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Research Paper

Slot air jet impingement cooling over a heated circular cylinder with and without a flow confinement

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HIGHLIGHTS

- Confinement at the nozzle exit on jet impingement heat transfer is investigated.
- Longer confinement at the nozzle exit reduces heat transfer for a small width jet.
- The effect of confinement on heat transfer is negligible for a large width jet.
- A correlation has been provided for average Nusselt number.

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ABSTRACT

In this work, a numerical investigation has been carried on an air slot jet impingement over a circular cylinder with and without a top confinement using the $\overline{v'^2} - f$ turbulence model. In the parametric study, the Reynolds number (Re_D), defined based on the cylinder diameter, D, is varied from 4500 to 20,000. The ratio of spacing between the nozzle exit to the cylinder target, H and the width, S of the nozzle, H/S is varied from 2 to 10. The non-dimensional slot width, D/S considered in the present study are 1, 2 and 4. The local distribution and average Nusselt numbers obtained from numerical simulations are validated against the available experimental data of jet impingement over a flat and cylindrical surfaces without confinement. It is observed that the local Nusselt numbers obtained from the present numerical model compare well with the experimental data. To understand the effect of confinement, a flat plate confinement at the exit of the nozzle has been considered. The non-dimensional length of the confinement, L_{conf}/D was varied from 0 to10 in the parametric study. Numerical results reveal that the top confinement reduces the average Nusselt number by 25% at $Re_D = 4500$, $D/S = 4$ and $H/S = 2$, while the influence confinement on the cooling rate is negligible for $D/S = 1$. Based on the numerical study, a correlation has been provided for the average Nusselt number over the heated cylinder.

1. Introduction

Jet impingement cooling/heating technique is widely used for various applications. Some of the application are cooling of electronics devices and gas turbine blades, the heating and cooling or drying of pulp, paper, textile, food items and materials and manufacturing processes. In manufacturing processes, a controlled quenching of material is essential to produce the desired grain size, phase composition and hardness. The quenching should be done rapidly and uniformly. Due to the availability and easy handling, air is widely used for cooling of materials instead of liquid for quenching. Rather than using multiple circular jets, a single slot jet is preferred as it may provide uniform cooling or heating which is important for the processing of cylindrical food items, shafts, end mills, etc.

Comprehensive reviews on jet impingement heat transfer provided in [1–5]. In these reviews, mainly the work carried out on jet impingement cooling or heating of flat surfaces with single or multiple jets. Even though jet impingement cooling of cylindrical surfaces have wider industrial applications, only limited studies have been carried out on this topic.

One of the earlier experimental studies on a slot jet impingement cooling of a circular cylinder using air as the cooling medium was carried out by Gori and Bossi [6]. In their study, the nozzle slot width, S of 5 mm and diameter of the heated cylinder, D of 10 mm were used. In order to investigate the effect of distant between the nozzle exit to the circular cylinder, H, they varied the non-dimensional distance parameter, H/S from 2 to 10 for the Reynolds number, defined based on the diameter of the cylinder, ranging

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Nomenclature

A	area of jet, m^2
D	diameter of circular target, m
d	hydraulic diameter of jet, m
f	elliptic relaxation frequency, 1/s
H	distance between the slot-jet exit 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
Nu	Nusselt number based on the cylinder diameter, hD/k_f
P	pressure, N/m^2 or production of turbulent kinetic energy, m^2/s^3
Pr	Prandtl number
Re_D	Reynolds number based on cylinder diameter and average jet exit velocity, U_oD/ν
S	slot-jet width, m
T	temperature, K
U_o	average velocity of jet at the nozzle exit, m/s
$\overline{v'^2}$	variance of fluctuating velocity, m^2/s^2
W	slot-jet length, 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	angle with the impinging point, in 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

conf	confinement
∞	Ambient condition
t	turbulent
m	area weighted average

from 4000 to 20,000. Based on the experimental data, they presented the variation of local Nusselt number along the circumferential direction of the cylinder and the average Nusselt number for the range of parameters considered in their study. They also presented experimental correlations for the average Nusselt number. Gori and Bossi [7] also extended their experimental study for D/S = 4 and H/S = 6–20. They have also consolidated heat transfer obtained from this study and the earlier studies and presented correlations for D/S = 1, 2 and 4 for a wide range of H/S and Re_D.

McDaniel and Webb [8] experimentally investigated jet impingement heat transfer from a circular cylinder with a slot nozzle with contoured and sharp-edged orifice configurations. In their study, Reynolds number, defined based on the diameter of the cylinder, was varied in the range of 600–8000 and the diameter of the cylinder-to-slot width, D/S of 0.66, 1.0 and 2.0 are considered. They varied the non-dimensional distance between the nozzle exit to the circular cylinder, H/S in the range of 1–11 in the parametric study. It was found from their study that the stagnation Nusselt number is higher in the case of jet impingement cooling of the circular cylinder when a sharp-edged nozzle is used.

Singh and Singh [9] carried out experimental and numerical studies on a slot jet impinging over a circular cylinder which was kept on a flat adiabatic surface. From their study, they concluded that placing a cylinder at the end of the potential core of the jet gives a higher cooling rate for a fixed ratio of the diameter of the target to the width of the nozzle, D/S. Olsson et al. [10] numerically investigated the heat transfer characteristics of a single slot air jet impinging over a circular kept on an adiabatic flat surface for D/S = 0.877 at Re_D = 23,000–100,000 for a wide range of H/S. They found that the cooling rate from the cylinder is dependent on H/S. Nitin et al. [11] and Dirita et al. [12] also experimentally and numerically investigated for the same configuration considering cooling of cylindrical food items is one of the main applications. They concluded that the surface heat transfer coefficient depends on the nozzle geometry and H/S.

Singh et al. [13] carried the experimental and numerical investigations of a circular jet impinging over the circular cylinder with geometric configuration d/D = 0.11, H/d = 4 to 16 at Re_d = 10,000 and 25,000. They provided a correlation for the stagnation point Nusselt number based on their experimental studies. Their numerical investigation carried out with the two-equation models; the standard k-ε, RNG k-ε, Realizable k-ε and SST k-ε models could not predict the stagnation point Nusselt number accurately for the low nozzle to cylinder distances.

The main reason for the poor prediction of the stagnation Nusselt number in jet impingement flows and flows with stagnation point when any two-equation model is used due to the prediction of higher turbulent kinetic energy at the stagnation point as discussed in Durbin [14]. Behenia and Durbin [26] used the four equation $\overline{v'^2}-f$ model of Durbin [15] for the prediction of turbulent impingement heat transfer on a flat surface using an axisymmetric model. Their numerical model could predict the stagnation Nusselt number within 10% of the experimental value. Zuckerman and Lior [16] studied the performance of various Reynolds Averaged Navier-Stokes (RANS) models for a circular air jet impinging on a flat surface and concluded that the $\overline{v'^2}-f$ model predicts the stagnation Nusselt number better among all the eddy viscosity models. They showed that the SST k–ω and the RSM models over predict the Nusselt number at the stagnation region with the error band of 30–100%. They also carried out a numerical investigation on multiple slot impingement over a long circular cylinder using the $\overline{v'^2}-f$ model. In their study, the slot jets were radially arranged and aligned with the axis of the cylinder. The numerical investigation was carried out for the Reynolds number ranging from 23,000 to 80,000 with d/D = 10, H/D = 3. They concluded that multiple radial slot jets cool the cylinder uniformly.

Obot et al. [17] studied the effect of semi-confinement on jet impingement cooling of a flat surface for H/d in the range of 2–16. The limit of the confining plate was extended radially from 8.7 to 17.4 times the diameter of the nozzle exit. Their results show that the semi-confinement reduced the cooling rate significantly when the jet-to-plate spacing, H/d was small. Behania et al. [18] numerically analyzed the influence of confinement for a circular jet impinging on a flat target with a flat confinement at the nozzle exit. They found that the effect of confinement reduces the average Nusselt number around 30% when $H/S \le 2$. They also reported that the confinement reduced the average heat transfer rate between a 5% and 10% compared to the non-confining jet flows for $H/S > 2$. Caggese et al. [19] investigated experimentally and numerically a fully confined single circular jet impinging over the flat surface for Reynolds number, defined based on the nozzle diameter, Re_d