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Combined effects of groups of vortices generated by a pulsating turbulent plane jet impinging on a semi-cylinder: Effects of the forcing frequency

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ABSTRACT

A submerged pulsating plane turbulent jet was simulated using Large Eddy Simulation at different forcing frequencies. Based on a previous work, interesting phenomena, related to the interaction of coherent primary vortices with the dynamical and thermal fields along the target curved wall, were elucidated for a forcing frequency equal to 600 Hz. As a systematic continuation, the present work extends the study to the effects of more forcing frequencies. The main objective remains the same which is investigating the time-dependent responses of Nusselt number, friction coefficient and pressure profiles to the passage of the coherent structures along the curved impingement wall. The distance s, along the target wall, is measured from the impact point and normalized by the jet exit width W.

It was found that for a forcing frequency equal to 200 Hz, coherent forced primary vortices induced by the pulsations are separated by less organized vortices naturally induced as in the unforced jet. The results showed clearly that the natural vortices have moderate effects on the boundary layer development on the impingement surface starting at relatively short distances from the stagnation point, $s/W < 3$. On the other hand, the forced vortices seem to have a more influential role on the wall jet behavior but further downstream.

Increasing the forcing frequency to 400 Hz reduces the distance separating successive forced vortices causing the pairing phenomenon to occur at $s/W = 6$ along the target wall. Increasing the forcing frequency further makes the pairing phenomenon followed by vortex breakdown to occur at shorter distances along the target wall. The smaller forcing frequencies such as 400 Hz generate large and strong distant vortices that affect the dynamic field noticeably with an important deterioration of heat transfer due to their strong mixing effect and entrainment of cold air from the surroundings towards the target wall. On the other hand, high frequencies (1500 Hz and 2200 Hz) generate smaller closely successive vortices, with a weaker effect, that do not disturb the boundary layer on the target wall considerably up to a distance of $s/W = 4$ where the lowest heat transfer is observed. In fact, the cold air from the surroundings is not entrained and does not approach the target wall over a long distance which generates the highest heat transfer away from the impingement region.

1. Introduction

Impinging jets are used extensively in the industry for different purposes including heating, cooling, drying and controlling film thickness on coated metal products. Thus, understanding the phenomena that govern heat transfer and flow dynamics over the target surface is essential for better process efficiency. These phenomena can be explored by considering the behavior of certain parameters such as Nusselt number, wall shear stress and pressure distributions.

It is important to distinguish the characteristic features of each configuration considered. Impinging jets can be laminar or turbulent, submerged or unsubmerged [1], heating or cooling the target surface, close to, or far from the target wall, plane or round (or any other unconventional shape of the jet exit), single or multiple jets. The impingement target wall can be flat or with a certain curvature. For example, Poitras et al. [2] studied a jet impinging on a concave surface contrary to the present study where a convex surface is considered. In addition, impinging jets can be steady or forced by imposing pulsations to the mean flow. Several studies from the literature investigated the behavior of pulsating impinging jets forced at different frequencies and amplitudes in conjunction with the abovementioned geometrical and flow parameters [3–9].

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Nomenclature

C_f	Friction coefficient $\tau_w/0.5\rho u_{zin}^2$
C_S	Smagorinsky constant
d	Distance closest to the wall
D	Semi-cylindrical convex surface diameter
f	Forcing frequency
H	Distance from the slot exit to the point of impact on the wall
L_s	Mixing length for subgrid scales
N	Number of samples for averaging
$Nu(s, t_i)$	Local and instantaneous Nusselt number
p	Pressure
q_j	Subgrid scale turbulent heat flux in the x_j direction
Re_W	Reynolds number
s	Distance from the impingement point along the curved wall
S_{ij}	Filtered strain rate tensor
St	Strouhal number $fW/u_{znozzle}$
t	Time
$\overline{T}$	Filtered temperature
$\overline{u}_i$	Filtered x_i-velocity component
u_{in}	Instantaneous inlet velocity
$u_{znozzle}$	Average z-velocity at the nozzle exit
V	Volume of the computational cell
V1-V6	Vortices identification names
W	Slot width
x_i	Cartesian coordinate
y+	Normalized wall distance

Greek letters

κ	Von Karman constant
μ	Fluid dynamic viscosity
μ_t	Turbulent dynamic viscosity
ν	Laminar kinematic viscosity
ν_t	Turbulent kinematic viscosity
ρ	Density
σ	Laminar Prandtl number
σ_{ij}	Laminar stress tensor
σ_t	Subgrid-scale turbulent Prandtl number
τ_{ij}	Subgrid-scale stress tensor
τ_w	wall shear stress

Previous studies, which mainly dealt with round jets impinging on plane surfaces, have identified the important and intricate role that coherent primary vortices, generated in the free jet shear layer, have on heat and momentum transfer on the target surface [10]. The passage of the primary vortices, generated in the free jet shear layer, above the target solid surface, affects the growth of the target surface boundary layer thickness. When the sweeping effect is strong enough, the primary vortices trigger the roll up of the boundary layer into an opposite signed vortex with sometimes a tertiary vortex. A further increase of the primary vortices' sweeping effect causes the ejection of the secondary vortices from the convex wall [11]. This complex interaction between the primary vortices and the solid surface developing boundary layer, is more pronounced in general when the jet exit nozzle is close to the wall (distances less than four times the jet exit width [12]) due to the persistence of the potential core which prevents the primary vortices from directly impacting on the target wall [11]. For steady jets (without pulsations), the primary vortices are generally not coherent and their interaction with the boundary layer tends to be relatively random. However, pulsations generate more organized turbulent structures (primary vortices) that would allow to control their interaction with the boundary layer along the target wall. Hence, pulsating jets provide a suitable turbulent flow field to elucidate the phenomena characterizing the interaction of the primary vortices with the boundary layer on the target wall and, consequently, derive a clearer idea about what enhances or deteriorates heat transfer by impinging jets along the target wall.

In previous experimental studies with pulsating forced jets, focus was on one parameter at a time such as Nusselt number, pressure or wall shear stress distributions over the target wall under the effect of the passage of single primary vortices. Previous contributions [13–16] found that the interaction of the primary vortex with the wall was characterized by a wall pressure signature. Positive pressure signatures were associated with high strain rates while negative pressure signatures with high vorticity. El Hassan et al. [17] investigated the effects of the coherent structures on the wall-shear stress distribution along the impingement wall. Flow expansion (upwash stream), resulted in an ejection of the fluid from the impinging wall at the front part of the transverse vortex, causing the wall shear stress to decrease. They noted the effect of the induced flow separation on the wall shear stress distribution. Hubble et al. [18], explored the effects of the coherent turbulent structures on the heat transfer along the impingement wall for cooling applications through simultaneous measurements of velocity and thermal fields. They distinguished three characteristic streams upstream (downwash stream), underneath (parallel stream) and downstream (upwash stream) of the coherent structures passing close to the impingement wall for an anticlockwise rotation of the vortex. The downwash stream caused heat transfer peaks due to the entrainment of cold air from the outer region and thinning of the boundary layer by the impinging stream. The stream parallel to the wall decreased the heat transfer because of the already gained heat by the air. The upwash stream decreased the heat transfer to its minimum.

Numerical studies on pulsating impinging jets, using advanced turbulence models such as LES and focusing on the interaction between the vortex structures and the surface boundary layer, are scarce in the literature. Most previous studies considered round jets impinging on plane surfaces.

Jiang et al. [19] used LES to simulate a rectangular free jet with different aspect ratios. They found that the dominant Strouhal number of a steady jet was equal to 0.22. By forcing the jet at Strouhal numbers in the range 0.1–2.5, they found that the dominant Strouhal number of the steady jet, is appropriate to generate the strongest vortices at an early stage leading to maximum entrainment and mixing. Uddin et al. [5] performed LES calculations of a pulsating jet and found, similarly to [19], that forcing at the preferred mode of a round jet and its subharmonics generated large vortical structures that strike the flat target surface, while at harmonic frequencies the vortices vanish and become less effective in enhancing heat transfer. They also observed an attenuation of the well-known second peak of the Nusselt number under the effects of forcing.

In a previous work, Kharoua et al. [20] conducted a LES study on the interaction of the primary vortices with the boundary layer, developing along a convex target wall impacted by a heating pulsating turbulent plane jet forced at a frequency equal to 600 Hz. The distance between the nozzle exit and target surface was 2 nozzle widths. The study showed the importance of superimposing the dynamic and temperature fields to understand the causes of enhancement and deterioration of heat transfer induced by impinging jets. It was seen, that the dynamical and thermal fields can be coupled or decoupled depending on the complex flow structure especially when more than one primary vortex affect the boundary layer on the target wall. Previous studies addressed the idealized case of a unique primary vortex interacting with the boundary layer. The interaction was, usually, explored