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The Effect of Swirl on Array of Turbulent Impinging Jets

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ABSTRACT

Impinging jets are widely used for their effective heat and mass transfer for several decades. Arrays of jet impingement have also been studied before due to its practical relevance to electronics cooling. A number of jet variations and jet-to-jet orientations have previously been studied, mainly to further improve the magnitude and uniformity of heat transfer. In recent years, swirling jets has also gained interest in heat transfer application due to their inherent mixing and spreading characteristics, which is believed to be an improvement on overall heat and mass transfer. As such, this paper numerically investigates an array of circular jets with and without swirl that impinges vertically onto a flat surface located at a fixed vertical distance H = 2D and at Reynolds number equals to 11,600, where D is the nozzle diameter. As the entire was symmetric, only quarter of the model was constructed for numerical analysis to save computational cost. In this case, numerical calculations were done via commercial software package ANSYS Fluent using SST k-ω turbulence model. Inlet conditions were taken from experimental data. The jet flows were in downward direction and gravity was not considered. This paper also compares numerical predictions with previously published literature for non-swirling and swirling jets.

Keywords: Swirl jet, Impingement, Turbulence, Heat transfer, CFD.

1. Introduction

Jet impingement is one of the most effective media for removing heat from heated surfaces with high heat flux. The high heat removal rate of jet impingement had gained a prior position of research topic among the researchers for several decades. Impinging jets are widely used in various engineering and industrial applications, such as cooling of turbine blades and micro electric components, quenching and annealing of non-ferrous sheet metals, tempering of glass, freezing of tissues in cryosurgery [1].

Jet is a stream of fluid that is projected into a surrounding medium, usually from some kind of a nozzle, aperture or orifice. Jets can travel long distances without dissipating. Swirl means to move with an eddying or whirling motion.

In majority of the previous research, orthogonal jet impingements onto flat surfaces or plates from which heat transfer occurs are primarily focused. The jet flows emanating from a nozzle may either be non-swirling or swirling, with their own pros and cons. Jets can also be categorized into circular jet, slot jet, inclined jet etc depending on the orifice opening or geometric arrangements. Their effects on fluid flow and heat transfer behavior are also different. For example, heat transfer by convection from a hot gas jet to a plane surface was observed to increase as twice as the initial value with the change of axis-symmetric angle of the jet from 15°-90° [2]. Again, for the same flow rate the circular jet yielded 8% higher heat transfer than the slot jet [3]. In comparison to non-swirling jet, swirling jets were examined by many researchers. Research out comes suggest that swirling jets are beneficial over non swirling jets. It had been found that swirling jet has higher Nusselt number and better uniformity in heat-transfer which is the prior criteria in many cooling operations to reduce fracture and to improve grain growth for higher strength [4].

In order to experiment that whether increasing the number of jets increases the heat transfer or not jet arrays were studied by several researchers during the past decades. Jet interference in impingement arrays is the main striking difference compared to a single jet. It is reported that in case of array impinging jet the nozzles spacing of from 4-6 diameters results best heat transfer results [5]. Results of many investigations on circular non-swirling jets are in a good agreement that single jet yields better heat transfer than that of array impinging jets [6]. The central jet has the shortest core and the highest kinetic energy due to higher number of neighboring jets and the reverse is true for peripheral jets [7]. For larger jet-to-jet distance regardless of jet-to-plate distances the cross flow doesn't disturb the fluid motion of the neighboring jets. It had also been reported that the jet-to-jet distance is the major factor whereas jet-to-plate is the minor [8]. The above results are valid only for non-swirling jets. As such, it would be interesting to examine swirling flows in arrays, as single swirling jets were found to have rather different behaviors.

In this paper, an array of circular air jets is studied to determine the effect of swirl on heat transfer during cooling by an array of swirl jets. The effect of swirl jets that impinged vertically onto a flat surface located at a fixed vertical distance *H/D* = 2 and at Reynolds number equals to 11,600 were studied. The widely used k-ω model does not properly represent the flow features and highly over predicts the rate of heat transfer and yields physically unrealistic behavior [9]. SST k-ω turbulence model is a combination of the k-epsilon in the free stream and the k-omega models near the walls. It does not use wall functions and tends to be most accurate

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when solving the flow near the wall. Hence this model had been used to calculate the results in this analysis.

2. Numerical Methodology

An array of 25 circular nozzles were considered for developing the swirling and non-swirling impinging jets. The nozzles are arranged in inline and staggered arrangements. All of them were axi-symmetric, equally spaced in 3 circles around a central nozzle in which the diameter of first circle is 5*D*, the second circle 9*D* and the third circle 13 *D*. The diameter of each nozzle is 40 mm, the distance between the centers of two corresponding nozzle is 80 (2*D*) mm while the distance between them is 40 (*D*) mm. As the entire two models were symmetric, only quarters of the models were constructed for numerical analysis to save computational cost. Jet-to-plate distance was *H*=2*D* and the radial extent of circular plate is considered 16 *D*.

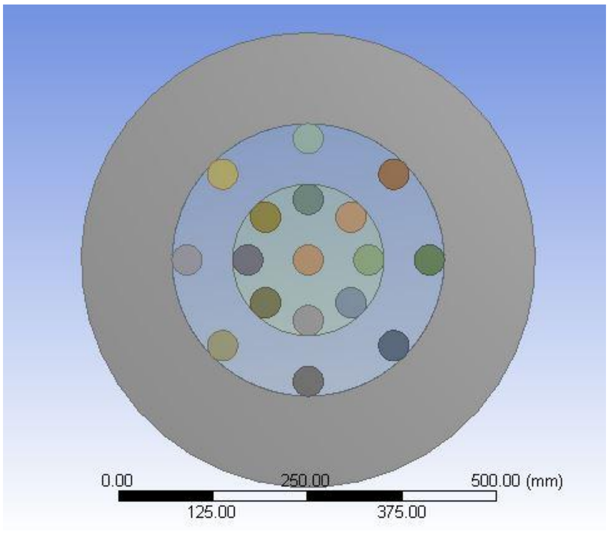


Fig.1 Top view of the array of nozzles

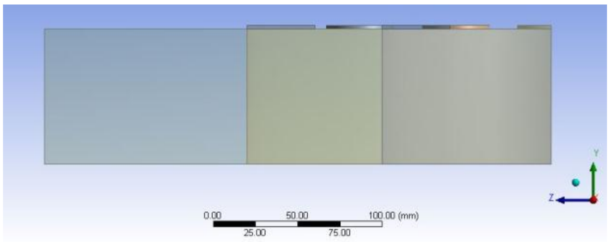


Fig.2 Front view of the array of nozzles

For numerical simulation, SST k-ω viscous model is used for solving the problem. Air was taken as fluid with the following properties: Density-1.225 kg/m^3, Specific Heat-1006.43 J/kg-K, Thermal Conductivity-0.0242 W/m-K and Viscosity-1.78e-05 kg/m-s. Inlet conditions of the swirling impinging jets were taken from Ahmed et al. [11] in which swirling jet was produced with an aerodynamic swirl generator. The profile of the data was set as the inlet boundary conditions in all nozzles. The fluid inlet temperature is set to ambient (300K). Outlet boundary was set as pressure outlet with backflow turbulent intensity 5% and backflow turbulent viscosity ratio 10 similar to the numerical simulation of Ahmed et al. [12]. Symmetry boundary condition was applied in two side surfaces for non-swirling jets and periodic boundary conditions for swirling jets. In this regard, corresponding surfaces were match controlled during meshing in order to impose periodic boundary. The pressure velocity coupling was solved using the coupled solver with Green-Gauss Cell special discretization for gradients, PRESTO for pressure and second order upwind was used for momentum, turbulent kinetic energy, specific dissipation rate and energy. All the residuals were set to 10^{-05} for accuracy except energy to 10^{-06}. Mesh consisting of 898k nodes was used to predict the final result. Inflation was applied with 15 layers and growth rate of 1.2 near the plate region and the mesh was generated from fine mesh near the axis to coarser mesh in the radially outward direction.

3. Data Validation

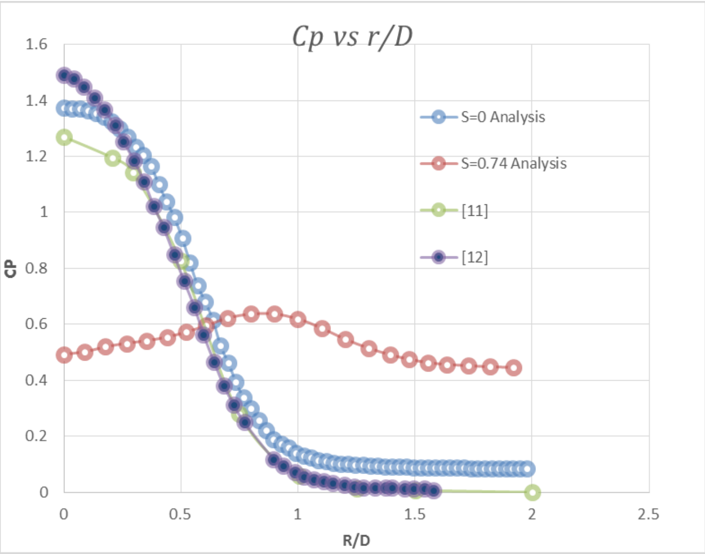


Fig.3 Data validation of *Cp* vs R/D chart

Fig. 3 presents a comparison of the effect of swirl on the radial distributions of (impingement surface) static pressure for S=0 and 0.74 and H=2D at Re=11600 between the current simulation data and experimental data derived from the literature. The current numerical data is found to be in good agreement with the literature except for swirl number 0.74 Cp decreases (with radial distance) from a maximum at the stagnation point and shows a Gaussian-like distribution, with maximum Cp at the center line similar to non-swirling flows. The radial position of the maximum Cp moves outward due to the higher centrifugal effects as swirl number increases. The reduction is largely attributed to the axial deceleration of the swirl flow.

4. Results and Discussion

Fig. 4 shows the *Cp* variation for non-swirl and swirl inline jets at impinging plane along the radial line in horizontal direction where r/D=0 indicates the origin and r/D=16 indicates the end of the fluid body. It is observed from the figure that for non-swirl, reductions of *Cp* occur particularly around the impingement regions between the jets and gradually decreases in between 6D to 16D.

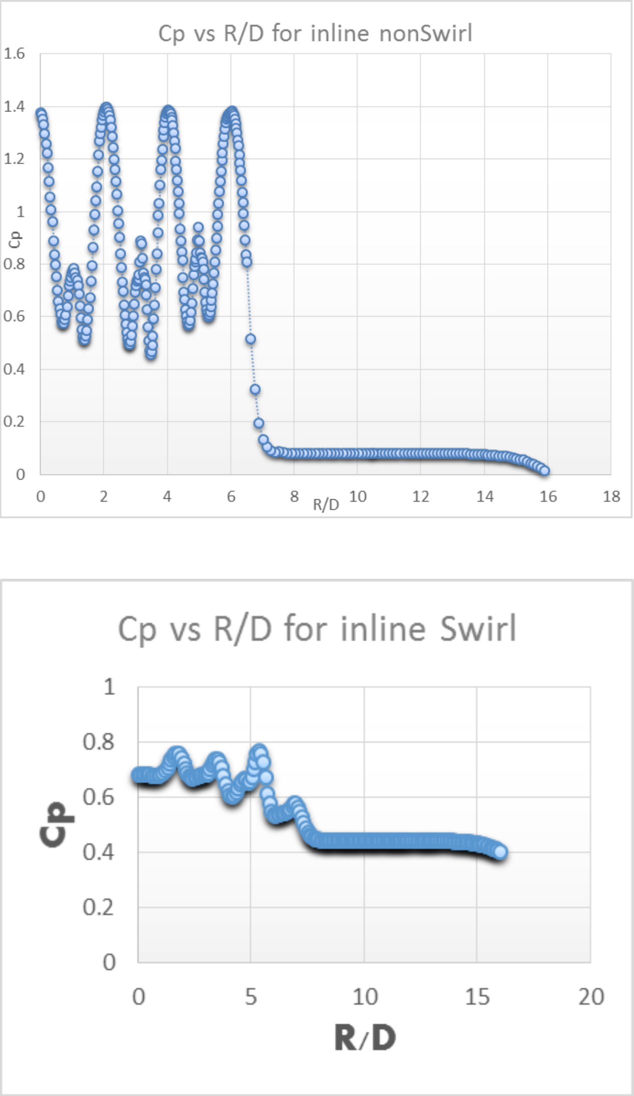
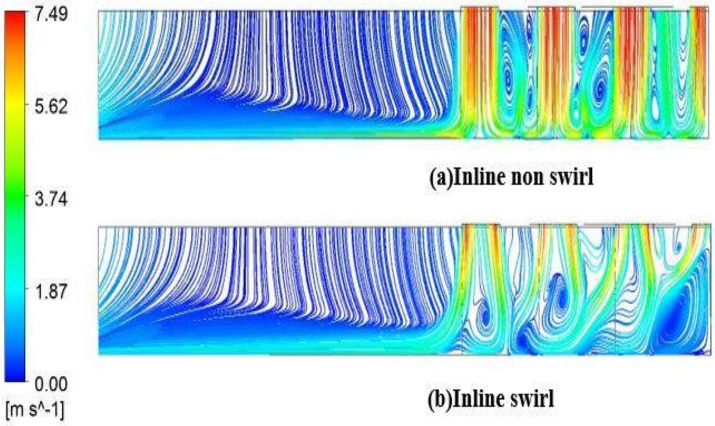


Fig.4 *Cp* for S=0 and S=0.74 at inline arrangement of nozzles

For swirl it is observed that gradual increasing and reduction of Cp happened in between impinging region (r/D <8). The radial position of the maximum Cp moves outward due to the higher centrifugal effects as swirl number increases. The results show that pressure is found to be the maximum in the stagnation regions where the flow strikes the plate and then it reduces fast both radially and circumferentially. For swirl flow the pressure is relatively more uniformly distributed over the impingement plate than non-swirl flow.

Fig. 5 represents the velocity streamline of array impinging jet for non-swirl and swirl flow for both inline and staggered arrangements of jets. The origin (0,0) corresponds to the center and the flow is distributed radially between 0 to 16*D*.



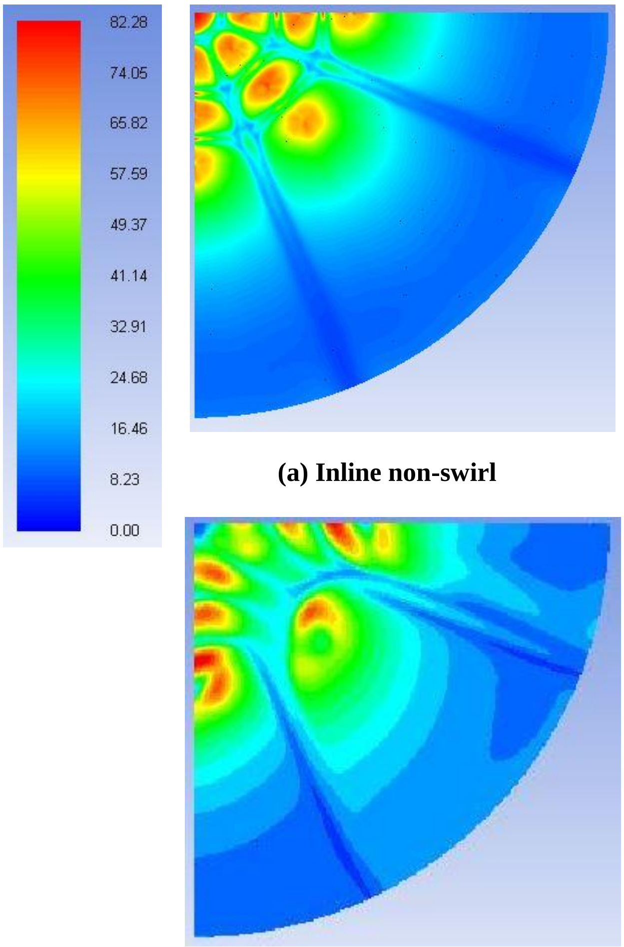
(a)Inline non swirl

(b)Inline swirl

Fig.5 Velocity streamlines for S= 0 and 0.74 at inline arrangement of nozzles

It is seen that a recirculation region appears between two jets for both non-swirling and swirling flows. For non-swirling jets, the jets create a fountain, with an upward movement of the flow, whereas in swirling jets such upward fountain is not evident. Rather, the flow passes between recirculating zones, which occurs between the first two jets from the center and between the jets near the wall. It is also clear from the above streamlines that for non-swirl flow the jet strikes the heated plate whereas swirl jets deviates from well before the impingement surface resulting a moderate recirculation around the stagnation zone. It is clear that from 4.5 D to 16 D both the streamline of swirl flow and non-swirl flow are closely attached to the heated plate. Depending on the distance or proximity of the neighboring jet the flow field may vary with significant changes which may affect the heat transfer distribution over the impingement surface. The results for velocity streamlines ensure that the strength of recirculation for swirl flow is greater than that of non-swirl flow and the distance between the neighboring jets plays a great role in this recirculation effect.

Fig. 6 shows contour map of convective heat transfer coefficient (*h*) over the range S=0 and S=0.74 in near-field (H=2D) impingement for the case of inline arrangement.



(a) Inline non-swirl

(b) Inline swirl

Fig.6 Convective heat transfer coefficient for S= 0 and 0.74 at inline arrangement of nozzles

For *S*=0, a higher convective heat transfer coefficient (*h*) band appears outside the jet center with a lower *h* zone occurring immediately at the jet center. Outside the periphery of this higher *h* zone, another (outer) low *h* zone occurs, before heat transfer peaks up again at even further radial distances. For the swirling jets, a strikingly difference heat transfer behavior is predicted. In this regard, maximum heat transfer occurs between the neighboring nozzles, not below the nozzle as in the case of non-swirling jet arrays. Additionally, the lowest heat transfer occurs under the central jet, which perhaps due to the recirculation seen in the velocity streamline. The occurrence of relatively two maxima in convective heat transfer coefficient (inner and outer) have been attributed to the rapid change of radial velocity in the streamline deflection region and to destruction of the thermal boundary layer by the large-scale eddies which strikes the surface. The minima in *h* around the jet center may also be attributed to the weak penetration of shear layer induced turbulence, which is particularly true at H = 2D due to this relatively small impingement distance.

5. Conclusion

This paper describes the behaviors of an array of incompressible turbulent impinging air jets for both non-swirl and swirl flows. The governing equations are solved using a commercial software package Ansys Fluent v16.2.by using a turbulence model SST k- ω. The study is performed for two conditions: non-swirling (*S* = 0) and highly swirling (*S* = 0.74) for a nozzle-to-plate distance of 2*D* at *Re*=11,600. Velocity streamline, pressure distribution, heat transfer distribution are investigated for both of these arrangements separately. The results for velocity streamlines ensure that the strength of recirculation for swirl flow is greater than that of non-swirl flow. The distance between the neighboring jets plays a great role in this recirculation effect. The pressure distribution indicated a more uniform distribution for swirl impinging arrays than its non-swirling counterpart. This distribution also plays a great role for achieving a better result in the goal of impingement cooling. Convective heat transfer coefficient distribution showed the larger heat transfer zones in the stagnation zone for non-swirling jets and between the neighboring jets for swirling jets.

NOMENCLATURE

Cp	: Coefficient of pressure
P	: Pressure, Pa
S	: Swirl Number
h	: Convective heat transfer coefficient
R	: Radial distance, m
T	: Temperature, K
D	: Diameter of nozzle, m
H	: Distance between nozzle tip and plate, m
Re	: Reynolds Number

REFERENCES

[1] Behnia, M., Parneix, S., and Durbin, P., Accurate modeling of impinging jet heat transfer, Center for Turbulence research, Annual Research Briefs, pp. 149-164, 1997

[2] Womac, D. J., Ramadhyani, S., and Incropera, F. P., Correlating equations for impingment cooling of small heat sources with single circular jets, Journal of Heat Transfer, vol. 115(1), pp. 106-155, 1993

[3] Fitzgerald, J. A., and Garimella, S. V., Flow field effects on heat transfer in confined jet impingement, Oceanographic Literature Review, V. 1(45), pp. 199, 1998

[4] Cooper, D., Jackson, D.C., Launder, B.E., Liao, g.x. Impinging jet studies for turbulence model assessment. Part I: Flow-field experiments, Int. J. Heat Mass Transfer, Vol. 36, pp. 2675-2684, 1993

[5] Brevet, P., Dejeu, C., Dorignac, E., Jolly, M., and Vullierme, J., J., Heat transfer to a row of impinging jets in consideration of optimization, International Journal of Heat and Mass Transfer, vol. 45(20), pp. 4191-4200, 2002

[6] Viskanta, R., Heat transfer to impinging isothermal gas and flame jets, Experimental Thermal and Fluid Science, vol. 6(2), pp. 111-134, 1993

[7] Geers, L. F., Tummers, M. J., and Hanjalic´, K., Experimental investigation of impinging jet arrays, Experiments in Fluids, vol. 36(6), pp. 946-958, 2004

[8] Wienand, J., Riedelsheimer, A., and Weigand, B., Numerical study of a turbulent impinging jet for different jet-to-plate distances using two-equation turbulence models, European Journal of MechanicsB/Fluids, vol. 61, pp. 210-217, 2017

[9] Behnia, M., Parneix, S., and Durbin, P. A., Prediction of heat transfer in an axisymmetric turbulent jet impinging on a flat plate, International Journal of Heat and Mass Transfer, vol. 41(2), pp. 1845-1855, 1998

[10] Geers, L. F., Multiple impinging jet arrays: an experimental study on flow and heat transfer, PhD Thesis, Technical University, Delft , The Netherlands, 2004

[11] Ahmed, Z. U., Al-Abdeli, Y. M., and Guzzomi, F. G., Impingement pressure characteristics of swirling and non-swirling turbulent jets, vol. 68, Experimental Thermal and Fluid Science, pp.722–732, 2015

[12] Ahmed, Z. U., Al-Abdeli Y. M., and Matthews, M. T., The effect of inflow conditions on the development of non-swirling versus swirling impinging turbulent jets, vol. 118, Computers & Fluids, pp. 255-273, 2015