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CFD ANALYSIS OF HEAT TRANSFER AND CHARACTERISTICS OF SWIRL FLOW JET IMPINGEMENT COOLING

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ABSTRACT

Impinging jets have been widely used for increasing heat transfer in engineering applications such as cooling of hot steel plates and turbine blades, tempering of glass, drying of papers and films and cooling of electronic components. In the last decades, the semiconductor industry developed so rapidly that the size of electronic component has become less and less. This trend results in the increase of power density, and the simultaneous increase of heat flux on the apparatus. As most of the electronic chips operate only in some range of temperature, it is very important to accelerate the heat dissipation of electronic components. It is obviously that the traditional natural and forced convection methods can't satisfy the cooling of such high heat flux density. In this situation, the swirling jet impingement gets more and more attention as a very potential alternative because of its much better heat transfer effect than the other methods. The objective of the study is to investigate the characteristics of the heat transfer for swirling jet impingement on a surface which aims to enhance the heat transfer rate and also to compare heat transfer characteristics of straight impinging jet and swirl flow impinging jet. The present study focuses on the verification of the swirling jet effect on the distribution of the local heat transfer coefficient on the impinged target surface. Studies would be conducted for a wide range of parameters including velocity, swirl Pitch and nozzle to target plane spacing. The motivation of this paper is to explore the efficiency of swirling jet impingement cooling and understand the mechanisms by which heat is removed from a constant heat flux surface. The heat transfer characteristics and flow structures are explored computationally to gain an understanding of the underlying physics of flow and heat transfer interactions in surface cooling with impinging jets.

Key words: CFD, Heat transfer, Swirl flow, Impinging jet.

INTRODUCTION

Jet impingement systems provide an effective means for the enhancement of convective processes due to the high heat and mass transfer rates that can be achieved. The range of

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industrial applications that impinging jets are being used in today is wide. In the annealing and tempering of materials, impinging jet systems are finding use in the cooling of hot metal, plastic, or glass sheets as well as in the drying of paper and fabric. Compact heat exchangers, with applications in the aeronautical or the automotive sector, often use multiple impinging jets in dense arrangements. Impingement systems in micro scale applications are commonly used for the cooling of electronic components, particularly electronic chips. In gas turbine applications, jet impingement has been routinely used for a long time. Requirements are being imposed by demands for increased power output and efficiency as well as for reduced emissions. High thermal efficiency can be realized by increasing turbine inlet temperatures and compressor ratios. As a result of this, many gas turbine components, such as rotor disks, turbine vanes and blades, or combustion chamber walls, are operated at temperatures well above highest allowable material limits. In order to assure durability and long operating intervals, effective cooling concepts are required for these highly loaded components. Depending mainly on geometrical conditions, flow and heat transfer characteristics of multiple impinging jets can differ substantially from those of single jets. This is, as in a multi jet configuration the individual jets can be affected by essentially two types of interactions that do not occur in single jet systems. 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 is of importance for arrays with closely spaced jets and large separation distances between the jets and the impingement surface. Secondly, there is the interaction between the impinging jets and the flow formed by the spent air of the neighboring jets. These disturbances predominantly occur for arrays with small inter jet spacing, small separation distances, and large jet velocities. The strength of cross flow within the impingement array is determined further by the design of the outflow. It is due to these interferences that the use of single jet heat transfer results for the design of multiple jet configurations becomes significantly complicated or even erroneous. While heat transfer rates due to single jets can be functionally expressed by relatively simple power-functions of Reynolds and Prandtl number, correlations for multi jet heat transfer rates require the consideration of a number of additional characteristic numbers. Impinging jets have been widely used in many industrial applications in order to achieve enhanced coefficients for convective heating, cooling or drying. A single air jet or arrays of air jet, impinging normally on a surface are an effective method to enhance heat and mass transfer. High convective heat transfer coefficient is a very important factor that leads to the many usage of impingement jets in industrial for heating and cooling purposes. Jet impingement is an attractive cooling mechanism due to the capability of achieving large heat transfer rates. This cooling method has been used in industrial applications such as annealing of metals, tempering of glass, cooling of gas turbine blades, cooling in grinding processes and cooling of photovoltaic cells. Jet impingement has also used for high-powered electronic and photonic thermal management solutions and numerous jet impingement studies have been aimed directly at electronics cooling.

Literature review

Nuntadusit, M. Wae-hayee (1) studied experimentally the Flow and heat transfer characteristics of swirling impinging jet (SIJ) at constant nozzle-to-plate distance. The swirling jet is generated by inserting twisted tapes within a pipe nozzle. Effects of swirl on the impinged surface are investigated for various twist ratios. The flow patterns of the free swirling jet and the swirling impinging jet were visualized by mixing dye with the jet flow. Distributions of temperature and convective heat transfer coefficient on the impinged surface were measured with thermo chromic liquid crystal (TLC) sheet and image processing technique.

Bakirci and Bilen (2) visualised the temperature distribution and evaluated heat transfer rate on the impingement surface for a swirling, multi-channel and conventional impinging jets using thermo chromic liquid crystals.They found the local Nusselt numbers of the multi-channel impinging jet were generally much higher than those of the swirling and conventional impinging jets.

H. T. Xu and J. L. Niu (3) used the latest CFD technique to investigate the airflow pattern and the impact on thermal comfort in the near nozzle region of a floor level swirl-type diffuser. The preliminary simulation results indicate that re-circulation region in the near nozzle can only be realistically predicted by including the swirling devices in the calculation domain. The results will be further validated with experiments, and the method is expected to be used to help optimize diffuser designs.

Karl J. Brown and Darina B. Murray (4) research is concerned with the effect of swirl on the heat transfer characteristics of jet impingement cooling. Two inserts were designed order to generate swirling flow. These two designs, “Swirl Insert A” and “Swirl Insert B”, were tested at various Reynolds numbers, between 8000 and 16000 inclusive, and at H/D = 0.5 and 1. The jet was directed downwards onto a 25 μm thick stainless steel foil which was chemically heated. Images were recorded using a thermal imaging camera focused on the underside of the foil. These images were then analysed using Matlab and the Nusselt

Modeling

Modeling was done using Pro E Wild Fire 2.0 and exported in IGES format. The models of nozzle heads have been shown in the following Figs.

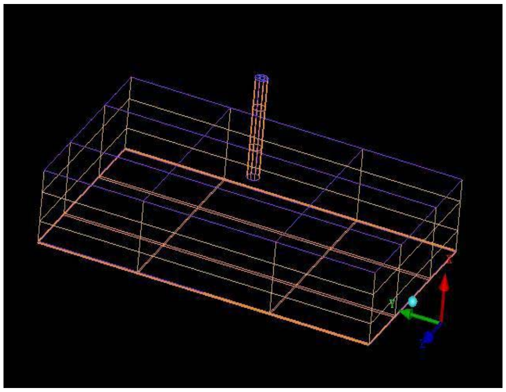


Fig. 1: H/D = 5 (Non Swirl)

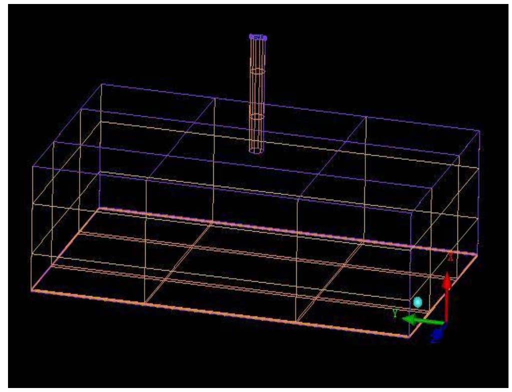


Fig. 2: H/D = 7.5 (Non Swirl)

Meshing

ANSYS ICEMCFD's mesh generation tools offer the capability to parametrically create meshes from geometry in numerous formats:

(i) Unstructured hexahedral unstructured tetrahedral

(ii) Cartesian with H-grid refinement hybrid meshes comprising hexahedral, tetrahedral, pyramidal and/or prismatic elements.

(iii) Quadrilateral and triangular surface meshes.

Mesh generation is the process by which spatial discretization of CFD model is accomplished. Meshing is based on tetrahedron element discretization. The model is exported in IGES format and is used in ICEM- CFD tool. Surface and volume meshes were generated using this tool by defining the type of meshing element and mesh element size.

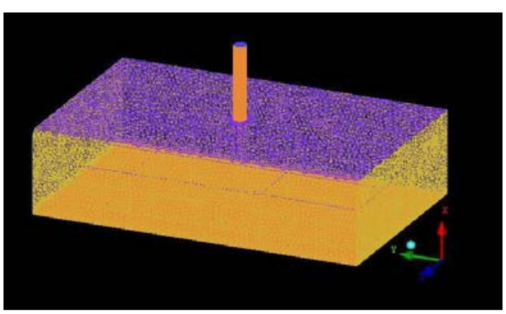


Fig. 3: H/D = 5

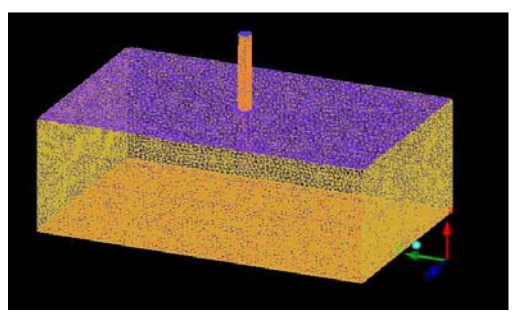


Fig. 4: H/D = 7.5

There are two types of grids to choose from for model meshing, i.e. structured and unstructured grids. The first one is composed of hexahedral elements while the latter one consists of tetrahedral elements. A general rule of thumb is to apply the structured grids on simple geometries and the unstructured grids on complex geometries.

A general guideline of model meshing is to always mesh the more critical domains (i.e. high velocity, high pressure or pressure drop flow fields in advance of the less critical ones. The fineness of grid applied increases with the criticalness of a domain.

After model meshing, the grids on model have to be optimized. This step is essential as it helps to minimize the numerical errors in computation during the simulation work. The intention of this optimization process is to determine an acceptable grid size that is able to reach a balance between the amount of computing time and the accuracy in the solution of flow variables.

Pre processing

The meshed model is exported in .msh format and is used in CFX tool. The CFD analysis was executed with following domain specifications and boundary conditions.

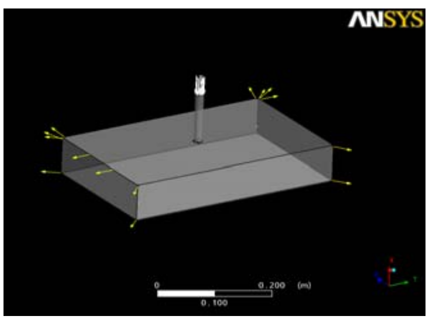


Fig. 5: H/D = 5

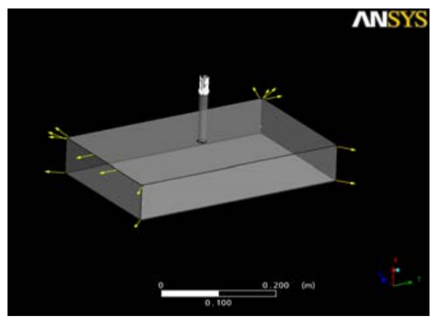


Fig. 6: H/D = 7.5

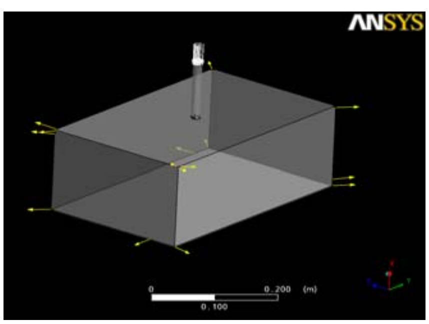


Fig. 7: H/D = 10

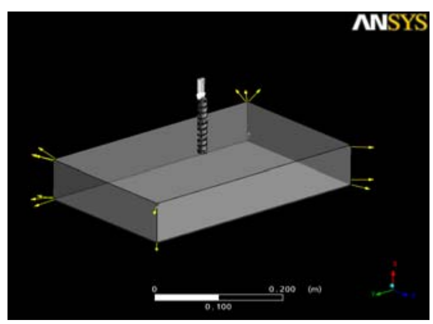


Fig. 8: H/D = 5 Swirl pitch = 10 mm

Specification of domain and boundary conditions

Domain specification

Fluid domain

Domain type : Fluid domain domain name : Swirl jet fluid : Air

Heat transfer : Thermal energy turbulence model : RNG K-Epsilon

Solid domain

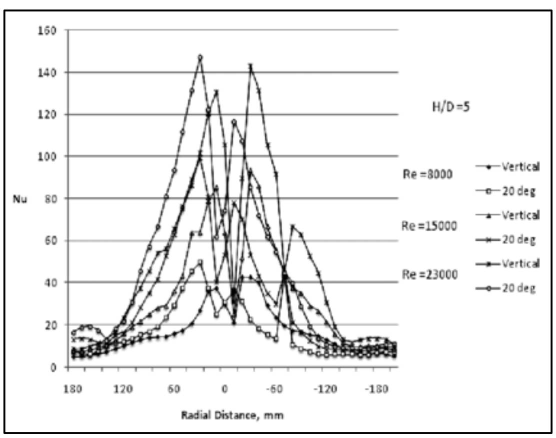
Domain type : Solid Domain Domain Name : PCB Plate

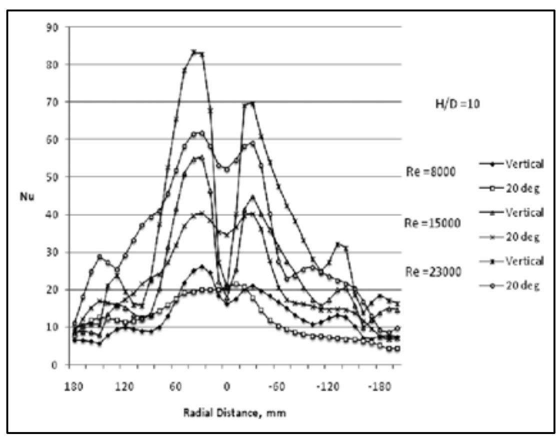
Material : Epoxy plate with copper foil

Domain interface : Interface type : Fluid and solid

RESULTS AND DISCUSSION

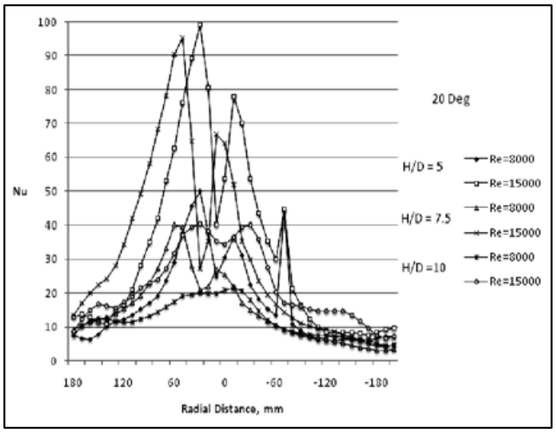
Details of exit flow structures in the case of an annular impinging jet with swirl and non swirl have been discussed in this section. Fig. 9 shows velocity vector distribution for non swirl jet with varying H/D distances. It is observed from the result that for H/D = 5 recirculation occurs symmetry to nozzle axis. This is due to reverse flow after impingement. This will obviously enhance the heat transfer rate. In the case of H/D = 7.5 no such recirculation zones in the reverse flow. When the H/D is further increased the stream of jet is carried away by fluid particles.





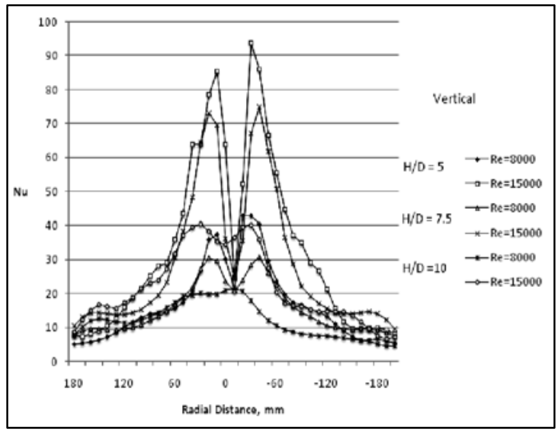
Re number for H/D =5 **Number for H/D =10**

Fig. 9. Nu number variation at varying **Fig. 10. Nu number variation at varying Re**



H/D distance for 20° Inclination

Fig. 11: Nu number variation at varying



H/D for vertical

Fig. 12: Nu number variation at varying

Fig. 9 shows radial distribution of Nusselt number for H/D = 5 for vertical and 20° position of nozzle. It is observed that for lower value of Reynolds number (Re = 8000) the radial uniformity of Nusselt number is more in the case vertical position. It is observed from the result that for vertical position immediately after stagnation region Nusselt number increases in the wall jet region for a while after that it decreases gradually. When the Reynolds number increases, the radial uniformity decreases. It is observed form the figure 10 that when H/D distance increases (H/D = 10) the value of Nusselt number also decreases. But the comparatively radial uniformity decreases. The radial distribution of Nusselt number is quiet uniform in the case of vertical Position. Fig. 11 shows that for impinging angle 20 deg the stagnation point heat transfer is high in the case of lower value of H/D distance. At the higher value of H/D distance the more uniform heat transfer is obtained both in lower and higher value of Reynolds number. It is observed from figure 12 that when H/D distance increases the value of Nusselt number decreases both in the lower and higher value of Reynolds number range but the radial uniformity is more in the case of high H/D distance.

CONCLUSION

Thus the heat transfer and flow analysis of swirl flow jet impingement cooling was carried out and the following conclusion has been drawn.

Effect of swirl and non swirl flow

When the separation distance (H/D) increases the radial uniformity of Nusselt number decreases and value of Nusselt number also decreases.

Increased radial distribution of Nusselt number has been observed in the swirl flow but comparatively Nusselt number decreases slightly.

When the Reynolds number increases the radial uniformity of Nusselt number decreases in both cases.

Increased Radial velocity components have been observed in the swirl flow and it leads to comparatively stronger recirculation zones.

At higher Reynolds number the value of Nusselt number is high.

Effect of pitch distance on swirl flow

At higher pitch distance the value of Nusselt number increases which will consequently increase the convective heat transfer but the radial uniformity of Nusselt number has significantly reduced.

At lower pitch distance increased radial uniformity of Nusselt number has been observed

When the separation distance (H/D) increases the radial uniformity of Nusselt number decreases and value of Nusselt number decreases.

At lower value of Reynolds number the increased radial uniformity of Nusselt number has been observed and when and it decreases when the Reynolds number is increased.

At lower pitch distance increased uniformity in radial velocity component and intensity of turbulence have been observed

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