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A numerical assessment of copper oxide and alumina nanoparticles during CHF occurrence

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ABSTRACT

Subcooled nucleate boiling in forced convection has been drawing significant attention in many fields due to its good heat transfer efficiency and high heat removal capacity. Such advancement in sub-cooled nucleate boiling is the result of continuing efforts from experimental, theoretical and numerical researchers, particularly focusing on critical heat flux (CHF). CHF heat transfer regimes are inefficient and the occurrence of CHF can cause a large temperature gradient in the heated wall leading to physical burnout. One way to increase the level of the CHF is to add certain nanoparticles to the base fluid. The present paper compares the effects of the addition of copper oxide and alumina nanoparticles on CHF phenomenon within the general-purpose computational fluid dynamics (CFD). The governing equations solved are generalized phase continuity, momentum and energy equations. Wall boiling phenomena are modeled using the baseline mechanistic nucleate boiling model developed in Rensselaer Polytechnic Institute (RPI). To simulate the critical heat flux phenomenon, the RPI model is extended to the dry-out phenomenon by partitioning wall heat flux to both liquid and vapor phases considering the existence of thin liquid wall film. It was shown that the presence of copper oxide in comparison with alumina nanoparticles in the base fluid, delays the dryout phenomenon more dramatically and in specific concentration, CHF threshold would be enhanced and consequently the safety margins of the operation would be improved.

1. Introduction

Subcooled flow boiling occurs in many industrial applications and is characterized by large heat transfer coefficients. Therefore, boiling plays an important role in industrial heat transfer processes such as macroscopic heat exchangers in nuclear and fossil power plants. However, for the incorporation of nucleate boiling in most practical applications, it is imperative that CHF is not exceeded. Critical heat flux signifies the highest limit of the nucleate boiling heat transfer in any system; micro or macro. Beyond critical heat flux, there is not only a deterioration of the capability of heat dissipation, but also a potential risk of damage due to burn-out. For decades, researchers have been trying to develop more efficient heat transfer fluids and also to increase the CHF threshold which would improve the thermal efficiency and reduce operational costs. To achieve this purpose, nanofluids have been employed in several experimental facilities.

In this study, it is tried to compare the effects of the addition of copper oxide and alumina nanoparticles on boiling flow field accompanied by critical heat flux using computational fluid dynamics. The activities performed by researchers in this area are mentioned in the following.

Velldandla et al. (1995) conducted an experiment to simulate subcooled flow boiling in a vertical annular channel. In this study, wall temperature distribution, fluid temperature and the volume fraction of vapor at various locations along the channel were measured. Hoyer (1998) organized an experimental setup on boiling flow while the dryout phenomenon occurred due to exertion of a high heat flux compared with CHF. It was observed that a film of vapor takes place around the channel wall, causing a sudden rise in wall temperature.

In addition to experimental researches, Li et al. (2010) investigated the two phase boiling flow field in a vertical channel using RPI model developed by Ransselaer Polytechnic Institute, using the available computational code named FLUENT. In the framework of analyzing, the water and vapor phases were considered separately based on Eulerian–Eulerian approach. Again, Li et al. (2011) simulated the boiling phenomenon as well as the dryout in a

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Nomenclature

A_b	Portion of wall surface covered by bubble (m^2)
$\vec{B}_f$	Body force (N)
C_{wt}	Bubble waiting time coefficient
d_{bw}	Bubble departure diameter (m)
d_b	Bubble diameter (m)
F_D	Drag force (N)
F_L	Lift force (N)
F_{TD}	Turbulent drift force (N)
f_{bw}	Bubble departure frequency (Hz)
H_{lv}	Latent heat (Jkg^{-1})
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
$\dot{m}$	Rate of mass transfer (kgs^{-1})
N_w	Nucleation site density (#sites m^{-2})
p	Pressure (Pa)
S_H	External heat source term
$\dot{q}$	Heat flux (W)

Greek letters

ρ	Density (kgm^{-3})
α	Void fraction
τ	Shear stress tensor
γ	Fluid/Phase heat diffusivity
σ	Surface tension coefficient
Φ	Turbulent parameter
Γ	Diffusion coefficient

Subscripts

c	continuous phase
C	Convection
d	dispersed phase
E	Evaporation
G	Other gas phases
l	liquid
v	vapor
r, q	qth and rth phase

vertical channel using the CFD code. In this research, they predicted the location of the occurrence of the dryout phenomenon by modifying the wall heat flux partitioning. The results were in relatively good agreement with experimental data. Jun et al. (2012) carried out a thermal hydraulic evaluation and safety analysis of a system by the TASS/SMR-S code. In this study, the validation of the heat transfer model in the TASS/SMR-S code on the steady state conditions was performed with the Bennett's heated tube tests and THTF (thermal hydraulic test facility) experiment (Bennett et al., 1976). From the results of the TASS/SMR-S code calculation, the critical heat flux point and the surface temperature along the channel were predicted conservatively compared to the test results.

Besides the studies that have been taken place to simulate the boiling flow field, there are various activities that investigated the influence of nanoparticles on both single phase heat transfer and boiling fluid flows.

White (2011) experimentally studied the effects of ZnO nanoparticle sedimentation on the heat transfer coefficients in pool boiling. In this research, the influence of the nanoparticles on the surface contact angle and subsequently on the nucleation site density of the wall was examined. It was observed that with nanoparticles being deposited on the wall, the boiling characteristics were enhanced by 62 percent as a result of an increase in the contact angle and consequently activation of more nucleation sites. It was also mentioned that without deposition of the nanoparticles on the wall, the nanofluid heat transfer coefficient experiences a growth equal to 25 percent in comparison with the base fluid. Heyhat et al. (2013) performed an experimental investigation of Al_2O_3/water nanofluid laminar convective heat transfer in fully developed flow regime. It was showed that the heat transfer coefficient increases by approximately 32% at 2 percent volumetric concentration of nanoparticles.

Prajapati and Rohatgi (2014) experimentally examined ZnO/water nanofluid with volume concentration of the nanoparticles varying from 0.0001 to 0.1% in a convective boiling flow field. In this research, the influence of pressure variation (1–2.5 bar), wall heat flux (0–400 kW/m^2) on the Heat transfer coefficients was studied in an annular test section. They showed that with the nanoparticles being more deposited on heater surface, the surface area of heater rod is increased and thus improves the heat transfer by convection.

In addition to researches that have been performed on the enhancement of nanofluid thermal conductivity, further investigations have been conducted on the effects of nanoparticles and inducing excessive fluctuations such as Brownian motion on the flow field. In the simulation organized by Gupta and Kumar (2007), the influence of Brownian motion has been investigated in a thermal flow field. They also indicated that particularly at lower concentrations, due to the occurrence of agglomeration, Brownian motion would not be the sole predictor of the increase in thermal conductivity.

Shima et al. (2009) numerically studied the effect of micro convection due to the Brownian motion on the thermal conductivity. They varied the particle diameter from 2.8 to 9.5 nm and reported a 19% increase in the effective thermal conductivity. They concluded that the Brownian motion is not the key mechanism in the thermal behavior of nanofluids. It was also stated that some characteristics of agglomeration like the aspect ratio could be considered responsible for the thermal conductivity enhancement.

Evans et al. (2006) also showed that Brownian motion induces only small augmentation in the conductivity compared to other effects. These findings led to the fact that the impact of Brownian motion can be assumed minor when dealing with nanoparticles.

To the best of author's knowledge, there are a few references about nanofluid accompanied by boiling flow especially in CHF condition. The purpose of this study is to compare the results of numerical code with the available experimental results and modeling the dryout phenomenon in the presence of copper oxide and alumina nanoparticles. In the current study, to properly simulate the boiling flow field and CHF, the change of flow regime from bubble flow to churn and finally mist flow has been included.

2. Numerical simulation of boiling flow field

In order to simulate the boiling flow field, averaged Navier–Stokes equations have been used with an Eulerian–Eulerian approach for each phase and the relations required to describe boiling phenomenon in equilibrium and non-equilibrium conditions as well. In this study, the effect of nanoparticles was considered by averaging the thermophysical properties involved in the flow field equations. Wall boiling phenomenon is modeled by the use of the mechanistic RPI boiling model and the extended formulations for the dryout phenomenon. Topological functions are