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Heat transfer enhancement on a flat surface with axisymmetric detached ribs by normal impingement of circular air jet

Vadiraj Katti, S.V. Prabhu *

Department of Mechanical Engineering, Indian Institute of Technology (I.I.T.), Bombay, Powai, Mumbai 400 076, India

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ABSTRACT

An experimental investigation is carried out to study the heat transfer enhancement from a flat surface with axisymmetric detached rib-rougheners due to normal impingement of circular air jet. A single jet from nozzle of length-to-diameter ratio (l/d) of 83 is chosen. Effect of rib width (w), rib height (e), pitch between the ribs (p), location of the first rib from the stagnation point and clearance under the rib (c) on the local heat transfer distribution is studied. Local heat transfer distribution on the impingement surface is investigated for jet-to-plate distances (z/d) varying from 0.5 to 6 using thermal infrared camera. Turbulence intensity using hot-wire anemometer and wall static pressure measurements are reported for the rib configuration in which maximum heat transfer was observed. Contrary to the results of smooth surface, there is a continuous increase in the heat transfer coefficient from the stagnation point in the stagnation region. This trend is well substantiated by the flow distribution in this region. The ratio of average Nusselt numbers of ribbed and smooth surface is seen to increase with Reynolds number. Correlation is developed for Nusselt numbers averaged upto an r/d of 1.5. Enhancements in heat transfer decrease for higher z/d s.

1. Introduction

Impinging jets have received considerable attention due to their inherent characteristics of simple geometry and higher rates of heat transfer. Such impinging flow devices allow for short flow paths on the surface and relatively high rates of cooling from a comparatively small surface area. Various industrial processes involving high heat transfer rates apply impinging jets. Few industrial processes which employ impinging jets are drying of food products, textiles, films and papers; processing of some metals and glass, cooling of gas turbine blades and outer wall of the combustion chamber, cooling of electronic equipments, etc. Heat transfer rates in case of impinging jets are influenced by various parameters like Reynolds 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 nozzle exit.

Many prior studies are mostly on jet impinging over flat and smooth surface. Review of the experimental work on heat transfer to impinging jets is reported by Livingood and Hrycak (1970), Martin (1977), Jambunathan et al. (1992) and Viskanta (1993). Gardon and Cobonpue (1962) have reported the heat transfer distribution between circular jet and flat plate for the nozzle plate spacing greater than two times the diameter of jet, both for single jet and array of jets. Specially designed heat flux gages were used for the measurement of local heat transfer distribution from a constant wall temperature plate. Gardon and Akfirat (1965) studied the effect of turbulence on the heat transfer between two-dimensional jet and flat plate. They also studied the heat transfer distribution due to impingement of multiple two-dimensional jets. Gardon and Akfirat (1966), Baughn and Shimizu (1989) and Hrycak (1983) have conducted experiments of heat transfer to round jet from flat plate employing different methods of surface temperature measurement. Lytle and Webb (1994) have studied the effect of very low nozzle-to-plate spacing ($z/d < 1$) on the local heat transfer distribution on a flat plate impinged by a circular air jet issued by long pipe nozzle which allows for fully developed flow at the nozzle exit. They observed that for lower nozzle-to-plate spacing ($z/d < 0.25$), maximum Nusselt number shifts from the stagnation point to the point of secondary peak and is more pronounced at higher Reynolds number. Lee et al. (2004) have studied the influence of nozzle diameter on impinging jet heat transfer and fluid flow. They reported that local Nusselt numbers in the region of $0 \leqslant r/d \leqslant 0.5$ increase with larger nozzle diameters. Katti and Prabhu (2008) reported experimental investigations and analysis of local heat transfer distribution on a flat surface due to jet impingement from a long pipe nozzle. Three regions are identified on the target surface namely stagnation region, transition region and wall jet region based on heat transfer distribution. Semi-empirical correlations for local Nusselt numbers separately for each region are reported.

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* Corresponding author. Tel.: +91 22 25767515; fax: +91 22 2572 6875/3480.
E-mail addresses: svprabhu@iitb.ac.in, svprabhu@me.iitb.ac.in (S.V. Prabhu).

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Nomenclature

A	surface area for smooth surface (m^2)
c	clearance under the rib (m)
d	diameter of the nozzle at exit (m)
e	height of the rib (m)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity of air (W/m K)
l	length of the nozzle pipe (m)
Nu	Nusselt number (hd/k)
$\overline{Nu}_r$	average Nusselt number over ribbed surface
$\overline{Nu}_s$	average Nusselt number over smooth surface
p	pitch between the ribs (m)
ΔP	differential wall static pressure (Pa)
q	heat flux (W/m^2)
q_{con}	net heat flux convected to the impinging jet (W/m^2)
q_{joule}	imposed Ohmic heat flux, (VI/A) (W/m^2)
q_{loss}	total heat flux lost from impingement plate (W/m^2)
$q_{rad(f)}$	radiation loss from the front surface of impingement plate (W/m^2)
$q_{rad(b)}$	radiation loss from the back surface of impingement plate (W/m^2)
q_{nat}	heat loss due to natural convection from the back surface of impingement plate (W/m^2)
r	radial distance from the stagnation point (m)
r_1	radial location of first rib (m)
Re	Reynolds number, ($\rho\overline{V}d/\mu$)
T_j	jet air temperature (K)
T_r	temperature of the target plate at given radial location (K)
u'	near-wall turbulent intensity (m/s)
U_r	near-wall radial velocity (m/s)
V	voltage (V)
$\overline{V}$	average velocity of flow at nozzle exit (m/s)
w	width of the rib (m)
y	normal distance from the surface of target plate(m)
z	nozzle plate spacing (m)

Greek symbols

μ	viscosity of air (Pa s)
ρ	density of air corresponding to supply pressure (kg/m^3)

The influence of surface rougheners on heat transfer enhancements are reported in literature. Hansen and Webb (1993) have studied the effect of the modified surface on the average heat transfer between impinging circular jet and the flat plate. They have found that for the pyramidal, short square and intermediate square fins, there is an increase in the average Nusselt number value by 12–23% and reduction in the value of the average Nusselt number by 4–38% for the other types of fins studied. The effect of surface rougheners, in the form of cubes, on the heat transfer between impinging jets and flat plate are studied in Chakroun et al. (1998). They have reported the heat transfer augmentation up to 8–28%. However, their data reflects the average Nusselt number variation rather than local data because of the large thickness of the target plate (brass plate of 10 mm thick) used. Ekkad and Kontrovitz (2002) have studied the effect of the dimpled surface on the heat transfer between array of circular jets and the flat plate. They have reported reduction in the heat transfer coefficient for the dimpled surface as compared to the smooth surface.

Miyake et al. (1994) studied heat transfer characteristics of an axisymmetric jet impinging on a wall with eleven concentric attached square ribs as roughness elements ($0 < r/d < 5.0$). Each rib is machined on concentric copper target surface (10 mm thick) are separated and heated individually so as to form isothermal surface. Thus, radial distribution of annular segment averaged heat transfer coefficients is presented. Only two concentric rib segments are located in the stagnation region and hence heat transfer distribution reported for this region may not be truly local. Nusselt numbers at each rib location are reported higher than the corresponding smooth surface. The ribbed surface with $p/e = 5.0$ and $e/d = 0.1$ is reported to have higher heat transfer augmentation. At lower z/d (3.0), Nusselt numbers in the stagnation region are lower than the corresponding case of smooth surface and they attributed it to the formation of a dam in the stagnation region by the first axisymmetric rib. In the downstream, Nusselt number increase by about 30% at an $r/d = 1.0$ and further decay monotonically. Fourth order polynomial curve fit correlations for radial Nusselt number distribution are reported for each configuration. Gau and Lee (1992, 2000) have reported the heat transfer augmentation to slot jet impinging on square ribbed and triangular ribbed walls, respectively. Constant heat flux heater surface is used in their experiments. Thermally active attached ribs on such a surface will have lower base temperatures and its effect is felt on adjacent area of rib base. Hence, it may be observed that heat transfer coefficients estimated from surface temperature distribution show higher values under the rib and its adjacent locations where there is no flow. Thus, the augmentations reported may be due to combined effect of two factors, namely (a) the enhanced turbulence mixing by distorting the flow fields caused by the presence of ribs and (b) the extension in heat transfer surfaces i.e., the fin effect caused by the ribs.

Few studies are reported on the heat transfer characteristics due to detached ribs in the internal flow situation. Tsia and Hwang (1999) have studied the effect of thermal conductivity of the attached ribs in internal flow using thermally active material (aluminum ribs) and thermally non-active turbulators (wood ribs). They concluded that higher enhancements with thermally active ribs are attributed to rib conduction effects. Their experiments with fully detached ribs show enhanced heat transfer due to enhanced turbulence. They speculated the flow over the detached ribs and reported shedding of vortices from the detached rib and the wall jets ejecting from the rib clearance. Liou and Wang (1995) and Liou et al. (1995) have studied different configurations of detached ribs on the walls in internal flows and reported improved thermal performance compared to the attached ribs. They reported higher forced convection resulting from higher acceleration of the flow between the rib base and the heated wall. The flow visualization results of Liou et al. (1998) show the presence of recirculating flow immediately behind the detached rib. They also observed an asymmetric wake behind the rib because of asymmetric flow area across the rib. The vortex shedding promotes the mixing of fluid and hence leads to a higher level of heat transfer distributions. Liou et al. (1997) have made LDV measurements for flows over detached ribs. They showed that the wake generates higher convective velocity and turbulent kinetic energy in the region behind the rib. This provides better heat transfer augmentation immediately behind the rib and depends on the clearance under the rib.

There is no information available on the heat transfer distribution on the flat plate with detached axisymmetric ribs due to jet