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A novel application for energy efficiency improvement using nanofluid in shell and tube heat exchanger equipped with helical baffles

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ABSTRACT

Hydrothermal characteristics of the water–Al_2O_3 nanofluid are numerically evaluated in shell-and-tube heat exchanger equipped with helical baffles using the two-phase mixture model. Heat transfer and pressure drop increase by increasing nanoparticle concentration and baffle overlapping, and decreasing helix angle. At smaller helix angles, changing the overlapping is more effective on the convective heat transfer coefficient and the pressure drop. Neural network is used for modeling, and based on the test data, the model predicts the convective heat transfer coefficient and the pressure drop with MRE (Mean Relative Error) values of about 0.089% and 0.65%, respectively. In order to obtain conditions of effective parameters which cause maximum heat transfer along with minimum pressure drop, optimization is performed on the neural network model using both two-objective and single-objective approaches. 15 optimal states obtain from two-objective optimization. The results obtained from single-objective optimization indicate that even when a low pressure drop is significantly important for designer, nanofluids with high concentrations can be employed. Meanwhile, when both high heat transfer and low pressure drop are important, a small helix angle can be used. In addition, using large overlapping is recommended only when the heat transfer enhancement is considerably more important than the reduction of the pressure drop.

1. Introduction

Heat transfer via fluid flow plays a pivotal role in various industries such as power plants, refineries, electronics, and so forth. Regarding recent technological advancements in industries, numerous studies have been conducted thus far in order to find different methods for heat transfer enhancement [1–4].

One of the major limitations on different methods of enhancement in heat transfer by means of fluid flow is the inherently poor thermal properties of conventional heat transfer fluids such as water and ethylene glycol in comparison with solids. Recent furtherance in the field of nanotechnology paved the way for production of solid nano-sized particles, which led to the introduction of the novel suspensions containing such particles, known as nanofluids, by Choi [5] to improve thermal properties of fluids.

Due to the size effect and Brownian motion of the nanoparticles in the base fluid, nanofluids exhibit proper stability compared to conventional suspensions with micro- or milli-sized solid particles. In addition, numerous studies have been carried out to improve the stability of nanofluids and to prevent two phenomena which are critical to the stability of nanofluid, i.e. aggregation and sedimentation [6,7]. Having this in mind, nanofluids have attracted the attention of many researchers, particularly in the field of thermal engineering [8–10].

Among the numerous investigations carried out thus far, several numerical studies have been implemented on nanofluids based on two general approaches, namely: single-phase and two-phase. The former assumes that the fluid phase and particles are in hydrothermal equilibrium, while the latter provides the possibility of understanding the interaction between the fluid phase and solid particles in the flow and heat transfer process. In single-phase approach, which is simpler and requires less computational time, the effective properties of nanofluids are taken into account to solve

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Nomenclature

A	area, m^2
a	acceleration, m/s^2
b	distance parameter
C_c	Cunningham correction factor
c_p	specific heat, J/kgK
D	internal diameter of the shell, m
D_2	objective function of compromise programming
d	diameter of tubes, m
d_p	diameter of nanoparticle, m
e_i	error for each pattern
h	convective heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/mK
k_B	Boltzman constant, J/K
$\dot{m}$	mass flow rate,kg/s
n	number of tubes
P	pressure, Pa
p	baffle pitch, m
Q	heat exchange quantity, *W*
r	radial coordinate
s	overlapping
T	temperature, K
$\mathbf{v}$	velocity, m/s
V_B	Brownian velocity, m/s
$v_{dr,p}$	drift velocity, m/s
v_{pf}	relative velocity, m/s
W	objective function
Z	objective function

Greek symbols

α	weight coefficients of objective functions
β	helix angle, degree
γ	performance ratio
δ	distance between the particles, m
λ	mean free path, m
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
φ	volume concentration

Subscripts

f	base fluid
in	inlet
m	mixture
out	outlet
p	particle

the conservation equations and most studies have benefitted from this approach to numerically simulate the flow and heat transfer of nanofluids [11–13]. However, due to several factors such as gravity, friction between the fluid and solid particles, Brownian force, sedimentation and so forth, not considering the interaction between the base fluid and nanoparticles can lead to error in numerical simulation. Therefore, as demonstrated by Haghshenas Fard et al. [14], two-phase approaches can better model nanofluids behavior. In addition, the numerical and experimental results of the study conducted by Bahiraei and Hosseinalipour [15] using the two-phase Euler–Lagrange method, and Naphon and Nakharintr [16] using the two-phase mixture model indicated that these methods present results very close to those of experiments. Just a limited number of studies have been launched using two-phase methods. Bahremand et al. [17] analyzed the turbulent flow of water-silver nanofluid in helically coiled tubes under constant wall heat flux. They applied the two-phase Euler–Lagrange approach along with an RNG (Re-Normalisation Group) k–ε turbulence model accounting for four-way coupling collisions. It was observed that the two-phase approach predicts the results much more accurately in comparison with the homogeneous model. Narrein et al. [18] performed a three-dimensional numerical simulation using the two-phase mixture model with modified effective thermal conductivity and viscosity equations to investigate nanofluid flow in a helical microchannel heat sink. It was stated that such numerical analysis provides a unique fundamental insight into the complex secondary flow pattern in the channel due to curvature effects.

A review on the existing literature indicates that most studies in the field of heat transfer enhancement using nanofluids have been conducted in simple geometries such as circular tubes, annuli and straight channels. However, the thermal systems which are used in industries, such as various types of heat exchangers, are far more complicated than the above mentioned geometries. Very few studies have assessed the effect of using nanofluids in different heat exchangers. Khoshvaght-Aliabadi [19] experimentally assessed the effects of VG (vortex-generator) and Cu–water nanofluid flow on the performance of plate-fin heat exchangers. It was observed that utilizing the VG channel instead of the plain channel remarkably enhances the heat transfer rate. In addition, it was concluded that application of VG is more effective than the using nanofluid on the performance of plate-fin heat exchangers, and the combination of the two heat transfer enhancement techniques has a noticeably high hydrothermal performance. Durga Prasad et al. [20] performed an experimental study to analyze on the heat transfer performance of nanofluid in a double pipe U-bend heat exchanger. Two methods of heat transfer augmentation were considered, i.e. active method by providing a bend in the test tube, and passive method using nanofluid as well as helical tape inserts. In the active method, about 5% heat transfer enhancement was observed for water flowing in a heat exchanger at Re = 30,000, while the enhancement was 8.7% for the case of using nanofluid with 3% concentration.

STHXs (Shell-and-Tube Heat Exchangers) are one of the mostly used types of heat exchangers in industry. Some studies have been conducted so far to investigate the effect of using nanofluids in such heat exchangers [21–28]. Shahrul et al. [29] investigated thermal performance of a STHX operated with nanofluids flowing in the tube-side at different mass flow rates. Different nanoparticles suspended in water at 0.03 volume fractions were considered. It is found that, for a certain mass flow rate of tube-side and shell-side fluid, the highest heat transfer coefficient belongs to Al_2O_3–water nanofluid and the lowest to CuO–water nanofluid. However, maximum energy effectiveness improvement took place by 43% for ZnO-water nanofluid, while the minimum improvement of 31% happened for Al_2O_3–water nanofluid. Farajollahi et al. [30] investigated the effects of Peclet number, nanoparticles concentration and particle type on heat transfer characteristics of γ-Al_2O_3-water and TiO_2–water nanofluids in a STHX. The experimental results indicated that for a given Peclet number, heat transfer characteristics of TiO_2–water nanofluid at its optimum nanoparticle concentration are greater than those of γ-Al_2O_3-water nanofluid, while γ-Al_2O_3-water nanofluid possesses better heat transfer behavior at higher nanoparticle concentrations. Bahiraei et al. [31] investigated heat transfer and flow field of water–Al_2O_3 nanofluid in the shell-side of a STHX with helical baffles. The effects of Reynolds number and volume fraction