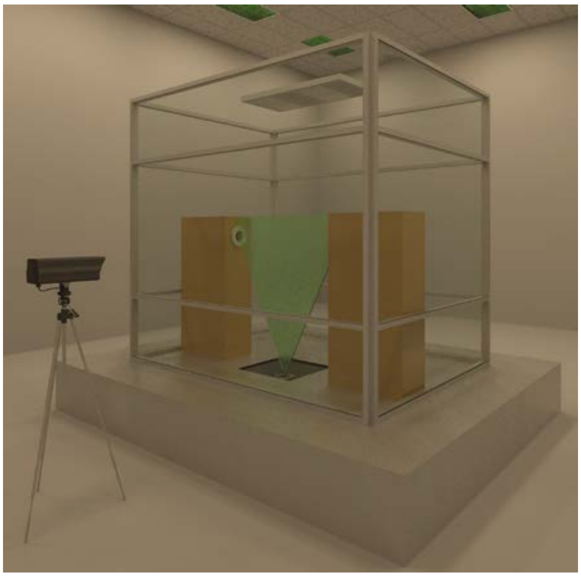

Figure 1. 3D rendering of a typical PIV setup in PEL at Syracuse University.

RESULTS

Flow visualization

Both the helium bubbles and fine oil droplets flow visualizations (Liu et al. 2009) show the stagnation region in the middle of the nozzle-to-nozzle centerline, and the radial resultant jets generated from the impingement region. Qualitatively, we found the radial jets fluctuate at a period of about 0.5 seconds; this will also be verified from spectrum analysis in the hotwire anemometry section.

Particle image velocimetry (PIV)

Dantec Dynamics PIV system was used for velocity measurements of 4" & 2" opposing jets, and 4" & 2" 10° angled opposing jets. All the PIV results were obtained by averaging 1,000 instantaneous velocity profiles, with 0.25 second recording time intervals.

The exit velocity of 4" opposing jets and 4" 10° angled jets, $\boldsymbol{U}_{0\ 4"}$, is 2.0 m/s (Reynolds number 13,000); while the exit velocity of 2" opposing jets and 2" 10° angled jets, $\boldsymbol{U}_{0\ 2"}$, is 3.0 m/s (Reynolds number 10,000). The mean velocity magnitude profiles of four configurations (Figure 2) are stitched by the velocity magnitude maps in several camera focus regions. In which x = 0 mm and x = 1200 mm correspond to the two 4" nozzle exit surfaces respectively (where the 2" nozzle adaptors are mounted), and y = 0 mm corresponds to the nozzle-to-nozzle centerline.

For all the four configurations, the protruding areas represent the potential core region (at a length of 3 to 4 nozzle diameters), where the “square hat” velocity profile at the jet exits gradually becomes rounded off as it moves towards the stagnation region. The concave areas in the figure represent the stagnation region, from where the radial resultant jets are generated. The two small convexes show the velocity peaks of radial jets, which magnitudes first increase rapidly and then decrease gradually as moving in the radial directions far away from the stagnation region. Furthermore, two counter rotating vortex (e.g. in vorticity maps) were detected near the shear layer of the radial resultant jets, which we believe are two ring vortex in the 3D coordinate system.

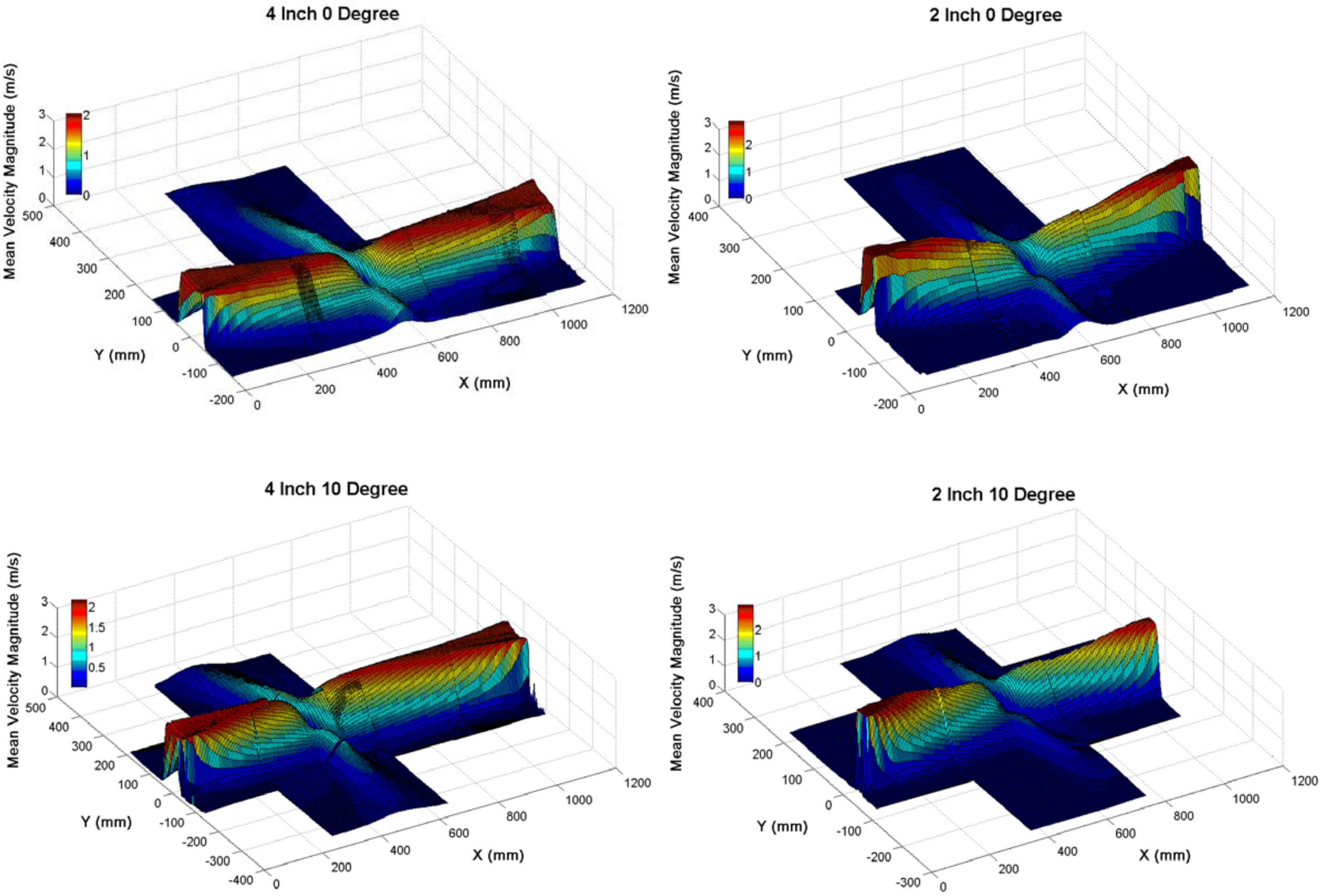

Figure 2. Mean velocity magnitude profiles of four configurations with $\boldsymbol{U}_{0\,4''}$ = 2.0m/s and $\boldsymbol{U}_{0\,2''}$ = 3.0m/s.

Bolashikov et al. (2003) measured that a mean velocity of 0.32 m/s is able to penetrate the free convection flow at the face. In the 4” and 2” opposing jets this velocity was found in the ring shaped region located about 3 nozzle diameters in the radial direction from the centerline. In the 4” and 2” 10° angled opposing jets, the mean velocity magnitude in the inclined direction is slightly stronger than that is in the opposite direction; and the velocity of 0.32 m/s can be found in the elliptical annular region located about 5 nozzle diameters from the centerline at the inclined side of the radial resultant jet, while about 2 nozzle diameters from the centerline at the opposite side.

Hotwire anemometry

Dantec constant temperature anemometer (CTA) and LeCroy oscilloscope were used for turbulence and spectrum analysis. The root mean square (RMS) fluctuation velocity (Liu et al. 2009) of 4” opposing jets shows an increased level of turbulence from the nozzle exit towards the stagnation region; and the peak RMS fluctuation velocity occurs further out from the nozzle to nozzle centerline.

All the spectrums were analyzed by averaging 24 sets of data, with each set contains 4,096 data points, at the sampling frequency of 500 Hz. By spot checking the data points of the radial jets near stagnation region for all the four configurations, we found the peak spectrum magnitude of the radial jets occurred at 2 ~ 4 Hz, where most of the energy exists. That is also the fluctuation frequency of the radial resultant jets, matching the flow visualization results obtained using fine oil droplets. Figure 3 shows the averaged spectrum of 2” 10° angled opposing jets with exit velocity $U_{0\ 2”}$, Reynolds number ***Re***, and Strouhal number ***St*** indicated.

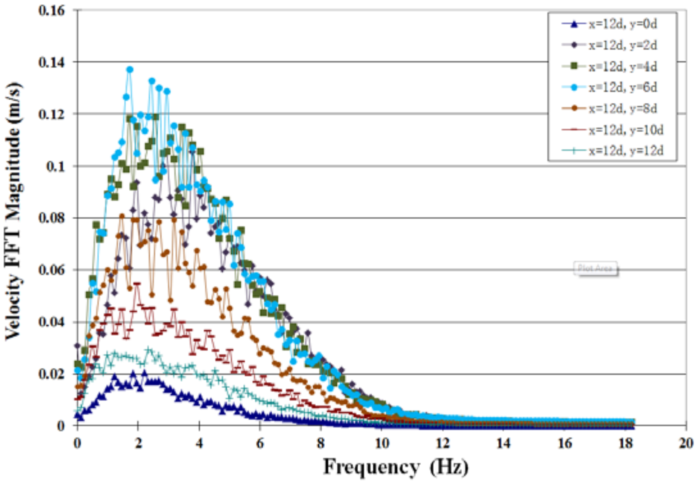

Figure 3. Averaged spectrum of 2” 10° angled opposing jets at nozzle to nozzle centerline (i.e. x/D=12) from y/D=0 to y/D=12. $U_{0\ 2”}$=3.0m/s, ***Re***=10,093, ***St***=0.05.

PIV measurement with thermal manikin

The PIV measurements with thermal manikin were conducted preliminarily for both 4” 10º angled and 2” 10º angled opposing jets with respective nozzle exit velocity 2 m/s and 3 m/s. Figure 4 shows the PIV setup with thermal manikin in the Personal Environmental Laboratory (PEL). Different from the previous setup, the PIV laser was located outside of the chamber with adjustable altitude; through the chamber plexiglass wall a horizontal sheet through the nose tip of the manikin can be illuminated. While the camera was mounted on a tripod supported by the two wooden towers, from the chamber top taking images downwards.

The thermal manikin was placed right in the middle of the two nozzles, with the nose tip in a line with the two center points of the nozzle exits. The manikin was preheated 3 hours before the measurements, in order to maintain the major parts a constant temperature of 85 ~ 95 ºF (29.4 ~ 35 ºC). The chamber temperature and relative humidity are controlled to be around 66 ºF (18.9 ºC) and 55% during the period of measurements.

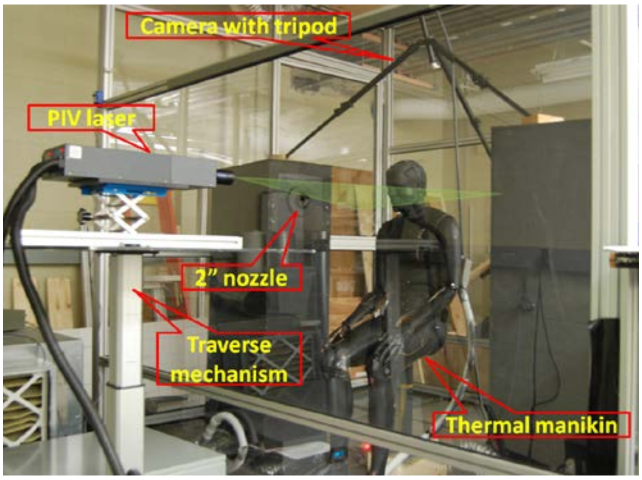

Figure 4. PIV setup with thermal manikin in the PEL at Syracuse University.

From the mean velocity vector and magnitude maps of both configurations (Figure 5), we found clear stagnation regions, and the jet potential cores ended before the impingement happened. The radial resultant jets were initially generated and growing in the radial directions as moving further away from the stagnation region; while the radial jet towards the thermal manikin was able to penetrate the free convection flow at the manikin's face. Further PIV measurements with thermal manikin are being conducted at Syracuse University.

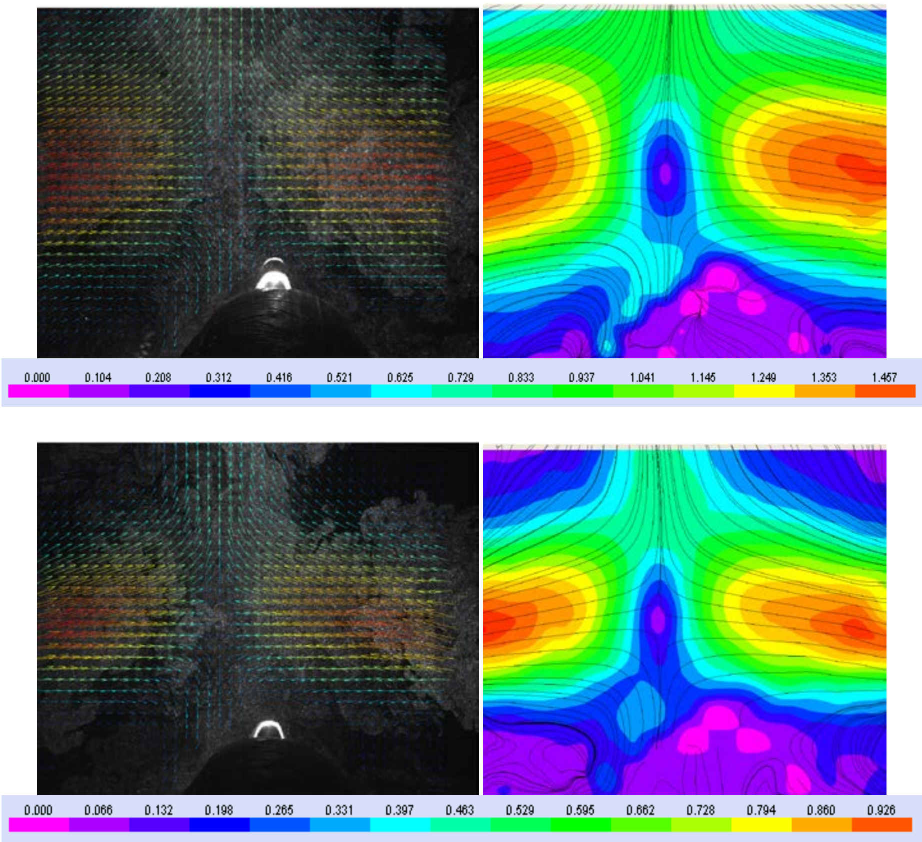

Figure 5. Mean velocity vector maps and mean velocity magnitude maps superposed by streamlines. (Top: 4" 10° angled opposing jets; bottom: 2" 10° angled opposing jets.)

Thermal comfort and perceived air quality

Refer to "Thermal comfort and perceived air quality of a PEC system" (Arens et al. 2011) for the parallel human subject tests of the same PEC system.

DISCUSSION

Conditioned air delivered by the PEC system is able to penetrate the free convection flow at a manikin's face, which will effectively control the microclimate around the occupant's head, providing improved thermal comfort and perceived air quality, with no dry eye discomfort.

Since large percentages of occupants prefer more air movement and ANSI/ASHRAE Standard 55-2004 is being updated with new provisions by using air movement to offset warm air (Arens et al. 2009), the authors believe the desired air movement frequency for comfort is 2 ~ 4 Hz. However, the possibility of a forcing with such frequency from the feed system or the chamber total volume cannot be ruled out for the current setup, and dedicated human subject tests are required.

CONCLUSIONS

PV or PEC should be more of a trend in HVAC design, rather than simply a commercial products installation. PV or PEC doesn't necessarily require expensive ventilation modules, it can be individual VAV or displacement ventilation, it can be dedicated outdoor air system, or even simply a split AC unit in occupied space. Weighing the huge energy savings and increased occupants' productivity, against the initial cost and HVAC system integration (depend on the design), the authors believe PV or PEC is very practical and should be considered by building designers and owners.

In terms of thermal comfort, air movement with a velocity field able to penetrate the body thermal plume and a fluctuation of 2 ~ 4 Hz is recommended for PV or PEC design.

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