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MEASUREMENT OF AIRFLOW PATTERNS IN VENTILATED SPACES USING PARTICLE IMAGE VELOCIMETRY

By

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Summary:

A Particle Image Velocimetry (PIV) system for room airflow study has been developed to quantitatively measure airflow patterns and air distribution in ventilated airspaces. Two-dimensional isothermal airflows were measured in a full-scale room (5.5×3.7×2.4 m). Measurements taken include the flow pattern of the room air, velocity vector maps and interpolated airflow pattern at two cross-sections of the test room with one typical ventilation system. This measurement method is part of a larger study of aerosol spatial distribution, ventilation effectiveness and aerial contaminant control strategies.

Keywords:

Airflow pattern, Air velocity map, Particle image velocimetry, Ventilation effectiveness

MEASUREMENT OF EFFECT OF AIR EXCHANGE RATE ON AIRFLOW PATTERNS IN VENTILATED SPACES USIG PARTICLE IMAGE VELOCIMETRY

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ABSTRACT: A Particle Image Velocimetry (PIV) system for room airflow study has been developed to quantitatively measure airflow patterns and air distribution in ventilated airspaces. Two-dimensional isothermal airflows were measured in a full-scale room (5.5×3.7×2.4 m). Measurements taken include the flow pattern of the room air, velocity vector maps and interpolated airflow pattern at two cross-sections of the test room with one typical ventilation system. This measurement method is part of a larger study of aerosol spatial distribution, ventilation effectiveness and aerial contaminant control strategies.

KEYWORDS:

Airflow pattern, Airflow velocity distribution, Particle image velocimetry, Ventilation effectiveness.

INTRODUCTION

Room air floor studies including airflow patterns, air quality, thermal comfort, and contaminant distribution are mostly conducted by experimental measurement and numerical simulation (Chen, 1992). Whole flow filed airflow pattern and air velocity distribution is essential information to understand performance of ventilation systems, occupants' comfort and well-being, contaminant spatial distribution, and CFD models.

Prototype studies are very expensive and time consuming largely due to limitations of the current available measurement technologies and instrumentation. However it is the only reliable way to study overall room airflow patterns and regional characteristics. Many previous researchers conducted intensive prototype measurements, obtained valuable date to gradually understand indoor airflow, and revealed many useful principles (Timmons, 1984; Sandberg, 1988; Zhang, 1991; Jin and Ogilvie, 1992; Riskowski, 1993; Wang, 1996; etc.). However they all used hot wire anemometers or other thermal effect based sensors to measure indoor air velocity distribution.

Thermal anemometers measure the flow velocity by sensing the heat transfer changes from a small, electrically heated sensing element. High temperature thermal sensing heads cause a significant amount of free convection. This phenomena creates flow velocity measurement error, especially in low velocity flow fields such as indoor air flow, which is typically in the range of 0~0.25m/s. Zhang (1991) evaluated the hot wire anemometer measurement error for indoor airflow and determined that the uncertainty is 25% of mean velocities of the measured airflow. In addition, point measurement results are difficult to interpolate into whole field studies.

Flow visualization is a classic method in aerodynamic and hydrodynamic studies. It was used to observe the indoor airflow pattern by several researchers. Carpenter et al. (1972), Nielsen (1974), Timmons(1979), Murakami(1989), and Zhang(1989) used either smoke or soap bubbles to visualize airflow patterns in a reduced scale ventilation room. Muller (1996) started use laser light and smoke to visualize airflow patterns in a livestock building. Due to the illumination and image acquisition difficulty, only the rough flow trends were obtained. Clear flow pattern pictures of room airflow have not been obtained, especially in a full-scale room.

As modern computer technology and image processing technology develop, qualitative floor visualization methods were improved to a quantitative measurement technology, Particle Image Velocimetry (PIV), which use particles and their images to measure flow velocities. PIV was initially invented for mechanical fluid study. Recently it has been adapted to study indoor air flow. A few researchers tried this technology and obtained promising progresses in different approaches (Brodie et al., 1993; Akikazu et al., 1996; Rasmus, 1996; Muller and Renz, 1996). Scholzen and Moser (1996) developed a three dimensional particle streak velocimetry system. Promising measurement results were achieved in a 2.4m×1.7m×1.2m ventilated model space. Zhao (1999) developed an alternative two-dimensional PIV airflow measurement method. However, no whole flow field PIV measurements have been done yet. New measurement techniques were applied to study typical test cases to obtain new information and understanding of indoor airflow.

MEASUREMENT SYSTEM AND PROCEDURE

Measurement System

The PIV measurement system consists of a test room, an illumination system with two sets of halogen lights with specially designed reflectors and cylindrical lenses, a flow seeding system with three helium filled bubble generators and specially designed bubble path tubes, an image acquisition system with a 4x5 photographic camera, an image shift system with a step servo-motor, and an image processing and interpolating system with a laser scanner, micro-computer, image processing software, and data analysis programs (Figure1).

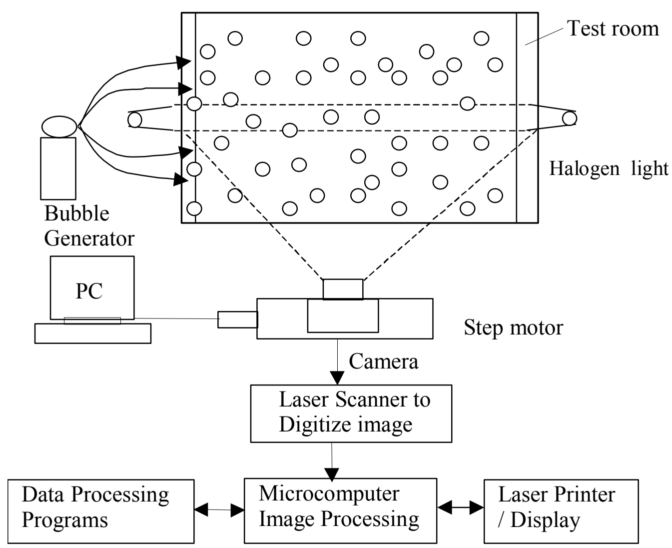

Figure 1. Schematic of the room air PIV system

A room ventilation simulator (RVS) was used to simulate the ambient environmental conditions of the study. The RVS consists of an outer room (12.2× 9.1×3.6m), which can simulate weather conditions from –25°C to 40°C any time during the year, and adjustable inner rooms to simulate ventilated buildings (Wu et al. 1989). A 5.5 × 3.7 × 2.4 m test room has been set up within the RVS for this study. One long wall of the test room is made of glass to permit convenient optical access. The two short-walls contain four glass slits to transmit the illumination light. The other long wall, floor, and ceiling surfaces are painted with non-reflective black paint to form a good optical background. The top view of the test room location and configurations are shown in Figure2.

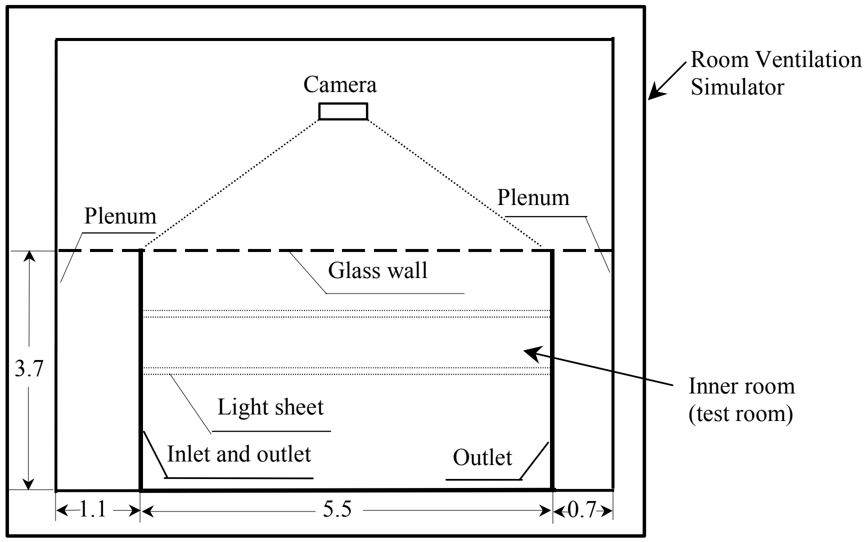

Figure 2. Plan view of inner test room location and configureation (all dimensions are in meters)

Experimantal Design

A traditional test layout, continuous ceiling slot inlet with slot outlet on the opposite side-wall (Figure 3), was simulated to compare the proposed method with traditional measurement methods. The air inlet is 50 mm wide and the air outlet is 200 mm wide. Four air change rates 8.6, 19.5, 28, and 66 ACH were set to simulate cold, mild, and hot weather ventilation situations. Isothermal test cases were conducted to determine the effect of ventilation rate on the airflow patterns. Inlet temperature was set at 24 °C. Test conditions are listed in Table 1. This study is part of a larger indoor air quality study.

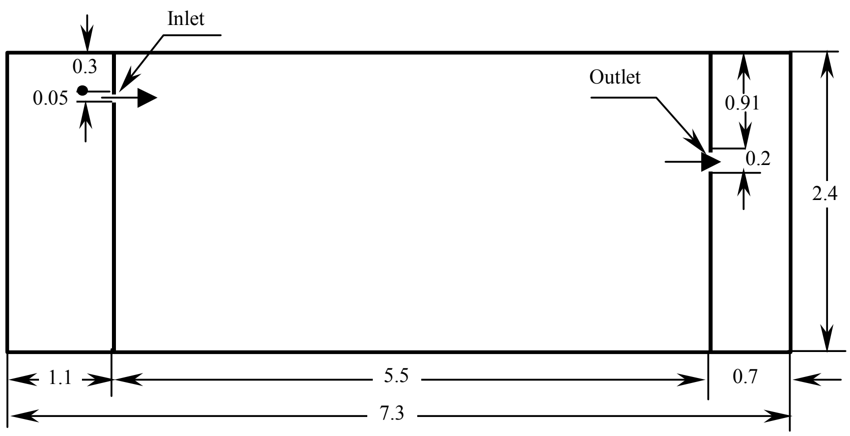

Figure 3. Room layout A inlet and outlet dimensions (meters).

Table 1. The experimental test cases:

Test Cases	Room Layout	Inlet Width (mm)	Inlet Temp (°C)	Outlet Temp (°C)	Air Exchange Rate (ACH)	Inlet Velocity (m/s)
Test 1	System A	50	24	24	19.5	1.78
Test 2	System A	50	24	24	28	2.54
Test 3	System A	50	24	24	8.6	0.76
Test 4	System A	50	24	24	66	6.10

Measurement Procedures

The whole flow field was divided into 10 areas according to flow characteristics and marked with white strings. The ventilation system was turned on for 30 minutes for the flow field to reach a stable state. Images of known size metal rulers were taken to calibrate the camera and lens. Reference images of each sub-area were taken for the noise removal purpose. Helium filled soap bubbles, which are neutrally buoyant and follow the air movements, was injected into the room through the inlet. A thin light sheet, which was generated by two opposite lights and has the dimensions of 2.4 ×7.3 ×0.065 m (H ×W ×D), was turned on to illuminate only the bubbles within the light sheet. When the bubble concentration reaches a point, at which most areas of the light sheet had sufficient bubbles, bubble visualized in the light sheet are recorded as streaks using a Sinar p2 4 ×5 photographic camera. To resolve the directional ambiguity, during image acquisition, the camera is shifted by a servo-motor, which is controlled by UNIDEX 500 motion controller software. Images of moving particles were streaks, which had any possible directions. With the shifted camera, images of particles in the flow field were shifted and become streaks toward a main direction, which can be recognized easily.

After the image is developed, it is digitized using a standard laser scanner. During image scanning, "bright' and "contrast" values were recorded for each image. The principle is to choose bright and contrast values to give clear scanned images. Generally, high contrast is better except for over exposed areas. To pick up streaks in dark shade, low contrast is needed. So some times, to pick up the streaks in a whole image, localized scan settings are needed due to non-ideal illumination. For the reference image, the scan setting should be the same as it was for the originals.

Scanned images are processed by Image Pro. A program is used to convert all images into a gray scale image and invert the negative to regular image. For each individual image:

- Subtract the reference image from its original image
- Dilate the processed image using a morphology function
- Count bright streaks and threshold the image locally
- Use Median filter to remove Salt and Pepper noise
- Measure length, angle, center X coordinator, and center Y coordinator
- Use a Visual Basic program to calculate displacement in X and Y direction, manipulate coordinate, and compensate shift.
- Use an extracted data file to draw raw velocity vector map
- Use a Visual Basic program in Excel to process the data further to create a data file required by the CleanVEC software (developed by Theoretical and Applied Mechanics Department at UIUC)
- Interpolate the raw vector map to generate velocity vector map with standard grid.
- Save the interpolated data and draw the final scientific vector map with TechPlot software.

RESULTS AND DISCUTIONS

Sample images are shown in Figure 4 and 5. The Figure 4 is a regular image with no shift action during image acquisition. The Figure 5 is a shifted image, which means that during the image acquisition process, the camera is moved horizontally (shifted) on a motor driven tray at a specially designed speed. Even through the two images were not taken at the same time and the flow field is not completely stable. We still assume the flow field is relatively stable for two-dimensional ventilation mode. Bubble steaks in Figure 4 has any possible directions, especially on the right lower part of the image. There is no way for people to confidently tell the direction of bubble streaks in a turbulent area. Bubble streaks in Figure 5 all mainly toward left. Theoretically, no shift bubble streaks plus shift amount should equal to shifted steaks in shifted image. Since the shift amount is known, it can be easily removed from shifted image data. Therefore, the direction of each bubble streak was calculated out.

Figure 6 shows a raw flow vector map extracted from the above shifted image. One can find bubble streaks in a flow field does have any possible directions.

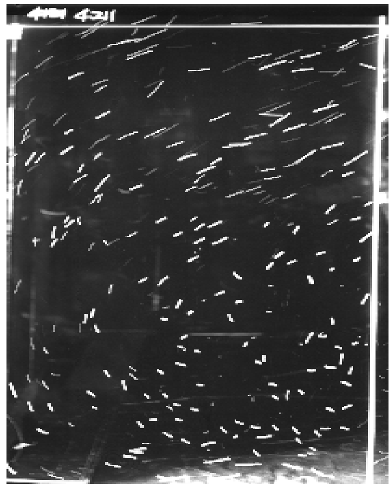

Figure 4. Samples of non-shift image and shifted image

Figure 5. Samples of shifted image

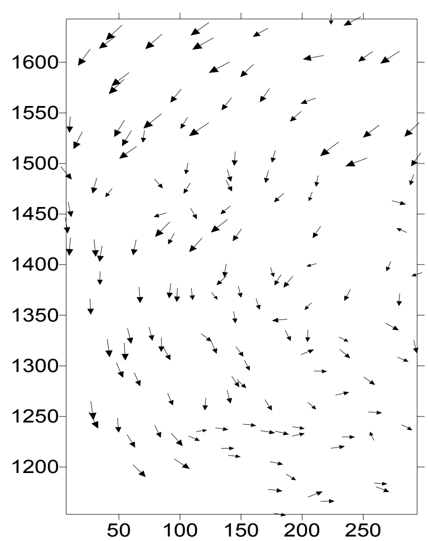

Figure 6. Raw velocity vector map extracted from shifted images

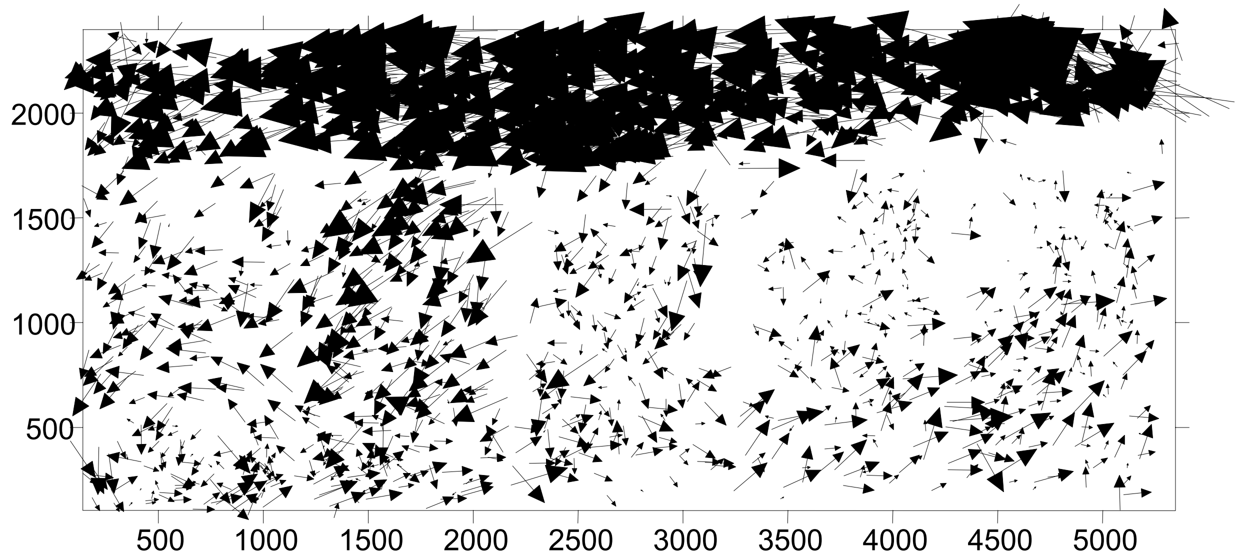

Figure 7. Raw velocity vector map of test 1(ACH =19.5), all units in mm

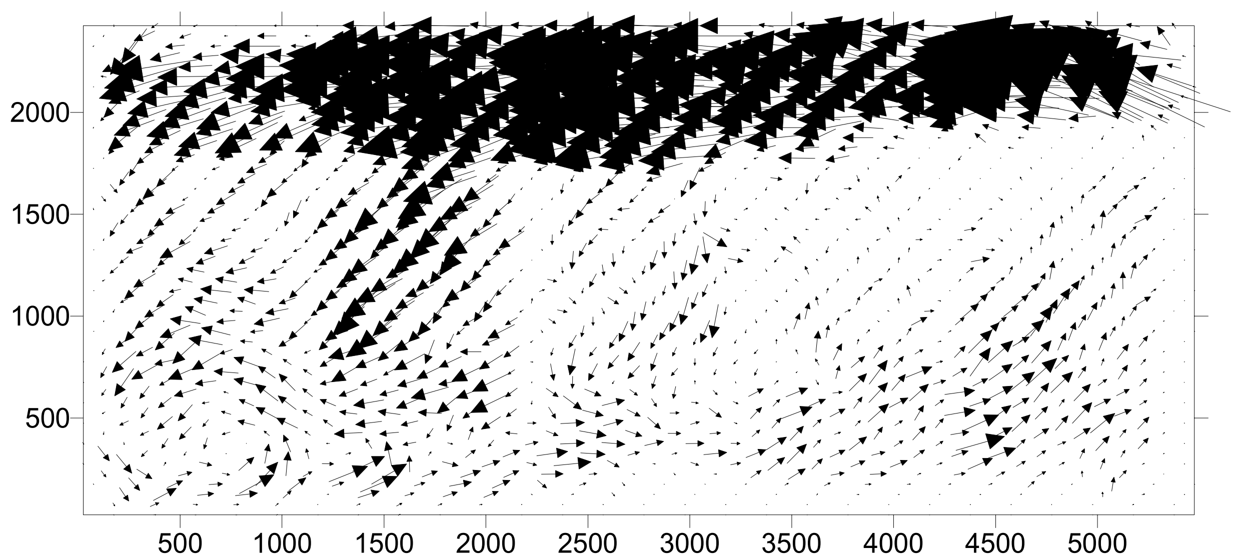

Figure 8. Interpolated velocity vector map of test 1 (ACH =19.5), all units in mm.

Figures 7 and 8 are the raw velocity vector map and the interpolated velocity vector map respectively, for the ventilation mode with 19.5 ACH. The well known Coanda effect can be clearly seen. The attachment length, in which inlet air travels before it is separated from the ceiling, is about four fifths of the room length. A major re-circulation zone was formed and a small vortex is formed at the corner near the room outlet.

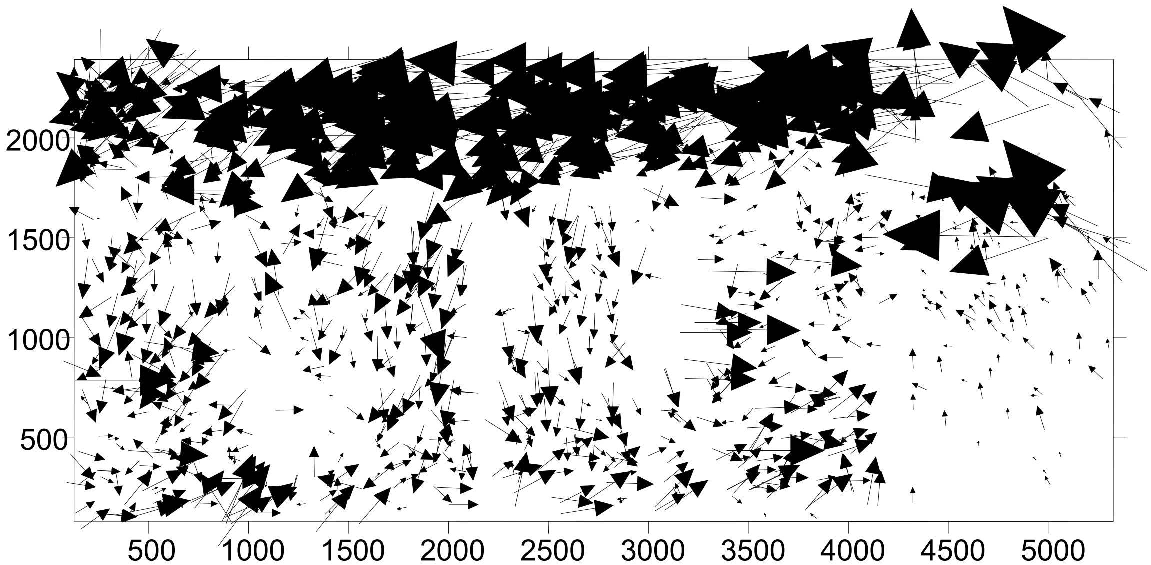

Figure 9. Raw velocity vector map of test 2(ACH =8), all units in mm.

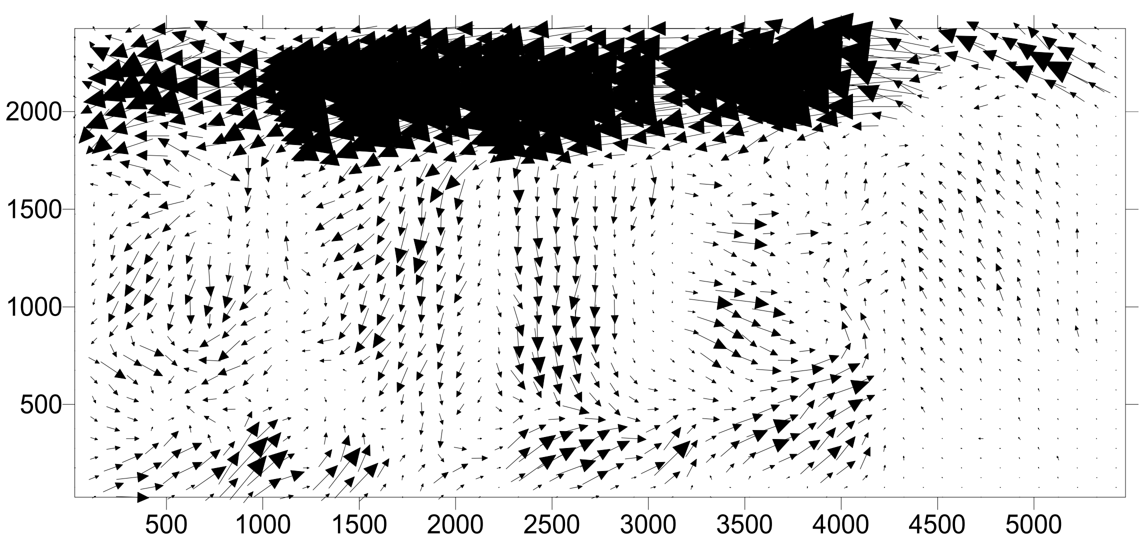

Figure 10. Interpolated velocity vector map of test 2 (ACH =8), all units in mm.

Figures 9 and 10 are the raw velocity vector map and the interpolated velocity vector map respectively, for the ventilation mode with 28 ACH. The well known Coanda effect also was shown. The attachment length was about four fifths of the room length. A relative small re-circulation zone was formed compared with the test 1. A small vortex is also formed at the corner near the room outlet. Near floor reverse flow patterns were stronger.

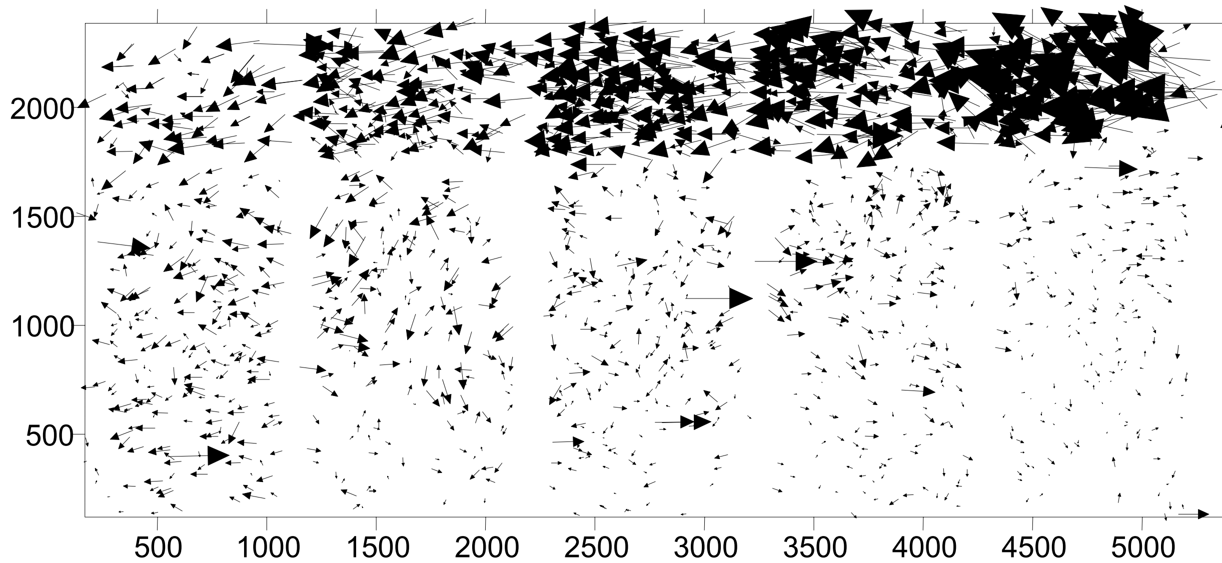

Figure 11. Raw velocity vector map of test 3 (ACH =8.6), all units in mm.

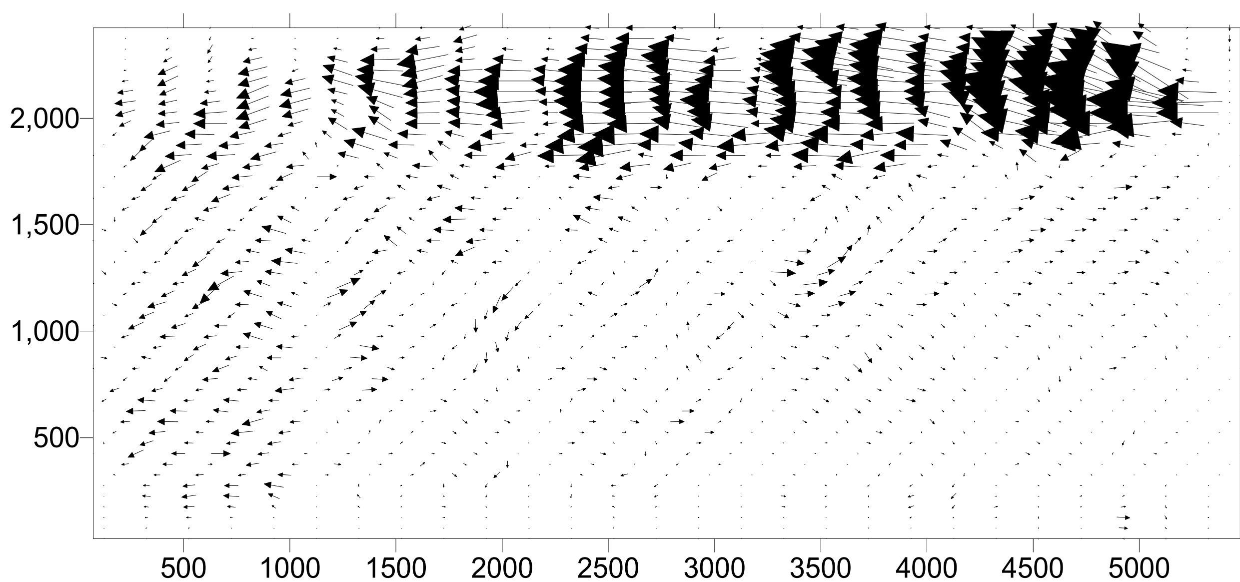

Figure12. Interpolated velocity vector map of test 3 (ACH =8.6), all units in mm.

Figure 11 and 12 is the raw velocity vector map and the interpolated velocity vector map for ventilation mode with 8.6 ACH. Famous Coanda effect also was shown. The attachment length about four fifth of the room length. No clear re-circulation zone was formed. A reverse flow was observed under the jet airflow. Airflow near the floor flows toward the outlet instead of flowing toward the inlet direction. Airflows in most occupied zones are very slow. The occupied zone near the outlet was more turbulent than other test cases.

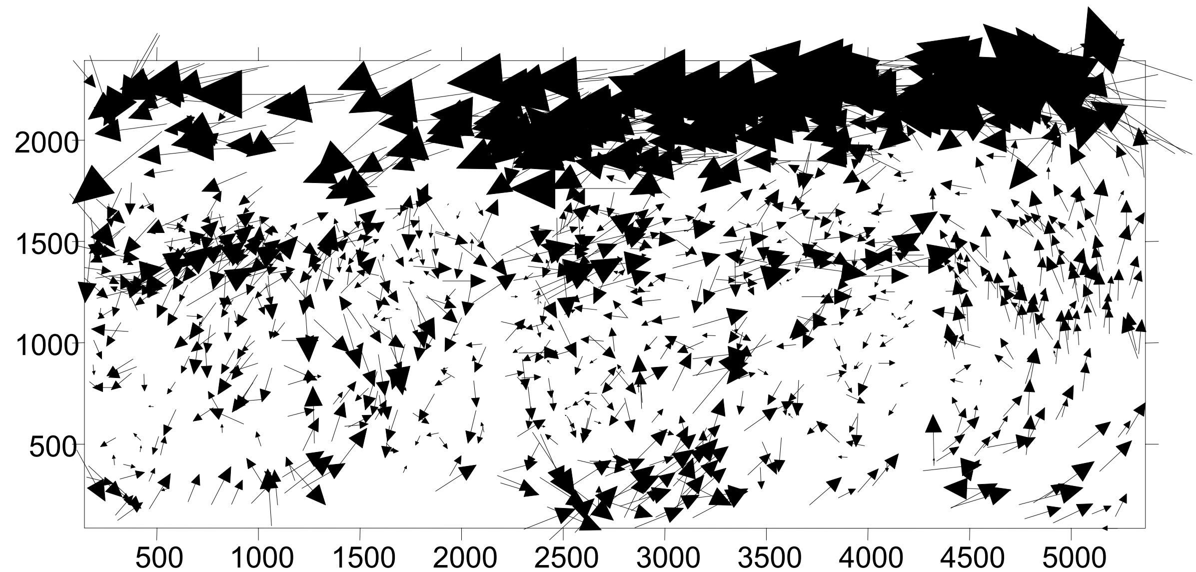

Figure 13. Raw velocity vector map of test 4 (ACH =66), all units in mm.

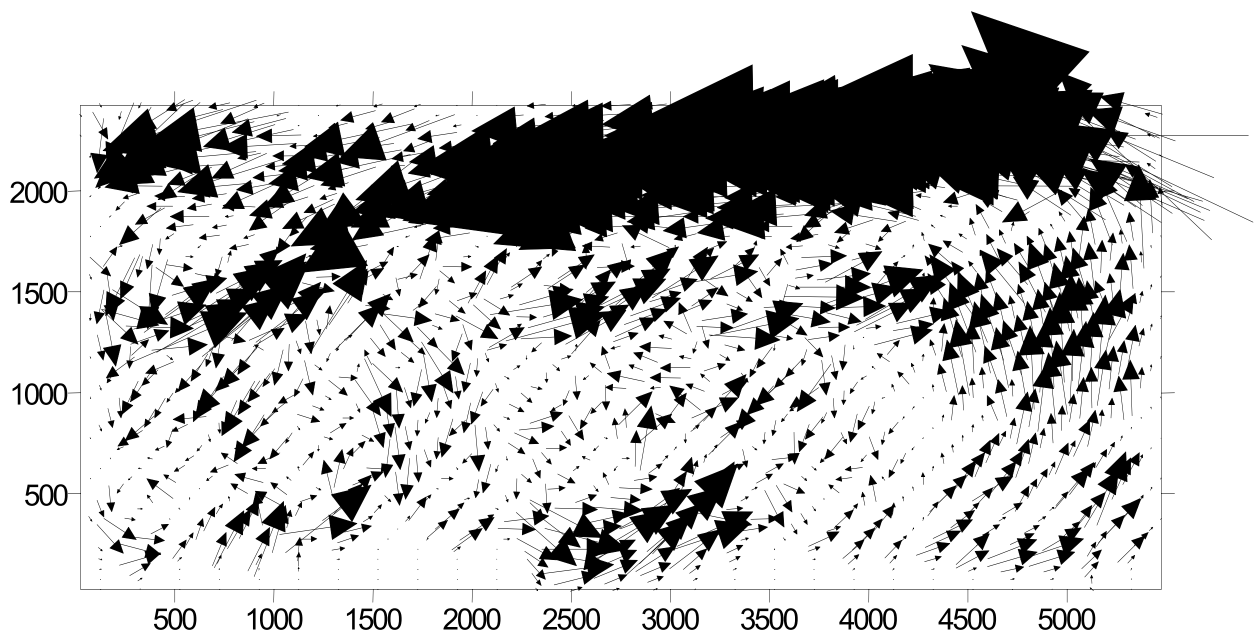

Figure 14. Figure11. Interpolated velocity vector map of test 4 (ACH =66), all units in mm.

Figure 13 and 14 is the raw velocity vector map and the interpolated velocity vector map respectively, for ventilation mode with 66 ACH. The well known Coanda effect also was shown. The attachment length about full room length. A strong re-circulation zone was formed. A reverse flow was observed under the jet flow. In near floor areas, reverse flow is very strong. In most occupied zones except the occupant area near room inlet, airflow is strongly turbulent.

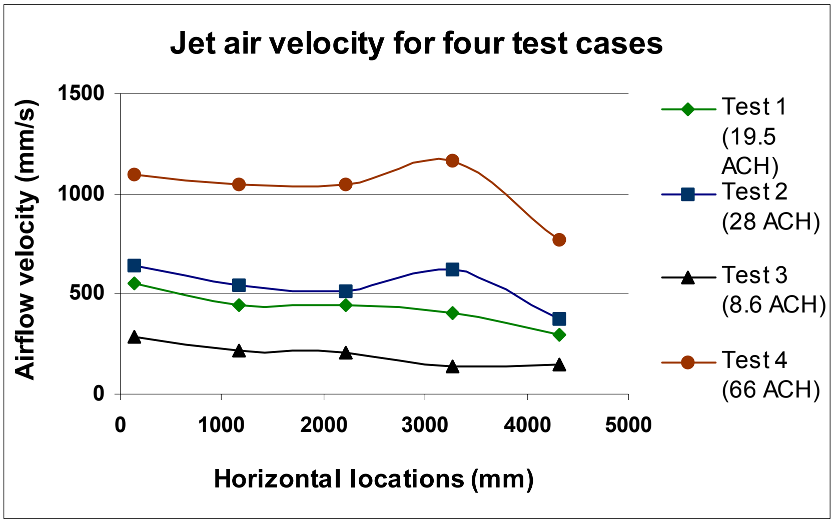

Figure 15 Variation of jet airflow velocity along the horizontal distance

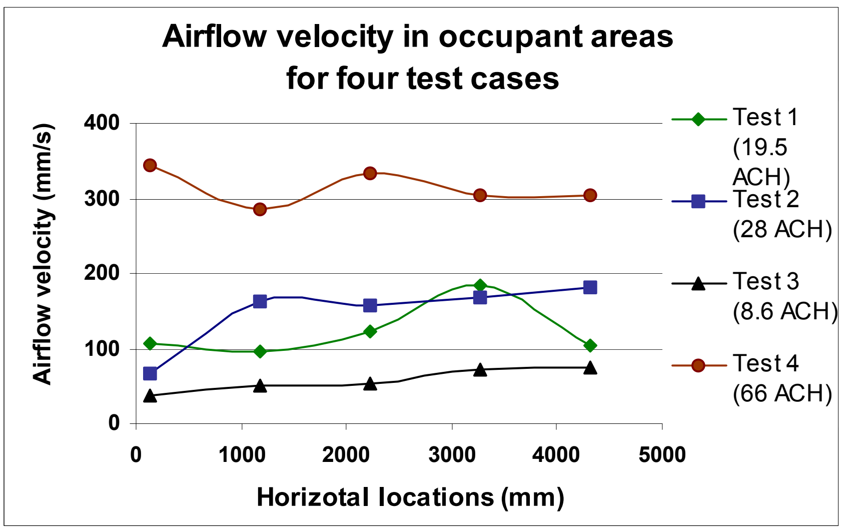

Figure 16. Variation of occupant area airflow velocities along horizontal distance

Figure15 shows that mean inlet air velocities decrease as the distance from inlet increases. Figure 15 also clearly shows jet airflow velocity range for four types of ventilation modes. Figure 16 shows similar information about airflow velocities in occupied zones. It is very interesting that the velocity change trends all different for four test cases.

CONCLUSIONS

PIV measurement system for indoor airflow has been developed and is mature enough to conduct whole flow field study. PIV is a good method to study low indoor airflow velocities. It can clearly show airflow patterns of an instantaneous flow. Meanwhile a quantitative data file is obtained to validate numeric models and conduct detailed feature analysis and factorial study.

Detailed experimental data and clear flow patterns are presented for four ventilation modes with small to large air exchange rates. The different ventilation modes do create quite different airflow patterns. Some parts of the patterns have conflicts with previous measurements and some parts agree very well with flow principles revealed by previous researchers. Airflow velocities in the occupant zones vary a lot for the tested four ventilation modes.

The PIV method still needs improvements. Illumination, calibration, and image processing are key factors for the accuracy of the measurement. A particle –seeding control device is needed to control the concentration and distribution of bubbles to ensure good quality images

Using a high resolution digital camera and laser light source to integrate the measurement system is suggested for further research.

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