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Heat transfer augmentation between impinging circular air jet and flat plate using finned surfaces and vortex generators

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Abstract

An experimental investigation is performed to study the effect of the finned surfaces and surfaces with vortex generators on the local heat transfer coefficient between impinging circular air jet and flat plate. Reynolds number is varied between 7000 and 30,000 based on the nozzle exit condition and jet to plate spacing between 0.5 and 6 nozzle diameters. Thermal infrared imaging technique is used for the measurement of local temperature distribution on the flat plate. Fins used are in the form of cubes of 2 mm size spaced at a pitch of 5 mm on the target plate and hexagonal prism of side 2.04 mm and height of 2 mm spaced at a pitch of 7.5 mm. Vortex generators in the form of a equilateral triangle of side 4 mm are used. Effect of number of rows of vortex generators, radius of a row, number of vortex generators in a row and inclination angle (i.e., the angle between the plane of the target plate and the plane of the vortex generators) on Nusselt number is studied. It is observed that the heat transfer coefficient between the impinging jet and the target plate is sensitive to the shape of the fin. The increase in the heat transfer coefficient up to 77% depending on the shape of the fin, nozzle plate spacing and the Reynolds number is observed. The augmentation in the heat transfer for the surfaces vortex generators are higher than that of the finned surfaces. The heat transfer augmentation in case of vortex generator is as high as 110% for a single row of six vortex generators at a radius of 1 nozzle diameter as compared to the smooth surface at a given nozzle plate spacing of 1 nozzle diameter and a Reynolds number of 25,000 at extreme radial location.

Keywords: Jet impingement; Vortex generators; Fins; Augmentation; Thermal infrared imaging

1. Introduction

Impinging jets have received considerable attention due to their inherent characteristics of high rates of heat transfer besides having simple geometry. 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 and 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 affected by various parameters like Reynolds number, nozzle 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, low scale turbulence intensity, i.e., turbulence intensity at the nozzle exit.

Gardon and Cobonpue [1] have reported the heat transfer distribution between circular jet and flat plate for the nozzle plate spacings greater that two times the diameter of jet, both for single jet and array of jets. They have used specially designed heat flux gage for the measurement of local heat transfer rates from a constant wall temperature plate. Gardon and Akfirat [2] have studied the effect of turbulence on the heat transfer between two-dimensional jet and flat plate. They also studied effect of multiple two-dimensional jets on the heat transfer distribution [3]. Baughn and

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Nomenclature

A	surface area for smooth surface (m^2)	Q	total heat input at the base of the fin (W)
A_b	base area for finned surface (m^2)	r	radial distance from the stagnation point (m)
A_c	cross section area of the fin (m^2)	Re	Reynolds number $\left(\frac{\rho \overline{V} D}{\mu}\right)$
A_{fin}	surface area of fins (m^2)	T_{Fin}	average fin temperature (°C)
A_{tot}	total surface area for finned surface (m^2)	T_j	jet air temperature (°C)
B	two-dimensional nozzle width (m)	T_r	temperature of the target plate at given radial location (°C)
D	diameter of the nozzle exit (m)	V	voltage (V)
H	height of the fin (m)	$\overline{V}$	average velocity of flow at nozzle exit (m/s)
h	heat transfer coefficient (W/m^2 K)	Z	nozzle plate spacing (m)
I	current (A)	ρ	density of air corresponding to supply pressure (kg/m^3)
k	thermal conductivity of fin material (W/m K)	μ	viscosity of air (Pa s)
k_f	thermal conductivity of air (W/m K)	ϕ	pitch circle diameter of vortex generators (mm)
L	length of the nozzle pipe (m)		
Nu	Nusselt number $\left(\frac{hD}{k}\right)$		
P	perimeter of the fin (m)		

Shimizu [4] and Hrycak [5] have conducted experiments of heat transfer between round jet and flat plate employing different methods of surface temperature measurement. Lyttle and Webb [6] have studied the effect of very low nozzle plate spacing ($Z/D < 1$) on the local heat transfer distribution on a flat plate impinged by a circular air jet and found that in the acceleration range of the nozzle plate spacing ($Z/D < 0.25$), maximum Nusselt number shifts from the stagnation point to the point of secondary peak with the effect being more pronounced at higher Reynolds number. Gao et al. [7] have studied the effect of triangular tabs put at the exit of the nozzle. Lee et al. [8] have studied effect of nozzle diameter (1.36, 2.16, and 3.40 cm) on impinging jet heat transfer and fluid flow. They reported that local Nusselt numbers in the stagnation point region corresponding to $0 \leqslant r/D \leqslant 0.5$ are increased with increasing nozzle diameter. This is attributed to the increase in the jet momentum and turbulence intensity with the larger nozzle diameter, which in turn results in the heat transfer augmentation at the stagnation point. Review of the experimental work on impinging jets is done by Martine [9], Jambunathan et al. [10] and Viskanta [11].

Beitelmal et al. [12] analyzed two-dimensional impinging jets and correlated heat transfers in the stagnation point, stagnation region and wall jet region with approximate solutions developed using simplified flow assumptions. Correlations for stagnation point and average heat transfer are reported by Zukerman and Lior [13]. Hoffman et al. [14] conducted an experimental investigation on flow structure and heat transfer from a single round jet impinging perpendicularly on a flat plate. The influence of nozzle-to-plate distance and Reynolds number on local heat transfer coefficient was investigated. Correlations for local and average heat transfer coefficients are reported.

Hansen and Webb [15] 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. Chakroun et al. [16] have studied the effect of surface roughners, in the form of cubes, on the heat transfer between impinging jets and flat plate. 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 (10 mm) used. Ekkad and Kontrovitz [17] have studied the effect of the dimpled surface on the heat transfer between array of circular jets and the flat plate. They have reported the reduction in the heat transfer coefficient for the dimpled surface as compared to the smooth surface.

Miyake et al. [18] 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 was separated and heated individually so as to form isothermal surface. Rib height to nozzle diameter ratios of 0.1 and 0.2, rib width to nozzle diameter of 0.1 and 0.2, pitch to rib height ratios of 5 and 10 for jet to plate spacing of 3–10 were covered in this study. Thus radial distribution of segment averaged heat transfer coefficients is presented. The ribbed surface with pitch to rib height ratio of 5 and rib height to hydraulic diameter ratio of 0.1 is reported to have higher heat transfer augmentation than other configurations. Gau and Lee [19] and Gau and Lee [20] have reported the heat transfer augmentation to slot jet impinging on square ribbed and triangular ribbed walls, respectively. In both the cases, the ribs were attached to the target plate. 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, fin effect, provided by the ribs. Can and Etemoglu [21] studied the enhancement of heat