Experimental Investigation of Blowing Effects on Turbulent Flow Over a Rough Surface

Mark A. Miller, Sean C. C. Bailey, Alexandre Martin

Department of Mechanical Engineering, University of Kentucky, Lexington, KY, 40506

UK University of Kentucky

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Background

Central to the design of any atmospheric re-entry vehicle is the proper modeling and simulation of a Thermal Protection System (TPS), commonly known as a "heat-shield". The TPS serves to protect the craft and its payload from the extreme heat generated during the descent through a planetary atmosphere. One type of TPS material is the "ablative" type which is composed of a carbon matrix infused with a resin compound. As the TPS is heated upon re-entry, the resin "ablates" through the carbon matrix and pyrolisis gasses eject from the surface into the near wall flow. The remaining carbon matrix forms a roughened surface which can potentially trip the laminar boundary layer to a turbulent state and result in hydraulically rough near-wall flow conditions. The combined effects of momentum ejection and surface roughness on near-wall turbulence are still poorly understood.

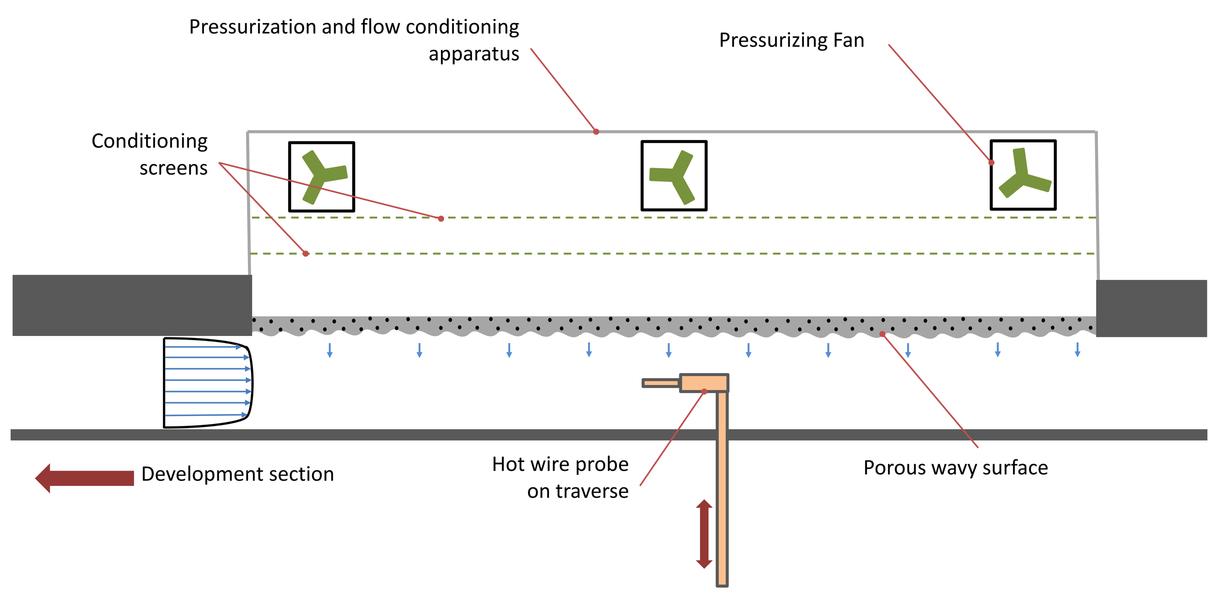
Motivation

The current study is aimed at increasing our understanding of the modifications made to near-wall turbulent flow structures which could occur near a TPS surface due to surface roughness and blowing. These structures play a large role in the transport of mass, momentum and energy. Better understanding of these basic flow phenomena can be used to further improve and validate numerical simulations. Here we mimic some of the basic conditions in which a TPS operates, namely that of surface roughness and uniform flow injection through the rough surface and experimentally measure the corresponding modifications to the near-wall turbulence structure.

Experiment Description

The experiments were performed in the Turbulent Channel Flow Facility (TCFF) at the University of Kentucky Experimental Fluid Dynamics Laboratory (EFDL). This facility is designed to produce fully-developed turbulent plane Poiseuille flow. Modifications were made to the TCFF test section to incorporate a flow injection, or "blowing", apparatus. The blowing apparatus drives laminar flow through a perforated surface into the TCFF. In this experiment, the surface used is a micro-perforated, nominally 2-D wavy surface with wavelength of 6.5mm and peak-to-peak amplitude of 1mm. Mean velocity was 10 m/s.

Hot wire anemometry was used to acquire streamwise, time-resolved, velocity data at different wall-normal locations. This technique is well-suited for measuring turbulence statistics including mean velocity streamwise Reynolds stress, and power spectral density.



Results

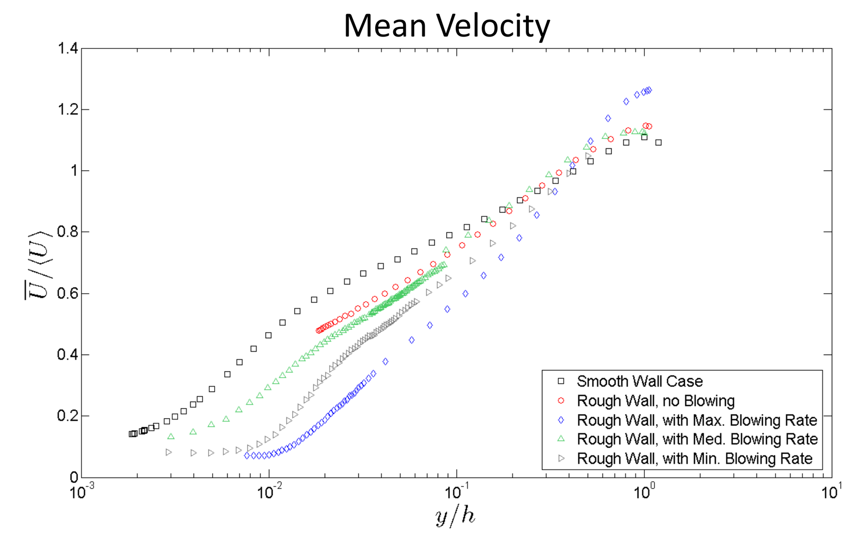


Figure 1. Mean velocity profiles for a range of blowing rates through the rough surface compared to the smooth-walled case with no blowing.

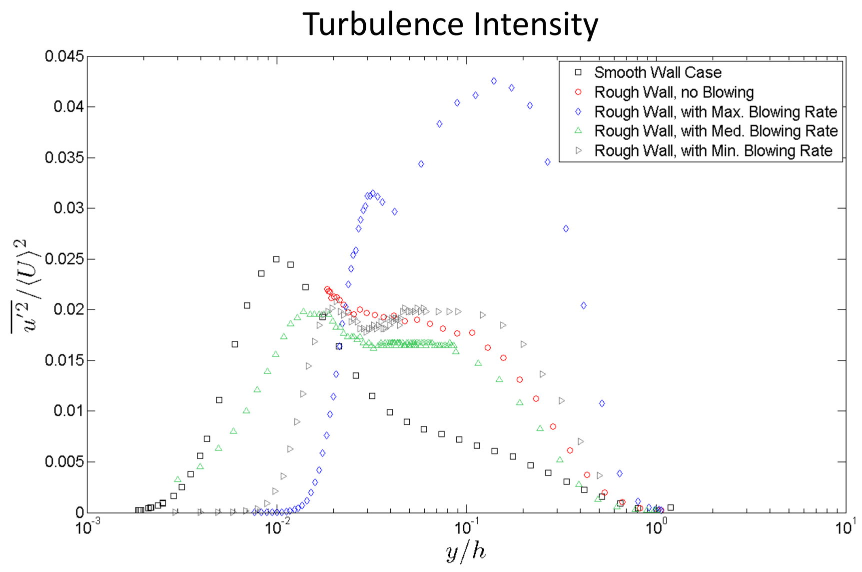


Figure 2. Profiles of turbulence intensity for the same conditions shown in figure 1.

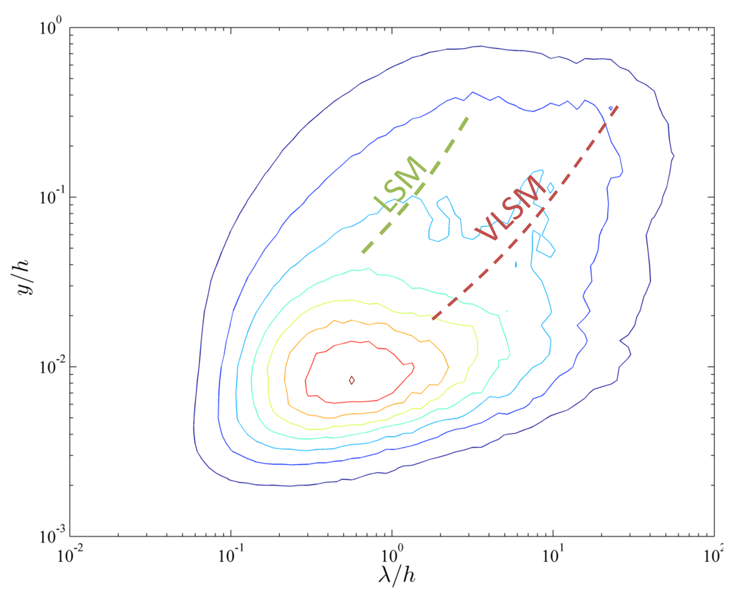


Figure 3a: Pre-multiplied power spectrum map for the smooth-walled case

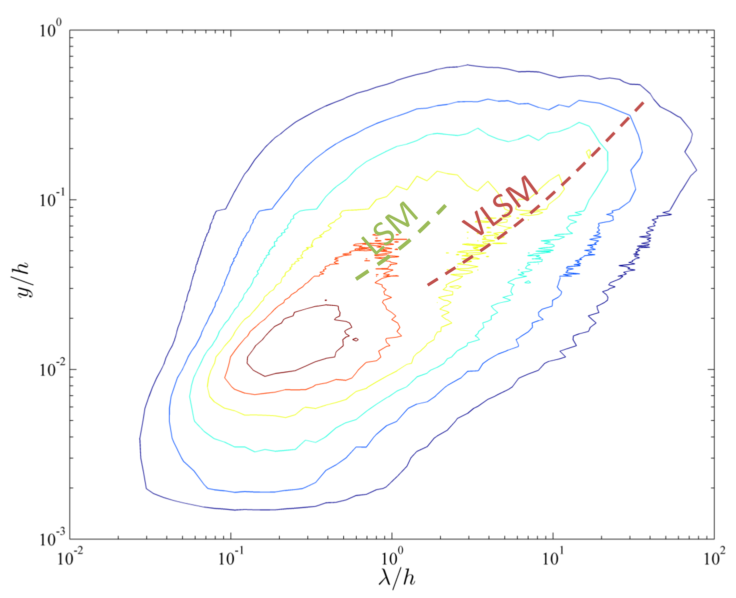


Figure 3b: Pre-multiplied power spectrum map for the rough-walled case: low blowing rate

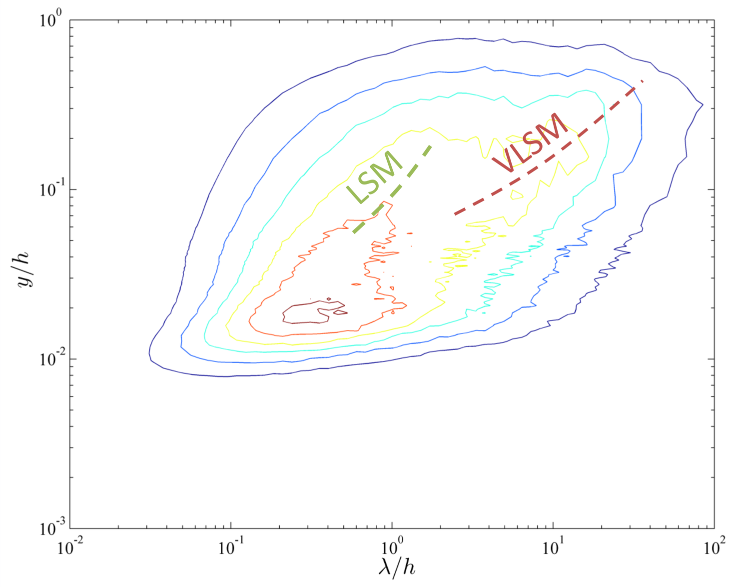


Figure 3c: Pre-multiplied power spectrum map for the rough-walled case: med. blowing rate

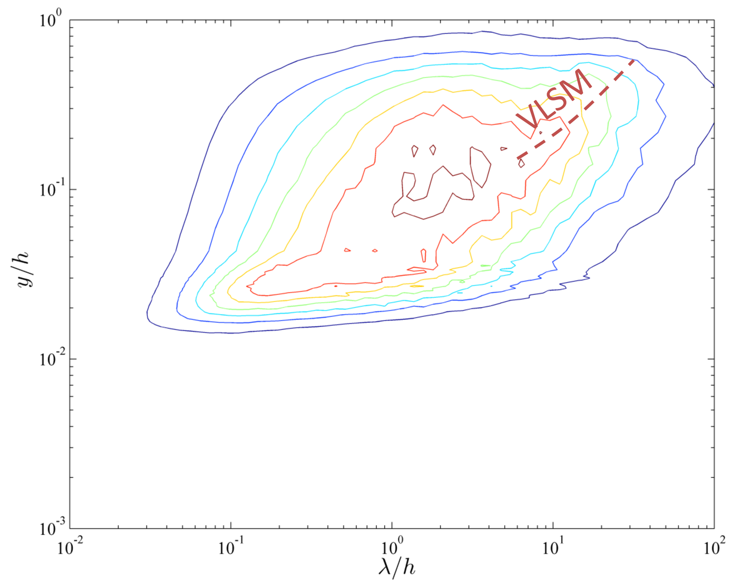


Figure 3d: Pre-multiplied power spectrum map for the rough-walled case: max. blowing rate

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Discussion

Data was collected on the rough surface at a variety of flow injection rates and compared to the smooth-walled case for the same channel centerline velocity. The mean velocity profiles shown in **Figure 1** demonstrate a clear variation between the cases, as the roughness introduces additional bias of higher momentum fluid towards the edge of the wall layer. This change in mean velocity is coupled with significant changes in the profiles of streamwise Reynolds stress shown in **Figure 2**. The Reynolds stress profiles show the expected increase in turbulence away from the surface as compared with the smooth walled case which can be attributed to roughness effects. In addition, a strong outer peak also forms at high blowing rates which indicates a significant shift in turbulence production away from the wall. There is a clear trend increasing turbulent kinetic energy as blowing rate is increased which can be attributed to additional energy transport from the kinetic energy introduced by the flow injection.

Corresponding modifications to the flow structure are illustrated through the pre-multiplied power-spectrum maps shown in **Figure 3a-c**. These spectral maps reveal the wavelengths at which the energy content of the turbulence exists. Several features exist in the smooth-walled results shown in **Figure 3a** which correspond to turbulent flow structures. First, a majority of the energy is contained in a peak near the wall at small wavelengths. This peak corresponds to small-scaled (inner-scaled) eddies which are formed by the near-wall production cycle which is the source of the majority of the turbulence in smooth-walled flow. In addition, there are ridges in the spectral map far away from the wall corresponding to large-scale and very-large-scale coherent motions, LSM and VLSM respectively. These motions have been attributed to the existence of packets of hairpin vortices within the wall-layer and corresponding alignment of the packets. When the surface is rough and blowing rates are low, as shown in **Figure 3b-c**, there are several modifications made to this basic organization. First, the near-wall peak moves to smaller wavelengths on the order of the wavelength of the surface and moves further away from the wall. In addition the signature of the LSM becomes weaker and does not reach as far into the outer layer whereas the signature of the VLSM remains unchanged. When blowing rates are increased further, as illustrated in **Figure 3d**, the near-wall peak moves even further away from the wall, and the LSM signature is no-longer apparent. Instead, the outer region of the flow is dominated by structures of a scale on the order of the channel height, corresponding to the formation of the outer peak in the Reynolds stress contours, which appear to be structures formed by interaction of the turbulent wall layer flow with the injected flow.

Conclusions and Future Work

The addition of roughness and blowing to a turbulent wall-bounded flow was found to introduce several modifications to the structure of the turbulence. The scales at which the near-wall turbulence was produced was found to shift to scales corresponding to that of the roughness, while the large-scale motions were found to be weakened by the addition of blowing. At high blowing rates the majority of kinetic energy was found to be contained within structures forming due to interaction between the injected and advected flow. Future work will focus on increasing fidelity with the actual TPS as well as quantifying the blowing rate and match that of the full system.