Measurements of the Temperature and Velocity Fields in a Free Shear Flow between a Vitiated Stream and Clean Air Stream using a Pr:YAG Thermographic Phosphor

Dustin Witkowski\textsuperscript{1}, David A. Rothamer\textsuperscript{1}, Amy Lynch\textsuperscript{2}, Vince Belovich\textsuperscript{2}

\textsuperscript{1}Engine Research Center, University of Wisconsin, 1500 Engineering Dr, Madison, WI 53705
\textsuperscript{2}Air Force Research Laboratory, Wright Patterson Air Force Base, OH 45433

A phosphor-based simultaneous velocimetry and thermometry imaging measurement system was applied to a free shear flow to obtain measurements of velocity and temperature distributions in the shear layer formed between a vitiated air stream and a clean air stream. The two flow streams were seeded with thermographic phosphor particles consisting of praseodymium doped into yttrium aluminum garnet (Pr:YAG). A luminescence intensity ratio (LIR) method was utilized for temperature measurements. Simultaneous velocity measurements were acquired using Mie scattering from the seeded phosphor particles for PIV. The apparatus studied with the thermometry measurements consisted of a flow of vitiated air separated from a flow of clean air by a splitter plate. At the end of the splitter plate separating the flows a shear layer is formed between the two streams due to the velocity difference. The clean air was operated at an inlet temperature of 500 K and the vitiated flow was operated at inlet temperatures of 755 K and 865 K. Average velocities in the clean air stream ranged from approximately 20 to 50 m/s and those in the vitiated stream ranged from 80 to 110 m/s. The higher velocities necessitated shorter integration durations (10 µs) than have previously been utilized for measurements with the Pr:YAG phosphor. Results for the measured average velocity and temperature fields agree well with similarity solutions for a plane mixing layer. The measurements demonstrate application of the temperature measurement technique to higher flow rates than previously measured in an applied measurement environment.

1. Introduction
Simultaneous measurements of temperature and velocity fields are an important step for understanding the physics governing flows involving heat transfer and chemical reactions. Acquiring this data in harsh environments, at high temperatures and high velocities, has proven to be a non-trivial experimental challenge. An experimental method utilizing particle image velocimetry and temperature imaging (PIV+T) with thermographic phosphors has been previously demonstrated (Omrane, Petersson et al. 2008; Fond, Abram et al. 2012; Neal, Jordan et al. 2013) and is being refined to enable such challenging measurements. The current thermographic phosphor based PIV+T method has the advantage of allowing the measurement of the relatively long-lived temperature dependent luminescence intensity of the thermographic phosphors upon laser excitation, while simultaneously using these particles to obtain particle image velocimetry (PIV) measurements from elastic scattering. The luminescence intensity is temperature dependent over a wide range, allowing for accurate measurements in fields with large temperature variations.

Until very recently, the simultaneous PIV+T technique using thermographic phosphors had only been demonstrated in simple laboratory flows such as jets or flows around bluff bodies (Omrane, Petersson et al. 2008; Fond, Abram et al. 2012). Demonstration of simultaneous velocity and temperature imaging has been recently performed in IC engines (Someya, Okura et al. 2012; Neal, Jordan et al. 2013) under motored engine operation. Application of the technique to higher flow velocity (>30 m/s) has yet to be performed, particularly in a more applied measurement environment.

In the current work a simultaneous PIV+T diagnostic is demonstrated in a test rig designed to investigate fundamental mixing at elevated temperatures. Elements of the flowfield include two flow streams at different velocities and temperatures with a splitter plate separating them. One of the streams is a vitiated high temperature stream which jet fuel (JP-8) can be injected into. The other is a clean air stream at lower temperature and velocity. At the end of the splitter...
plate the streams form a turbulent shear layer. A bluff body can be placed in the flow downstream of the end of the splitter plate when fuel is being injected to stabilize the flame. For the work reported here, measurements were performed without fuel injection and combustion did not occur in the test section. The resulting temperature and velocity fields presented for the non-reacting cases are compared to turbulent mixing theory to assess the diagnostic measurements. Thermocouple measurements of temperature, and bulk flowrate measurements are also used to assess the accuracy of the technique.

2. Methods

Diagnostic Background

For the luminescence intensity ratio (LIR) thermometry method, thermographic phosphors are seeded into the flow stream of choice and a laser sheet is formed and used to excite the phosphors. When the phosphors are excited, they emit luminescence in well-defined spectral regions. The thermographic phosphor used for the simultaneous PIV+T measurements performed in the current work was praseodymium doped yttrium aluminum garnet (Pr:YAG). The Pr:YAG phosphor was recently shown to provide high signal levels while also allowing for relatively short integration durations (Jordan and Rothamer 2012; Neal, Jordan et al. 2013). The technique for measuring temperature using the Pr:YAG phosphor is described in two recent publications (Jordan and Rothamer 2012; Neal, Jordan et al. 2013), so only a brief outline is given here.

Figure 1 shows a Dieke diagram for Pr:YAG that highlights the energy levels and emission wavelengths for transition relevant to the current measurements. Excitation is performed at 266 nm, populating the 4f5d states in Pr$^{3+}$. These states rapidly decay (~20 ns at room temperature) via radiative and non-radiative mechanisms to populate the 4f states of Pr$^{3+}$. Luminescence emission from two different states is required for the LIR temperature measurements. For the current measurements emission from the $^1D_2 \rightarrow ^3H_4$ transition (~610 nm) and from the $^3P_J$ ($J=0,1,2) \rightarrow ^3H_4$, $^3H_5$ (~480 nm) transitions was imaged. The ratio of emission from these states is related to temperature. By capturing the luminescence in two different spectral regions and taking the ratio of the two signals the laser energy and seeding concentration dependences are eliminated making the measurements independent of laser-sheet profile. Additionally, the relatively long lifetime of the emission compared to fluorescence allows for the start of the camera exposure to be delayed 100 ns from the center of the laser pulse enabling the rejection of fluorescence and laser-induced incandescence signals generated by the laser excitation pulse. This is important for the current work since measurements were also attempted during combustion of JP-8 (results not presented here).

Figure 1: Dieke diagram of energy levels for Pr:YAG showing excitation and emission wavelengths (energy levels from (Gruber, Hills et al. 1989))

Simultaneous with the temperature measurements, the phosphor particles were used for Mie scattering. This scattered light can be used to gather information regarding the flow velocities using particle image velocimetry (PIV). In addition to the laser pulse used for excitation of the phosphor particles a second laser pulse from a double-pulsed Nd:YAG laser is used to produce the second image needed for PIV.
Experimental setup

Figure 2 shows the experimental setup for the measurements. The fourth harmonic of a Nd:YAG laser at 266 nm was used to excite the thermographic phosphors, resulting in the luminescence emission required for temperature measurements. A fraction of the residual 532 nm beam remaining after 4th harmonic generation was co-propagated with the 266 nm beam and the resulting elastic scattering of the thermographic phosphors from the 532 nm laser sheet was captured for the PIV measurements. To obtain a reasonable amount of 532 nm residual light the two dichroic harmonic separators in the laser system were replaced with a broadband mirror with high reflectivity from 240 to 350 nm (with some measurable but lower reflectivity at 532 nm) and with a right angle prism anti-reflection (AR) coated for 266 nm. It was necessary to co-propagate the 532 nm light for PIV since the PIV camera used was not sensitive to 266 nm light.

Both oscillators in the laser were used and each was operated at 10 Hz (i.e. two laser pulses every 0.1 s), with an interpulse spacing of 11 µs. Immediately outside of the laser, the beam was directed through a 90 degree angle using a turning prism. This beam was then raised to a height of approximately 8 ft. above the ground using a periscope consisting of two 90 degree turning prisms. A Bosch strut structure held an optical rail that was used to mount the upper turning prism post base. The beam was then directed horizontally towards the rig where another turning prism sent the beam downward, perpendicular to the top window on the rig. A second optical rail mounted to the Bosch strut was used to mount the turning prism and the sheet forming optics. A -50 mm focal fused silica cylindrical lens was placed close to the turning prism and expanded the beam in the wide direction of the sheet. A 500 mm focal length fused silica spherical lens was placed ~450 mm away to collimate the sheet width and then focus the beam waist in the test section. The waist of the sheet was positioned near the center of the rig cross-section and the sheet thickness at the waist was estimated to
be approximately 300 µm. Laser energy used for the measurements was between 45 to 50 mJ/pulse at 266 nm and between 10 and 15 mJ/pulse at 532 nm. Positions of the laser sheet in the rig test section used for the measurements are shown in Figure 3 and Figure 4.

![Side View](image1)

**Figure 3:** Schematic illustrating the location of the data plane relative to the rig under vitiated and combusting conditions.

![Top View](image2)

**Figure 4:** Top view of location of laser sheet imaging planes for cases with and without the bluff body. Positions for each condition are noted in the schematic.

A second lower optical breadboard was used to support the aluminum breadboard which the cameras were mounted to. Tall posts (~355 mm) were needed to raise the aluminum breadboard height up so that the cameras could image the centerline of the rig. Three cameras were required for the simultaneous PIV+T measurements. Two cameras were required for temperature measurements, and one camera was used for the PIV measurements. An uncoated pellicle beamsplitter (~8% reflectivity) was used to reflect Mie scattered light to the PIV camera, and a 50/50 beamplitter was employed to transmit and reflect equal amounts of the phosphors’ luminescence signal to the temperature cameras. The camera used for the PIV measurements was a 1300 x 1030 pixel interline transfer CCD camera (Princeton Instruments, MicroMax). It was fitted with a Nikkor lens (f/1.2, 50 mm) equipped with a narrow bandpass filter centered at 532 nm (10 nm bandwidth) to capture the elastic scattering from the 532 nm laser sheet. Temperature camera 1 (T Camera 1) was a 1024 x 1024 pixel intensified charge coupled device (ICCD) camera (Princeton Instruments, PI-MAX3). Temperature camera 2 (T Camera 2) was originally the same model as T Camera 1, but had to be switched out for a different ICCD camera (Princeton Instruments, PI-MAX1) due to issues with the original camera. Both cameras utilized Nikkor lenses (f/1.4, 85 mm). Temperature camera 1 captured luminescence from the excited phosphors due to emission from the $^1D_2$ transition. T camera 2 captured luminescence from the excited phosphors due to emission from the $^3P_1$ states. Detailed information on the filters used on the cameras is provided in Table 1.

The phosphor particles used for the measurements consisted of Pr$^{3+}$ doped into YAG at 0.5% (Phosphor Technology) and had a 1.8 µm mean diameter. The particles were coated with a thin layer of aluminum oxide by the manufacturer to
improve flow characteristics. Phosphor particles were aerosolized into the seed flow using a custom seeding system consisting of a volumetric feeder situated inside of a pressure vessel. The volumetric feeder had an electric motor with eccentrics attached to it. The motor is designed to vibrate the feeder and improve the flow of material by keeping the helix screw full. A rotometer was used to control air flow to the seeder. The flow out of the seeder was transported to the rig through an electrically grounded 5/8 in. outside diameter copper tube. This tube was connected to a 1/4 in. diameter stainless steel tubing manifold that divided the flow and sent it to the three stainless steel 1/4 in. tubes in the rig.

Table 1: Camera filters used for PIV+T measurements.

<table>
<thead>
<tr>
<th>PIV</th>
<th>532 nm, 10 nm bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{1}D_{2}$</td>
<td>630 nm shortpass filter</td>
</tr>
<tr>
<td>600 nm longpass filter</td>
<td></td>
</tr>
<tr>
<td>$^{3}P_{1}$</td>
<td>Visible bandpass filter, BG Schott Glass</td>
</tr>
<tr>
<td>473 nm longpass filter</td>
<td></td>
</tr>
<tr>
<td>526 nm shortpass filter</td>
<td></td>
</tr>
<tr>
<td>532 nm OD 6 Notch filter</td>
<td></td>
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</tbody>
</table>

Phosphor was seeded into the flow through three 1/4 in. outside diameter tubes. The tubes were bent 90 degrees to allow the seeded flow to exit the tube along the centerline of the rig. One of the tubes was used to seed the clean flow, and the other two tubes were used to seed the vitiated flow. The tube in the clean stream was positioned in the center of the clean stream. The two tubes in the vitiated flow were spaced approximately equidistant from each other and the walls in the vertical direction (the exit was along the rig centerline in the horizontal direction).

Figure 5 shows the timing between the laser pulses and cameras for the current measurements. An oscilloscope was used to set the delay between the laser external sync out trigger and the actual laser pulse to approximately 1 µs. The laser’s external sync was then used to trigger T Camera 1. T Camera 1 was then used to trigger T Camera 2, and T Camera 2 was used to trigger the PIV camera. For both temperature cameras, an oscilloscope and a fast biased photodiode were used to ensure that the gate delay was set to 100 ns with respect to the center of the laser pulse. Temperature cameras were set to a gate width (exposure duration) of 10 µs. For the PIV camera, the dual-image feature mode was used (two images per trigger) to capture the elastic scattering from both laser pulses. The laser pulses occurred during the exposures for the PIV camera. The exposure duration for each PIV image was 10 µs.

![Figure 5: Camera timing diagram](image)

**Temperature Calibration**

A temperature calibration is required to obtain a quantitative relationship between the luminescence intensity ratio and temperature. The calibration was performed in a tube furnace (CM Furnaces, Rapid Temp Model 1720-12) with a 0.305 m heated length centered in a 0.914 m long working tube used to improve temperature uniformity. The furnace is specified to have temperature uniformity of ± 2 K for the central 100 mm of the hot zone. The phosphor powder was placed in a small alumina (>99.6% purity) dish. The dish was angled upward so that the contents of it could be imaged
by viewing down the axis of the furnace tube. The phosphor was excited with 0.5 ±0.2 mJ/pulse of laser energy at 266 nm with a beam diameter of approximately 3 to 4 mm. Residual 532 nm light was separated out of the beam using a Pellin Broca prism. A wedged window was used to pick off a small fraction of the beam energy from the main pulse allowing the laser to be operated with close to the same Q-switch delay as was used for taking the actual experimental measurement. The cameras were setup with an identical configuration to that used for the measurements. Calibration measurements were performed for temperatures from 300 K to 1700 K in 50 K increments. These measurements were made at the highest temperatures to date. Previous calibration measurements (Jordan and Rothamer 2012; Neal, Jordan et al. 2013) were limited to temperatures of 1300 K due to the specifications of the previous furnace used.

The results of the calibration are plotted in Figure 5. As can be seen, the ratio (normalized by its room temperature value) peaks, at 1300 K. The signals for temperatures greater than 1200 K are low for the \(^1\text{P}_j\) emission and are rapidly decreasing for the \(^1\text{D}_2\) emission. Above 1400 K thermal emission from the phosphor begins to be significant.

The velocity vectors presented here were calculated from the PIV images using the post-processing software Insight3G (TSI, Inc.). The data processing utilized a recursive Nyquist grid with 50% overlapping. A final interrogation region of 32 × 32 pixels was used, giving velocity vectors every 1.8 mm in the horizontal and vertical directions. A ZeroPadMask was used in the processing which calculated the average intensity in each interrogation region and subtracted this average from each pixel, which increased the SNR of the PIV images. A direct correlation method was used and the peaks were fit with a Gaussian to calculate displacement between the images with sub-pixel accuracy. Vector filling was accomplished using a 3×3 median replacement with only measured vectors from the PIV processor being used. For the higher flow velocity cases the interpulse spacing is slightly too large leading to displacement of greater than ¼ the interrogation region dimension and potentially impacting the velocity results (Keane and Adrian 1990).

3. Results and Discussion
The conditions tested are summarized in Table 2. Four vitiated cases were run at two different flow splits. The position of the laser sheet was moved between condition 3 and condition 4. For condition 4 the bluff body was put in and the laser sheet was shifted toward the front window as indicated in Figure 3.
Table 2: Conditions for measurements

<table>
<thead>
<tr>
<th>Cond. #</th>
<th>Clean Stream (T_{\text{ave}}) [K]</th>
<th>Vitiated Stream (T_{\text{ave}}) [K]</th>
<th>Flow Split</th>
<th>Clean Stream (U_{\text{ave}}) [m/s]</th>
<th>Vitiated Stream (U_{\text{ave}}) [m/s]</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>501</td>
<td>873</td>
<td>0.2</td>
<td>25</td>
<td>109</td>
</tr>
<tr>
<td>2</td>
<td>499</td>
<td>760</td>
<td>0.2</td>
<td>36</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>496</td>
<td>756</td>
<td>0.5</td>
<td>55</td>
<td>84</td>
</tr>
<tr>
<td>4*</td>
<td>496</td>
<td>861</td>
<td>0.5</td>
<td>52</td>
<td>90</td>
</tr>
</tbody>
</table>

*Bluff body in for these cases (sheet position is also different).*

For each condition given in Table 2 at least two data sets of 280 temperature images and 35 PIV image pairs were acquired. Fewer PIV data pairs are available due to the time required to readout an image pair at full resolution for the PIV camera used. Typically only 25 of the 35 PIV image pairs had sufficient seeding for processing and only 25 image pairs were processed for PIV measurements for each condition. The temperature cameras on the other hand were able to take data at the 10 Hz laser repetition rate. Due to the nature of the phosphor seeding process typically only about 5 to 15% of the temperature images acquired had sufficient phosphor present to generate the required signal levels for good temperature measurements. The seeding in the vitiated stream was generally lower than that in the clean stream during data sets. This can be seen from the single-shot Mie scattering image used for PIV measurements shown in Figure 6.

![Mie scattering image](image)

**Figure 6:** Mie scattering image from phosphor particles taken for condition 1 showing seeding in the clean and vitiated streams.

**PIV+T Average and Single-shot Imaging Results**

Average velocity and temperature imaging results for condition 1 are shown in Figure 7 along with a set of simultaneous single-shot PIV+T image results. The average images show the vertical stratification in temperature and velocity due to the mixing layer formed between the clean and vitiated streams. It is useful to remember the only about 1/3 of the height of the clean stream is visible in the data as illustrated in Figure 3. The average temperature image is calculated using all available data which has signal intensity greater than 250 counts above background on the \(^3\)P\(_1\) camera. Each pixel which meets this criterion is included and the number of pixels at each location is counted and used to calculate the average at that pixel.

The quality of the single-shot images varies significantly shot-to-shot due to the variation of phosphor seeding levels. The single-shot temperature image in Figure 7 (d) exhibits varying signal-to-noise ratio throughout the image due to phosphor seed density variation within the image. The single-shot images show variability in the mixing layer formed between the clean and vitiated streams. The average temperature and velocity profiles in the vertical direction are shown in Figure 8. The average temperatures measured with thermocouples located directly upstream of the test section in the vitiated and clean streams are shown as horizontal lines with labels. As seen in the figure the values of temperature obtained in the clean and vitiated streams agree well with the measurements performed with thermocouples.
Figure 7: Condition 1 simultaneous velocity and temperature fields (a) average velocity, (b) average temperature, and corresponding single-shot velocity (c) and single-shot temperature (d).

Figure 8: Average temperature and velocity profiles for condition 1. Also shown are horizontal lines indicating the temperatures measured for the vitiated flow and clean flow with thermocouples immediately upstream of the test section.

The temperature and velocity data in Figure 9 correspond to condition 2, where the vitiated stream temperature was cooler than for condition 1. The overall average temperature field is similar to condition 1, but the average temperature and velocity profiles in Figure 10 show slightly different profiles than for condition 1. In particular, the temperature over the vitiated stream appears to be more uniform for this condition. The single-shot images again show the variability in mixing between the two streams.

The results for condition 3 which has the same sheet position in the rig cross section with the bluff body not present are shown in Figure 11. Condition 3 has the same vitiated stream temperature as condition 2, but has a flow split of 0.5 versus 0.2 for conditions 1 and 2. This means that the velocity difference between the two streams is smaller than for conditions 1 and 2. The average temperature and velocity profiles in the vertical direction are shown in Figure 12. Due to the smaller velocity difference between the two streams it appears to have a steeper temperature gradient indicating less mixing between the streams as expected due to the lower velocity difference. The average temperatures in the vitiated and clean streams also appear to be captured accurately.

The temperature and velocity distributions for condition 4 are shown in Figure 13. This case had the bluff body placed in the test section. The temperatures and flowrates for condition 4 are the same as condition 3 except for the higher vitiated flow temperature and the bluff body being in place. Due to the bluff body position the laser sheet position was shifted closer to the front window staying parallel to the plane of the window. The presence of the bluff body causes the velocities at the sheet position to be higher than those listed in Table 2. Figure 14 shows the average temperature and velocity profiles in the vertical direction for condition 4.
Figure 9: Condition 2 simultaneous velocity and temperature (a) average velocity, (b) average temperature, and corresponding single-shot velocity (c) and single-shot temperature (d).

Figure 10: Average temperature and velocity profiles for condition 2. Also shown are horizontal lines indicating the temperatures measured for the vitiated flow and clean flow with thermocouples immediately upstream of the test section.

Figure 11: Condition 3 simultaneous velocity and temperature (a) average velocity, (b) average temperature, and corresponding single-shot velocity (c) and single-shot temperature (d).
Figure 12: Average temperature and velocity profiles for condition 3. Also shown are horizontal lines indicating the temperatures measured for the clean flow and vitiated flow with thermocouples immediately upstream of the test section.

Figure 13: Condition 4 simultaneous velocity and temperature (a) average velocity, (b) average temperature, and corresponding single-shot velocity (c) and single-shot temperature (d).

Figure 14: Average temperature and velocity profiles for condition 4. Also shown are horizontal lines indicating the temperatures measured for the vitiated flow and clean flow with thermocouples immediately upstream of the test section.
Table 3: Comparison of average vitiated stream temperatures measured with the diagnostic and with a thermocouple positioned directly upstream of the test section, and precision of the average images and the typical precision of high quality single-shot images.

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<tbody>
<tr>
<td>1</td>
<td>881</td>
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<td>756</td>
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<td>34</td>
</tr>
<tr>
<td>4</td>
<td>846</td>
<td>861</td>
<td>11.0</td>
<td>25</td>
</tr>
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</table>

The vitiated flow temperatures calculated using the diagnostic and the values measured with the thermocouple immediately upstream of the test section are summarized in Table 3. Agreement between the diagnostic measurements and thermocouple measurements in the vitiated flow is quite good. The average temperatures were calculated by spatially averaging over a 10 mm wide by 20 mm tall region in the middle of the vitiated flow. Also shown in the table is the spatial variation in temperature (1-standard deviation) in a region which was relatively uniform in the average image and the typical values for the same calculation in some of the higher-quality single-shot images, giving an approximate feel for the potential single-shot precision obtainable with the technique.

Table 4 shows a comparison between the measured average velocities from the diagnostic and the average velocities anticipated based on flowrate measurements. Agreement for cases 1-3 between the diagnostic and the flowrate determined average velocities is generally good. It is not obvious why the vitiated velocity for condition 1 doesn’t agree as well as the other points. Due to the relatively small number of images averaged (25) it is possible that a few underpredicted velocities in the dataset threw off the mean. Also as mentioned earlier the maximum velocities may fall outside of the criterion that the maximum displacement be less than ¼ of the interrogation region dimension. For case 4 the flow rate information cannot be used to predict the velocity due to the location of the laser sheet just slightly downstream of the bluff body.

Table 4: Comparison of average measured velocity magnitudes in vitiated and clean flow streams compared with the expected values based on flowrate measurements.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vitiated $U_{ave}$ Diagnostic [m/s]</th>
<th>Vitiated $U_{ave}$ Flowrate [m/s]</th>
<th>Clean $U_{ave}$ Diagnostic [m/s]</th>
<th>Clean $U_{ave}$ Flowrate [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85</td>
<td>109</td>
<td>26.1</td>
<td>25</td>
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<tr>
<td>2</td>
<td>87</td>
<td>100</td>
<td>25.1</td>
<td>26</td>
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<td>3</td>
<td>83</td>
<td>84</td>
<td>49</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bluff body is in for these cases and expected velocity at laser sheet position is not known

Comparison of Results to the Similarity Solution for a Turbulent Plane Mixing Layer

It has been shown previously (Pope 2000), that the turbulent plane mixing layer has well-known self-similarity velocity profile solutions. A conserved passive scalar, such as a temperature excess where buoyancy effects are unimportant, also varies in the axial direction in the same way that the mean velocity does. We can consider the effects of buoyancy on the turbulent shear layer to be negligible so long as the bulk Richardson Number (Strang and Fernando 2001) meets the criterion

$$Ri_B = \frac{(\Delta b)D}{(\Delta U)^2} = \frac{g\Delta \rho}{\rho_1} \frac{D}{(\Delta U)^2} = \frac{gT_L}{(\Delta U)^2} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) < 1.5 \quad (1)$$

where $\Delta b = \frac{g\Delta \rho}{\rho_1}$ is the buoyancy jump across the interface, $\Delta U$ is the velocity difference between the two streams, and $D$ is the height of the cooler temperature clean stream. For all cases examined, it can be shown by considering the values in Table 2 that $Ri_B \ll 1$. Therefore, for the current flow the buoyancy effect is small relative to the kinetic energy of the flow and temperature will act essentially as a passive scalar as it will not substantially alter the flow field. Thus, we may use these solutions as an additional check on both the temperature and velocity diagnostics.
For the case of the plane mixing layer, two characteristic quantities can be defined (Pope 2000)

\[
\Phi_c = \frac{1}{2} (\Phi_H + \Phi_L) \tag{2}
\]

\[
\Phi_S = \Phi_H - \Phi_L. \tag{3}
\]

For our purposes, the quantity \( \Phi \) represents either the velocity or temperature and the subscripts \( H \) and \( L \) denote the values of these quantities in the two streams. A characteristic width \( \delta(x) \) is defined by defining the cross stream location \( y_\alpha(x) \) using (Pope 2000)

\[
\langle \Phi(x, y_\alpha(x), 0) \rangle = \Phi_L + \alpha(\Phi_H - \Phi_L) \quad (0 \leq \alpha \leq 1). \tag{4}
\]

Then the non-dimensional cross-stream coordinate is given by (Pope 2000)

\[
\xi = \frac{(y - \bar{y}(x))}{\delta(x)} \tag{5}
\]

with the characteristic width given by

\[
\delta(x) = y_{0.9}(x) - y_{0.1}(x) \tag{6}
\]

and

\[
\bar{y}(x) = \frac{1}{2} (y_{0.9}(x) + y_{0.1}(x)). \tag{7}
\]

The scaled velocity profile is given by (Pope 2000)

\[
f(\xi) = \frac{\langle (\Phi)_c - \Phi_C \rangle}{\Phi_S}. \tag{8}
\]

Our experimental data were plotted in this non-dimensional form and the results for both temperature and velocity were compared to the analytical solution.

As can be seen in Figure 15, Figure 16, and Figure 17, for all three conditions considered, the temperature profiles show reasonable agreement with the similarity solution. This provides us with further confidence that our temperature diagnostic is capturing the correct temperature distribution within the turbulent mixing layer. The velocity also agrees well with the analytical solution although the worse spatial resolution for the velocity measurements and the fewer number of images used to calculate the average velocity fields (25) result in poorer agreement at some locations.

In addition to the profiles shown, the characteristic width of the mixing layer should increase linearly with downstream distance, indicating a constant spreading rate of the plane mixing layer, i.e.,

\[
\frac{d\delta(x)}{dx} = \text{Constant}. \tag{9}
\]

![Figure 15: Comparisons of experimental results to similarity solutions for velocity and temperature at condition 1.](image)
Figure 16: Comparisons of experimental results to similarity solutions for velocity and temperature at condition 2.

Figure 17: Comparisons of experimental results to similarity solutions for velocity and temperature at condition 3.

Figure 18, Figure 19, and Figure 20 are plots for the temperature measurements illustrating the characteristic width and y values corresponding to 10% and 90% locations (as defined in equation (4)) as a function of downstream distance (0 corresponds to 0 location in the images shown earlier).

Figure 18: Characteristic width and lines of constant y for temperature at condition 1.
Again it can be seen that the diagnostic measurement agrees well with theory, in that the characteristic width of the mixing layer is growing approximately linearly with downstream distance. In addition, it is also observed that the characteristic width of the mixing layer does not spread symmetrically, but rather it spreads in the direction of the low temperature flow, which is also in agreement with known theory (Pope 2000). As can be seen, this directional spreading is more pronounced for condition 1 than for conditions 2 and 3. This is intuitively correct because the temperature difference between the vitiated flow and the clean flow is highest in condition 1.

4. Conclusions
The phosphor based PIV+T diagnostic was successfully applied in a difficult diagnostic environment with very high system mass flow rate requiring a modified seeding strategy to get sufficient seeding levels. Temperature accuracy and velocity accuracy of the technique were established to be quite good based on comparison to average measurements of temperature and velocity. As an additional check on the diagnostic, the measurements were compared to known solutions of the turbulent plane mixing layer. It was found that the temperature profile agreed well with the theory, helping to give us further confidence in the LIR method in the vicinity of turbulent shear layers. The measurements demonstrate application of the temperature measurement technique to higher flow rates than previously measured in an applied measurement environment.
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