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A plane turbulent wall jet on a fully rough surface

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A B S T R A C T

The mean velocity field and skin friction characteristics of a plane turbulent wall jet on a smooth and a fully rough surface were studied using Particle Image Velocimetry. The Reynolds number based on the slot height and the exit velocity of the jet was $Re = 13{,}400$ and the nominal size of the roughness was $k = 0.44$ mm. For this Reynolds number and size of roughness element, the flow was in the fully rough regime. The surface roughness results in a distinct change in the shape of the mean velocity profile when scaled in outer coordinates, i.e. using the maximum velocity and outer half-width as the relevant velocity and length scales, respectively. Using inner coordinates, the mean velocity in the lower region of the inner layer was consistent with a logarithmic profile which characterizes the overlap region of a turbulent boundary layer; for the rough wall case, the velocity profile was shifted downward due to the enhanced wall shear stress. For the fully rough flow, the decay rate of the maximum velocity of the wall jet is increased, and the skin friction coefficient is much larger than for the smooth wall case. The inner layer is also thicker for the rough wall case. The effects of surface roughness were observed to penetrate into the outer layer and slightly enhance the spread rate for the outer half-width, which was not observed in most other studies of transitionally rough wall jet flows.

1. Introduction

The plane turbulent wall jet is a flow with many important practical applications in industry. It also retains special importance in theoretical studies as the plane wall jet is a prototypical near-wall flow that is significantly more complex than a boundary layer. It consists of an inner layer which resembles a turbulent boundary layer and an outer layer which exhibits the mixing characteristics of a turbulent free jet. Fig. 1 gives a schematic of a plane wall jet on a rough surface where: (x, U) and (y, V) are the spatial coordinate and mean velocity component in the streamwise and wall-normal directions, respectively; U_m is the maximum streamwise velocity; and y_m is the corresponding wall-normal location. As shown here, the inner region extends from the wall up to y_m, while the outer region stretches from y_m to the outer edge of the jet. The parameter $(y_{1/2})_{out}$ denotes the wall-normal location where $U = U_m/2$ in the outer region. There is also a half-width denoted $(y_{1/2})_{in}$ which characterizes the thickness of the inner region, which is not shown in Fig. 1. The parameter k denotes the height of the roughness elements on the ground plane.

In their recent computational study, Banyassady and Piomelli (2014) provide a comprehensive and insightful review of the literature on plane turbulent wall jets. Therefore, the present paper will only reference select papers which are directly relevant to the results of this study. The plane turbulent wall jet on a smooth surface has been relatively well studied over past decades using experimental and more recently computational methods. Bradshaw and Gee (1960) proposed a power law relationship between the skin friction coefficient C_f and the local Reynolds number $Re_m = U_m y_m/\upsilon$. Wygnanski et al. (1992) measured both the mean and fluctuating velocity components in a plane turbulent wall jet on a smooth surface for a number of different slot Reynolds numbers. They also evaluated the self-similarity of the mean velocity profile and found that when using inner coordinates it did not match the canonical logarithmic law used to characterize the overlap region of a turbulent boundary layer. In contrast, as discussed below more recent studies all support the existence of an overlap region within the inner layer of the wall jet and have used a logarithmic or power law to characterize it. Eriksson et al. (1998) measured both the mean and fluctuating velocity fields for a wall jet on a smooth surface using laser Doppler anemometry (LDA). Their data indicated that the mean velocity profile is reasonably self-similar in the region $40 < x/H < 150$. George et al. (2000) proposed a similarity theory for the plane turbulent wall jet using a power law formulation, and derived a theoretical relation for C_f which was in good agreement with the correlation by Bradshaw and Gee (1960), especially at higher Reynolds numbers. Barenblatt et al. (2005) proposed a theory of incomplete similarity for the entire flow field of the wall jet, and noted the existence of a triple-layer structure

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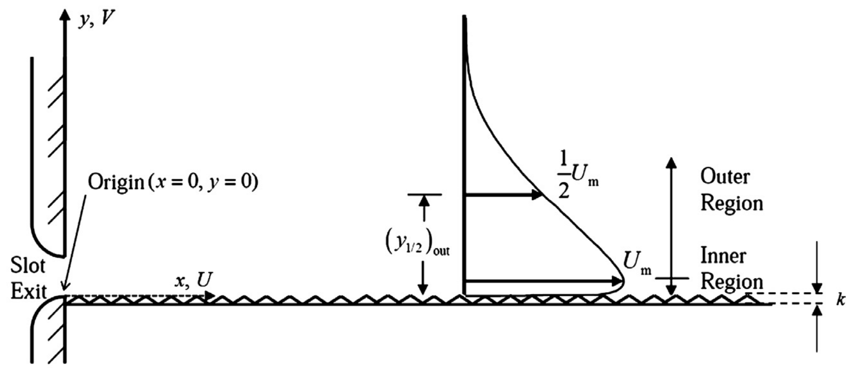

Fig. 1. Schematic representation of a plane turbulent wall jet on a rough surface.

consisting of two self-similar layers (i.e. the inner and outer layers) separated by a mixing layer. Their analysis based on the data set of Karlsson et al. (1991) confirmed the existence of incomplete similarity for a plane turbulent wall jet on a smooth surface, including a strong dependence on the slot width.

More recently, Large Eddy Simulation (LES) has been used to study the velocity field in a plane turbulent wall jet. Dejoan and Leschziner (2005) performed a simulation for a slot Reynolds number of $Re = 9600$ using a relatively short solution domain. They calculated the fluctuating energy budgets and used them to analyse the interaction between the inner and outer layers, which is a fundamental question for wall jet research. Banyassady and Piomelli (2015) used LES to study the interaction of inner and outer layers in both plane and radial wall jets. They concluded that the local Reynolds number was indicative of the level of intrusion of the outer layer into the inner level, and noted that this influenced the value of the log-law constant in the over-lap region of the inner layer.

Compared to the case of a smooth surface, there have been relatively fewer investigations of wall jet flows on a rough surface. Hogg et al. (1997) developed scaling laws for the case of a two-dimensional wall jet on a rough surface by applying the approach of Wygnanski et al. (1992) to the experimental data of Rajaratnam (1967). Hogg et al. (1997) observed a weak dependence of the mean velocity field on the length scale associated with the rough surface. Tachie et al. (2004) used LDA to study wall jets on both a smooth and transitionally rough surface. They observed that the surface roughness did not significantly change the outer spread rate of the jet or the decay rate of the maximum mean velocity, although the skin friction coefficient increased by 15%–30% due to the rough surface. Smith (2008) used hot-wire anemometry to investigate the effects of sand-grain roughness of different grain size on the mean and fluctuating velocity fields in a plane wall jet. He observed that the displacement and momentum thicknesses vary noticeably with changes in the roughness grain size, but the maximum velocity, mixing layer length scale $(y_{1/2})_{\text{out}}$ and the maximum velocity location y_m did not vary in a consistent manner. More recently, Rostamy et al. (2011) used LDA to investigate the effect of surface roughness on the mean velocity field in a plane wall jet on both smooth and transitionally rough surfaces. They observed a distinct change in the shape of the mean velocity profile due to roughness, as well as a significant increase in the value of the skin friction coefficient on the transitionally rough surface. Tang et al. (2015) used the data of Rostamy et al. (2011) to assess the issue of incomplete similarity, and observed that the inner and outer layers developed separately for both the smooth and transitionally rough surfaces, and retained a downstream dependence on the slot width. Banyassady and Piomelli (2014) performed an LES study of a plane turbulent wall jet for both smooth and transitionally rough surfaces at a Reynolds number of $Re = 7500$, similar to the experimental study of Rostamy et al. (2011). They concluded that the effects of surface roughness were confined to the inner layer, and that the decay rate of the maximum velocity U_m and the growth rate of the location y_m decrease over the rough surface compared to the smooth one. Table 3 of their paper, which summarizes the effects of surface roughness observed in different wall jet studies, indicates that there is still some disagreement on the effect of roughness on the streamwise development of the mean velocity field. Note that the streamwise extent of their LES solution domain was much smaller than for most experimental studies.

From the summary presented above, there still appear to be some questions related to the effects of surface roughness on the streamwise development of the plane turbulent wall jet, especially for the case of fully rough flow. Furthermore, there are very few experimental measurements of the skin friction coefficient for a plane turbulent wall jet on a fully rough surface. Although most studies conclude that the effects of surface roughness are confined to the inner layer, most of these studies only considered the case of a transitionally rough surface. In this context, the present study focuses on investigating the mean velocity field as well as the skin friction coefficient for a plane turbulent wall jet on a fully rough surface based on a new set of PIV measurements.

2. Experimental facility

The measurements were conducted with a Particle Image Velocimetry (PIV) system in the same facility used by Dunn (2010) and Rostamy et al. (2011). The facility was modified to allow higher slot exit velocities. The water flow was supplied by a pump which discharged through a rectangular slot at a bulk exit velocity of $U_o = 2.23$ m/s based on a volume flow measurement made by an orifice plate and the slot dimensions. The corresponding slot Reynolds numbers was 13,400 which is 80% higher than the value of $Re_o = 7500$ used in Rostamy et al.'s (2011) experiments. The jet exit had a width of $W = 750$ mm and height of $H = 6$ mm, so that the width-to-height ratio was large enough to ensure that the plane wall jet was two-dimensional at the slot exit. The slot had a contraction ratio of 36 to 1, resulting in a velocity profile near the exit that was approximately uniform except for the region near the ground plane and the outer edge of the jet. Fig. 2 presents the mean and fluctuating streamwise velocity profiles just downstream of the slot exit, along with similar data by Dunn (2010). The mean streamwise velocity profile had a maximum deviation of 1% over the middle two-thirds of the slot height, and the turbulence intensity in the central region of the slot was less than 3.3% for both surface conditions.

A rectangular glass plate was used as the smooth surface, while the rough surface was created by attaching a 36-grit traction tape