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Numerical Study of Heat Transfer Augmentation Using Pulse Jet Impinging on Pin Fin Heat Sink

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ABSTRACT

Pulse jet impinging laterally on the pin fin surface have a dual effect (increment and decrement) on the heat transfer rate. The present work manifests the decrement observed in heat transfer rate because of pulse jet impinging on uniform and non-uniform dimensional pin fin heat sink compared with the steady jet. In order to justify and scale the degree of decrement in heat transfer rate, various non-dimensional correlations for both types of the heat sink has been involved. A newly defined dimensionless number is proposed in the present work, followed by a materialistic rationalization using thermal images and flow pattern. Interpretation of the characteristic length on the target side and its effect on heat transfer rate by amending the percentage of void spaces present on it (non-uniform dimensional heat sink) is the indispensable assignment of the present research.

1. Introduction

Cooling rate in micro-electro-mechanical, electronic packaging and robotic systems, as well as heat transfer, are the future challenges. The calling task of the looming world is to use air in the form of jets so that the heat transfer coefficient can be enhanced for better efficiency. The blades of the gas turbine and electronic packaging system are cooled using steady air jets. This practice is still insistence. While the use of pulsating jet currently possesses limited application due to its abnormal behaviour towards the heat transfer rate. Pulsating jet is capable of developing the dual heat transfer characteristic curve, either enhancement or degradation as compared with the steady jet. Because of the pulsating jet, there is a decrease in the heat transfer. Hence it finds the application in material processes industries where the cooling rate of the melted mould during solidification process plays an important role. The abundant application is found in drying industries using pulse jet that impinges on heat sink for heat transfer degradation. Determining the coefficient of performance of heat sink in transferring the heat to impinging air jet is a paramount parameter.

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Considering the duplex nature of pulse jet in heat transfer rate and the magnitude of research performed in combination with pin fin surfaces. Author inclines the present research towards heat transfer study due to pulsating jet in the presence of the modified target surface (Pin fin surface).

1.1. *Literature Review*

Extensive research is performed on steady jet impinging over flat and pin finned surfaces. Cheng – Hung *et al.,* [1] considered two forms of the non-uniform dimensional heat sink and compared it with uniform dimensional one. They noticed that heat transfer in heat sinks of non-uniform dimensions is 10% more than heat sinks of uniform dimensions. Using thermal images and velocity vector plots, he justified more use of fresh and pure air in the heat sink of non-uniform dimensional type. On the other hand, Cheng and Hsiang [2] observed vortices at the start of the target surface. These vortices are disturbed using the more fresh air. It is done in the presence of non-uniform heat sink (dimensional). Above all heat transfer enhancement in the non-uniform dimensional heat sink is due to the diminishing vortices which result in more application of fresh air.

As far as non-uniformity in height is considered, the optimal non-uniform height of the pin fin heat sink was calculated by Yue and Huan [3]. They concluded that there exists an optimal fin height which varies with Reynolds number of the impinging jet. The modification in heat transfer rate because of variation in dimensions of pin fins at the base plate is due to the generation of small depression at the centre which avoids the vortices generation at the entrance.

The effect of the external electromagnetic parameter on the heat transfer rate was first studied by Mousa [4]. He performed experiments by impinging air jets longitudinally in a strong magnetic field (0.8 Tesla) on fins of square and cylindrical shapes. He found that using square fins yields a 40% increase in heat transfer as compared to cylindrical fins. On the isothermal surface, jets were impinged longitudinally by Nawaf H. Saeid [5], and the effect of oscillating flow was studied. Because of the oscillating jet, 25% enhancement was achieved as compared to steady jets. This is because, at the base of the surface, the hotspots formed are carried away. Unlike anything else, intermediacy in penetrating momentum causes this hot spots in the oscillating jet. When the target is an electric field, Wen – Junn *et al.,* [6] stated that 33-50% increased heat transfer rate can be obtained by air impingement. Also, better rate of heat transfer is achieved in an unsteady electric field as compared to the steady one.

The vibration generated using piezoelectric agitator affects the target surface. Taiho Yeom *et al.,* [7] observed that it helps in enhancing the heat transfer. The vibration produced at the base of the plate causes a disturbance in the formation of the hydrodynamic boundary layer. This is because of some type of disturbance process that takes place in the flow field. This increases heat transfer rate by 55%. This occurs at a specific jet to the target spacing. Rozli *et al.,* [8] further exercised the effect of the shape of pulse jet over heat transfer rate and reported a negligible change. The above incomplete research enabled Tim *et al.,* [9] to clarify the degree of enhancement in heat transfer rate. He successfully obtained a minimum enhancement of 15% by use of pulse jet impinging on a hot flat plate. Siddique *et al.,* [10] determined the critical value of geometric thickness below which the non-uniformity in the Nusselt profile starts by numerically examining different target surfaces under constant Reynolds number and nozzle-target spacing.

Hung *et al.,* [11] used infrared thermography technique for calculation of thermal resistance of a pin fin sink experimentally. He compared the heat transfer rate in the flat surface by changing the parameters such as Reynolds number, the width of pin fins and jet-to-target spacing. He came to a result that there are existences of the optimum relationship between Z/d, sizes of pin fin, and Reynolds number. Hung *et al.,* also found that geometric dimensions have more effect on heat transfer at smaller Reynolds number. By varying parameters such as Reynolds number, the diameter of the nozzle, jet-to-target spacing; Hani and Garimella [12] studied the heat transfer coefficient. They compared it by using single as well as multi-jet for pinned and unpinned surfaces. The proportionality of heat transfer coefficient on impinging jet air flow rate was also proved by them graphically. This ultimately proved the independence on the type of jet. Pinned surface provides approximately 60% increase in heat transfer rate in combination with multi-jet. This increase is compared concerning unpinned surfaces. According to them, with impinging and geometric parameters; Nusselt number can be as $Nu = 3.361 \times (Re)^{0.724} \times (Pr)^{0.4} \times (De/d)^{-0.689} \times (S/d)^{-0.10}$. Vincent and Garimella [13] found the heat transfer coefficient of pin fin surface at different radial distances by changing Z/d as well as Reynolds number. They compared the array of 9 mm × 1.59 mm being impinged by multi jets and 4 mm × 3.18 mm by single jet. With respect to 9 mm × 1.59 mm, 4 mm × 3.18 mm gives 20% better coefficient of heat transfer. The dominance of multi-jet on heat transfer coefficient is because of secondary intermediate peaks that occur radially. The secondary peaks move towards the centre because of which the curve of Nu versus radial distance becomes flattened and smooth, stating uniform distribution of temperature. This happens with the combined effect of an increase in Re and decreases in the jet to target spacing [13]. $Nu = 0.161 \times (Re)^{0.707} \times (Pr)^{0.4} \times (Z/d)^{-0.104}$ was the non-dimensional correlation given by Garimella and Vincent [13]. Chougule *et al.,* [14] stated the existence of most favourable jet-to-target spacing that serves as a parameter dependent on Reynolds number which was previously given by Garimella and Vincent. FLUENT was used for concluding this result in a flow field. It helps to analyse velocity vectors. Chougule *et al.,* [14] further physically justified the existences of most favourable jet-to-target spacing. This is because of premixing of air jets which further causes weak stagnation point and thereby decreasing heat transfer rate. The cause of jet-to-target spacing and inter-jet spacing on the rate of heat transfer was given by Yoshisaburo *et al.,* [15]. They studied this with the help of thermocronic liquid crystal and proved that the developing boundary layer thickness is a result these injection parameters, which is considered as a resistance to the rate of heat transfer. The rate of heat transfer also finds a substantial modification with the change in nozzle side parameters.

Luis and Garimella [16] along with Garimella and Vincent studied the outcome of 4 mm × 3.18 mm single jet nozzle on the rate of heat transfer. They also analysed nozzles of 9 mm × 1.59 mm (multi-jet). Experiments were conducted on bare and modified surfaces. With the outcome more protuberant for nozzles of larger diameter, they came on a result that the rate of heat transfer depends on heat supply. Luis and Garimella [16] also forwarded the effect of jet-to-target spacing on the rate of heat transfer that exists at the beginning. Above the critical value, with an increment in the target distance, this effect decreases. Luis and Garimella also came to a result that larger effective use of penetrating momentum and smaller creation of swirling flow occurs at an optimum clearance ratio. Also, pin fin enhancement factor of 2.8 – 2.9 was obtained for the bare surface. Modified surfaces gave comparatively better and more rate of heat transfer in all the conditions of impingement. On the other side of the coin, the rate of heat transfer is affected by the metallurgical properties of the base plate. Maveety and Hendricks [17] focussed on the outcome that is obtained because of the base material. They observed it by changing jet-to-target spacing. They found out that found that with the help of aluminium-based alloys, 50% decrement in thermal resistance can be achieved. They concluded that in a composite alloy higher rate of heat transfer exists at a smaller thermal gradient. Umair *et al.,* [18] performed an experiment comprising of the impinging nozzle, target surface and thermocouple fixed on it to study characteristic decrement of the heat transfer rate of the flat aluminium plate in the presence of pulsating jet over constant jet. They concluded that heat transfer augmentation due to pulse jet lies either above or below that of the steady jet for which the magnitude of G. No. is the final parameter. Umair and Gulhane [19] studied numerical investigation of non-uniformity in cooling characteristic for different materials of target surfaces that are exposed to impingement of air jet. They concluded that the appearance of secondary peaks could be concluded to exist between 2, 205 to 26, 46, 000 of the jet to the target spacing based Reynolds number. Umair and Gulhane [20] further took a step for numerical investigation of non-dimensional constant representing the occurrence of secondary peaks in the Nusselt distribution curves. The outcome of this investigation was that the appearance of secondary peaks in Nusselt profile exits when the value of non-dimensional constant exceeds 6000. Umair *et al.,* [21] investigated the Nusselt distribution curve to find the critical range for occurrence of secondary peaks. They concluded that this lies in the range of 1,76,000 $\leq Re_z \leq$ 2,20,5001. S. A. Khan *et al.,* [22] studied about threaded spikes for bluff body base flow control. They found that the threaded spike was very effective in regulating the base pressure as well as the base drag. Also they found the the dependency of base pressure on Mach number.

1.2. *Objectives of the Paper*

From the above literature survey, it is noted that geometric parameters of base plate play a vital role in deciding the type of augmentation in heat transfer rate because of pulse jet. Also, implementation of pin fin surface (Modified surface) in transferring the heat to pulse jet is not yet investigated. On behalf of this, author environs the current work toward the experimental investigation of heat transfer rate due to pulsating jet, exposed to pin fin surface. Also, the present work establishes a Numerical and Non-dimensional correlation ship between the Nusselt number of the pulsating and steady jet, impinging and geometric non-dimensional parameters.

2. Methodology

2.1. *Experimental Approach*

Impingement of air jet on the heated base surface causes heat transfer to ambient due to convection. The heat transfer coefficient due to forced convection in the present study is given by Eq. (1).

$$h = \frac{Q}{A\times (T_b - T_a)} \tag{1}$$

The magnitude heat transfer coefficient decides how well the air impinging on the base surface is capable of taking away the heat possessed by the surface. However, with the change in the area, the coefficient gets disturbs. Hence examining Nusselt number which is defined as the ratio of heat convected to that conducted as shown in Eq. (2) becomes necessary. Since the side wall of the base surface is well insulated hence heat loss due to conduction is neglected.

$$Nu = \frac{h}{K_a} \times d \tag{2}$$

The definition of heat transfer rate and Nusselt coefficient in the presence of pulsating jet remains the same as that for a steady jet.

2.2. *Numerical Methodology*

Computational simulation of a 2-D geometric model is constructed in order to record the accurate temperature profile over the target surface. The computations are usually done in a commercial solver of ANSYS CFX. The numerical method commands the continuity and energy equation to be solved simultaneously in order to develop the flow regime and plot the corresponding heat transfer. The computational simulations are carried out through the second-order upwind scheme with standard values of turbulence intensity (1-3%) and turbulence Prandtl number (0.7). Taking into consideration the computational time and cost, a 2-D axis symmetric model is developed. During the process of simulation, it is assumed that the flow of air is incompressible and occurs at a single phase. The appropriate choice of turbulence model is very important, as far as the prediction of flow profile and prediction of heat transfer rate is concerned. K- Epsilon turbulence model has the ability to predict the Nusselt profile in the stagnation region whereas K- Omega predicts better in wall jet region. On the other side of the coin, SST turbulence model incorporates simultaneously the effect of near wall as well as far-field areas of the flow regime. The magnitude of decrement in Nusselt number due to pulsating jet as seen in Eq. (3) is a function of a momentary term (Nu_i) occurring due to pulsation in addition with an appellation (Nu_{ip}) occurring due to the presence of pin fin.

$$Nu_p = Nu_s \pm Nu_i \pm Nu_{ip} \tag{3}$$

If the flat plate is used instead of pin fin array heat sink the third term occurring on the right side of Eq. (3) doesn't occur. The transient term (Nu_i) occurring on the right side of Eq. (4) is compulsory every time whenever steady jet gets converted into pulsating jet. While the occurrence of third term (Nu_{ip}) justifies the generation of turbulence due to the presences of pin fin. The present research takes a further effort to develop a non-dimensional correlation between these parameters. This is achieved by performing regression analysis between various dominating geometric and injection parameters.

As stated the transient term Nu_i can be determined best when target surface is a flat plate. From the experimental readings of flat plate (Not mentioned) it is found that this transient term is a function of Strouhal number, jet-to-target spacing, dimensions of the plate and duty cycle of pulsating jet.

The inlet boundary condition is given a velocity profile input while the walls are treated as opening. The base plate is given the constant heat flux input and the L1 is given the symmetry boundary condition

$$Nu_i = f\ (Sh.no., G.no.). \tag{4}$$

3. Results and Discussion

Non dimensional correlation ship between Nusselt number as a dependent variable is developed with Strouhal number, characteristic length of base, jet-to-target spacing and duty cycle number as an independent variable. The present case calculates the deviation of heat transfer rate because of pulsating jet compared to steady jet as shown in Eq. (5)

$$Nu_s - Nu_p = a + b \times Sh.no + c \times ({}^{Z}/{}_{L_b} \times DC) \tag{5}$$

According to Tim *et al.,* [9], the constants ‘a’ and ‘b’ is found to have a magnitude of -0.079 and 0.805 where heat transfer augmentation due to pulsating jet occurs in the positive region. In the present case since the heat transfer characteristic lies below the steady jet hence $^{Z}/_{L_b} \times DC$ is the additional parameter considered. This decides the optimum compromise between penetrating momentum and capability of base a surface to digest the stagnation heat. While Reynolds number plays a least role in deciding the deviation in the magnitude of area average Nusselt number, Tim *et al.,* [9] also concluded the same for area average Nusselt number. Heat transfer augmentation data characteristic length of base the surface and duty cycle. The corresponding best fit line is obtained in Figure 1 with R^2 1(a) as a function of Strouhal number, jet to target spacing value of 0.815 and the magnitude of constants determined is shown in Eq. (6) for the nozzle diameter of 8mm and 16mm is shown in Figure 2. Eq. (6) is derived using the regression analysis between Nusselt number, Strouhal number, duty cycle and Z/d

$$Nu_s - Nu_p = 2.19 + 28.89 \times Sh.no + 10.9 \times (\,^{Z}/_{L_b} \times DC\,) \tag{6}$$

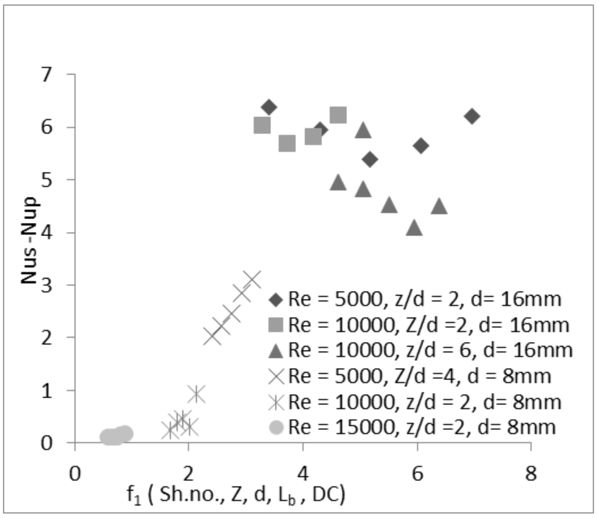

Fig. 1. Scaling of various data used to fit a line

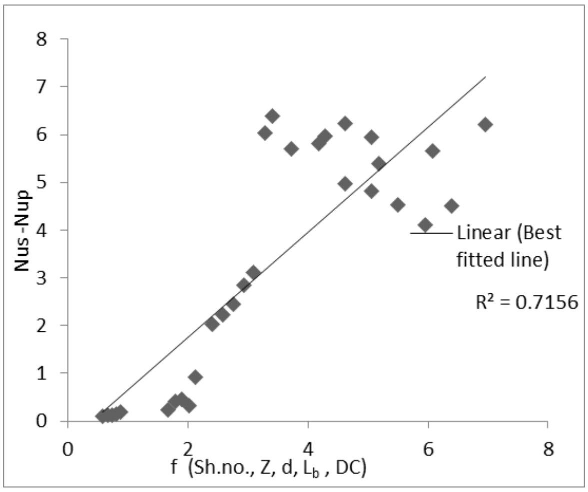

Fig. 2. Best fit line between the salient data with R^2 value of 0.8

Eq. (6) gives a generalized expression for transient Nusselt term which occurs in presences of pulsating. Figure 3 shows the changing of local Nusselt number versus radial distance for different turbulence model. The corresponding mesh defining the best result consists of 550 number of divisions over edge L1 and 400 number of division over edge L2. Here, L1 and L2 are the horizontal lengths representing the length of the flat plate and Z/d respectively. At Z/d = 4, the present grid dependence test is executed. Also impinging Reynolds number of 10,000 is selected for the test. However, with the change in the value of Z/d, it is advised to vary the number of divisions accordingly. The deviation in Nusselt value recorded using numerical turbulence models are due to consideration of various effects like intermediancy and onset transition of Reynolds number.

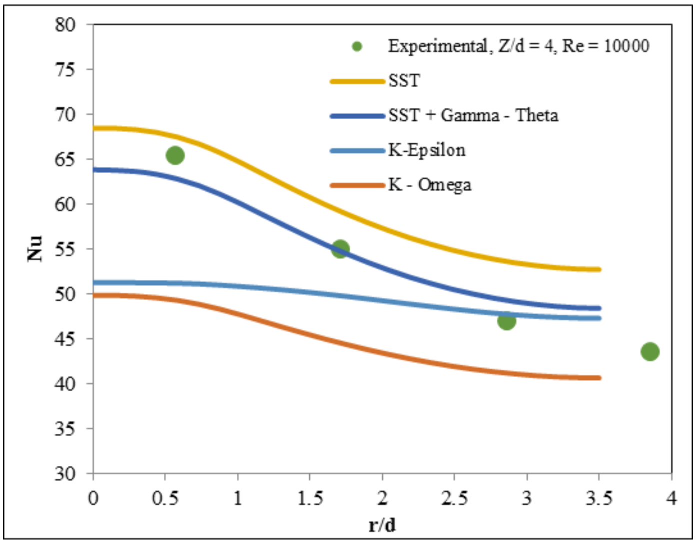

Fig. 3. Validation of turbulence model with an experimental profile

4. Conclusions

Heat transfer augmentation because of pulse jet lies either above or below of steady jet for which the magnitude of G.No. Signifies which type of the augmentations are possible. A remarkable decrease in heat transfer rate is seen as a result of the pulsating jet, the degree of dependencies majorly involved that non-dimensional numbers with Nusselt number need to be correlated. The present work considers Strouhal number, G. no. Reynolds number as dependent variables, of which the degree of dependency for Reynolds number was found to be the minimum, as the viscosity and density effect of air remains the same. Also, the occurrence of pulsation plays a minimum role in changing the heat transfer rate of a flat plate as the variable distance between two pulsed mass of air generated, due to the frequency change, offers negligible importance to flat plate in this present work.

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