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Influence of the orifice shape on the local heat transfer distribution and axis switching by compressible jets impinging on flat surface

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A B S T R A C T

An experimental investigation is performed to study the effects of the orifice shape and Mach number (M) on the local heat transfer distribution by normally impinging compressible jets. Four different orifice cross-sections namely circular, elliptical, square and triangular are used and jets Mach number is maintained from 0.4 to 1in present study. The heat transfer is measured by thin foil IR technique for different nozzle to plate distances. To calculated Nusselt number, adiabatic wall temperature is used as a reference temperature. The stagnation point Nusselt number is significantly higher for circular orifice as compared to other three shapes while that for the elliptical orifice is minimum. Recovery factor distribution is independent of the Reynolds number and the Mach number. The square, triangular and elliptical orifice respectively undergoes a 45°, 180° and 90° axis switching.

1. Introduction

Impinging jets have received considerable attention due to their inherent characteristics of high rates of heat transfer coupled with their simple geometry. Impinging jets are used in several applications like preheating of steel billets, preheating of glass in manufacturing industries, drying of paper and fabric, cooling of electronics components and in food processing industries etc. Heat transfer rates in case of impinging jets are affected by various parameters like Mach Number, jet to plate spacing, radial distance from stagnation point, Prandtl number, target plate inclination, confinement of the jet, nozzle geometry, curvature of target plate, roughness of the target plate and turbulence intensity at the exit of the orifice.

Many prior studies on jet impingement reported experimental and numerical results for heat transfer influence by parameters like nozzle profile, Reynolds number and jets initial condition etc. Livingood and Hrycak [1], Martin [2], Jambunathan et al. [3] and Viskanta [4] reported in detail about various studies carried out earlier in their reviews. Gardon and Cobonpue [5] reported the heat transfer distribution between circular jet and flat plate for the nozzle plate spacing greater than two jet diameters ($z/d < 2$), for single jet and array of jets. Specially designed heat flux gauge were used for the measurement of local heat transfer distribution from a constant wall temperature plate. Lytle and Webb [6] studied the effect of very low nozzle-to-plate spacing ($z/d < 1$) on the local heat transfer distribution over a flat plate impinged by a circular air jet, issued from a long pipe nozzle. It was found that in the acceleration range of the nozzle plate spacing ($z/d < 0.25$), maximum Nusselt number shifts away from the stagnation point to the point of secondary peak, This effect is more pronounced at higher Reynolds number. Lee et al. [7] studied the effect of nozzle diameter on impinging jet heat transfer and fluid flow. They reported that local Nusselt numbers in the region corresponding to $0 \leq r/d \leq 0.5$ will increase with increasing nozzle diameter. Lienhard [8] analyzed heat transfer by impingement of circular free-surface liquid jets and analytical solutions was given for heat transfer in different regions over the target plate. Hofmann et al. [9] performed an experimental investigation on flow structure and heat transfer from a single round jet impinging perpendicularly on a flat plate. They proposed a correlation for local Nusselt number in impinging axisymmetric jets.

Some jet impingement studies investigated the effects of nozzle configuration on the impinging jet heat transfer. Pan et al. [10] Stevens et al. [11] and Lee and Lee [12] studied the effect of nozzle configuration on heat transfer by examining jet impingement and

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Nomenclature

A	Surface area for smooth surface, (m^2)
C_p	Specific heat of air at constant pressure, (kJ/kg K)
d	Equivalent diameter of the orifice, (m)
D	Diameter of supply pipe, (m)
h	Heat transfer coefficient, (W/m^2 K)
h_o	Heat transfer coefficient at the stagnation point, (W/m^2 K)
I	Current, (A)
k	Thermal conductivity of air, (W/m K)
l	Length of pipe, (m)
M	Mach number, $M = \frac{U_j}{\sqrt{\gamma\ R\ T_{js}}}$
Nu	Nusselt number, (hd/k)
Nu_{avg}	Average Nusselt number, over $0 \le r/d \le 2$ over 360°
Pr	Prandtl number, ($\mu C_p/k$)
q_{conv}	Net heat flux convected to the impinging jet, (W/m^2)
q_{joule}	Heat flux, (W/m^2)
q_{loss}	Total heat flux loss from impingement plate, (W/m^2)
$q_{rad(f)}$	Radiation heat loss from the front surface of impingement plate, (W/m^2)
$q_{rad(b)}$	Radiation heat loss from the back surface of impingement plate, (W/m^2)
q_{nat}	Heat loss by natural convection from the back surface of impingement plate, (W/m^2)
R	Recovery Factor, Characteristic gas constant of jet fluid, (kJ/kg K)
r	Radial distance from the stagnation point, (m)
T_d	Dynamic temperature, (°C) $T_d = U_j^2/2C_p$
T_r	Temperature of the target plate at given radial location, (°C)
T_{jo}	Stagnation Fluid temperature at orifice inlet, (°C)
T_{js}	Jet static temperature at orifice inlet, (°C)
T_{aw}	Adiabatic wall temperature, (°C)
T_{jd}	Jet dynamic temperature, (°C)
U_j	Jet exit velocity, (m/s)
V	Voltage across the bus bars, (volts)
z	Orifice plate spacing, (m)

Greek symbols

γ	Specific heat ratio
μ	Dynamic viscosity of air (Pa s)
ρ	Density of air corresponding to supply pressure (kg/m^3)

fluid flow characteristics for unconfined free surface water jet. They reported that due higher turbulence intensity at exit for sharp edge orifice, heat transfer is enhanced around 40% compare to long pipe. And larger mean velocity decay and highest turbulence intensity along the jet axis for sharp edge orifice is also measured. Brignoni and Garimella [13] studied the effect of nozzle inlet chamfering on pressure drop and heat transfer characteristics for confined air jet impingement, choosing nozzle length to diameter ratio of 1.0. They concluded that chamfering the nozzle inlet reduces pressure drops without affecting the heat transfer characteristics much.

Singh et al. [14] reported axial velocity decay, jet spreading and entrainment properties of non-circular jets at a Reynolds number of 7200. Eight different nozzle shapes were used in this study. They concluded that rectangular jet decays 10% faster than the circular jet and entrainment is greater for non-circular jets compared to circular jets. Mi et al. [15], Quinn and Militzer [16], Quinn [17] Vouros et al. [18] Singh et al. [19] and Quinn and Azad [20] reported experimental results for axial velocity decay, turbulence intensity, velocity half width and entrainment for free jets issuing from nine different orifice shapes including circular, triangular(-equilateral and isosceles) and square orifice. Hot wire anemometer and Pitot tube are used to measure velocity and pressure drop in flow fields. Results show that non-circular jet decay faster compared to circular jets and have greater amount of entrainment in jet stream. The equilateral triangle provides maximum amount of entrainment.

Miller et al. [21] and Zhang et al. [22] presented the numerical simulations for jets issued from circular and non-circular nozzles of identical equivalent diameters. Elliptical, rectangular and triangular jets were considered with aspect-ratios of 1:1 and 2:1. The axis-switching phenomenon was captured for all non-unity aspect-ratio jets and also in the equilateral triangular jet. The square jet does not show axis-switching, however the rotation of jets axis by 45° was captured, which plays a significant role in entrainment. Quinn [23], Zaman [24] and Gorman et al. [25] reported mechanism of axis switching by conducting experimental studies for square, rectangular and elliptical free jets. They reported that axis switching is caused by two different flow dynamics mechanisms named as ω_θ and ω_x dynamics. In elliptical free jets, ω_θ dynamics causes jet to switch axis after some nozzle diameter distances from nozzle exit. However, in case of square or rectangular jets, ω_x dynamics causes jet to switch axis for $z/d < 1.25$. The ω_x dynamics is caused by the presence of counter rotating vortex pair at the corners of square or rectangular nozzle exit. The presence of these vortex pairs at the nozzle exit is also reported by Kim and park [26] by conducting numerical simulation for free jets of circular, square and triangular shapes having same equivalent diameter. These counter rotating vortices, as they move away from nozzle exit, grow in volume and move away towards the major axis and then form new pairs of vortices. Fluid between two vortices in a pair moves at four times the velocity of vortex towards major axis. Because of such motion of a vortex pair, the fluid flow profile attains a switch in the jet axis very close to the nozzle exit ($z/d < 1.25$) which is reported by Quinn [23] and Zaman [24].

Influence of noncircular shapes on hest transfer was studied by Zhao et al. [27] numerically for square, elliptic, and rectangular jets. They used the RNG k-ε turbulent model to conduct the impinging jet simulations. It was concluded that for nozzle to plate distance of 6d ($z/d \sim 6$) circular jets provides best heat transfer, while for lower z/d noncircular jets shows better performance. Kanamori et al. [28], Meena et al. [29] and Vinze et al. [30] studied the effect of nozzle shapes on fluid flow and heat transfer for incompressible jets of Reynolds number ranging from 5000 to 50,000. Orifice shapes like triangle, square, pentagon, hexagon and circular are used in these studies. Flow properties like maximum axial velocity decay and turbulence intensity are reported. They observed axis switching for non-circular jets and concluded that the noncircular jet decays faster compared to circular jets.

Kim et al. [31] carried out the experiments to measure recovery temperature for under expanding jets. It is shown that the surface pressure is a function of the under expansion ratio. Due to the presence of shock cell, recovery factor varies from cooling to heating range with the under expansion ratio. Goldstein et al. [32] investigated the radial distribution of the recovery factor and local heat transfer, for Reynolds number ranging from 61,000 to 124,000 for nozzle-to-plate spacing from 2 to 12. They observed that the