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Effectiveness distribution measurements for a row of heated circular jets impinging on a cylindrical convex surface at different inclinations

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ABSTRACT

The spatially resolved effectiveness distributions for a single jet and row of circular jets impinging on a convex surface are reported in the present study. The impinging surface was inclined at 0°, 15°, 30° and 45° to the jet axis. Studies were conducted for a single curvature ratio equal to 0.05 at a constant Reynolds number equal to 40,000 for non-dimensional jet-to-target distances, L/d equal to 2, 4, 6, 8 and 10. Two non-dimensional jet-to-jet spacings, S/d, equal to 4 and 8 were studied. The effectiveness distribution for multiple jet impingement was noticed to be different from that for a single jet impingement. The entrainment from the surrounding was mitigated for the inner jets by the outer jets. The interaction of adjacent walljets forms a 'barrier' against the percolation of entrained ambient from the outer jet region towards the inner region. The zone of walljet interaction and region near to the inner jets were therefore observed to result in high effectiveness values. The inclined impingement of the jet reduces the strength of interaction of the walljets on up and downhill sides and thereby reduces the 'barrier effect' against the entrainment of ambient, which causes similar variation of effectiveness for all the jets in a row at high inclinations.

1. Introduction

Jet impingement heat transfer is characterized by high local heat transfer coefficients and is preferred in the cooling/heating of surfaces experiencing severe thermal constraints. A single jet results in a sharp reduction in heat transfer coefficient away from the impingement location, and therefore multiple jets are used for cooling/heating of large surfaces. The interaction of the jets before and after the impingement in a multiple jet configuration alters the heat transfer behaviour from the target surface. Saripalli (1983) reported flow visualization of twin circular jets impinging on a flat surface. The interaction of wall jets was observed to result in the formation of a fountain for all jet-to-jet spacing studied (S/d = 12, 6 and 4.1). The heat transfer and flow phenomenon for oblique impinging jets are different from that existing for perpendicular impingement since more fluid is diverted towards the downhill side. Beltaos (1976) reported pressure and shear stress data in the impingement region for inclined single jets and observed a shift of the maximum wall pressure from the geometric impinging point to the uphill side, and attributed it to the shift in stagnation point due to the inclination of the jet. Yan and Saniei (1997) reported heat studies on circular jets impinging at an angle on a flat surface. The local variation of Nusselt number showed non-axisymmetric pattern and the maximum heat transfer was observed to be shifted to the uphill side. O'Donovan (2005) measured the mean and fluctuating velocities in both axial and radial directions (perpendicular and parallel to impinging surface respectively) with straight and obliquely impinging single circular jets on a flat surface. The rate of decline of axial velocity and the rate of generation of turbulence in the downhill side were reported to decrease with increase in inclination, whereas the rate of turbulence generation on the uphill side was reported to increase. Kito (2012) reported flow visualization of an inclined slot jet impinging on a flat surface and observed the presence of vortices just uphill to the geometric impinging location. Lee et al. (1997) reported heat transfer data of circular jet impinging perpendicularly on a convex surface. The non-dimensional jet-to-target distance (L/d) corresponding to the maximum heat transfer coefficient was reported to increase from 6 to 8 as the Reynolds number increased from 11,000 to 50,000.

A submerged jet with different temperatures for the jet and the ambient can be termed as a non-isothermal jet. The entrainment of the surrounding fluid into the jet results in a recovery temperature on the target which is different from the jet exit temperature, T_j. Hollworth and Wilson (1984) reported that this recovery temperature can be experimentally measured on an adiabatic surface (i.e. adiabatic wall temperature, T_{aw}) and presented the recovery temperature in a non-dimensional form. Hollworth and Gero (1985) demonstrated that the heat transfer coefficients measured for jets with different exit

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Nomenclature

A_{surf}	Area of impinging surface, m^2
d	Diameter of circular jet tube, m
D	Diameter of the cylindrical convex surface, m
L	Jet-to-target distance, m
h	Heat transfer coefficient with T_{aw} as reference temperature, W/m^2K (eq. (3))
h_1	Heat transfer coefficient with T_{amb} as reference temperature, W/m^2K (eq. (3))
I	Current, A
k	Thermal conductivity of air, W/mK
q''	Heat flux, W/m^2
q	Heat transfer rate, W
Re	Reynolds number, vd/ν
S	Jet-to-jet distance, m
T	Temperature, K
V	Voltage, V
v	Average exit velocity of jet, m/s
r	Circumferential direction (Fig. 2)
y	Longitudinal direction (Fig. 2)

Subscripts

amb	Ambient
aw	Adiabatic wall
j	Jet
loss	Loss
w	Wall

Greek

θ	Angle between the jet axis and the normal to target
η	Effectiveness
ν	Kinematic viscosity of air
ϕ	Azimuth angle on convex surface

temperatures, T_j, collapse to a single value when (T_w-T_{aw}) was used as the temperature potential instead of (T_w-T_j). Goldstein et al. (1990) and Baughn et al. (1991) presented the non-dimensional recovery temperature as effectiveness and reported data for a single circular non-isothermal jet impinging perpendicularly on a flat surface. The effectiveness was observed to be maximum at the impingement location and progressively reduced in the radial direction and the variations were reported to be independent of Reynolds number. The effectiveness values were reported to decrease with increase in jet-to-target distance and the drop was very significant for distances greater than the length of the potential core. Vinze et al. (2016) reported local effectiveness distribution for heated circular, square and triangular jets impinging perpendicularly on a flat surface. The shapes of contours of effectiveness by square and triangular jets were observed to be rotated by 45° and 180° respectively compared to the corresponding jet exit shape. Fénot et al. (2005) reported effectiveness data for a circular jet impinging perpendicularly on a flat surface and the method for the calculation of effectiveness was similar to that used by Metzger et al. (1973), where the linearity in the wall temperature and heat flux variation is used to calculate the heat transfer coefficient and the adiabatic wall temperature.

Goldstein and Seol (1991) reported effectiveness data for a row of heated circular jets impinging perpendicularly on a flat surface and the values were observed to be independent of Reynolds number. The effectiveness values for small jet-to-jet spacings were observed to be maximum at midway position between the jets at locations far away from impingement point. Fenot et al. (2005, 2008) reported effectiveness data for a row of circular jets impinging perpendicular on flat surface and concave surfaces respectively. The drop in effectiveness after impingement was observed to decrease with decrease in jet-to-jet spacing and with the presence of confinement. Abraham et al. (2015) reported effectiveness and Nusselt number data for an obliquely impinging slot jet on a convex surface along the minor axis. The drop in effectiveness values on downhill and uphill sides were reported to decrease and increase respectively with increase in inclination. Abraham and Vedula (2016) reported local effectiveness and Nusselt number data for normally impinging rectangular jets of different aspect ratios on a flat surface. The entrainment of the ambient from the edges of the jet after impingement was reported to have a significant influence on the effectiveness and the Nusselt number distribution on the target surface.

Several studies reporting effectiveness data for individual as well as row of jets impinging perpendicularly on a flat surface are available. However, effectiveness variation for circular jet impingement, either individual or as a row, on a convex surface does not appear to be reported in the literature and is the focus of the present study. The present study presents local variation of effectiveness for an individual jet and row of circular jets with two different jet-to-jet spacings impinging on a convex surface, for a single curvature ratio. The jets impinged perpendicular and at an inclination to the convex surface at several jet-to-target distances.

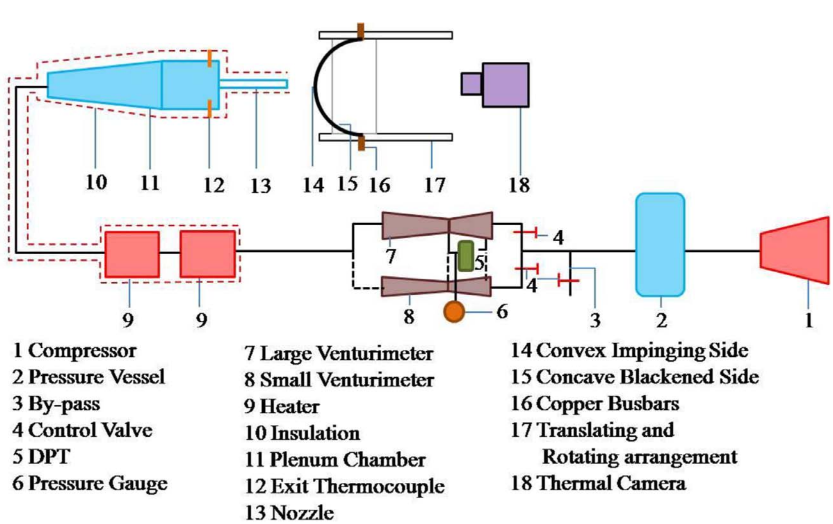

Fig. 1. Schematic of experimental setup.