International Journal of Thermal Sciences 131 (2018) 114–131

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Effect of the shape of flow confinement on turbulent slot jet impingement cooling of a heated circular cylinder

Sharad Pachpute, B. Premachandran*

Department of Mechanical Engineering, IIT Delhi, Hauz Khas, New Delhi, 110016, India

ARTICLE INFO

Keywords:
Jet impingement
Slot jet
Circular cylinder
Confinement shape
Turbulent flow

ABSTRACT

In this paper, details of experimental and numerical investigations carried out on slot jet impingement over a heated circular cylinder with and without a flow confinement have been presented. In this study, to enhance heat transfer rate in the rear side of the cylinder, circular, quadrilateral and hexagonal flow confinements with openings at the top and bottom of the confinements are used around the target cylinder. The Reynolds number, Re_D, defined based on the average velocity at the nozzle exit and the cylinder diameter, is varied from 6000 to 20000. The non-dimensional distance between the nozzle exit and the heated cylinder, H/S is varied in range of $2 \le H/S \le 12$. The ratio of the cylinder diameter to the slot width, $D/S = 8.5$ is fixed in all the cases considered in the present study. The results of present study shows that the bottom surface of the cylinder is substantially cooled when flow confinement walls are used compared to the case of unconfined flow. The overall enhancement in the average Nusselt number over the heated cylinder due the quadrilateral and the hexagonal confinements is in the range of 20–42%.

1. Introduction

Jet impingement cooling and heating of cylindrical surfaces are encountered in a wide range of industrial applications such as cooling/heating of circular food items in food processing industry, cooling of gas turbine blades, cooling of continuous casting of metal billets. Reviews of Hrycak [1], Downs and James [2], Martin [3], Jambunathan et al. [4] and Viskata [5]are mainly focused on the jet impingement cooling of flat surfaces without flow confinements. Slot jet impingement cooling or heating is widely used for uniform or controlled cooling of cylindrical surfaces.

Cornaro et al. [6] experimentally investigated the circular round air jet impingement over a semi-cylindrical surface for the ratio of the diameter of a semi-cylinder (D) to the diameter of round jet (d), $D/d = 2.6$–5.6 and $\mathrm{Re_d} = 6000$–16000. Their results revel that the heat transfer rate increases with increases in the Reynolds number and the curvature (D/d) in all cases. Gori and Bossi [7] experimentally studied slot impingement cooling of a circular cylinder without a flow confinement for the ratio of diameter (D) of the cylinder to the nozzle width (S), $D/S = 2$. The Reynolds number ($Re_D = U_jD/\upsilon$) considered in the range of 4000–20000 for $H/S = 2$–10. Their finding showed that the local Nusselt number depends on the angle from the stagnation point, H/S and Reynolds numbers. The same authors [8] extended a similar investigation for $Re_D = 4500$–22000 and $H/S = 6$–20 for a fixed value of $D/S = 4$. Their studies showed that the local Nusselt number is higher at the stagnation region and continuously decreases from the impingement point. They also studied the effect of the slot width (D/S) on the average Nusselt numbers obtained for $D/S = 1$, 2 and 4. For three slot width configurations, $D/S = 1$,2 and 4, the average Nusselt number is observed to be higher for a lower width of the slot ($D/S = 4$). Their studies showed that the local cooling rate is significantly lower at the rear side of the cylinder irrespective of Reynolds number, H/S and D/S values.

McDaniel and Webb [9] experimentally studied slot jet impingement cooling of a single heated circular cylinder using a contoured orifice and a sharp-edged orifice as nozzles to investigate the effect of D/S and H/S on the cooling rate. The ratio of the diameter of the cylinder to the slot width, (D/S) of 0.66, 1.0 and 2.0 were considered. The non-dimensional distance between the nozzle exit and the cylinder, H/S was varied in the range of 1–11 for the Reynolds number, $Re_D = 600$–8000. They concluded that heat transfer was higher in the case of sharp edge orifice type nozzle. Olsson et al. [10] carried out a numerical investigation of slot impingement cooling of a circular cylinder kept on a flat surface for $Re_D = 23000$–100000 and $H/S = 2$–8 for a fixed value of $D/S = 0.877$ using the SST k-ω turbulence model. They developed correlations for the stagnation and average Nusselt numbers in terms of Reynolds number and curvature of the cylinder (D/S). Singh and Singh [11], Nitin et al. [12] and Dirita et al. [13] also

* Corresponding author.
E-mail address: prem@mech.iitd.ac.in (B. Premachandran).

https://doi.org/10.1016/j.ijthermalsci.2018.05.026
Received 15 August 2017; Received in revised form 13 May 2018; Accepted 14 May 2018
1290-0729/

Nomenclature

A	area of jet, m^2
D	diameter of the circular heated cylinder, m
d	hydraulic diameter of jet, m
f	elliptic relaxation frequency, 1/s
H	distance between the slot-jet ext and the target cylinder, m
h	convective heat transfer coefficient, W/m^2-K
I	turbulent intensity, %
k_f	thermal conductivity of air, W/m-K
k	turbulent kinetic energy, m^2/s^2
l	turbulent length scale, m
$\dot{m}$	mass flow rate of jet fluid, kg/s
Nu_i	local Nusselt number based on the cylinder diameter, h_iD/k_f
P	pressure, N/m^2 or production of turbulent kinetic energy, m^2/s^3
Pr	Prandtl number
q	heat flux over the heated cylinder, W/m^2
R	radius of the circular heated cylinder, m
R_c	radius of confinement, m
Re_D	Reynolds number based on cylinder diameter and average jet exit velocity, U_jD/ν
S	slot-jet width, m
T	temperature, K
$\underline{U_j}$	average velocity of jet at the nozzle exit, m/s
$\overline{v'^2}$	variance of the fluctuating velocity,m^2/s^2
W	width of opening, m
X	non-dimensional x-coordinate, x/D
x_i	coordinate in ith direction
Y	non-dimensional y-coordinate, y/D
y^+	Non dimensional wall coordinate, $y\sqrt{\tau_w/\rho}/\nu$

Greek symbol

Θ	Nom-dimensional temperature, $(T\text{-}T_j)k_f/(q''D)$
θ	angle with the impinging point, degree(°)
ν	kinematic viscosity of air, m^2/s
ρ	mass density of air, kg/m^3
ε	dissipation rate of turbulent kinetic energy,m^2/s^3
τ	turbulent time scale, s

Subscripts

conv	convection
∞	Ambient condition
t	turbulent
m	area weighted average
c	confinement

investigated the same problem experimentally and numerically. Their results reveal that the surface heat transfer coefficient strongly depends on D/S and H/S.

Chan et al. [14] carried an experimental investigation to understand the effect of a heated slot jet impingement over a semicircular convex surface for $D/S = 24$ and $H/S = 2$–10. The Reynolds number defined based on the slot width, $Re_S = U_j S/\upsilon$ was varied from 5600 to 13,200. In their study, a secondary peak was observed in the circumferential local Nusselt number at $H/S = 2$, $Re_S = 5600$ and 8500. They highlighted that the secondary peak is due to flow transition from laminar to turbulent.

Zuckerman and Lior [15] carried out a numerical investigation on heat transfer from a circular cylinder with 2,4 and 8 slot jets using the $\overline{v'^2} - f$ model. They varied Reynolds number from 23000 to 80000 for the ratio of hydraulic diameter (d_{hyd}) of a slot nozzle to the diameter of the heated cylinder, $d_{hyd}/D = 10$ and $H/D = 3$. They concluded that higher heat transfer is achieved with multiple radial slot jets and heat transfer is uniform over the cylindrical surface compared to a single slot jet impingement which provides higher cooling rate only at the stagnation region. Wang et al. [16] experimentally studied cooling of a circular cylinder with a single and two jets for $D/d = 2.5$–10, and $Re_d = 20000$. In the case of double jet impingement cooling of a circular cylinder, two jets are positioned opposite sides of the cylinder. They reported that reverse jet flow occurred in the case of jet impingement cooling of a circular cylinder with two counter jet due to opposing wall jet interaction. These reverse jet flows enhance heat transfer from the circular cylinder. However, its effect reduces when the size of the circular cylinder increases.

Jet impingement cooling with confinement may increase or decrease the overall heat transfer rate depends on the location and the shape of the flow confinement. Obot et al. [17] analyzed the effect of a circular flat confinement of radius, R_{conf} at the nozzle exit of a round jet emerging from a circular nozzle of diameter, d impinging on a heated flat target. They carried out a parametric study for $2 \le H/d \le 16$ and $8.7 \le R_{conf}/d \le 17.4$. They found that the top circular confinement reduces the cooling rate considerably for a lower non-dimensional spacing between the nozzle exit and the flat surface (H/d). However, no significant change in the average heat transfer coefficient was observed when the nozzle diameter reduced by one-half and doubling the size of confinement. Colucci and Viskanta [18] conducted experiments for the confined circular jet impinging over a heated flat surface using different nozzle geometries such as an orifice and hyperbolic shaped nozzle exit for $0.25 \le H/d_{hyd.} \le 6$, $R_{conf}/d_{hyd} = 10$ and $Re_{d,hyd} = 10000$–50000. In their investigation, the stagnation Number is found to be lower for an orifice shaped nozzle compared that for the jet impingement with hyperbolic shapes of the nozzle exit for $H/d_{hyd} = 0.25$, 1 and 6 at $Re_{d,hyd} = 30000$.

The effect of confinement for single or multiple jet impingement on the flow and heat transfer characteristics has been studied numerically and experimentally. Li et al. [19] numerically investigated the effect flow pattern for a laminar confined slot jet by changing the conditions at the outlet boundary for $Re_S = 20$–275 and $H/S = 2.5$. Their results showed that the size of recirculation observed in the confined passage is dependent on the Reynolds number. The stagnation Nusselt number is unaffected by the confinement but its value is significantly reduced due to the flow separation near the exit of confinement. Behania et al. [20], San et al. [21], Shi et al. [22] and Bayder and Ozmen [23] investigated of the effect of a top circular confinement at the nozzle exit for the turbulent round jet impingement over a heated flat surface and showed that because the recirculation in the confined region, the stagnation heat transfer rate decreases significantly the for $H/d_{hyd} < 2$. Fenot et al. [24] experimentally investigated various configurations of multiple circular air jets impinging on a flat surface with and without a top flat confinement around at the nozzle exit for $Re_{d,hyd} = 23000$, $H/d_{hyd} = 2$ and 5. Their study showed that the effect of confinement on the local heat transfer rate is not significant. To enhance the heat transfer at the impingement surface, Qiu et al. [25] and Xu et al. [26] [27], showed based on their numerical studies that the addition of finned or rough surface over a flat heated surface increases heat transfer rate in some cases. However, such an artificial roughness is undesirable in many cases including curved objects.

Imran and Sharma [28] [29], experimentally and numerically investigated the slot jet impingement over a circular heated cylinder placed between two confined walls for $Re_S = 1000$–12000, $D/S = 0.66$–1 and $H/D = 2$–22. Their numerical results show that the size of recirculations increases with an increase in the spacing between the