Heat transfer analysis of slot jet impingement using Nano fluid on convex surface

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Abstract. Numerical simulation is performed for investigating the heat transfer performance using nanofluids in a confined slot jet impingement on a convex surface. The impinging jet is water - alumina nanofluids (40 nm average particle size). The aim of this numerical study is to evaluate the augmentation of heat transfer with suspended nanoparticles (in this case Al2O3 - water) using temperature independent nanofluids properties. Different parameters such as various Reynolds numbers, distance between jet to target plate have been considered to investigate the flow behaviour and convective heat transfer performance of the system. Results in the form of distribution of average Nusselt number and convective heat transfer coefficients at the curved surface are shown to elucidate the heat transfer and flow behaviour process. In addition, qualitative analysis of both stream function and isotherm contours is carried out to perceive the flow pattern and heat transfer mechanism due to addition of nanofluids. The results reveal that average Nusselt number and heat transfer coefficient significantly rises with rise in jet inlet Reynolds number. It is also proved that heat transfer is augmented when nano particles are added to a base fluid.

1. Introduction

Impinging jets can enhance heat and mass transfer, hence these jets have numerous significant technological applications in many practical areas such as combustor components and gas turbine cooling, electronic cooling, glass sheet tempering, metal plate annealing and medical processing (i.e. freezing of tissues). Air jet impingement has a disadvantage due to acoustic concerns; hence air jet cannot be suitably used in micro-electronics. Now the curved surface flow has a characteristic to create massive flow and giant streamline curvature near the wall. The curved surfaces have extensive influence on the flow topology due to high streamline profile in the wall jet region and formation of strong flow entrainment. The curved surfaces even have influence on the turbulent boundary layer development along the impingement region. Sharif and Mothe [1] showed that the heat transfer rate increased by 20% for the curvature of surface rather than that of flat surface. Although numerous practical engineering applications occurred on curved surfaces with jet impinging but the significant details of curved surfaces are yet not discussed properly.
Impinging jets have so many practical applications like paper products, glass tempering plate, textile drying, and annealing to metal sheets. The characteristics of heat transfer and the flow field on moving surface are studied. Firstly, Raju and Schlunder [2] performed the task to impinging jet on a stationary plate. Huang et al. [3] numerically investigated turbulent air jet through a duct. They obtained that the Nusselt number (Nu) is small as compare to the region where plate movement is so high. Zumbrunnen et al. [4] numerically analysed impinging jet on isothermal dynamic plate with constant heat flux for slot laminar flow. They found that the heat transfer is much effectual due to the decrement of the growth of the boundary layer at some distance from the jet. Chattopadhyay et al. [5] and Chattopadhyay and Benim [6] numerically analysed the heat transfer of plane jets impinging on a dynamic wall using large eddy simulation (LES). They used Re at jet exit in the range of 500 and 3000 and for different plate-jet velocity ratios of 2, 1, 0.5 & 0.

They justified the variation of Nusselt number invariable when there is a decrease in plate velocity. Saha and Chattopadhyay [7] examined the behaviour heat transfer using a single jet impinging on a dynamic heated plate using LES. Rsj was considered between 0 and 2 at Reynolds number 5800. Their main focus was to study the velocity profile, the flow structure and the stresses. Senter and Sollicc [8] examined numerically air jet impingement to normal plate in confined flow filed. This experiment was performed for four Rsj (0, 0.25, 0.5, and 1.0), slot widths of 8 mm and Reynolds numbers (5300, 8000, and 10,600). They studied that the flow pattern was independent of the jet Reynolds number and Rsj. Bennouhoub and Mataoui [9] numerically analysed impinging jet on an isothermal plate. They have consider Re in the range of 10,000 to 25,000, plate to nozzle distance of 8e and Rsj between 0 to 4. They obtained a relation for skin friction coefficient in terms of Re and Rsj. The curved surfaces even have influence on the turbulent boundary layer development along the impingement region. Previous studies Choi et al. [10] and Gau and Chung [11] showed that the heat transfer rate rises by approximately 18% for the curvature of surface rather than that of flat surface. Although numerous practical engineering applications occurred on curved surfaces with jet impinging the significant details of curved surfaces are yet not discussed properly.

Jet impingement on convex surface has been investigated both experimentally and numerically in literature. However using nanofluids on convex surface is scarcely reported. Based on the available literature, a simplified jet impingement problem with curved surface has been numerically studied by the addition of nanoparticles in water; called $\text{Al}_2\text{O}_3$ nanofluids. Geometric parameter- jet to plate spacing ($h/W$) is varied for better understanding of the results.

2. Mathematical formulation

Adapting two dimensional, incompressible and steady case for the continuity, momentum and energy equations. These equations are as follows,

$$\frac{\partial U_i}{\partial x_j} = 0$$

$$\rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu \left( \frac{\partial U_j}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \right]$$

$$\rho U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\mu}{Pr} \frac{\partial T}{\partial x_j} - \rho \overline{T u_i'} \right]$$

2.1 Turbulence modelling

For implementation of governing equations in the case of turbulent flows, experimental or approximate models are essential to take into account the turbulence phenomenon. According to Sagot
et al. [12] and Menter [13], it has been suggested to use k-ω SST turbulence model for confined slot jet impingement. The k-ω SST turbulence model presents two equations, which are as follows,

\[
\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_j} \left( U_j k \right) = \frac{P_k}{\beta} - \rho \omega \frac{\partial P_k}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \left( \nu + \sigma_k \nu_T \right) \frac{\partial k}{\partial x_j} \right]
\]

(4)

\[
\frac{\partial \omega}{\partial t} + \frac{\partial}{\partial x_j} \left( U_j \omega \right) = \alpha S^2 \frac{\partial \omega}{\partial x_j} + 2 \left( 1 - F_1 \right) \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \left( \nu + \sigma_\omega \nu_T \right) \frac{\partial \omega}{\partial x_j} \right]
\]

(5)

2.2 Nanofluids thermo-physical properties

The data are used to determine the equations consisted of nanoparticles of Al₂O₃ (Table 1) with the size 40 nm; while the base fluids is water, \( \lambda \) is used to denote thermal conductivity, while all other symbols have their usual meanings. The suffices bf stand for base fluid and nf is stand for nanofluids respectively.

\[
\rho_{nf} = (1 - \phi) \rho_{bf} + \phi \rho_p
\]

(6)

\[
\rho_{nf}C_{nf} = (1 - \phi) \rho_{bf}C_{bf} + \phi \rho_pC_p
\]

(7)

\[
\lambda_{nf} = \lambda_{bf} \left[ 1 + 4.44 \Re^{0.4} \Pr^{0.66} \left( \frac{T_{nf}}{T_{bf}} \right)^{10} \left( \frac{\mu_p}{\mu_{bf}} \right)^{0.03} \phi^{0.66} \right]
\]

(8)

\[
\mu_{nf} = \frac{\mu_{bf}}{1 - 34.87 \left( \frac{d_p}{d_{bf}} \right)^{-0.3} \phi^{1.03}}
\]

(9)

| Material     | \( \rho \) (kg/m³) | \( C_p \) (J/kg K) | \( \mu \) (Pa s) | \( \lambda \) (W/m K) |
|--------------|------------------|------------------|----------------|------------------|
| Water (H₂O)  | 998.2            | 4182             | 998 x10⁻⁶      | 0.597            |
| Al₂O₃        | 3880             | 773              | -              | 36               |

3. Results

For validation purpose, the jet impingement over a concave surface (Figure 1a, Choi et al. [10]) is considered. Figure 1b shows the average Nusselt number profiles for Re=4740, h/W=4, D/W=50 and constant heat flux of 5000W/m² to the heated plate. From this results it is observed that the numerical data obtained is in good agreement with that of experimental one. This problem is also reported in details in Jaiswal et al. [14].
Figure 1a. Schematic diagram of Concave surface with confined slot jet impingement (validation case).

Figure 1b. Validation of present results of Nusselt number with published results.

Figure 2. Schematic diagram of Convex surface with confined slot jet impingement (Present case).

Analysis is performed on structured grid based on finite volume method. Figure 2 shows the simplified figure of the convex surface. The top wall is consider as adiabatic wall and the side wall has given simply pressure outlet condition. The two dimensional model has 150 mm length (D) and jet to target plate spacing is (h/W) is 3 and 7. The jet diameter is consider as 5 mm. The nanofluid used is water-Al₂O₃ at various volume fraction (1, 4 and 6%). A constant heat flux of 5000 W/m² is applied at target bottom plate.

Figure 3. Average Nusselt number variation as function of Reynolds number for various volumetric concentration at h/W=3 respectively.

Figure 4. Average Nusselt number variation as function of Reynolds number for various volumetric concentration at h/W=7 respectively.

In the figure 3 and 4 the profile of average Nusselt number is a function of Reynolds number as shown below for h/W=3 and 7. From this figure it is clear that the average Nusselt number is increases with increasing the Re. It can also be seen that as the Φ value rises the average Nusselt number also rises. As we go from Φ=0 % to Φ=1 % a marginal rise in the Nusselt number is obtain for h/W=3. For Re=5000 and Re=20000 there is a rapid rise in average Nusselt number is obtained.
Figure 5. Average Nusselt number variation as a function of Reynolds number for h/W=3 and h/W=7 at φ=0%.

Figure 6. Average Nusselt number variation as a function of Reynolds number for h/W=3 and h/W=7 at φ=6%.

The average Nusselt number variation in terms of Re is shown in figure 5 and 6 for various h/W ratios at Φ =0 and 6%. From this diagram it is observed that the average Nusselt number rises linearly as the Reynolds number increases same thing is happening with h/W ratio. The peak value of average Nusselt number is observed for h/W=7 while the lowest is for h/W=3. Figure 7a and 7b shows the stream function profile for different cases of h/W ratios. From the above figure it is observed that two counter rotating vortex is created as the jet strikes on the heated plate. It can also be observed that intensity of vortex and shape depend on h/W ratios and Reynolds number.

Figure 7a. Stream function at h/W=3 Re=10,000 φ=0%.
Figure 7b. Stream function at h/W=7 Re=10,000 φ=0%.

4. Conclusion:

The numerical analysis of the confined jet impingement model using nanofluids on convex surface is performed to investigate the heat transfer, fluid flow behavior and velocity and temperature
profiles. The bottom surface is the target plate which is maintain a constant heat flux at 5000 W/m². The stream function profile shows that the intensity and shape of vortex is dependent on the h/w ratios, Re and volume fraction of the nanoparticle. The maximum value of the average Nusselt number rises with particle consolidation and Reynolds number. The highest increase of Nusselt number is found 17 % using nanofluids as compared to that of base fluid when h/W is equal to 7.

5. References
[1] Sharif M A R and Mothe K K 2010 Parametric Study of Turbulent Slot-Jet. Impingement Heat transfer from Concave Cylindrical Surfaces, Int. J. Therm. Sci. 49, 428-442
[2] Raju S K and Schlunder EU 1977 Heat MassTransf. 131-136
[3] Huang S D and Cho H H 2003 Int. J. Heat Fluid Flow. 199-209
[4] Zumbrunnen D A, Incropera F P and Viskanta R 1992HEAT MASS TRANSF. 311–319
[5] Chattopadhyay H, Biswas G and Mitra N K 2002J Heat Transfer. 124,433–440.
[6] Chattopadhyay H and Benim CA 2011 J Heat Transfer. 104, 502–506.
[7] Chattopadhyay H and Saha S K 2003 Int J Heat Fluid Flow. 685–697.
[8] Senter J and Solliec 2007 Int J Heat Fluid Flow. 708–719.
[9] Benmouhoub D and Mataoui A 2013 J Heat Transfer, Trans ASME. 135,1–9
[10] Choi M, Yoo H S, Yang G, Lee J S and Sohn D K 2000 Int. J. Heat Mass Transfer 18111822.
[11] Gau C and Chung C.M 1991J. Heat Transfer. 113, 858–864.
[12] Sagot B, Antonini, G, Christgen A and Buron, F 2008 Int J Therm sci. 1610-1619.
[13] Menter F R 1994 AIAA journal 1598-1605.
[14] Jaiswal A, Datta A and Halder P 20171st ICMMRE. 8-10