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Flow and heat transfer of hot impinging jets issuing from lobed nozzles

X.T. Trinh, M. Fénot*, E. Dorignac

Institut Pprime, UPR 3346, CNRS, ENSMA, Université de Poitiers, Téléport 2, Bd Marie et Pierre Curie BP 30179, Futuroscope, 86962 Poitiers, France

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ABSTRACT

This article studies the aerodynamic and thermal characteristics of impinging jets issued from lobed injections. They are compared to "traditional" jets issuing from tube. All nozzles have the same free area A_o, and the equivalent diameter for a tube is $D = 14$ mm. Experiments have been conducted for injection Reynolds numbers from 23,000 to 45,000, for orifice-to-plate distances from $H/D = 1–5$ and for an injection jet temperature: $T_\infty \leq T_j \leq 50$ °C. Flow measurement has shown very specific tridimensional flows particularly for small injection-to-plate spacing ($H/D = 1$ or 2) and resulting heat transfer rates are very different from those of a jet issuing from a tube. For higher impinging distances, flows and heat transfer become more axisymmetric and more similar to those due to tubular injection.

1. Introduction

Impinging jet flow and heat transfer have been extensively studied as recorded by Martin (1977), Jambunathan et al. (1992), Viskanta (1993) and, more recently, by Zuckerman and Lior (2006) in their reviews. The abundant literature is to some extent due to the complex flow structure of an impinging jet and to the numerous influence parameters, but the main reason is its frequent use in a wide range of industrial applications including glass production, drying of textile and metal, cooling of electronic components, heat exchangers and turbo-machinery cooling. Consequently, many recent studies (Lei et al., 2014; Ahmed et al., 2016; Vadiraj and Prabhu, 2008) have focused on improving jet heat transfer rate by modifying its flow.

Basically, round impinging jet flow structure is divided into three regions as recorded by Viskanta (1993) and Zuckerman and Lior (2006). Figs. 1 and 2 present the velocity fields of jets issuing from a long tube for two dimensionless injection-to-plate distances: $H/D = 1$ and 5. The jet presented in these figures will serve as a reference case for the present study. In the first region, as it is flowing from the injection, the jet is not yet affected by the plate. It could be considered as a free jet with a potential core surrounded by a shear layer. The potential core is the central part of the jet, with high mean axial velocity values and relatively low root mean square values (RMS). If the injection-to-plate distance is sufficient, the potential core length is between 4 diameters and 6 diameters (Gauntner et al., 1970; Sparrow et al., 1975). According to Fig. 1, the potential core length is equal to 4 diameters (4D). The high RMS value region is the surrounding shear layer. High RMS values are principally due to roll–up vortices, which are created near the nozzle lip by instability waves. Closer to the impinging wall, the jet is affected by their presence and the "free jet" zone is replaced by the stagnation zone, which is characterized by pressure gradients that stop the flow in the axial direction and turn it radially outward. Finally, in the third zone, the wall jet (for $r/D > 1.5$ in Figs. 1 and 2), the flow decelerates. Vortices of the "free jet" shear layer are deflected and roll along the impinging plate. For small injection-to-plate distance (in Fig. 1 for example), shear layer vortices pass close to the impingement wall and interact with it, thereby creating a high RMS value region (for $r/D \approx 1.5$).

Resulting heat transfer rate may vary from one author to another due to the large number of influence parameters. As regards a jet issuing from a round injection, heat transfer variation is globally similar and examples of Nusselt number (Nu) variation for a jet issuing from a tube can be observed in Fig. 3. Maximum heat transfer rate is situated at the impinging point (Goldstein and Behbahani, 1982). According to Baughn and Shimizu (1989), the highest value is reached for $H/D = 6$, and it seems to coincide with the end of the free jet potential core. After that, Nusselt number decreases with increasing distance from the impinging

Abbreviations: 6L, Relative to six-lobe injection; 4L, Relative to four-lobe injection; MP, Major plane (see figure 1d and figure 9); mP, Minor plane (see figure 1d and figure 9); RMS, Root mean square.

* Corresponding author.
E-mail address: matthieu.fenot@ensma.fr (M. Fénot).

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Nomenclature

A_o	Free injection area
D	Jet Diameter (m)
H	Jet exit to impingement plate distance (m)
e	Impingement plate thickness (m)
h	Heat transfer coefficient on impinged side of the impinged plate (Wm^{-2} K^{-1})
Nu	Nusselt number = hD/λ_{air}
$\overline{Nu}$	Azimuthally averaged Nusselt number
$\overline{Nu}(6D)$	Averaged Nusselt number between r = 0 and r = 6D
Re	Injection Reynolds number = $\rho u_0 D/\mu$
T_j	Injection jet temperature (K)
T_{aw}	Adiabatic wall temperature (K)
T_w	Impinging side wall temperature (K)
T_∞	Ambient temperature (K)
r,θ,X	Cylindrical coordinates (m)
u_r,u_θ,u_x	Mean velocities in the cylindrical system (ms^{-1})
u_r^{rms}, u_θ^{rms}, u_x^{rms}	Root mean square velocities in the cylindrical system (ms^{-1})
u_o	Injection mean flow rate velocity (ms^{-1})

Greek symbols

ε_w	Impinged plate emissivity
η	Effectiveness = $(T_{aw}-T_\infty)/(T_j-T_\infty)$
λ_{air}	Air thermal conductivity (Wm^{-1} K^{-1})
λ_w	Impinged plate thermal conductivity (Wm^{-1} K^{-1})
μ_{air}	Air dynamic viscosity (Nsm^{-2})
ρ_{air}	Air density (kgm^{-3})
σ	Stefan-Boltzmann constant = 5.67×10^{-8} (Wm^{-2} K^{-4})
φ_{comv}	Convective heat flux density on the impinged side (Wm^{-2})
$\varphi_{conv\ r}$	Convective heat flux density on the rear side (Wm^{-2})
φ_{elec}	Electrical flux density dissipated by Joule effect (Wm^{-2})
$\varphi_{rad,f}$	Radiative heat flux density on the impinged side (Wm^{-2})
$\varphi_{rad\ r}$	Radiative heat flux density on the rear side (Wm^{-2})

point. For small injection-to-plate spacing (Figs. 11c and 18c, however, a local maximum could be present for r/D ≈ 2 as noted by Jambunathan et al. (1992) or Baughn and Shimizu (1989). Several explanations have been proposed, such as transition to turbulent boundary layer and extremum of energy separation in the shear layer vortices (Goldstein et al., 1986). Nevertheless, most of the authors link this local maximum to the interaction of shear layer vortices with the impinging wall (Hadžiabdić and Hanjalić, 2008). The local maximum amplitude decreases with increasing H/D. In Fig. 23c, it is barely visible, and it is no longer recorded for H/D > 6 (Baughn and Shimizu, 1989).

Over the past few years, this basic configuration has been largely modified for the purpose of increasing heat transfer rate. To this end, authors have tried to modify the impingement plate by adding ribs (Katti and Prabhu, 2008) or "dimples" (Ekkad and Kontrovitz, 2002). Others have modified the injection flow by pulsating the jet (Sailor et al., 1999; Roux et al., 2014).

One of the most efficient modifications seems to consist in nozzle shape change. Indeed, minor modification of the injection shape could have important effects on both jet flow and heat transfer. Roux et al. (2011) have shown that changing from a convergent nozzle (flat velocity profile) to a tubular nozzle maximal (velocity at the center) causes a heat transfer increase of up to 20%. Moreover, chamfering of the nozzle also has an influence (Attalla and Salem, 2013; Brignoni and Garimella, 2000). Attalla et al. have shown that the chamfering of a long tube injection can affect Nusselt number values (≈9–10%).

More drastic changes in the nozzle shape can more significantly affect the flow and resulting heat transfer. Meena et al. (2016) have tested four different injection shapes (round, square, triangle and ellipse) and noticed differences of Nusselt number values up to 30%. Influence of the injection is particularly strong in the vicinity of the impingement point and Meena et al. (2016) explain those differences by the modification of the jet vortices. With this in mind, several authors have tried to specifically affect those vortices by using chevron nozzles, cross-shaped orifices or lobed injections.

Several different lobed nozzle configurations have been tested. Some use planar injection (Rau and Garimella, 2014; Kristiawan et al., 2012; Martin and Buchlin, 2011; Gao et al., 2003), while others are tridimensional (Violato et al., 2012). Moreover, injection Reynolds number values seem to have a major influence over the heat transfer resulting from the impingement of such jets. For relatively low Reynolds number (<5000), Violato et al. (2012) have observed that a chevron nozzle increases the heat transfer rate up to 44% compared to a round injection. Nozzle influence is particularly effective near the impinging point and for low injection to plate spacing. The authors attribute this to a deeper penetration of turbulence induced by greater mixing and to higher arrival speed. Similar conclusions are presented by Rau and Garimella (2014) for a planar cross-shaped orifice with small Reynolds number. Kristiawan et al. (2012) have investigated flow and mass transfer of a jet issuing from a cross-shaped orifice for $Re_j = 5500$. Their results are consistent with those of Violato and Rau: a mass transfer increase (up to 175% locally). Flow measurement seems to link these local high transfers to an increase of turbulent kinetic energy due to streamwise structures and to Kelvin-Helmholtz vortices. Moreover, Kristiawan's results show higher ambient fluid entrainment into the jet for the cross-shaped orifice.

For higher Reynolds number values (10,000 to 50,000), the influence of "chevrons" over heat transfer is reduced (Gao et al., 2003) and could even degrade the heat transfer rate (Martin and Buchlin, 2011). Major effects are generally situated in the impingement region. Unfortunately, studies with high injection Reynolds number values are essentially thermal studies and few flow measurements are available to explain heat transfer rate variation.

For these reasons, the present study aims at providing both experimental flow and heat transfer results for various lobed orifices Fig. 4c. Two different orifice patterns are investigated: one with four lobes (cross-shaped) and the other with six lobes. Each of these patterns has been engraved on a flat surface. All of the orifices have been positioned at the end of a long tube. While several injection Reynolds number values have been tested from 23,000 to 35,000, we have chosen to focus on $Re_j = 23{,}000$ as it is the most frequently studied injection Reynolds number value (both experimentally and numerically) and because flow and heat transfer variation are very similar for the whole Re range. As some authors (Kristiawan et al., 2012) have mentioned specific jet entrainment effect, we have decided to study a hot jet ($T_j = 50$ °C) expanding in colder ambient air ($T_\infty \approx 20$ °C). Both Nusselt number and efficiency have been measured to characterize heat transfer. Finally, considering the crossed influence of injection shape and injection-to-plate distance observed by different authors (Kristiawan et al., 2012; Martin and Buchlin, 2011), measurements have been conducted for $1 \le H/D \le 5$. As tubular injection is the most widely