Stereoscopic Particle Image Velocimetry Measurements of Flow Through a Doorway of an Enclosure Fire Analogue

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Introduction

A fire within a room or enclosure acts as a pump, pulling ambient air in while pushing combustion products mixed with air out. The openings through which the gases flow are referred to as vents and typically are doorways and windows. Quantifying the ventilation available to an enclosure fire is an important step to understanding fire behavior. Ventilation provides the necessary oxygen to the fire while also serving to moderate the temperature of the compartment in the early stage of the fire growth. The gaseous products that move out of an enclosure transfer heat and combustion products from the localized point of the fire to remote locations within a built structure. Ventilation therefore can play two important roles in fire spread, 1) to reduce the hazard by moderating the enclosure temperature, 2) to increase the hazard by transferring the heat, smoke and toxic gases to other locations of a built structure.

Fire-induced flow through a vent is counter-current and three-dimensional. The best measurement of mass flow rate of gas through the vent requires a full mapping of the velocity and density fields across the opening. Typical fire ventilation measurements consist of a single vertical array of differential-pressure probes and thermocouples placed on the centerline of the ventilation plane to determine velocity and density, respectively. [1] The pressure probes, called bi-directional probes [2], can measure local flow velocity in areas were the bulk flow can change direction. However, these probes are intrusive to the flow, have low spatial resolution and produce a limited number of point measurements. Past measurements have traversed a vertical array of probes across the width of a doorway to map the velocity field for a steady-state fire system. [3,4] These measurements confirmed the three-dimensional nature of fire-induced vent flows and also imply the need for more advanced measurement techniques to allow a more detailed characterization of such flows.

Laser based measurement techniques such as Particle Image Velocimetry (PIV) offer the capability to map the velocity field of the entire area of a vent opening in a single acquisition. PIV offers increased spatial resolution over bi-directional probe measurements and orders of magnitude more data points. In addition all three components of the velocity vector are resolved when Stereoscopic PIV is applied.

In the present study a reduced-scale fluid flow analogue of a fire experiment [5] has been constructed and used to produce a buoyancy induced flow through the doorway of an enclosure. The resulting fluid dynamics are similar to that of the full-scale fire experiment, therefore the reduced-scale experiment served as an intermediate test before applying PIV to full-scale fire tests.. Stereoscopic PIV measured the velocity field across the doorway, gas sampling measurements provided oxygen concentration to infer the gas density field, and mass flow rate through the doorway was computed. The velocity vector field results show that areas of the flow exist where the contribution to the velocity magnitude is not dominated by the velocity component normal to the vent plane. This is an assumption of bi-directional probe measurements, which, due to their size, respond more to magnitude more than to a specific component of the flow velocity.

Experiment

The reduced-scale experiment consisted of a Plexiglas room that was geometrically similar to the full-scale enclosure of a fire experiment [5] and 0.55 the scale. A helium plume was employed as the buoyant source to produce an isothermal convective analog of the fire experiment. Dynamic similarity between the real experiment and reduced-scale model was achieved by preserving the Froude number in the set of non-dimensional equations to describe the source flows. [6] The source mass flow rate of helium was determined from the scaling analysis and is described by the following relation:

$$\dot{m}_{He} = \frac{0.7\dot{Q}_{FS}}{C_p T_\infty}\left(\frac{l_{RS}}{l_{FS}}\right)^{5/2}\frac{\rho}{\Delta\rho} \qquad (1)$$

In this relation, $\dot{Q}_{FS}$ is the full-scale fire heat release rate , l the geometric length scale, ρ is the gas density in the plume, $\Delta\rho$ is the density difference between the ambient and plume gas ($\rho_\infty - \rho$), and C_p and T_∞ are the ambient gas specific heat and temperature respectively. The subscripts *FS* and *RS* represent full-scale and reduced-scale respectively. The helium flow is scaled with respect to the convective component of the full-scale heat release rate which is nominally 70% of the total heat release rate.

A schematic of the experiment is shown in Figure 1 below. An expanding laser sheet was formed which passed through the rear Plexiglas wall to form a vertical sheet perpendicular to the doorway plane. The enclosure was traversed horizontally to allow for eleven such vertical slices spaced at 50 mm. Due to space restrictions only part of the vertical expanse of the laser sheet could be imaged for PIV, therefore three vertical layers of measurements were performed and the resulting vector fields combined to produce a total image region of 0.7 m x 1.0 m (l x h). The Stereoscopic PIV system (not shown) consists of a double pulsed Nd:YAG laser operating at approximately 150 mJ/pulse at 532 nm and two double framed CCD cameras with 2 Megapixel CCD chips (1008 pixels x 1016 pixels) oriented on opposite sides of the laser sheet. The seed particles were gas-filled microspheres with polymer shells and having a weight averaged diameter of 30 micrometers to 50 micrometers and a density of 42 kg/m^3. The seed particles were manually introduced into the quiescent flow outside the room using a shaker. The particles entering the enclosure were entrained by the helium plume and transported to the upper layer to provide seeding for the outflow.

In a typical run of the experiment the helium flow was 0.0031 kg/s for a maximum duration of 4 minutes; 1 minute was allowed to pass before any measurements were recorded. Forty seconds after the helium flow was started, seed particles were introduced to fill the region that supplied the inflow gas at the doorway. When the seeding was determined to be sufficient and the 1 minute duration had completed, the system was triggered to record 60 images for velocity vectors. Upon completion of the measurement the helium flow was shut down and the room was horizontally traversed to the next measurement location. A vertical profile of oxygen volume fraction was measured in a separate set of experiments using a sampling probe. These measurements were used to compute a vertical distribution of gas density.

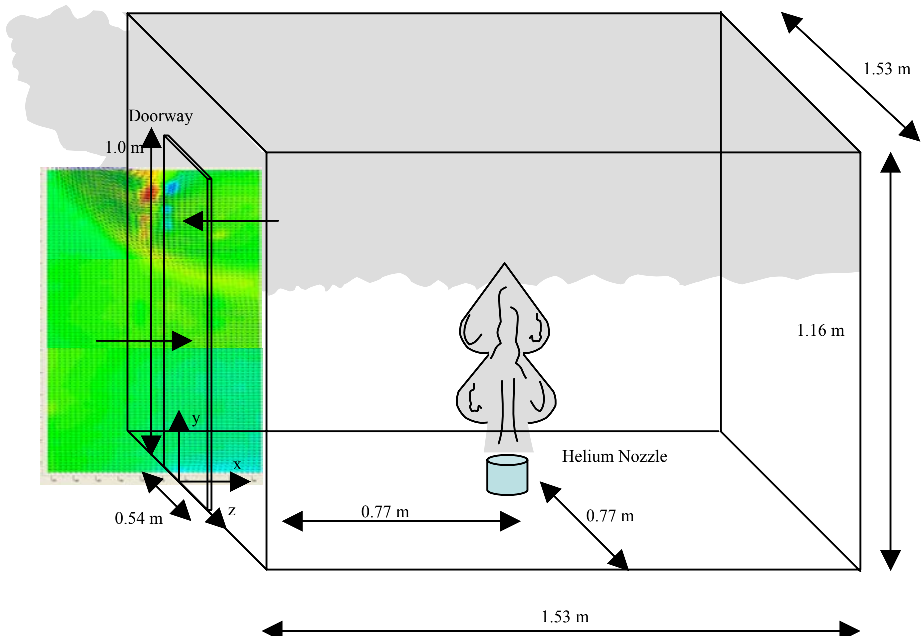

Figure 1 Schematic of reduced-scale experiment of an enclosure fire analogue

Results

Two countercurrent flows exist within the doorway of the enclosure: air enters at the bottom and helium and air exit at the top. The interface of these two flows, called the neutral plane, is the vertical location where the horizontal velocity component slows to zero in order for the flow to change direction. In Figure 2, the vertical slice of the mean velocity vector field at the doorway center (z = 0 mm) displays the countercurrent flows and the location of the neutral plane. The color map displays the out-of-plane velocity component, w, which is not insignificant even on centerline. The standard deviation of the mean is taken as the standard uncertainty for the velocity results. For such a large field of measurements, the range of relative uncertainty varies. Therefore relative standard uncertainties representative of the velocity filed are estimated at 0.04, 0.20, and 0.12 for u, v, and w, respectively. The interrogation area for a velocity vector is 32 pixels x 32 pixels, which results in a spatial resolution of 20 mm x 20 mm in real space for the resulting optical magnification.

A vertical slice of the mean velocity field in the entire doorway plane is shown in Figure 3. Flow normal to the doorway plane, u, is displayed as a color field. The neutral plane height is relatively uniform across the doorway, with an average height of 730 mm. Along with the physical boundaries of the doorway, the neutral plane location defines the limits of integration for computing gas mass flow rate into the enclosure.

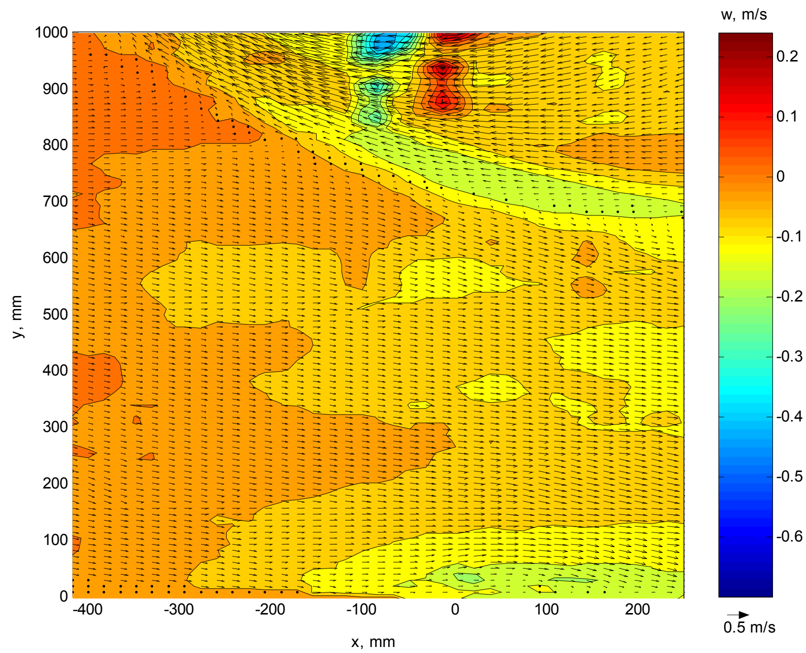

Figure 2 Mean velocity field through doorway centerline, z = 0 mm. Color map represents w velocity component, vectors represent u and v velocity components.

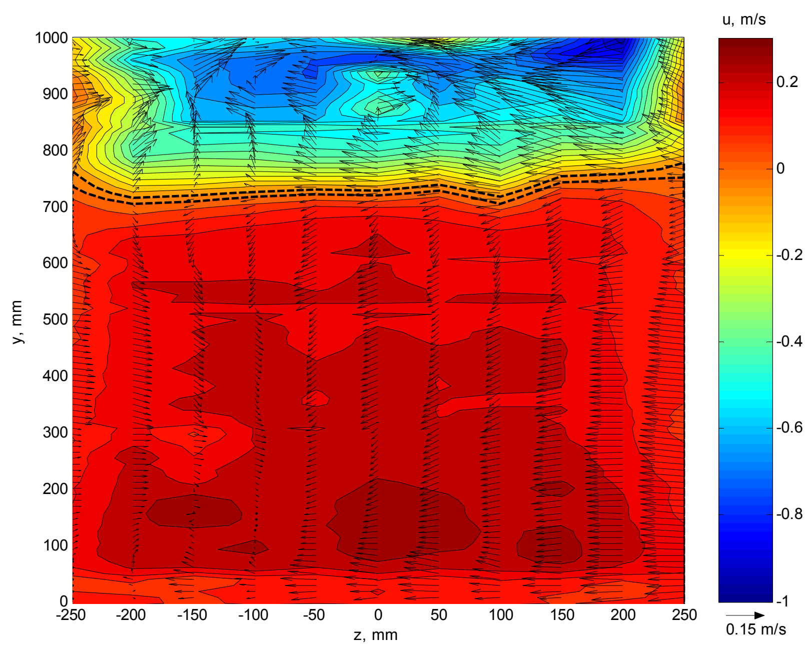

Figure 3 Mean velocity field across doorway plane, x = -14 mm. Color map represents u velocity component, vectors represent v and w velocity components. The color map is interpolated between vertical slices. Neutral plane is indicated by heavy dashed lines outlining adjacent contours where flow changes direction.

Ideal mass flow rate into the enclosure is described by Equation 2, where W is the width of the doorway, and h_N is the height of the neutral plane. The gas density field is approximated from a single vertical profile of gas density measured at the center of the doorway, $\rho(y,z) \approx \rho(y,0)$. Measurements of gas density in the outflow region and along a line at constant elevation varied by 1 % or less. Therefore in the inflow where the incoming gas is ambient air except for the small interface region, this assumption is valid. Relative standard uncertainty for the gas density measurement is estimated at 0.02. The resulting mass flow rate is computed in row 1 of Table 1 below.

$$\dot{m}_{in,ideal} = \int_0^W \int_0^{h_N} \rho(y,z)u(y,z)\partial y \partial z \tag{2}$$

The angular sensitivity of bi-directional probes is 10 % or less in the range of 0 to 40 deg for off-axis flow. This suggests that these probes respond better to flow speed instead of specific velocity components. Stereoscopic PIV measures the complete velocity vector and therefore allows for a comparison of flow speed, $|V|$, and the desired velocity component, u. Figure 3 is a good illustration of how velocity magnitude may have significant contribution from velocity components other than u in areas of the flow such as near solid boundaries.

An example comparison of methods of mass flow rate computations from the measurements is shown in Table 1. Mass flow rate computed from the velocity magnitude field (row 2), is 11 % greater than the result arrived at by employing the normal velocity component field (row 1). This is similar to having a vertical array of bi-directional probes and scanning them across the doorway. Mass flow rate computed from a velocity magnitude field assumed to vary in only the vertical direction (row 3) is 25 % greater than the resulting mass flow rate computed from the normal velocity component field. This is similar to performing velocity measurements on centerline of the doorway with a vertical array of probes. These example results are consistent with need for a flow coefficient to correct the experimentally determined mass flow rate to agree with the ideal mass flow rate.[1,7,8]

Table 1 Comparison of mass flow rate computations.

Integrand	Mass Flow Rate, kg/s
$\rho(y,0)u(y,z)$	0.079
$\rho(y,0)\lvert V(y,z)\rvert$	0.088
$\rho(y,0)\lvert V(y,0)\rvert$	0.099

Conclusion

In the present study Stereoscopic PIV measurements in the doorway of a reduced-scale fluid flow analogue of a fire experiment were conducted. The complete velocity vector field was determined in the plane of the doorway, therefore satisfying part of the measurement requirements for mass flow rate into the enclosure. For gases flowing into the enclosure the gas density field is mostly uniform except for the small interface region near the neutral plane and was therefore approximated by the vertical distribution of oxygen measured on centerline. Planar field results confirm the three-dimensional nature of fire-induced flows. These slow moving buoyancy induced flows are subject to local flow currents, which are difficult to control and reduce. Stereoscopic PIV has a greater capability to measure what is naturally occurring, therefore reducing the need to make assumptions about the flow directions, as common with probe measurements. An example comparison of mass flow rate computations demonstrates that PIV measurements increase the capability to determine true mass flow rate while also suggesting an alternate method of determining doorway flow coefficients. This reduced-scale experiment served as an intermediate step before applying PIV to full-scale fire experiments.

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