International Communications in Heat and Mass Transfer 91 (2018) 262–273

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Discrete phase numerical model and experimental study of hybrid nanofluid heat transfer and pressure drop in plate heat exchanger

Atul Bhattad, Jahar Sarkar*, Pradyumna Ghosh

Department of Mechanical Engineering, Indian Institute of Technology (B.H.U.), Varanasi, UP 221005, India

ARTICLE INFO

Keywords:
Hybrid nanofluids
Plate heat exchanger
Discrete phase model
Experimentation
Heat transfer rate
Pressure drop

ABSTRACT

In the present study, numerical as well as experimental investigations have been done on the plate heat exchanger using hybrid nanofluid (Al_2O_3 + MWCNT/water) at different concentration to investigate its effect on heat transfer and pressure drop characteristics. Discrete phase model has been used for the investigation using CFD software and results have been compared with the experimental result as well as result of the homogenous model. Effects of different operating parameters (nanofluid inlet temperature, flow rate and volume concentration) have been studied on coolant outlet temperature, heat transfer rate, convective and overall heat transfer coefficients, Nusselt number, friction factor, pressure drop, pumping power, effectiveness and performance index. Velocity and temperature profiles have been also studied for base fluid, nanofluid and hybrid nanofluid. By using hybrid nanofluid, heat transfer coefficient enhances by 39.16% (merit) with negligible increase in pumping power of 1.23% (demerit). An enhancement in heat transfer and pressure drop characteristics; and hence on the effectiveness of plate heat exchanger has been observed while using hybrid nanofluids instead of base fluid.

1. Introduction

Need for improvement in thermal systems and properties of working fluid make the researchers focus on the design of plate heat exchangers and use of one or more nanosized particles with single base fluid or the mixture of different fluids. Properly engineered nanofluid have many advantages like more heat transfer area, more stability, reduced pumping power, etc. because of which, it plays a vital role in developing the cooling technology [1]. Nanofluid with more than one nanoparticle dispersed in base fluid simultaneously is known as hybrid nanofluid [2]. Huang et al. [3] experimentally show that the heat transfer coefficient of the hybrid nanofluid (MWCNT-Al_2O_3/water) mixture is slightly larger than that of the Al_2O_3/water nanofluid and water when a comparison was based on the same flow velocity. Hence, using hybrid nanofluids have been found more beneficial regarding the heat transfer characteristics. He et al. [4] experimentally and numerically (Eulerian-Lagrangian model) investigated the heat transfer behavior of laminar TiO_2-H_2O nanofluid flow in a horizontal circular pipe. Influence of nanoparticle concentration, size and Reynolds number on heat transfer characteristics has been studied. A similar study has been done by Bianco et al. [5] and Moraveji et al. [6] on laminar forced convection Al_2O_3-H_2O nanofluid flow using single phase and Eulerian-Lagrangian discrete phase models with constant and temperature dependent properties. Eulerian-Lagrangian method benefits in tracking the trajectory of an individual stream of nanoparticles. The dispersion of particles due to turbulence in the fluid phase can be taken into account by using the stochastic tracking model [7]. Tahir and Mital [8], Shirvan et al. [9] and Zhou et al. [10] used discrete phase model for their investigation using alumina-water nanofluids for laminar flow at constant heat flux. They observed that on increasing the Reynolds number and volume fraction, the Nusselt number and heat transfer coefficient increases while the effect of particle agglomeration decreases. Bahiraei [11] used discrete phase model in a circular pipe for laminar flow and observed that at higher Peclet number, the effect of viscosity gradient and the shear rate had been intensified on particle migration. Due to simplicity and strength of visualizing the flow of nanoparticle and base fluid, the discrete phase model is highly used for numerical investigations in the vertical tube [12]. Effect of Brownian motion and gravity on transport phenomenon has been investigated by Aminfar et al. [13] using discrete phase model. Sidik et al. [14] reviewed different numerical approaches to investigate the heat transfer and flow characteristics. It has been observed that two phase discrete model performs better in comparison to the other models for nanofluids. Comparative investigation of internal flows under laminar and turbulent region using nanofluids has been performed by different authors [15–20] using different single phase and two phase model. They

* Corresponding author.
E-mail address: jsarkar.mec@itbhu.ac.in (J. Sarkar).

https://doi.org/10.1016/j.icheatmasstransfer.2017.12.020

Nomenclature

A	Effective area of heat transfer (m^2)
c_p	Specific heat ($J \cdot kg^{-1} K^{-1}$)
d	Particle diameter (m)
D_h	Hydraulic diameter (m)
D_p	Port diameter (m)
F	Force (N)
G	Mass velocity ($kg \cdot s^{-1} m^{-2}$)
h	Heat transfer coefficient ($W \cdot m^{-2} K^{-1}$)
H	Total enthalpy (J)
κ	Turbulence kinetic energy (J)
k	Thermal conductivity ($W \cdot m^{-1} K^{-1}$)
k_B	Boltzmann constant
L	Length (m)
ṁ	Mass flow rate ($kg \cdot s^{-1}$)
Nu	Nusselt number
P	Pump work (W)
p	Pressure (Pa)
Pr	Prandtl number
q	Heat flux ($W \cdot m^{-2}$)
Q	Heat transfer rate (W)
Re	Reynolds number
S_m, S_e	Particles source terms in the base fluid equations for momentum and energy
T	Temperature (°C)
U	Overall heat transfer coefficient ($W \cdot m^{-2} K^{-1}$)
δV	Cell volume (m^3)
V	Velocity ($m \cdot s^{-1}$)

Abbreviation

PHE	Plate heat exchanger
CFD	Computational fluid dynamics
DPM	Discrete phase model
FVM	Finite volume method
UDF	User defined function
MWCNT	Multiwalled carbon nanotube

Greek symbols

μ	Dynamic viscosity (pa·s)
ε	Rate of dissipation per unit mass ($m^2 \cdot s^{-3}$)
ρ	Density ($kg \cdot m^{-3}$)
Φ	Volume concentration
τ	Stress tensor ($N \cdot m^{-2}$)
ξ	Unit variance, zero mean independent Gaussian random number

Subscript

1	Particle 1
2	Particle 2
nf	Nanofluid
bf	Base fluid
p	Particle
h	Hot
c	Cold
i	Inlet
o	Outlet

observed that the results obtained from discrete phase model are in good agreement with experimental results as compared to other models. Discrete phase model also found suitable while analyzing flow through microchannels using nanofluids at constant temperature [21–22].

Single phase (homogeneous) model has been used by many investigators for plate heat exchanger using nanofluids. Pantzali et al. [23] conducted a numerical investigation to examine the performance of a miniature plate heat exchanger using nanofluid with modulated surface and observed that size of equipment and pump work get reduced while using CuO/water nanofluid. Fard et al. [24] have done numerical analysis on plate heat exchanger using the ZnO/water (0.5 v%) nanofluid as the hot stream. Their results showed that the heat transfer rate and heat transfer coefficient of the nanofluid in the heat exchanger was found higher than that of the base liquid. Gherasim et al. [25] performed the numerical investigation to study heat transfer and flow characteristics under laminar and turbulent flow in plate heat exchanger using homogeneous single phase model with CuO and alumina nanofluids. They observed a significant enhancement in heat transfer with higher pressure losses using nanofluids in comparison to base fluid (water). Ray et al. [26] compared the performance of three nanofluids (1.0 v%) comprising of ethylene glycol and water mixture in a compact minichannel plate heat exchanger. All three nanofluids exhibit increase in convective heat transfer coefficient, reduction in the volumetric flow rate and pumping power requirement for the same amount of heat transfer in the PHE. Tiwari et al. [1] also used single-phase numerical model and got the promising result with various nanofluids. Stogiannis et al. [27] numerically found a reduction of coolant and pumping power while using SiO_2 nanofluid as a coolant in plate heat exchanger. Luan et al. [28] noted that using computational fluid dynamics approach in the plate heat exchangers can improve grid quality without deteriorating the results and hence suitable for studying the influence of different geometrical parameters on PHE design. A contradictory result like an increase in thermal conductivity and decrease in heat transfer with an enhancement in volume concentration has been observed during the numerical investigation conducted by Jokar and O'Halloran [29].

From the above survey, it has been found that many types of research have been performed on nanofluids in PHE, but very few investigations have been done using hybrid nanofluids in plate heat exchangers and there is no numerical work on plate heat exchanger using hybrid nanofluids for low temperature application. Also, no research is available on numerical analysis of plate heat exchanger with hybrid nanofluids using discrete phase model. These facts provide thrust to work in this area. Hence in this paper, the numerical investigation has been performed for hybrid nanofluids (MWCNT-Al_2O_3/water) in PHE using discrete phase model at low temperature applications to investigate the effects of different coolant flow rate, inlet temperature and particle volume concentration. Experimentation has been also conducted to validate the model.

2. Experimental setup and procedure

The experiments were aimed at determining the heat transfer and pressure drop performances for different hybrid nanofluid concentrations (0.01, 0.02 & 0.03 v%) in 9:1 ratio with various coolant flow rates (2.0, 2.5, 3.0, 3.5 and 4.0 lpm), and operating inlet temperatures of coolant (15, 20, 25 and 30 °C). Here, hybrid nanofluid is used as a coolant. Commercial PHE, supplied by Alfa Laval India Limited, has been used for this purpose and its geometrical parameters are shown in Table 1. The experimental setup mainly includes two flow loops, one for the cold fluid and another for hot fluid (hybrid nanofluid as cold and distilled water as hot) as described in Fig. 1. Experimental data have been used to determine the heat transfer and pressure drop characteristics, each of the involved fluids. Reynolds number of hot water and hybrid nanofluid can be calculated based on channel mass velocity and