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Analysis and predictive modeling of nanofluid-jet impingement cooling of an isothermal surface under the influence of a rotating cylinder

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ABSTRACT

In this paper, numerical study and thermal prediction for a nanofluid jet impingement cooling of an isothermal hot surface with an adiabatic rotating cylinder were performed. Finite volume method was used for the solution of resulting governing equations along with the boundary conditions. Influence of various pertinent parameters such as Reynolds number (between 100 and 400), angular rotational velocity of the cylinder (between −0.1 and 0.1), horizontal location of the cylinder (between 0 and 3.75w) and solid particle volume fraction (between 0 and 0.04) on the fluid flow thermal characteristics were examined. It was observed that cylinder rotation and its location affect the cooling performance of the hot surface. It can be used as control element for heat and fluid flow. At the highest angular rotational speed as compared to motionless cylinder case, average Nusselt number reduces by about 20.16% for clockwise rotation. Solid particle addition to the base fluid affects the variation of first and secondary peaks in the Nusselt number along the hot wall. At the highest solid when the cylinder is away from the inlet slot and average Nusselt number enhancement is by about 8.08% at the highest volume fraction. An efficient modeling strategy was developed based on proper orthogonal decomposition and radial basis neural networks for thermal predictions. Accurate and fast results were achieved as compared to high fidelity computational fluid dynamics simulation results.

1. Introduction

Impinging jet is important for various thermal engineering applications such as in drying, glass annealing, turbine blade cooling, thermal treatment of surfaces and many others [1–9]. The complicated effects of flow recirculation, local change of boundary layer thickness and pressure gradient result in complex fluid flow and heat transfer characteristics. Various active, passive and hybrid techniques are proposed in thermal engineering systems to change the thermal characteristics. In one of these techniques, rotating cylinder were found to change effectively these characteristics for a wide range of different applications [10–17].

Recently, nanofluid technology was successfully implemented in various thermal engineering applications. A vast amount of literature study can be found with nanofluids application in heat transfer engineering problems [18–33]. The higher thermal conductivity of the metallic or non-metallic nano-sized particles make them attractive to be added in the base fluid such as water or ethylene glycol which have relatively very low thermal conductivity values. The particle may be in different sizes, shapes and average particle size is generally less than 100 nm. Various particle shapes other than spherical ones may be utilized which also have influence on the thermal characteristics [34,35]. The use of nanofluids for jet impingement problems was considered by many researchers. Nguyen et al. [36] conducted an experimental study for the jet impingement onto a flat, horizontal and circular heated surfaces with nanofluids. It was observed that for some combination of parameters (plate to plate spacing, particle volume fraction), heat transfer rate was reduced. Li et al. [37] made an experimental study with nanofluid containing Cu nanoparticles with two different sizes. Favorable properties of nanofluid were observed such as an enhancement in the heat transfer and no extra pressure drop. In the study by Rehman et al. [38], fluid flow and heat transfer characteristics of jet impingement onto a heated copper plate with water, nanofluid and nano-encapsulated phase-change material were investigated numerically. It was observed that when nanofluid was used as coolant, effective thermal conductivity was enhanced which increases the cooling performance. Jaberi et al. [39] performed an experimental study for the heat transfer characteristics by using nanofluid impingement on a flat circular disc.

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Nomenclature

b_k	modal coefficient
d	particle size (m)
h	local heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
H	distance between plates (m)
L	plate length (m)
M	number of snapshots
M	molecular weight of base fluid (kg/mol)
n	unit normal vector
N	Avogadro number
N_m	number of POD modes
Nu	Nusselt number, hD_h/k
p	pressure (Pa)
Pr	Prandtl number, ν/α
R	residual
Re	Reynolds number, $u_0\, D_h/\nu$
s	source term
T	temperature (K)
u, v	x-y velocity components (m/s)
w	double slot width (m)
x, y	Cartesian coordinates (m)

Greek characters

α	thermal diffusivity (m^2/s)
ϕ	solid volume fraction
ν	kinematic viscosity (m^2/s)
θ	non-dimensional temperature
κ_b	Boltzmann constant
ρ	density of the fluid (kg/m^3)
Ψ	scalar transport variable
ω	angular rotational speed (rad/s)

Subscripts

c	cold
h	hot
m	average
n	neighbor
nf	nanofluid
p	solid particle
st	static

Nanoparticle concentration was changed between 0.0198 and 0.0757 in the weight percentage. An optimum value of solid particle concentration was reported beyond which adding more nanoparticle was not effective. In a recent study, effects of nanofluids for a solar photo-voltaic thermal collector with jet impingement was studied. Various nanoparticles were tested and SiC/water nanofluid system was found to give the highest electrical and thermal efficiency of the photo-voltaic thermal module. In a recent study by Selimefendigil and Oztop [40], numerical and optimization analysis of nano-jet impingement cooling of a partly curved isothermal surface was performed with finite element method and COBYLA optimization algorithm. CuO nanoparticles were used as additives to the base fluid and 20% enhancement of the average heat transfer was achieved for the nanofluid at the highest particle volume fraction as compared to water.

In this study, effects of a rotating circular cylinder on the fluid flow and heat transfer characteristics for a jet impingement onto a hot isothermal surface with nanofluids were numerically examined. Cylinder angular rotational speed, its locations and SiO_2-nanoparticle solid volume fraction are used as control parameters to effect the thermal characteristics for a jet impingement cooling where a lot of engineering application areas ranging from drying to turbine blade cooling can be found for which this application is of interest. SiO_2 nanoparticles are added to the base fluid due to its low cost, favorable physical and chemical properties even though it has a low thermal conductivity as compared to other nanoparticles. In the last part of the study, an efficient method based on radial basis function artificial neural networks was proposed to make effective thermal predictions which could be replaced for high fidelity computational fluid dynamics simulation.

2. Mathematical modeling

A schematic description of the impinging jet with an adiabatic rotating cylinder is shown in Fig. 1(a). A jet is emerged from the rectangular slot with width $0.5w$. Hydraulic diameter based on the slot width is taken as $D_h = w$. Two plates are separated by distance $H = 5w$ and plate length is $L = 50w$. The jet with velocity u_0, temperature T_c impinges onto the hot isothermal surface kept at temperature of Th with $T_h > T_c$. The cylinder rotates with angular rotational speed of ω and has diameter of D. Its center is located in the position (x_c, y_c). The vertical location of the cylinder is fixed to $y_c = 0.5H$ and horizontal location was varied with the parameter $cx = |x_c| - 0.25w$.

The SiO_2-water nanofluid was used due to low cost, favorable physical and chemical properties of this nanoparticle. Spherical shape particle with average particle size of 30 nm was used. Thermo-physical properties of base fluid and nanoparticle are given in Table 1. Incompressible and Newtonian fluid assumptions were used. The flow is two dimensional, laminar and steady. Effects of natural convection, viscous dissipation and radiation are assumed to be negligible.

Mass, momentum and energy conservation equations are written as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x} + \nu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right), \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y} + \nu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right). \tag{4}$$

2.1. Boundary conditions

Boundary conditions in the dimensional form can be expressed as:

- For the inlet, temperature and velocity are uniform,

$$u = 0,\ v = -u_0,\ T = T_c.$$

- For the side surfaces, gradients in the x-direction are zero,

$$\frac{\partial u}{\partial x} = 0,\ \frac{\partial v}{\partial x} = 0,\ \frac{\partial T}{\partial x} = 0$$