

LDA-Measurements of Transitional Flows in a Large Refractive Index Matched Flow Facility

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Abstract

Useage of laser-Doppler anemometry (LDA) requires optical access to the flow field of interest. This is not always easy, since complex geometries or very near-wall boundary layer measurements can optically distort the laser beams. One solution is to employ a solid material and fluid of the same index of refraction. In this case, there is minimal optical interference of the solid with the LDA. Although this technique is not new, previous studies have been limited to relatively small and specialized flow aparati as well as unpleasant fluids. Two large scale flow facilities have now been constructed, permitting matched-index-of-refraction (MIR) LDA measurements in difficult geometries at higher Reynolds numbers and with increased spatial resolution than previously possible. This paper describes the facilities and fluids employed, and presents some preliminary results for very near wall measurements of a transitional boundary layer behind a roughness element (Figure 1).

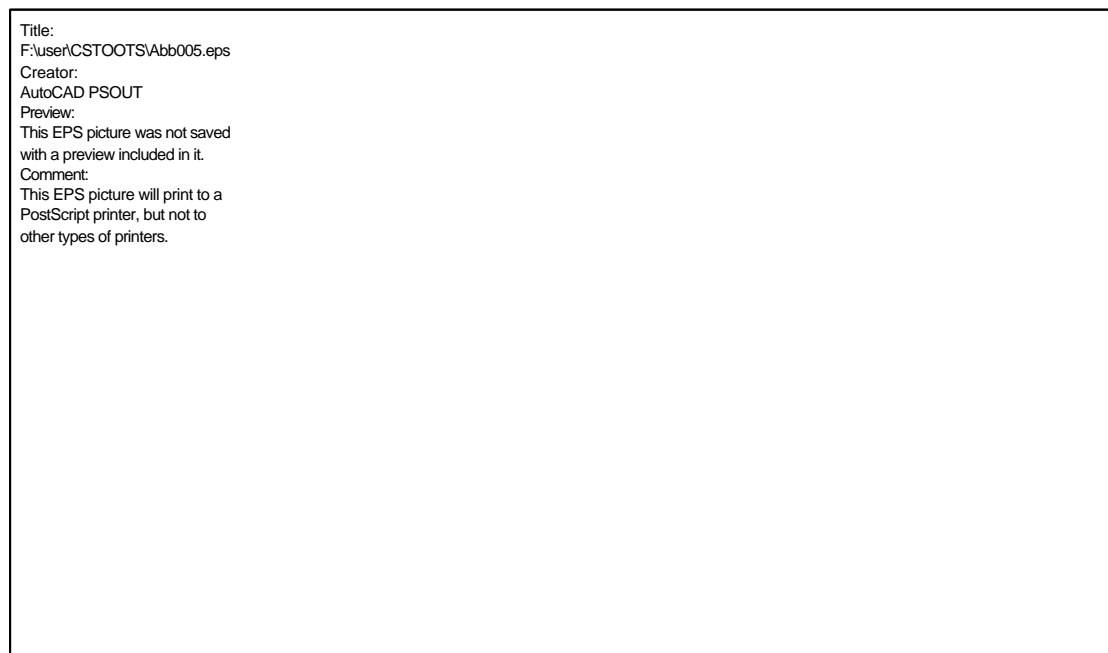


Figure 1. Schematic of flat plate with roughness element and LDA measurement system.

1. Introduction

Laser-Doppler anemometry (LDA) measurements near a boundary layer wall, in complex flow geometries such as within tube bundles, or inside complicated passages are difficult. The usage of LDA suffers from optical interference of the laser beams by the wall or physical geometry. When light travels through a region of non-uniform refractive index, it bends in different directions depending on the local refractive index and the angle it makes with the interface between the two media. This can result in undesirable effects, such as spatially shifted measuring volumes, changes in beam crossing angle, or unwanted light reflection or scatter (i.e., poor signal-to-noise ratio). One way to eliminate this optical interference is to make the experimental fixture of a suitable transparent solid material and employ a fluid that possesses the same refractive index as the solid material. In this way, the experimental fixture disappears optically (and therefore has no influence on the laser beams) but maintains its full mechanical influence on the flow.

Refractive index matching has been performed in the past by matching the refractive indices of the fluid and solid boundaries in the case of wall-bounded flows [Liu et al., 1990]. Another example is matching the refractive indices of two fluids in the case of buoyancy-driven flows [McDougall, 1979; Alahyari and Longmire, 1994]. However, the index matching technique to now has been limited to small-scale experiments in rather specialized apparatus. To date, no MIR flow facility existed that permitted the study of flow past complex geometries at high Reynolds numbers, fine spatial resolution, and larger scale. The Idaho National Engineering and Environmental Laboratory (INEEL) decided to construct such a large facility. Similar to a water tunnel, the facility utilizes a light mineral oil with temperature control such that the index of refraction of quartz glass can be matched. The success of this facility prompted the Institute for Fluid Mechanics (LSTM) at the University of Erlangen-Nuremberg to construct a similar facility. This paper describes the development, similarities, and differences of these two large-scale facilities, as well as their capabilities. The first investigation performed in the INEEL facility entailed measurements very near the wall in a transitional flat plate boundary layer. Some preliminary results are presented here to exemplify the advantages of using such a large-scale MIR facility.

2. INEEL and LSTM MIR Facilities

The goals of the INEEL and LSTM were to design and construct significantly larger MIR facilities than previously. These flow facilities were to be versatile enough to be capable of many different experiments and have high flow quality entering their test sections. Finally, the fluid employed was not only to have the same index of refraction as some transparent solid, but to also be relatively cheap (due to the large quantities required), non-toxic, noncombustible, and have a low vapor pressure. Since these facilities employ oil and not water, special design considerations had to be made concerning spill containment, construction material compatibility, fluid storage, and maintaining fluid purity.

Table 1 is a comparison between the INEEL and LSTM MIR facilities. The test section of the INEEL facility is somewhat larger than that of the LSTM, but the LSTM facility is capable of higher velocities and Reynolds numbers. The LSTM could not use the same fluid as the INEEL due to availability in Europe, and had to identify a second oil. Figure 2 is a schematic of the INEEL facility and Figure 3 is a photograph of the INEEL facility test section with a two-component LDA system mounted on a 3-D traversing system. Similarly, Figures 4 and 5 are a schematic and photograph of the LSTM facility. Both facilities are primarily stainless steel, utilize axial flow pumps, settling chambers with honeycombs and screens for flow conditioning, clear-walled test sections (acrylic with glass inserts for the INEEL, glass for the LSTM), and bellows for vibration isolation and thermal expansion.

Table 1. Comparison of the INEEL and LSTM MIR facilities.

	INEEL	LSTM
Test Section Dimensions	2.44m x 0.61m x 0.61m	2.30m x 0.60m x 0.44m
Maximum Velocity	3 m/s	5 m/s
Fluid	Penreco Drakeol #5	Shell Onida 913
Optimum Temperature	23.75 C	~ 28.7 C
Kinematic Viscosity	$13.9 \times 10^{-6} \text{ m}^2/\text{s}$	$12.0 \times 10^{-6} \text{ m}^2/\text{s}$
Density	831 kg/m ³	831 kg/m ³
Capacity	13000 liters	20000 liters

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Figure 2. Schematic of the INEEL MIR facility.

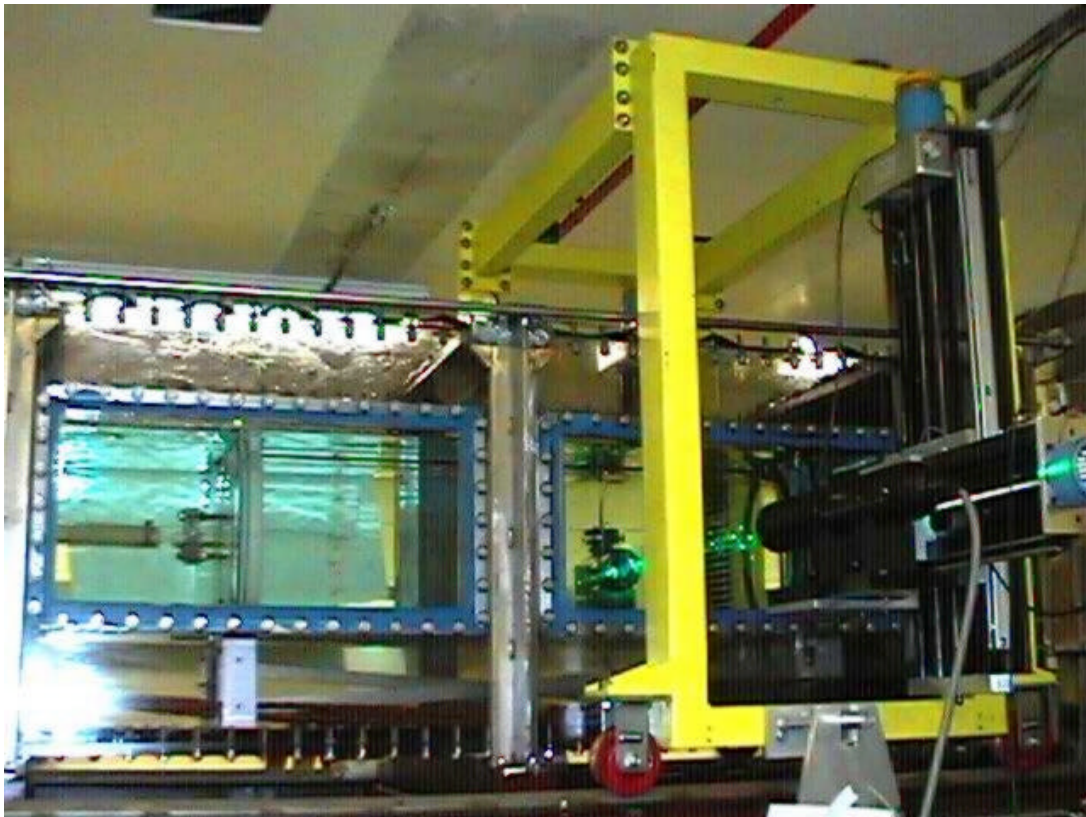


Figure 3. INEEL test section.

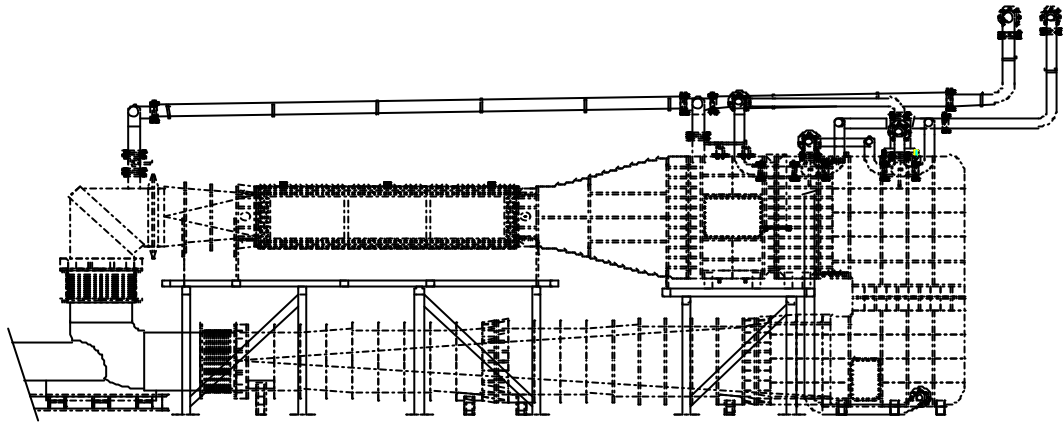


Figure 4. Schematic of the LSTM MIR facility.

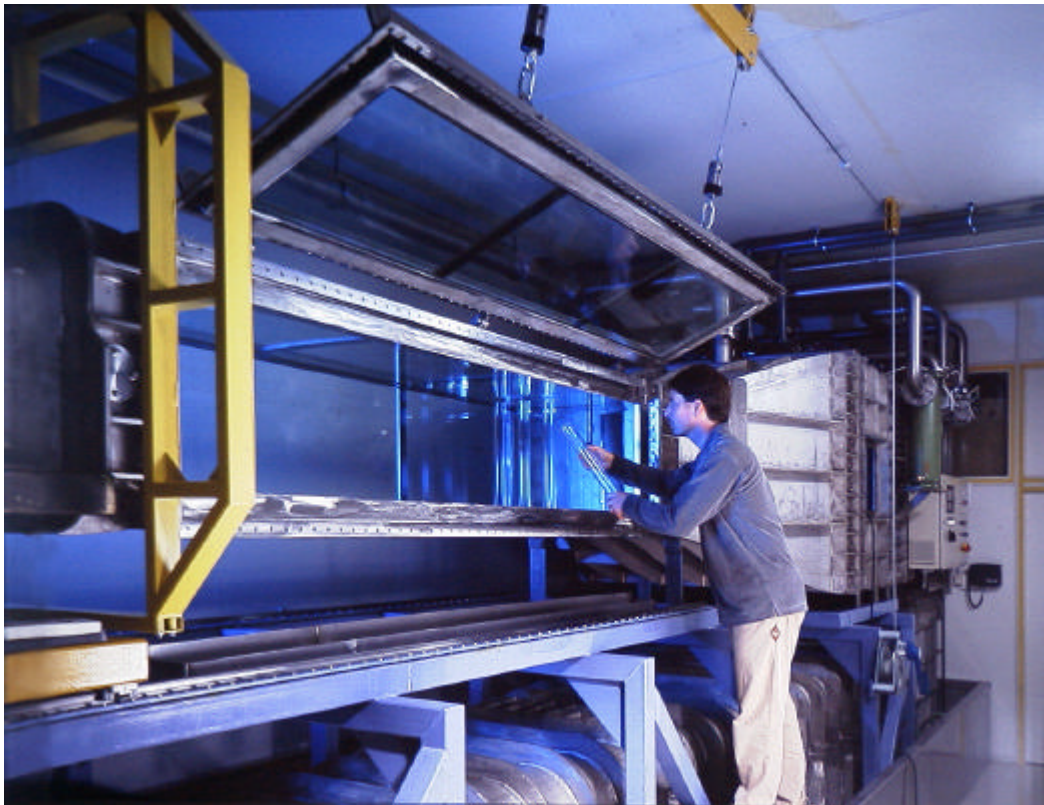


Figure 5. LSTM test section.

Based on guidance from an earlier study of Durst, Keck and Kleine (1979), it was estimated that the oil temperature must be controlled to be steady and uniform to within 0.3 C to match the refractive index of quartz adequately for high-quality LDA measurements. The INEEL and the LSTM took two different approaches for temperature control. The INEEL implemented a mixing approach utilizing jet injection. Approximately 300 l/min of the oil is extracted from the main loop through two pipes upstream of the main pump. Optimum temperature is achieved by means of a water cooled heat exchanger and a DC 10 kW heater. In this approach, the heat exchanger provides coarse control and removal of thermal energy from the fluid and then the more precise variable electrical power supply gives fine control to the heater to achieve the desired temperature. The fluid is reinjected into the main

loop downstream of the main pump through 36 peripherally-located 3 mm diameter orifices. This external temperature control system also includes a 5 μm filter to remove contaminants. Tests have been conducted to assess the performance of the temperature control system. The control system can maintain the fluid temperature to within ± 0.003 C of the specified temperature.

Coarse estimates of the required oil temperature can be made using a refractometer. However, index of refraction is wavelength dependent. Since a two or three component LDA (ie, two or three wavelengths of light) is used in these facilities, the optimum temperature is a compromise. Thus, the temperature at which the indices are matched best for all components is determined experimentally. Consider a two component LDA. With the LDA positioned so one blue beam and one green beam pass through a quartz obstacle, the LDA data acquisition is operated in the two velocity coincidence mode for short time series and the oil temperature is gradually varied. The temperature at which the maximum sampling rate is obtained serves to indicate the optimum operating conditions. The results of this investigation for the INEEL facility are shown in Figure 6. For the oil in the INEEL MIR flow system this maximum in sampling coincidence occurs at about 23.75 C. The optimum temperature for the LSTM facility is still to be determined.

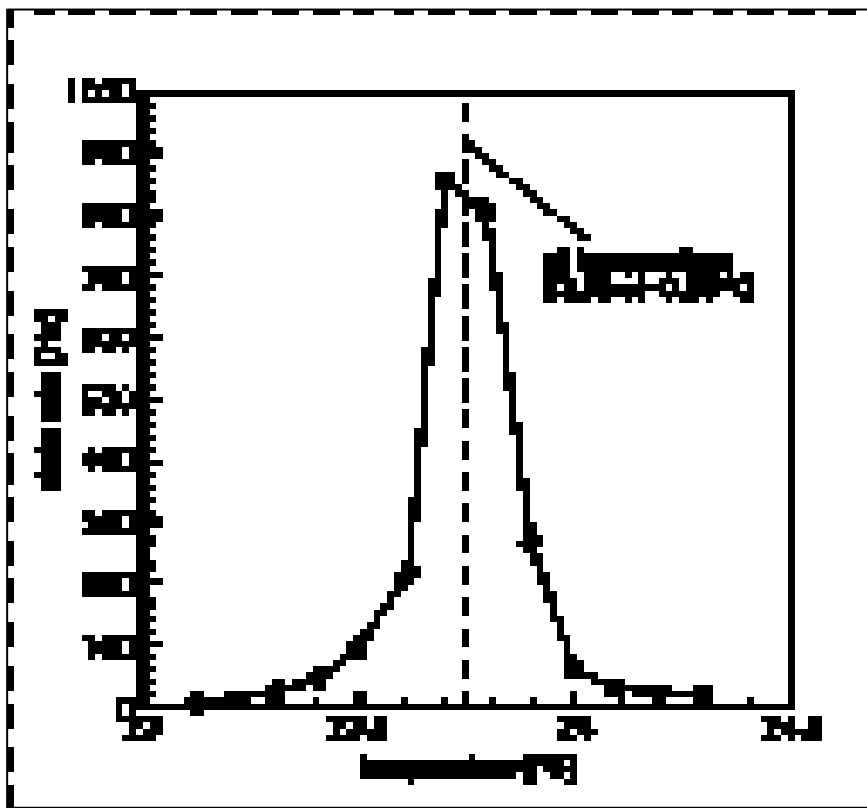


Figure 6. Determination of optimum fluid temperature for the INEEL facility.

An unexpected problem arose in both facilities when operated at velocities above approximately 2.5 m/s. The low pressure at the axial pump blade tips causes any dissolved air in the oil to come out of solution, forming bubbles. For the LSTM facility, a vacuum deaeration system was designed and constructed. This system includes a glass packed column with Raschig rings, vacuum pump, transfer pump, and control system. No such system has been implemented yet for the INEEL facility.

In the INEEL facility, velocity and turbulence measurements are primarily obtained with a two-component, fiberoptic-based LDA operated in forward or back scatter mode. The LSTM facility will have three-component LDA capability. The INEEL LDA system is composed of TSI optics and electronics, except for the receiving optics. The receiving optics were custom designed and constructed by the LSTM to obtain a higher signal-to-noise ratio. Although the backscatter LDV mode is more convenient in operation, the forward scatter signal-to-noise ratio is 10 to 1000 times higher, resulting in superior signal quality and validation rates, especially near an obstacle or wall. This is illustrated in Figure 7, which compares velocity data obtained in forward scatter versus back scatter. Furthermore,

the higher quality signal in forward scatter allows higher data rates and hence less measurement time to obtain statistically meaningful results. Thus, the test section was specifically designed with optical access on both sides such that LDA measurements in forward scatter could be obtained. With this configuration, the LDV measurement control volume diameter is approximately 60 μm . A very high precision traversing system is integrated with the LDV to allow movement in all three axes and to ensure constant alignment of the sending and receiving optics.

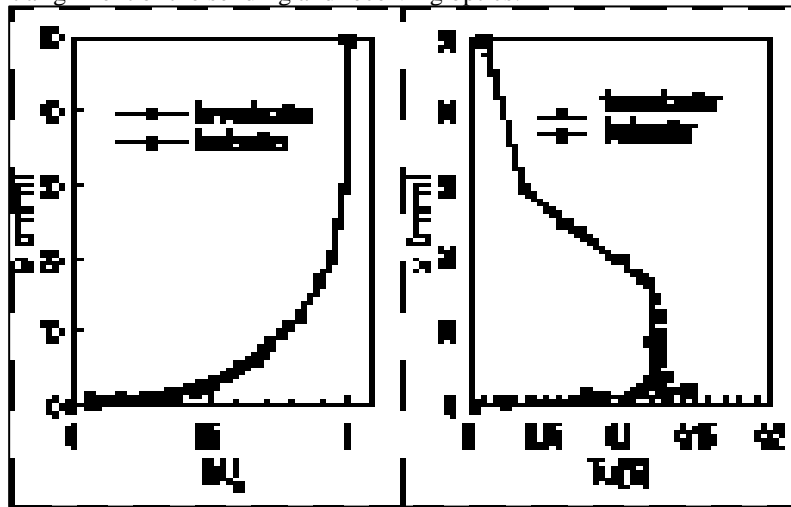


Figure 7. Comparison of measurements made in forward scatter versus back scatter.

3. Induced Laminar-to-Turbulent Boundary Layer Transition

Because of the LSTM's prior experience with index-matching experiments, one of their researchers was invited to conduct the first experiment in the INEEL MIR facility. This experiment addresses induced laminar-to-turbulent transition within a flat plate boundary layer. Quantification of boundary layer transitional flows requires measurements very close to the wall for determination of the wall shear stress. When making such very-near wall measurements with a multicomponent LDA system, some of the beams must travel within the wall and emerge in the flow undistorted. Also, substantial length is required for development of the laminar boundary layer. Thus, this experiment is a good first test of a large-scale MIR facility.

Limited experimental results are presented to demonstrate the performance of the MIR facility. Figure 8 illustrates the transitional process on a flat plate and defines the nomenclature. The roughness element serves to induce the transition process. Because measurements were desired very close to the roughness element and to the plate behind the element, the element and the downstream plate are constructed of quartz glass. The leading plate is constructed of anodized aluminum. A flapping plate downstream of the quartz plate is adjusted in angle to produce a zero pressure gradient boundary condition.

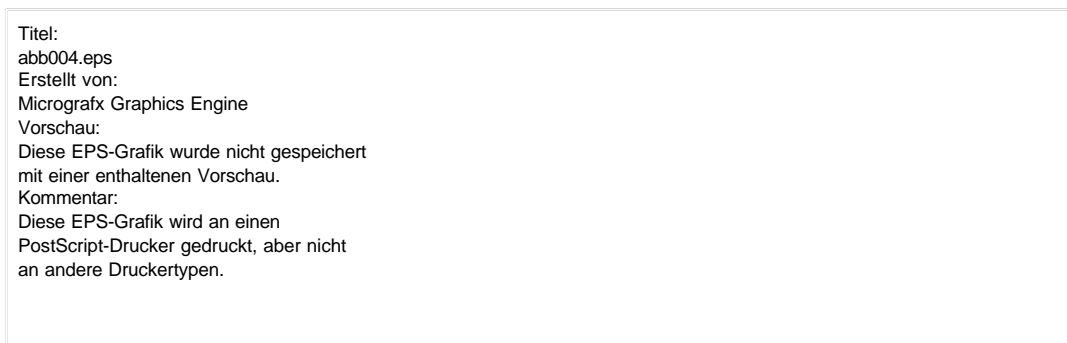


Figure 8. Induced laminar-to-turbulent transition process with nomenclature.

Figure 9 presents some of the measured freestream velocity results immediately behind the roughness element. The purpose of this figure is to emphasize the fine spatial resolution of the measurements and

how extremely close to the wall measurements could be obtained. Measurements were obtained within 0.05 mm of the wall surface. Such proximity is only possible in a MIR facility. Spatial resolution and wall proximity are two important factors for accuracy when calculating the wall shear stress.

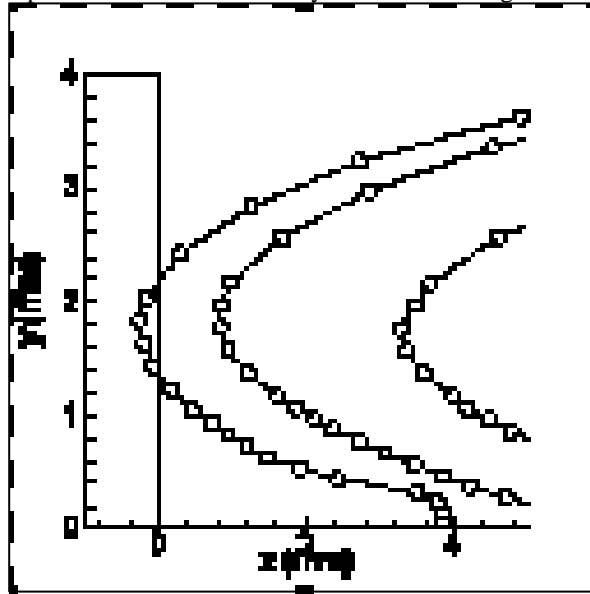


Figure 9. Freestream velocity measurements immediately behind the roughness element.

Figures 10 and 11 present freestream velocity measurements in the vicinity of the roughness element. Figure 10 is for a Reynolds number (based upon the roughness element height) of 360 and Figure 11 for 486. The upper half of the plots are profiles of velocity as a function of position. The lower half of the plots presents shape factors (ratio of the boundary layer displacement thickness to momentum thickness) for various streamwise locations. The shape factor for a laminar boundary layer is a constant (2.59). In Figure 10, the boundary layer upstream of the roughness element conforms to a laminar profile, as shown by the shape factor values. In the vicinity of the roughness element, the boundary layer shape factor deviates significantly, and then converges again to that of a laminar boundary layer. Figure 11 shows quite different behavior, due to the higher Reynolds number. Again, upstream of the roughness element, the boundary layer shape factor matches that of a laminar profile. Behavior around the roughness element is also similar to that displayed in Figure 10. However, further downstream the boundary layer shape factor deviates from a laminar profile, indicating the beginning of transition to a turbulent boundary layer.

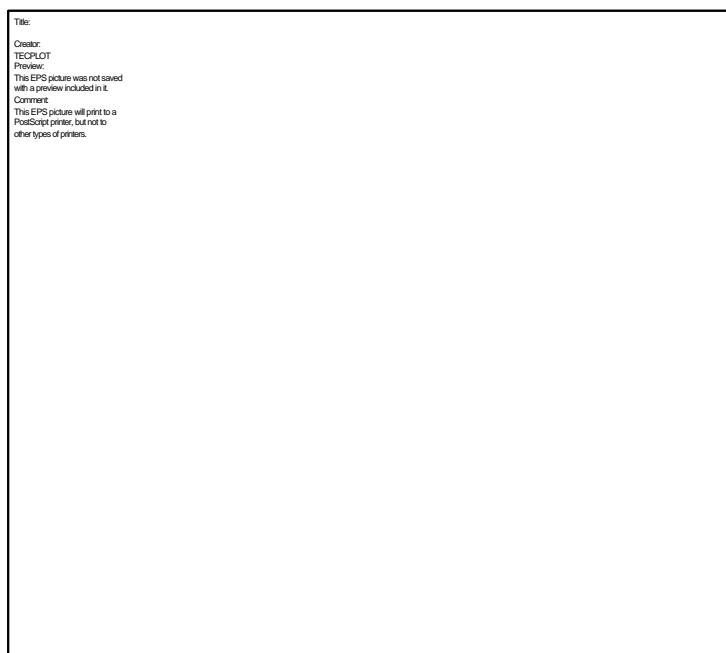


Figure 10. Profiles of streamwise velocity and shape factors for $Re_k = 360$.

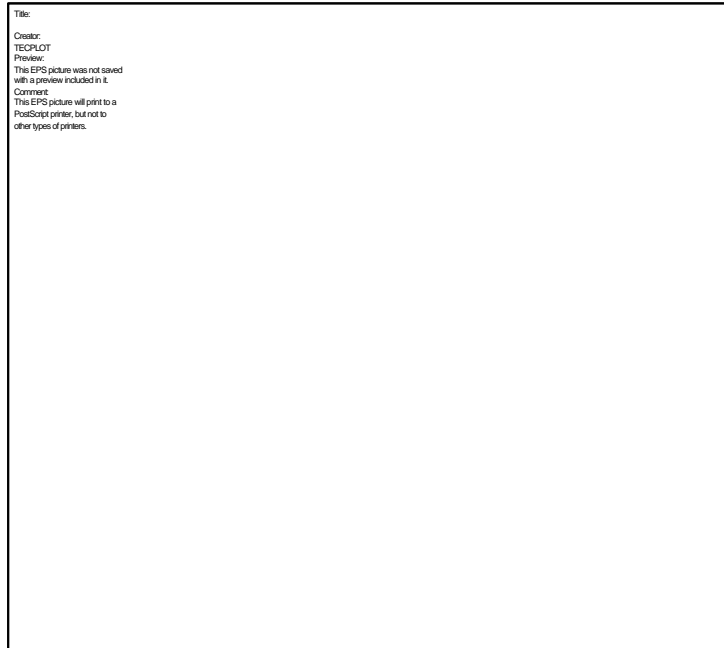


Figure 11. Profiles of streamwise velocity and shape factors for $Re_k = 486$.

4. Conclusions

Two large scale matched-index-of-refraction flow facilities have been designed and constructed. Fluids with the same index of refraction as quartz glass have been identified that are safe to use and relatively cheap. These facilities offer new measurement capabilities: LDA studies of flows within or through complex geometries can now be performed at a scale not before possible with extremely fine spatial resolution / proximity to the solid surface. To illustrate this, studies of a transitional boundary layer on a flat plate were performed within the INEEL MIR facility. Two component velocity measurements were obtained at the plate surface. The success of this experiment has encouraged further boundary layer transition studies to be performed within the LSTM MIR facility.

Acknowledgements

This research received financial support through the Laboratory Directed Research and Development Program of the INEEL under the United States Department of Energy Idaho Field Office Contract DE-AC07-94ID13223 and the Deutsche Forschungsgemeinschaft under project Du 101/44. The authors gratefully acknowledge this support of their work.

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