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Numerical study on free-surface jet impingement cooling with nanoencapsulated phase-change material slurry and nanofluid

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ABSTRACT

The free-surface jet impingement technique operating with two-phase advanced coolants has recently drawn much favorable attention in cooling applications. However, numerical understanding of free-surface jets along with improved realization of pros and cons associated with these advanced coolants remains a challenge. In this work, the flow and thermal performances of free-surface jet impinging on a heated copper plate are numerically investigated using water, nanoencapsulated phase-change material (NEPCM) slurry, and nanofluid as coolants. Three-dimensional continuity, momentum, and energy equations are discretized with a commercial finite volume code in accordance with a standard k-ε turbulence model. The volume of fluid multiphase technique is adopted in this study to model the free surface between the liquid jet and surrounding ambient air. A single-phase fluid approach is employed using existing models from other references to determine the effective thermophysical properties of NEPCM slurry and nanofluid. The predicted *Nu* and pressure drop calculations agreed well with the experimental data from references. Physical understanding of the effects of fluid jet inlet temperature, nozzle-to-target distance, and nanoparticle concentration is reported. The addition of both NEPCM and Al_2O_3 particles to water helps in improving the Nusselt number and decreases the stagnation point temperature with certain pressure drop penalty. The NEPCM slurry enhances the cooling performance of the system by improving its latent heat storage capability, whereas nanofluids improve the cooling performance by enhancing the effective thermal conductivity. The thermal performance can be further improved with increased particle concentration. The NEPCM slurry demonstrates performance superior to nanofluid working at the same particle loading. Overall, the proposed model can provide valuable guidelines for the use of advanced coolants in a free-surface jet impingement cooling system.

1. Introduction

Jet impingement cooling is one of the most effective and flexible techniques of flux removal from heated surfaces; this strategy has been extensively applied in heat treatment, cooling of stock material and electronic chips, drying, etc. [1]. Free-surface jets are among the major classifications of impinging jet cooling [2]. In a free-surface jet configuration, the fluid jet exits through the nozzle plenum into an ambient gas, which is air in most cases, before hitting upon the target surface [3]. The free surface appears immediately at the nozzle exit and maintains throughout the flow regime, including the wall-jet regions [4]. The shape of the free-surface jet is decided by many factors, including gravitational, surface tension, and pressure forces, and it is constructed by adopting kinematic conditions, as well as a balance between normal and shear forces at the fluid–gas interface [5]. Turbulence exerts prominent effects on heat and mass-transfer performances of jet impingement cooling [6]. At least 30–50% elevation of heat-transfer coefficients is reported by incorporating turbulence effects on jet impingement cooling compared with laminar theory [7]. The flow, turbulence, and heat-transfer effects are strongly influenced by the geometry of the jet nozzle [8].

Free-surface jets are further distinguished as single or two phase depending on the coolants used inside during operation. Single-phase free-surface jet impingement cooling incorporates cool air as coolant, which exits into ambient air; this process is termed as air entrainment. The effect of air entrainment on heat-transfer coefficients and heated surface temperature distribution during jet impingement cooling was examined by Goldstein et al. [9]; they suggested that entrainment of ambient air is an important

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Nomenclature

List of symbols

D_p	particle diameter [mm]
H	nozzle-to-plate distance [mm]
ΔH	nozzle length [mm]
D	jet nozzle diameter [mm]
D_h	hydraulic diameter [mm]
L	length of copper plate [mm]
p	pressure [kPa]
Δp	pressure drop [kPa]
q''	heat flux [$\mathrm{W/cm^2}$]
C_p	specific heat capacity of fluid [$\mathrm{J/(kg \cdot K)}$]
K	thermal conductivity [$\mathrm{W/(m \cdot K)}$]
k_b	static thermal conductivity [$\mathrm{W/(m \cdot K)}$]
Re	Reynolds number
Pe	Peclet number
Nu	Nusselt number
h	heat-transfer coefficient [$\mathrm{W/(m^2 \cdot K)}$]
T	temperature [K]
T_1	lower melting temperature [K]
T_2	upper melting temperature [K]
T_{MR}	melting range [K]
T_m	melting point [K]
T_w	impinged wall temperature [K]
h_{ls}	latent heat of fusion of PCM [J/kg]
V	velocity [m/s]
$\vec{w}$	velocity vector
u, v, w	velocity components [m/s]
x, y, z	spatial coordinates [mm]
A	area [$\mathrm{mm^2}$]
R_{th}	surface thermal resistance [K/W]
F_{vol}	surface tension source term
i	turbulence intensity
k	turbulence kinetic energy [$\mathrm{m^2/s^2}$]
l	turbulence length scale
R_1, R_2	surface curvature

Greek symbols

φ	volume concentration of alumina nanoparticles
ξ	volume concentration of NEPCM particles
ρ	density [$\mathrm{kg/m^3}$]
μ	dynamic viscosity [$\mathrm{Pa \cdot s}$]
υ	kinematic viscosity [$\mathrm{m^2/s}$]
$\dot{\gamma}$	shear rate [1/s]
α	volume fraction
ε	turbulence energy dissipation rate [$\mathrm{m^2/s^3}$]
K	curvature of free surface
σ	surface tension coefficient
$\sigma_k, \sigma_\varepsilon$	turbulence transport equations empirical constants
μ_l, μ_t	laminar and turbulent viscosity [$\mathrm{Pa \cdot s}$]
τ	wall shear stress [Pa]

Subscripts

o	stagnation point
avg	average
out	outlet
p	particle
b	bulk
j	jet
nepcm	nanoencapsulated phase-change material
nf	nanofluid
f	fluid
s	solid
eff	effective properties of slurry

factor affecting even the centerline temperature of jet flow. Jambunathan et al. [10] studied the parameters affecting the flow and heat-transfer characteristics of single-phase free-surface jets impinging on heated surfaces; they reported that the most prominent parameters affecting the flow and heat-transfer behavior are nozzle geometry, flow confinement, turbulence intensity, free-surface parameters, and many dimensionless parameters, including *Re* and *Pr*. Mohanty and Tawfek [11] investigated the thermal behavior of a round-air free-surface jet impinging on heated plate; they conducted experiments for 3, 5, and 7 mm diameter circular jet nozzles, with the nozzle-to-plate distance ratio varying from 4 to 58, and the nozzle Reynolds numbers ranging from 4860 to 34,500; they also developed a valuable correlation to predict the average heat-transfer coefficient for free-surface jet impingement cooling, which is a function of various operating and geometrical parameters.

Free-surface impinging jets are not only restricted to single-phase flows. The two-phase flow scenario constitutes of a liquid jet emerging into ambient air before impinging on the heated target, thus yielding improved heat-transfer performance because of enhanced cooling capability of liquid compared with air, which is previously used in single-phase free-surface jet impingement [12]. Many researchers have devoted their efforts to investigate the fluid flow and heat-transfer behavior of two-phase free-surface jet impingement cooling. Jafar et al. [13] have numerically reviewed the flow characteristics and heat-transfer behavior of liquid jet impingement with heat transfer from different surfaces subjected to flux. A two-phase 2D computational domain is numerically discretized by commercial CFD software Fluent, which incorporated air as primary phase and water as secondary phase. The predicted results indicated that heat-transfer coefficients are enhanced with an increase in *Re*. Furthermore, the nozzle-to-target distance significantly influences jet hydrodynamics and heat-transfer behavior. Teamah and Farahat [14] studied heat transfer on impinging of a single free-surface liquid jet both numerically and experimentally; they observed that both local and average Nusselt numbers were higher in the shooting-flow region than in the streaming-flow region. This finding is attributed to the mean velocity of fluid, which is much higher in the shooting-flow region. A good agreement between the numerical and experimental results was found. Yang et al. [15] numerically investigated the fluid flow and heat-transfer features of a free-surface liquid jet impingement cooling method by using the volume of fluid (VOF) two-phase approach based on finite volume method; they found that the stagnation point features varied with the geometry of jet nozzle. The optimum condition found for the maximum heat-transfer efficiency is $H/d_0 = 7.86$, where H and d_0 are the nozzle-to-target distance and nozzle diameter at inlet, respectively.

Conventional coolants such as water, oil, and glycol demonstrate inefficient heat-transfer behavior in many valuable engineering and industrial applications because of their low thermal conductivities and energy-storage densities [16]. Over the past years, substantial research has been conducted to improve the thermophysical properties of coolants. Advancement in nanotechnology has permitted the synthesis of solid particles down to nanometer scale, and nanoparticles are further suspended in conventional fluids like water in accordance with the Maxwell law to develop a new class of two-phase advance coolants [3]. Enhanced effective thermophysical properties, particularly thermal