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Numerical and experimental investigation of flow structure and behavior of nanofluids flow impingement on horizontal flat plate

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ABSTRACT

Numerical and experimental studies have been conducted to investigate flow structure and heat transfer of nanofluid jet normally impinging on a flat plate. Al_2O_3–water is used as working fluid. The governing equations are numerically solved using finite volume approach together with SIMPLER algorithm. A wide spectrum of experimental and numerical simulations has been done. The results covered wide ranges of Reynolds number, *Re*, from 3000 to 32,000, nanofluid volume fraction, ϕ, from 0 to 10%. The dimensionless distance from jet nozzle to the horizontal plate was kept constant at 3. An experimental apparatus was constructed to measure the film thickness distribution, wall temperature and temperature of flowing fluid. The effects of *Re* and ϕ are investigated on the film thickness distribution, isothermal contours, and both local and average Nusselt numbers. A good agreement was found between the numerical and experimental results as well as the previous cited results. The results showed that the increasing of nanoparticle percent increases the convective heat transfer coefficient compared with the pure water. At ϕ = 10.0% and *Re* = 24,000 the heat transfer coefficient increases by 62% compared with the pure water. The effect of nanofluid type (Al_2O_3–TiO_2–CuO) is studied numerically. It has been observed that the CuO nanofluid increases the heat transfer by 8.9% and 12% compared to aluminum and titanium nanofluid respectively.

1. Introduction

Impinging cooling is an effective way to generate a high cooling rate in many industrial applications such as steel or glass industry, cooling of turbine blades, laser or plasma cutting processes and cooling of electronic equipment. Refs. [1–4] presented different engineering and industrial applications for jet cooling. Steven and Webb [5] investigated the flow structure of impinging liquid jet on flat surface. They used the Laser-Doppler velocimetry technique for measuring free surface velocities. Their results covered Reynolds number from 16,000 to 47,000. Liu et al. [6] investigated analytically and experimentally the cooling of uniformly heated surfaces with laminar circular liquid and single phase jets. Kazuya et al. [7] investigated the effect of varying the impingement angles between the vertical planar jet and the inclined solid surface on the heat transfer characteristics of a planar free water jet impinging onto a flat substrate experimentally. The planar jet of a rectangular slot nozzle with cross section of 1.62 mm 40 mm was used. The Reynolds number range based on the nozzle gap and the mean velocity was 2200–8800. Teamah and his coworkers [8–11] studied the heat transfer due to the impingement of circular jet on a horizontal heated surface. They studied single and multi-jets numerically and experimentally. Their study covered water flow rates from 1.5 to 8 l/min per jet. They concluded that, for multi jets the interaction between the jets leads to reduce the mean velocity of the fluid film, which in turn leads to the reduction of both the local and the average local Nusselt number compared to the single jet. The overall average Nusselt number for multi jet is higher than single jet of one jet of the multi jets.

Stevens and Webb [12] investigated experimentally the effect of jet inclination on the local heat transfer under an obliquely impinging, round; free liquid jet striking a constant heat flux surface. The parameters investigated are the jet Reynolds number in the range 6600–52,000, and jet inclination, ranging from 40° to 90°. They found that the point of maximum heat transfer shifted upstream. Whelan and Robinson [13] investigated the average heat transfer coefficient and pressure drop of both impinging free-surface and confined-submerged water jet arrays experimentally. Dou et al. [14] studied the heat-transfer characteristics of the water jet on stainless steel plate by using inverse heat conduction

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Nomenclature

A_n	area of segment n, m^2
dj	nozzle diameter, m
g	gravity acceleration, m/s^2
h	heat transfer coefficient, w/m^2 k
H	dimensionless film thickness, t/dj
k	fluid thermal conductivity, w/m k
Nu	local Nusselt number
m°	mass flow rate, kg/s
Pr	Prandtl number, $\mu C_p/k$
q	heat flux, W/m^2
r	radial coordinate, m
R	dimensionless radius, r/d_j
Re	Reynolds number
t	water film thickness, m
T	fluid temperature, °C
T_c	jet temperature, °C
T_h	wall temperature, °C
u_o	jet velocity, m/s
v	radial velocity, m/s
u	axial velocity component, m/s
z	axial coordinate, m

Greek symbols

α	thermal diffusivity, m^2/s
μ	dynamic fluid viscosity, kg/m s
ν	kinematic fluid viscosity, m^2/s
ρ	fluid density, kg/m^3
θ	dimensionless temperature, $(T - T_o)/(T_w - T_o)$
ϕ	volume fraction of nanoparticle, %

Subscript

avr	average
nf	nanofluid
n	number of segment
s	solid
w	wall

method. Karwa and Stephan [15] investigated experimentally the thermo-hydrodynamic phenomenon occurring during quenching of a hot stainless steel plate that was heated at an initial temperature of 900 °C, with a free-surface sub-cooled water jet.

Nanofluids enhanced both the thermal conductivity and the convective heat transfer coefficient than the base fluid [16–18]. Liu and Qiu [19] studied experimentally the jet impinging of water–CuO nanofluids on a large flat surface. The effects of the nanoparticles concentration and the flow conditions on the nucleate boiling heat transfer and the critical heat flux have been investigated. The results showed that the critical heat flux of nanofluids increased gradually with the increase of particle concentration in the low concentration range and the enhancement in critical heat flux for nanofluids was about 25% compared with that of water. Planar jet impinging vertically on a V-shape plate using Al_2O_3–water was investigated experimentally by Yousefi et al. [20]. They studied the effects of Reynolds number and nanoparticles volume fractions on the heat transfer coefficient. The effect of using Al_2O_3–water nanofluid as a liquid coolant for confined impinging jet on the heat transfer was investigated experimentally [21–24]. Jaberi et al. [25] investigated the convective heat transfer coefficient of using Al_2O_3–H_2O nanofluid impingement jet on circular disk experimentally. Their results covered ranges of Reynolds number from 4200 to 8200 and nanoparticles concentration from 0.0198 to 0.0757 wt%.

The effect of using TiO_2–water nanofluid on the jet impingement heat transfer characteristics of a mini-channel heat sink have been studied by [26,27]. Roy et al. [28] investigated numerically the heat transfer and hydrodynamic behavior of various types of water-based nanofluids inside a typical radial flow cooling device. Turbulent radial nanofluid flow between two parallel disks with axial injection was considered. Chang et al. [29] investigated experimentally the effects of the particle volume fraction on the spray heat transfer performance of nanofluid comprising de-ionized water and Al_2O_3 particles with a diameter of 35 nm. The performances of TiO_2–water nanofluid jets impinging on hot steel plates have been experimentally investigated by Chakraborty et al. [30]. A significant enhancement has been observed in cooling rate with the nanofluid along with lower surface tension of the nanofluid, compared to pure water. Zeitoun and Ali [31] had an experimental investigation on the heat transfer between a vertical round Al_2O_3–water nanofluid jet and a horizontal circular round surface. Their results indicated that using nanofluid as a heat transfer medium enhances the heat transfer process and also decreases the Reynolds number and the Nusselt numbers as the nanoparticles concentration increased.

Heat transfer in impinging jet is very high. Therefore, the impinging jet cooling is characterized by super cooling. The nanoparticles have high thermal conductivity compared with pure fluid. The criterion of using nanofluids is to enhance the heat transfer. The impinging jet with nanofluid will be more superior in cooling applications. The aim of the current work is to study the flow structure and heat transfer enhancement of an impinging liquid jet on a target plate cooling system, by replacing the base fluid, water, with Al_2O_3–water nanofluid experimentally and numerically. In addition, the effect of nanoparticles volume fractions on the enhancement of the heat transfer characteristics is investigated. The tests are carried out at various Reynolds numbers under laminar flow regime. The effect of type of nanofluid is investigated numerically.

2. Experiments set up

Fig. 1 shows a schematic of the experimental set-up used in the present study. The Al_2O_3–water nanofluid flows in closed circuit consists of collecting tank, circulating pump, header tank and jet nozzle. The pump delivers the fluid to the header tank. The level of the header tank is higher than that of the pump by 5 m. A cooling coil was used to cool the fluid in the header tank. A vertical PVC tube connects the header tank and the jet nozzle. The PVC tube diameter and length are 3.91 and 130 cm respectively. A circular nozzle was used of diameter 5.5 mm. A gate valve was used to regulate the flow rate. A Rota-meter was used for measuring the flow rate. A mechanical mechanism was used to adjust jet center to be at the center of plate and also to adjust the vertical distance between the nozzle and the heated plate.

The hot plate was manufactured from stainless steel sheet of 6 mm thickness. This plate was heated by saturated steam. An electric laboratory steam generator was used to generate the steam required for heating. The steam generator heating element consists of three-electric heaters of 6 kW capacities each. The steam generator and all connections are insulated with glass wool to reduce the heat losses. The steam generator was equipped with required instrumentations. The generated steam was throttled using a