International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 04 | Apr-2018 www.irjet.net p-ISSN: 2395-0072

Study of Jet Impingement Heat Transfer

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Abstract - *Jet impingement systems provide an effective and simple means for the enhancement of convective processes due to the high heat and mass transfer rates that can be achieved. The range of industrial applications that impinging jets are being used in today is wide. A number of researchers have studied the forced convection heat transfer from jet arrays. This review paper gives various experimental and numerical approaches on jet impingement heat transfer process. In the course of the review, the flow and heat transfer characteristics of multiple impinging jets are introduced. Influencing factors on heat transfer are discussed, which include the effects of cross flow, jet Reynolds number, jet pattern, separation distance between a jet and target plate, and of the open area. In the review of numerical works, the suitability of the turbulent models in predicting local heat transfer rates for multi-jet systems is discussed.*

***Key Words*: jet impingement heat transfer, turbulence models, multiple jets, jet Reynolds number.**

1. INTRODUCTION

Impingement heat transfer has emerged as a principle source for both controlled cooling and heating of a target surface because of its exceptional ability to enhance heat and mass transfer in a variety of industrial processes. Jet impingement can be seen cooling turbine blades and vanes, combustors, electrical and electronic equipment, heating surfaces, etc. thereby contributing to improving product performance, longevity, efficiency, and quality. A specific amount of liquid or gaseous flow directed against a surface can efficiently transfer large amounts of thermal energy or mass between the surface and the fluid. Heat transfer applications include cooling of stock material during material forming processes, heat treatment, drying requirements in paper industries, cooling of turbine components,

Impinging jets offer an effective and flexible approach to transfer energy or mass in many industrial applications by changing the flow and geometric parameters, such as, jet Reynolds number (*Re*), nozzle geometry/shape, assembly of jet array, nozzle-to-plate spacing, angle of jet impingement, turbulence properties at the exit of the jet, ribbed surfaces and flow pulsation, etc.

Here a detailed review of the heat transfer characteristics of systems of single as well as multiple impinging air jets is presented. The objective is to provide a profound physical knowledge for the design of these impingement configurations, for which the factors that influence heat transfer are categorized and illustrated by exemplary results collated from different sources.

Freidman and Mueller [1], Kezios [2] etc. first experimentally studied the topics connected with the heat transfer from the impinging jets. Since that time, many investigators have tried both analytical and practical approaches, to establish models, designer formulas, charts, graphs and correlations that would enable him to handle various heat transfer problems related to the impinging jets.

In general, the flow field and mechanism of even a single impinging jet are quite complicated, and the heat transfer aspects depend significantly on the corresponding fluid flow structure. Therefore, in the literature review, fluid flow aspects of the impinging jets will be reviewed first and then our attention will be turned to the items more directly related to heat transfer from the impinging jets.

1.1 General Features of Jets

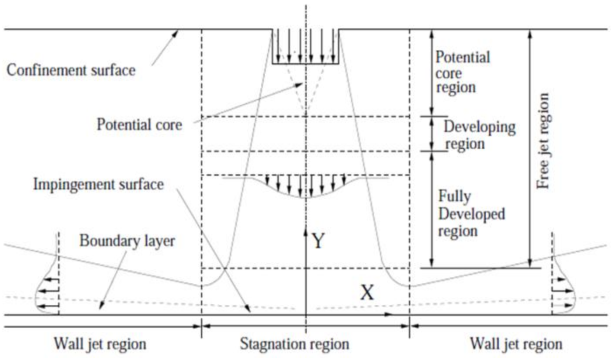

Fig -1: Schematic diagram of an impinging jet.

As in virtually all forced convection problems, fluid flow aspects of impinging jets cannot be really separated from the heat transfer aspects (and vice versa), since the energy equation is dependent upon the momentum equation. Of fundamental importance is here the distinction between the laminar and the turbulent flow regimes. As a starting point of this review, the flow structures of a single impinging jet are considered. According to Vickers [3], the critical Reynolds number, Re, based on the nozzle diameter, is most likely 1000. McNaughton and Sinclair [4], observed four characteristic jet patterns namely:

1. Dissipated laminar jet, Re < 300.
2. Fully laminar jet, 300 < Re < 1000.

3. Semi-turbulent jet, that starts as a laminar jet, then becoming turbulent, 1000 < Re < 3000.

4. Fully turbulent jet, Re > 3000

Hrycak et al. [5] obtained a similar result using air jets. Cederwall [6] found that jets with Re > 3000 are already turbulent. Heat transfer results of Gardon and Cobonpue, [7] and those by Chamberlain, [8] seem to indicate that, for impingement in the potential core region, the Nusselt number (for the given fluid and flow geometry) depends on parameters other than Reynolds number for Re> 7000 or in other words turbulence patterns influences heat transfer characteristics. Tani and Komatsu's [9] Experimental observations suggest that the impinging surface has no effect in the momentum or mass flux of the jets. Several studies are conducted to find the potential core length which refers to the length up to which the nozzle exit velocity persist along centerline of the nozzle and several empirical relations were also developed by Schlichting [10], Levey [11], Albertson et al. [12], Hegge Zinjen et al. [13], Abramovich [14], Schauer and Eustis [15], Poreh and Germak [16], Gauntner et al. [17], Snedeker and Donaldson [18], Warren [19], Pai [20], etc . The exact potential core length must be known for maximum cooling efficiency. Studies suggest for single jets maximum intensity of heat transfer take place at the tip of nominal potential core.

Gauntner et al [17], distinguish four characteristic regions of flow (figure 1).They are

1. A transition zone of flow establishment.

2. A zone of established flow in the original direction of the jet.

3. A deflection zone.

4. A zone of established flow in the radial direction.

According to Livingood et al [21], the core is typically visible up to a distance of 6–7 jet diameters from the nozzle. Once the free jet is fully developed (a fully developed free jet region is formed), its axial velocity profile can be approximated by the Gaussian distribution. The flow in the stagnation flow region is strongly affected by the presence of the wall. As the jet approaches the wall, the axial velocity component is decreased and transformed into an accelerated horizontal component. In developing region, the velocity distribution may be considered similar to that of a free jet diffusing into an infinite medium. The flow in the stagnation flow region is strongly affected by the presence of the wall. As the jet approaches the wall, the axial velocity component is decreased and transformed into an accelerated horizontal component. Brady and Ludwig [22], prepared a chart to indicate the extent of the laminar region near the stagnation point. Abramovich [23] reports that maximum rate of momentum exchange between the jet boundary and the surrounding occur at a distance of about one jet diameter from the stagnation zone. In the fully developed wall jet region, the wall parallel velocity is again decelerated. This deceleration will generally be accompanied by the transition from a laminar to turbulent flow, as the stabilizing effect of acceleration, which helped to keep the flow laminar, has disappeared at this point.

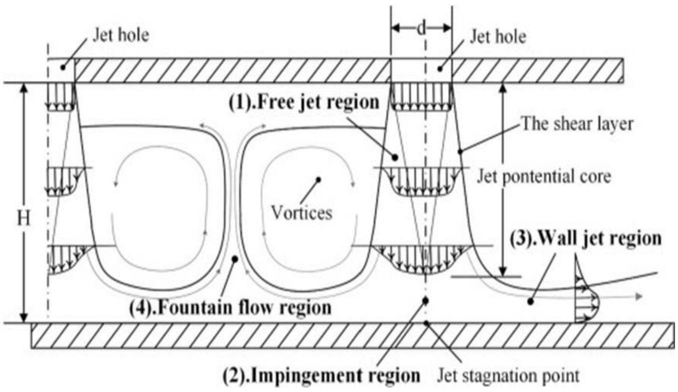

Fig -2: Multi jet impingement system.

The flow from a system of multiple impinging jets has the same regions as the flow field from a single impinging jet however, there are some fundamental differences. These are primarily due to two types of interactions that do not occur in single-jet systems as shown in figure 2. The first is the possible jet-to-jet interaction between pairs of adjacent jets prior to their impingement onto the target plate. This type of interference, which is due to shear layer expansion, is of importance for arrays with closely spaced jets and large separation distances between the jet orifices and the impingement target surface. The second is the interaction due to the collision of surface flows from adjacent jets, also referred to as secondary stagnation zones. These regions are characterized by boundary layer separation and eddying of the flow. Depending on the strength of this interaction, fountains can develop between pairs of adjacent jets and form recirculating vortices. The above effects can be accentuated further by an additional interaction with the cross flow formed by the spent air of the jets.

2. LITRATURE REVIEW

Initial attempts to analytically predict heat-transfer from an impinging jet to a plane surface were limited to the neighborhood of the stagnation point, where even for turbulent jets, laminar flow predominates in the boundary layer. Researchers like Kezios, [2], Walz [24], Eckert [25], Meyers, et al. [26], Livingood [27],Tomich [28], Brdlik and Savin [29] ,Sparrow and Wong [30], Miyazaki and Silberman [31], Hrycak [32] Vader et al. [33], etc. developed correlations for heat transfer due to single jet impingement. From looking at available analytical solutions, it is seen that they all have certain common features. The general form of the equation for the Nusselt number (*Nu*) is

$$Nu = C\, Pr^m\, Re^n \quad (1)$$

Where Pr is the Prandtl number, Re is the jet Reynolds number with m ranging from 1/3 to 0.4 and n ranging from 0.5 at the stagnation point to 0.7 and more in the wall-jet region. The value of constant **C** varies from 0.763 to 1.09 for circular jets, and is 1.14 for slot jets.

For the heat transfer from a system of multiple impinging jets, this relation has to be extended. For average heat transfer coefficients from arrays with a regular jet pattern ($S = Sx = Sy$), a relation of average nusselt number ($\overline{Nu}$) is of the form

$$\overline{Nu} = C Re^m Pr^n (\frac{H}{D})^a (\frac{S}{D})^b \quad (2)$$

has been considered appropriate. These approaches differ from the formulation for single jets by accounting of the separation distance and the jet-to-jet spacing.

Empirical correlation average heat transfer coefficients on multi-jet impingement systems are predicted by many researchers [34-40] and can be expressed as

$$\overline{Nu} \propto f\left(Re, Pr, \frac{G_c}{G_j}, \frac{S_x}{D}, \frac{S_y}{D}, \frac{H}{D}\right) \quad (3)$$

This relation is also useful for cases involving crossflows. The results from experimental investigations on jet impingement heat transfer are summarized. The results are classified into different categories that represent physical changes to the impingement configuration.

Goodro et al. [42] and Park et al. [41] emphasized the importance of addressing the effects of Reynolds number and Mach number on multi jet impingement heat transfer separately, in particular for high jet velocities. The degree to which average Nusselt numbers depend on the separation distance is determined mainly by the jet-to-jet spacing, and has been reported to be significant only for densely spaced arrays .Various studies indicate that only minor differences in average heat transfer rates exist for inline and staggered pattern [43, 44,45] Florschuetz et al. [46, 47 ,49] pointed out that the differences due to hole pattern can become significant for densely spaced arrays, large separation distances, and increased crossflow. For such configurations, inline arrays typically perform better in terms of average heat transfer rates. With an inline pattern, the jets of a given stream wise row tend to be protected from the oncoming crossflow, which is the primary cause of heat transfer degradation, by the jets of the immediate upstream row. Goldstein & Timmers [50] studied impingement of a co-linear array of 3 circular jets onto a flat plate. They used jets at Re = 40,000, with a nozzle-to-nozzle distance of S/D = 4 at nozzle-to-surface distances of H/D = 2 and 6. The overall heat transfer levels at the larger nozzle-to-surface distance of H/D = 6 were found to be lower than those at the smaller distance. Goldstein & Timmers [50] and San & Lai [51] studied the effects of jet interference before impingement and jet fountains between two adjacent jets after impingement on the heat transfer rates. San & Lai [51] concluded that the two factors affecting the heat transfer were jet interference before impingement and jet fountain after impingement. The jet interference before impingement reduces the jet strength, thereby reducing the overall heat transfer .They proposed the optimum nozzle-to-nozzle spacing. Huber & Viskanta [52] investigated the effects of jet interference and jet fountains on the heat transfer rates for multiple jets compared with those of single jets and found that amongst the jet arrays, the profiles for the largest S/D give the highest levels of heat transfer coefficient, as a result of less interference between neighbouring jets. Some of the review works on impinging jets have been done by Jambunathan et al. [53], Viskanta [54], Weigand and Spring [55] and Dewan et al. [56]. Viskanta [54] reviewed on heat transfer characteristics of single and multiple isothermal turbulent air and flame jets impinging on surfaces. He identified areas in need of research such as cross flow and simultaneous motion of the impingement surface, curved impingement surface along with the emphasis on physical phenomena.

In most of the cases, the crossflow lowers the heat transfer coefficients because it can sweep away the jets and delay impingement. The type of crossflow within multi-jet systems can typically be characterized by crossflow of a defined free stream type flow or by a flow formed by the spent air from the impinging jets. The strength of the crossflow within the impingement array is determined by the design of the outflow and by the associated routing of the spent air. It typically differs between a minimum, intermediate, and a maximum crossflow.

Florschuetz et al. [58-61] studied the crossflow effect and found that due to sweep away of jet and delay impingement it may affect the heat transfer performance in many cases. They investigated the effects of the initial crossflow on both the flow distribution and heat transfer for different array configurations. The initial crossflow was kept at a temperature different from the jet temperature.

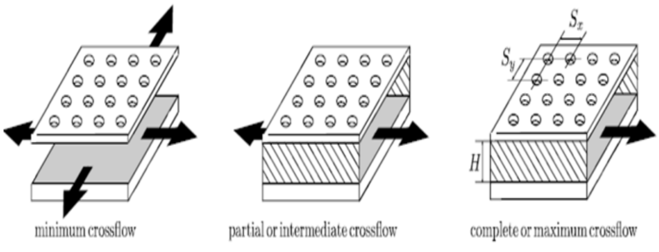

Fig -3: Definition of crossflow schemes in multi-jet systems (according to [57])

This condition allowed the assessment of the influence of the initial flow and its penetration into the array by means of streamwise distributions of a dimensionless adiabatic wall temperature. In general, dominance of the initial crossflow depends mainly on the crossflow-to-jet mass flux ratio and on the separation distance, with more crossflow influence for configurations with higher values of H/D. The authors also confirmed the overall decrease in average heat transfer due to the initial crossflow, except for some cases with $\frac{M_c}{M_f}$<< 1. Metzger and Korstad [62] observed a degradation of heat transfer upstream of the impingement and a simultaneous enhancement in the downstream zones. These combined effects are more pronounced for smaller spanwise jet spacings (*Sy*). For average heat transfer coefficients, the authors concluded that heat transfer degradation always outweighs the enhancement. According to Saad et al. [63], this attenuation of the Nusselt number peaks becomes appreciable only for higher ratios of the jet-crossflow mass flux, i.e., $\frac{M_c}{M_f}$ > 4. Chambers et al. [64] stated that one advantage of the initial cross-flow is the ability to produce fairly uniform upstream heat transfer but again with a decrease of the hih peak values that would occur in the case of no crossflow. They also observed that a large fraction of the total heat transfer of their geometry can be driven by a small quantity of initial crossflow (5%–10%). Barata [65] carried out a visualization study of the effects of initial crossflow on the fluid dynamics. Obot and Trabold [57] did a comprehensive comparison of the three crossflow schemes for an inline jet array. It was established from the results that the best heat transfer performance with regard to the magnitude and uniformity occurs with the minimum crossflow scheme. The intermediate and maximum crossflow conditions result in moderate and substantial reductions in the average heat transfer, respectively. Crossflow induced degradation effects are pronounced strongest in the vicinity of the exhausts, so that the regions farthest away from the latter are affected insignificantly. A significant amount of visualization studies on crossflow effects due to spent air exists for both flow and heat transfer [66-68]. Junsik Lee [69] studied the effects of impingement cross-flows on local, line-averaged, and spatially-averaged Nusselt numbers.

Many of the widely used turbulence models for predicting momentum and heat transfer have been developed by reference to flows parallel to walls, such as simple boundary layer flows. To use these models in complex flows, it is important that they can perform accurately regardless of the flow orientation relative to the bounding surfaces. In particular, for impinging jets, the models should be able to predict correctly both flows parallel to and normal to the walls. Due to these differences in the flow behaviour, many turbulence models such as linear k-ε models, and even some stress transport models, give incorrect predictions of impinging flows.

Craft et al. [70] compared the performance of four turbulence models in predicting the flow characteristics of impinging flow on a flat surface. The models used were the Launder & Sharma [71] low-Reynolds number *k-ε* model with the Yap [72] length-scale correction added to the ε transport equation, and three second moment closure models with different pressure-strain terms. Amongst their conclusions was that the *k-ε* model gives poor predictions of the impinging jet when compared with experimental results. Suga [73] introduced a cubic stress-strain relationship into the two equation k-ε eddy viscosity model which Craft et al. [74] tested over a range of applications including flow in a curved channel, through a rotating pipe, transitional flow over a flat plate, impinging flow and flow around a turbine blade. Particularly in the case of flat plate impinging jet simulations, Craft et al. [74] reported that the Suga [73] cubic non-linear *k-ε* model predicted results which were reasonably close to the experimental data. Behnia et al. [75] used the normal velocity relaxation v^2- f turbulence model of Durbin [76] to predict the flow field and heat transfer of an axisymmetric fully developed turbulent jet impinging on a flat plate. Accurate results were obtained but at the cost of solving two supplementary equations in addition to the k and ε equations. The standard *k-ε* model significantly over predicts the local Nusselt number when compared with measured values, whereas the v^2–f model gave fairly good predictions. Mounir B. Ibrahim et al. [77] conducted for heat transfer with jet impingement over solid surfaces with varying parameters and found that v^2-f model gives the best overall performance, though the *k*–ω model gives good predictions for most of the flow, with the exception of near the stagnation zone for some cases.

Spring et al. [78] showed impingement configurations at high jet Reynolds numbers and maximum crossflow can be numerically predicted at reasonable cost by standard commercial CFD tools, as long as the domain boundaries are defined properly. For flow field simulations on the jet-to-jet and jet-to-crossflow interaction, Barata et al. [79, 80], Chuang et al. [81], and Leschziner and Ince [82] found the *k*-ε model to adequately represent the gross features of the flow. However, the method failed to predict the turbulent structure of the impingement zones and the fountain flow because of the inapplicability of the eddy-viscosity hypothesis. Thielen et al. [83] reported on the successful reproduction of the complex jet interaction, the formation and collision of wall jets, and the consequent upwash and recirculation, by virtue of a modified v^2-*f* model. Angioletti et al. (84) extensively investigated the flow field behavior in the vicinity of the stagnation region. Later, by using commercial CFD package, they evaluated the suitability of three different turbulence models by comparing the numerical results with the experimentally obtained results. They found that the k −ω SST (shear stress transport) model gave good result for lower Re and k− ε RNG (renormalization group) or RSM (Reynolds stress model) performed better for high Re. More recent studies, e.g., [85, 86] included the SST model into the list of investigated turbulence models. Kaminski et al. [87] compared the performance of standard k–ε model and the Yang-Shih (YS) model for a three-dimensional numerical simulation of impingement with cross flow.

Dutta et al. [88] recently used eight different RANS equations based turbulence models to check the performance of the computation of turbulent jet impingement flow. They found that both the standard and the SST k−ω models showed the best agreement with the experimental data in terms of secondary peak of local Nusselt number distribution for small nozzle-to-plate spacing. For high nozzle to plate spacing the standard k−ω and the standard k−ε models only showed good agreement with the experimental data in terms of local Nusselt number. Afroz et al. [89] used SST k− ω model 5 on the subject including the latest developments in literature including the effect of crossflow in jet impingement heat transfer. The numerical simulation of arrays of multiple impinging jets is evolving as a complement to costly experimental investigations, which is due to the large amount of scientific and commercial effort spent on the development of simulation tools and the recent progress of computing resources. However, the numerical prediction of multi jet systems remains a challenging task due to high complexity. In the field of numerical methods used for the prediction of multi-jet impingement heat transfer, present CFD methods seem, in principle, applicable as a design tool. However, strictly speaking, this is true only when numerical accuracy is properly assessed and a turbulence model, that is suited for the specific configuration, is selected. There are hardly any studies which deal with the combined effects of jet impingement and insertion of baffles.

3. CONCLUSION

The detailed review of jet impingement heat transfer has been presented. Single phase as well as two phase cooling with jet impingement method was found to be capable of removing large amount of heat flux using various coolants and surface enhancements. Compared with single jet impingement, multi-jet impingement achieved better thermal performance. The parameters affecting multiple jet impingement heat transfer were studied. Influencing parameters related to jet (impact velocity,, jet shape and size, impact distance etc.) and related to target surface (smooth, finned) onto the performance of heat transfer by impingement were studied. In the field of numerical methods used for the prediction of multi-jet impingement heat transfer, present CFD methods seem, in principle, applicable as a design tool. But, strictly speaking, this is true only when numerical accuracy is properly assessed and a turbulence model, that is suited for the specific configuration, is selected.

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