

THE BOUNDARY LAYER OVER TURBINE BLADE MODELS WITH REALISTIC ROUGH SURFACES

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Objectives

Surface roughness is known to have a significant impact on turbine heat loads and performance. Over time, as the turbine blades are exposed to these loads, the external surfaces become rougher, which results in the increase of heat loads and friction losses. While there have been several investigations that included surfaces with uniform or two-dimensional roughness patterns there is now a clear need to measure the influence of *realistic surface* roughness on turbine blade flow and heat transfer.

The objective of the proposed investigation is to conduct measurements that will reveal the influence of *realistic surface* roughness on the near-wall behavior of the boundary layer. The test surface will be a large-scale version of rough surfaces that are specified by the Air Force Research Laboratory/Propulsion Directorate. That is, geometric models of real surfaces would be employed but in much larger size so we can obtain high quality velocity and turbulence data in the near-wall region, including the viscous layer. Thus, the measurements obtained would be related to convective heat transfer from the surface. Since the near-wall region is still subsonic in a transonic boundary layer, such detailed measurements should be valuable to assess and guide development of computational fluid dynamics models proposed for predictions of flows over realistic surfaces in gas turbine passages at engine operating conditions.

Approach

The measurements are being conducted in the Matched-Index-of-Refraction (MIR) Facility at the Idaho National Engineering and Environmental Laboratory (INEEL), the largest MIR Facility in the world (Stoos et al., 2001). Optical flow measurement techniques, such as laser Doppler velocimetry (LDV) and Particle Tracking Velocimetry, permit flow field determination without locating transducers in the flow. By using transparent models, complex flow fields can be studied and the results can be used to assess the validity of computational fluid dynamic codes for difficult conditions. However, refraction of light beams can distort the views, introduce positioning errors and block measurements in some desired regions. A solution to these difficulties is to match the indices of refraction of the model and the fluid so that light rays are not deflected. While the INEEL MIR flow system has the refractive matching advantage that permits measurements that would otherwise be impossible, its innovation and technical

significance is its large size. It is considerably larger than most other systems using the MIR technique; consequently, it provides significantly better spatial and temporal resolution at a given Reynolds number, typically by an order-of-magnitude.

Progress

Apparatus. Figure 1 is a schematic drawing of the improved experimental apparatus that has been designed, constructed, and installed in the MIR Facility. The working fluid

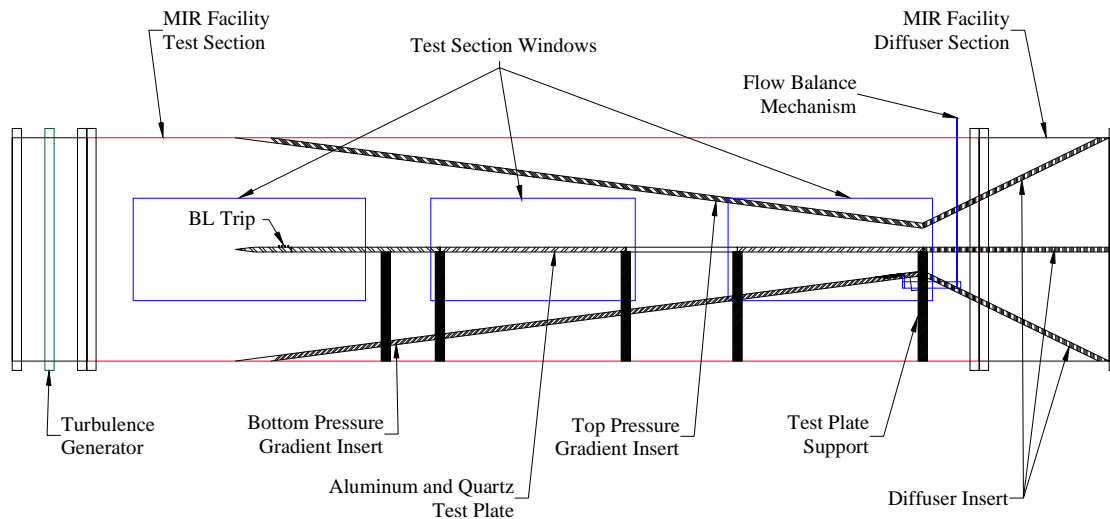


Figure 1. Schematic illustration of the test section with model installed.

(mineral oil) flows from left to right in the Figure 1 schematic. A turbulence generator is located upstream of the test section. The test plate is constructed of aluminum and quartz and is supported by five supports. An additional aluminum plate is installed above the test plate to achieve the desired streamwise pressure gradient in the flow, and a similar plate is installed beneath the test plate to provide balance and to control flows between the upper and lower surface of the test plate. Velocity measurements are conducted with a two-component fiber optics LDV.

Smooth Plate Baseline Results. We have completed baseline experiments with a smooth plate model in the oil tunnel. The test plate for these experiments is made of three sections of 1.3 cm thick aluminum plate and two sections of 1.3 cm thick GE124 clear fused quartz. The first section of the test plate is a 15.2 cm long with the leading edge machined into the shape of a NACA 009 airfoil. A turbulence trip is located 12.7 cm downstream of the leading edge. The trip consists of the four staggered rows of vertical dowel pins across the plate. The trip was designed to simulate the boundary layer disturbances due to the film cooling jets that are located near the leading edge of a turbine blade. The quartz sections are installed so that they are centered in the middle and end glass windows of the test section. The top and bottom pressure gradient inserts are made

of 1.3 cm thick aluminum plate and are placed in the test section to produce an acceleration parameter, $K = (v/U_\infty^2)(dU_\infty/dx)$, of approximately 3×10^{-6} . This value of K is important because we are attempting to model flow over the first 1/3 of the suction side of a high-pressure turbine vane. We estimated the appropriate value of K by applying potential flow analysis to a circular cylinder model with typical at-altitude high-pressure turbine inlet conditions. This estimate established that K values in the range of 1×10^{-6} to 4×10^{-6} were desired. Additionally, Blair (1983), Keller and Wang (1996), Volino and Simon (1997), Zhou and Wang (1996) and others have conducted related boundary layer studies with K ranging from 0.2×10^{-6} to 4.1×10^{-6} .

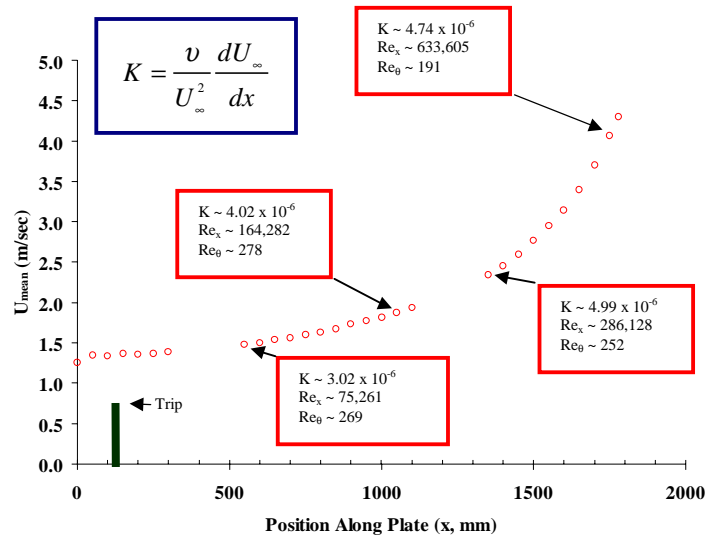


Figure 2. Freestream velocity and dimensionless parameter results for the smooth plate baseline study.

The freestream velocity and dimensionless parameters for these experiments are shown in Figure 2. The resulting K and Reynolds number values are in the correct range for the first 1/3 of the suction side of a high-pressure turbine vane. The graph in Figure 3 shows the freestream turbulence intensity that was generated by an active grid at the entrance to the test section. We have achieved a turbulence intensity of over 5% at the leading edge of the plate – to model the elevated turbulence intensity that is found at the entrance to a high pressure turbine. The results in Figure 3 reveal that the turbulence intensity decays in the downstream direction. This result is as anticipated and is due to freestream acceleration and to viscous dissipation.

Boundary layer measurements were conducted at 10 locations along the plate. Results include velocity profiles, streamwise and vertical turbulence intensities, and Reynolds stress. We present only a brief sample of results in this extended abstract due to page limitations. Figure 4 is a graph of the boundary layer velocity profiles. The wall shear stress was estimated from the slope of the profile very near the wall. Figure 5 is graph of the velocity profile at $x = 812$ mm in wall coordinates. In the oil tunnel it is possible to obtain velocity measurements (u and v) very close to the wall (down to $y^+ < 1$).

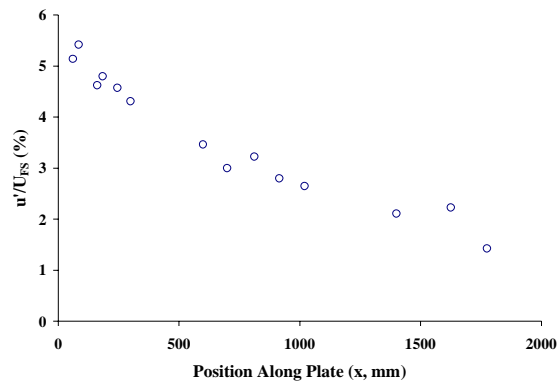


Figure 3. Freestream streamwise turbulence intensity results for the baseline study.

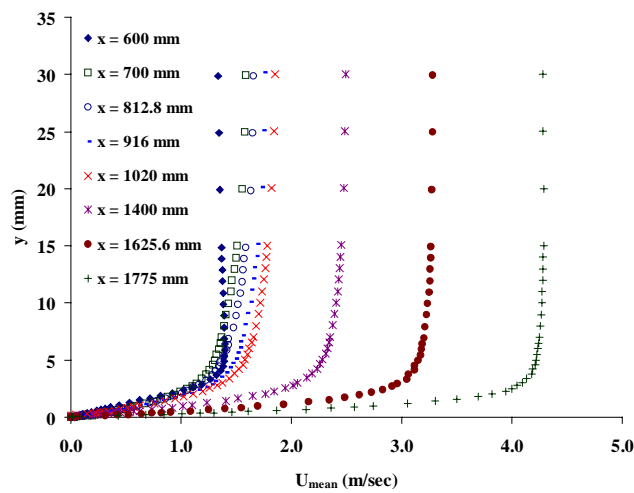


Figure 4. Boundary layer velocity profiles.

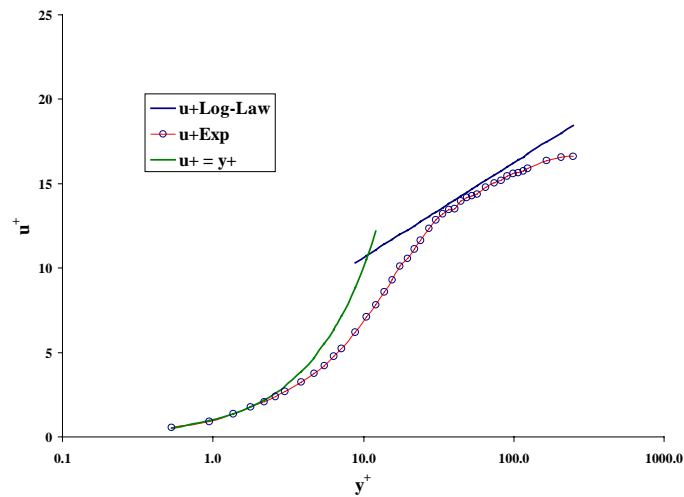


Figure 5. The boundary layer profile at $x = 812$ mm in wall coordinates.

Figure 6 is a plot of the development of the skin friction coefficient along the plate. The solid line is a plot of the theoretical skin friction coefficient obtained by using a 4th order polynomial fit to the freestream velocity curve in Figure 2 and the correlation method of Thwaites (1949). This polynomial input into the Thwaites method produces a theoretical skin friction coefficient, C_f , for a **laminar** boundary layer in accelerating flow. The open circles are values of the skin friction coefficient, C_f , calculated from our experimental measurements. The experimental values of C_f rise above the theoretical laminar curve

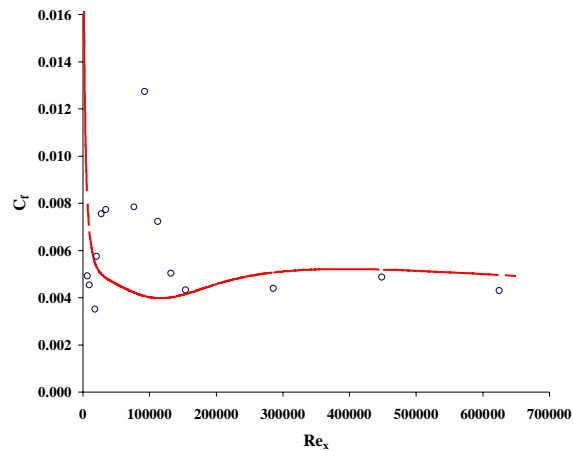


Figure 6. Development of the skin friction coefficient along the plate.

for the range $5 \times 10^4 < Re_x < 1.5 \times 10^5$ indicating that the boundary layer is transitional over this range. The data points beyond $Re_x = 1.5 \times 10^5$ are just below the theoretical curve – indicating that the boundary layer has relaminarized. This relaminarization is due, presumably, to the strong favorable pressure gradient.

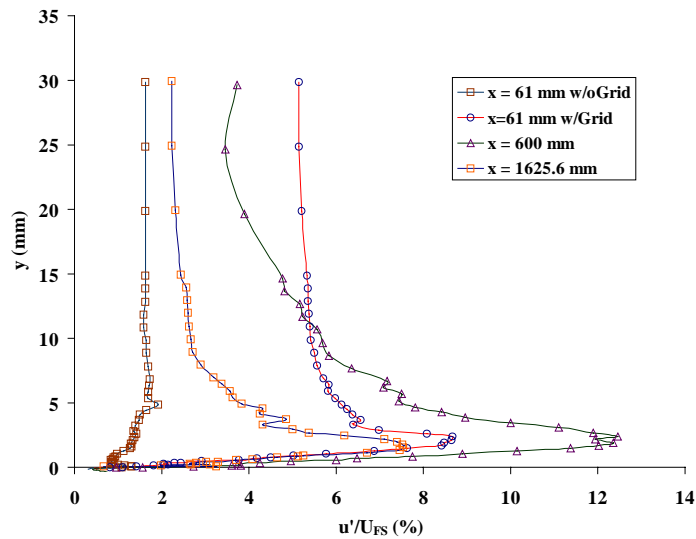


Figure 7. Streamwise turbulence intensity profiles in the boundary layer.

Figure 7 is a plot of streamwise turbulence intensity profiles in the boundary layer at three locations along the plate. The $x = 61$ mm profile reveals the turbulence intensity in the boundary layer is elevated, even before the trip, when the turbulence generating grid is installed. The corresponding turbulence intensity profile (at $x = 61$ mm) **without the grid** installed is not elevated. This indicates that bypass transition occurs when the elevated freestream turbulence is present.

Future Plans

We are currently completing the detailed design for a realistic rough surface model. The model is patterned after a suction side surface that was evaluated by Bons et al., 2001. We plan to collect and analyze the rough plate results in the fall of 2002. An additional graduate student has been added to the project team (Mr. William Dalling). He is designing floating element sensors with the objective of obtaining direct measurements of wall shear stress for both the smooth and rough plate models.

Acknowledgement /Disclaimer

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