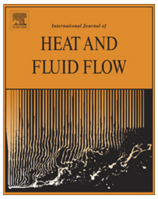
International Journal of Heat and Fluid Flow 53 (2015) 167–182

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff



Experimental investigation on an axisymmetric turbulent jet impinging on a concave surface

A. Hashiehbaf[a], A. Baramade[b], Amit Agrawal[b,*], G.P. Romano[a]

[a] Department of Mechanical and Aerospace Engineering, La Sapienza University, via Eudossiana n18, 00184 Rome, Italy
[b] Department of Mechanical Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 13 July 2014
Received in revised form 18 March 2015
Accepted 19 March 2015
Available online 15 April 2015

Keywords:
Impinging jet
Turbulent axisymmetric jet
Concave surface
Particle image velocimetry
Linear stochastic estimation

ABSTRACT

An experimental study of an axisymmetric turbulent jet impinging on a semi-cylindrical concave surface is carried out using Particle Image Velocimetry (PIV). The measurements are performed on two orthogonal planes: parallel and perpendicular to the axis of the cylinder. The study is focused on the impinging jet, the generated wall jet and on the boundary layer developing on the cylinder surface. Linear stochastic estimation is applied for identifying the dominant structures in the flow and coupling then with other relevant parameters as the peak *r.m.s.* velocity of the wall jet to estimate secondary peak in Nusselt number distribution along the wall. Measurements are performed for two different surface curvatures and four nozzle to target distances (L/d ratio) at a Reynolds number equal to $Re \approx 30,000$. The mean and *r.m.s.* velocity profiles are investigated and the evolution of half-velocity width close to the wall is illustrated for both planes of interest. The results show a strong lateral movement of the flow brought about by the surface geometry for curved surface, especially for large L/d ratios. The *r.m.s.* profiles indicate higher values along the curved surface with respect to the quasi-flat one. The results show the most probable position of secondary peak in the Nusselt number distribution along quasi-flat and curved surfaces to be located at $y/d = 3.2$ and $4.39 < s/d < 5$, respectively. These results can be used toward interpretation of heat and mass transfer aspects on concave surfaces, and are also useful for benchmarking future numerical studies.

1. Introduction

Laminar and turbulent impinging jets are part of industrial devices in various applications such as heating or cooling of electronic devices, turbine blade cover (Tabakoff and Clevenger, 1972; Souris et al., 2004; Chaudhari et al., 2010), drying process and propulsion of vertical-flight aircrafts when in supersonic conditions. In addition, they are employed in short take-off and landing aircrafts, where the high-speed exhaust from the jet engine is deflected by direct impingement on the flaps to create extra lift during take-off. Every impinging jet can be divided into four main flow modules: a free turbulent jet, series of vortices in the curved shear layer, a stagnation flow, and a developing wall jet (Ho and Nosseir, 1981). Each module of the flow has its own distinctive characteristics, making the physics of the impinging jet quite complicated. Jets impinging on flat surfaces have been studied extensively by previous researchers (Cooper et al., 1993; Katti and Prabhu, 2008; Anwarullah et al., 2012). Recently, the study of jets impinging onto curved surfaces has grown rapidly due to its important applications mentioned above and also for improving the heat transfer coefficient on walls (Hrycaka, 1981; Brahma et al., 1990; Royne and Dey, 2006; Eren et al., 2006).

Indeed, most of the available literature data regarding such jets is devoted to studying the heat transfer phenomenon rather than the flow behavior alone, especially for jets impinging over curved surfaces. For example, in a work by Chan et al. (2002), the heat transfer and fluid flow characteristics of the impinging jet on a convex surface were investigated recovering a correlation between the position of second peak in Nusselt number distribution ($Nu_s = hd/k = q/\Delta T \times d/k$) and position of transition from laminar to turbulent flow. It was also shown that the transition to turbulence is anticipated by increasing the Reynolds number and no secondary peak was observed in Nusselt number distribution for $L/d > 8$ due to turbulent effects in the stagnation region.

Cornaro et al. (1999) visualized the impingement of a round jet issuing from a pipe on convex and concave surfaces using smoke visualization technique for high relative curvature values (up to $d/D = 0.38$). They showed that if the nozzle to surface distance is

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* Corresponding author. Tel.: +91 (22)2576 7516; fax: +91 (22)2572 6875.
E-mail addresses: amit.agrawal@iitb.ac.in, aagrawal.iitb@gmail.com (A. Agrawal).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.03.003
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Nomenclature

d	circular nozzle inlet diameter (m)
D	radius of curved surface (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity
L	axial distance from jet to surface (m)
q	heat flux (W)
r	coordinate normal to the curved surface (m)
$r_{0.5}$	wall jet half-velocity width for curved plate (m)
s	coordinate along the curved surface (m)
t	semi-cylinder surface thickness (mm)
ΔT	temperature difference between the wall and jet temperature (K)
U_0	nozzle exit velocity (m/s)
U_{cl}	velocity at the centerline of the jet (m/s)
U_r	time-averaged radial velocity for curved surface (m/s)
U_θ	time-averaged tangential velocity for curved surface (m/s)
U	time-averaged streamwise velocity for quasi-flat surface (m/s)
V	time-averaged crosswise velocity for quasi-flat surface (m/s)
$U_{r.m.s.}$	root mean square of streamwise velocity for quasi-flat surface (m/s)
$U_{r.m.s.r}$	root mean square of radial velocity for curved surface (m/s)
$U_{r.m.s.\theta}$	root mean square of tangential velocity for curved surface (m/s)
$UV_{r.m.s.}$	Reynolds shear stress for quasi-flat surface (m^2/s^2)
$(U_rU_\theta)_{r.m.s.}$	Reynolds shear stress for curved surface (m^2/s^2)
U_{ym}	maximum crosswise velocity on a characteristic line (m/s)
$U_{y\theta}$	maximum tangential velocity on a characteristic line (m/s)
$V_{r.m.s.}$	root mean square of crosswise velocity for quasi-flat surface (m/s)
X	coordinate normal to the flat surface
$X_{0.5}$	wall jet half-velocity width for quasi-flat plate (m)
Y	coordinate along the quasi-flat surface
Z	coordinate along the quasi-flat surface

less than the potential core length, coherent vortices appear on the curved surface. However, for cases larger than potential core length, no vortex structure is formed in the upstream due to the strong radial oscillation of the stagnation point. They also showed that at $L/D = 4$ and $L/D = 1$, the effect of curvature is diminished owing to strong radial oscillation at the jet impingement region for $L/D = 4$ and to the strong axial oscillation of the flow at the surface for $L/D = 1$, where L/D is the non-dimensional distance of the jet from the plate. The surface curvature effect on the impinging flow structure and the heat transfer along a concave and a convex surface has also been investigated experimentally by Gau and Chung (1991). They found that increase of surface curvature can increase the size of the counter rotating vortices, which results in further increase of the stagnation point Nusselt number. They also found that the flow structure in the region far away from the stagnation point is turbulent. Yang et al. (1999) studied the effect of orifice shape like round nozzle, rectangular and 2*D* contoured nozzle on the ensuing flow field characteristics. They showed that the distance at which the peak stagnation point Nusselt number occurs approximately corresponds to the location of the maximum turbulence intensity of a free jet for round shaped and 1*D* contoured nozzle but not for the rectangular nozzle. They further concluded that the effect of curvature becomes more prominent as the Reynolds number increases. Chan et al. (2003) investigated the fluid flow characteristics of flow over a convex plate. They realized that the radial location in the wall jet region where the normalized streamwise *r.m.s.* velocity is maximum decreases as s/d (the non-dimensional circumferential distance from the stagnation point) increases. A similar pattern was also observed for the Reynolds shear stress. They also showed that with respect to the cross-stream *r.m.s.* velocity, the streamwise one is more strongly affected by the dimensionless parameters: d/D, L/d and s/d in the near wall region. It was also found that the Reynolds shear stress is rather sensitive to the surface curvature. Gilard and Brizzi (2005) undertook PIV investigations for a flow impinging into a curved surface only for relatively low Reynolds numbers ($Re < 6500$). They observed three stable modes depending on the Reynolds number in the range $500 < Re < 6400$: one impacting the lower part of the wall, another the upper part and the last one at the center of the wall. Therefore, for small curvatures, a triangular region exists close to the stagnation point with very low velocities. It should be noted that this region will not exist for higher Reynolds number as reported in the current paper. Therefore, the focus of the current study is characterizing the jet fluid flow impinging on curved surfaces using PIV method to estimate the position of secondary peak in circumferential Nusselt number solely based on the turbulence characteristics of the flow. To the best of our knowledge, there is no literature data available on the detailed fluid flow characteristics of high Reynolds number jets impinging on both planes of concave surfaces.

Turbulence statistics of flow inside the semi-cylinder are also discussed in detail. These data are then employed to estimate the position of secondary peak in Nusselt number distribution along the curved and quasi-flat part of the cylinder.

2. Experimental setup

A schematic view of the experimental setup is shown in Fig. 1. A centrifugal pump is used to carry water from a feed tank through a long pipe (length = 2 m) and discharging into a test chamber ($525 \times 460 \times 300$ mm^3) through a straight pipe nozzle (diameter = 11 mm, length = 225 mm). The ratio between the length of the pipe and the nozzle outer diameter is selected high enough to produce fully developed turbulent flow at the exit of the pipe. The flow rate is adjusted by opening or closing the control valves which during the experiment is kept at $Re \approx 30,000$. The overflow water from the test chamber discharges into a small tank and then by a recirculating pump to the feed tank. The levels in both the water tanks are kept constant during the experiments and the curved plate is mounted opposite to the jet and the center of the curved plate is along the same line as the nozzle centerline.

The entire test section is made of Plexiglas to allow optical access. The flow is seeded by hollow glass particles, 8–12 μm in diameter, and illuminated by twin Nd:YAG pulsed lasers (200 mJ per pulse, 532 nm wavelength) sheet with 2 mm thickness (Sewatkar et al. 2012). The images are acquired by a CCD camera with 1392×1024 pixels resolution at 1 Hz such that successive frames are statistically independent. The measurements are performed typically for four different nozzle to target distances ($L/d = 1$, 2, 4 and 6) and images are captured at two different illuminated planes: one perpendicular to the axis of the cylinder