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# Experimental investigation of heat transfer characteristics and wall pressure distribution of swirling coaxial confined impinging air jets

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ABSTRACT

In the present study, swirling coaxial confined impinging turbulent air jets issuing from a novel designed nozzle is studied experimentally. Heat transfer characteristics and pressure distribution on the impingement plate are analyzed. Experiments have been conducted at different dimensionless nozzle-to-plate distances ($H/D$ = 0.5, 1.0, 1.5, 2.0 and 2.5) and dimensionless flow rates ($Q^*$ = 0.25, 0.50 and 0.75) for a constant total flowrate of $1.33 \times 10^{-3}$ m$^3$ s$^{-1}$ (80 L/min). The results show that the flowrate ratio improves the uniformity of the heat transfer through the impingement surface and increases the average Nusselt number. Also, the intensity of convective heat transfer is shown to enhance significantly with decreasing nozzle-to-plate distance. With regards to the pressure distribution, subatmospheric regions occur on the impingement plate. Contribution of swirl is also compared against the pure circular impingement jet condition ($Q^*$ = 0.0).



## 1. Introduction

Enhancement of the convective heat transfer is the primary agenda of many researchers, because effective removal of high heat fluxes from the surfaces is necessary for the systems with regards to reliable working conditions, longevity, more performance and minimized thermal stresses. As stated by Spinato et al. [1] one of the most popular/novel cooling techniques is the jet impingement. However, this unique technique is not only limited to the cooling applications, but also covers the heating and mass transfer processes [2,3]. Hence, it is related to many industrial applications such as cooling of electronic equipments and turbine blades, drying of textiles and paper, annealing of glass [4] and quenching of heated surfaces at nuclear reactors [3]. Due to the potential of the large usage area, a great deal of research attention has been devoted to the subject.

In general manner, a classical impinging jet consists of three basic regions [3,5]: A free jet region, an impingement flow region and a wall jet region. The flow structures in these regions are complex and influenced by many geometrical and physical parameters such as nozzle type, nozzle to impingement surface distance, confined or unconfined jet configurations, impingement surface geometry, fluid type and flow rate. The most common type of the impinging jet is the one issued through single circular or noncircular nozzles. In this regard, lots of studies were presented in the literature on the above parameters. Colucci and Viskanta [6] investigated the effect of hyperbolic type nozzle on the heat transfer coefficient for confined impinging turbulent air jets. They stated that Reynolds number and the nozzle-to-plate distance were more influential in the heat transfer behavior for confined jet conditions than the unconfined jets. They also stated that the local Nusselt numbers were independent of nozzle geometry for larger nozzle-to-plate distances ($H/D > 6$), while the Nusselt numbers had two maxima for lower distances ($H/D < 1$). The hyperbolic type nozzles were shown to present higher heat transfer performance than the conventional round types. Baydar [7] studied fluid flow characteristics of impinging air jet both for the laminar and turbulent conditions in the case of single and double jet. He stated that a subatmospheric region took place up to nozzle-to-plate distance of two for Reynolds number higher than 2700. He also underlined the relation between the subatmospheric region and the peaks in the heat transfer coefficients. Duda et al. [8] employed smoke-wire visualization technique to investigate the behavior of a round jet from a straight tube. They measured the velocity and turbulence intensity at the jet exit. They concluded that when the jet exit-to-surface spacing increased from two to five, significant effects could be seen, which were listed as stabilization of the flow, extension of the potential core and a reduction in vortex formation before impingement. Yakkatelli et al. [9] explored the behavior of a single round jet through smoke-wire visualization technique. They used foamed aluminum heat sink as the impingement body. They stated that an increase in Reynolds number from a laminar to a

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**Nomenclature**

| | |
|---|---|
| $A$ | cross sectional area [m$^2$] |
| $A_r$ | cross sectional area of the inner circular nozzle [m$^2$] |
| $A_s$ | surface area of the impingement plate [m$^2$] |
| $D$ | outer diameter of the nozzle [m] |
| $D_i$ | inner diameter of the circular passage [m] |
| $h$ | local convective heat transfer coefficient [W m$^{-2}$ K$^{-1}$] |
| $H$ | distance between the impingement surface and the nozzle exit [m] |
| $h_s$ | height of the helical swirling passage [m] |
| $k$ | thermal conductivity [W m$^{-1}$ K$^{-1}$] |
| $q_{conv}$ | heat loss due to the convection [W] |
| $Nu$ | local Nusselt number, $Nu = hD/k$ |
| $Nu_{avg}$ | area-averaged Nusselt number, $Nu_{avg} = \bar{h}D/k$ |
| $Q$ | volumetric flow rate, [m$^3$ s$^{-1}$] |
| $Q^*$ | dimensionless flowrate ratio, $Q^* = Q_s/Q_{tot}$ |
| $P$ | Pressure |
| $r^*$ | dimensionless radial distance, $r^* = r/D$ |
| $r$ | radial distance [m] |
| $r_{hi}$ | radial distance from the center of the nozzle to the inner surface of a swirling passage [m] |
| $r_n$ | radial distance from the center of the nozzle to the outer surface of a swirling passage [m] |
| $Re$ | Reynolds number, $Re = u_m D_i/v$ |
| $S$ | swirl number, $S = \frac{2}{3}\left[\frac{1-(r_{hi}/r_n)^3}{1-(r_{hi}/r_n)^2}\right]\tan\theta$ |
| $T_j$ | jet temperature [K] |
| $T_s$ | impingement surface local temperature [K] |
| $u$ | velocity [m s$^{-1}$] |
| $w_s$ | width of the helical swirling passage [m] |

*Greek symbols*

| | |
|---|---|
| $\beta$ | impingement plate angle |
| $\Delta P$ | pressure difference between the local static pressure on the impingement surface and the atmospheric pressure [kPa] |
| $\theta$ | swirl angle |
| $v$ | kinematic viscosity [m$^2$ s$^{-1}$] |

*Subscripts*

| | |
|---|---|
| $a$ | ambient |
| $j$ | jet |
| $m$ | mean |
| $r$ | round |
| $s$ | swirl |
| $st$ | stagnation |
| $tot$ | total |

turbulent jet lead the flow to penetrate the porous media more evenly and decreased the recirculation region at the exit of the foam. Öztekin et al. [10] experimentally and numerically explored the heat transfer characteristics of a turbulent slot air jet impinged on concave plates. They stated that the average and stagnation point Nusselt numbers decreased with increasing nozzle-to-plate distance and increased with Reynolds number. They underlined the importance of the curvature radius on the heat transfer performance. The best performance was obtained for the dimensionless curvature radius of 1.3. Guo et al. [11] studied transient heat transfer characteristics of turbulent impingement air jet issuing from a circular nozzle with an inner diameter of 6 mm. At different non-dimensional distances (from the stagnation point), the local Nusselt number reached its maximum value within 50–80 s and then it became constant through the experiment. A comprehensive review of the similar studies can be found in the review article presented recently by Shukla and Dewan [12].

Conventional impinging jets may be a good choice for spot cooling applications since the Nusselt number has its maximum values in the vicinity of the stagnation point and then suddenly decreases. However, for some applications such as cooling of electronic components, an efficient thermal management and thus, providing the radial uniformity of the heat transfer is essential. This is important for decreasing the thermal stresses, which provides reliable working conditions, longevity and more performance for technological systems. In this context, as also stated by Eiamsa-ard et al. [13], a swirling jet is a good alternative due to introducing the tangential component. Therefore, some researchers focused on swirling impinging jets. However, the swirl flow can be provided by many different ways, which provides larger research potentials/areas in the relevant literature. Huang and El-Genk [14] investigated and compared the performance of swirling and conventional multi-channel impinging jets by conducting heat transfer and flow visualization experiments. They etched four swirling passages around a solid rod with different swirl angles (15°, 30° and 45°). They stated that swirling impinging jets presented higher Nusselt numbers and significant enhancements in radial uniformity of heat transfer than the multi-channel impinging jets and conventional impinging jets. Yang et al. [15] experimentally investigated the characteristics of annular impinging jet with and without swirling motion. They inserted helical guide vanes in the annular gap of the test piece to form the swirling motion. It was declared that the swirling annular jet caused more non-uniform wall pressure and heat transfer distributions than conventional annular ones at short and intermediate separation distances; on the contrary, the reverse is valid for larger separation spacing. Nuntadusit et al. [16] experimentally explored the flow and heat transfer characteristics of multiple swirling impinging jets for different jet to jet distances for a fixed nozzle-to-plate distance of 4. The swirl motion was obtained via twisted tapes with a constant swirl number of 0.4. They concluded that the multiple swirling impinging jets showed higher heat transfer than the multiple conventional ones. In another article [5], the authors investigated the effect of twist ratio which was defined as the width of the twisted tape over each twist length. The each twist length was obtained by dividing the length of the twisted tape into the number of twist. They obtained an optimum twist ratio for the heat transfer enhancement. Eiamsa-ard et al. [13] performed an experimental study in order to investigate the heat transfer behavior for co/counter-dual swirling impinging jet arrangements. They placed two twisted-tapes into a pipe as a swirl generator. They stated that for smaller nozzle-to-plate distances ($H/D$ = 1 and 2) swirling jets presented higher average Nusselt number against the conventional jets. Ahmed et al. [2,3] investigated fluid flow and heat transfer characteristics of swirling and non-swirling turbulent impinging jets. They concluded that at lower nozzle-to-plate distances the swirling jet leads to higher heat transfer than the non-swirling ones, and high jet turbulence are related to the peak in the Nusselt number.

On the contrary of the above articles, in some studies, it was stated that swirling structure affected adversely the averaged heat transfer [17–19]. Most probable reason of this contradiction may be attributed to the geometrical arrangement of the nozzles. As stated clearly by a recent article [3], in the literature, there are ongoing debates with regards to the fundamental relationship