HEAT TRANSFER AUGMENTATION USING NANOFLUID OF A CONFINED SLOT IMPINGEMENT JET ON CONCAVE SURFACE

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Abstract. Numerical investigation of heat transfer process using Al2O3-water nanofluid in a confined slot jet impingement on concave surface is performed. The simulation is conducted on a two-dimensional turbulent flow with k − ω SST model for the turbulence computation. A constant heat flux is considered on concave surface. Different parameters such as various Reynolds numbers, and nozzle-to-surface spacing have been considered to study the flow field and convective heat transfer performance of the system. Results in form of distribution of local and average Nusselt number and convective heat transfer coefficients at the curved surface are shown to elucidate the heat transfer and fluid flow 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 as well as heat transfer coefficient significantly rises with jet inlet Reynolds number. It is also proved that heat transfer is augmented when nanoparticles are added to a base fluid.

Keyword: Nanofluids; Al2O3; k − ω SST model; Concave surface; Confined slot jet impingement

1. Introduction

Since impinging jets can eliminate heat and mass in reasonably low pressure drop, 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 strong flow entrainment and high streamline curvature in the wall jet region. The curved surfaces have extensive influence on the flow topology due to high streamline curvature in the wall jet region and construction of strong flow entrainment. The curved surfaces even have influence on the turbulent boundary layer development along the impingement region. Previous studies 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 the significant details of curved surfaces are yet not discussed properly.

Jet impingement on flat surfaces using various turbulence model such as k-\(\varepsilon\), k-\(\omega\), Reynolds–averaged–Navier–Stokes (RANS) and large eddy simulation (LES) with unconfined and confined are investigated [2–9]. On the other hand, Jet impingements on curved surfaces are scarcely studied to extend of heat performance. Previous literatures have showed that characteristics of jet impingement on curved surfaces have significant dissimilarity in the flow dynamics from those of flat surfaces [10–14]. Sharif and Mothe [1] worked with air as working fluid to simulate jet impingement on curved surface using four different turbulence models such as RNG k-\(\varepsilon\), SST k-\(\omega\), RSM and standard k-\(\varepsilon\). However none of the models predicted Nusselt number profiles of experimental data. RSM model achieved closest proximity to experimental data. Singh et al. [20] studied on concave surface using RANS turbulence model. They have concluded with over–calculated data of the Nusselt number to experimental data. Recent experimental studies of jet impinging on concave and convex surfaces are investigated in many literature; Fenot et al. [17], Lee et al. [13], Chang et al. [14], Kayansayan and Kucuka [9], Iacovides et al. [11], Gau and Chung [2], Hu and Zhang [16], Eren et al. [15]. Kumar and Prasad [24] numerically investigated the flow and heat transfer from a row of circular jets impinging on a concave cylindrical surface using the Fluent CFD code and the SST k-\(\omega\) turbulence model.

Jet impingement on concave surface has investigated both experimentally and numerically. However using nanofluids on concave surface is scarcely reported as per author knowledge. Based on the insights garnered from the available literature, a simplified jet impingement problem with concave curved surface has been numerically studied by the addition of nanoparticles in water; called Al2O3 nanofluids. Geometric parameters jet nozzle diameter to plate distance (h/W) has varied for better understanding.

2. Governing equation

The Reynolds averaged mass, momentum, and energy conservation equations for the steady incompressible flow, neglecting the viscous dissipation, are given as

\[
\frac{\partial U_i}{\partial x_i} = 0
\]

\[
\rho U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu \frac{\partial T}{\partial x_j} - \rho T u' u'_j \right]
\]

\[
\rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_j} \right) - \rho u' u'_j \right]
\]

a. Turbulence modelling

For closing the governing equations in the case of turbulent flows, experimental or approximate models are necessary to take into account the turbulence phenomenon. In Sagot[25] it is suggested the use of k-\(\omega\) SST turbulence, proposed by Menter [22]. The k-\(\omega\) SST turbulence model introduces two new equations, one is for the turbulent kinetic energy and other is for the specific dissipation rate. The two equations are expressed as,
\[ \frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[ (\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \]  

(4)

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

(5)

**b. Nanofluid thermo-physical properties**

The data are used to determine the equations consisted of nanoparticles of Al₂O₃ with the size 20 nm; while the base fluids is water, \( \lambda \) is used to denote thermal conductivity, while all other symbols have their usual meanings. The suffices \( bf \) and \( nf \) stand for base fluid and nanofluid respectively.

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

(6)

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

(7)

\[ \lambda_{nf} = \lambda_{bf} \left[ 1 + 4.4Re^{0.4}Pr^{0.66} \left( \frac{T_{nf}}{T_{bf-f}} \right)^{10} \left( \frac{\lambda_p}{\lambda_{bf}} \right)^{0.03} \phi^{0.66} \right] \]  

(8)

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

(9)

**3. Results and discussion**

The heat transfer augmentation using nanofluids of a confined slot impingement jet on concave surface is performed. The introducing of nanofluids has a major effect on the heat transfer process. The
hydrodynamic and thermal field is computed using k-ω SST turbulence. Numerical simulations have been carried out by changing the inlet Reynolds number (7000, 14000 and 10000), nozzle-to-surface spacing (h/W) and nanoparticle volume fraction (ϕ = 0%, 1%, 4% and 6%).

To validate the results, the jet impingement over a concave surface (Figure 2, Choi et al. [16]) is considered. From this results it can be seen that the numerical data obtained is in good agreement with that of experimental one. Analysis is performed using structured grid based finite volume method. Figure 1 shows the schematic diagram 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 4 and 6. The jet diameter is consider as 5 mm. The nanofluid used is water- Al₂O₃ at various volume fraction. A constant heat flux of value 5000 W/m² is applied at target bottom plate.
Fig 6: Average Nusselt number profiles along Reynolds number for different volumetric concentration at h/W=4

Fig 7: Average Nusselt number profiles along Reynolds number for different volumetric concentration at h/W=6

Fig 8(a): Stream function at h/W=4 Re=14000 φ=6%

Fig 8(b): Stream function at h/W=6 Re=21000 φ=6%

Fig 9(a): Temperature contour at h/W=4 Re=14000 φ=6%

Fig 9(b): Temperature contour at h/W=6 Re=21000 φ=6%
4. Conclusion

The heat transfer augmentation using nanofluids of a confined slot impingement jet on concave surface is performed. The introducing of nanofluids has a major effect on the heat transfer process. The hydrodynamic and thermal field is computed using k-ω SST turbulence. Numerical simulations have been carried out by changing the inlet Reynolds number (7000, 14000 and 21000), height to jet slot width (h/W), nanoparticle volume fraction (ϕ), nanoparticle material (Al2O3, only water). The main observations from this study can be summarized as follows:

• Increasing h/W, for same concave surface diameter
  
  • Near the impingement surface, temperature grows and tends to decrease at edge of plate.
  
  • Heat transfer enhancement is evident.

• Increasing nanoparticle concentration, increases fluid bulk temperature which elevated heat transfer rate of mixture.

• Moreover it is again proved that increasing Reynolds number as well as concentration increased heat transfer rate compare to base fluid.

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