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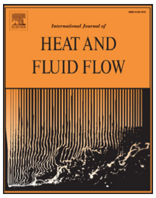

Large-eddy simulations of a turbulent jet impinging on a vibrating heated wall

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ABSTRACT

High-resolution large-eddy simulations (LES) are performed for an incompressible turbulent circular jet impinging upon a vibrating heated wall supplied with a constant heat flux. The present work serves to understand the flow dynamics and thermal characteristics of a turbulent jet under highly dynamic flow and geometric conditions. The baseline circular vibrating-wall jet impingement configuration undergoes a forced vibration in the wall-normal direction at the frequency, $f = 100$ Hz. The jet Reynolds number is $Re = DV_b/\nu = 23{,}000$ and the nozzle-exit is at $y/D = 2$ where the wall vibrates between 0 and $0.5D$ with amplitude of vibration, $A = 0.25D$. The configuration is assembled through validation of sub-systems, in particular the method for generating the turbulent jet inflow and the baseline circular jet impingement configuration. Both time-mean and phase-averaged results are presented. The mean radial velocity increases upon positive displacement of the wall and decreases upon negative displacement but this correlation changes with increased radial distance from the stagnation point. Vortical structures are shown to play a major role in convective heat transfer even under the vibrating conditions of the impingement wall. Periodic shifts in the secondary Nusselt number peak are observed that depend upon the travelling eddy location and strength of large-eddy structures. Enhancement in heat transfer is seen in the stagnation region but this beneficial effect of vibration on heat transfer is confined to the impingement region, $r/D < 1.5$.

1. Introduction

Impinging jets have played a pivotal role in applications that require efficient heat- and mass-transfer. The canonical jet-impingement problem presents a deceptively simple configuration, yet produces a complex array of flow features. The analysis of impinging jets has grown in sophistication with improvements in experimental measurement techniques as well as numerical methods that enable powerful and accurate simulations by harnessing the rapid growth of affordable computing power.

Predicting accurate flow features of a jet impinging upon a stationary wall is in itself demanding considering the complex flow physics, which includes Kelvin–Helmholtz type shear layer development in the free-jet, a high static pressure region generated upon impingement, change in flow streamline curvature into the wall-jet region, development of a boundary layer along the wall and entrainment along the exit boundaries of the domain. Several studies have described these regions in detail along with their fluid flow and heat transfer characteristics. The reader is referred to the works of Martin (1977), Jambunathan et al. (1992) and Viskanta (1993) for exhaustive reviews on experimental jet-impingement studies. Conventionally, jet-impingement studies have either been performed with jets discharging cold fluid on a heated wall or conversely impingement of a hot fluid on a cold wall. Several studies have been performed on this fundamental configuration with changes to the geometry besides the fluid parameters. There have been few studies with impingement-wall vibrations (see Ichimiya and Yoshida, 2009; Wen, 2005), that focus predominantly on the heat transfer characteristics with inadequate or only qualitative data on the flow physics that cause heat-transfer variations on the impingement wall. Both augmentation and reduction in heat-transfer have been observed. Noticeably absent is information on the flow dynamics either at the near-wall region or elsewhere in the domain that is directly responsible for the resulting thermal signatures on the impingement-wall in the context of forced con-

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vection. This has been overlooked by previous studies creating a gap in the understanding of the cause of the changes observed on the impingement-wall. The flow-physics spawned by a turbulent circular jet impinging upon a vibrating wall remains largely unknown. The present work attempts to close this gap by establishing the relationship between the flow features and the resulting heat-transfer on the impingement-wall.

A substantial amount of work has been carried out in analysing impinging jet configurations, in which the nozzle-to-wall distance (y/D), the jet Reynolds number, Re, inflow conditions of the jet, types of nozzles and number of jets issuing have been investigated in an extensive range of parametric combinations, with both experimental and numerical techniques. Cooper et al. (1993) were the first to present an in-depth experimental analysis of impinging jets with varying nozzle-to-wall spacings. Their experiments reported turbulent flow field statistics for varying nozzle-to-wall distances and Reynolds numbers. A companion paper to this work by Craft et al. (1993) examined the development of eddy-viscosity models to model turbulence. Although the models initially demonstrated poor agreement in the stagnation region, improvements have been made to the turbulent viscosity parameters, yielding better agreement with experimental data (Craft et al., 2000). Baughn and Shimizu (1989) presented experimental results for a simple impinging jet flow, featuring an impingement wall that produced uniform heat flux. This work has proven valuable as a benchmark for numerical work since uniform heat flux boundary conditions are straightforward to model. These results were later investigated numerically by several researchers including (Bovo and Davidson, 2013; Katti and Prabhu, 2008; Yan and Saniei, 1998) for $Re =$ 23,750. The Nusselt number (Nu) is broadly used as an indicator of the heat-transfer rate on the impingement-wall. At small nozzle-to-wall distances, a secondary outer peak is observed in the radial distribution of the mean Nusselt number in addition to the primary inner peak within the stagnation region.

Analysis of the formation of a secondary Nu peak was conducted by Gardon and Akfirat (1965) for various Reynolds numbers. They argued that a local thinning of the boundary layer was the cause of the secondary Nu peak. This was also observed in the work of Chung and Luo (2002) for a laminar flow. They attributed the reduction in thermal boundary layer thickness to the large-scale interaction between the jet vortices and the impinging wall that resulted in the secondary Nu peak. Direct numerical simulations (DNS) of a laminar flow jet-impingement by Chung et al. (2002) showed that heat-transfer at the impingement-wall is very unsteady and is mainly caused by the primary vortices emanating from the jet nozzle that interact with the wall shear layer. It was shown that the vortex location has a much stronger effect on Nu than the vortex strength. Although a correlation between the Nu and the flow field was seen, a breakdown in the Reynolds analogy was seen at downstream radial distances. Instantaneous skin friction coefficient, C_f and Nu variations show that local heat transfer distributions correlate closely with the flow fields. Recent DNS performed by Dairay et al. (2015) for a turbulent jet with $Re = 10{,}000$ showed that the primary and secondary vortices are responsible for the increased heat transfer since they constantly renew the wall with cold fluid due to their inherent induced velocity. This was also observed in the DNS of Rohlfs et al. (2012) for a laminar flow Reynolds number.

In the recent experimental work of Tummers et al. (2011), the turbulent characteristics of an impinging jet (Reynolds number comparable to Baughn and Shimizu (1989)) were studied, and near-wall measurements revealed that flow reversals were related to the formation of secondary vortices. LES of these experiments were later conducted by Uddin et al. (2013). They used digital filtering of random data to generate the inflow velocity fluctuations. Hadžiabdić and Hanjalić (2008) used inflow conditions from a pipe flow. However, only a quarter of the full three-dimensional domain was used in their LES study. They showed that the vortex roll-up phenomenon along the impingement-wall is the main event governing the flow. The connections between the convection of the primary vortices, the formation of the counter-rotating secondary vortices and the unsteady separation phenomena were elucidated. Also, a recent DNS study by Dairay et al. (2015) states that the secondary Nusselt number peak becomes less pronounced when a long tube profile is used for the inflow. A similar observation has been made in the experimental work of Roux et al. (2011) indicating a requirement for further investigation of this effect. A review of recent LES studies is available in Dewan et al. (2012).

Tsubokura et al. (2003) presented the development or transition of both plane and circular jets and identified the large-scale structures based on the Laplacian of pressure. They found that the eddy structures differed for the plane and circular jet configurations, and no organised structures were seen at the stagnation zone of the circular jet. Popiel and Trass (1991) stated that the development of these large-scale vortex structures considerably enhanced the entrainment rate and mixing processes. An interaction of the well-ordered toroidal vortex structures convected downstream from a transient circular shear layer of a natural free-jet with the normally impinged flat wall was shown. It was inferred that these near-wall eddies are responsible for the additional enhancement of local momentum and heat or mass transfer. The wall eddies are rolled up on the wall between the large-scale toroidal vortices, which diverge in the radial direction.

It is evident from the aforementioned literature that events within the hydrodynamic boundary layer are largely accountable for the variations in the thermal characteristics of the impingement-wall. The boundary layer originates at the stagnation region and grows gradually, moving away from the stagnation region into the wall-jet region. Martin (1977) reported that the thickness of the boundary layer δ_0, defined as the locus of the maximum of the wall-jet velocity in the stagnation zone would reach about one-hundredth of the nozzle diameter. The wall-jet profile formation occurs as a result of the simultaneous growth of wall boundary layer and the free-jet boundary. Since the boundary layer has a shearing influence upon the wall, increasing the shear on a stationary wall may be favourable in terms of increasing heat and mass transfer. This can be achieved by setting the impingement-wall in a periodic oscillatory motion perpendicular to the nozzle-exit, to modify the boundary layer formation and the corresponding events within it. A clear relationship between the vortical structures and their influence on the heated wall can be established since the vortical structures will oscillate (vertically) due to the wall motion.

Experimental work on vibrating impingement walls was first carried out by Ichimiya and Yoshida (2009), for planar impinging jets. They considered the range of Reynolds numbers $1000 < Re < 10{,}000$ and concluded that both enhancement and reduction of heat transfer could occur as a result of vibration. Ichimiya and Watanabe (2009) examined moderate Reynolds numbers of 200 and 500 and observed improved heat-transfer in the wall-jet region. Since the investigations were carried out for such low Reynolds numbers, the effect of turbulence, (which is a key contributor to heat transfer improvement) is neglected. Investigations by Klein and Hetsroni (2012) used vibrations generated by a piezoelectric actuator for a micro liquid jet. An increase in heat-transfer was observed for micro-amplitudes. Wen (2005) conducted experimental studies on impingement wall undergoing forced vibrations. The focus was on tubes with swirling strips and micro vibrations. The study concluded that the Nu was strongly dependent upon the wall vibration frequency, f, wall vibration amplitude, A, and the jet Reynolds number. However, a substantial dependence of the Nusselt number upon the nozzle-to-wall distance was not observed.

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