A NEW APPROACH TO VENTILATION MEASUREMENTS IN ENCLOSURE FIRES

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ABSTRACT

The application of Stereoscopic Particle Image Velocimetry (SPIV) is a new approach to quantifying the ventilation in enclosure fires. Stereoscopic PIV is a non-intrusive optical measurement technique which measures the displacement of tracer particles in a flow. The technique is completely independent of temperature and differential pressure measurements typically applied to quantify ventilation in enclosure fires. Stereoscopic PIV is capable of performing thousands of measurements over large planar regions and resolving the flow velocity into its three components, (v_x, v_y, v_z) . Using the International Organization for Standards (ISO) 9705 room and a natural gas burner to generate conditions similar to the developing stages of an enclosure fire, SPIV was applied to measure the complete velocity vector field of the flow of air supplied to the room through a doorway. Two separate SPIV configurations were performed to measure the particle displacements normal to the doorway plane. Very good agreement was achieved for the velocity results from the two SPIV configurations, therefore permitting greater confidence in the SPIV results. Conventional measurements of temperature and differential pressure were also performed in the doorway using bare bead thermocouples and bi-directional probes, respectively. This allowed for a comparison of bi-directional probe velocity measurements to an independent method of measuring flow velocity in real fire conditions. There was a wide range of discrepancy between the velocity inferred from the physical probe measurements and the velocity measured with SPIV. The results suggest that flow field characteristics play a significant role in interpreting the measurements from the bidirectional probes.

INTRODUCTION

The release of heat due to fire causes the surrounding gases to move due to expansion and buoyancy. The resulting fire-induced flows are of very low speed and they may occur over large spatial regions, especially in the case of full-scale enclosure fires. Accurate measurements to quantify the ventilation in enclosure fires are difficult due to the need to measure small gas velocities for a large area and all while contending with the hazardous conditions of the fire. The net ventilation of an enclosure fire includes the amount of fresh air supplied to the room and the amount of hot fire gases escaping out of the room. The fresh air provides the oxygen necessary to sustain the fire hazard but it also helps to moderate the temperature of the room interior. The escaping hot air and combustion products increase the physical extent of the hazard by transferring heat, smoke, and toxic gases to other locations of a building.

Quantifying the ventilation of a burning room in terms of mass flow rate requires measurements of gas velocity and gas density. The flow through vents is countercurrent and three dimensional, therefore a full mapping of the velocity and density fields is required to achieve the best accuracy. Due to the spatial extent of full-scale fire experiments, a complete velocity and density mapping of vent flows was not a feasible option for early investigations. Early efforts to measure the ventilation of room fires employed only a few well placed pressure and temperature measurements and relied on Bernoulli's equation and the assumption of one dimensional flow. ^{1, 2} Later treatments were improved by making pressure and temperature measurements were improved by making pressure and temperature measurements were is and bare-bead thermocouples. The vertical arrays were scanned across the vents in order to address the three dimensional nature of the flows.³,

Since the introduction of the bi-directional probe, it has been the accepted method of measuring flow speed and quantifying the ventilation in fire experiments. The probe is simple to apply and very robust to withstand the harsh environment of the fire. It has been characterized in well conditioned wind tunnel and duct flows^{5, 6}, however these flows only simulated the effect of Reynolds number and not the actual use in complicated flow patterns and under high temperature conditions. The bi-directional probe is a physically intrusive device. Its response to the conditions surrounding it governs how flow velocity is inferred from the measurement. It is anticipated that for flow conditions different from the wind tunnel and duct flows of previous investigations, the response of the probe will be different.

The following sections will describe an effort to compare flow velocity measurements from bi-directional probes with an independent technique, Stereoscopic Particle Image Velocimetry, under the conditions of an actual fire-induced flow. Using the ISO 9705 room and a natural gas burner to generate conditions similar to the developing stages of an enclosure fire, SPIV was applied to measure the velocity of the air moving into a room through a single vertical opening, the doorway. A planar interrogation over the lower 80 % of the doorway resulted in a measurement of the complete velocity vector field of the flow of air into the room. SPIV is a non-intrusive optical measurement which measures the displacement of tracer particles in a flow, making it completely independent of the bi-directional probe method. The technique is capable of performing thousands of measurements over large planar regions and resolving the flow velocity into its three components, (v_{x} , v_{y} , v_{z}). Directly measuring the velocity component normal to the plane of the doorway is essential to increasing the accuracy of the computation of volume flow rate or velocity flux across a plane. The large spatial extent of the measurement allows for a complete mapping of the velocity field. The technique is also capable of high spatial resolution, thereby revealing greater detail about the flow structure which allows for better interpretation of the results.

EXPERIMENTAL SETUP

The fire experiments were performed using the ISO 9705 Room. This is a full-scale room used to evaluate wall surface products for their contribution to fire growth. Fabrication of the room followed the specifications stated in the standard.⁷ The interior dimensions of the room were measured using a flexible tape measure and determined to be 3.60 m x 2.40 m x 2.40 m (length x width x height). The interior walls of the enclosure were lined with both drywall (lower half of the vertical walls and the floor) and calcium silicate panels (upper half of the vertical walls and the ceiling). Both materials were applied as two sheets and the resulting wall thickness was 2.5 cm. The estimated standard uncertainty of the interior dimensions is ± 0.04 m. A doorway served as the only vent for the enclosure. It was located on the center of one of the 2.4 m x 2.4 m walls, and had internal dimensions of 0.79 m x 1.96 m (width x height). The depth of the doorway was larger than usual due to the requirement of a window mounted on one side of the doorway to pass the laser sheet across the doorway for the PIV measurements. The depth of the doorway or jamb depth was 0.30 m, resulting in a doorjamb that extended beyond the exterior framework of the enclosure. The estimated standard uncertainty of the doorway dimensions is ± 0.01 m. A rectangular coordinate system, (x,y,z), was adopted for dimensions and measurement locations. Its origin (0,0,0) was located at the floor of the doorway and at the geometric center of the plane defined by the width of doorway and the depth of the doorjamb, Figure 1.

Measurements of differential pressure through the doorway were acquired with a vertical array of 14 bidirectional probes placed on the centerline of the doorway. The bi-directional probe is an impact probe similar to the Pitot-static probe. The probe obstructs the flow and creates a pressure differential, ΔP , between its front and rear surfaces. The pressure differential was measured using a differential pressure transducer (one for each probe) with a measurement range of (0 to 133) Pa. The probe dimensions used for the present investigation are displayed in Figure 2. The probe array began at coordinates (0,14,0) cm (14 cm above the floor of the ISO 9705 room) and the vertical spacing between each probe was 14 cm, with the exception of a spacing of 12.5 cm between the topmost probe and its adjacent probe.



Figure 1 Schematic of ISO 9705 room and instrumentation.

Figure 2 Bi-directional probe dimensions.



Temperature measurements from bare-bead thermocouples were used to estimate the vertical profile of gas temperature, T, in the doorway. The thermocouples were placed next to each bi-directional probe to provide an estimate of the local gas temperature. All thermocouples were Type K with 0.6 mm bead diameters, with the exception of the 4 topmost thermocouples (located above an elevation of 1.4 m). These thermocouples were exposed to the high temperature gas flowing out of the room and were therefore insulated with fiberglass and had a bead diameter of 1.0 mm.

Using the familiar relation for Pitot-static probes, the flow velocity, V, was inferred from the local differential pressure, ΔP , and temperature, T, measurements.

$$V = \frac{1}{C} \sqrt{\frac{2R_u}{P_{ref} M W_{gas}}} \Delta PT$$
[1]

For a well designed Pitot-static probe, the probe constant, C, is equal to unity. Because the bi-directional probe is not an ideal Pitot-static probe, its probe constant deviates from unity. McCaffrey and Heskestad⁵ determined the constant, C_{bdp} , to be 1.08 for flows with Reynolds number greater than 1000. They estimated the expanded (k = 2.0) relative uncertainty to be ±0.10 for flow velocity determined using this constant. The same probe constant was applied to the present computation of flow velocity as typically performed for fire test results. Measured thermocouple temperatures were not corrected for radiation but were applied directly as estimates of gas temperature. A comparison of thermocouple measurements in close proximity but somewhat shielded from the fire suggest that radiation effects were small and therefore this was a reasonable estimate.

Particle Image Velocimetry (PIV) is an optical imaging technique that measures the displacement of tracer particles in a flow and computes the flow velocity. A typical PIV setup requires tracer particles to be added to the flow, a light source to illuminate the particles at least twice within a very short interval, and a camera to record the light scattered by the particles. The particle displacement and particle velocity is determined through sophisticated post processing of the recorded images.



Figure 3 Typical PIV experimental setup.

Figure 3 is a simple illustration of a typical PIV setup. Tiny tracer particles are added to a flow and are assumed to fully follow the flow. A laser(s) delivers two laser pulses that are coincident in space but separated in time by a precisely known delay. The pulses are expanded into light sheets and illuminate the tracer particles in the flow field of interest. Light is scattered from the particles and recorded on two separate frames, one for each laser pulse, of a Charge Coupled Device (CCD) camera. Post processing of the images involves dividing the images up into smaller interrogation regions and computing the average displacement vector of tracer particles for each interrogation region.⁸ After the displacement vector field, d(x,y), is computed, the velocity vector field, v(x,y), is computed by dividing the displacement vector field by the time delay, Δt , between consecutive laser pulses.

$$(v_{x}(x, y), v_{y}(x, y)) = \frac{(d_{x}(x, y), d_{y}(x, y))}{\Delta t}$$
[2]

In the present experimental setup, diagrammed in Figure 4, the PIV system consisted of a double pulsed Nd: YAG laser, two double-framed CCD cameras for Stereoscopic PIV, and a desktop computer for image acquisition, time synchronization, and vector processing. The two camera SPIV setup allows for the measurement of the out-of-plane particle displacement, d_z . Therefore the full velocity vector, (v_x, v_y, v_z) , was computed.



Figure 4 Schematic of SPIV system configured to measure the velocity field in the plane of the doorway.

The laser delivered two beams with average pulse energy of 200 mJ/pulse at 532 nm. A sheet forming optics assembly expanded the beams to a height of approximately 1.8 meters at the doorway and a sheet thickness of approximately 1.3 cm. Positioning of the laser sheet at the doorway was performed by a 90° mirror attached to a translation stage.

The double-framed CCD cameras had sensors of 2048×2048 pixels with pixel dimensions of 7.4 π m on a side. The maximum frame rate of the cameras was 16 frames per second. Actual frame rates achieved during the experiments were on the order of 1 frame per second due to the data transfer limits of the desktop computer. Wide angle 20 mm focal length lenses were used in order to keep the cameras close to the doorway and capture as much of the doorway as possible in the images. Each camera was placed in a housing that was purged with air in order to protect it from the heat and the seeding particles. Laser line filters (532 nm) were placed in front of each camera to reduce the amount of background light collected from the ambient lighting and from the fire.

The seed particles were gas filled hollow plastic spheres, commonly referred to as microspheres. The particles had a weight averaged diameter range of (100 to 140) \mathbf{m} m and a density of 30 kg/m³. A paint sprayer was used to inject a fine cloud of seed particles into the vestibule area outside of the ISO room.

Particle injection was remotely applied; a trigger pulse engaged a pneumatic actuator only during PIV image acquisitions.

The coordinates for each measurement technique are listed in Table 1. Positioning of the probes and laser sheet with respect to the coordinate origin was performed manually and confirmed using a flexible tape measure. The estimated standard uncertainty of their position is ± 0.01 m. The bi-directional probe and thermocouple measurements were conducted with a simple vertical array located in the geometric center of the doorway. Stereoscopic PIV measurements were conducted in two configurations: a flux slice and a centerline slice. For the flux slice, the laser sheet was parallel to the front wall of the ISO room and passed through a window mounted on one side of the extended door jamb, crossing the plane of the doorway. The laser sheet illuminated the particles in the lower 80 % of the doorway where the air flowed into the room. In this configuration, fluid elements containing tracer particles entered the ISO room by crossing the plane of the laser sheet and the doorway boundaries, the result was a measurement of the velocity flux into the room. For the centerline slice configuration, the laser sheet propagated down the center of the doorway into the ISO room and was perpendicular to the front wall of the ISO room. In this configuration, the laser sheet propagated down the center of the doorway into the ISO room and was perpendicular to the front wall of the ISO room.

| Technique | Measurement | x (m) | y (m) | z (m) |
|-----------------------|--------------|-----------------------|-----------------------------|-----------------------|
| Bi-Directional | Differential | 0 | 0.14 to 1.95 | 0 |
| Probe | Pressure | 0 | $(\text{spacing} = 0.14)^*$ | 0 |
| Thermocouple | Tomporatura | 0 | 0.14 to 1.95 | 0 |
| | remperature | | $(\text{spacing} = 0.14)^*$ | 0 |
| SPIV, Flux Slice | Particle | -0.40 to 0.40 | 0.00 to 1.65 | 0.05 |
| | Displacement | (spacing = 0.02) | (spacing = 0.02) | |
| SPIV, Centerline | Particle | 0.00 | 0.00 to 1.45 | -0.68 to 0.85 |
| Slice | Displacement | | (spacing = 0.02) | (spacing = 0.02) |

Table 1 Physical probe and SPIV measurement locations.

*spacing = 0.125 m between the two topmost probes in the array.

Fires were generated using a natural gas burner (30.5 cm x 30.5 cm) placed in the center of the floor of the ISO room. The volume flow rate of natural gas was measured by a rotary displacement meter upstream of the burner. Assuming complete combustion of the natural gas, the real-time heat output of the burner was computed using the volume flow rate corrected for local conditions and the heat of combustion of natural gas. The burner supplied fires ranging from 32 kW to 512 kW; all fires were over-ventilated for the room and doorway dimensions.

A complete experiment started with achieving pseudo steady-state conditions inside the room for the minimum fire size, acquiring the SPIV measurements, increasing the natural gas flow to reach the next fire size, and repeating the process until the final fire size was attained. Pseudo steady-state was defined by a relatively constant temperature reading from an aspirated thermocouple located in the upper layer inside the room. Upon reaching steady-state, tracer particles were injected into the flow and SPIV measurements were taken. At least 200 SPIV measurements were recorded at each fire size. Temperature and differential pressure measurements at the bi-directional probe array were performed continuously.

A total of 9 experiments were conducted to reproduce the conditions of the enclosure fire. This resulted in 58 total fires. Doorway measurements of temperature and differential pressure were conducted during 3 experiments, and SPIV measurements were conducted during 9 experiments. Out of the 9 experiments, SPIV flux slice measurements were conducted for 6 experiments and centerline slice measurements were conducted for 3 experiments.

RESULTS AND DISCUSSION

Stereoscopic PIV was applied to measure the flow of air into the ISO room through the doorway. Figure 5a demonstrates the vector field measured when SPIV was applied in the flux slice configuration. The vectors represent the velocity components within the plane of the laser sheet, (v_x, v_y) , while the color contours represent the velocity component normal to the laser sheet, v_{τ} . Each vector represents the average flow velocity over an area of 4 cm x 4 cm, the spatial resolution of the measurement. A 50 % overlap of the image interrogation regions during processing produced a final measurement spacing of 2 cm in each direction. Fewer vectors are presented here for clarity. Fresh air flowing into the room is presented as blue contours while the hot air and products leaving the room are presented as the yellow to red contours. The green band between the two flows represents velocity normal to the plane of the doorway that approaches zero. This is the interface of the counter-current flows. This interface has previously been called the neutral plane, however the SPIV measurements reveal that the interface is not planar but curved for the present experiments. The results show that the curvature of the interface decreases with increasing fire size. The cause of the curvature in the interface region is unclear. Note that the entire region of air flowing into the room was captured by the SPIV measurements. Only part of the flow out of the room was captured due to the limitations of measurement quality with respect to image size and the survival of tracer particles in the hotter regions of the flow.

Figure 5 a) Flux slice of velocity vector field for a 160 kW fire; contours represent v_z , b) centerline slice of velocity vector field for a 160 kW fire; contours represents flow speed and include directional information (v_x not shown).



Stereoscopic PIV measures the particle displacement in the plane of the laser sheet like traditional PIV, but with the addition of the second camera imaging the same region, SPIV is capable of reconstructing the outof-plane particle displacement from the two images.⁹ In the flux slice configuration, Figure 5a, d_z is reconstructed from the measurements of d_x and d_y . In the centerline slice configuration, Figure 5b, d_z is measured along with d_y and d_x is reconstructed from the two measured displacements. The relative uncertainty of the measured displacement was demonstrated to be less than ±0.02 for displacements as small as 1 mm. The component of velocity normal to the plane of the doorway, v_z , is required for computation of global parameters such as volume flow rate and mass flow rate. The two SPIV

configurations are different measurements of the same experiment and therefore result in two different determinations of v_z .

The intersection of the flux slice and centreline slice measurements occurs along a vertical line at x = 0 cm and z = 5 cm. This is represented by the white dashed line in Figure 5a and Figure 5b. Temperature measurements of the ISO room interior demonstrate that the experimental conditions were very reproducible and therefore the mean measurements at this location can be compared. Figure 6 displays the comparison of the v_z determined from the two SPIV measurement configurations. There is very good agreement for the vertical profiles of v_z . This is significant because it demonstrates the repeatability of the SPIV results for both configurations. Most importantly, the agreement for v_z between the two SPIV measurements increases the confidence in the SPIV technique which has been applied to large-scale fire induced flows for the first time. Note that there is good agreement even in the flow interface region where the velocity gradient is larger and there is greater intermittency between the counter-current flows. The estimated standard relative uncertainty of the SPIV measurements is ± 0.03 . This estimate includes the uncertainty due to the displacement measurement and the estimated settling velocity of the particles.



Figure 6 Vertical profiles of SPIV measurements of v_z on the doorway centerline.

The intersection of the centerline slice measurements and the bi-directional probe array occurs along a vertical line at x = 0 cm and z = 0 cm. This is represented by the white squares in Figure 5b. Since the physical probe measurements and the SPIV measurements could not occur simultaneously at the same locations, the bi-directional probe measurements were conducted during the SPIV flux slice measurements, but with the laser sheet passing 5 cm in front of the bi-directional probe array. The contour lines in Figure 5b demonstrate that the horizontal change in flow speed is significant in the region defined by the thickness of the door jamb and at all elevations in this region. The SPIV data confirms that it is important to compare data at identical spatial locations and not assume flow uniformity in any one direction. The bi-directional probe measurements were therefore compared to the SPIV centerline slice measurements at the same locations but from repeated experiments. Recall that the reproducibility of the conditions inside the ISO room were demonstrated by the interior temperature measurements and the SPIV measurements in the

doorway.



Figure 7 Direct comparison of bi-directional probe velocity measurements and v_z from SPIV measurements.

The ratio of the velocity inferred from the bi-directional probe measurement and the v_z component of velocity inferred from the SPIV measurements is plotted in Figure 7 with respect to v_z . Negative v_z represent the flow into the room while positive v_z represent flow out of the room. Each bi-directional probe in the lower portion of the doorway, for flow into the room, had companion SPIV measurements for comparison, however only a few of the bi-directional probes in the upper portion of the doorway, for flow leaving the room, had companion SPIV measurements. Near the flow interface, $v_z = 0$ m/s, the discrepancy between the bi-directional probe and SPIV results was large. In this region the probe results were consistently lower than the SPIV results. Figure 7 demonstrates an increasing ratio which passes through unity as the magnitude of v_z increases. The data suggest that the ratio approaches a limiting value of approximately 1.11 for the inflow and approximately 1.34 for the few probes representing the outflow. For the inflow data the limiting ratio occurs at lower elevations in the doorway where the velocity of air flowing into the room is the greatest.

The speed of the flow, |V|, was computed from the SPIV measurements since the full velocity vector was resolved. Figure 8 presents the ratio of the velocity inferred from the bi-directional probe measurement and the flow speed inferred from the SPIV measurements. Since the flow speed is dominated by v_z , there is a similar wide range of discrepancy observed when comparing the velocity data from the bi-directional probes and v_z . However, in the inflow region, the limiting value for the ratio with respect to air speed decreased slightly to 1.08, while in the outflow region, there was a more significant decrease in the limiting ratio to 1.20. A possible explanation for the decreased discrepancy when comparing flow speed is that the bi-directional probe was designed to be less sensitive to flow angle, therefore when flow angles are large its response is more representative of flow speed than the normal component of velocity. Flow angles are on the order of 30° for the flow leaving the ISO room and near the interface of the countercurrent flows.



Figure 8 Direct comparison of bi-directional probe velocity measurements and |V| from SPIV measurements.

SUMMARY AND CONCLUSIONS

Stereoscopic PIV has been applied to characterize the flow of air into the doorway of an enclosure induced by a full-scale fire within the enclosure. The ISO 9705 room with standard dimensions served as the enclosure and a natural gas burner served as the fire source. This is a new approach to quantifying the ventilation in enclosure fires that is non-intrusive and completely independent of the temperature and differential pressure measurements typically applied in fire testing. Each velocity vector component was measured using SPIV, but most importantly the component normal to the plane of the doorway, v_z , was measured. Using two separate SPIV configurations to produce different methods of measuring v_z , very good agreement was achieved for v_z . This established confidence in the SPIV technique for the present application.

Conventional measurements of temperature and differential pressure used to infer flow velocity were also performed in the doorway using bare bead thermocouples and bi-directional probes, respectively. This work describes the first comparison of bi-directional probe measurements with PIV measurements for a full-scale fire-induced flow. There was a wide range of discrepancy between the velocity results from the bi-directional probe measurements and those from SPIV. The discrepancy was the greatest in regions of very low flow and in regions with large flow angles. The discrepancy appeared to approach a limiting value for higher speed flows. However the limiting values were different depending on the flow direction, flow into the room or flow out of the room. These observations in the data suggest that the characteristics of the flow field must be considered when inferring flow velocity using bi-directional probes. Multiple causes of the discrepancy are likely, but further investigation is required to determine which dominates. Detailed flow characterizations such as this provide information that is essential to developing a better relationship between the measured response of the bi-directional probe to the flow and the actual flow velocity.

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