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Self-similar behavior of turbulent impinging jet based upon outer scaling and dynamics of secondary peak in heat transfer

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ABSTRACT

The flow field of an impinging wall jet created by the impingement of a turbulent axisymmetric jet normal to a flat surface was characterized by the particle image velocimetry technique. Experimental data is analyzed to explore two basic features of the impinging jet: first, to bring out unexplored aspects which are responsible for secondary peak in heat transfer distribution and to understand the reason for discrepancies in the existing observations about the peaks in heat transfer. Second, to analyze the self-similarity of radial wall jet based upon outer scaling. Measurements of the cross-wise mean velocity and turbulence statistics were initially used to explain the dynamics of secondary peak. Our results show that flow separation/reattachment occurs along the surface. At the reattachment location an intense increase in crosswise velocity, normal stresses and higher mixing are evident, which would lead to a peak in heat transfer. The separation/reattachment location is further found to depend upon the specific stage of vortical structure and is a function of surface spacing. The location of maximum value of mean cross-wise velocity and normal stress is located at the intersection of inner and outer shear layers. While the maximum Reynolds shear stress location is shifted to the outer shear layer and is located between the location of maximum velocity and jet half-width. The impinging jet exhibits a self-similar behavior as evident by the collapse of mean velocity and turbulent stress profiles when scaled with appropriate parameters. The outer scaling is able to bring out the self-similar profile of mean velocity and normal stresses. However, the shear stress profile does not show the self-similar behavior by the use of outer scaling. Data in the inner shear layer show small scatter compared to the outer shear layer especially close to the surface. The results show that the outer scales are not suitable to scale the data in the inner layer. It is also observed that the presence of vortical structure in wall jet delays attainment of self-similarity and the location beyond which self-similarity is observed is a function of surface spacing. These results aid in interpretation of heat transfer behavior from a flat surface and provide comprehensive benchmark data for theoretical modeling of the flow.

1. Introduction

Flow phenomenon and heat transfer characteristics of an impinging wall jet are widely studied because it is important from both practical and fundamental points of view. Impinging jet finds applications in various heat and mass transfer areas (Viskanta 1993; Hashiehbaf et al., 2015; Chaudhari et al., 2010). Study of turbulence behavior and self-similar region is also useful in theoretical modeling of the flow (Cooper et al., 1993; Dejoan and Leschziner 2005). Several studies have been conducted to study the heat transfer and flow dynamics of an impinging jet (Carlomagno and Ianiro 2014; Zuckerman and Lior 2006; Narayanan et al., 2004; O' Donovan and Murray 2007a). However, the reason for appearance of secondary peak in heat transfer has not yet been fully resolved, although studies have explored the different mechanisms involved behind its appearance. Kestin et al., (1961) reported that the presence of a favorable pressure gradient in the impingement zone stabilizes the laminar boundary layer flow. As the wall jet becomes parallel to the surface, the pressure gradient vanishes and the laminar boundary layer becomes turbulent; this promotes formation of a secondary peak in heat transfer. Gardon and Akfirat (1965) observed the presence of two peaks in heat transfer along the wall. They proposed that local thinning of the boundary layer due to flow acceleration is the reason for the first peak; further, transition from laminar to turbulent boundary layer was attributed to the existence of secondary peak in heat transfer. Gulati et al., (2009) reported the heat transfer characteristics for distinct types of nozzle and observed the presence of secondary peak along the wall for Reynolds number (Re) ≥ 10,000. They reasoned that the phenomenon of transition from laminar to turbulent is responsible for the secondary peak in heat transfer.

There are some other studies which provide alternative opinions for

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secondary peak in heat transfer. Lytle and Webb (1994) reported that along the wall jet shear interaction of wall jet with ambient fluid leads to an increase in local turbulence. This effect penetrates up to the impinging plate and is responsible for the secondary peak in heat transfer. Katti et al., (2011) provided some support to the results of Lytle and Webb (1994). Behnia et al. (1999) reported that a higher turbulent kinetic energy is responsible for the secondary peak in heat transfer distribution. Goldstein et al., (1986) attributed the air entrained by vortex rings in the shear layer as the reason for the appearance of secondary peak. Popiel and Trass (1991) used the smoke wire technique and observed that the presence of wall eddies causes an enhancement in heat transfer and are responsible for the secondary peak in heat transfer distribution. Benhacine et al., (2012) in a large eddy simulation (LES) based study observed that vortical structures break down within the wall jet of the boundary layer and are responsible for the secondary peak in Nusselt number. O' Donovan and Murray (2007a) observed that at low nozzle to surface spacings ($L/D < 2$; where L is the surface to nozzle distance, and D is the nozzle diameter), secondary peaks in Nusselt number form due to the combined effect of high local velocity along the wall jet and an abrupt increase in the turbulence intensity. Their result showing the distribution of Nusselt number along the surface is reproduced here as Fig. 1. The figure shows the heat transfer distribution at different surface spacings at a fixed Reynolds number of 10,000. In the figure, r denote the distance from the stagnation measured along the surface and H has the same definition as L. O' Donovan and Murray (2007b) reported that a significant increase in turbulence occurs at the point where vortical structure breaks down, which leads to an increase in the local Nusselt number. This is manifested as a secondary peak in heat transfer distribution.

As part of impinging jet studies, several works have been conducted on wall jet to observe the self-similar behavior of velocity and stress profiles (Launder and Rodi 1983; Wygnanski et al., 1992; George et al., 2000, Naqavi et al., 2017, Banyassady and Piomelli, 2015). The self-similar behavior of free jet has been investigated by numerous authors. Boguslawski et al. (1979) and Surma and Friedel (2004) reported that the self-similar region occurs between eight to ten nozzle diameters from the nozzle. Yadav et al., (2016a) reported that self-similarity occurred beyond 6D from the nozzle exit and depends upon the jet potential core length. Knowles and Myszko (1998) reported the self-similarity behavior of an impinging jet. They found that self-similarity in

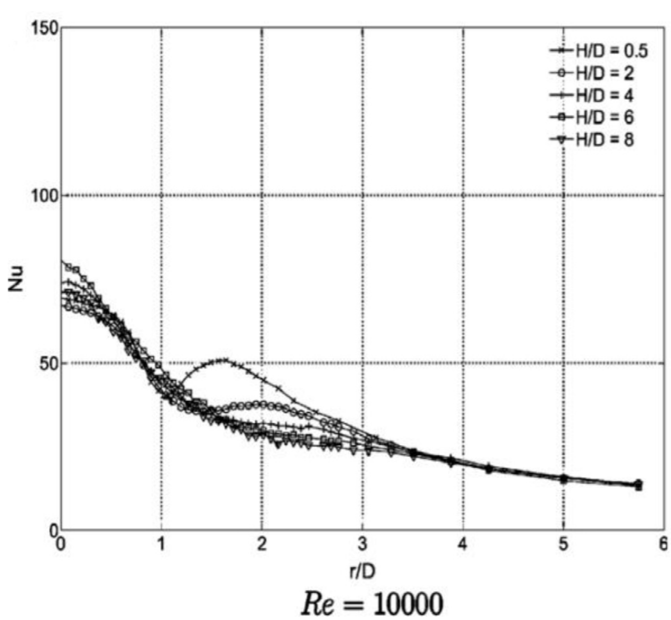

Fig. 1. Variation of time averaged Nusselt number along the surface. (O'Donovan and Murray 2007a).

velocity occurs at a lateral location of three diameters from the stagnation point.

However, some studies introduced separate inner and outer scaling parameters for the purpose of normalization in the self-similar region. The inner scaling parameters are shear length (ν/u_τ; where ν denotes the kinematic viscosity of the fluid, and u_τ is frictional velocity), while the outer scaling parameters are half-width distance ($Z_{0.5}$) and maximum streamwise velocity (V_m). The inner layer thickness extends from the surface to the location of maximum streamwise velocity, also known as boundary layer thickness (Z_m); while the outer layer thickness extends from the maximum streamwise velocity location to the location of ambient fluid, also known as free shear layer (Ahlman et al., 2007; Rostamy et al., 2011). Naqavi et al. (2017) used two different scalings for the inner and outer regions: In the inner region, friction velocity was used as the velocity scale and viscous length used as the length scale. In the outer region, local maximum streamwise velocity was used as the velocity scale and half-width used as the length scale. The normal stresses were normalized with the maximum velocity and the Reynolds shear stress scales with the friction velocity. Dejoan and Leschziner (2005) used the LES technique to simulate the flow and to study the self–similar behavior of the wall jet with different scalings. They observed that in the inner layer, frictional velocity and viscous length are appropriate scales to normalize the parameters; while in the outer region, the maximum local streamwise velocity and jet half-width were used. Ahlman et al., (2007) used the direct numerical solution technique to simulate a turbulent plane wall-jet. They observed self-similarity of both mean and turbulent properties in the inner and outer layers. George et al., (2000) proposed a similarity theory for plane wall jets. They further proposed that the appropriate scales in the inner region for velocity and length are frictional velocity and viscous length respectively, while the appropriate scales for the outer layer are maximum local streamwise velocity and jet half-width. However, these scalings are strictly valid for infinitely large Reynolds number. In addition to this, they observed that in the outer layer, the maximum velocity used to scale the Reynolds shear stress failed to collapse the data on to a single curve. If the maximum velocity was replaced with friction velocity, the collapse of data was much better and the normal stress show a self-similar behavior with maximum velocity. Rostamy et al., (2011) however do not support the proposal of George et al., (2000) about the normalization of the Reynolds shear stress. Glauert (1956) observed in his theoretical study that a single similarity solution for the entire wall jet is not possible.

Several works related to planar wall jet introduced appropriate parameters in the inner and outer shear layers to study the self-similar behavior of wall jet. However, only few work discuss the self-similar behavior of a radial wall jet on a flat surface. Further, available studies on radial wall jet do not introduce separate inner and outer scaling parameters for normalization. As the behavior of plane wall jet and radial wall jet are geometrically similar in the fully developed region (Rao and Inderjit 2013), introduction of inner and outer scales will be helpful in study of self-similar behavior of impinging wall jet. To the best of our knowledge, there is only one study on impinging (synthetic) jet which discuses about the inner and outer scalings (Krishnan and Mohseni 2010). They observed that the mean and rms velocities in the outer layer collapsed well with the outer scaling, while the profiles in the inner layer do not collapse. They proposed that the inner region does not scale precisely with the outer variables.

Despite several investigations on impinging jet, the question of local peaks in heat transfer distribution has not been fully resolved. In addition, the issue of self-similarity and scaling of impinging jet has not been addressed in terms of scaling of inner and outer regions. Therefore, the aim of the present investigation is to bring out an improved understanding of the unexplored aspects responsible for secondary peak in heat transfer distribution, and to try to reconcile the discrepancies related to secondary peak in heat transfer mentioned in the literature. The present study also discusses the effect of scaling parameters on the self-similar behavior of a wall jet.