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Numerical investigation of heat transfer and fluid flow in plate heat exchanger using nanofluids

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Numerical investigation of heat transfer and fluid flow in a single pass counter flow chevron corrugated-plates plate heat exchanger considering nanofluids (CeO_2 and Al_2O_3) as homogeneous mixtures has been presented in this paper using the Commercial CFD software, ANSYS FLUENT. The required thermophysical properties of the nanofluid were measured and used in the CFD model through UDF (User Defined Function) commercial CFD software ANSYS/FLUENT. Individual optimum concentration of CeO_2/water and Al_2O_3/water nanofluids yield maximum heat transfer improvement has experimentally determined and then CFD simulation has been done with those concentrations to obtain the temperature, pressure, and velocity fields. The results of numerical simulation were compared with experimental data in order to verify the accuracy of the homogeneous model. Validation of the CFD model suggests that considering nanofluid a homogeneous mixture, simulation can be performed to predict the plate heat exchanger performance with reasonable accuracy. CFD simulation shows that corrugation pattern of the plate develops turbulence and vortices of fluid which results in high heat transfer rates.

1. Introduction

Plate heat exchangers (PHEs) were introduced during 1930s to meet the hygienic demands of the dairy industry and are still the most popular heat transfer devices widely used in many engineering applications because of their several advantages such as small size and weight, high thermal efficiency, suitability in hygienic applications, flexibility and ease of sanitation as well as their superior thermal performance compared to other types of compact heat exchangers. Innovative heat transfer fluids with suspended nanometer-sized solid particles are called 'nanofluids', the term coined by Choi [1]. These particle include metal oxides (e.g., Al_2O_3, SiO_2, TiO_2, CeO_2, CuO), chemically stable metals (e.g., Cu, Au, Ag, Fe) and several allotropes of carbon (e.g., diamond, single walled and multi-walled carbon nanotubes, fullerence) with thermal conductivities typically an order-of-magnitude higher than those of the base fluids and with sizes significantly smaller than 100 nm. Nanofluids have the potential to reduce thermal resistances, which is significantly beneficial in industrial groups such as transportation, electronics, medical, food, and manufacturing [2].

Roetzel et al. [3] experimentally evaluated thermal parameters of plate type heat exchangers using a temperature oscillation technique, and a mathematical model was used to calculate heat transfer coefficient characterized by Number of Transfer Units and Peclet Number. Martin [4] developed the theoretically generalized equation to predict the thermal performance of PHE. Charre et al. [5] presented a general heat transfer and pressure drop model which is based on the theory of porous media and included the influence of eleven geometrical parameters of the plate. Ciofalo [6] explored the effect of the longitudinal heat conduction along the dividing walls and showed that it may enhance the exchanger's heat transfer performance. The laminar flows of Newtonian and power-law fluids through cross-corrugated chevron-type plate heat exchangers (PHEs) were numerically analyzed in terms of the geometry of the channels [7]. Dović et al. [8] developed generalized correlations for predicting the performance of chevron-type PHE by obtaining the heat-transfer coefficients in fully developed laminar or turbulent channel flow.

Galeazzo et al. [9] studied experimentally and numerically the heat transfer in an industrial PHE. They simulated flow and heat

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Nomenclature

C_p	fluid specific heat capacity at constant pressure, J/kg K
$C_{\mu 1}$,$C_{\mu 2}$	constants
f_1,f_2	wall damping functions
k	thermal conductivity, W/m K
p	pressure drop, Pa
T	temperature, K
U	mean velocity, m/s

Greek letters

ε	rate of dissipation per unit mass, m^2/s^3
k	turbulence kinetic energy, J
μ	viscosity, cP
μ_T	kinetic eddy viscosity
ϕ	particle volume concentration, %
ΔP	pressure drop, Pa
$\Delta P/\rho U^2$	dimensionless pressure drop
ρ	density, kg/m^3
σ_k	prandtl number
τ	shear stress, Pa

Subscripts

A	cold side fluid
B	hot side fluid
bf	base fluid
CFD	computational fluid dynamics
nano	nanofluid
p	nano-particles
nm	nano meter
UDF	user defined function
PHE	plate heat exchanger
vol_fr	volume fraction of nanofluid particles
temp	temperature
sqrt	square root function

transfer in a four-channel PHE with flat plates and two distinct configurations. The authors have compared experimental results with numerical predictions. Lin et al. [10] developed dimensionless correlations using the Buckingham Pi theorem to predict the heat transfer performance of the corrugated channel in a PHE. Lozano et al. [11] analyzed the flow distribution inside one channel of a PHE for the automotive industry, without considering the heat transfer. Also, the use of PHE to improve energy efficiency in phosphoric acid production was investigated [12]. Tsai et al. [13] investigated hydrodynamic characteristics and distribution of flow in two cross-corrugated channels of PHE. Han et al. [14] studied the effect of corrugated chevron PHE, which is used in a broad range of industrial applications. Downsized exchanger without loss of thermal-hydraulic performance is crucial matter for the industry applications [15]. Gherasim et al. [16] investigated experimentally the hydrodynamic and thermal fields in a two-channel chevron-type PHE for laminar and turbulent conditions. The friction factor and the Nusselt number were obtained for laminar and turbulent conditions. The temperature distributions on the first and the last of the three plates for a laminar case and two turbulent cases are also discussed.

Literature reviews shows that the theoretical and experimental research on heat transfer and pressure drop characteristics of nanofluids are mainly for flow through tube/channel with constant temperature or constant heat flux boundary conditions, however, investigations on heat transfer and pressure drop characteristics of nanofluids flow in plate heat exchangers (practical cases) are very limited [17]. Pantzali et al. [18] investigated experimentally the efficacy of nanofluids as coolants in a commercial herringbone-type PHE. The experimental data relating to the use of nanofluids in a commercial heat exchanger confirmed that the type of flow inside the heat exchanging apparatus plays an important role in the thermal effectiveness of a nanofluid. Pantzali et al. [19] studied numerically and experimentally the effects of nanofluids on the performance of a miniature plate heat exchanger with modulated surface and reported that, for a given heat duty, the required volumetric flow rate of nanofluid is lower than that of water causing lower pressure drop and resulting in less pumping power. Mare' et al. [20] compared experimentally the thermal performance of two types of commercial nanofluids (oxides of alumina dispersed in water and aqueous suspensions of nanotubes of carbons) in two plate heat exchangers and reported improvement in heat transfer performance. Zamzamian et al. [21] prepared nanofluids of Al_2O_3 and CuO in ethylene glycol separately and evaluated forced convective heat transfer coefficient in turbulent flow using double pipe and plate heat exchangers. Tiwari et al. [22] investigated experimentally the effect of CeO_2 nanofluid as coolants on heat transfer and pressure drop performance for a wide range of concentrations of 0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 3 vol. %, at fluid flow rates 1.0, 2.0, 3.0, 3.5, and 4.0 lpm, and operating temperatures. Tiwari et al. [23] compared experimentally the heat transfer performance of various nanofluids. The heat transfer performance of the plate heat exchanger has been investigated using different nanofluids (CeO_2, Al_2O_3, TiO_2 and SiO_2) for various volume flow rates and wide range of concentrations. Among the nanofluids tested at optimum volume concentration, CeO_2/water nanofluid obtained the highest overall heat transfer coefficient ratio, followed by Al_2O_3/water, TiO_2/water, and SiO_2/water.

Jain et al. [24] considered a 3D turbulent model with a complete cold channel and two halves of the adjacent hot channels. This model uses more realistic hydrodynamic and thermal boundary conditions. The simulations of stirred yoghurt processing in a PHE were performed using CFD calculations. CFD program was used to calculate the shape factor and the tortuosity coefficient which is used to estimate heat transfer coefficients [25,26]. It was found that the use of depth-averaged flow and energy equations reduced the elapsed time of CFD simulations [27]. Comparison was made between results from 2D simulation and 3D model of different corrugation angles and lengths. The 2D simulation results presented a relatively good result of pressure loss and temperature variation with respect to corrugation angle and length. The numerical simulation of the PHE is widely reported [11,25,28–30]. The majority of the previous studies are water based simulation of PHE. It is worth noting that there is no numerical study for nanofluid as a coolant in a simpler approach (two fluid bodies and one plate rather than taking entire PHE like Pantzali et al. [19]).

The objective of the present work is to predict the heat transfer enhancement in case of a PHE using nanofluid as a coolant with a 3-D CFD model which considers more complex and realistic geometries of the fluid distribution regions. Moreover, it can be beneficial to visualize the flow distribution and prediction of performance of PHE using the correctly measured thermo-physical properties without performing experiments. CFD based analysis of PHE to predict the internal flow and temperature field which otherwise is not possible.