Particle Image Velocimetry Experiments in a Wind Tunnel to Study Wind-driven Airflow through Building

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SUMMARY

Today's low energy and sustainable buildings often call for innovative designs involving strategies such as natural ventilation. However, natural ventilation airflows are often difficult to estimate, in large part due to the unsteadiness of the wind. This study investigates wind-driven natural ventilation experimentally using particle image velocimetry (PIV) in a boundary layer wind tunnel using a glass building analogue with modeled openings. Using the PIV technique, both the outdoor wind flow and the resulting indoor airflow were visualized and measured. By varying the opening sizes in the glass model and the wind directions, the airflow behavior near the openings was investigated. While PIV in a wind tunnel provides a useful investigative method to study wind-driven airflow, there are significant challenges in the experimental design and setup. This paper discusses the difficulties and presents possible solutions for improving the quality of data gathered from the experiment.

Keywords: NATURAL VENTILATION, Indoor airflow, PIV, Wind tunnel

INTRODUCTION

With today's focus on low energy and sustainable buildings, building designers, engineers and researchers are increasingly proposing to incorporate natural ventilation in innovative building designs. Despite these interests and the progress to date, one key component of natural ventilation, i.e., the wind, has proven to be a difficult problem due to its unsteady nature. One difficulty with predicting wind-driven airflow is the determination of the fundamental fluid mechanics involved in the vicinity of the ventilation openings. While it is common practice to model the airflow though building openings as simple pressure-driven pipe flows, with specific discharge coefficients for individual openings using the orifice equation (Karava et al., 2007)), this assumption is not valid when the openings became large (Seifert et al., 2006). Even with this knowledge, it is not clear when the transition between small opening flow (pressure-driven pipe flow) and large opening flow (momentum driven flow preserving wind characteristics) occurs. Researchers have assumed small openings to be roughly 2 % of wall porosity (Chang and Meroney, 2001), with large openings over 15 % wall porosity (Seifert et al., 2006). These values leave a large grey area for many common building openings (e.g. windows and doors).

To investigate this issue, experiments were conducted using a boundary layer wind tunnel, particle image velocimetry (PIV) and a glass building model with openings to simulate wind-driven flow through a building. Using the PIV technique, both the simulated outdoor wind flow and the resulting indoor cross ventilation flow can be visualized and measured through the glass model. By varying the opening sizes in the glass model and the wind directions, the fluid behavior near the openings was investigated. The experimental results will provide a novel representation of the airflow characteristics for wind-driven flow through a building. At this point, the study is ongoing and only partial results and specific discussion on PIV experimental setup are presented.

METHODOLOGIES

While PIV investigation of wind-driven airflow had been conducted by Karava et al. (2011), the previous study only focused on opening location variations in the vertical plane along the center of the windward and leeward walls. This current investigation focuses not on the opening location, but on the effect of opening size and wind incident angle on wind-driven ventilation. This study also marks the first attempt to use glass models to improve data quality for the PIV image. The glass model was placed inside a recirculating boundary layer wind tunnel to simulate specific airflows required for the experiment. A schematic diagram of the experimental setup is shown in Figure 1

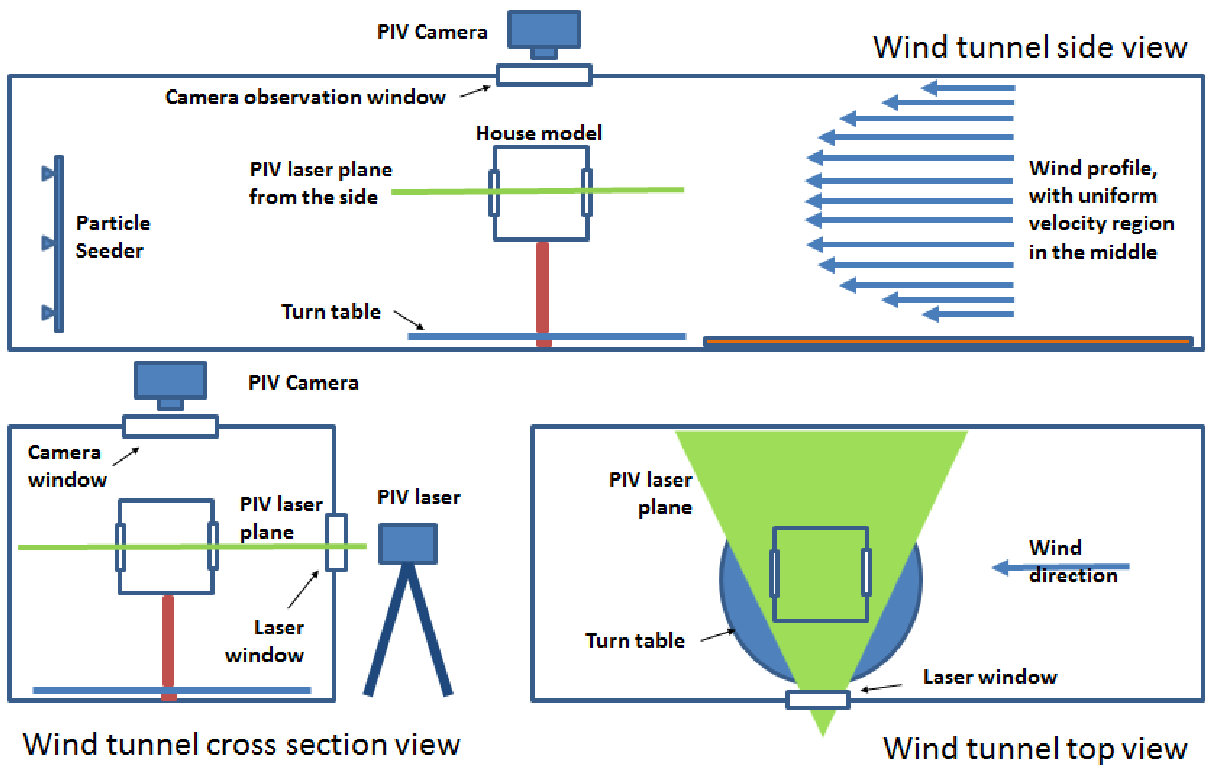

Figure 1. Experimental setup (not to scale). The glass model is place on a raised platform to reach the uniform velocity region of the wind tunnel, while the PIV laser projects the laser sheet parallel to the ground from the side. The PIV camera observes the area of interest from the top of the wind tunnel through an observation window.

Glass Models

Four glass cubes with 10 cm sides were constructed for the experiment, modelling a 2 meter real size cube building at 1/20 scale. Each glass cube has two identical square openings, placed in center of the opposite walls; with the sizes varying between the models at 2 %, 5 %, 10 % and 15 % wall porosity. Wall porosity is defined as the ratio of the area of the opening to the wall surface for the given façade. The corresponding opening sizes used are listed in Table 1. Un-tinted quartz glass is used for its optical quality over window glass or poly-methyl methacrylate. A photograph of one of the glass cubes is shown in Figure 2.

Table 1. Opening size test cases for the class models

Wall porosity (%)	Opening side length (cm)	Opening area (cm^2)
2	1.4	1.96
5	2.2	4.84
10	3.2	10.2
15	3.9	15.2

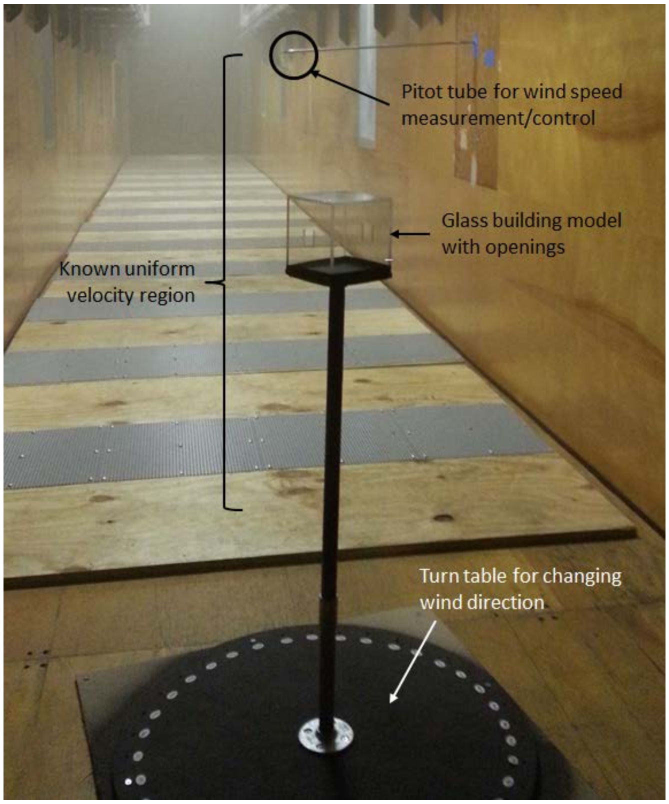

Figure 2. Experimental setup inside the wind tunnel, including the turntable, the elevated stand, the glass model, and the pitot tube used for measuring the wind tunnel air speed

Wind Tunnel Setup

For the current stage of investigation, a uniform wind velocity profile with little turbulence is used for studying the sole effect of opening sizes and wind incident angle. This specific wind condition was achieved in the NIST Physical Measurement Laboratory's Fluid Metrology wind tunnel (T. T. Yeh and J. M. Hall, n.d.), which provides a uniform velocity profile in the middle of the test section (averaging ± 0.1 m/s), low turbulence intensity (2 %) and airspeed control precision of ± 0.01 m/s using a pressure/temperature/relative humidity feedback control loop. This configuration has the capability of providing a stable wind velocity profile from 1 m/s to 5 m/s in 1 m/s intervals.

The upper velocity constraint of 5 m/s was imposed due to the small vibration caused by the wind tunnel operation. The vibration introduces additional movement in the PIV image and renders the image unusable at higher speeds. One difficulty introduced by the inability to increase the wind velocity is the failure to achieve dynamic similarity using the 1/20 scaled model as the wind tunnel speed is similar to the full scale wind. However, Cermak (1995) stated that wind tunnel testing for buildings have always suffered such problems as the building model scales are usually extremely small while upper wind tunnel air speed is limited. The concept of Reynolds Number Independence is used for wind tunnel testing for buildings, which ignores the similarity for high frequency turbulence, as long as the mid-frequency turbulences relevant to buildings are matched via the use of the wind speed power density spectrum.

The wind tunnel setup also involved the installation of the temporary turn-table (See Figure 2) for varying the wind incident angle. Due to the symmetry of the model (see the glass model section), only one-quarter of the possible wind incident angles (wind direction) were tested, from 0 degree to 90 degree in 10 degree intervals. Between the three parameters tested (opening size, wind direction and wind velocity), a total of 200 test cases are planned. At this time, 70 selected tests have been completed. Figure 2 also shows one of the glass models being tested, with the model elevated above the turn-table using a round steel pipe for support. The steel pipe eliminated most of the subtle vibration from the wind pressure, which otherwise would affect the PIV image quality.

PIV Setup

The particle image velocimetry system used in this project consists of one pair of Class 4 (200 mJ per pulse) Nd:YAG lasers at 532 nm wavelength, a high speed camera with a band pass filter for the 532 nm wavelength, particle seeders, and software to facilitate the hardware. The setup schematic was described previously in Figure 1, where the lasers were installed on the side of the wind tunnel with the laser sheet parallel to the ground and the camera was installed above the glass to obtain the imaged for the flow field. Figure 3 shows photographs of the installation. The seeding criteria follows Melling's (1997) suggestion with 1 μm particle size used for PIV and 10 μm particles used for visualization images. Each PIV investigation includes 30 pairs of high speed images with a 250 μs time step. The resulting velocity profile is the average of 30 image pairs. The specific interrogation and post processing methods are currently being tested and developed, and only preliminary results and visualization images are included in this paper.

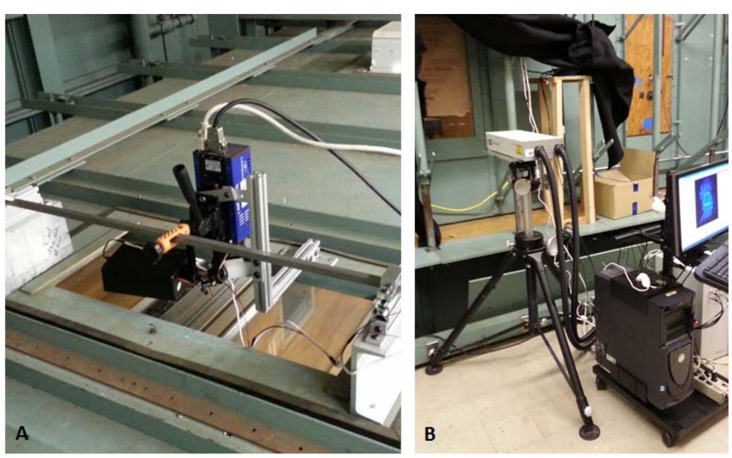

Figure 3. (a) PIV camera installed on the top of the wind tunnel with the observation window, and (b) the PIV laser located on the side of the wind tunnel

RESULTS AND DISCUSSION

Preliminary results of the ongoing study are presented here along with discussions of challenges with using PIV on a glass model in a wind tunnel.

Difficulty due to reflective and opaque surfaces

Figure 4 shows a processed velocity profile with one of the images used for averaging (insert). In Figure 4 there is missing PIV data (the empty regions) in both left and right areas of the glass model. This is due to the reflection of the model surface, which created a brighter area near the laser inlet (right side of the figure) and a darker spot near the outlet (left side of the figure). Additionally, as seen in Figure 4 insert, Figure 5 and Figure 6, there are several dark streaks on the left side of each image. These streaks are laser shadows cast from the rougher edges of glass in the model, which also affect the PIV data quality in those areas. Improvement of optical quality is possible by using a wavelength-specific filter coating on the glass and finer polishing on all edges. Such treatment will be considered in the future work.

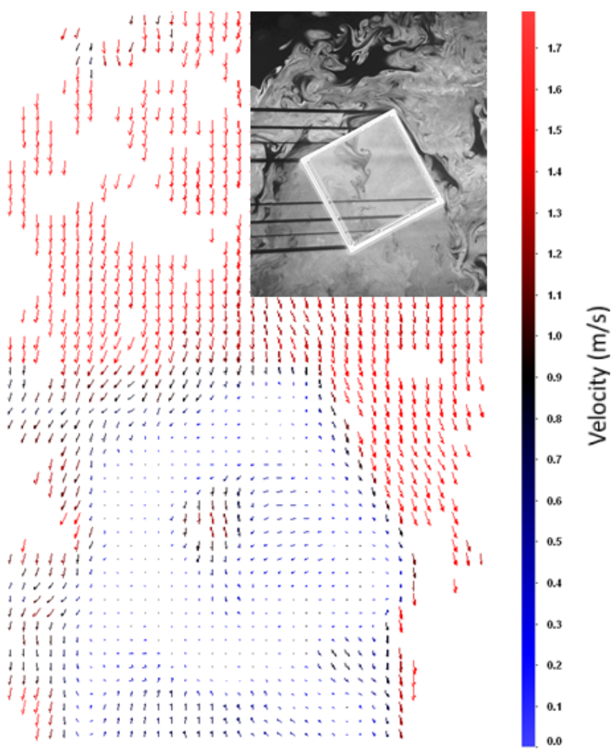

Figure 4 PIV results of airflow velocity vectors on the x-y plane for the test case 10 % wall porosity, 2 m/s wind speed and 30 degree wind direction. Problem areas include streaks from shadows, uneven particle concentration at various spots, and bright reflection on the bottom right of the vector field.

Difficulty in obtaining dual purpose images

Figure 5 shows a side by side comparison of the two type of imaged acquired during the experiment. Figure 5a is a visualization image while 5b is an image used for PIV. 5a does not work well for PIV purposes due to the large particle concentration difference between various regions, making PIV image post processing difficult and often inconclusive. Figure 5b provided good particle seeding concentration (almost uniform), but it resulting in an image without visible flow features, not suitable for visualization purposes.

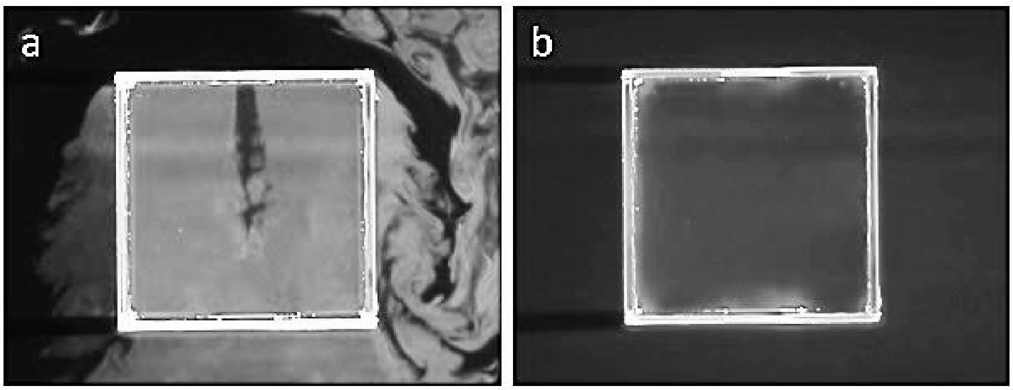

Figure 5 Different images for different purposes: a) good visualization image with definitive flow structures, b) good PIV image with no missing or bright particle clusters

Uncertainty of device placement

One of the key issues with the PIV technique is the problem with determining the measurement uncertainty. As Cao et al. (2014) noted in their review paper on the use of PIV for indoor airflow measurement, the technique is prone to position induced errors due to complication in experimental setup. Besides the possible errors mentioned by Cao et al., additional obstacles were discovered in this experiment, specifically associated with the optical quality of the PIV setup.

Evidence of pressure driven flow

While insufficient data have been analyzed to identify the transition point between the pressure driven and momentum driven airflow at this time, qualitative verification of previous assumptions has been accomplished. For example, the 2 % opening case at 10 degree wind direction (Figure 6b) yield a visible jet that is perpendicular to the wall surface in the smoke visualization image, a phenomenon that only happens if a complete pressure driven flow is present. As the wind incident angle increases to 30 degrees (Figure 6c), however, the jet destabilized and tilted, resulting in an airflow that is not purely driven by the static pressure around the opening. Such results are most likely produced by significant pressure differences around the opening as the incident angle increases. Additional experiments are planned to study the flow shape inducing mechanism and the impact on indoor flow field estimation.

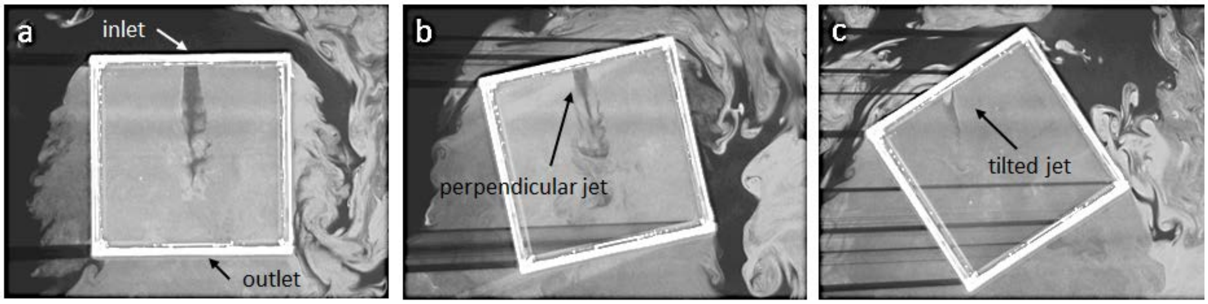

Figure 6 Flow visualization of the 2 % wall porosity test cases at 2 m/s wind speed (wind tunnel airflow from top to down) with variation in wind direction (a) 0 degree (b) 10 degree (c) 30 degree

Evidence of momentum driven flow

As the opening becomes larger, the visualization images in Figure 7 (progression from 7a to 7c) show that momentum based flow starts to dominate. In Figure 7a, where the opening size is at 2 % wall porosity, the small opening pressure driven jet is still evident. When the opening size increases to 5 % in Figure 7b, additional eddies entering from outside the cube become visible. When the opening size increases to 10 % in Figure 7c, there doesn't seem to be much pressure driven jet remaining.

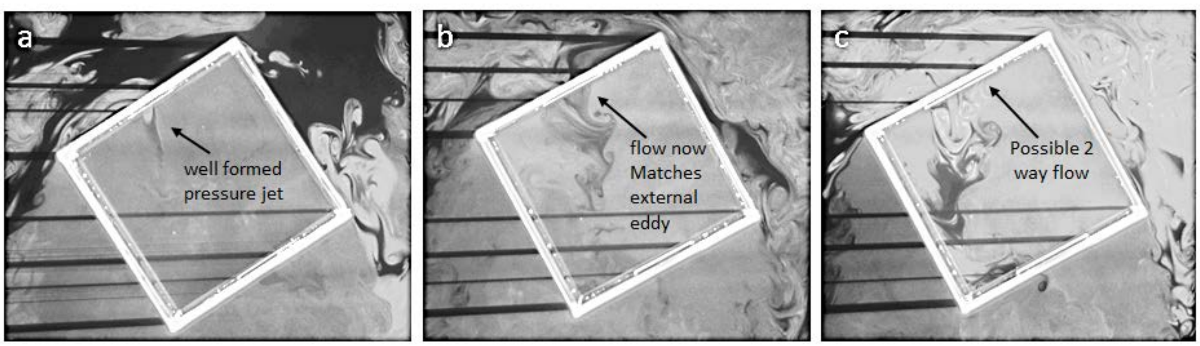

Figure 7 Flow visualization of the 30 degree test cases at 2 m/s wind speed (wind tunnel airflow from top to down) with variation in opening sizes (a) 2 % (b) 5 % (c) 10 %

Transition between momentum and pressure driven flow

From visual inspection, the evidence provided in Figure 6 places the transition point between the pressure and momentum driven flows somewhere between 2 % and 5 % wall porosity. While further PIV analysis will provide more quantitative data to formulate a model of this transition, it is difficult to experimentally obtain the exact transition wall porosity due to accuracy required to identify small changes in opening size between 2 % and 5 %. A computational fluid dynamics (CFD) investigation could provide the necessary accuracy for virtual experimentation, while using the PIV data for validation purposes.

Implications on natural ventilation flow estimation

As mentioned in the introduction, the typical estimation of wind driven natural ventilation flow assumes a simple pressure driven pipe flow and employees the orifice equation, as seen in ASHRAE Handbook Fundamentals (2009), chapter 16. Without precise pressure data on building façades, an engineer might also consult chapter 24, airflow around the building, to estimate the pressure at the façade as the driving force for the ventilation flow. However, this approach's base assumption is that the airflow is pressure driven. As the visualization in Figure 5 and 6 imply, this assumption would only be valid at very low wall porosity. Since most intentional openings, such as windows, are potentially larger than 2 % wall porosity, estimating wind-driven flow rate using the pressure assumption could result in significant error. While the most recent manual for natural ventilation design, Chartered Institution of Building Services Engineers' Application Manual 10, Natural Ventilation in Non-domestic Buildings (CISBE, 2005) discussed possible errors in large opening cases, the manual referred to using other estimation technique such as CFD to simulate the resulting airflow. Therefore, the parameters investigated in this study will have significant impact on designers in their efforts to simulate and estimate natural ventilation flow.

CONCLUSIONS

PIV investigation of wind-driven natural ventilation airflow was conducted in a wind tunnel using a glass model. The preliminary results indicate the PIV technique can be used to investigate the effect of wind direction and opening sizes on the ventilation flow. Qualitative visualization for the conditions tested suggests the transition opening size from pressure to momentum based airflow is over 2 % but smaller than 5 % wall porosity. Such small opening size implies that pressure based airflow assumption might not be correct when estimating wind-driven natural ventilation airflow through a building. Further analysis and CFD based parametric analysis will provide data for ongoing modelling efforts to more accurately describe the interactions between the factors impacting transition over wider range.

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