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Evaluating practical measurements of fire-induced vent flows with stereoscopic PIV

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Abstract

Stereoscopic particle image velocimetry (SPIV) was applied to a fire-induced doorway flow to provide the velocity field for computations of the mass flow rate of air into an enclosure. For a flow of uniform temperature and concentration, the technique met all of the requirements to provide the best estimate of the mass flow rate. Simultaneous measurements of vertical distributions of velocity and temperature were also conducted with conventional vent flow techniques, bi-directional probes and thermocouples. Correction factors for mass flow rate computations using the conventional techniques were determined based on comparisons to the SPIV results. An average correction factor of unity was determined for the bi-directional probe technique thus further confirming the utilization of velocity distributions acquired using the technique in mass flow rate computations. An average correction factor of 0.69 was determined for mass flow rates computed from vertical temperature distributions inside and outside the enclosure. This agrees with average correction factors determined in previous studies. The results from the present study suggest that the conventional techniques, which are practical and affordable for routine fire testing, may be applied with greater confidence for fires up to 500 kW.
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Keywords: Fire-induced flow; Particle image velocimetry; Flow measurement; Vent flow

1. Introduction

Accurate measurements to quantify the ventilation in full-scale enclosure fires are difficult due to the requirement to measure small gas velocities over a large area while contending with the hazardous conditions of the fire. Typical fire-induced flow measurement techniques use physical probes to measure gas pressure and temperature and are sufficiently robust for the harsh conditions, but it is often impractical to fully interrogate large spatial regions with numerous probes or traverse mechanisms. The fire-induced flow through vents will vary in all directions and may be countercurrent in the case of vertical vents. Therefore a full mapping of the velocity and density field is required to achieve the best accuracy when quantifying the ventilation in terms of the mass flow rate. Studies by Steckler and his colleagues were the first to fully characterize the velocity and temperature fields in fire-induced vent flows [1,2]. They used bi-directional probes (BDP) to conduct gas velocity measurements and from these measurements mass flow rates were computed. The mass flow rate results were used to evaluate existing room flow theories developed using less sophisticated measurement techniques.

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Since its inception, the bi-directional probe has been the accepted method of measuring gas velocity in fire experiments. Only recently has it been challenged in a full-scale fire with a state-of-the-art measurement technique such as particle image velocimetry (PIV) [3]. Conducting PIV measurements over a large field of view in a gas flow is difficult and there are only a limited number of investigations reporting PIV measurements in large-scale gas flows and specifically fire experiments [4–6]. The present study describes full-scale enclosure fire experiments and computations of the mass flow rate from measurements of gas velocity and temperature. The focus is on measuring the flow of air into an enclosure containing small fires that are characteristic of the conditions prior to flashover. Like the investigations by Steckler and his colleagues, the velocity field across the width of the doorway was characterized, but with the PIV technique. Measurements were also conducted using the existing techniques for fire-induced vent flows; bi-directional probes and thermocouples. Mass flow rates were computed from these measurements as well. The objectives are to demonstrate the use of PIV for vent flow mass flow rate measurements and to use the results to evaluate the existing vent flow measurement techniques.

2. Experimental description

The fire experiments were conducted in a full-scale enclosure used for standard fire test, the International Organization for Standardization (ISO) 9705 Room. The interior dimensions of the room were 3.60 m × 2.40 m × 2.40 m ($L_r \times W_r \times H_r$). Gypsum panels lined the lower half of the vertical walls and the floor and calcium silicate panels lined the upper half of the vertical walls and the ceiling. The wall thickness was 2.5 cm for both materials. A doorway was located on the center of one of the 2.40 m × 2.40 m walls. It had internal dimensions of 0.79 m × 1.96 m ($W_d \times H_d$) and served as the only opening for the enclosure. The door jamb had a depth, D_d, of 0.30 m and extended beyond the exterior wall. Mounted on one side of the door jamb was a window which was required to pass the laser sheet across the doorway for the PIV measurements. A schematic of the experimental setup is shown in Fig. 1. Natural gas fires were generated from a square burner (0.31 m × 0.31 m) placed in the center of the enclosure. The top of the burner stood 0.30 m above the enclosure floor. The natural gas flow was held constant during the experiments and measured to compute the ideal heat release rate. Resulting heat release rates ranged

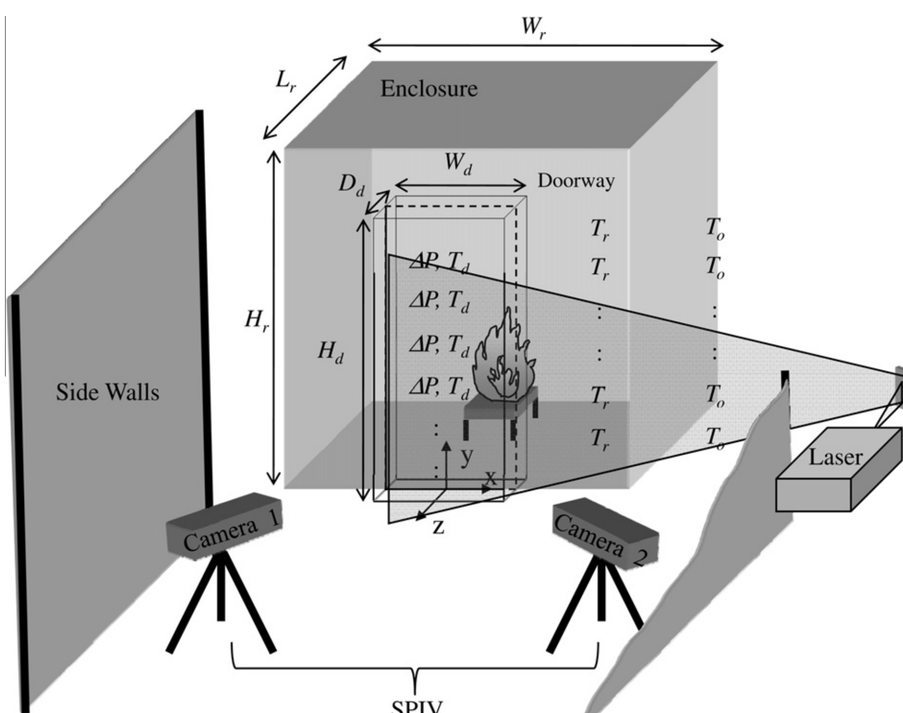

Fig. 1. Diagram of the enclosure fire, doorway, SPIV configuration, and probe measurements.

from 34 kW to 511 kW with a relative expanded (coverage factor of 2 for an estimated 95% confidence interval) uncertainty of ±0.02 [7]. This range of fires simulated the developing stage of a fire for the dimensions of the enclosure and the opening.

Bi-directional probes, devices similar to pitot-static probes, were used to conduct gas velocity measurements, Fig. 2. Its response to a flow is a pressure differential between the total and static ports. This differential pressure is proportional to the square of the flow velocity. The ports on the bi-directional probe are symmetric and have large openings that are oriented perpendicular to the flow. If the probe is attached to a bi-directional pressure transducer, flow in either direction can be sensed [8]. Using a vertical array of bi-directional probes with adjacent bare bead thermocouples, measurements of differential pressure, ΔP, and gas temperature, T_d, were conducted on the centerline of the doorway. Vertical profiles of gas velocity in the doorway were computed from the measurements. Vertical profiles of gas temperature inside the enclosure, T_r, were measured using an array of aspirated thermocouples while a vertical array of bare bead thermocouples placed adjacent to the enclosure provided the gas temperature outside, T_o. Beginning at 14 cm above the floor of the enclosure, the probes were vertically distributed 14 cm apart.

Planar measurements of gas velocity across the width of the doorway were conducted using stereoscopic particle image velocimetry (SPIV). The SPIV system consisted of a double pulsed Nd:YAG laser, two double-framed CCD cameras, and a desktop computer for image acquisition, time synchronization, and vector processing. 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 m at the doorway and a sheet thickness of approximately 1.2 cm. The spatial resolution of the SPIV measurements was 4 cm × 4 cm. Overlap of the image interrogation regions resulted in a spatial sampling of 2 cm × 2 cm. Seeding of the flow occurred in the vestibule (created by erecting side walls) prior to its entry into the doorway. Seed particles were gas filled microspheres with a weight averaged diameter ranging from 100 μm to 140 μm and a density of 30 kg/m^3. Due to limits of the imaging optics and the thermal decomposition of the plastic seed particles, valid velocity vectors could not be achieved for the entire height of the doorway flow. Valid vectors were achieved for the lower 70–75% (1.37–1.47 m) of the doorway height, which was sufficient to capture the flow of air into the enclosure. Details on the SPIV setup and vector processing are discussed in a separate article [9].

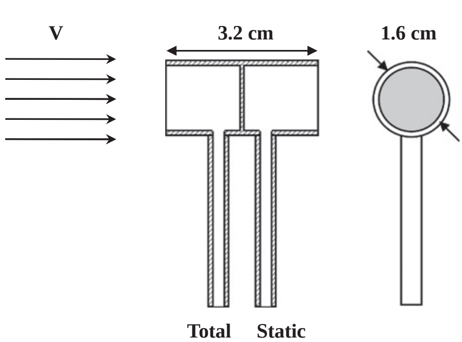

Fig. 2. Diagram of the bi-directional probe. The listed dimensions describe the probes used in the present study.

The data presented here is time averaged over a period of quasi-steady-state conditions, therefore after the initial transients due to the change in fire size have abated. During the experiments, quasi-steady-state was defined by monitoring a relatively constant temperature reading from an aspirated thermocouple located in the upper layer inside the room. A minimum of nine repeat experiments were conducted for all fire conditions. Probe measurements of temperature and gas velocity were conducted for three repeat experiments. SPIV measurements of gas velocity across the doorway were conducted for a minimum of six repeat experiments. Simultaneous probe measurements were made for three of the six SPIV repeats; therefore allowing the gas temperature measurements to be utilized in the mass flow rate computation. The conditions inside the enclosure were highly repeatable as demonstrated by the upper layer temperature measurement which had a standard deviation relative to the mean of the repeats of less than 0.01 for all fire conditions [9].

3. Results and discussion

3.1. Mass flow rate computed from velocity field measurements – SPIV

The most accurate determination of mass flow rate is achieved by conducting measurements of mass flux, $\rho v_\perp$, where ρ is the gas density and $v_\perp$ is the velocity component normal to the cross-section of the flow. The measurements should be performed at numerous positions in the cross section and then integrated numerically over the entire cross section. SPIV gives numerous measurements in a plane of the full velocity vector (v_x, v_y, v_z) of the gas. In the present coordinate orientation, v_z is normal to the cross section of the doorway. Figure 3 displays the planar map of contour lines of v_z and demonstrates the complex nature of the doorway flow. The zero contour defines the flow interface where the direction of flow changes. All contours below and within the envelope of the zero contour are negative contours which represent air

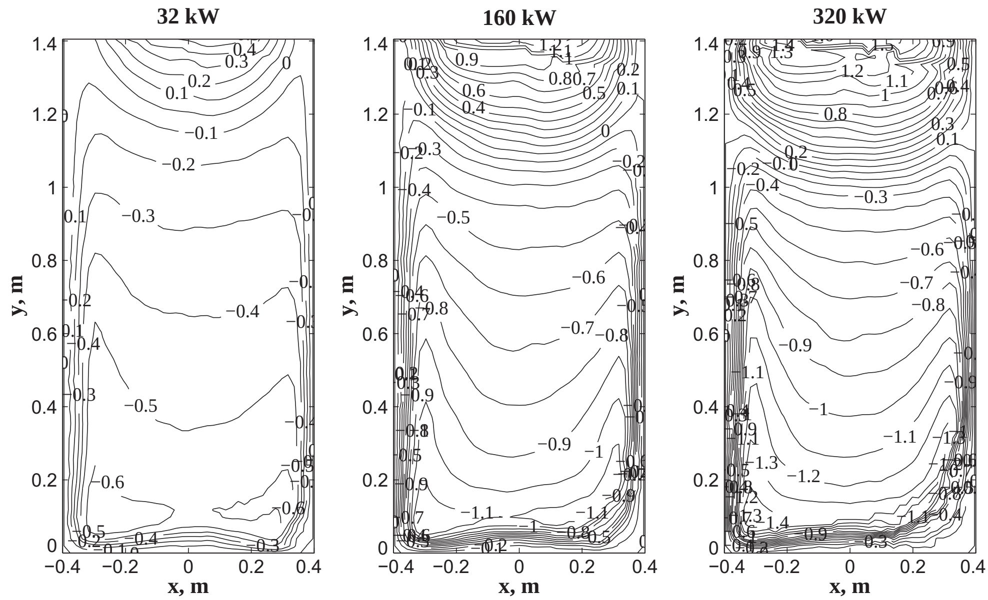

Fig. 3. SPIV measurements of the velocity field in the doorway of the enclosure. Contours lines represent the velocity component normal to the doorway cross-section, v_z. Contour values have units of m/s.

flowing into the enclosure. Therefore, the region below the zero contour and between the solid boundaries defines the cross sectional area of the flow into the enclosure. It is evident from the shape of the contours that the flow is non-uniform across the width of the doorway. Steckler et al. first reported horizontal profiles in the in-flow region that were characteristic of a flow through an orifice that originated as an ideal flow at rest [1]. Horizontal profiles of the same character, a valley in the center with symmetric peaks near the solid boundaries, can be extracted from the contours of Fig. 3. The relative expanded uncertainty of the SPIV measurements was estimated to be ± 0.06.

The mass flow rate computation requires that gas density is also measured. Assuming that the air flowing into the enclosure is an ideal gas, $P = \rho RT/M$, gas density is derived from measurements of gas temperature in the doorway. For the present experiments, the flow of gas into the enclosure is mostly ambient air and of uniform temperature. In Fig. 4, the temperature profile in the doorway is relatively constant below the flow interface. Therefore temperature measurements conducted along a vertical array on the centerline of the doorway were sufficient to describe the temperature field. Below the flow interface, maximum gas temperatures ranged from $298\ \mathrm{K} \pm 3\ \mathrm{K}$ to $324\ \mathrm{K} \pm 29\ \mathrm{K}$ for the fires considered.

The flow of air into the room occurs over a cross sectional area defined by the width of the doorway and the height of the flow interface, $h(x)$, which was non-uniform across the width of the doorway. The following integration was performed numerically to compute the flow of air into the room from the SPIV and thermocouple measurements in the doorway.

$$\dot{m}_{\mathrm{in,SPIV}} = \frac{P_{\mathrm{amb}} M_{\mathrm{air}}}{R} \int_{-W_{d/2}}^{W_{d/2}} \int_0^{h(x)} \frac{v_z(x,y)}{T_d(y)} dy dx \quad (1)$$

The SPIV measurements provide a complete mapping of the velocity field, the velocity component normal to the doorway cross section, and an accurate determination of the cross sectional area for the flow into the room. Coupled with an almost constant air temperature flowing into the room, SPIV meets all of the requirements to provide the best estimate of mass flow rate of air into the enclosure. Figure 5 displays the air mass flow rate computed from the SPIV measurements, Eq. (1), as a function of the heat release rate of the natural gas fires. In the range of 34–160 kW, the results agree with the results from traverse measurements with bi-directional probes and thermocouples by Steckler et al. [10]. The interior dimensions of the enclosure and the doorway are similar for both studies. The present study extends the fire strength from 160–511 kW. In this range, there is slower rate of increase in air mass flow rate, which suggests that a ventilation limit is being approached based on fire size and opening dimensions. At 511 kW, the measured mass flow rate of air is well below the empirical ventilation limit, $0.5\, A_d(H_d)^{1/2} = 1.09$ kg/s [11], where A_d is the cross sectional area of the doorway. An uncertainty propagation was performed to estimate the

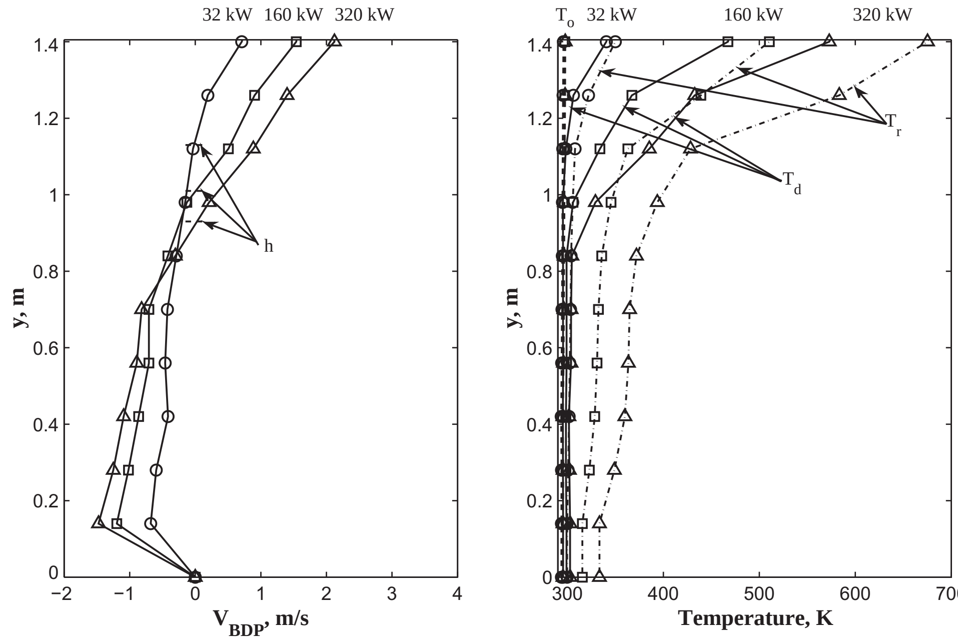

Fig. 4. Vertical profiles of flow speed in the doorway of the enclosure measured with the bi-directional probes; flow interface heights, h, are shown as dashed horizontal lines. Vertical profiles of thermocouple measurements of gas temperature inside the enclosure, T_r, in the doorway, T_d, and outside the enclosure, T_o.

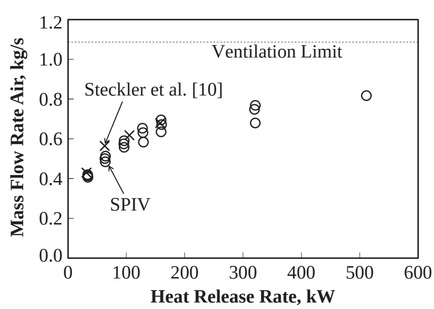

Fig. 5. Mass flow rate of air into the enclosure relative to fire strength. "∘" represents the results from the present SPIV measurements, while "×" represents the cited study.

combined uncertainty for the numerical integration as applied to Eq. (1). The estimates of relative expanded uncertainty for the computed mass flow rate ranged from ±0.0014 to ±0.0031 for the 34 kW and 511 kW fires, respectively.

3.2. Mass flow rate computed from vertical distributions of pressure and temperature

It is most often impractical to conduct a planar measurement of mass flow rate for a standard enclosure fire test due to the complexity of the equipment required to interrogate the full spatial extent of the measurement region. In the presence of these limitations, assumptions regarding the spatial characteristics of the flow have guided the use of more practical measurements. By assuming the flow through the doorway changes with respect to elevation in the doorway and is invariant in the horizontal direction, mass flow rates may be estimated from vertical arrays of measurements in the enclosure, the doorway, and the space outside the enclosure.

3.2.1. Differential pressure measurements – velocity probes

Vertical profiles of gas velocity and gas density in the doorway were computed using measurements from the vertical array of bi-directional probes and bare bead thermocouples located on the doorway centerline. The bi-directional probes integrate the local gas pressure over the space of their openings. The openings are large to reduce clogging and sensitivity to flow angle, therefore the measurement is more representative of the flow speed, V. The resulting vertical profiles of the flow speed are displayed in Fig. 4. Negative flow speed represents air flowing into the enclosure while the flow above the interface is positive and flows out of the enclosure. The no-slip condition applies at the floor, $V_{BDP}(0) = 0$ m/s. Estimates of the relative expanded uncertainty ranged from ±0.14 to ±0.22 for the gas velocity computed from the bi-directional probe measurements.

The SPIV results demonstrated that the velocity field was not invariant in the horizontal direction. However, it has long been practical to assume a vertically distributed flow only. Once again, the gas density distribution in the doorway was computed from the doorway temperature distribution, Fig. 4. The height of the flow interface was determined by performing a linear interpolation of the velocity distribution to determine the location where $V_{BDP} = 0$ m/s. Vertical distributions of velocity and temperature from the centerline of the doorway were used to estimate the mass flow rate of air into the room by numerically computing Eq. (2). Like the velocity and temperature distributions, the flow interface height was assumed constant across the width of the doorway.

$$\dot{m}_{\text{in,BDP}} = W_d \frac{P_{\text{amb}} M_{\text{air}}}{R} \int_0^h \frac{V_{\text{BDP}}(y)}{T_d(y)} dy \qquad (2)$$

3.2.2. Temperature measurements – thermocouples

The difference in gas density between the enclosure and the space outside the enclosure induces a static pressure difference across the doorway. This static pressure distribution can be computed from measurements of the vertical temperature distribution inside and outside the enclosure, Fig. 4. Uncertainty estimates (expanded) for the temperature measurements inside the enclosure and outside the enclosure were ±20 K [12] and ±2 K, respectively. Following the treatment described by Steckler et al. [1], the vertical velocity distribution was computed from the static pressure distribution by applying Bernoulli's equation along horizontal streamlines, assuming the flow started from rest far from the doorway. The temperature measurements in the doorway were once again used to compute the gas density distribution in the doorway. Meanwhile the flow interface height that was determined from the bi-directional probe measurements was used for the vertical integration limit. Using measurements of the vertical temperature distributions, the mass flow rate of air into the room was estimated from a numerical computation of the following integration, with g being the acceleration due to gravity.

$$\dot{m}_{in,T} = W_d \frac{P_{\text{amb}} M_{\text{air}}}{R} \times \int_0^h \left[\frac{2g}{T_d(y)} \int_{y'}^h \left(\frac{1}{T_o(y')} - \frac{1}{T_r(y)'} \right) dy' \right]^{1/2} dy \qquad (3)$$

3.3. Correction factors

A comparison of the mass flow rates computed from the measurements of the different techniques is presented in Fig. 6. Mass flow rate computed

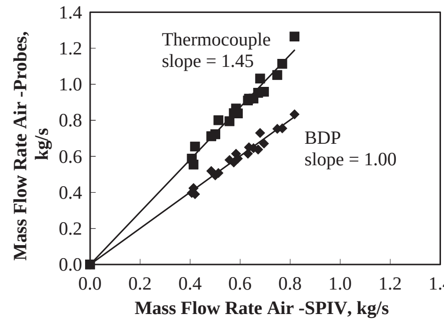

Fig. 6. Mass flow rate correction factors (1/slope) for centerline bi-directional probe measurements and room temperature measurements.

from the differential pressure measurements, Eq. (2), and thermocouple measurements, Eq. (3), is plotted with respect to mass flow rate computed from the SPIV measurements. The combined uncertainty of the mass flow rate computed from the probe measurements was estimated by performing an uncertainty propagation for the numerical integrations as applied to Eqs. (2) and (3). The estimates of relative expanded uncertainty for the mass flow rate computed from the differential pressure measurements, Eq. (2), ranged from ±0.06 to ±0.10 for the 34 kW and 511 kW fires, respectively. In the case of the mass flow rates computed from the temperature measurements, Eq. (3), the trend in the uncertainty was reversed. The largest estimate of relative expanded uncertainty, ±0.20, occurred for the 34 kW fire and the same estimate for the 511 kW fire was ±0.05.

There is a linear relationship between the results of the three techniques. SPIV provides the most comprehensive measurement of the gas velocity field in the doorway of the three techniques applied. The other estimates rely on the simplifying assumptions that the flow is invariant in the horizontal direction and that the flow speed estimates the normal velocity component. To account for the error in these techniques induced by the simplifying assumptions, linear fits to the data were applied to estimate correction factors. The correction factor as defined here is determined by taking the inverse of the slope of the linear fit.

$$\dot{m}_{\text{in,SPIV}} = C_{\text{in,BDP}} \dot{m}_{\text{in,BDP}} \qquad (4)$$

$$\dot{m}_{\text{in,SPIV}} = C_{in,T} \dot{m}_{in,T} \qquad (5)$$

The average correction factor, $C_{\text{in,BDP}}$, for the air mass flow rate computed from the bi-directional probe measurements is 1.00 ± 0.02. Therefore, the mass flow rate results from the bi-directional probe measurements do not require a corrective factor. This result increases the confidence in the bi-directional probe technique to provide measurements for computing mass flow rate of air into an enclosure containing a fire. A comparison of volume flow rate computed from centerline profiles extracted from SPIV velocity field measurements yielded a similar agreement [9]. The agreement suggests that the measurements of the vertical distribution of velocity and temperature on the centerline of the doorway can provide accurate estimates of the mass flow rate of air into an enclosure.

The SPIV velocity contours of Fig. 3 demonstrate that it is incorrect to assume that gas velocity is invariant in the horizontal direction. This is a significant simplifying assumption for computing mass flow rate from vertical distributions of velocity and temperature. However, for the case of the bi-directional probe measurements excellent agreement for mass flow rate was achieved despite the invalid assumption. This brings attention to the fact that an integration method can achieve the same result for different distributions of measurements. For this study, the locations of the bi-directional probes and their response to the flow were effective in capturing a velocity distribution that was characteristic of the doorway flow.

The average correction factor, $C_{in,T}$, for the mass flow rate computed from the temperature distributions inside the enclosure, in the doorway, and outside the room is 0.69 ± 0.03. This agrees with the average correction factor, 0.68, previously determined by Steckler and his colleagues [1,2], who compared mass flow rates computed from bi-directional probe measurements and temperature distributions. In their study, the bi-directional probes were traversed across the width of the doorway to obtain a planar mapping of the gas velocity field. The agreement with the previous study is significant because the gas velocity field was determined using two independent measurement techniques, SPIV and bi-directional probes. Confirmation of the correction factor for the temperature distribution method of computing mass flow rate of air gives greater confidence to this practical and affordable measurement that can be applied in routine fire testing for the developing stages of a fire.

4. Conclusions

SPIV provides a detailed mapping of the gas velocity field in the doorway of an enclosure containing a fire and coupled with measurements of gas temperature in the doorway; it also provides estimates of the mass flow rate of air available to the fire. There was excellent agreement between the mass flow rate computed from SPIV and from gas velocity distributions measured with bi-directional probes. An average correction factor of unity was determined. This result suggests that for similar developing fire conditions, the vertical velocity distribution on the centerline of the doorway is a characteristic distribution that can be applied to compute the mass flow rate of air available to a fire. It also further confirms the utilization of velocity distributions acquired using bi-directional probes in the mass flow rate computation. The average correction factor for the mass flow rate computed from vertical temperature distributions inside the enclosure and outside the enclosure was 0.69 ± 0.03, which agrees with average correction factors determined in previous studies. Compared to SPIV, vertical arrays of bi-directional probes and thermocouples are far more practical and affordable methods to estimate mass flow rate for routine fire testing. The maximum size fire for the present study was 511 kW. Therefore, the results suggest that both methods can be applied with greater confidence for fires up to 500 kW.

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