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Research Paper

CFD assessment of the effect of nanoparticles on the heat transfer properties of acetone/$ZnBr_2$ solution

Hayder I. Mohammed [a,*], Donald Giddings [a], Gavin S. Walker [b], Henry Power [a]

[a] Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[b] Faculty of Engineering, The University of Nottingham, Innovation Park, Nottingham NG7 2TU, United Kingdom

HIGHLIGHTS

- A vapour absorption refrigerant nano-fluid is tested in a CFD model.
- Heat transfer is significantly affected by solution salt concentration.
- Heat transfer enhancement is observed up to 180% of the base-fluid value.
- Brownian motion, assumed in the numerical method, affects heat transfer.
- Experimental observation of nano-fluid shows settling within 5 h.

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ABSTRACT

A potential novel working fluid for vapour absorption refrigeration utilising very low grade waste heat, is based on acetone and zinc bromide as the salt solution. A Computational Fluid Dynamics (CFD) model is presented of the fluid with zinc oxide nano-particles in a flat tube flow. A two phase type of model represents the zinc oxide nano-particles as a distinct fluid phase. The cases of laminar and turbulent flow are explored numerically for a wide range of acetone and nanoparticles concentrations. The velocity is varied between 1.5 and 6 ms^{-1}, representing typical heat exchanger conditions. Reynolds number depends significantly on the solution concentration. Heat transfer coefficient increases with *Re*, by turbulent mixing, and with the concentration of nanoparticles and of acetone by the enhanced thermal diffusivity. The shear wall stress is not affected by changing the concentration of nano-particles. The nano-fluid is demonstrated to work well for heat transfer enhancement over the base fluid; the further issue of suspension of the nano-particles in the solution is explored experimentally. The nano-fluid can be achieved by ultra-sonic excitation, with a settling time in the order of several hours. Subject to the particle suspension time being increased, this fluid combination is a good candidate for the application considered.

1. Introduction

With increasing demands on energy efficiency, making use of low grade waste heat using vapour absorption refrigeration systems (VARS) is receiving renewed interest; Sun et al. [1] provides an extensive review of the various working fluids for absorption refrigeration, where acetone and zinc bromide operate at the lowest boiler temperatures. These materials work with low temperature heat sources [2], much lower than most common binary fluid systems (e.g. NH_3/H_2O & $H_2O/LiBr$), in the order of 10 s of °C above ambient. There is a large body of research focused on nanofluids, which are defined as a base fluid with particles in nanoscale (<100 nm) since 'nanofluid' was first termed by Choi and Eastman [3]. It is well known that enhancement of heat transfer is possible and vehicle engine coolant heat exchangers, with either water (H_2O) or ethylene glycol (EG), in particular, have received some attention in the area.

The effect and mode of action of nanofluid on heat transfer appears to be flow situation specific. Wen and Ding [4] stated that the improvement of heat transfer of spherical Al_2O_3-water nanofluids might be caused by the particle movement due to viscosity and Brownian motion. They claimed that particle movement generates a non-uniform thermal conductivity performance which results in a higher Nusselt number. Hwang et al. [5] argued that it is caused by nano-particle migration toward the centre of the channel which generates a random velocity caused by a non-uniform viscosity.

* Corresponding author.
E-mail addresses: eaxhm1@nottingham.ac.uk, haidarnuceng@gmail.com (H.I. Mohammed).

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Nomenclature

Ac	acetone
c	correction factor
C_f	skin friction
c_p	specific heat (J/kg K)
d	diameter (m)
d_h	hydraulic diameter (m)
h	heat transfer coefficient (W/m^2 K)
K_t	turbulence kinetic energy
k	thermal conductivity (W/m K)
k_b	Boltzmann cons.
n	shape factor
Nu	Nusselt number
p	pressure (pa)
Re	Reynolds number
T	temperature (K)
Ti	turbulence intensity
V	volume (m^3)
V_B	Brownian velocity (m/s)
X	length (m)
Phi	volume fraction

Greek letters

ρ	density (kg/m^3)
δ	distance between centres of two particles (m)
μ	viscosity (kg/m s)
φ	volume fraction
τ_w	wall shear stress
v	velocity (m/s)
ε	rate of dissipation

Subscripts

t	turbulence
av	average
cl	centreline
dr	drift
f	base fluid
k	component
m	mixture
nf	nanofluid
p	particle

Wen and Ding [6] and Hwang et al. [5] state that most heat transfer enhancement for Al_2O_3-water nanofluids occurs in the developing region of the flow.

Ding et al. and Garg et al. [7,8] explained the mechanism of improved heat transfer for carbon nano-tube (CNT) nanofluid by a three dimensional web of nanotubes with heat transferred within the nanotubes, which has a much higher thermal conductivity than the base fluid. Ding et al. [7] reported for carbon nano-tube (CNT) and water (0.5 wt% of CNT) nanofluid a heat transfer enhancement of 350%. Garg et al. [8] and Lao and Liu [9] reported much lower local heat transfer coefficient enhancements for CNT nanofluids when they used a higher solid concentration.

Some researchers try to develop the nanofluid to enhance the heat transfer. In two separate studies [10,11] Takabi and his groups numerically studies the effect of the hybrid nanofluid (two or more types of nanoparticle in form of mixture or composite suspend in a basefluid [12]) which presented by Al_2O_3 – Cu/H_2O on the heat transfer in the uniform heated circular tube for turbulent and laminar regimes. They found that the heat transfer improved for the hybrid nanofluid more than the pure water or Al_2O_3/H_2O in the laminar case, which studied in [10] the *Nu* which present the heat transfer enhanced by 7.2% for the hybrid nanofluid compared with the base fluid. However, in [11] which involved with the turbulent flow with the wide range of *Re* (10^4–10^5) and volume fraction of the nanoparticles (0–2%) they confirm that the maximum improvement in the *Nu* reaches to 32.02% in the Hybrid nanofluid compared with the pure fluid.

Some researchers [13–15] reported that heat transfer in nanofluids can be modelled using classical correlations (based on Maxwell) for single-phase fluids with adjustment for properties with the nano-particles. Others stated that the heat transfer behaviour obeys a two phase model with variation due to concentration of nano-particles varying in the flow. There is a debate in the literature about which analysis provides a better prediction.

Utomo et al. [16] investigated the heat transfer coefficient arising from alumina, titania and CNT nanofluids. They found that the addition of nanoparticles to liquids enhances the heat transfer coefficients by no more than 10% at a constant turbulent velocity. They state nanofluids behaved as homogenous mixtures with experimental Nusselt numbers following classical relations developed for the single-phase approach, modified for the mean nanoparticle concentration, being accurate to within ±10%; this uncertainty is explained by movement of nanoparticles due to Brownian motion and viscosity gradient due to concentration, with non-uniform shear rate having insignificant effect on heat transfer. Similar uncertainty was found for metal oxide nanofluids [17] and for CNT nano-fluids [9].

Pantzali et al. [18] investigated a nanofluid of 4 vol% CuO in H_2O numerically and experimentally using a laminar flow on a plate heat exchanger. They found that the flow rate of the nanofluid required for a particular heat transfer rate was lower than the base fluid. Jafari and his group [19] numerically investigated the heat transfer enhancement for the laminar and mix convection in a cavity used with Cu/H_2O nanofluid. They confirmed that the Grashof and Reynold Numbers have a great impact on improving the *Nu* and they stated that with increasing in the nanoparticles, the heat transfer is enhanced and it becomes more effective with a high Grashof numbers.

A two dimensional single phase CFD model was numerically studied by Demir et al. [20] using Al_2O_3 and TiO_2 in water nanofluid in a horizontal pipe heat exchanger. They found that the heat transfer increased with the concentration of nanoparticles. Goktepe et al. [21] studied the single and the two phase models for nanofluid inside a uniformly heated tube. They found that the convective heat transfer coefficient is more correctly predicted with a two phase model than the single phase.

Amoura et al. [22] studied the heat transfer for three different types of nanofluid (H_2O/CuO, H_2O/Al_2O_3 and H_2O/TiO_2) in horizontal tubes in 2D with different Reynolds number up to 600 and different volume fraction of nanoparticles (0, 0.01, 0.02, 0.03 and 0.1) using a single phase technique. They found that the Nusselt number of nanofluids is larger than that of the base fluid and that the Pressure loss coefficient drops by increasing Reynolds number for all types of nanofluids. Moraveji et al. [23] modelled fully developed flow in a circular tube with laminar flow, assuming constant heat flux on the tube wall, and using a single phase approach. With nanofluid (up to 6 wt% Al_2O_3 + water), they recorded higher heat transfer than base fluid. Akbari et al. [24] showed, theoretically, the heat transfer improvement with increasing Reynolds number (*Re*) and concentration of nano-particles in the nanofluid solution (H_2O/Al_2O_3). The two phase model was applied in three different CFD based two phase approaches, i.e. volume of fluid (VOF),