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The effect of nozzle geometry on local convective heat transfer to unconfined impinging air jets

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ABSTRACT

In an impinging jet, nozzle geometry markedly impacts heat transfer between jet and plate by affecting the velocity profile at the jet exit and thereby potentially modifying the behavior of the jet's vortex structures. This study analyzed the influence of three different injections: a tube used as a reference, a round orifice, and a cross-shaped orifice perforated on a hemispherical surface. They all possess the same free area A_o, and the equivalent diameter is $D = 14$ mm. Experiments have been conducted for Reynolds numbers $23{,}000 \leqslant Re \leqslant 45{,}000$, for orifice-to-plate distances $1 \leqslant H/D \leqslant 5$ and for the temperature of the jet $T_\infty \leqslant T_j \leqslant 50\,^{\circ}$C. Aerodynamic results indicate that the hemisphere produces a "vena contracta" effect, which is greater in the round than in the cross-shaped orifice. The velocity profile at the jet exit ($X/D = 0.1$) presents a parabolic shape for the tube and an inverted parabolic shape for the round orifice, while the presence of two shear layers renders the cross-shaped orifice more complex and three-dimensional. Thermal results also show that a round orifice on the hemisphere causes higher heat transfer rate than the other injections.

1. Introduction

Impinging jets are well-known as an efficient way to improve heat transfer mechanisms. They are widely used in industry, particularly in manufacturing processes for cooling, heating or drying. The influence of nozzle geometry on heat transfer has been extensively studied in the literature on impinging jets. Moreover, attempts have been made to improve impingement heat transfer by changing the nozzle configuration, especially with regard to the velocity profile and turbulence levels at the nozzle exit. Taking into account the generation of vortices as well as ambient fluid entrainment, the flow structure produced by different nozzle geometries can be highly complex.

Reviews by Martin [1], Popiel and Trass [2] and Hadziabdic and Hanjalic [3] have investigated the effect of impingement jet on flat surface in terms of aerodynamics and heat transfer. They show that an impinging jet can be divided into three zones: a free jet, a stagnation zone and a wall jet zone. The free jet consists of a potential core and a shear layer. A number of authors have investigated the latter and observed regular vortex structures, such as primary vortex rings and secondary vortex rings in the wall jet zone.

In addition, heat transfer distribution has been studied [4–10] as regards tube or convergent injection. For low orifice-to-plate distances ($H/D < 4$), previous studies [4–7] showed that the heat transfer rate was maximum at the stagnation point. Conversely, other studies [8–10] showed that the heat transfer rate was actually minimum at the stagnation point and the primary peak was found to be $r/D \approx 0.5$. Lytle and Webb [9] attributed this phenomenon to a significant increase in turbulence, while Saad et al. [12], Rohlfs et al. [13] and Roux et al. [14] ascribed it to specific inlet velocity profiles. More specifically, the primary peak was determined as concerns a uniform velocity profile (for convergent injection). In the parabolic profile (due to tube injection), the maximum level is located at the impinging point. A different heat transfer peak, which can be called the "secondary peak", had previously been detected from $r/D = 1.2$ [9] to $r/D = 2.1$ [5,11], and is probably due to a laminar-turbulent transition of the boundary layer [11] or to a sudden increase in local velocity fluctuations [7–9,14]. Hadziabdic and Hanjalic [3] explained the local velocity fluctuations by pointing out the interaction of shear layer vortices with the impingement plate.

A few studies have explored the effect of nozzle geometry on the impinging jet. More precisely, the influence of non-round injection geometry such as lobed nozzles and cross-shaped orifice on heat transfer has been investigated. Herrero Martin and Buchlin [15] compared heat transfer between three-lobe geometry, four-lobe geometry and a circular jet and showed that while three-lobe geometry provides better heat transfer rate for $H/D \leqslant 1$, four-lobe geometry affords optimal heat transfer for $H/D > 7$. Kristiawan

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Nomenclature

A_o	free injection area (m^2)
D	injection diameter (m)
H	jet exit to impingement plate distance (m)
e	impingement plate thickness (m)
x	axial coordinate (m)
r	radial coordinate (m)
$\dot{q}$	mass flow rate (kg s^{-1})
u_o	injection outlet velocity ($u_o = \dot{q}/(\rho_{air}A_o)$ (m s^{-1})
u_x	axial velocity (m s^{-1})
u_r	radial velocity (m s^{-1})
u_x^{rms}	RMS axial velocity (m s^{-1})
u_r^{rms}	RMS radial velocity (m s^{-1})
$h_{conv,f}$	heat transfer coefficient on the front side of the impinged plate (W m^{-2} K^{-1})
h_r	heat transfer on rear side (W m^{-2} K^{-1})
Nu	Nusselt number ($Nu = h_{conv,f}D/\lambda_{air}$) (–)
$\overline{Nu}(6D)$	averaged Nusselt number between $r = 0$ and $r = 6D$ (–)
Re	Reynolds number ($Re = \rho u_o D/\mu$) (–)
St	Strouhal number ($St = fD/u_o$) (–)
T_w	impinging side wall temperature (K)
T_{wa}	adiabatic wall temperature (K)
T_j	injection jet temperature (K)
T_∞	ambient temperature (K)
t	time (s)
RMS	squared root of the mean squared deviation (–)

Greek symbols

ε_w	impinged plate emissivity (–)
λ_w	impinged plate thermal conductivity (W m^{-1} K^{-1})
λ_{air}	air thermal conductivity (W m^{-1} K^{-1})
ρ_{air}	air density (kg m^{-3})
μ_{air}	air dynamic viscosity (N s m^{-2})
η	effectiveness $= (T_{wa} - T_\infty)/(T_j - T_\infty)$ (–)
$\bar{\eta}$	averaged effectiveness (–)
φ_{elec}	electrical flux density dissipated by Joule effect (W m^{-2})
$\varphi_{conv,f}$	convective heat flux density on the front side (W m^{-2})
$\varphi_{conv,r}$	convective heat flux density on the rear side (W m^{-2})
$\varphi_{rad,f}$	radiative heat flux density on the front side (W m^{-2})
$\varphi_{rad,r}$	radiative heat flux density on the rear side (W m^{-2})
θ	angle (degree)

et al. [16] studied mass transfer rate between a circular convergent nozzle and a plane cross-shaped orifice nozzle for a Reynolds number 5500 and jet-to-plate distances ranging from 1 to 5. They concluded that the mass transfer rate in the impingement region of the cross-shaped nozzle is 40% higher than in the impingement region of the convergent nozzle. Meslem et al. [17] investigated mass transfer between a convergent nozzle and a plane circular orifice nozzle for a Reynolds number 1360 and jet-to-plate distances ranging from 1 to 5. They observed that the mass transfer of an orifice impinging jet on a flat plate is 18% higher than is the case with a convergent nozzle jet. Violato et al. [18] compared heat transfer between chevron jet and circular jet with a range of jet-to-plate distances $2 < H/D < 10$ and with a Reynolds number equal to 5000. They concluded that heat transfer is improved with the chevron nozzle. In the center of the impinged area, the latter yields heat transfer values higher than those provided by the circular jet for all jet-to-plate distances, with a maximum improvement up to 44% at the stagnation point for $H/D = 4$. The lobed orifices (cross-shaped, chevron) seem to heighten the heat transfer rate by increasing the vorticity of the jet; that said, most of the just-cited studies involve low Reynolds number.

Orifice geometry on a hemispherical surface has not been widely studied. As far as we know, hot jets issuing from the latter have never been investigated. In this paper, we shall study the effect of two different orifice injections (one of them round and the other cross-shaped, both on a hemispherical surface) on flow structure and heat transfer and compare the results with those recorded using a tube case. The three injections – tube, round orifice and cross-shaped orifice – have the same free area A_o and the diameter of tube is $D = 14$ mm. The round orifice and the cross-shaped orifice were perforated on a hemispherical surface (Fig. 3) and screwed on a tube with a diameter of 30 mm. Both flow and heat transfer will be studied using two respective methods: high speed particle image velocimetry (HS-PIV) and infrared thermography. Study was carried out for Reynolds numbers $23{,}000 \leqslant Re \leqslant 45{,}000$, for $1 \leqslant H/D \leqslant 5$ and for $T_\infty \leqslant T_j \leqslant 50\,^\circ C$.

2. Experimental setup

The experimental apparatus is presented in detail in Fig. 1. Air flow is assured by a compressed air system through a valve. Mass flow rate is supplied by an adjustable pressure regulator coupled to a sonic throat. The flow passes through an electric heater to ensure the desired injection temperature, and is then expanded to measure jet total temperature as it goes through a plenum chamber. As injection velocity values are relatively low (24.5 m s^{-1}), the jet total temperature is nearly equal to the static one. Consequently, in the rest of the article, we will use the term "jet temperature". Originating in an injection, it goes directly to an impingement plate, which is located at a distance H (Fig. 2) from the injection and placed perpendicularly to the jet axis.

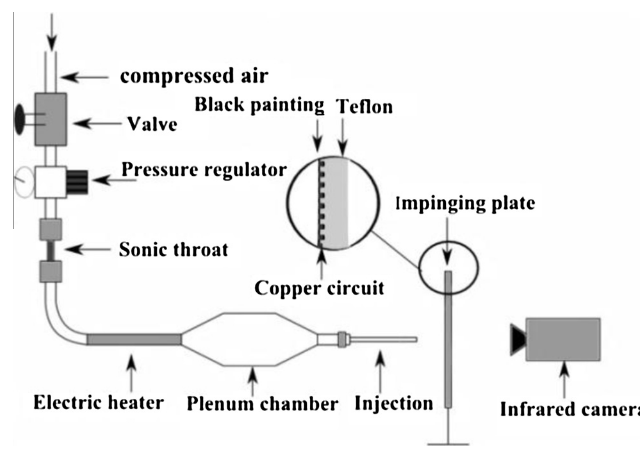

Fig. 1. The experimental apparatus.

The impinged plate depends on the measurement type. The plate used for thermal measurements is made of Teflon (thermal conductivity $\lambda_w = 0.296 \pm 0.05$ W m^{-1} K^{-1}) with a thickness of 1.6 mm. Its impinged side is covered with thin copper foil with a thickness of 35 μm. Two electrical circuits are engraved in this copper foil. They are linked to a DC supply and it is consequently possible to heat the plate by Joule effect. The circuit is spiral-shaped. The impingement plate is painted in black (front and rear side) for the purposes of the high uniform emissivity ($\varepsilon_w = 0.95$) needed to accurately calculate radiative heat flux and for thermographic measurements. An infrared "FLIR titanium" camera is positioned behind the impingement plate at a distance of 1.5 m to measure the rear side temperature of the plate.