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Local heat transfer distribution on a flat plate impinged by a swirling jet generated by a twisted tape

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ABSTRACT

An experimental investigation is conducted to study the local heat transfer distribution on a flat surface normally impinged by a swirling air jet. Twisted tapes of twist ratios equal to 2, 3.2, 4.5 and 7.5 (corresponding swirl numbers $S = 0.79$, 0.49, 0.35, 0.21) are inserted in a circular tube to generate swirling effect. Experiments are carried out for Reynolds number varying from 500 to 3000 for jet to plate spacing varying from 1 to 4. The local heat transfer characteristics are estimated using thermal images obtained by thermal infrared imaging technique. The jet flow profile on the target plate is evaluated by the flow visualisation carried out using lamp black technique. The heat transfer rate is found to initially increase with the increase in twist ratio (or decrease in swirl number) from 2 to 4.5 and thereafter it reduces with the increase in the twist ratio from 4.5 to 7.5. The heat transfer rate is maximum for a twist ratio of 4.5 and minimum for a twist ratio of 7.5. The jet to plate spacing also shows strong influence on the heat transfer rate. With the increase in jet to plate spacing, the heat transfer rate decreases. The maximum heat transfer rate is obtained at $z/d = 1$ for the different twist ratios and Reynolds number.

1. Introduction

Impinging jets are used extensively in industries due to its high rates of heat transfer. It is therefore used for cooling turbine blades and combustion chamber walls in gas turbine engines, glass processing industries, cooling of electronic circuits and equipments and surface treatment of metals [1–5]. The rate of heat transfer by jet impingement depends on various parameters such as Reynolds number *(Re)*, the distance of nozzle exit from surface of impingement (jet to plate spacing), the radial distance from stagnation point (r/d), nature of jet (conventional or swirling), geometry of the surface of target plate, the nature of surface plate, Prandtl number, target plate inclination, confinement of the jet, nozzle geometry, cross-flow, curvature of target plate as reported in literature [5–11]. Attempts are made to improve the jet impingement heat transfer rate by various augmentation techniques. The methods adopted mainly involved the techniques to increase turbulence intensity by increasing flow rate or modifying flow characteristics.

The swirling jet impingement has shown improved results as compared to the conventional jet impingement heat transfer methods [12,13]. A swirling jet has angular velocity of the jet in addition to the axial velocity. The combination of angular and linear velocity gives rise to the spiral motion of the jet and hence it is deemed to have better mixing and uniformity before impinging on the target plate. The swirling jet impingement on the target plate shows enlarged stagnation and wall jet region due to angular velocity component which results in wider distribution of heat transfer as explained by Gupta et al. [14]. Huang et al. [15] carried out flow visualisation of swirling air jet impingement. They observed that more uniform distribution of heat transfer is obtained for swirling jets as compared to the conventional jets and the uniformity improves with the increase in the jet to plate spacing. Authors reported that swirl induces more entrainment than conventional jet. Wen et al. [16] investigated on the swirling jet impingement cooling for the flow rate corresponding to Reynolds numbers of 500–27,000 for jet to plate spacing (z/d) ranging from 3 to 16. A flow visualisation was done using smoke flow visualisation technique. The local Nusselt number for swirl jet was found to enhance up to 14% as compared to the non-swirling impinging jet. Experimental investigation by Lee et al. [17] on

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Nomenclature

A	Surface area for smooth surface (m^2)
C	Clearance
d	Diameter of jet (m)
h	Heat transfer coefficient (W/m^2 K)
I	Current (A)
k	Thermal conductivity of air (W/m K)
$\dot{m}_j$	Mass flow rate of the jet (kg/s)
Nu	Nusselt number (hd/k)
Nu_{avg}	Average Nusselt number
Nu_o	Maximum Nusselt number
q''	Heat flux (W/m^2)
q''_{joule}	Imposed Ohmic heat flux (VI/A) (W/m^2)
q''_{loss}	Total heat flux loss from impingement plate (W/m^2)
$q''_{rad(f)}$	Radiation heat loss from the front surface of impingement plate (W/m^2)
$q''_{rad(b)}$	Radiation heat loss from the back surface of impingement plate (W/m^2)
q''_{nat}	Heat loss by natural convection from the back surface of impingement plate (W/m^2)
Re	*Reynolds number* ($4/\pi d\mu$)
S	Swirl number
T_{amb}	Ambient temperature (° C)
T_{aw}	Adiabatic wall temperature (° C)
T_w	Wall temperature (° C)
TR	Twist ratio
V	Voltage (V)
w	Width of twisted tape
y	Axial distance of twisted tape corresponding to 180° twist angle
p/w	Twist ratio
z/d	Non-dimensional jet-to-plate spacing
μ	Dynamic viscosity (N-s/m^2)

swirling jet (created by vane type swirl generators) impingement on heated plate for $Re = 2300$, $z/d = 2$ to 10 and Swirl numbers (S) = 0, 0.21, 0.44 and 0.77. It is observed that the stagnation point Nusselt number in case of swirl jet is lesser than that for the jet without swirl and the maximum Nusselt number is found to be shifted for swirl jet at either side of the stagnation point. Stagnation point Nusselt number is the Nusselt number obtained at the point corresponding to the location of stagnation point on the flat plate as obtained in conventional circular jet. Due to presence of twisted tape, the air jet is divided into two parts. The velocity of air jet impingement corresponding to the stagnation point is reduced significantly. The jet splits into two parts and gives two new stagnation points compared to the conventional jet. There are two local peaks of Nusselt numbers in swirling jet compared to single peak of stagnation point Nusselt number obtained in conventional jet without swirl. The local Nusselt number in swirl jet at stagnation point is reduced due to presence of twisted tape but it is increased considerably on either side of stagnation point. Hence, there is an increase of average Nusselt number. The swirl jet impingement is found to produce more uniform heat transfer and giving higher average Nusselt number compared to without swirl jet impingement. The effect of swirling is prominent for lower jet to plate spacing ($z/d \leq 2$). The effect of swirling reduces with the increase in z/d. Beyond $z/d = 10$, the effect of swirling is negligible.

Yuan et al. [18] carried out experimental studies on swirling and conventional jet of carbon di-oxide stream submerged in air using thermo chromic crystal liquid technique. The Reynolds number of the flow considered ranges from 7500 to 28,300. They reported that the local Nusselt number for the swirling jet impingement is higher compared to that of the conventional jet (except stagnation point region). The increase in heat transfer was found to be pronounced in the region $0.35 \leq r/d \leq 0$. Ianiro e*t al.* [19] conducted experimental analysis on the multichannel swirling impinging jets generated by helical multi-channel inserts for Reynolds number (Re) 28,000 for various swirl numbers ($S = 0$, 0.2, 0.4, 0.6 and 0.8) and jet to plate spacing *(z/d)* equal to 2, 4, 6 and 10. The swirling jet is found to have better radial distribution of heat transfer rate. The average heat transfer rate is higher at swirl number equal to 0 and reduces further with increase in the swirl number.

Experiments were conducted by Nuntadusit et al. [20] on swirling jet impingement on a flat plate, The twisted tapes with twist ratios ($TR = p/w$) equal to 0, 3.64, 2.27, 1.82, and 1.52 are used as swirl generators with corresponding swirl numbers *(S)* equal to 0.0, 0.4, 0.62, 0.78 and 0.94. Reynolds number considered for the jet is $Re = 20{,}000$ and the jet to plate spacing *(z/d)* equal to 4 is maintained constant. The flow visualization is done using dye visualization technique. Heat transfer rates for S equal to 0 and 0.4 are found to compare with that of conventional circular jet. However, heat transfer rates reduced for higher swirl numbers *i.e.*, 0.62, 0.78 and 0.94. The flow visualization indicates spreading of jet before impingement on the plate. The spreading increased with the swirl number. Nuntadusit et al. [21] carried out experimental investigation on multiple swirling jets of 3 × 3 inline configuration with pitch *(s/d)* equal to 2, 4, 6 and 8 at a constant jet to plate spacing *(z/d)* equal to 4. The twisted tapes are used as swirl generators with twist ratio *(p/w)* equal to 3.6 corresponding to a swirl number *(S)* equal of 0.4. The heat transfer rate with multiple swirling jet is found to be higher compared to that of conventional multiple jets for all *s/d*. Nanan et al. [22] carried out experiments on swirling jet impingements over a flat plate to assess its potential of heat transfer augmentation. The results are obtained for various twist ratios ($p/w = 3$, 4, 5 and 6), jet to plate spacing (z/d = 2, 4, 6 and 8) and Reynolds number (Re = 4000, 8000, 12,000 and 16,000). It is observed that the heat transfer rate increases with the increase in twist ratio and reduces with the increase in jet to plate spacing (z/d). Amini et al. [23] have carried out CFD analysis of swirling air jet impinging on a flat plate for Re varying from 4000 to 16,000 and $TR = 3$ to 6. It is reported that two jets when replaced by a single jet with the same mass flowrate would increase the heat transfer rate and also provide better uniformity. Hindasageri et al. [24] have used twisted tapes for generating swirling flame jet impinging on a flat plate. The Reynolds number is varied from 500 to 2500 for equivalence ratio of 0.85–1.3. It is reported that swirl results in lowering of the premixed flame cone height and therefore the average Nusselt number decreases for larger distances of burner tip to impingement plate (z/d). At lower z/d, there is enhancement in average heat transfer and has better uniformity of heat transfer distribution.

Literature review suggests that the heat transfer studies with swirl are studied at high Reynolds number. Generally, twisted tapes perform better for lower Reynolds number because of the generation of the secondary flows. Hence, in this study, the influence of the twist ratio ($p/w = 2$, 3.2, 4.5 and 7.5), jet to plate spacing (1, 2, 3 and 4) on the local heat transfer distribution for different lower Reynolds number (500–3000 in steps of 500) is investigated. The