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CFD simulation of a concentrated salt nanofluid flow boiling in a rectangular tube

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ABSTRACT

Improvement of heat transfer and critical heat flux (CHF) via nanofluid in pool boiling is well known. Flow boiling is usually represented by heat transfer correlations. But in the case of a concentrated salt solution nanofluid, there is no suitable representation. A model is generated using commercial CFD code with additional user defined function, (UDF) to address this for the case of determining the heat and mass transfer in a boiler duct for a vapour absorption refrigerator. Computational fluid dynamics (CFD) simulations are performed to assess the effect of varying nanoparticle concentrations, fluid velocity and boiler temperature on the boiling and phase change characteristics of the system. Four phases are treated in this case, which were liquid acetone, vapour acetone, liquid Acetone/$ZnBr_2$ solution and solid nanoparticles cloud. Zinc oxide nanoparticles are represented as a cloud-like phase in the mixture. In addition, this study evaluates the key characteristics of the nanofluid system, and how the different components and phases behave when the single component evaporates. Previous research concentrates on water based fluids or commonly found refrigerants and heat transfer fluids. In this work the process was modelled using ANSYS® Fluent V.15 using the mixture multiphase flow model, however, the volume of fluid (VOF) method is also used to show the behaviour of the vapour phase. A UDF was applied from the literature (LEE, 1980) for boiling of nanofluids to model the mass transfer on boiling. It was found that increase in nanoparticle loading (0, 0.1, 0.3, 0.5 & 1 vol%) leads to an increase in the exiting vapour volume fraction and the heat transfer coefficient. This is primarily due to an increase in the heat transfer in the system due to the increased thermal conductivity in the nanofluid. Incremental increases in the boiler temperature (330, 333, 335 K) creates an increase in both vapour volume fraction and heat transfer coefficient because the process still in the nucleate boiling which, the heat flux increase with increasing the temperature difference. This new approach for the four phase system is capable to demonstrating concentrated salt solution nanofluid boiling.

1. Introduction

Enhancement of heat transfer properties of fluids can reduce the size of heat transfer systems and operational cost [2]. Flow boiling heat transfer occurs in vapour absorption refrigeration systems as well as in various industrial areas, such as refrigeration systems in many applications, power generation, chemical engineering, high-power electronics component cooling, and nuclear reactor cooling [7]. Improvements in flow boiling heat transfer systems can improve energy efficiency and offer a route to reduce global energy consumption. To improve the heat transfer of the fluid, the behaviour and the properties of the fluid itself shall enhanced. Nanofluids (i.e. homogenous base fluids interlaced with nano-scale particles that are modified with chemical/physical processes such as sonication and adding surfactants) are an alternative to Newtonian fluids for thermal and industrial applications, due to their modified thermo-physical properties which can enhance the efficiency of processes such as boiling [14].

The early stages of boiling start with single phase natural convection, with heat transferred from the hot surface to the fluid; after this, nucleate boiling begins, which is a two phase natural convection process. In nucleate boiling, bubbles are created and grow from the hot surface. If the heat flux through the surface is further increased, then a layer of vapour forms between the hot surface and the liquid which called film boiling. The process between nucleate and the film boiling is called transition boiling [8].

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Nomenclature

t	time (s)
S	source term
$\dot{m}$	mass flow rate (kg/s)
T	temperature (K)
v	velocity (m/s)
p	pressure (N/m^2)
K_b	Boltzmann constant
g	gravity (m/s^2)
F	body force (N)
E	energy (J)
H	enthalpy (kJ/kg)
n	current time step
n + 1	next time step
U_f	volume flux of face (m^3/s)
V	volume of cell (m^3)
k_{eff}	effective thermal conductivity (W/m K)
x	length (m)
q	number of phases
k	phase

Greek letters

ρ	density (kg/m^3)
φ	volume fraction of the particles
μ	viscosity (kg/m s)
∇	vector gradient operator
ϵ	time relaxation factor (1/s)
δ	the mean distance between the centres of two particles

Subscripts

k	phase
lv	phase change from liquid to vapour
q	secondary phase
l	liquid
v	vapour
sat	saturated
m	mixture
t	turbulent
dr	drift velocity
h	hot

The number of studies of nanofluid boiling has increased significantly over the last decade with emphasis mainly on pool boiling rather than flow boiling, even though flow boiling has more applications than pool boiling [13]. There are several recent experimental studies on flow boiling effects of nanofluids with significant consequences for enhancing boiling heat transfer. Henderson et al. [18] studied the flow-boiling heat transfer of R-134a-based nanofluids in a horizontal tube and found that the nanofluid has an insignificant influence on the flow pressure drop compared to the base fluid and that the heat transfer coefficient increases to double over the base-fluid. Kim et al. [21] studied subcooled flow boiling (boiling adjacent to a surface hotter than the saturated temperature (T_s), whilst the bulk temperature of the local fluid is below T_s) using different types of nanofluid. They found that the heat transfer coefficient and mass flux of the nanofluid increases during boiling and that the flow boiling CHF (transition between the nucleate boiling and the film boiling) was enhanced using nanoparticles. Kim et al. [20] investigated the enhancement of flow boiling for alumina nanoparticle based nanofluid in water at the low pressure. They found that the CHF can improve up to 30% with 0.01 vol% of alumina nanoparticles. Boiling heat transfer and pressure drop through a rectangular channel of nanofluid is experimentally studied by Boudouh et al. [9]. Here, the local heat flux, vapour volume fraction and heat transfer coefficient all increase with increasing nanoparticle concentration. CHF improvement during forced convection of flow boiling of a nanofluid on a short heated surface is experimentally studied by Ahn et al. [3]. They found that the nanofluid flow boiling heat transfer is enhanced under forced convection and they suggest that this enhancement is mostly caused by the deposition of nanoparticles on the heater surface during boiling.

Not all studies confirm the enhancement of boiling heat transfer as the nanoparticles concentration increases. For example, Abedini et al. [1] investigated experimentally a comparison of nanofluid flow boiling in vertical and horizontal tubes. They found that subcooled flow boiling decreases with increasing concentration of TiO_2 nanoparticles. They found that the bulk temperature decreases at the end of the channel with nanofluid compared to pure water, implying that the vapour volume fraction increases in the nanofluid. Suriyawong and Wongwises [26] studied the heat transfer in the pool boiling of diluted concentration of TiO_2–water nanofluids. They found that the heat transfer coefficient of the fluid decrease with increasing the concentration of the nanoparticles. They found also, that the heater surface type and the roughness of the surface have an effect on the heat transfer. Whereas, aluminium surfaces generated better heat transfer than copper surfaces and the surface roughness of 4 μm produced a higher heat transfer coefficient than the surface roughness of 0.2 μm.

Pool boiling characteristics are addressed by many researchers, with the heat transfer behaviour varying significantly between studies. Several researchers found an increase in the heat transfer coefficient with increasing concentration of the nanoparticles [28], however, others have found the heat transfer coefficient is insensitive to nanoparticle concentration [27,32] or even negatively correlated [10,34]. Furthermore, some studies confirm a significant increase in the CHF even with low concentrations of nanoparticles [6,19,27,32]. Kim et al. [19] found that the water based nanofluid significantly improves the CHF compared with a pure fluid and enhancement of the CHF of the water due to nanoparticles surface coating on the heater (prepared by deposition of suspended nanoparticles during pool boiling of nanofluids, immersed in pure water) increase as the concentration of the nanoparticles increases. They conclude that the reason for this improvement of CHF is the change of surface microstructure and topography of the heater because of the nanoparticle surface coating during pool boiling of nanofluids.

There are several numerical studies dealing with boiling heat transfer effects in nanofluids using CFD. Hasheminia et al. [17] numerically studied the effect of different parameters of forced flow boiling of nanofluids. They found that the CHF in Al_2O_3/water and SiO_2/water nanofluids decreases with increasing nanoparticle volume fraction. Which was explained by stating that the contact angle increases with increase in concentration because each single particle may contact with other particles at more locations. Abedini et al. [2] numerically investigated the subcooled flow boiling of nanofluids, finding that the heat transfer coefficient increases with increasing nanoparticle concentration and that decreasing the inlet mass flow rate can cause the heat transfer coefficient to rise or fall depending on the effect of forced convection, bubble generation and latent heat transport on the overall heat transfer coefficient. Experimental and numerical investigation of the dynamics of bubbles in the nanofluid pool boiling was studied by Shoghl et al. [25]. They found that both CHF and boiling heat transfer coefficient were enhanced by hydrophilic surface and worsened