EXPERIMENTAL AND CFD ANALYSIS OF SWIRL, NOZZLE ARRANGEMENT, CROSS-SECTION AND JETS DIAMETER ON HEAT TRANSFER IN MULTI-JET AIR IMPINGEMENT COOLING

by

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Experimental investigation and CFD analysis were performed to study the effects of swirl, nozzle arrangement, cross section of nozzle, number of jets and jet diameter on heat transfer coefficient in multi-jet air impingement cooling for a target surface of 100 ×150 mm size supplied with a constant heat flux of 7666 W/m^2*. The normalized heat transfer coefficient based on unit volume of air is evaluated through measurement of temperature for flow Reynolds numbersin the range of 8000-22000 with H/D ratiosof 1, 2, 4, and 6. Investigations with and without swirl reveal that among the tested conditions, for 8 mm jets, introducing swirl reduces the heat transfer where as for 10 mm and 12 mm jets, swirl improves the average heat transfer rate. For sets of 12 nozzles configurations, the staggered arrangement for 6 mm and 8 mm nozzles results in higher heat transfer rate than in-line arrangement unlike in 4 mm nozzles where in-line arrangement is better. Heat transfer coefficients for circular, square and triangular cross-sections of same flow area have been compared. Circular cross-section offers better heat transfer coefficient for all the tested conditions. For a given number of nozzles, there is an optimum diameter corresponding to maximum value of normalized heat transfer coefficient. The results are corroborated with CFD analysis for a few representative conditions tested.*

Key words: *heat transfer, jet impingement cooling, normalized heat transfer coefficient, swirling jet*

Introduction

Jet impingement cooling finds application in many engineering industries due to its ability to produce high local heat transfer coefficients. Annealing of metal and plastic sheets, tempering of glass sheets, drying of paper and textiles, cooling of gas turbine blades and electronic components, chemical vapour deposition and anti-icing of aircrafts are some of the important applications. Several researchers have studied the fluid-flow and heat transfer characteristics of a single jet impinging on a flat surface. It is reported by many authors that jet Reynolds number, jet to target spacing, turbulent intensity are the important operating parameters that decide the magnitude of the heat transfer coefficient attained [1-7]. Hrycak [8] has compiled the correlations proposed by several authors for the Nusselt number governing heat transfer of a flat surface exposed to a jet impinging on it as a function Prandtl number, Reynolds number, and

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the ratio of distance of the target space from the jet to the diameter of the jet. Jambunathan *et al*. [9] have critically reviewed and consolidated the data pertaining to rate of heat transfer from impinging turbulent jets with nozzle exit Reynolds numbers in the range of 5000-124000, nozzle to plate spacing of 1.2 to 16 times the diameter of the nozzle within a flow region of six times the nozzle diameter from the stagnation point. It was observed that the constant exponent of Reynolds number in the expression for Nusselt number is a function of ratio of nozzle to plate spacing to diameter of the jet (H/D) and the until a H/D of 12, Nusselt number is independent of H/D, in the region beyond radii greater than six nozzle diameters from the stagnation point. Zuckerman and Lior [10] have reported the physics of fluid-flow and heat transfer phenomena and have compared different CFD turbulent models applied for impingement jet cooling and their relative merits and demerits. A comprehensive list of various correlations for predicting Nusselt number for circular and slot jets of different configurations proposed by many researchers has been presented by the authors. Katti *et al* [11] have investigated experimentally the effect of jet to plate distances on Nusselt number in the case of impinging submerged circular air jet. The stagnation point Nusselt number is found to be maximum at H/D of 6 for high Reynolds numbers and for the low Reynolds numbers (less than 12000) the maximum value occurs at H/D of 0.5.

Uniformity of cooling can be improved by using an array of impinging jets when the area to be cooled is large. Study of heat transfer by multi-jet impingement cooling has also been taken up by several authors. Heat transfer characteristics of multi-jet are different from that of a single jet. This is due to the interaction between the jets prior to impingement on the plate and also due to the flow of spent air of the adjacent jets. Weigand and Spring [12] have reviewed and summarized correlations proposed by many researchers for average heat transfer coefficients in multi-jet impingement cooling. It is observed that the correlation for average Nusselt number of a multi-jet is similar to that of a single jet except for an additional parameter known as open area ratio which is the ratio of total jet area to heat transfer area.

Chougule *et al* [13] have carried out CFD analysis of multi-jet air impingement on flat plate and also conducted experiments to validate the CFD results. It was found that for a given Reynolds number, as observed in single jet, lower H/D resulted in higher heat transfer coefficient and higher Reynolds number yielded better heat transfer for given H/D. It was also observed that for higher H/D, the jets in the outer rows become vibrant and do not impinge at the target as expected. Further it results in poor heat transfer coefficient due to mixing of jets before impinging on the target. Bailey and Bunker [14] have studied mainly the effects due to dense impingement of arrays having a jet to jet spacing of 3 times nozzle diameter and H/D ranging from 1.25 to 5.5 with jet-averaged Reynolds numbers of 15000 to 58000. An extended correlation has been formulated by the authors for stream wise row heat transfer for the entire range of parameters tested.

In most of the studies on multi-jet impingement cooling [12-20], the number of jets and jet diameters are fixed and the influence of Reynolds number and H/D and jet to jet spacing has been investigated. It has also been demonstrated that the interaction between the jets in the wall jet region after striking the target at stagnation point is an important factor which in turn is decided by the number of jets and the jet diameter. Not much evidence is found demonstrating the influence of Reynolds number and H/D for various combinations of jet diameters and number of jets on the heat transfer rate in the available literature. Further, the correlations available in the literature to predict the average Nusselt number for a given case, with all the parameters within the recommended range, the Nusselt numbers predicted by different correlations for the selected conditions fall in a very wide range, indicating that the correlations can help only to predict a highly approximate value. One of the objectives of this work is to arrive at the right combination of jet diameter and number of nozzles that gives better heat transfer rate for a given target area to be cooled. In the absence of a reliable correlation, it is essential to perform experimental investigations to meet this objective.

Effect of introducing swirl in the single jet impingement has been investigated by several researchers. Physics of swirling flow and its applications have been critically reviewed by Beer and Chigier [21] and Gupta *et al*. [22]. Kinsella *et al*. [23] have focused on the design of a swirl jet which aims to enhance the surface heat transfer from a heated surface in a radially uniform manner. They have demonstrated that local heat transfer coefficient is less at the stagnation point when swirl is introduced. The reason for this reduction is the blockage of the jet flow by the swirl generator at the stagnation point. However the local heat transfer coefficient increases when we move away from the stagnation point. The authors have also demonstrated that average heat transfer coefficient over an area extending to five times the diameter for jets with swirl is higher compared to that of jets without swirl. It has also been found that the optimum degree of swirl from a heat transfer perspective is a function of the nozzle to impingement surface spacing. As the effect of swirl in a multi jet has been not investigated and reported so far, in this present work, the effect of swirl has been investigated for different nozzle configurations and the observation made has been reported.

Flow characteristics of three jets of rectangular cross-section have been investigated by Sastry *et al* [24]. However heat transfer studies and comparison of performance of non-circular multi-jets with circular multi-jets for the same conditions have not been reported widely. In this work a study on the relative performance of jets of square and triangular cross-section with circular jets has been carried out experimentally.

The flow and heat transfer characteristics of in-line and staggered arrangement of an array of 6 × 4 nozzles were investigated by Makatar *et al*. [25] with $H/D = 3$ and jet to jet spacing of 3-D for jet Reynolds number Re = 5000, 7500, and 13400. The results show that in-line arrangement gives 13 to 20% higher average Nusselt number when compared to staggered arrangement. However the relative influence of diameter and number of nozzles for a given target space pertaining to arrangement of nozzles on Nusselt number has to be investigated further.

Several researchers have employed numerical simulation using CFD techniques to gain an insight into the fluid-flow and heat transfer behaviour of multi-jet impingement cooling to corroborate their experimental results. In this work also, in line with the practice followed for the investigation on multi-jet cooling, CFD analysis has been carried out for some of the salient conditions tested.

Experimental study

Experimental set-up

The photographic view of experimental set up is given in fig. 1. A rectangular heating foil of size 15 × 10 cm^2 of 600 W heating capacity is sandwiched between two identical steel plates of same size as that of the heating foil and thickness 18 mm. A dimmer stat is used to vary the heat power supplied to the heating element and in turn the rate of heat supplied. Fifteen K-type thermocouples are brazed to the target plate to measure the surface temperature of the top plate which is exposed to the jets. Grooves and holes are made appropriately such that the top of the beads of thermocouple is as close to the top surface as possible. The thermocouples are placed at equidistance to obtain temperature distribution across the length and breadth. Thermocouples are connected to the data acquisition system (Agilent 34972A) to record the temperatures at 15 points on the target plate. The data logger is connected to a personnel computer with required software (Bench link data logger-30) for data acquisition and storage. Calibration of the thermocouples was done by comparison method under the ambient condition. Except the top surface, all the faces of the plate area are covered with ceramic wool of sufficient thickness. The hot plates with heating foil are placed over a stand whose height can be varied by a lead screw mechanism to obtain the required H/D.

Air supply to the nozzle is through a centrifugal blower through a plenum chamber. The purpose of the plenum chamber is to make the flow stable and free from fluctuations. A hot wire anemometer is used to measure the velocity of air in the main duct which takes air from the blower exit to the plenum chamber. A summary of the details of air jets of different configurations considered for the analysis in the present work is shown in the tab. 1.

Figure 1. Photographic view of experimental set-up

Table 1. Air velocity and flow values used in experiments

Diameter / side of the nozzle in (mm)	Number of nozzle	Arrangement of nozzle and swirl
ϕ2, ϕ4, ϕ6, ϕ8	8	In-line
ϕ4, ϕ6, ϕ8	12	In-line and staggered
ϕ8, ϕ10, ϕ12	4	Without swirl and with swirl
ϕ8, ϕ10, ϕ12	6	Without swirl and with swirl
□3.5, □5.3, □7.0	8	In-line
Δ12, Δ 16, Δ 17	8	In-line

Experimental procedure

After fixing the particular nozzle assembly to the plenum chamber the blower is switched on. Simultaneously, the power is supplied to the heating coil through the regulator (dimmer stat) such that a constant heat flux (7666.67 w/m^2) is supplied to the heater. By adjusting the gate valve, the rate of air-flow is controlled until the required Reynolds number is attained. The temperatures at fifteen points were observed periodically in the personal computer which is connected to the data acquisition system until steady state is attained. Reynolds number is varied from 8000 to 22000 and H/D is kept as 1, 2, 4, and 6. Figure 2 shows the different configurations of nozzles taken up for the investigation.

The heat transfer coefficient is calculated:

$$h = \frac{q_s}{T_s - T_b} \tag{1}$$

where, q_s [Wm^{-2}] is the heat flux on the target surface, T_s [K] the mean surface temperature, T_b [K] the bulk mean temperature of air at the exit of nozzle.

The normalized heat transfer coefficient can be calculated:

$$h_{norm} = \frac{h}{AV} \tag{2}$$

where A [m^2] is the cross sectional area of the nozzle, and V [ms^{-1}] the Velocity of the nozzle.

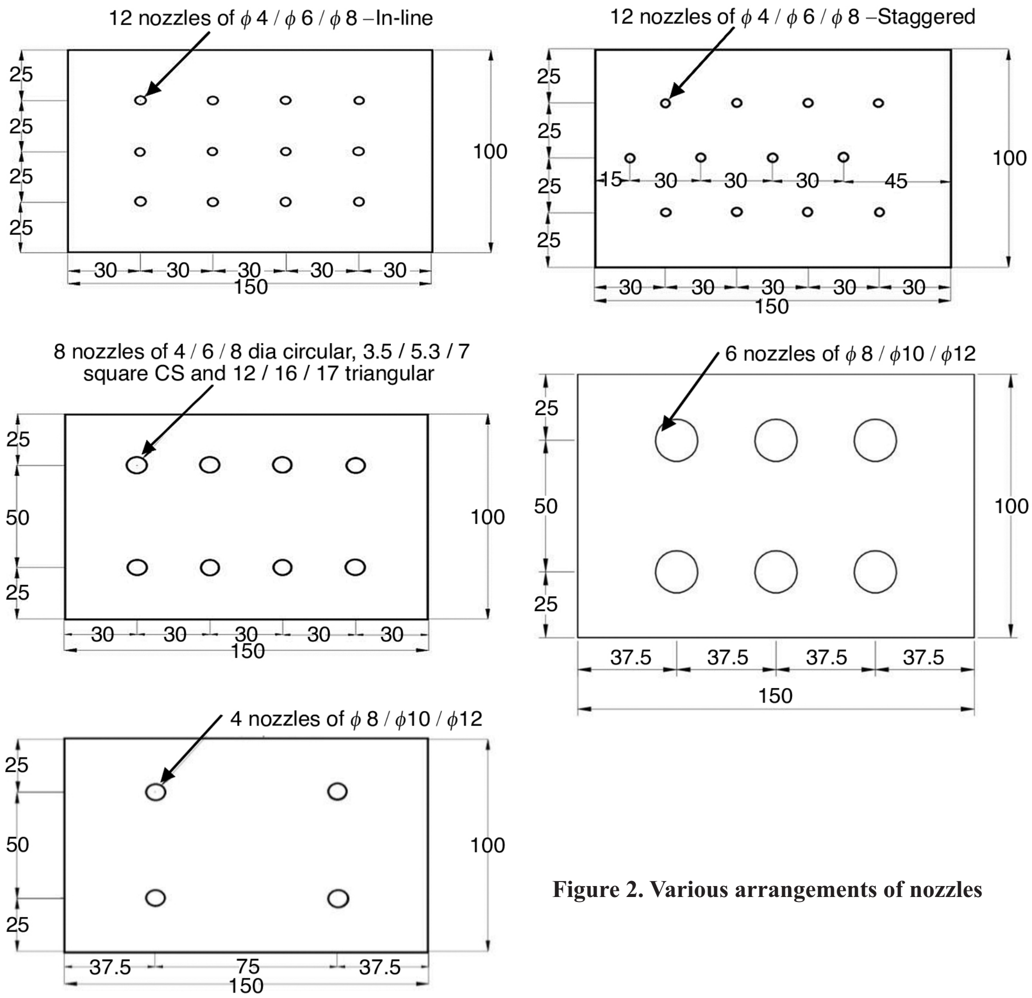

Figure 2. Various arrangements of nozzles

Results and discussion

Experiments were conducted to study the effect of (1) introducing swirl, (2) nozzle arrangement namely in-line, and staggered, (3), nozzle cross-section, and (4) jet diameter and number of nozzles combination. The performance comparisons were made based on heat transfer coefficient normalized based of volume flow rate of the air supplied to the jet termed as 'normalized heat transfer coefficient h_{norm}.

The effect of introducing swirl

It has been established by several researchers that introduction of swirl movement in an impinging jet gives better overall heat transfer rate in the region of impingement up to a circular area covering a few times of radius for a single jet. There is no evidence in the published literature comparing the relative performance of multi jet cooling with and without swirl. To investigate the effect of swirl in a multi jet arrangement, experiments were conducted for similar conditions for jets without swirl and jets with a helical strip of 65° swirl angle. The nozzle configurations tested for the study of flow with and without swirl are as mentioned in the tab. 1.

Figure 3 shows the comparison of normalized heat transfer coefficient for nozzles with swirl (WS) and without swirl (WOS). For the same Reynolds number, introduction of swirling effect results in higher heat transfer per unit volume as compared to nozzles without swirl effect in case of 10 mm and 12 mm diameter nozzles, this result is in line with the observation made by Kinsella *et al* [23]. However, incase of 8 mm jet swirl reduces the heat transfer per unit volume. This decrease may be due to the reduction in heat transfer coefficient near the stagnation point dominating the increase in heat transfer coefficient outside of the jet. Therefore we can infer that the effect of swirl in smaller diameter nozzle is counterproductive as the effect of turbulence is subdued by frictional effects.

The influence of number of nozzles with swirling effect is investigated among the sets (4 and 6 nozzles) with same diameter of nozzles. Nozzles of 8 mm, 10 mm, and 12 mm diameter are taken for investigation in this case. From fig. 4 it can be observed that the normalized heat transfer coefficient decreases with increase in number of nozzles of same diameter as the jet to jet distance is reduced, thereby increasing the interaction between the jets leading to intense fountain effect.

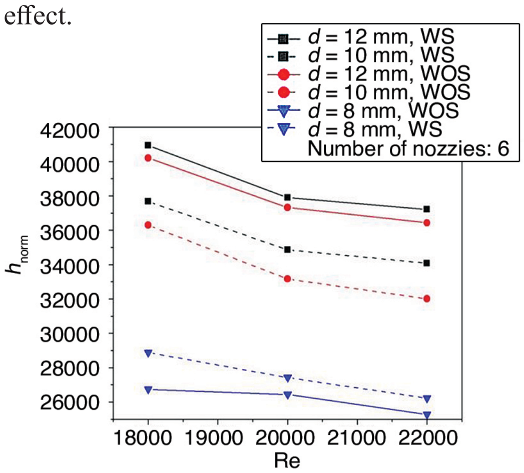

Figure 3. Comparison of heat transfer coefficient of nozzles with and without swirl (6 Nozzles)

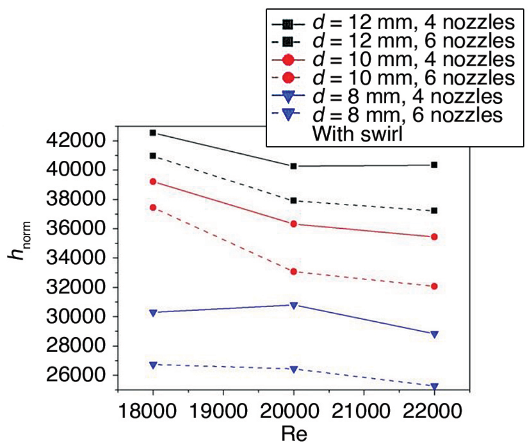

Figure 4. Effect of number of nozzles of same diameter with swirl (4 and 6 nozzles each of 8 mm, 10 mm and 12 mm diameter)

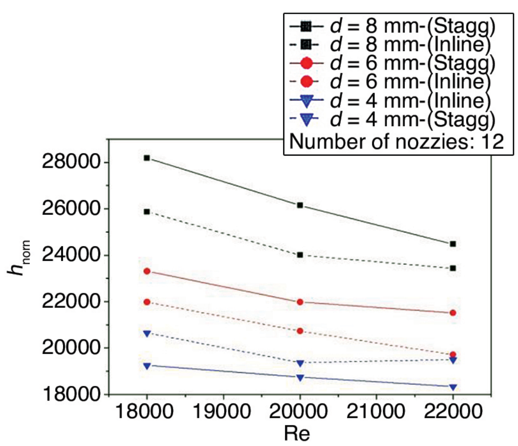

Figure 5. Comparison h_{norm} for Inline and staggered arrangement of nozzles

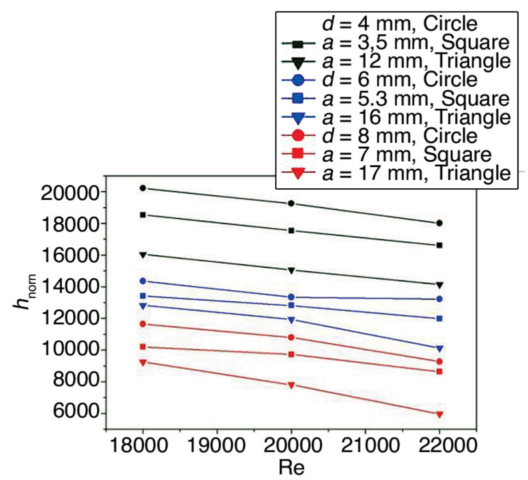

Figure 6. Comparison of heat transfer coefficients in circular and square nozzles

The effect of nozzle arrangement

The effect of staggering the nozzles is studied with three sets of 12 nozzles (4 mm, 6 mm, and 8 mm diameter sets) as mentioned in tab. 1. The normalized heat transfer coefficient is estimated for inline and staggered arrangement of nozzles. The staggered arrangement of nozzles results in increase in heat transfer except in the case of 4 mm nozzle as shown in fig. 5. With same number of jets, larger diameter nozzles in case of staggered arrangement have interaction effects not as intense as in inline arrangements and hence results in increase in heat transfer.

The effect of nozzle cross-section

Figure 6 shows the comparison of normalized heat transfer coefficient for different sets of same number of nozzles of circular (with diameter, *d*), square (with side, *a*) and triangular (with side, *s*) cross-sections having same flow area. It can be observed that normalized heat transfer coefficient is higher in circular nozzles as compared to nozzles of square and triangular cross sections of same flow area for all the tested conditions. Flow separation near the edges and non-axisymmetric nature of the wall jet flow after hitting the target space may be the reason for the low h_{norm} in nozzles of square section when compared to the circular jets.

The effect of jet diameter

To arrive at the right combination of diameter and number of nozzles for a given area to be cooled more efficiently, investigation is to be carried out keeping the number of nozzles same and varying the diameter of the nozzles. First the number of nozzles is fixed as 4. The variation in normalized heat transfer coefficient with Reynolds number for three different diameters (8 mm, 10 mm, and 12 mm) has been studied. The results obtained are shown in fig. 7. With of the jet fixed, to increase the Reynolds number, velocity should be increased. This causes higher momentum and higher flow rate. The additional flow rate does not proportionally increase the heat transfer and hence the drop in h_{norm}.

Among three the sets of nozzles, for a given H/D, the set of 10 mm diameter nozzle gives highest h_{norm}. For better comparison among the three sets of four nozzle configurations with diameters 8 mm, 10 mm, and 12 mm, the results are presented in different plane with diameter on x-axis instead of Reynolds number for $H/D = 1$ as shown in fig. 8.

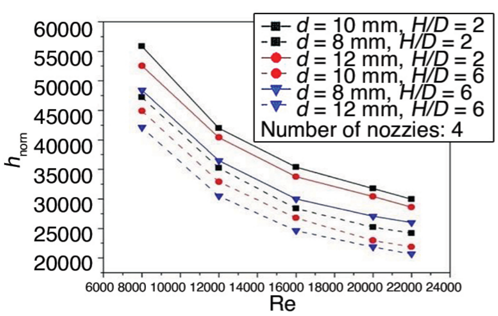

Figure 7. Variation of normalized heat transfer coefficient with Reynolds Number for different sets

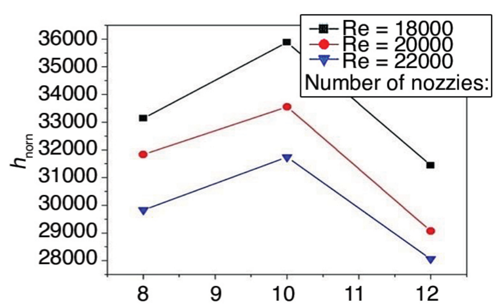

Figure 8. Comparison of variation in h_{norm} with diameter of nozzle for different Reynolds number

The impact of increase in diameter, keeping the number of nozzles same, without changing the centre distance between the adjacent jets for the same Reynolds number on the variation of heat transfer can be understood by noting the following points:

– By increasing the diameter, more area is directly exposed to the jet with more quantity of air which tends to increase the heat transfer rate.
– By increasing the diameter, free space available between the adjacent jets for the air to flow away from the heating surface is reduced leading to intense interaction of air in the wall jet region causing fountain effect which tend to reduce the heat transfer rate.

When the diameter is increased from 8 mm to 10 mm, more amount of air is supplied for the same Reynolds number. The relative increase of heat transfer rate because of the additional flow outweighs the decrease due to interactive effect so that the increase per unit volume of air flow rate is higher for 10 mm compared to that of 8 mm. Further increase in diameter from 10 mm to 12 mm also results in higher volume flow rate and heat transfer rate. But the extent of increase of heat transfer due to increase of air-flow rate is presumably outweighed by the extent of decrease of heat transfer by the interactive effect. This leads to steep fall in h_{norm}. Experiment have also been carried out keeping all other conditions same and increasing the number of nozzles to 6 instead of 4. The variation of h_{norm} with sets of 6 nozzle has also a similar trend as that of 4 nozzles as shown in the fig. 9.

To investigate the influence of nozzle diameter with still higher number of jets, for the same heating surface area and other testing conditions, experiments were conducted with a set of 8 nozzles. Four sets of 8 nozzles having diameters 2 mm, 4 mm, 6 mm, and 8 mm are selected for investigation. Figure 10 shows the variation in h_{norm} with respect to diameter of nozzles. It can be observed that for the tested conditions, similar to the trends observed earlier, there is an optimum diameter for which h_{norm} is maximum for a given number of nozzles. In the case of 8 nozzle configuration, the diameter corresponding to the maximum h_{norm} is 4 mm.

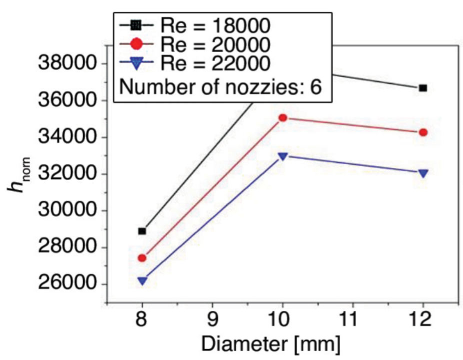

Figure 9. Variation of normalized heat transfer coefficient with diameter of jet for 6 nozzle configurations

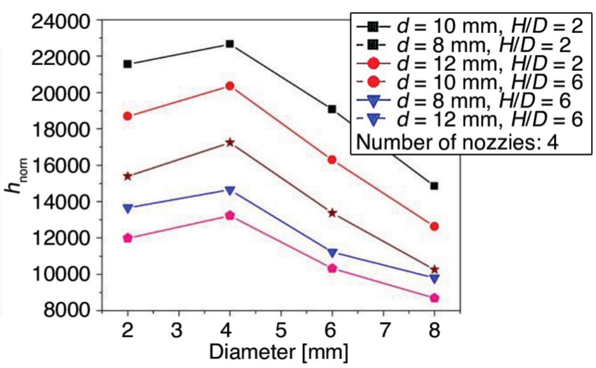

Figure 10. Variation of normalized heat transfer coefficient with diameter of jet for 4 nozzle configurations

The CFD Analysis

In multi-jet impingement cooling, the flow conditions in wall jet region after the jet hits the target surface which influence the heat transfer coefficient significantly are complex in nature. Many researchers have used CFD analysis to get an insight into the flow conditions. The methodology adopted for the analysis in the present study is based on the work reported by Chougule *et al.* [13] and Ahmed *et al.* [26]. The CFD analysis is carried out using ANSYS 14.5 with SST $k-\omega$ as the turbulence model. Grid independence test has been carried out for a grid size ranging from 1 mm to 0.5 mm. It is found that a grid size of 0.75 mm with 8.6 million elements is reasonable for this application.

In order to get further insight into the behavior of multi-jet through CFD analysis let us consider two typical cases among the tested conditions. In first case, the effect of introducing swirl for a given diameter is considered. In section *The effect of introducing swirl*, it was observed that introducing swirl causes decrease in heat transfer rate for 8 mm diameter 4 nozzle configuration. Temperature contour obtained from CFD analysis is consistent with this observation as shown in figs. 11 and 12. Therefore it is evident that CFD analysis can be used as an efficient tool to predict the influence of various operating parameters in designing mult-jet impingement cooling arrangements.

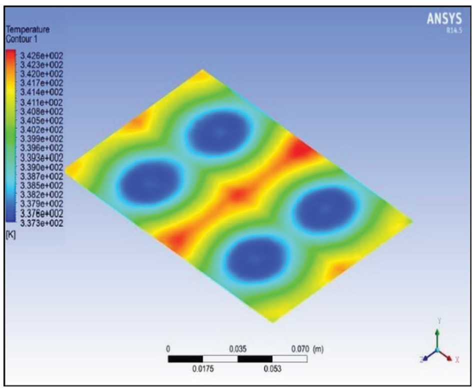

Figure 11. Temperature contour for 8 mm - 4 nozzles without swirl for Re = 22000 and *H/D* = 1

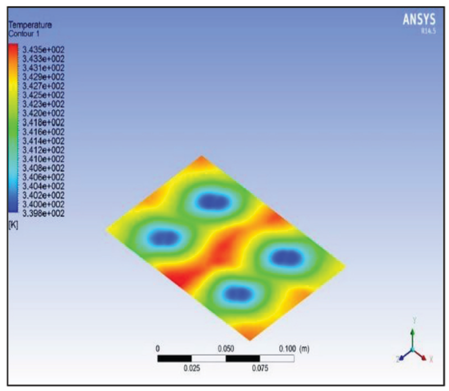

Figure 12. Temperature contour for 8 mm - 4 nozzles with swirl for Re = 22000 and *H/D* = 1

In second case, let us consider the influence of number of nozzles in flow with swirl. It was observed that the heat transfer rate is higher in 12 mm diameter 6 nozzle set with swirl, compared to 12 mm diameter 4 nozzle set with other flow conditions remaining the same. However the heat transfer rate per unit volume [h_{norm}] is smaller for 6 nozzle set compared to 4 nozzle set as given in fig. 4 in section *The effect of introducing swirl*. The reason attributed for this drop could be the extent of interaction between jets after impacting the target surface in the wall jet region, which is substantiated by the velocity contours obtained from CFD analysis. Figures 13 and 14 show the velocity contours in case of 12 mm diameter - 6 numbers and12 mm diameter - 4 numbers with swirling effect, respectively. The intense fountain effect between the jets in case of 6 number set compared to 4 number set observed from aforesaid velocity contour diagrams explains the reason for the drop in h_{norm}.

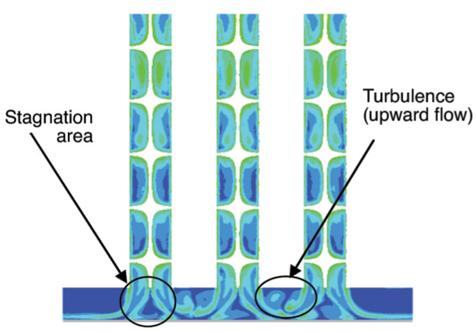

Figure 13. Velocity contour of 12 mm - 6 nozzles with swirl

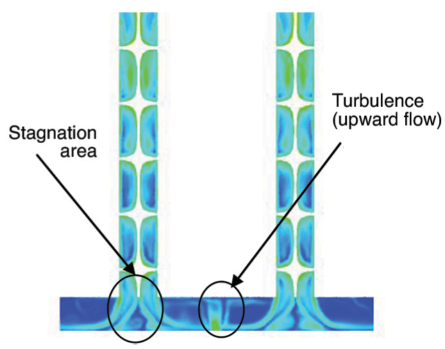

Figure 14. Velocity contour of 12 mm - 4 nozzles with swirl

Experimental uncertainty in heat transfer coefficient

The heat transfer coefficient values were experimentally obtained from the rate of heat transfer per unit area and the difference in temperature between the hot plate and the ambient:

$$h = \frac{(Q / A)}{\Delta T} \tag{3}$$

The uncertainty in the value of heat transfer coefficient calculated using the expression depends on the uncertainties in the measurement of the rate of heat transfer which in turn depends on the uncertainty of air velocity and the uncertainty in the measurement of temperature.

Using the method recommended by Holman [27], uncertainties in the experimental heat transfer coefficient is computed from the uncertainty of air velocity which is given by the manufacturer as ±5% and the uncertainty in the temperature measured estimated as ±0.676%. The maximum uncertainty in the estimation of h_{norm} is 5.05 %.

Conclusion

Experiments were conducted to obtain the heat transfer coefficient in case of a hot surface subjected to multi-jet impingement cooling of different configurations.

- Introduction of swirling action results in higher normalized heat transfer coefficient in case of larger diameter nozzles. Among the tested sets of nozzles, 10 mm and 12 mm diameter nozzles offered higher h_{norm} compared to 8 mm nozzles.
- When diameter of nozzle is less, in-line arrangement results in higher h_{norm} compared to staggered as observed for a set of 12 numbers of 4 mm nozzles. As the diameter increases, with jet interaction coming into play, staggered arrangement proves to be better as in the case of 6 mm and 8 mm nozzles.
- For all the tested conditions circular nozzles are more effective than square nozzles.
- In 4 nozzle and 6 nozzle configurations, 10 mm nozzles give higher h_{norm} compared to 8 and 10 mm. In 8 nozzle configuration, 4 mm diameter nozzle gives maximum h_{norm} compared to 2 mm, 6 mm and 8 mm diameter nozzles.
- Velocity contour in CFD analysis gives an insight into interaction between the jets in the wall-jet region. Temperature contour aids in comparing the jet performance to study the effect of swirl.

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