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EXAMINATION OF THE BIDIRECTIONAL VELOCITY PROBE USED IN FLAMES

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Abstract

The bidirectional velocity probe has been used in various flames to measure the local velocity. The device is based on the pressure difference between a closed forward facing cavity, and a closed rearward facing cavity. The probes are represented to be insensitive to a variation of 30^{O} in yaw angle and have also been noted to indicate a pressure difference greater than that which would be predicted based on Bernoulli's equation. Each device must be experimentally calibrated to determine the "amplification factor", which is greater than unity. The presumed explanation is that probes do not actually achieve flow stagnation on the approach centerline; rather, flow is diverted around the probe and hence a component of the effect may be the change in x-direction momentum along this centerline.

This study uses both CFD and PIV to examine the flow field around the probe, as well as an experimental study which compares various probe configurations for measurement of velocity by pressure differential.

Introduction

Pool fires are characterized by modeling, visualization, and experimental techniques. A bi-directional velocity probe (BDVP) design has been used to gather data from open pool liquid hydrocarbon and warehouse fires documented in various publications. A few fire characteristics of interest to modelers and scientists are flame speed, localized flame direction, pulse frequency and heat flux; one of which the BDVP can readily obtain: flame speed. The BDVP has been utilized to obtain localized differential pressure measurements and subsequently flame velocities via the energy equation and an amplification factor. Investigations performed by McCaffery and Heskestad have calculated amplification factors ranging from 1.1 to 1.2 for probes diameters of 12.7 mm to 25.4 mm. Discrepancies in the amplification factor have been observed at low velocities and probe diameters less than 12.5 mm [3]. To better understand why variations in amplification factor occur, a study including both experimental and computational analysis has been performed to exploring the flow characteristics in and around the probe.

Instrumentation

Experimental work was performed at New Mexico State University facilities. Delta pressure measurements were performed in two subsonic wind tunnels. The small wind tunnel (SWT) is an open circuit tunnel with a circular cross section. The inlet incorporates 30 one-inch diameter cardboard tubes for flow straightening prior to entering a converging section. The test section is 0.304 meters in diameter by 0.304 meters long and produces velocities ranging from ~4 m/s to 20 m/s which were determined using the Venturi calculation. The large wind tunnel (LWT) is also an open circuit sub-sonic tunnel but has a square cross section. The test section has a 1.216m side dimension and a 2.432m length. The flow is straightened in the inlet using a cardboard honeycomb and a filtering mesh. Test section velocities range from ~0.8 m/s to 15 m/s and were calculated using Pitot – Static tubes. Velocities were also confirmed with Venturi calculations based on the pressure differential between room and test section sidewall. The Venturi calculated velocities are used for all subsequent wind tunnel data referenced against velocity.

Velocity calculation via energy equation: $v = \sqrt{\frac{2\Delta p}{\rho}}$

Pressure measurements for the LWT are taken with a Dwyer slant tube manometer having an accuracy of 0.01 inches of water and two MKS differential differential pressure transducers with ranges of zero to 0.2 torr and zero to one torr. Both differential pressure transducers have an accuracy of +/- 0.5% full scale.

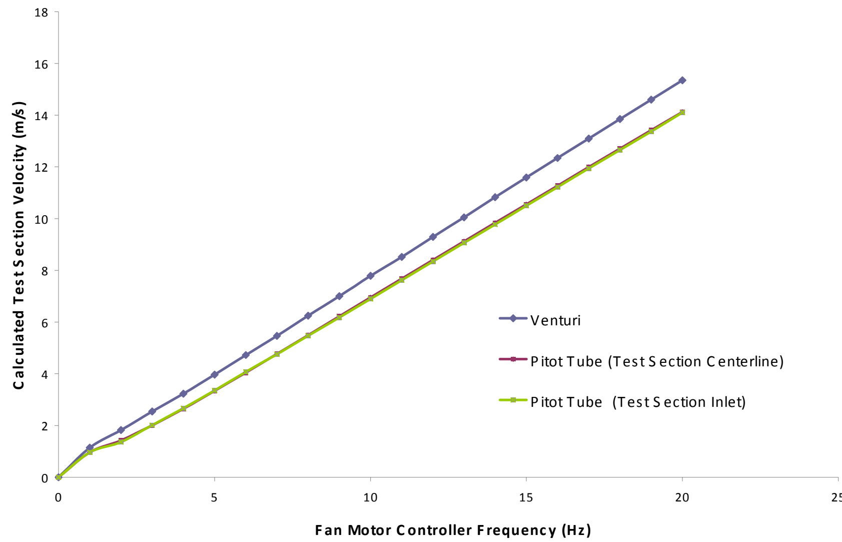


Figure 1. Wind tunnel calibration

Probe Characterization: Wind Tunnel

The bi-directional probes design relates fluid velocity with differential pressure similar to the commonly used Pitot - static tube. The upstream cavity is designed to achieve or approach flow stagnation while the downstream cavity is near the static pressure. The amplification factor is necessary when the differential pressure is measured and differs from the dynamic pressure. The deviation is a result of the intrusiveness of the probe design and its impact on the flow. The PIV analysis and CFD calculations help to quantify the impact the probe has on the flow. Figure 2 shows the momentum and energy equations compared to the velocity readings from the BDVP.

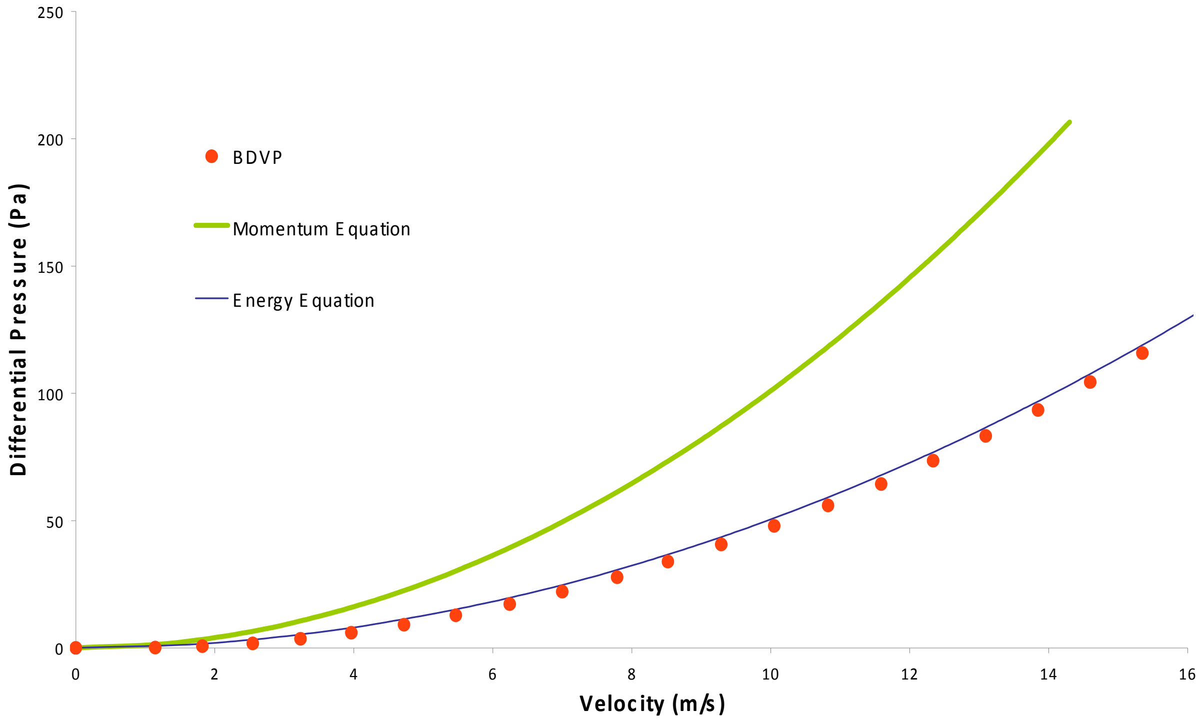


Figure 2. Bi-directional velocity probe comparison to the Momentum and Energy Equations

Amplification factor (k): $k_p = \frac{\sqrt{\frac{2\Delta p}{\rho}}}{v}$ or $k_p = \sqrt{\frac{\Delta p}{p_d}}$

Three Flame speed probes (FSP) were constructed in similar design to the BDVP. The FSP's were manufactured from aluminum round stock and tested in the LWT over a velocity range 4 – 15 m/s. The outer diameter was constant at 5/8" for all three probes and the inner diameters were 25/64", 1/4" and 1/8". The FSP's show an increased sensitivity in measured differential pressure over the larger diameter of the BDVP especially at velocities greater than ten meters per second.

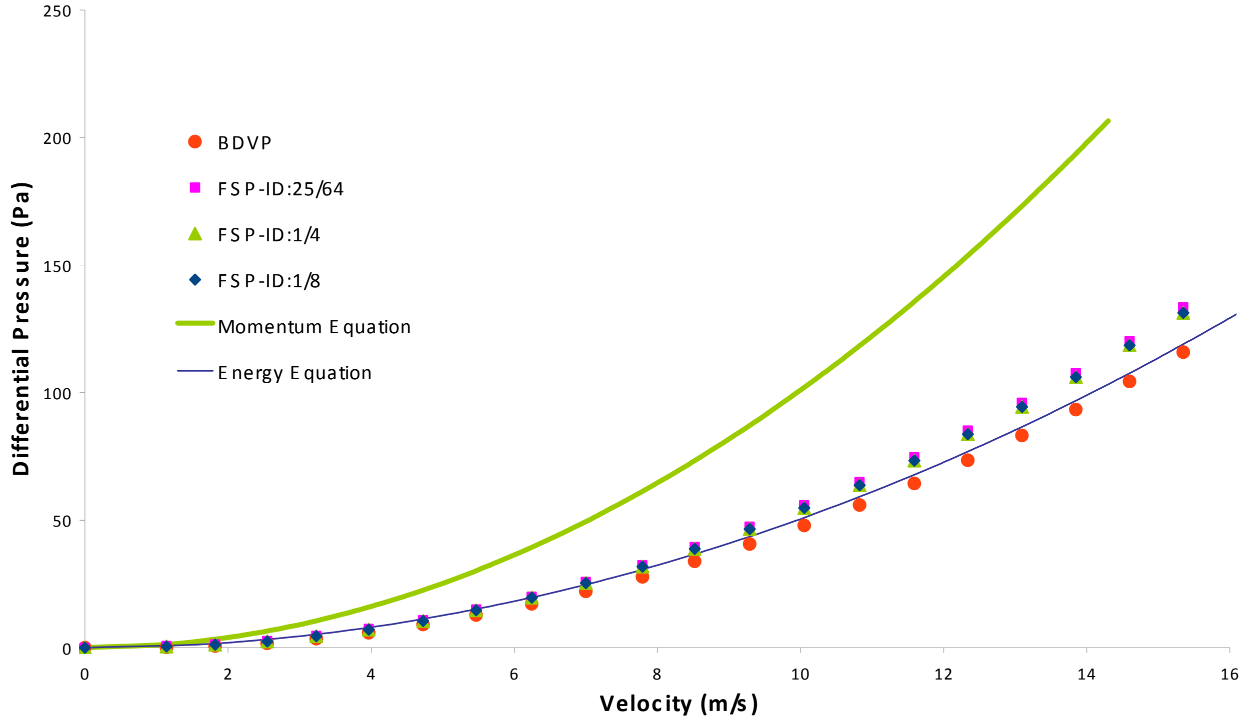
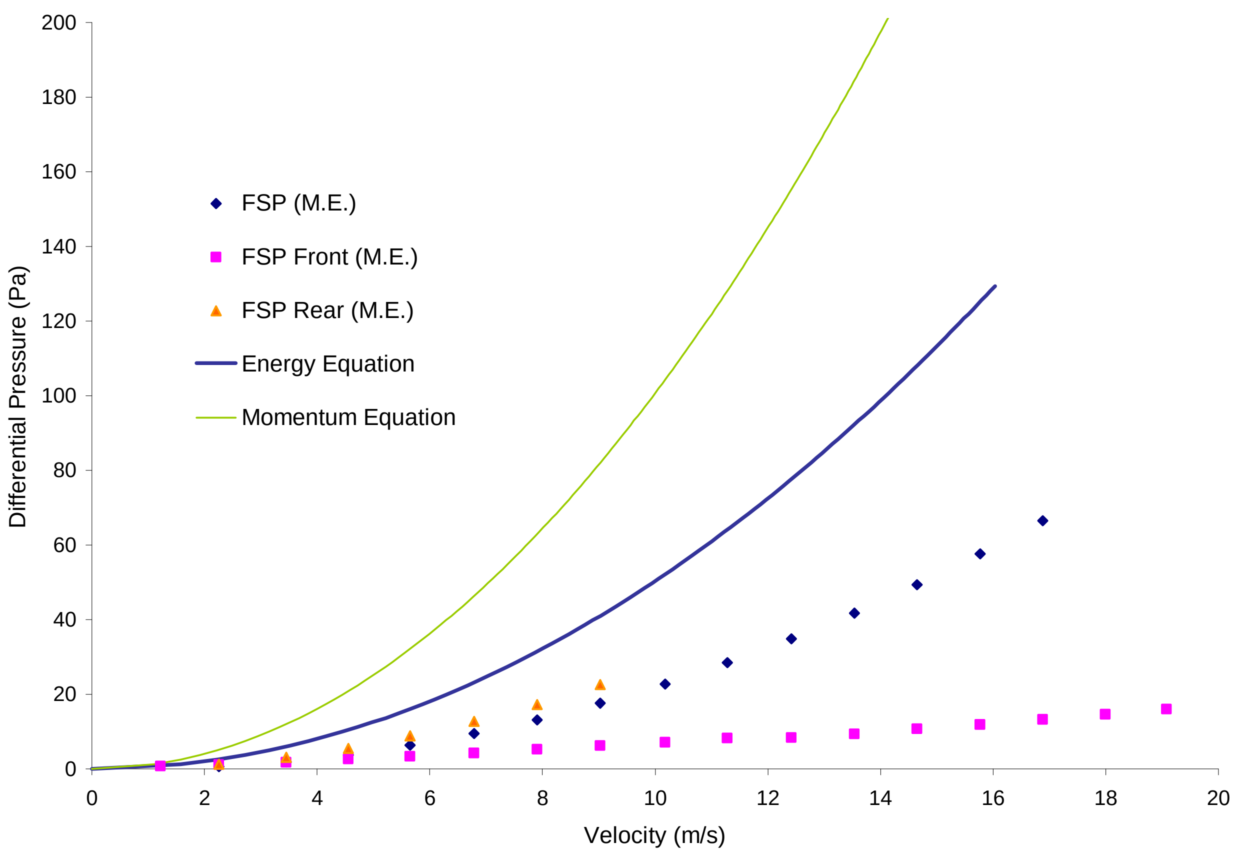


Figure 3. Probe performance comparision with Momentum and Energy equations



The amplification factor of the probes analyzed deviated from the trends in amplification factor published in previous studies [1-4]. The deviations are thought to be a result of measurement uncertainties at low velocities.

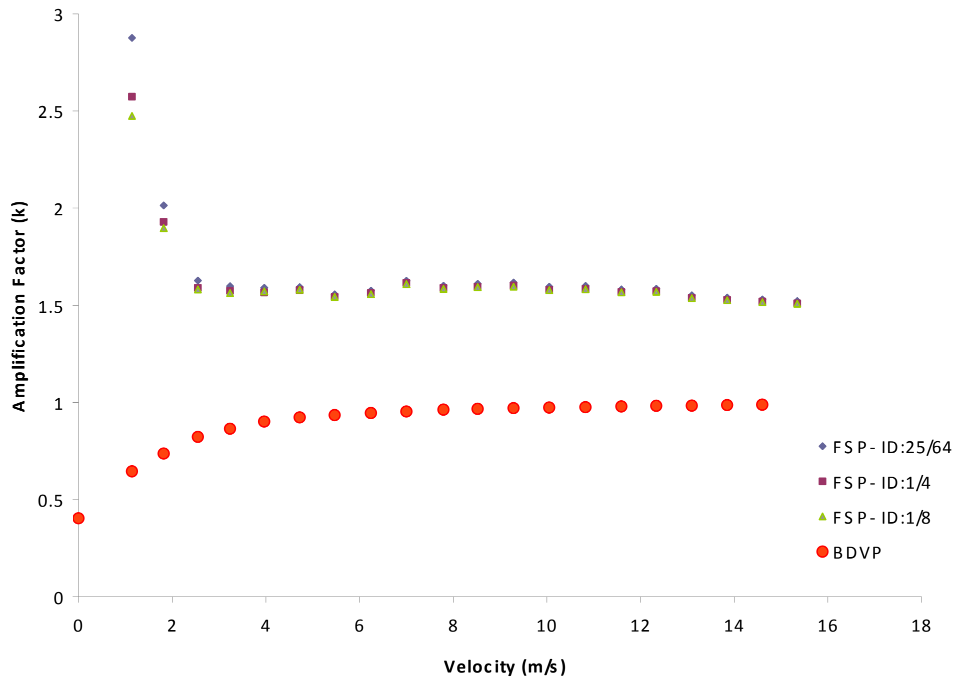


Figure 4. Probe amplification factor k

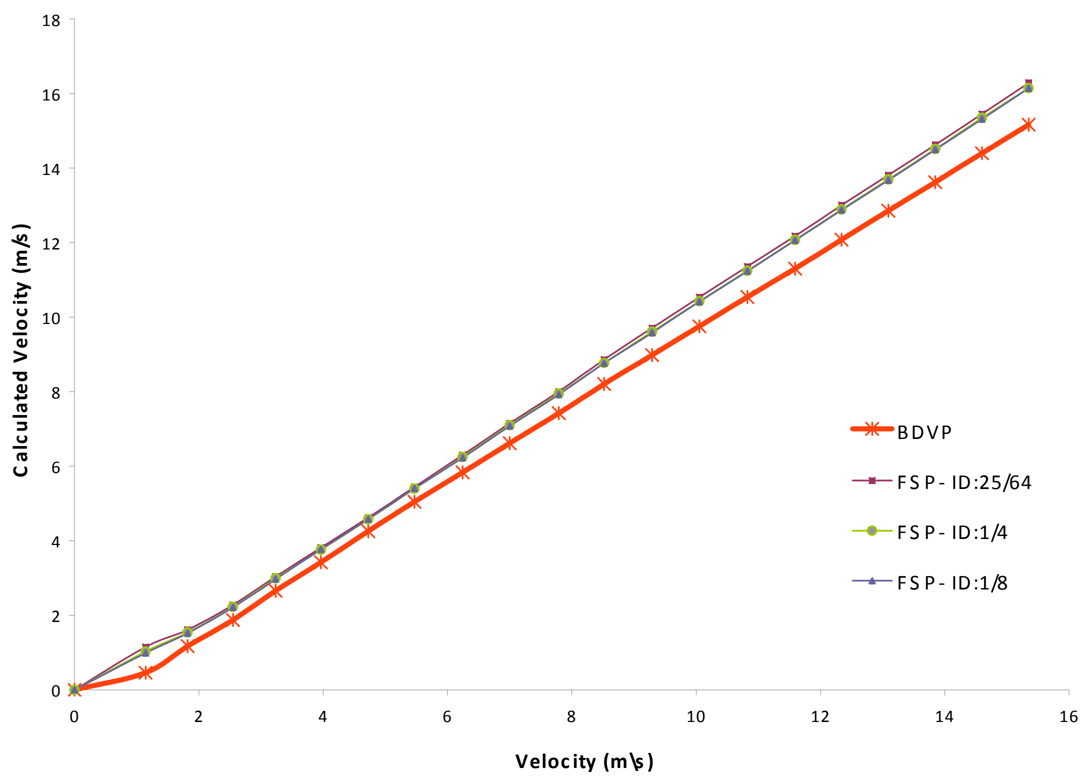


Figure 5. Probe indicated velocity vs. wind tunnel velocity

Computational Fluid Dynamics Analysis

A CFD analysis of an H-beam profile was performed at New Mexico Technological Institute to explore the flow conditions in and around the probe. The model was analyzed for flow in water with velocity ranges equivalent to 2 - 10 meters per second in air. The 2 m/s in air case is presented for comparison with Particle Image Velocimetry (PIV) analysis performed in the water channel because of similarities in flow conditions. The H-beam profile is considered to explore fluid behavior inside the upstream and downstream cavities. The CFD analysis model is two dimensional. A three dimensional version was constructed for PIV.

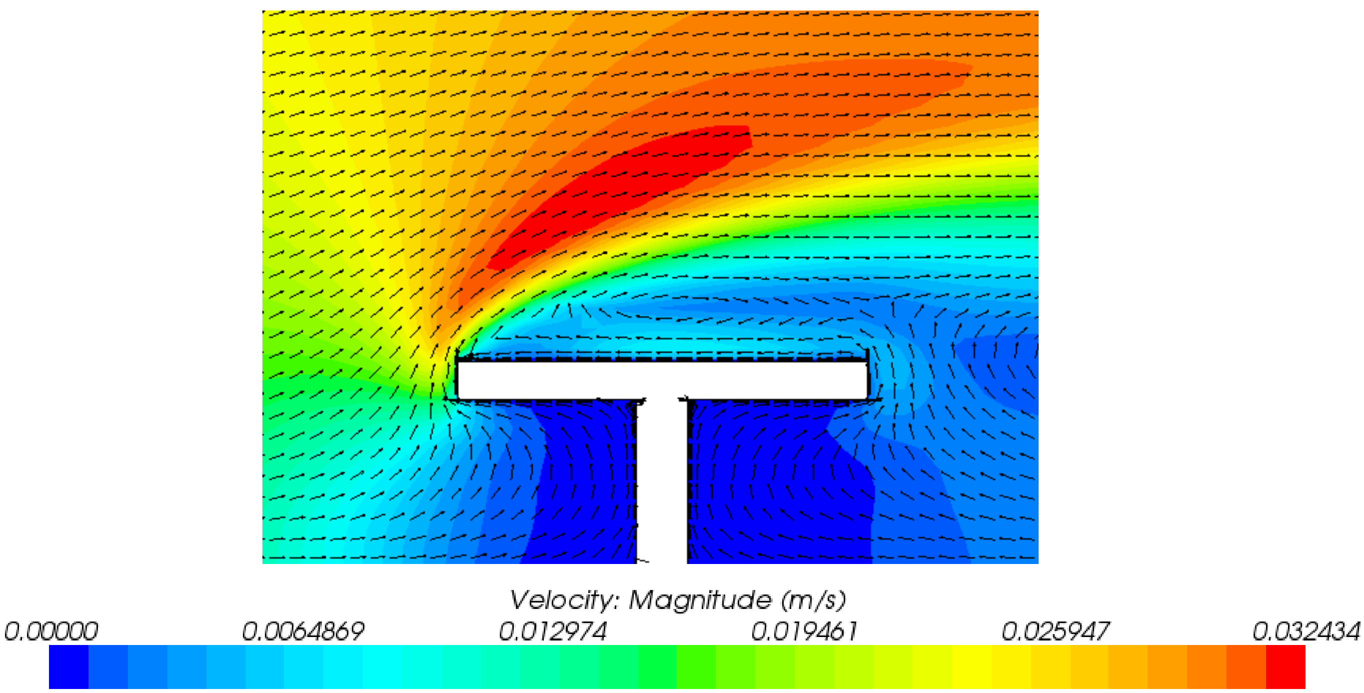


Figure 6. CFD velocity results for half of H-beam

The velocity on either side of the wall separating the up and downstream cavities is zero. The pressure field shown in figure was determined from the solution of the Navier-Stokes equation and is consistent with the momentum equation. The results indicate that the major component of the differential pressure measurements come from the front port.

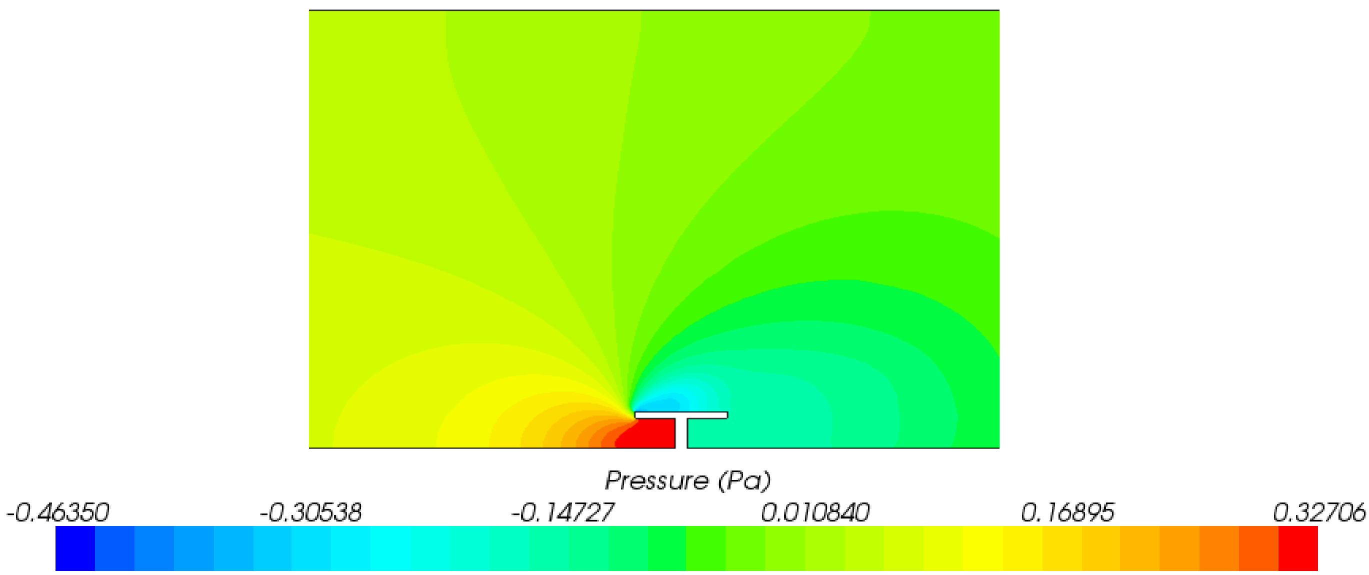


Figure 7. CFD results for pressure distribution for half of H-beam

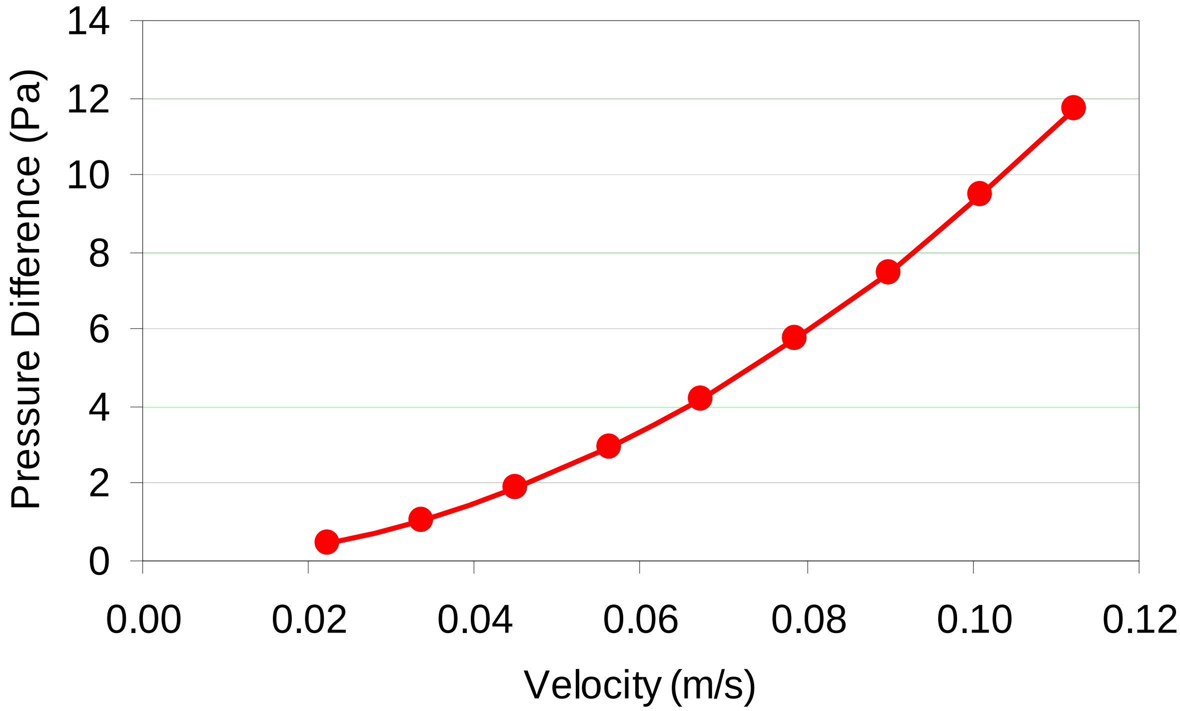


Figure 8. CFD indicated pressure difference between upstream and downstream cavities

Particle Image Velocimetry

PIV analysis was performed in the NMSU water channel with the BDVP and H-beam cavity model at a channel speed of 0.035 m/s, corresponding to a velocity of approximately 4 m/s in air. The BDVP is similar to previously studied designs [1,3,4] and retains the L/D = 2 configuration with an outer diameter of 25.4 mm and length of 50.8mm. During analysis the BDVP was suspended from above the channel in a manner consistent with its deployment in real situations. The H-beam profile also retains the L/D = 2 with a height of 25 mm and length of 50 mm.

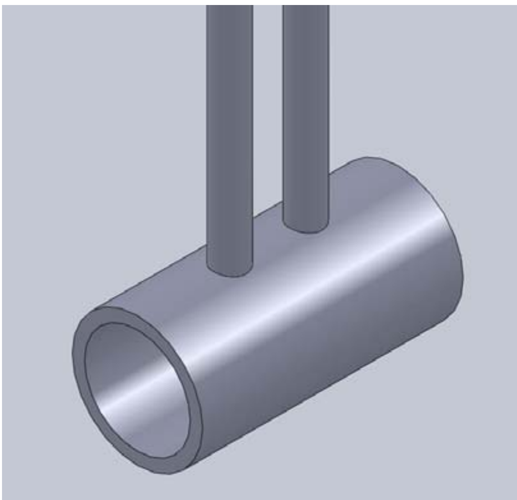


Figure 9. BDVP solid model

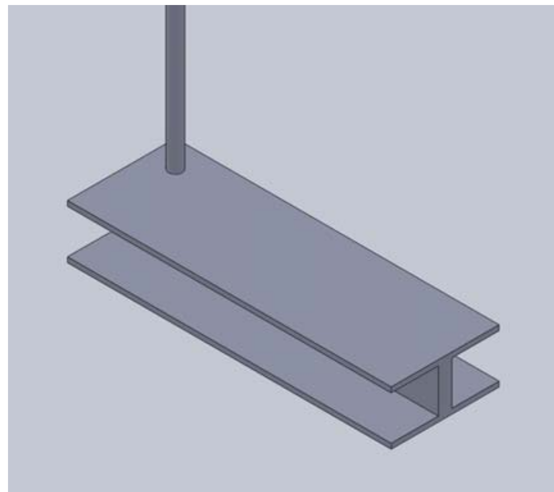


Figure 10. H-beam solid model

The behavior of water at the ends of the H-beam profile is considered and the model depth is designed with a dimension three times the characteristic length of the model. To minimize edge effects the H-beam has a depth of 152.4 mm. During imaging, the water channel was seeded with glass micro spheres and illuminated with a dual pulsed ND:Yag laser. The laser sheet used to illuminate particles passed through the center of the H-beam. PIV analysis provides average velocity measurements and flow field images for the fluid around the probe. The PIV legends are all presented in meters per second of water. Both models indicate maximum average velocities in the x-direction occurring along external edge of the seperated boundary layer caused by the leading edge of the upstream cavity.

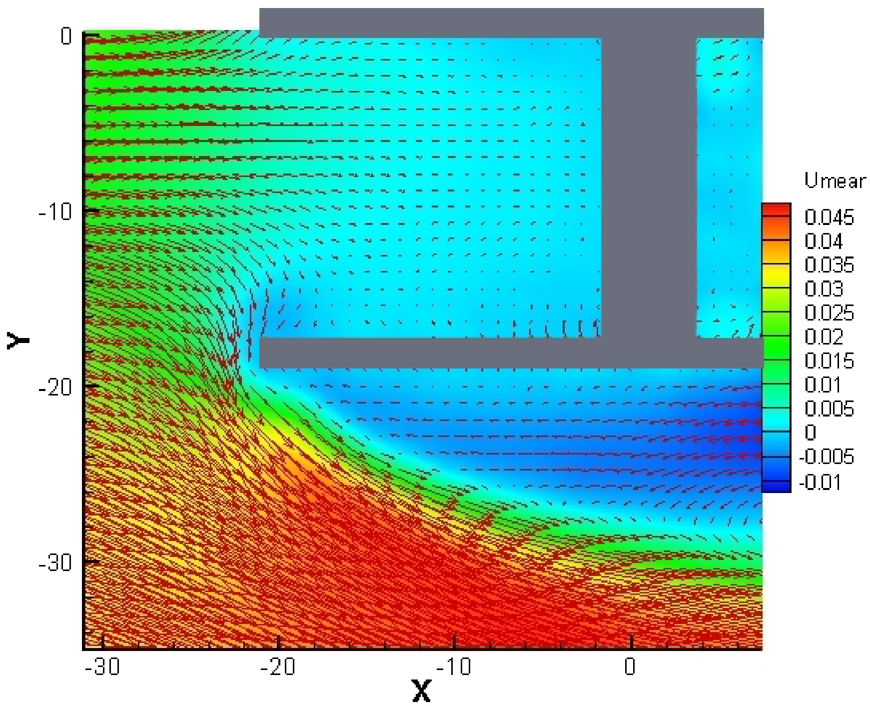


Figure 11. PIV indicated average velocity in the x-direction at the leading edge of the H-beam

The results indicate velocity in the upstream cavity slows to zero meters per second. figure 13 and 14 show enlarged views of the downstream half of figure 12 where vector fields indicate vortices. The vortices occur behind the leading edge of the probe along its sidewall and behind the trailing edge where the lower pressure region of the downstream cavity causes re-circulation zones.

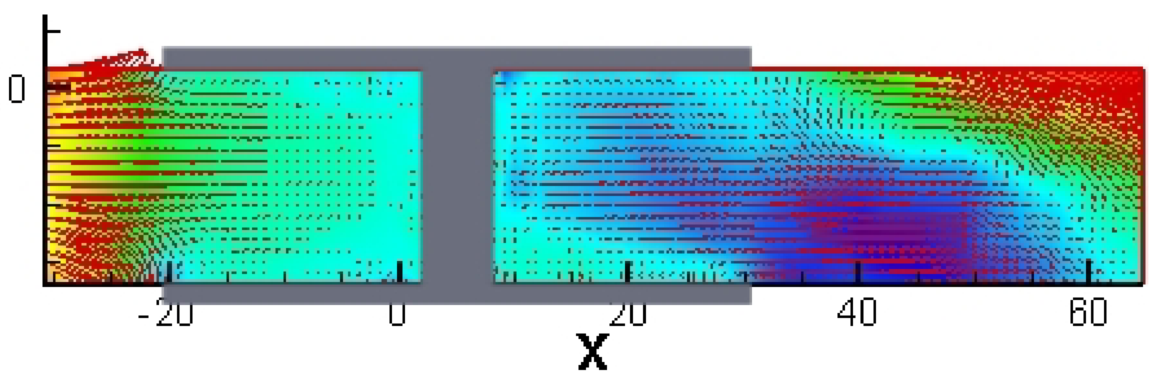


Figure 12. PIV indicated average velocity in the x-direction before and after the H-beam model

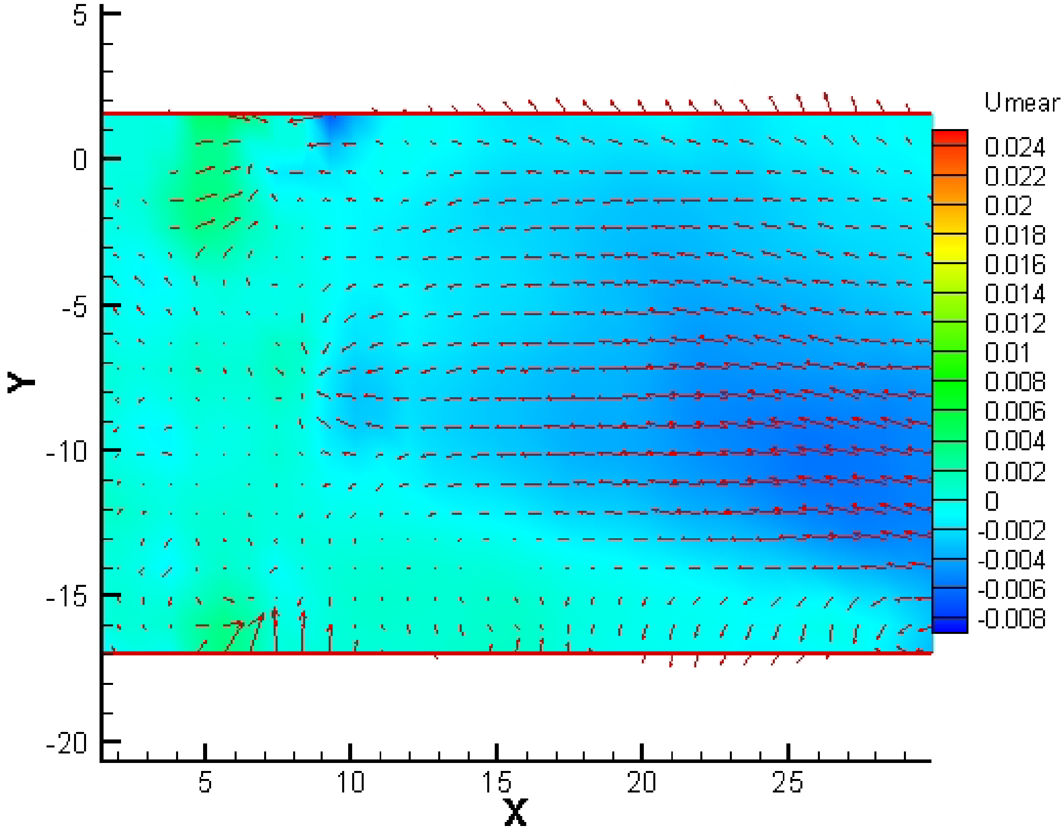


Figure 13. PIV indicated average velocity in the x-direction for the downstream cavity of the H-beam

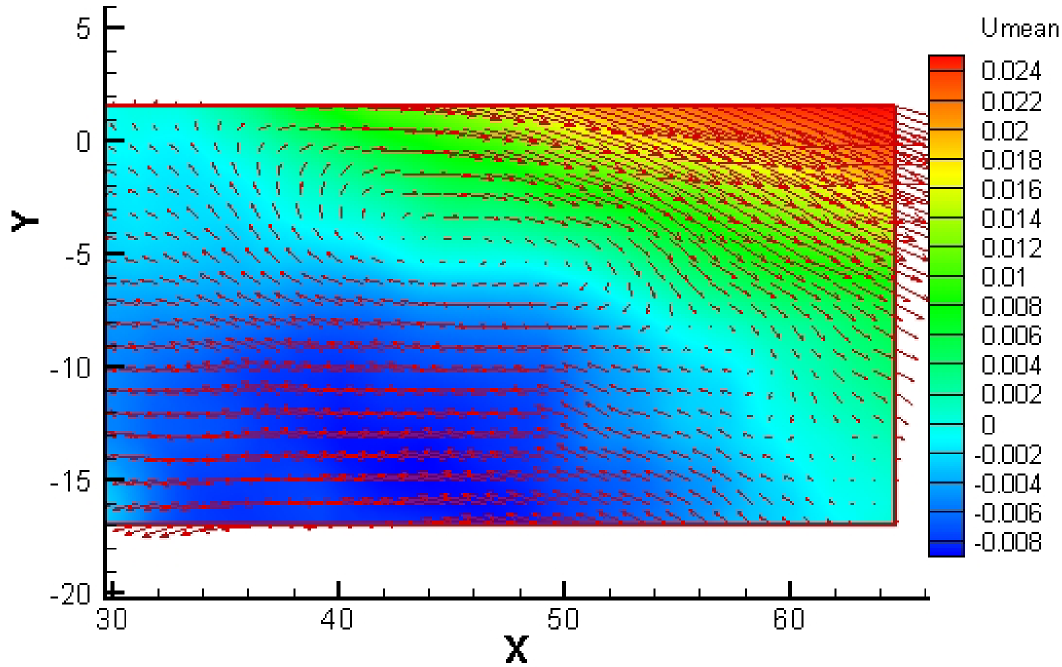


Figure 14. PIV indicated average velocity in the x-direction for the wake of the H-beam

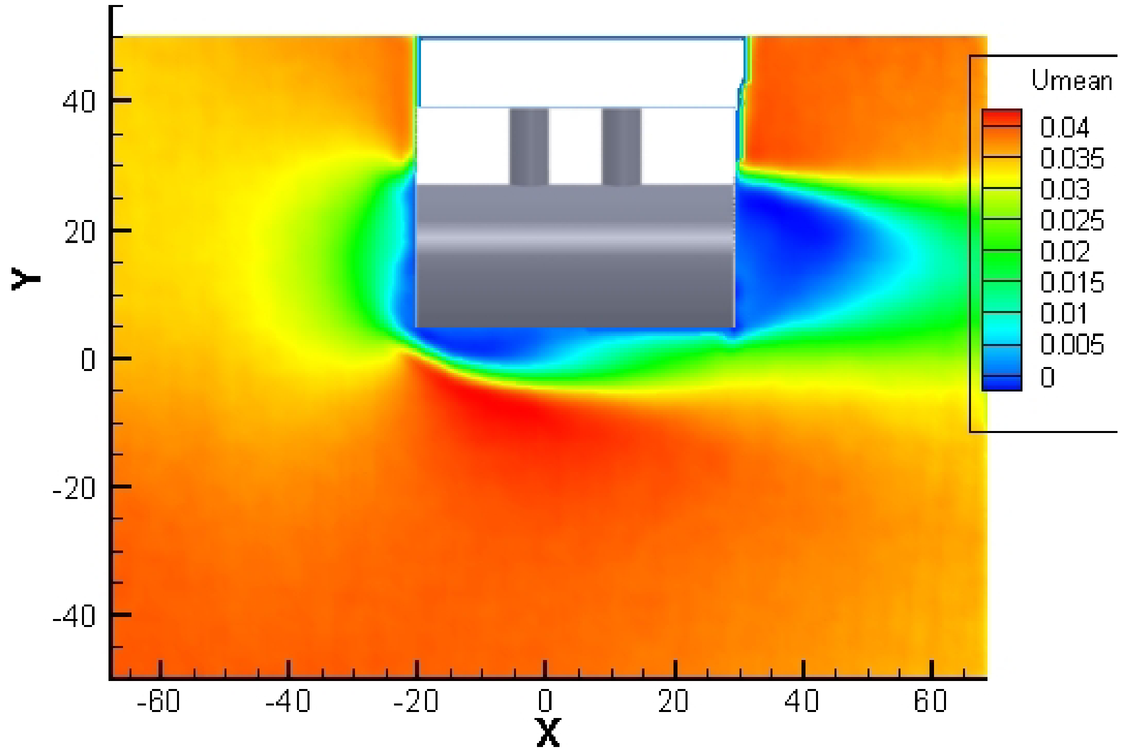


Figure 15. PIV indicated average velocity in the x-direction around the BDVP

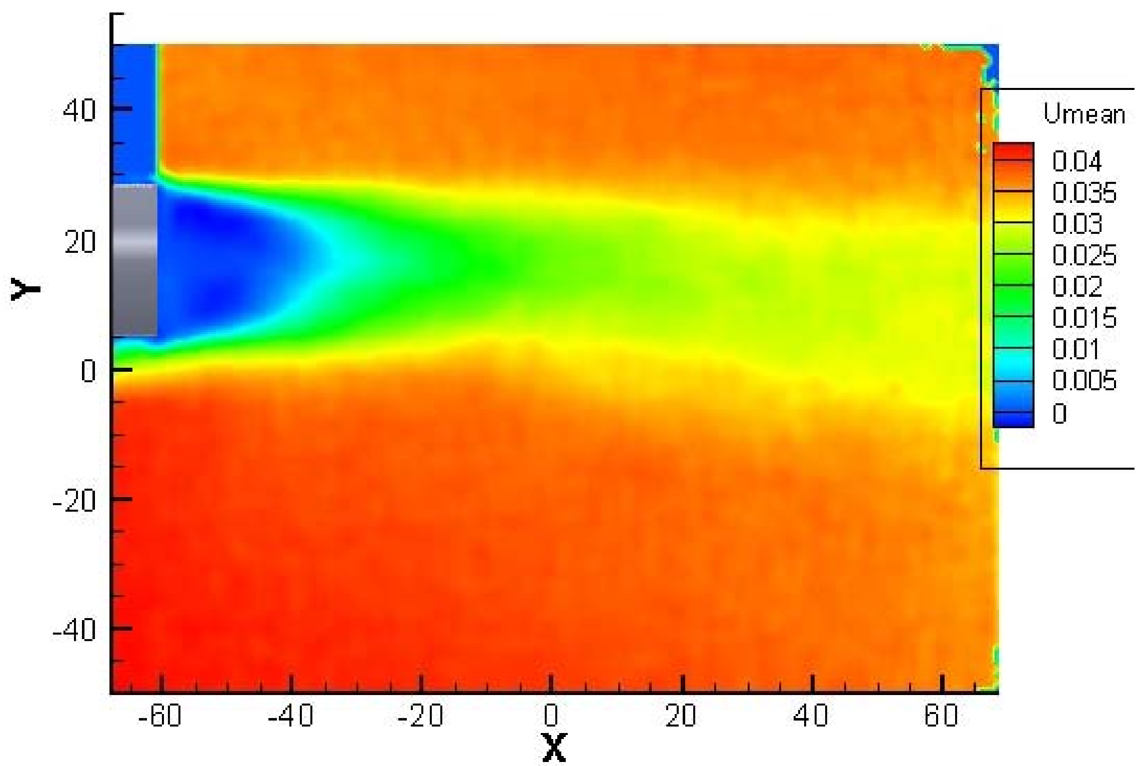


Figure 16. PIV indicated average velocity in the x-direction of the BDVP wake

Flow visualization

High resolution video was taken of the H-profile model to determine the flow characteristics in the cavities and nearby the model. Smoke was generated with an electrically heated wire oriented vertically in the LWT.   Upstream the model the flow is primarily undisturbed except for the region just leading the model. The front leading half of the model behaves much like a blunt object in flow. The flow in the front cavity approached stagnation causing the flow to divert around the probe. The flow is drawn around the leading edge along the external sidewall boundary layer.

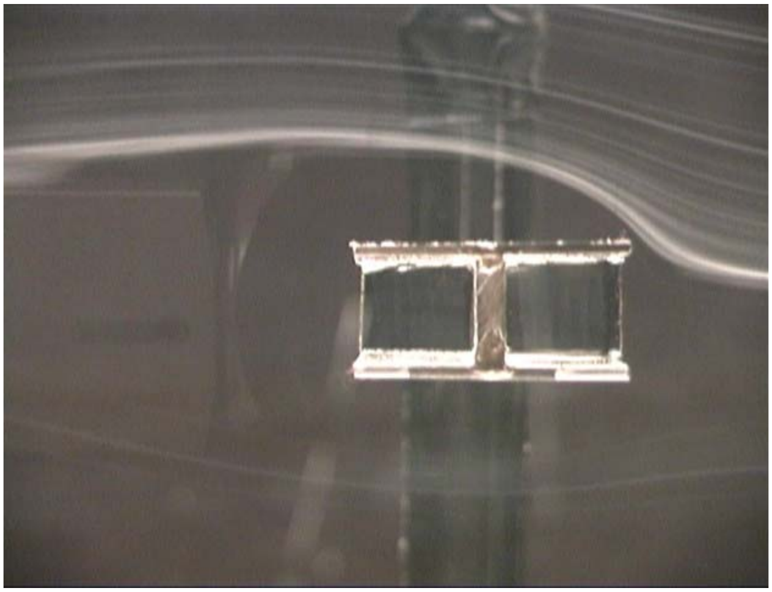


Figure 17. Streamline indicating flow past the leading edge along the boundary layer

Recirculation zones are created above and below the sidewalls and streamlines loose structure from increased turbulence. The downstream cavity is completely turbulent indicated by the general haziness of smoke drawn from the faster moving flow along the sidewall boundary layer. Although not shown, the flow rejoins approximately three lengths behind the trailing edge of the model

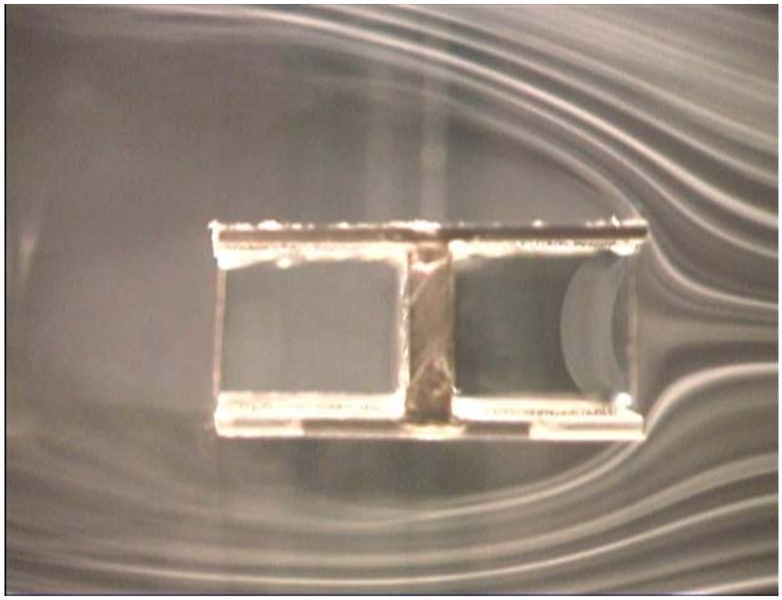


Figure 18. Flow patterns in the upstream and downstream cavities

Conclusions

From the FSP's differential pressure data, the upstream port appears to achieve the stagnation pressure for velocities below three meters per second but deviates as the velocities increase and flow becomes more turbulent. Recirculation zones on the trailing edge of the bi-directional probe may cause differential pressure data between the upstream and downstream ports to be less than the pressure differential between the upstream port and the static pressure. This difference causes deviations in the measured flame speed indicating a lower speed than may actually exist. As previously documented by others [1-4], the amplification factor is used to account for the deviation from the energy equation. Our data analysis was unable to provide motivation for use of an amplification, factor possibly due to increased uncertainties in our equipment at smaller measured differential pressures from lower velocities.

While the measured differential pressure does not vary greatly from design to design it seems reasonable that as the outer diameter of FSP's becomes smaller, perturbations to the flow caused by the probe itself are reduced creating a more Pitot-Static like device and subsequently improving the measurement accuracy. PIV analysis provided insight to the actual effects probe has on the surrounding flow and most notably the identification of recirculation zones along the probe body and at its trailing edge. Many of the environments where instruments of this or similar design are used have turbulent flow characteristics and

References

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4. Sette B. J. G., “Critical Considerations on the use of a bi-directional probe in heat release measurements,” Fire and Materials, Fire Matter, Vol. 29, pp. 335-349