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Numerical Investigation of Arrays of Circular Swirling 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 swirl that impinges vertically onto a flat surface located at a fixed vertical distance H/D = 2 and at Reynolds number equals to 11,600, where D is the nozzle diameter. In this case, governing equations were solved by coupled algorithm via commercial software package ANSYS Fluent using SST k-ω turbulence model. The results show a significant change in velocity field, which also influence heat transfer when compared to correspond to its non-swirl jet impingements. The paper also compares numerical predictions with previously published literature for non-swirling jets.*

Keywords: Swirl jet, Impingement, Turbulence, Heat transfer

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].

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 too by many researchers. Research outcomes 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-ε 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 when solving the flow near the wall. Hence this model had been used to calculate the results in this analysis.

2. METHODOLOGY

An array of 17 circular nozzles were considered for developing the swirling impinging jet. All of them were axi-symmetric, equally spaced in 2 circles around a central nozzle in which the diameter of first circle is 2*D* and the second circle 4*D* (Figure 1). 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 model was symmetric, only quarter of the model was 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 15 *D* and made of steel.

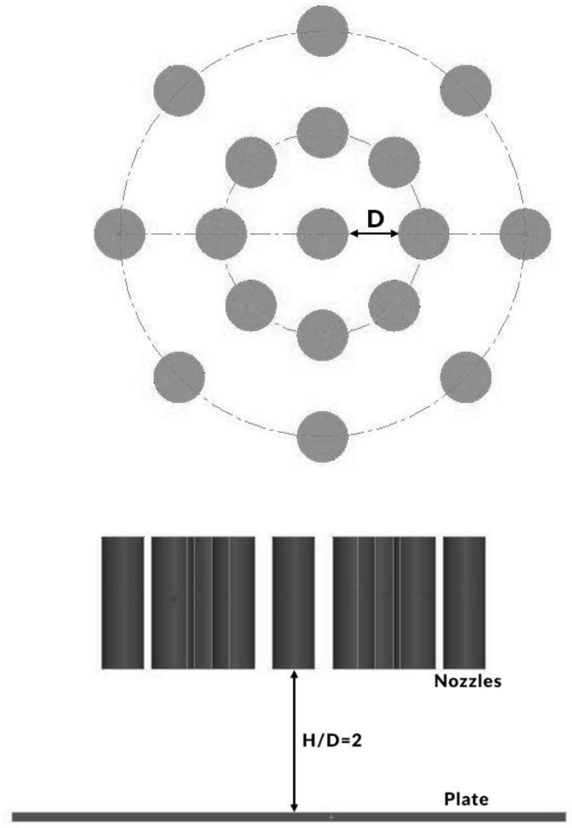

Fig.1: Physical setup and geometry of the nozzles

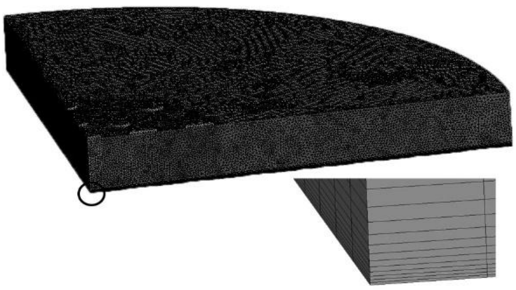

Fig.2: Solution domain and its mesh. Detailed view shows the near wall mesh refinement

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/m3, 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 (300 K). 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 of the computational domain is shown in the Figure 2. 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. Mesh independency was performed (not shown here) and the mesh consisting of 470010 nodes was found to be sufficient to predict the final result.

3. VALIDATION

To validate the numerical model and solutions, the current results are validated against published literature for both velocity and heat transfer data.

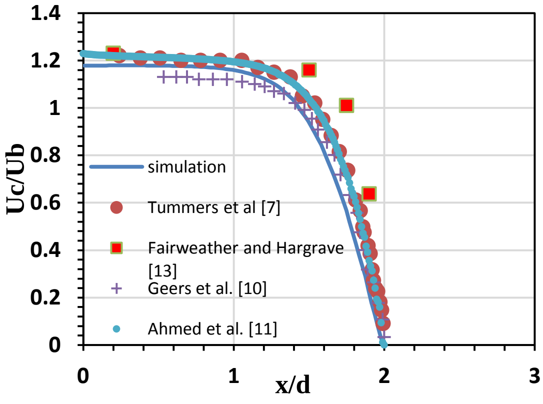

Fig.3: Comparison of the current simulation for velocity

distribution for single nozzle flow along centerline

Figure 3 presents a comparison of radial distribution of non-dimensional centerline axial velocity (U_c/U_b) of non-swirling jets between the current simulation data and experimental data derived from the literature [7, 13, 10, 11]. The current numerical data is found to be in good agreement with the literature, except Fairweather and Hargrave [13], where relatively larger deviation is observed as the jet approaches impingement surface. It may be due to the difference in nozzle dimension and difference in inlet conditions. The maximum velocity appears at the center and then diminishes as the impingement region starts, which eventually becomes zero at the surface.

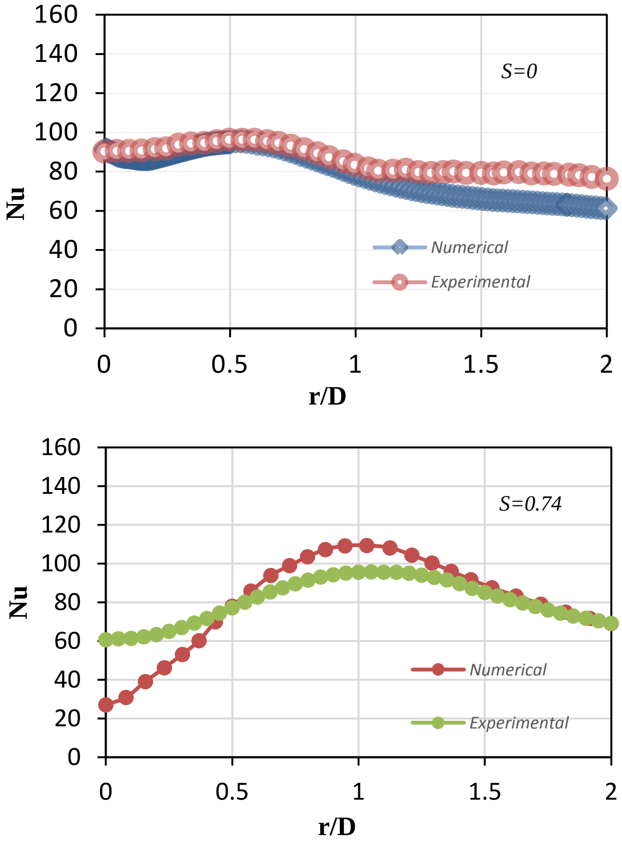

Fig. 4: Local Nusselt number comparison along radial direction for both non-swirling (S=0) and swirling (S=0.74) single nozzle flow at Re=11,600 and H/D=2.

The validation of local Nusselt number distribution of the non swirl flow and swirl flow is also necessary in order to demonstrate the accuracy of surface heat transfer and reliability of our numerical results. For this purpose, numerical results for both swirling and non-swirling cases are compared with the experimental data [Ref for Ahmed et al]. Similar to the velocity, a good agreement is again obtained in terms of both distribution and magnitudes. A slight deviation from the experimental data is also observed at $r/D > 1.5$ for non-swirling flow and $r/D < 0.5$ for swirling flows. These are due to the in the intense flow mixing and turbulence in those regions [11, 14]. Both velocity and heat transfer comparisons showed the reliability and accuracy of current numerical methodology.

4. RESULTS & DISCUSSIONS

Figure 4 (a) represents the velocity streamline of array impinging jet for non-swirl and swirl flow. The origin (0,0) corresponds to the center and the flow is distributed radially between 0 to 15D.

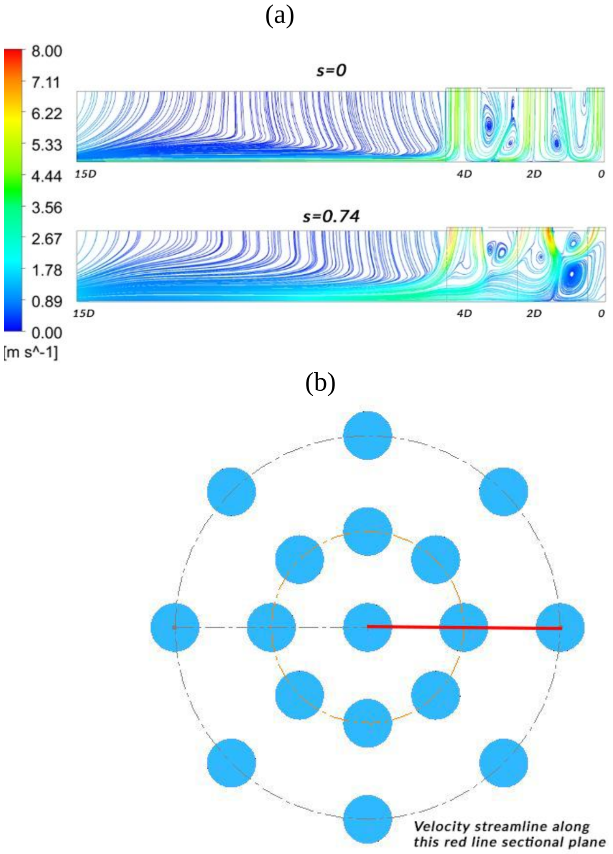

Fig.4 (a) : Velocity Streamline for array impinging jet non swirl flow and swirl flow, (b): the plane for the streamlines

As mentioned earlier, the basic additional observation parameter between the single jet and array of impinging jet is the interaction between the neighboring jets. It is seen from Figure 4a 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. These results for non-swirl flow agrees well with Geers et al. [10], who studied impinging jet arrays at low H/D for the large jet spacing. They also suggests that strong cross flow streams near the heated surface caused the horse-shoe vortices around the peripheral jets, swept the fluid away, and even break up the jets. It is clear that from 4.5 D to 15 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 which is further scope of our analysis.

Figure 5 presents the static pressure distributions over the impingement surface for both non-swirling and swirling flows. The color scale is same for both figures in order to better comparison. The results show that for non-swirl flow 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. In contrast, the pressure is relatively more uniformly distributed over the impingement plate.

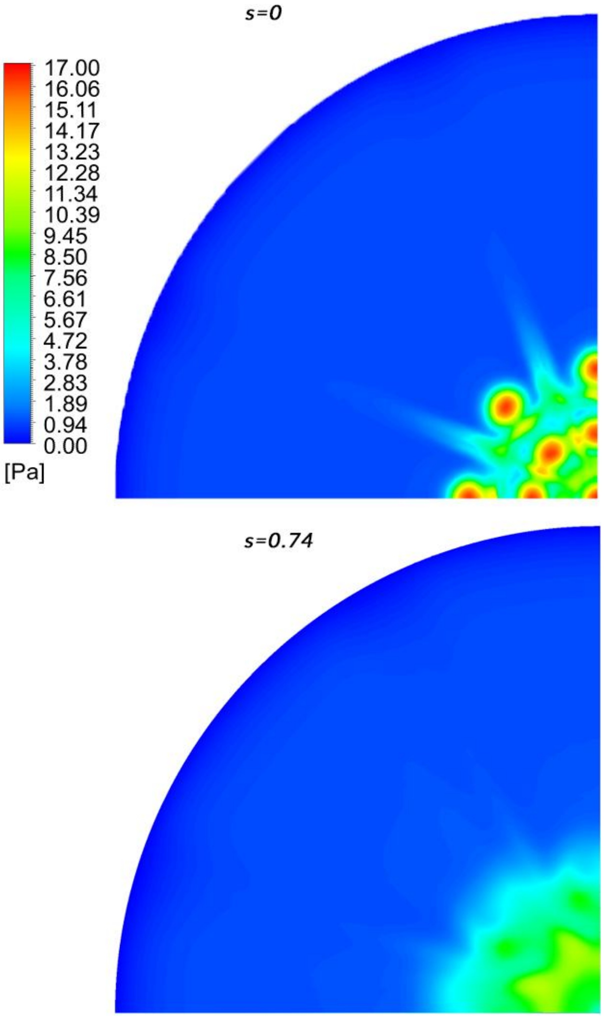

Fig.5: Pressure Distribution over the impingement surface for swirl flow and non-swirl flow

Figure 6 shows the heat transfer distributions in terms of a non-dimensionless Nusselt number over the impingement surface for both non-swirl and swirl flow at H/D=2 and Re=11,600. Nusselt number is defined here as $Nu=hD/K$, with h the convective heat transfer coefficient, D the diameter of the jet and K the thermal conductivity of the surface. Again, same color scale is used for both figures. The result shows that whilst maximum heat transfer occurs in the stagnation point and surrounding zone for each jet and then reduces as it moves away from the stagnation point. This behavior is similar for non-swirling single jet. However, the difference in the distribution is that a heat transfer reduction due to the upwash between the jets. For non-swirl impingement it is evident that below the nozzle heat transfer is not uniform. Geers et al. [10] reported this non-uniformity is due to the flow asymmetry over the whole domain, which, in fact, is a natural phenomenon.

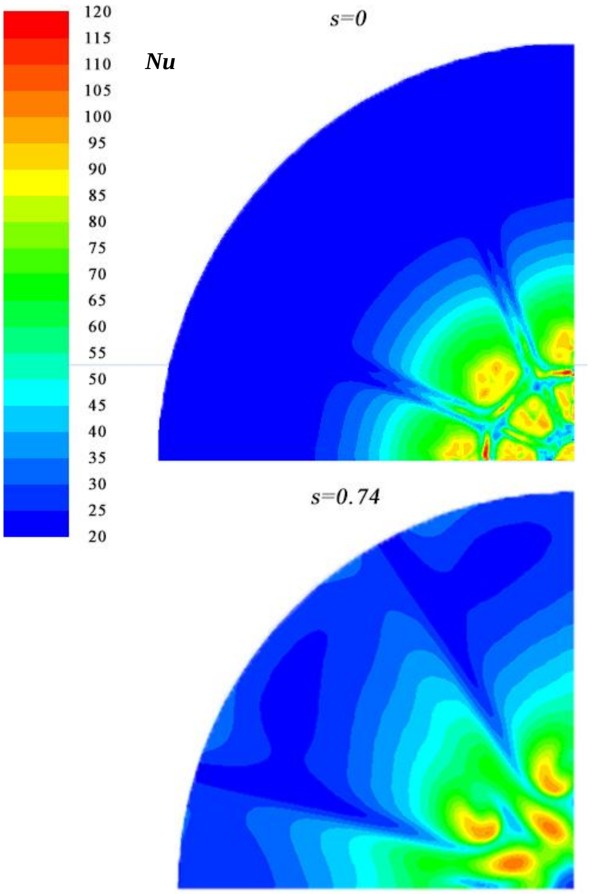

Fig.6: Nusselt number distributions for swirl flow and non-swirl flow over the impingement surface

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. Such low Nu region is also observed in the midst of neighboring jets, which may also be due to the recirculation occurred near the surface.

5. CONCLUSION

This paper describes the behavior 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 v17.0. 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 2D at Re=11,600. The numerical results are compared with the experimental data and found to be in good agreement. 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. Nusselt number distribution showed the larger heat transfer zones in the stagnation zone for non-swirling jets and between the neighboring jets for swirling jets.

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7. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(K)
P	Pressure	(Pa)
U_c	Velocity along Centerline	(ms^{-1})
U_b	Bulk velocity	(ms^{-1})
Nu	Nusselt Number	-
S	Swirl number	-
Re	Reynolds Number	-
r	Radial distance	(m)
D	Diameter of nozzle	(m)
H	Distance between nozzle tip and plate	(m)