International Journal of Theoretical and Applied Mechanics.
ISSN 0973-6085 Volume 12, Number 2 (2017) pp. 209-226

http://www.ripublication.com

Study on Heat Transfer during Rectangular Slot Air Jet Impingement on Curved Surfaces

Satheesha V[1], Dr. B. K. Muralidhara[2] and Dr. C. K. Umesh[3]

[1] *Research Scholar, Bangalore University & Assistant Professor, Department of Mechanical Engineering, Raja Rajeswari College of Engineering, Bengaluru, Karnataka, India.*

[2] *Former Professor, University Visvesvaraya College of Engineering, Bangalore University & Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bengaluru, Karnataka, India*

[3] *Professor, Department of Mechanical Engineering, University Visvesvaraya College of Engineering, Bangalore University, Bengaluru, Karnataka, India.*

Abstract

An appropriate configuration of cooling jet and target plate geometry helps in optimizing an efficient heat-transfer design. This part of research investigation is an experimental study on heat transfer during rectangular slot air jet impingement on curved surfaces of different radius of curvature. The average Nusselt Number on the impingement surface is presented for different target plates of R/L ratio 0.5, 0.725, 1.3 and flat surface manufactured from aluminum plate of thickness 3 mm. Reynolds number based on hydraulic diameter (D_h) between 1589.5 to 5881.6 and four values of nozzle-to-impingement surface distances from 10 to 16 times nozzle width are considered. The heat transfer results of this investigation indicates that the shape of the target surfaces and nozzle geometry have significant effect on the heat transfer distribution. The results showed that average Nusselt number has significant dependency on the wall-to-jet-spacing. For small wall-to-jet spacing the Nu_{avg} increases and for larger wall-to-jet-spacing the Nu_{avg} decreases and found to be unaffected for higher H/W ratio. The closeness of the target plate from the jet exit and surface curvature of the target plate has an impact on the average heat transfer coefficient.

Keywords: Heat Transfer, Impingement Cooling, Nusselt Number, Radius of curvature, Rectangular slot jet.

NOMENCLATURE

B	Breadth of slot jet (m)	D_h	Hydraulic diameter of the slot jet (m)
W	Width of slot jet (m)	k_a	Thermal conductivity of air (W/m K)
H	Distance from plate to nozzle (m)	T_p	Plate temperature
L	Trace length of plate (m)	T_j	Jet temperature
R	Radius of concave plate (m)	P	Perimeter of slot exit of nozzle (m)
H/W	Nozzle to surface dimensionless distance	Q_{total}	Total heat supplied to the plate (W)
R/L	Dimensionless radius of curvature	$Q_{convection}$	Convection losses for full plate (W)
Re	Reynolds number	$Q_{conduction}$	Conduction losses for full plate (W)
$\dot{m}$	Mass flow rate of air (kg/s)	$Q_{radiation}$	Radiation losses for full plate (W)
h	Convective local heat transfer coefficient (W/m^2 K)	A	Area of the plate (m^2)
Nu_{avg}	Average Nusselt number	I	Current supplied for heater plate (A)
h_{avg}	Average convective heat transfer coefficient (W/m^2 K)	V	Voltage supplied for heater plate (V)

1. INTRODUCTION

Air jet impingement is an effective means of cooling of gas turbine blades, electronic equipments, hot steel plates, drying of textiles and paper, annealing of steel and glass and rocket launcher cooling. Jet impingement is one of the more effective means of transferring heat by convection and convection coefficient well in excess of 100

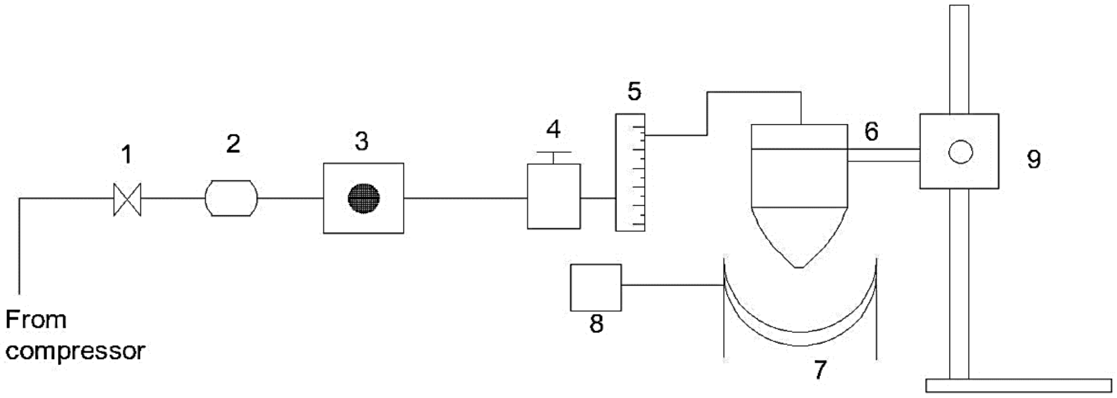
W/m^2.K may be achieved. Among all heat-transfer enhancement techniques jet impingement has the most significant potential to increase the local heat-transfer coefficient. Therefore impingement heat transfer is used in locations where thermal loads are excessively high. Study on configuration of cooling jets, different aspects needed to consider for optimizing an efficient heat-transfer design is needed.

Brahma et al. [1] studied stagnation point heat transfer for a single round jet impinging on a concave hemispherical surface. Gau and Chung [2] investigated the effects of surface curvature on heat transfer for a slot jet impinging on concave/convex surfaces. Lee et al. [3] experimentally studied turbulent flow and heat transfer of a jet impinging on a hemispherical concave surface. Yang et al. [4] experimentally studied slot jet impingement cooling on a concave surface. Cornaro et al. [5] conducted flow visualizations for a turbulent axisymmetric jet impinging on semi cylindrical concave and convex surfaces. Choi et al. [6] experimentally studied fluid flow and heat transfer for jet impingement cooling on a semi-circular concave surface. Kayansayan and Küçüka [7] experimentally studied the impingement cooling of a semi-cylindrical concave channels by confined slot jet. Chan et al. [8] studied the surface heat transfer characteristics of a heated slot jet impinging on a semi-circular convex surface and they presented correlations of local and average Nusselt numbers with Reynolds numbers and the dimensionless slot nozzle-to-impingement surface distance for the stagnation point and the circumferential distribution. Souris et al. [9] performed the numerical modelling of jet impingement cooling onto a semi-circular concave surface and evaluated the performance of two-equation turbulence models (such as the k-ε model). Olsson et al. [10] investigated the heat transfer from a slot air jet impinging on a cylinder shaped food product placed on a solid surface by using computational fluid dynamics and examined the distribution of the local Nusselt numbers around the cylinder for various Reynolds numbers, jet-cylinder distances, and cylinder curvature. Gilard and Brizzi [11] studied the aerodynamics of a slot jet impinging on a concave wall. They investigated the influence of the radius of the wall curvature, the impingement height and the Reynolds number on the flow field by conducting flow visualizations, velocity measurements by particle image velocimetry (PIV) and mean pressure measurements. Jefferson-Loveday and Tucker [12] numerically studied turbulent heat transfer impinging on a concave surface by using large-eddy type simulations. Sharif and Mothe [13] conducted a parametric study of the turbulent slot-jet impingement heat transfer from concave surfaces by using the RNG k-ε model with the two-layer enhanced wall treatment approach. In a very recent study, Yang et al. [14] numerically studied turbulent slot jet impingement cooling on a semi-circular concave surface by using the standard k-ε model.

The impingement surfaces used in practice are generally slightly curved, i.e. the impingement surface to be cooled may have less curvature than semicircular/ hemispherical concave / convex surfaces. Oztekin et al. [15] studied a turbulent slot jet impinging on concave surfaces with varying surface curvature from the viewpoint of hydrodynamics.

Literature survey indicates that the shape of the nozzle, the layout of jet holes, the shape of the target surfaces have a significant effects on the heat transfer distribution and very less research information are available on jet flow related to heat transfer on curved surfaces in the published literature. However this experimental study is to describe key heat transfer features of single slot air jet impingement on curved surfaces.

2. EXPERIMENTAL METHODOLOGY



1.Ball valve
2.Pressure gauge
3.Air filter
4.Pressure regulator
5.Rotameter
6.Nozzle
7.Target plate
8.Temperature controller
9.Traverse

Figure 1: The Schematic view of Jet Impingement heat transfer test facility used in this investigation.

In the first phase of this investigation a nozzle with specially designed air orifice plates is used to facilitate different dimension rectangular slot jet pattern is designed and fabricated. In the second phase of the investigation different radius of curvature target plates were designed and fabricated. In the third phase of the investigation it has been proposed to study the heat-transfer during rectangular slot air jet impingement on curved surfaces.

For different air flow conditions for different target plates tested to understand the role of H/W ratio and R/L ratio of the plate geometry on the heat transfer.

Experimental setup consists of an air supply unit including air compressor, air tank, filter, pressure regulator, and flowmeter, nozzle, and an impingement surface. As indicated in the figure 1. A jet of air with high velocity is made to pass through slot that impinges on the flat and curved surface. Cooling jet for the experiment obtained by using different orifice plate geometry at the nozzle exit. The cross sectional view of nozzle designed, fabricated and used in the present investigation has been presented in figure.2. The main flow is supplied by the air compressor (500 L capacity and maximum pressure of 12 bar). The air is passes through the filter and then goes through the high precision pressure regulator where its pressure is adjusted to the desired value. Then the pressurized air is injected tangentially into the settling chamber containing a mesh screen to reduce the flow fluctuations at the nozzle inlet. Finally, the pressurized air goes through the rectangular slot nozzle and generates the slot jet. The flow rates were measured directly from the rotameter. Two dimensional slot nozzle with 3 mm width and an aspect ratio of 21:1 to produce uniform velocity profile at its exit is used for the study. According to the hydraulic diameter of the nozzle exit cross section, the jet Reynolds numbers is varied. The dimensionless nozzle-to-impingement surface distance (H/W) was adjusted to 12,14,16 and 18 by a traverse unit with an accuracy of 1 mm for each impingement surface.

The construction of the impingement module, which consists of an impingement surface made up of Aluminium of 3 mm thickness, below it heater plate made up of mica heater is placed, provided glasswool insulation layer, asbestos and a supporting plate is provided. Four different impingement surfaces with relative curvatures of R/L =0.5, 0.725, 1.3 and a flat surface were tested. The geometric parameters of each surface are given in Table 1. Note that each surface has same projection area which is 150 mm X 150 mm.

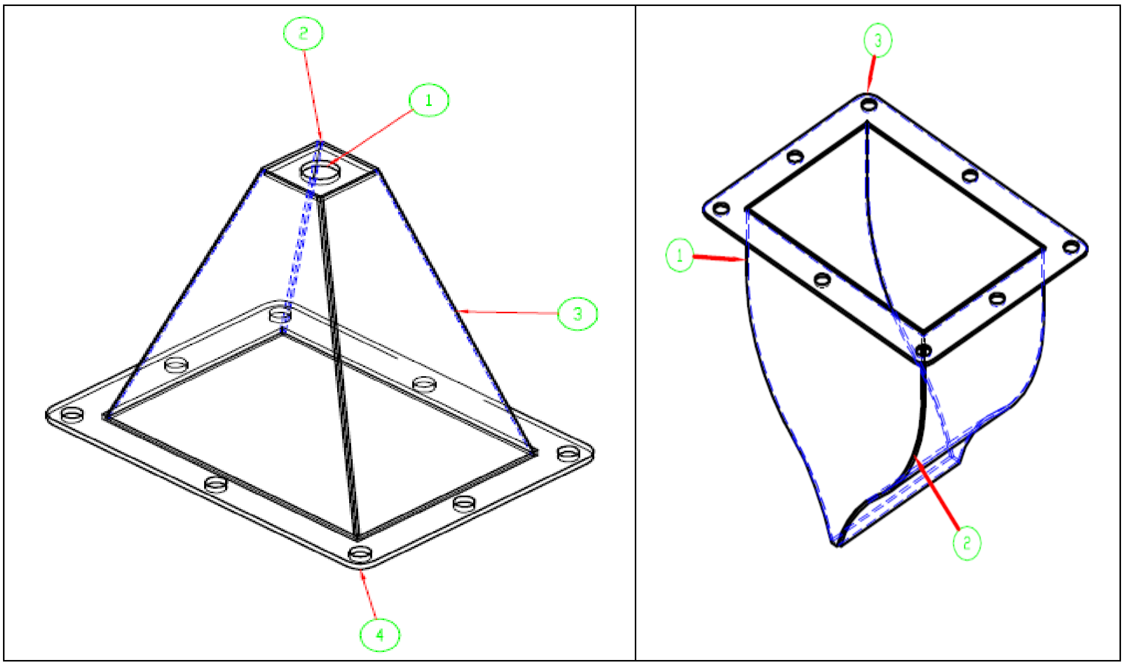


Figure.2: Cross sectional view of nozzle designed, fabricated and used in the present investigation

Table 1: Geometric parameters of each impingement surface

Plate Number	**Radius (R) in mm**	**Trace length (L) in mm**	**Radius of curvature (R/L)**
1	75	150	0.5
2	108.75	150	0.725
3	195	150	1.3
4	---	150	Flat plate

A plate heater of operating parameters of 5A and 230 V having a thickness of 2 mm is adhered to the bottom side of each impingement surface using thermal interface material. The input electric power to the heater is controlled by digital temperature controller using DC power supply at each experiment. To prevent the dissipation of heat energy from the bottom side of the heater plate, an insulation layer consisting of asbestos sheets and glass wool of thickness of 40 mm is provided.

The temperature of the jet and the local temperatures of the concave surfaces were measured by a K-type thermocouple. For each measurement, the flow is considered to have reached a steady state and the readings of local temperatures and jet velocity do not change anymore with time. At such a steady state, the temperatures and velocities are recorded for about 5 min. The experiments are conducted with four different values of dimensionless surface curvature (R/L = 0.5, 0.725 and 1.3 and flat plate) and four different values of nozzle-to-impingement surface distance (10,12,14,16 and 18).

The dimensions of nozzle exit is varied by fitting nozzle exit plates of dimension of breadth and width (63mm*1mm), (63mm*2mm), and (63mm*3mm) slot of rectangular shape. The Reynolds numbers used in the experiment is between 1589.5 and 5881.6 according to the hydraulic diameter of slot of the nozzle exit. This slot jet of air coming out of the nozzle is made to impinge on the target plate which is maintained at a constant temperature of 50^0 C and the temperature across the target plate surface is measured with the help of generated grid points on the plate. The grid size used in the experiment is 10 mm X 10 mm and the number of grids are 15 X 8 along the length and width of the plate, i.e., each plate will have 120 numbers of points across the plate where the temperature is measured.

When the temperature of the plate reaches steady state after impinging the jet on it, temperatures are measured along the generated 120 grid points using probe type digital temperature sensor which uses K-type thermocouple and temperatures are noted down and tabulated to corresponding grid name.

This is continued for the different distance of nozzle exit to target surface for H/W of 10, 12, 14, 16 and 18 and for the different R/L plates.

Experiment was conducted different mass flow rate of the jet corresponding to different Reynolds numbers of 1589.5, 3178.9, 4768.4 and 5882.6. The repeated trials were conducted in calculating average Nusselt number.

Data Reduction

1. Using the mass flow rate of air ($\dot{m}$) measured by Rotameter, the Reynolds number (Re) can be calculated by following equation,

   $$Re = 4\dot{m}/\mu P$$

2. 'P' in the equation (1) can be calculated by,

   $$P=2(W+B)$$

   Where, W=1 mm, 2 mm and 3 mm and B=63 mm.

3. In jet impingement cooling heat transfer coefficient , average Nusselt numbers are to be defined for the temperature so they are calculated by,

   $$h = (Q_{convection}/A_s)\,(T_P-T_j)$$

   after finding 'h' for all the temperatures of the plate surface on generated grids average of it has to be taken so that it will become 'h_{avg}'

   $$Nu_{avg}=(h_{avg}D_h) / K_a$$

   In the equation (3) '$Q_{convection}$' is the heat lost due to convection , 'A_s' is surface area of the target plate, 'T_p' is the temperature of the plate surface which is measured for grid points and 'T_j' is the jet temperature. 'D_h' is the hydraulic diameter. It is found by the equation

   $$D_h=2WB/(W+B)$$

4. Heat lost due to convection can be calculated by using,

   $$Q_{convection}= Q_{total} - Q_{conduction} - Q_{radiation}$$

   in the above equation 'Q_{total}' is the total heat supplied to the heater, '$Q_{conduction}$' is heat lost due to conduction. In this experiment we are assuming conduction losses are negligible as the bottom surface of the plate is completely insulated. And '$Q_{radiation}$' is the heat lost due to radiation. That can be calculated by the formula,

   $$Q_{radiation}= \sigma A(T_P^4 \text{-} T_a^4)$$

   Where, $\sigma=5.67\times10^{-8}$ W/m^{2}K^4.

5. Total heat input is calculated using,

   $$Q_{total}= IV$$

   Where, 'I' is current and 'V' is voltage.

3. RESULTS AND DISCUSSION

The aim of the experiment is to study heat transfer in a curved plate resulting from a slot air jet impinging normally on to heated target plates of different radius of curvature. The Reynolds numbers used in this experiment study is between 1589.5 to 5881.6. The ratio of distance from to nozzle exit to width of the nozzle (H/W) is varied from 10 to 18. The different radius of curvature of the plates (R/L ratio) used for study are 0.5, 0.725, 1.3 and flat plate. All plates used for study are having same projection area of 0.0225 m^2.

The experiment is conducted for one particular R/L ratio curved plate for different H/W ratio for all the values of Reynolds number considered.

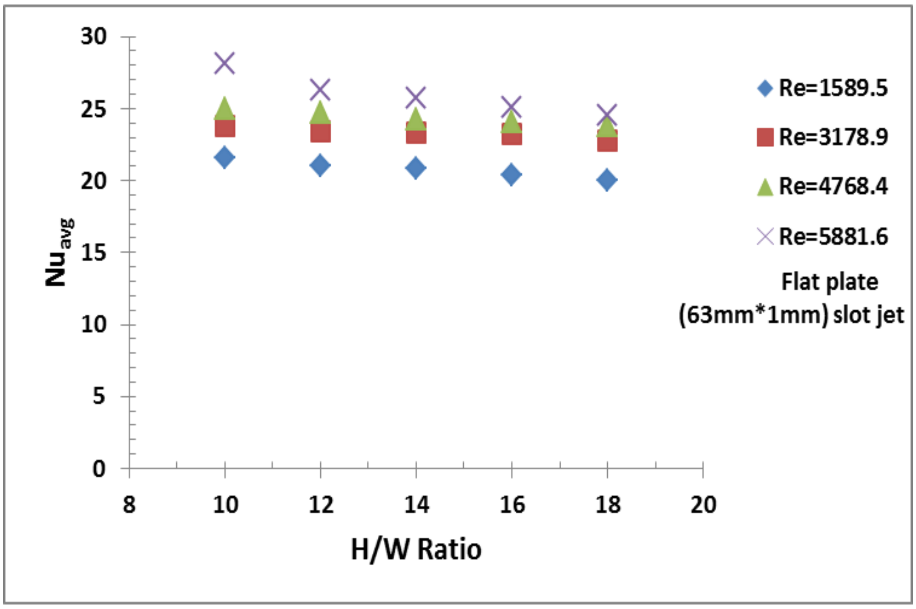


Figure.3(a): The average Nusselt number values for (63mmx1mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (Flat plate)

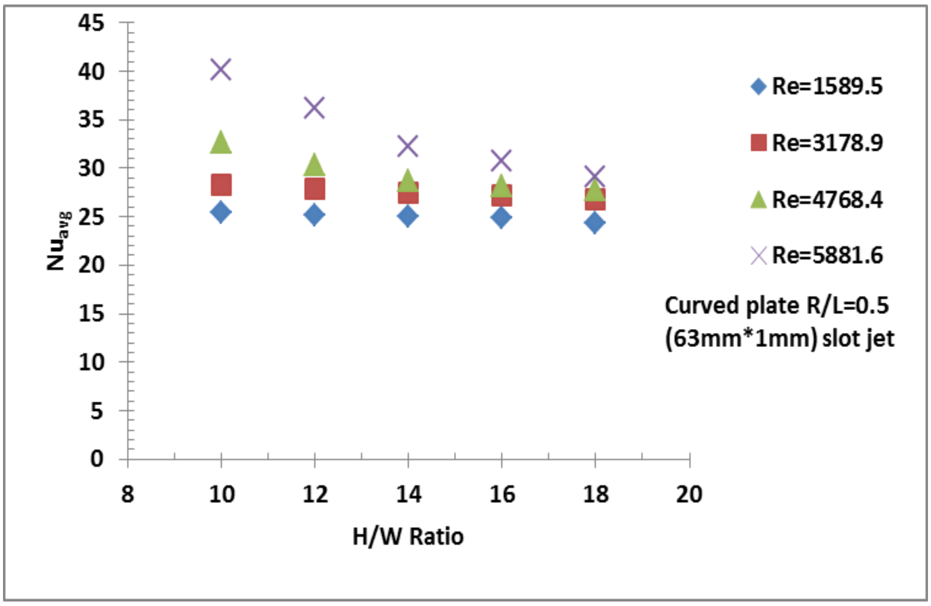


Figure.3(b): The average Nusselt number values for (63mmx1mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.5)

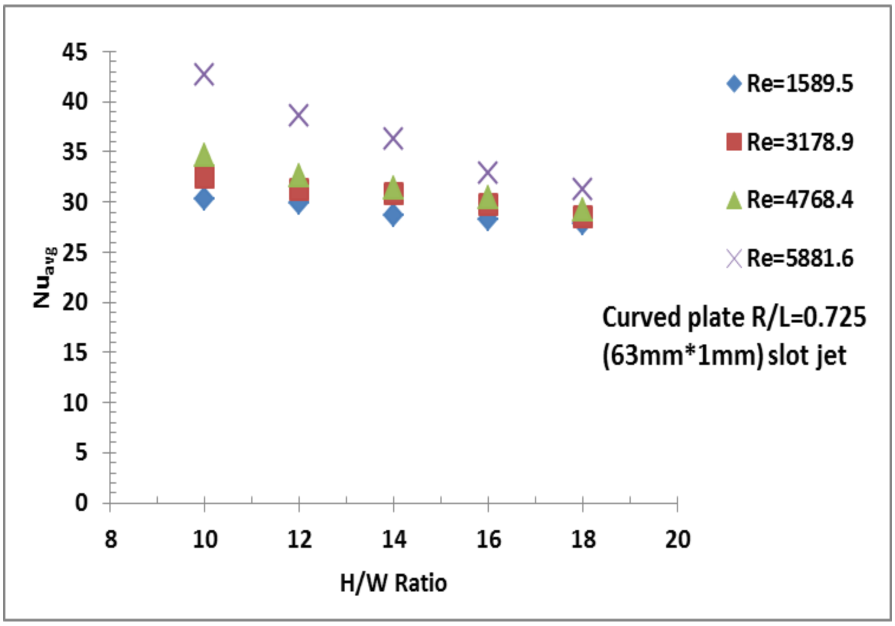


Figure.3(c): The average Nusselt number values for (63mmx1mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.725).

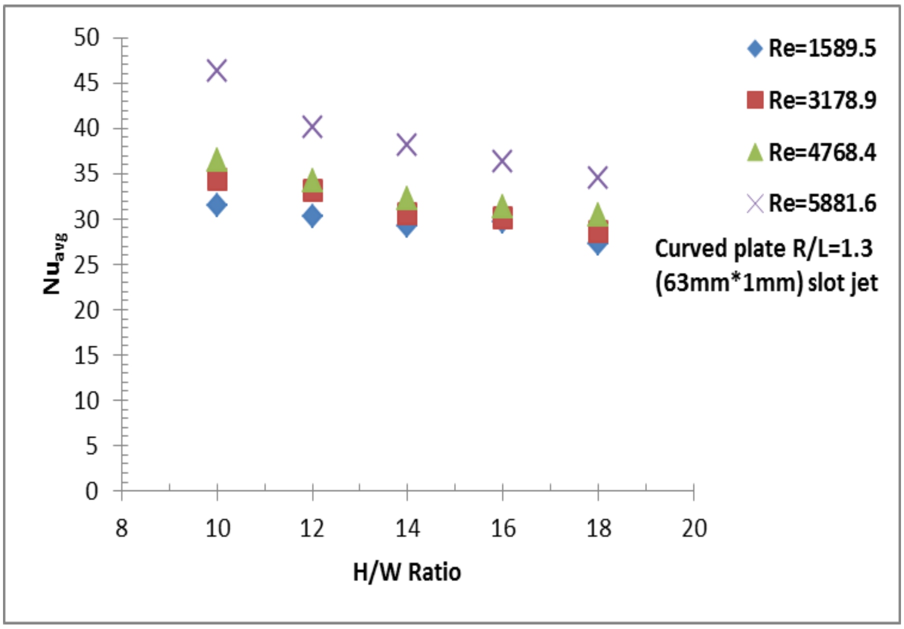


Figure.3(d): The average Nusselt number values for (63mmx1mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=1.3).

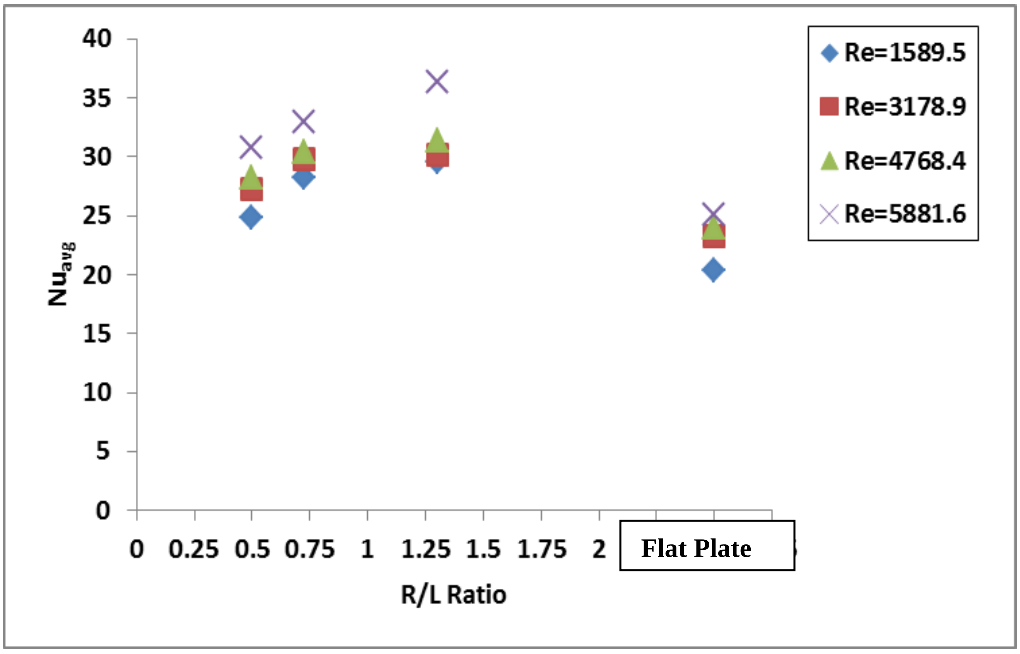


Figure.3(e): The effect of the dimensionless curvature radius (R/L) for (63mm X 1mm) slot jet on the average Nusselt number for fixed values of H/W ratio (=16)

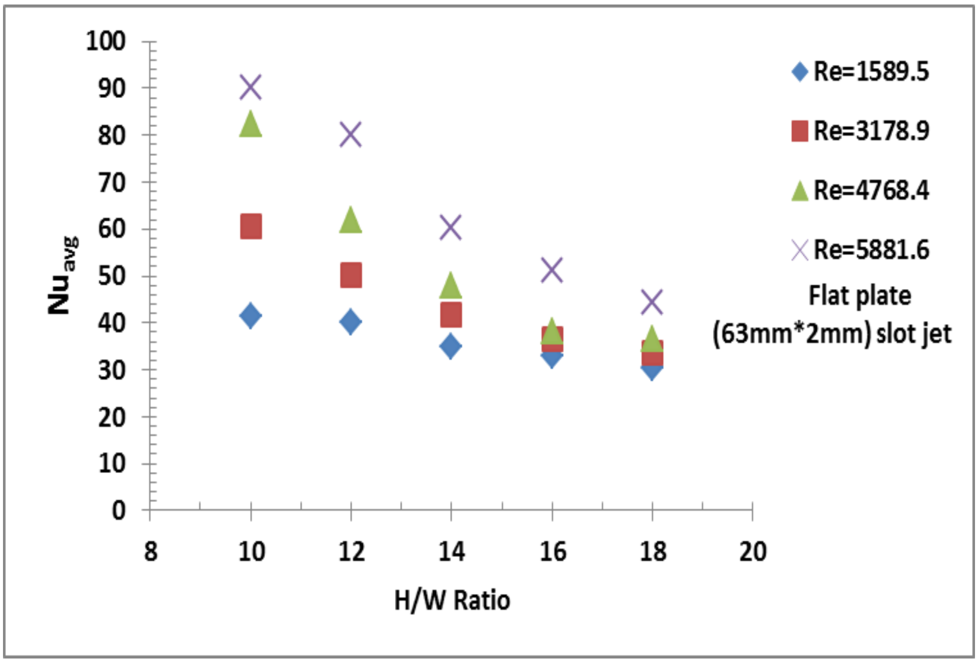


Figure.4(a): The average Nusselt number values for (63mm X 2mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (Flat plate)

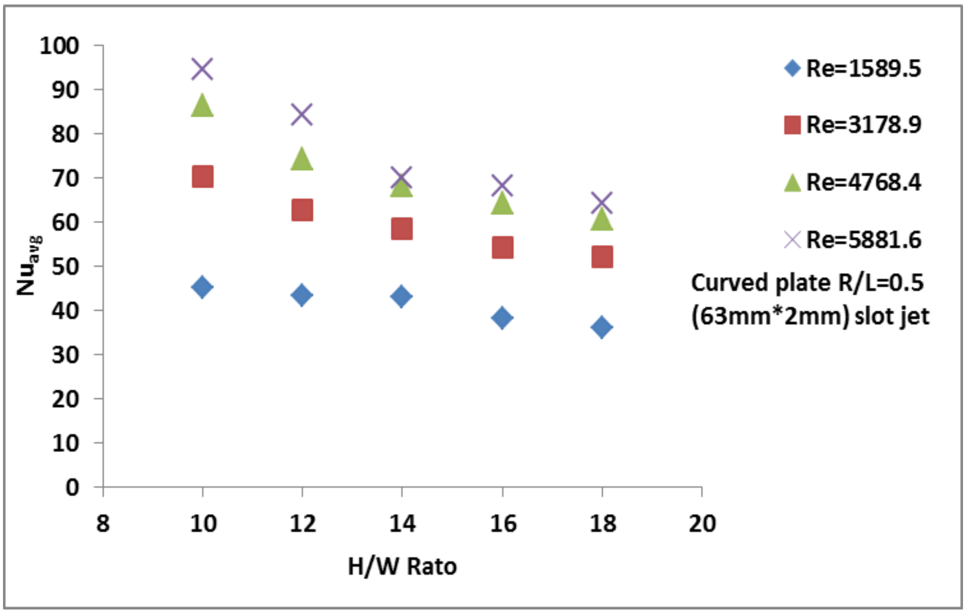


Figure.4(b): The average Nusselt number values for (63mm X 2mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.5)

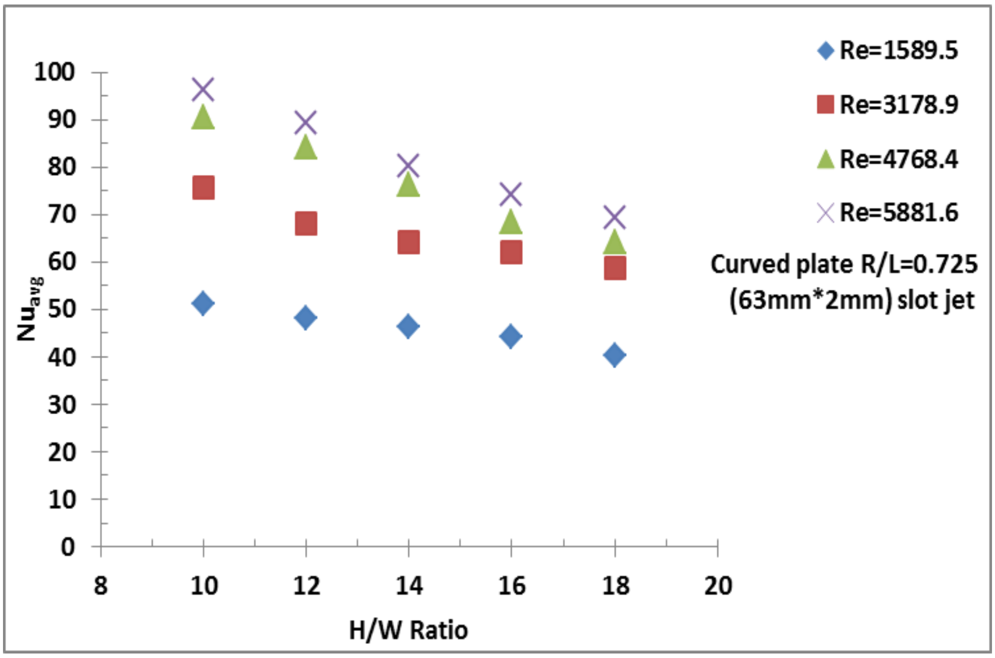


Figure.4(c): The average Nusselt number values for (63mm X 2mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.725).

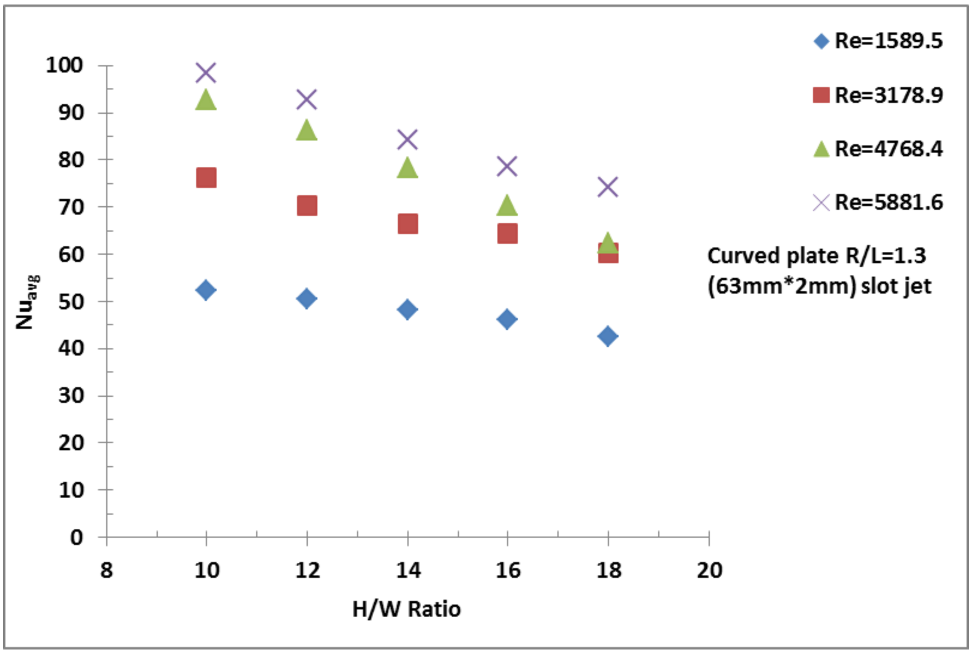


Figure.4(d): The average Nusselt number values for (63mm X 2mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=1.3)

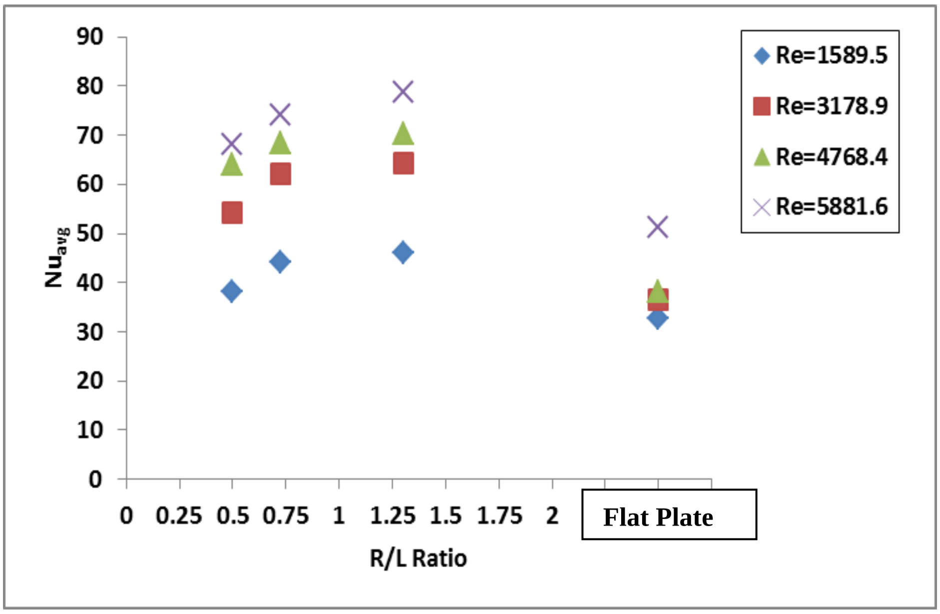


Figure 4(e): The effect of the dimensionless curvature radius (R/L) for (63 mm X 2 mm) slot jet on the average Nusselt number for fixed values of H/W ratio (=16)

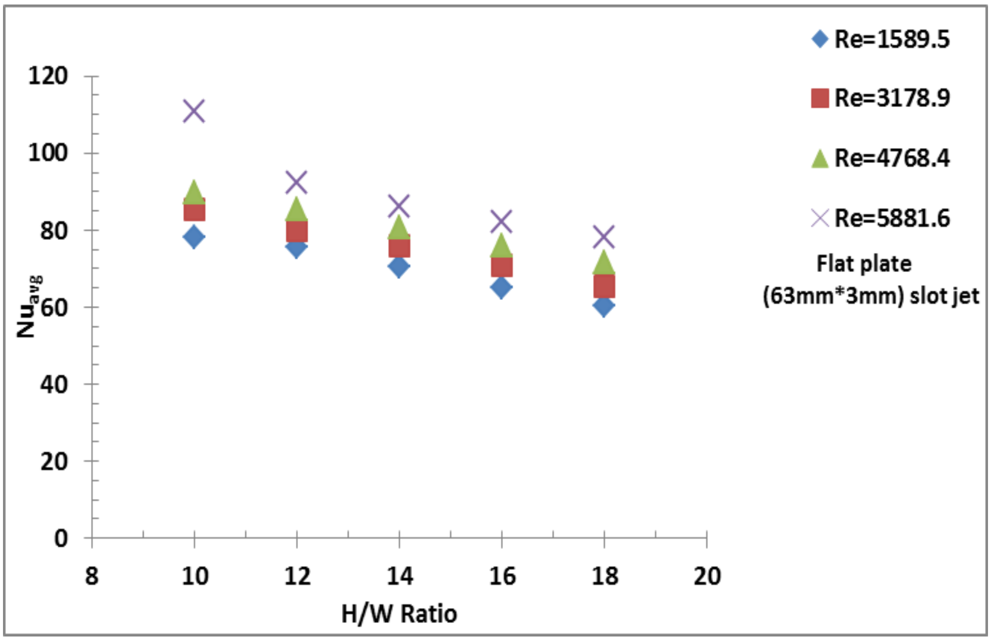


Figure.5(a): The average Nusselt number values for (63mm X 3mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (Flat plate

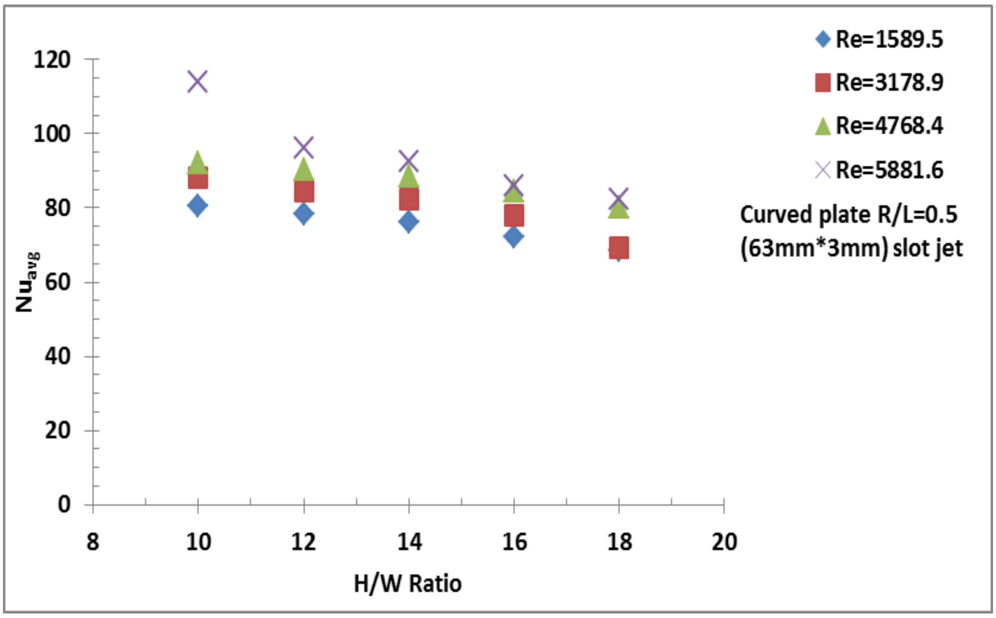


Figure.5(b): The average Nusselt number values for (63mm X 3mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.5)

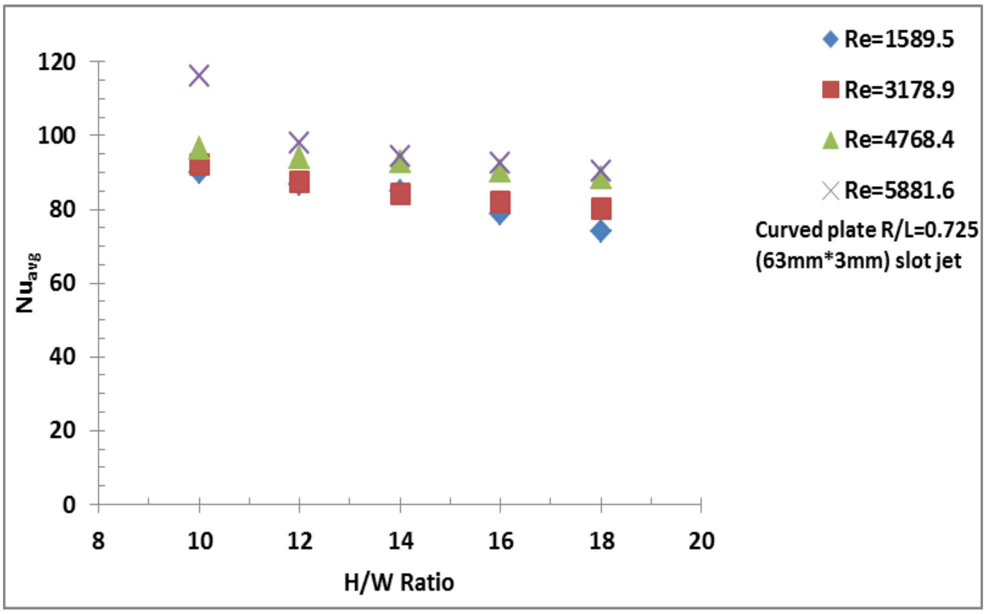


Figure.5(c): The average Nusselt number values for (63mm X 3mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=0.725)

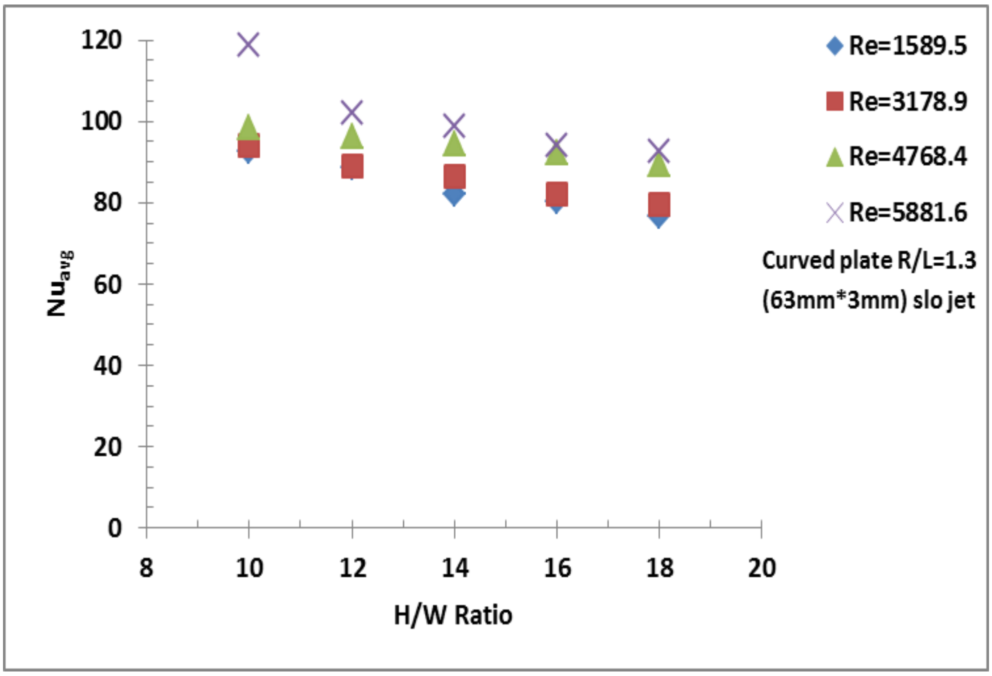


Figure.5(d): The average Nusselt number values for (63mm X 3mm) slot jet at varying values of H/W ratio and at specific values of Re for a fixed value of R/L (=1.3)

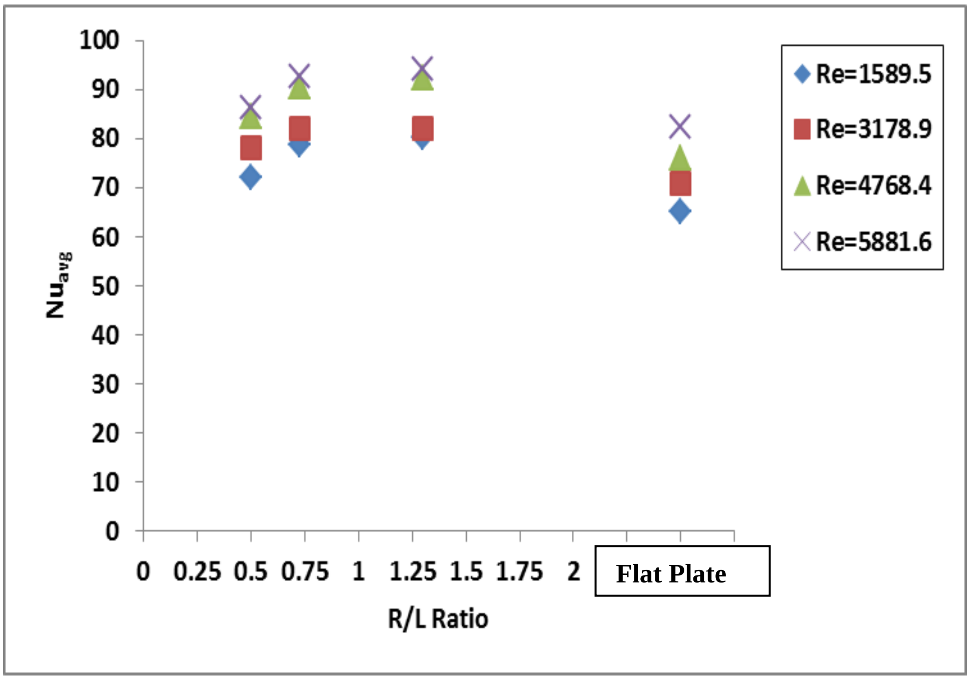


Figure: 5(e): The effect of the dimensionless curvature radius (R/L) for (63mm X 3mm) slot jet on the average Nusselt number for fixed values of H/W ratio (=16)

The above graphs from figures 3(a,b,c,d), figures 4(a,b,c,d) and figures 5(a,b,c,d) shows the variation of Nu_{avg} average Nusselt Number values as function of distance between target plate and nozzle exit. It shows that average Nusselt number is found to decrease with increasing H/W ratio for all target plates studied. The trend of graph is observed for all impingement target surfaces considered for study. It is found that heat transfer is maximum for H/W ratio 10 for all Reynolds number considered for study. Average Reynolds number increases with increasing Reynolds number for particular R/L ratio of the plate. Where high velocity jet impinges on the plate and as the mass flow rate increases the kinetic energy of the fluid particles traces on the surface of the plate there by carrying more heat from the plate.

For all R/L ratio curved plates 0.5, 0.725, 1.3 and flat plate considered for study and for H/W ratio of 10 the Nu_{avg} obtained is maximum for all Reynolds number considered for study and it is decreased as H/W ratio increases.

The effect of dimensionless curvature radius (R/L) on the Average Nusselt number was shown in the figures 3(e), 4(e) and 5(e). From the figures it is found that average Nusselt number increases with increase in R/L ratio of the plate. The Average nusselt number is critically dependent upon the Reynolds number. Flow characteristics of impingement jets before and after striking the plate have significant role in the heat transfer. Results indicate that the Nu_{avg} strongly dependent on the jet-to-target-plate distance. The Average nusselt number is higher for slot jet of H/W=10. Results indicate that the spreading of higher jet-to-target-plate spacing does not increase the effectiveness of heat transfer. For given Reynolds number, for given mass flow rate, the 2D flow field created by the slot (63 mm*3 mm) is more effective in heat transfer coefficient enhancement.

The results showed that a significant dependency on the wall-to-jet-spacing and for small wall-to-jet spacing the Nu_{avg} increases. On the other hand larger wall-to-jet-spacing showed that Nu_{avg} decreases or found to be unaffected for higher H/W ratio so the closeness of the target plate from the jet has an impact on the average heat transfer coefficient.

It is too difficult to generalize the results in order to have an account of the interactive effects of the main governing parameters, i.e. Re, H/W and R/L. When all the values of R/L were taken into consideration in view of the interactions of other effects such as Re and H/W=10, R/L = 1.3 can be considered as the best heat transfer geometry. This observation is hoped to stimulate new and innovative designs in heat dissipating elements.

5. CONCLUSION

The heat transfer characteristics of a rectangular slot jet flow impinging on concave and flat surfaces with constant heat flux have been studied experimentally. The effects of the surface curvature (R/L), the dimensionless nozzle-to-surface distance (H/W) and the Reynolds number (Re) on average Nusselt numbers have been obtained. The major findings of the present study can be summarized as follows:

- It is found that jet impingement is one of the effective method for convective heat transfer.
- Since heat transfer coefficients associated with gas flows are generally small, it can be considerably improved by employing jet impingement heat transfer.
- Heat transfer can be greatly enhanced by employing rectangular slot jet nozzles.
- Slot nozzle is easy to fabricate using sheet metal hence slot nozzles have considerable advantage over round nozzles.
- For all the plates considered for study the average Nusselt numbers decrease as H/W increases.
- For range of Reynolds number and for plates considered for study, the average Nusselt numbers increases as Reynolds number increases.
- For Reynolds number 5881.6 there is high average Nusselt number obtained for impingement surfaces of R/L ratio of 1.3 is observed.
- The closeness of the target plate from the jet and surface curvature of the target plate has an impact on the average heat transfer coefficient.

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