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Large-eddy simulation of jet impingement heat transfer using a lobed nozzle

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ABSTRACT

The jet impingement heat transfer issuing from a lobed nozzle constructed using three circular orifices at a Reynolds number (Re) of 10,000 is investigated intensively with large-eddy simulation (LES). A comparative view was obtained for three nozzle configurations with different ratios of the orifice center offset (a) to the orifice radius (b) (i.e., a/b = 0, 0.8, and 1.15) at two nozzle-to-wall distances (H/D_e = 2 and 4). A constant equivalent diameter D_e is fixed for all of the configurations to ensure the nozzles' constant cross-section area. Good agreement of the LES data with the results obtained with temperature-sensitive paint (TSP) and particle image velocimetry (PIV) is established for the azimuthal-averaged Nusselt number on the impingement wall and the velocity distributions in the wall-jet and impingement zones, respectively. For all three nozzle configurations at $H/D_e = 2$, the LES results delineate two heat removal mechanisms of the impinging jet. Near the second-peak circle, the heat transfer is enhanced by the secondary vortices near the wall, whereas beyond the second-peak circle the instantaneous flow impingement onto the wall plays a significant role in heat transfer enhancement. The secondary vortices and instantaneous flow impingement are strengthened significantly in the configuration with $a/b = 0.8$ at $H/D_e = 2$, giving rise to a substantial increase in the Nusselt number in the region $1 < r/D_e < 4$. For the three configurations at $H/D_e = 4$, the instantaneous flow impingement is the main mechanism for heat transfer enhancement in the region $r/D_e < 0.5$, whereas the increase in a/b results in frequent activation of the intense flow impingement along with high turbulent kinetic energy, yielding better heat transfer on the heated wall.

1. Introduction

As an effective technique for wall heat removal, impinging jets have been widely used for industrial applications such as gas turbine cooling and aircraft deicing [1]. Given the cause-and-effect relationship between flow dynamics and heat transfer, such processes are subject to substantial modulation by unsteady behavior of the jet shear layer. In this regard, the jet impingement heat transfer could be considerably enhanced by passive control of the flow dynamics, such as placement of tabs at the nozzle exit [2], variation of the impingement angle [3] and modification of nozzle geometries [4]. Accordingly, insightful understanding of the wall heat removal mechanism in terms of the underlying flow dynamics is essential to improve the jet impingement configuration.

Many studies have sought to effectively intensify the wall heat transfer using various nozzle geometries, including the chevron nozzle and tab placement near the nozzle exit. Infrared thermographic measurement by Violato et al. [5] showed better performance in impingement heat transfer with the chevron nozzle than with a circular one, and measurement of the flow field with particle image velocimetry (PIV) attributed this improved performance to the development of streamwise vortices associated with deep penetration of turbulence mixing. Measurements by Vinze et al. [6] revealed that the mean Nusselt number increased with an increase in the number of chevrons for a given chevron angle and an increase in the tip angle for a given number of chevrons. Gao et al. [2] improved the wall heat transfer performance by adding triangular tabs to the nozzle exit and observed a series of distinct regions in which the Nusselt number was significantly increased; this benefit was attributed to the increased streamwise velocity fluctuation in the wakes of the tabs [7]. Martin and Buchlin [8] used infrared thermographic measurement to successfully demonstrate considerable heat transfer on the impingement wall by a lobed nozzle; this cost-effective nozzle can be constructed

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Nomenclature

A	area of the heated surface
A_0	area of the nozzle cross-section
a	orifice center offset
B	non-dimensional scalar defined in the buffer region
b	orifice radius
C_f	mean skin-friction coefficient
$C_f\prime$	fluctuating skin-friction coefficient
C_s	dynamic LES model coefficient
$C_{s,0}$	constant LES model coefficient (= 0.18)
$C_{s,b}$	modified LES model coefficient in the buffer region
D_e	Nozzle's equivalent diameter $(=\sqrt{\frac{4A_0}{\pi}})$
H	nozzle-to-wall distance
k	turbulent kinetic energy
L_{ij}	intermediate quantity to compute C_s
M_{ij}	intermediate quantity to compute C_s
P_{ij}	intermediate quantity to compute Pr_{sgs}
p	pressure
Q_{ij}	intermediate quantity to compute Pr_{sgs}
q_w	joule heating on the FTO glass
q_r	heating loss due to the radiation
q_c	heating loss due to the tangential conduction
r	radial coordinate
$\Delta\vec{r}$	vector from the upwind node to the surface center in numerical method
S	strain-rate tensor
T_0	reference (room) temperature
T	temperature
$T\prime$	fluctuating temperature
t	time
U_0	mean (bulk) axial velocity at the nozzle exit
U_c	mean (bulk) axial velocity on the jet centerline
U_{max}	maximum mean axial velocity on the jet centerline
U_{mag}	velocity magnitude
u_i	instantaneous velocity tensor
u_{ip}	instantaneous velocity at the surface center in numerical method
$u_{Central}$	instantaneous surface velocity predicted by central schemes in numerical method
u_{Upwind}	instantaneous surface velocity predicted by upwind schemes in numerical method
W	mean velocity in z direction
w	instantaneous velocity in z direction
w'	fluctuating velocity in z direction
x	coordinate
y	coordinate
z	coordinate
Nu	Nusselt number
$\overline{Nu}$	mean Nusselt number
Re	Reynolds number $(=\frac{U_0 D_e}{\upsilon})$
Pr	Prandtl number
Pr_{sgs}	subgrid-scale Prandtl number

Greek symbols

γ	intermittency
λ	heat conductivity of the air
ρ	correlation coefficient
σ	hybrid coefficient in numerical method
υ	kinematic viscosity
υ_{sgs}	subgrid-scale viscosity
ω_θ	Azimuthal component of the instantaneous vorticity
Δ	filter width at the grid level
$\hat{\Delta}$	filter width at the test level, $\hat{\Delta} = 2\Delta$

Abbreviations

LES	large-eddy simulation
PIV	particle image velocimetry
PDF	probability density function
TSP	temperature-sensitive paint

simply by drilling several circular holes in an overlapped fashion, and it shows great potential for industry application. There is no doubt that the substantial increase in heat transfer is resulted from spatiotemporal variations in flow behavior, which is fundamentally changed by the lobed nozzle.

As for the flow dynamics of the lobed nozzle, most studies have focused on mixing enhancement in free jets, which are characterized by pairs of large-scale streamwise vortices at each lobe crest; this causes azimuthal perturbations in the jet flow and breakdown of the Kelvin-Helmholtz (K-H) vortices, dominating the jet spreading and mixing enhancement [9]. Nastase et al. [10] experimentally confirmed that the increase in the jet entrainment rate was achieved by the breakdown of the K-H vortices into ring segments, as the entrainment rate attenuation was strongly associated with the passing of the K-H vortices. Hassan and Meslem [11] claimed that the axis-switching phenomenon observed in the lobed jet was attributable to a local contraction of the mean flow in both major and minor planes. This behavior is closely associated with different growth rates of the jet shear layer in the azimuthal direction, whereas the lobe troughs serves as the "axial vortex generator" [12] by dramatically increasing the shear layer thickness in the minor plane. Alternatively, similar to the mixing tabs [13], the existence of the lobe troughs generate streamwise vortices and then enhance the jet spread in the minor plane. The impingement jet certainly exhibits entirely different behavior than the free jet due to stagnation and deflection of the jet by the impingement wall. However, to the best of our knowledge, the understanding of the underling flow dynamics is insufficient for jet impingement heat transfer of the lobed nozzle.

This study is motivated to elucidate the heat transfer intensification of impingement jet issuing from a lobed nozzle in terms of the spatiotemporal variations in flow behavior. To this end, large-eddy simulation (LES) of the jet impingement heat transfer at a Reynolds number Re = 10,000 is performed on a lobed nozzle constructed by three overlapping circular orifices; a comparative view is obtained for three nozzle configurations with different ratios of the orifice center offset (a) to the orifice radius (b) (i.e., a/b = 0, 0.8, and 1.15) at two different nozzle-to-wall distances (H/D_e = 2 and 4). Here, the configuration with a/b = 0 is used as the benchmark for comparison. The wall temperature and flow field are measured using temperature-sensitive paint (TSP) and PIV, respectively, to provide data for strict validation of the LES work in a comprehensive manner. The highly unsteady flow behavior in various configurations are clarified, particularly the strongly coupled near-wall flow dynamics and the conjugate heat transfer.

2. Large-eddy simulation fundamentals

2.1. Governing equations

As the Reynolds-averaged Navier-Stokes (RANS) models are unable to capture the unsteadiness and small-scale structures in the flow, the wall-resolved LES model is used for turbulent flow