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Heat Transfer of Single Jet Impingement at Low Reynolds Number

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ABSTRACT*:* The current article concerned with jet impingement, which has great impact in heat transfer applications. The Nusselt number was determined numerically and validated experimentally. Nuzzle diameters and nozzle-to-target plate distance effect were investigated under constant heat flux and steady conditions. The range of Reynolds number was 500-2500, with temperature-dependent thermo-physical properties. The gained outcomes showed that the nozzle-plate distance and nozzle diameter have the prime effect on heat transfer, where, Nusselt number increased with nozzle diameter decrease, while it deceases with nozzle-target plate distance increase. The maximums heat transfer was obtained at 6 mm nozzle diameter and 40 mm nozzle- target plate distance.

KEYWORDS*:* nuzzle diameter, Nusselt number, nuzzle heat transfer

I. INTRODUCTION

The cooling of heated plates poses a chronicle issue in application in the field of high energy production equipment such as the turbine blades. One of the most reliable technique the impingement jet [1]. Where it simply describes as a fluid that been forced from a nuzzle at a specific velocity toward a target hot plate. the classification of impinge process could be sorted into two types, which are the free and submerged jet type.[2]. significant efforts have been put in the field of impingement jet during the last decade because its effectiveness and also for economical purposes. One of the most interested studies was proposed by Yang [3], where the transient row impingement jet were studied numerically under Reynolds number range of 200-15000. The major finding was that the flow unsteadiness is directly related to flow accumulation. Air bubble-water mixture was studied numerically by Pakhomov [4] to clarify both of heat transfer enhancement and flow pattern at Reynolds number range of 2×103-6×104. The core finding of the study was that both the wall function and heat transfer increase up to 40% and 50% respectively when the air is added to the water. Unfortunately, the study didn't mentioned added ratio of air at which these enhancement happened. For the comprehensive understanding of conjugate heat transfer, Zhu et al. [5] studied single air jet numerically at Reynolds number range of 5×103-50×103. By using the heat transfer methodology, the reported results showed conjugated effect prompt toward decaying of Nusselt number. Both free and submerged target plate jet impingement were studied numerically by Bieber [6] at Reynolds number range of 100-1000. Correlations for free and submerged surface were proposed for wide range of Prandtl number and unfortunately, narrow range of Reynolds number. A high temperature difference impingement jet was studied numerically by Zhou et. al. [7] at Reynolds number range of 4×103-12×103. The effect of density ant thermo-physical properties were taken into account. The results showed that the thermal properties and density have a crucial rule in heat transfer rate whether they increased or decreased. Moreover, it was found that the Nusselt number is independent of temperature difference.

In spite of all the achieved progress in this field, the optimum solution for this issue never attend yet. As literature showed there were limited studies concerns with low Reynolds number impingement jet. In addition, most previous studies were conducted numerically in two dimension. Hence the current article focuses on laminar flow heat transfer impingement jet. Its aimed to get comprehensive understanding of 3D heat transfer characteristics for different arrangement of Reynolds number, nuzzle diameter and nuzzle-to-target plate distance.

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II. NUMERICAL APPROACH

Numerical model

SolidWorks software package was the tool which adopted to create the 3D geometrical model. It has a fixed diameter D and target plate thickness δ of 80 mm and 3 mm respectively, target plate material was selected to be steel as shown in figure 1. On the other hand, the nozzle jet (bronze metal)has a diameter values of 3mm, 4mm, 5mm and 6 mm. while, the nozzle-to-target plate distance Z has a range of values 40mm,50mm, 60mm and 70 mm.

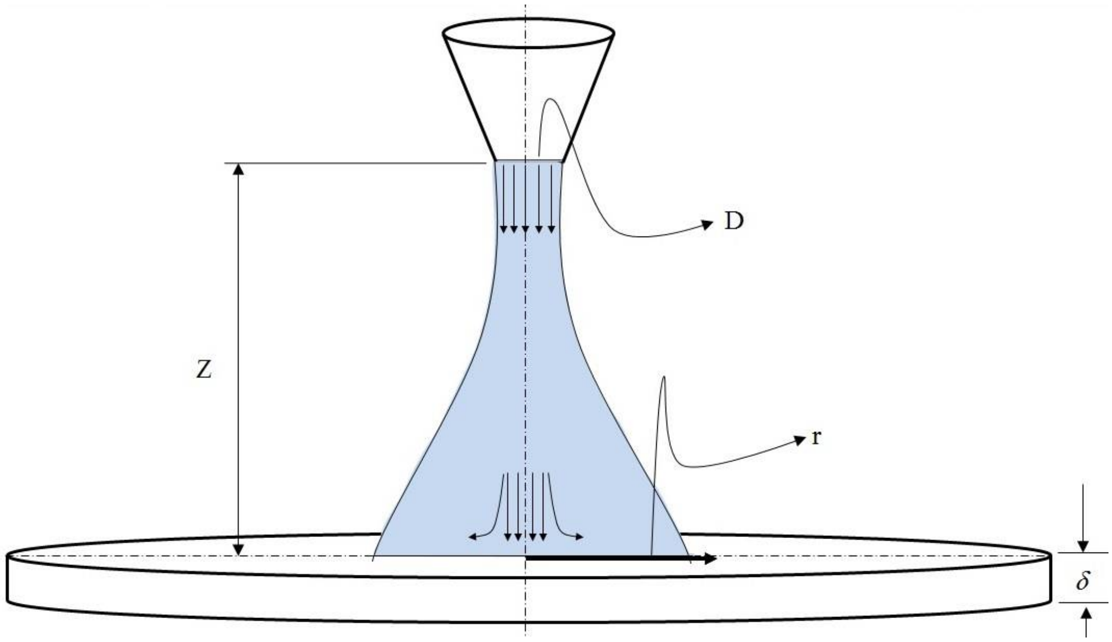

Figure 1. Single jet impingement scheme

Meshing process

Gambit 2.4.6 software package makes the meshing process easier and has variable meshing option, therefore it was selected for the meshing process. The primary goal of the meshing process is to create a fine and smooth mesh with attention being brought to the important domains of the problem. The high grid density should be applied to specific regions that have the desired details, such as stagnation region. There are three parameters govern meshing process (mesh quality), they are have a vital role in the solution convergence and can be controlled by setting a proper value for each of skewness ratio, aspect ratio and smoothness [8]. For 3D geometry configuration, the recommended range of the skewness ration angle is 0.75 – 0.85 [9], accordingly, it was set to be 0.8 in the current study. On the other hand, the aspect ratio which represent the mesh cell size was set to be1 to give uniform shape (cube of equal side length) for the mesh [10]. While, the smoothness which represents the change in size ration between each two successive cells was set to be 20% to avoid big jump in size.

Boundary conditions and numerical simulation

The numerical simulations were conducted by using ANSYS Fluent 14.0, the plain water was selected as a working fluid with temperature-dependent thermo-physical properties. It was assumed that the water is a Newtonian fluid, uncompressible and the flow is steady state. The water issued from the nozzle with T_f of 300 K and impinge the target plate which subjected to constant heat flux of 10 kw/m^2. No heat convection to surrounding and perfect isolation were also assumed.

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Laminar flow with Reynolds number range of 500-2500 was considered. Simulations were performed under laminar flow, where the following govern equations discretized in term of finite volume method prior to being analyzed[11, 12]

Conservation of mass :

$\nabla \cdot \rho \vec{V} = 0$ (1)

Momentum equation:

$\nabla \cdot (\rho \vec{V}\vec{V}) = -\nabla P + \nabla \cdot (\mu \nabla^2 \vec{V})$ (2)

Energy equation:

$\nabla \cdot (\rho \vec{V} C_p T) = \nabla \cdot (K \nabla T)$ (3)

The SIMPLEC algorithm was select for the coupling between velocity and pressure field, while the second-order upwind was selected as a scheme. Simulation is always accompanied by numerical error. in such case, the challenge is to minimize the error as much as possible. It can be reduce by perform grid convergence study in term of grid convergence index GCI. It can be achieved by set three mesh space to each simulation case course, fine and finer, then calculate the GCI value. It should be approach to zero as the mesh get finer, this sign indicates that the numerical error reach it is minimum value. The grid convergence index of the current study was as follows

Table 1: GCI's of the case Z=40 mm, D=3 mm

No	GCI32 h3=1mm, h2=2mm		GCI21 h2=2mm, h1=3mm	
	r=2	r=1.5	r=2	r=1.5
1	3.01%	6.53%	5.31%	9.42%
2	1.00%	2.21%	3.83%	5.34%
3	0.97%	1.06%	1.91%	3.18%

Where h holds for mesh space and r is the refinement ratio.

Eventually, the final step after validation representing by displaying results. Tecplot 360 software package was utilized for this purpose as shown in figure 2.

III. EXPERIMENTAL WORK

The experimental setup was built to validate the numerical results obtained from the modelling. The experiment consists: pump, connecting pipes, heater plate, flow meter, target plate attached to heater, insulated circular tube and the jet. The flowing flow from the jet impinging the target plate at the same range of Re 500-2500. Also the heat flux from the heater to the target plate surface is 10 kw/m^2. The good insulated was used for the circular tube containing the setup to reduce the heat losses. The other important condition is to fix the impinging velocity of the water to obtained constant Re. The experiment needed at least 30 min to reach the steady state conditions. The inertia force is another factors that used to increase the heat transfer by increasing the momentum of flow.

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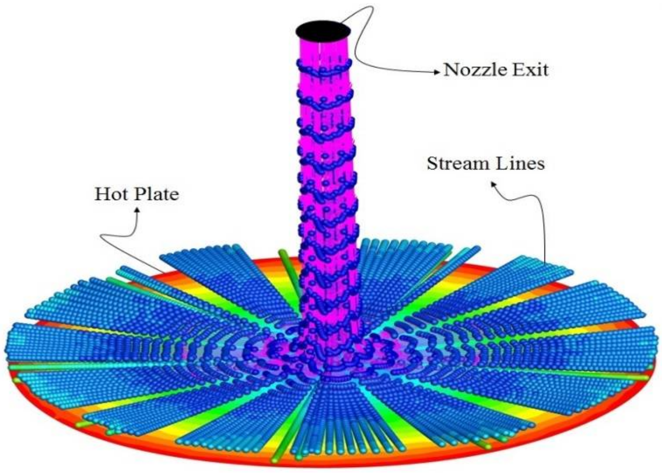

Figure 2. Single jet impingement data Sample

IV. RESULTS AND DISCUSSION

Validation

Validation should be mad prior to continue on simulation processes. The simulation datum will take into account once the validation shows good matching with an analog study. For validation purpose, one case was simulated analogous of that conducted by Sagot [10], where hot air was set as a working fluid under constant heat flux condition. Reynolds number of validation was set at 10000 to mimic Sagot [10] case, besides the Z/D ratio was taken as 2 as shown in figure 3. At the same time the figure shows clearly the comparisons of the experimental results with numerical results and the results obtained by Sagot[10]. The good agreement was obtained between the experimential and numerical results. While the maximum deviation between the results is 3%.

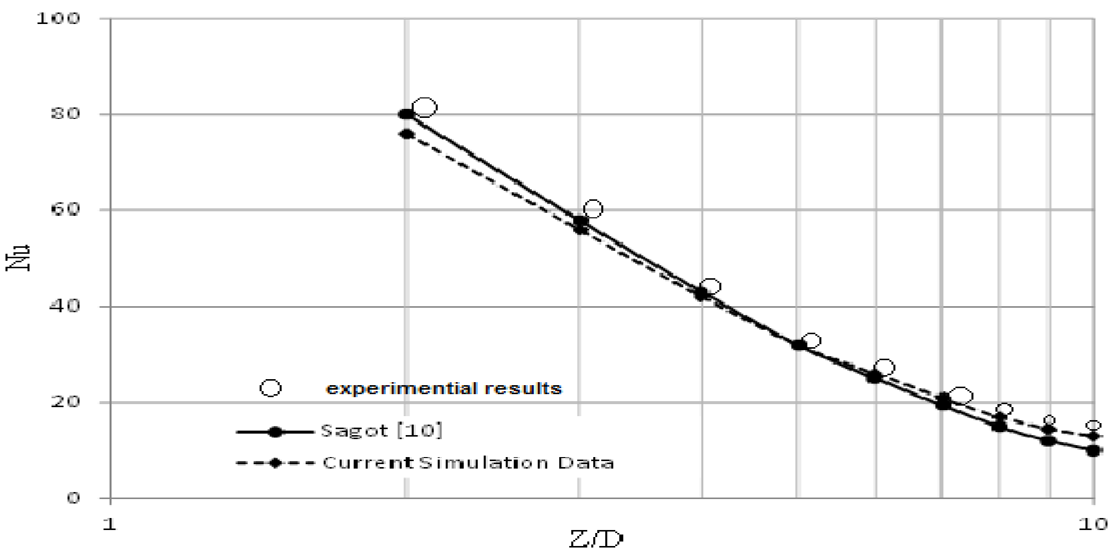

Figure 3. Nusselt number validation with Sagot [10], at Re=10000 and Z/D=2.

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The deviation showed in the validation curve came up due to inherent uncertainty in the experimental apparatuses. In addition, some came up from the assumptions and approximation in the current simulation. In spite of all these deviation reasons, the maximum deviation still within ±6%, which seems to be good.

Effect of Reynolds number

Reynolds number has great effect on cooling process of the plate, the increase in Reynolds number from 500 to 2500 increase both the heat transfer between plate surface and working fluid and the radius of cooled area as shown in figure 4(a, b, c, d and e). This action attributes to the fact that the fluid momentum increase as the flow rate increase.

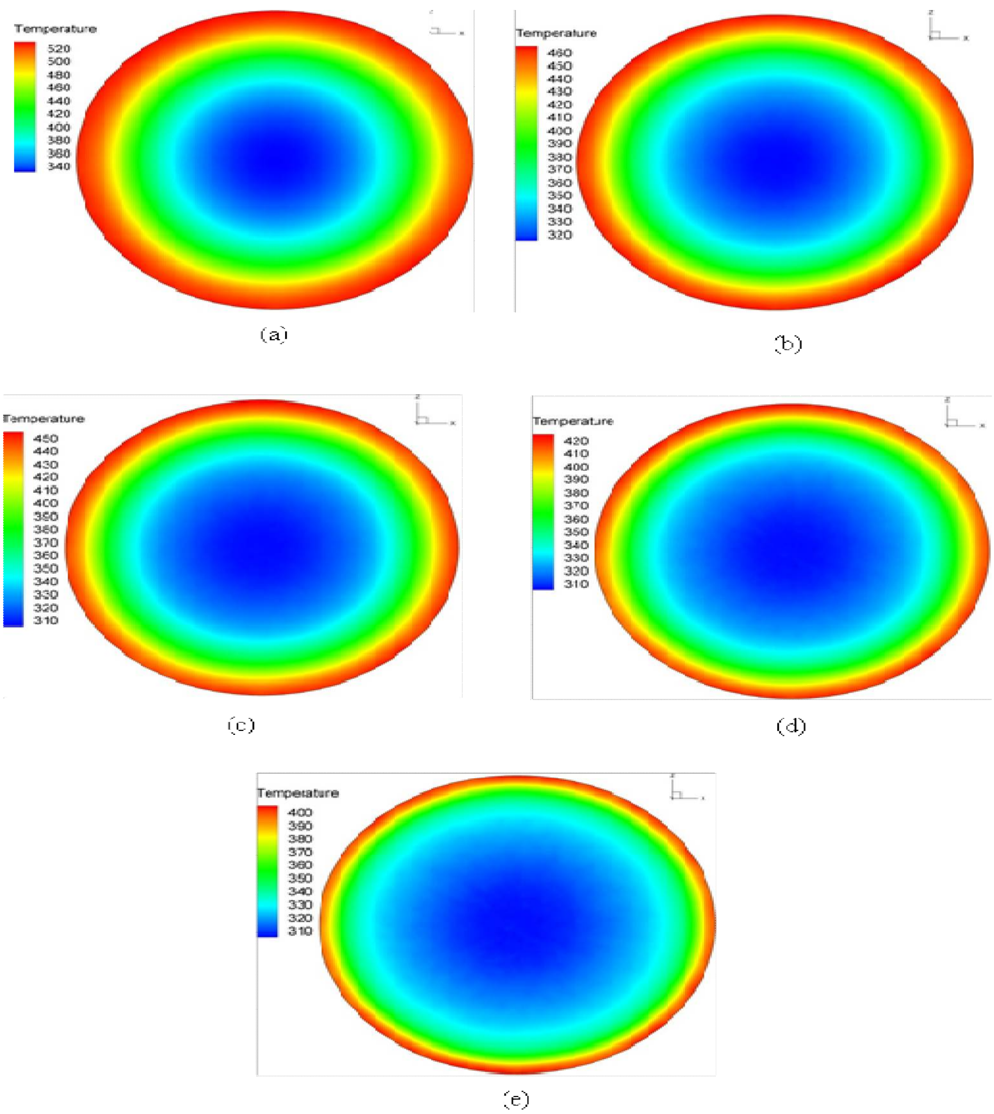

Figure 4. Temperature contours for the case Z=40 mm and D=3 mm, where (a) Re=500, (b) Re=1000, (c) Re=1500, (d) Re=2000 and (e) Re=2500.

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Effect of nozzle diameter

The diameter of nozzle has a significant effect on heat transfer rate and also on hydraulic parameters, such as stagnation point and flow pattern. In addition, the diameter shape has a notable effect, whether it was rounded or slot or else. In spite of it is effect, the temperature contours do not show the real effect of variation in heat transfer when adopt multi diameter size. But it can be remarkable shown in the following figure 5

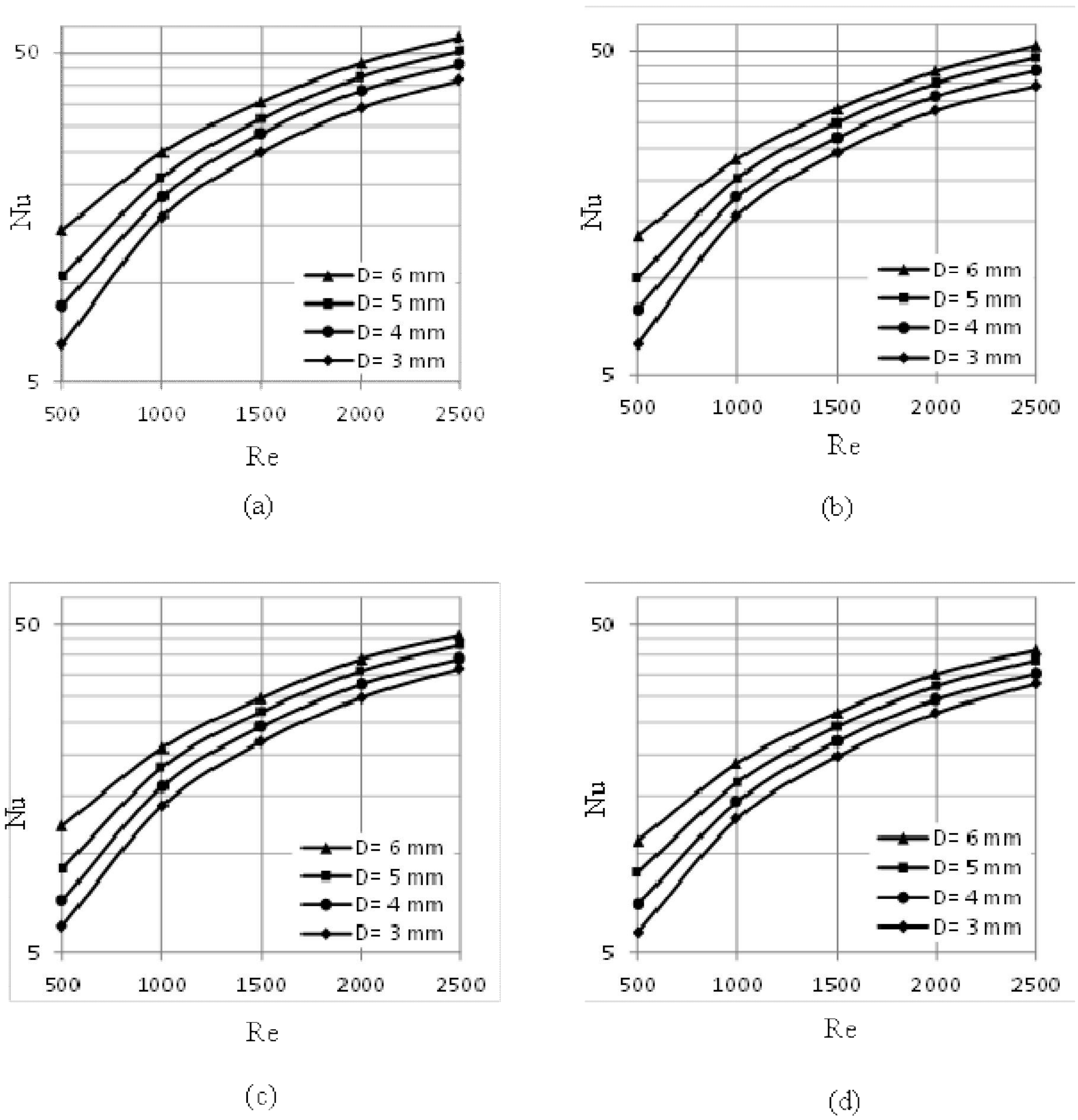

Figure 5. Nusselt number versus Reynolds number for (a) Z=40 mm, (b) Z=50 mm, (c) Z=60 mm and (d) Z=70 mm.

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The last figure indicate two important things, first one is that the increase in nozzle diameter lead to an increase in Nusselt number. The increase in nozzle diameter by 1 mm leads to an enhancement about 4% in Nusselt number at Constant Reynolds number due to the increase in flow rate. Second one is that the Nusselt number decrease with the increase of the nozzle-target plate distance Z. This resulted due to decrease in fluid momentum when impinge the target plate.

V. CONCLUSIONS

The heat transfer characteristics of the impingement jet on the hot plate was conducted numerically, while the experimental setup was used within the same Reynolds number range 500 to 2500 for the validation purpose only. The current study showed that the increase of the Reynolds number lead to increases in Nusslet number. as well as, the same trend was noted when the diameter increased from 3 to 6 mm. In contrary, the increase of the distance from 40-70 mm lead to decreases in the Nusslet number.

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