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Jet impingement heat transfer of a lobed nozzle: Measurements using temperature-sensitive paint and particle image velocimetry

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ABSTRACT

The impingement jet issuing from the lobed nozzles constructed using three small circular orifices is intensively investigated; the heat transfer characteristics and flow fields are respectively determined using temperature-sensitive paint (TSP) and particle image velocimetry (PIV). A piece of fluorine-doped tin oxide (FTO)-coated glass with uniform wall heat flux is used for optical access in TSP measurements. In particular, the effects of the geometrical variations are compared by varying the ratio of the orifice centre offset to the orifice radius, i.e., a/b = 0, 0.5, 0.8, 1.0, 1.1 and 1.15, at a constant equivalent diameter D_e for all configurations to ensure a constant cross-section area of the nozzles. The TSP measurements of the impingement heat transfer at Reynolds numbers $Re =$ 10,000 and 40,000 are performed using different nozzle-to-wall distances, i.e., H/D_e= 2, 4 and 6, to determine the mean Nusselt number distribution on the heated wall. The results show that the heat transfer is enhanced using lobed jets at $H/D_e \leq$ 4. At H/D_e= 2, the optimal Nusselt number is obtained using a lobed nozzle $a/b =$ 0.8 in the region $1 < r/D_e < 4$, with a heat transfer enhancement of up to 10% compared with that in the case of a circular jet. At H/D_e= 4, the azimuthal-averaged Nusselt number increases (up to 16%) consistently in the region $r/D_e < 0.5$ with an increase in a/b, while the Nusselt number shows a slight decay in the region $2 < r/D_e < 4$. However, at $H/D_e =$ 6, the Nusselt number in the entire measured region decays with an increase in a/b. Finally, the PIV measurements of the flow fields at $Re =$ 10,000 are performed at H/D_e= 2 and 4 and $a/b =$ 0, 0.8 and 1.15. The results show that the heat transfer enhancement can be attributed to the increased turbulence level in the wall-jet zone at H/D_e= 2 and in the stagnation region at H/D_e= 4.

1. Introduction

Impingement jets, which substantially improve heat transfer rates in the stagnation region, have been widely used for applications such as gas-turbine and aircraft de-icing (Han et al., 2012). To this end, a perforated thin frame constructed with a large number of small nozzles is usually placed inside a considerably limited space to generate an arrayed jet impinging onto a hot surface. These nozzles are mostly featured by circular orifices in terms of the compromise between the heat transfer characteristics and manufacturing cost. However, studies (Koseoglu and Baskaya, 2010; Violato et al., 2012) have established that varying the nozzle geometry alters the flow patterns and then modifies the heat transfer characteristics. Therefore, an exploration of an economical geometrical variation strategy with effective heat transfer intensification is highly desirable.

A literature survey shows that various experimental efforts have been sought to improve the jet impingement heat transfer by changing the nozzle geometry. Lee and Lee (2000a) proposed an elliptic nozzle to increase the stagnation heat transfer rate in the case of a nozzle-to-wall distance smaller than the potential core length of a jet. This heat transfer augmentation in the stagnation region results from the enhanced turbulent kinetic energy along the jet centreline due to the different spreading rates along the major and minor axis planes. Subsequently, Lee and Lee (2000b) measured the impingement heat transfer of a sharp-edged orifice jet at $H/D =$ 2–6; the results showed a significantly high heat transfer rate in the stagnation region when compared with that observed in the cases of standard- and square-edged orifice jets. By chamfering the nozzle inlet, Brignoni and Garimella (2000) demonstrated a substantial reduction in the pressure drop, while the average heat transfer coefficient was not strongly affected when compared with that in the case of a square-edged nozzle. As for the chevron nozzle, an infrared thermography measurement by Violato

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Nomenclature

A	area of the heated surface
A_0	area of the nozzle cross-section
a	orifice centre offset
b	orifice radius
D_e	nozzle's equivalent diameter ($= \sqrt{\frac{4A_0}{\pi}}$)
d_p	black paint thickness
f_T	TSP calibration function
H	nozzle-to-wall distance
I	light intensity of the images
I_R	light intensity ratio
k	two-dimensional turbulent kinetic energy
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
T_0	reference (room) temperature
T_w	wall temperature
U_0	mean (bulk) axial velocity at the nozzle exit
x	coordinate
y	coordinate
z	coordinate
Bi	Biot number ($= \frac{d_p h}{\lambda_p}$)
Nu	Nusselt number ($= \frac{(q_w - q_r - q_c)D_e}{\lambda A(T_w - T_0)}$)
$\overline{Nu}$	mean Nusselt number
Re	Reynolds number ($= \frac{U_0 D_e}{\upsilon}$)

Greek symbols

λ	air conductivity
λ_p	black paint conductivity

Abbreviations

PIV	particle image velocimetry
TSP	temperature-sensitive paint

et al. (2012) showed that this nozzle exhibited better performance in impingement heat transfer than a circular one; a particle image velocimetry measurement of the flow field attributed this improved performance to the development of stream-wise vortices associated with a deep penetration of turbulence-induced mixing. Subsequent measurements by Vinze et al. (2016) revealed that the mean Nusselt number increased with an increase in the number of chevrons for a given chevron angle, as well as an increase in the tip angle for a given number of chevrons. However, for the perforated thin frame, these geometrical variations of small holes (usually less than 1 mm in practice) pose a challenging issue in the manufacturing process. As for free jets using lobed nozzles, early studies revealed a pair of large-scale stream-wise vortices at each lobe crest (Fig. 1(a)), dominating the jets' spreading and mixing processes (Hu et al., 2000); the lobe troughs (Fig. 1(a)) served as mixing tabs in the shear layers of the jets, which generated counter-rotating stream-wise vortex pairs shed from each tab and then dramatically increased the thickness of the mixing layer (Samimy et al., 1993). Such flow behaviour, when it occurs in the impingement jet, activates a considerably favourable heat removal mechanism (Sodjavi et al., 2016), as demonstrated by infrared thermography measurements by Martin and Buchlin (2011). However, the impingement flow and heat transfer of a lobed nozzle have not been studied sufficiently as yet.

The present study is focused on the jet impingement heat transfer and flow quantities of a lobed nozzle, and uses complementary techniques of temperature-sensitive paint (TSP) and planar particle image velocimetry (PIV). Here, the lobed nozzle is constructed by three circular orifices (Martin and Buchlin, 2011), and the effects of the geometrical variations are compared by varying the ratio of the orifice centre offset to the orifice radius, i.e., $a/b =$ 0, 0.5, 0.8, 1.0, 1.1 and 1.15 (as shown in Fig. 1(a)), at a constant equivalent diameter D_e for all of the configurations to ensure a constant cross-section area of the nozzles. The configuration with $a/b =$ 0 is in fact a large circular orifice of diameter D_e and is considered as the benchmark configuration. In the experiments, TSP measurements are performed at Reynolds numbers $Re =$ 10,000 and 40,000 and nozzle-to-wall distances of H/D_e= 2, 4 and 6 for different configuration a/b values, quantifying the spatial distribution of the mean Nusselt number. Finally, the PIV measurements of the flow fields are performed at two different distances H/D_e= 2 and 4 for three configurations, i.e., $a/b =$ 0 (circular nozzle), 0.8 and 1.15. The distinctly different distributions of the flow quantities are clarified to reveal the underlying mechanism of the intensified impingement heat transfer.

2. Experimental apparatus and method

2.1. Impingement plate and flow configurations

In the TSP measurement, the impingement wall is constructed using a piece of fluorine-doped tin oxide (FTO)-coated glass of size 200 × 300 mm. The FTO glass is a type of heat-resistant glass with a thickness of 0.4 mm, which is coated with a 200-nm-thick FTO layer on one side (the front side as shown in Fig. 1(b)) forming a square resistance of 10 Ω. As shown in Fig. 1(b), two copper-foil strip electrodes are attached to both ends of the FTO glass on the front side to establish good electrical contact. The copper electrodes are then connected to a 100-W direct-current (DC) power supply. With the DC electric current flowing through the FTO layer, an essentially uniform wall heat flux boundary condition is established on the front side of the FTO glass. The wall temperature of the heated surface is measured by TSP, which is air-sprayed on the front side of the FTO glass above the FTO layer. To prevent the background light, which is mainly generated by the reflection from the nozzle, from passing through the transparent FTP glass, a very thin layer of black paint is sprayed onto the TSP layer. To minimize the heat transfer from the rear side of the heated wall, a 20-mm-thick Plexiglas plate is attached to the rear of the FTO glass. A 500-mm-long pipe with an inner diameter of 28 mm and the jet nozzle are installed on the right-hand side as shown in the figure, forming the jet impingement on the front side of the FTO glass. The wall-normal position of the nozzle is accurately controlled with a precision of 0.01 mm by using a traverse mechanism. The jet fluid is air and is supplied by a fan, while the flow rate is calibrated using a Pitot tube.

The nozzle geometries tested in the heat transfer experiment are shown in Fig. 1(a). The nozzle orifice has an equivalent diameter of $D_e =$ 14 mm and a rather small orifice length ($0.14D_e$). The pipe diameter ($2D_e$) and length (500 mm) are selected so as to have no effect on the velocity distribution in the orifice. Precursor Reynolds-averaged Navier–Stokes simulations using a considerably long pipe to provide the fully developed velocity distribution, or a relatively large diameter to provide uniform velocity upstream the nozzle, showed no effect on the velocity distribution at the orifice exit. The lobed nozzles are formed using three smaller circular orifices with the nozzle parameter, i.e., the ratio of the orifice centre offset to the orifice radius, $a/b =$ 0 (circular nozzle), 0.5, 0.8, 1.0, 1.1 and 1.15, at a constant equivalent diameter D_e for all nozzle configurations to ensure a constant cross-section area of the nozzles. The Reynolds number of the impinging jet based on the bulk velocity at the nozzle exit U_0 and the nozzle's equivalent diameter D_e is $Re =$ 10,000 and 40,000. Measurements are performed at the