International Communications in Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical investigation of laminar thermal-hydraulic performance of Al_2O_3–water nanofluids in offset strip fins channel

Ningbo Zhao, Jialong Yang, Shuying Li *, Qiang Wang

College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Available online xxxx

Keywords:
Nanofluids
Plate–fin heat exchanger
Offset strip fin
Laminar
Heat transfer enhancement

ABSTRACT

Using the single-phase based numerical approach, this paper studies the three-dimensional laminar flow and heat transfer behavior of Al_2O_3–water nanofluids in an offset strip fins channel. Parametric variations are analyzed for explaining the influences of different nanoparticle volume fraction (0%–4%) and Reynolds number (500–1000). The numerical results indicate that both the heat transfer and pressure loss of offset strip fins channel are enhanced significantly with the increases of nanoparticle volume fraction and Reynolds number. At Reynolds number of 1000, the average heat transfer coefficient can be improved by 26.69% when adding 4% volume fraction of Al_2O_3 nanoparticles in the base fluid. Besides, the Nusselt number of Al_2O_3–water nanofluids is higher than that of the base fluid at various Reynolds number only when the volume fraction of Al_2O_3 nanoparticle is more than 2%. Moreover, it is also demonstrated that when the heat transfer rate remains constant, Al_2O_3–water nanofluids with 1% nanoparticle volume fraction has the most obvious advantage due to the reduction of pumping power.

1. Introduction

As one of the most important process equipment for exchanging the heat quantity, plate–fin heat exchangers are applied in many fields of chemical engineering, energy storage and conversion due to its high efficiency and compactness [1]. According to actual needs, various types of working fluids and fin structures can be used in the plate–fin heat exchangers [2]. Offset strip fins is designed to enhance heat transfer by enlarging surface area and regenerating thermal boundary layer in each flow channel [3]. However, this type of fins also can increase the pressure drop within the heat exchanger. In the past few decades, Kays [4], London and Shah [5], Hu and Herold [6], Dong et al. [7], Peng and Ling [8], and Fernández-Seara et al. [9] experimentally studied the effects of different surface geometries on the flow and heat transfer performance of offset strip fins. Based on such experimental data, many empirical correlations have been carried out with various working conditions [10–14]. Recently, with the rapid growth of computational capabilities, some numerical investigations [15–17] have been performed to capture and explain the thermal-hydraulic behaviors of different working fluids in the offset strip fins. Besides, in order to realize the full potential of heat exchangers with offset strip fins, a large number of previous researches were published to optimize the geometric variables of offset strip fins based on different algorithms [18–21]. However, with the rapid increase in heat flux and owing to manufacturing limitation, it is difficult to significantly improve the heat transfer capabilities of offset strip fins by changing geometric variables only. In addition, conventional working fluids including water, ethylene glycol and oil exhibit relative low thermal conductivity. Therefore, there is a need for developing new and innovative technologies to enhance the heat transfer of plate–fin heat exchangers with offset strip fins.

Nanofluids, consisting of the conventional working fluids and different nanometer-sized particles, seem to be a potential replacement of conventional coolants [22]. In recent years, the research on various nanofluids has received great attention due to the superior characteristics of nanofluids [23–28]. Most of the investigations in general indicated that thermo-physical properties of nanofluids could be affected by nanoparticle properties (such as type, volume fraction and size), temperature and base fluid. However, the specific influence of each factor is still not very clear. There are also some inconsistencies in existing literatures, due to the differences in preparation technology, measuring and data analyzing methods [29–31]. All of these make it difficult to reliably model and predict the thermo-physical properties of different nanofluids, which limit the further application of nanofluids. For most of the investigations, the addition of nanoparticle is expected to enhance the heat transfer of base fluid considering the fact that nanofluids have relatively high thermal conductivity [32–35]. However, it is worth pointing out that the suspensions of nanoparticles also can increase the viscosity and decrease the specific heat, which mean that the improvement in thermal conductivity of nanofluids may be counteracted by the negative effects of viscosity and specific heat [36–38]. Hence, a further research for quantifying the effects of nanofluids on the thermal-

* Corresponding author.
E-mail address: lishuyingheu@126.com (S. Li).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.024
0735-1933/© 2016 Published by Elsevier Ltd.

Nomenclature

A_t	Total heat transfer area, m^2
C_p	Specific heat, J/(kg·K)
d	Nanoparticle diameter, nm
D_h	Hydraulic diameter, mm
f	Fanning friction factor
Fh	Fin height, mm
Fs	Fin space, mm
Ft	Fin thickness, mm
G	Mass velocity, kg/(m^2·s)
h	Heat transfer coefficient, W/(m^2·K)
j	Colburn factor
k	Thermal conductivity, W/(m·K)
l	Fin length, mm
L	Channel length, mm
m	Mass flow rate, kg/s
M	Molecular weight, kg/mol
N	Avogadro number
Nu	Nusselt number
$N_{X,\,Y,\,Z}$	Nodes number in X, Y, Z directions
P	Pressure, Pa
PP	Pumping power, W
Pr	Prandtl number
Q	Heat transfer rate, W
Re	Reynolds number
T	Temperature, K
V	Velocity, m/s
V'	Volume flow rate, m^3/s
Greek symbols	
φ	Particle volume concentration, %
ρ	Density, kg/m^3
μ	Viscosity, Pa·s
δ	Cover plate thickness, mm
κ	Boltzmann constant
Subscripts	
bf	Base fluid
in	Inlet
nf	Nanofluids
out	Outlet
p	Nanoparticle
w	Wall

hydraulic performance of various types of heat transfer structure is needed.

Huminic et al. [39] presented a review on the heat transfer enhancement of heat exchangers by using nanofluids as coolant. Through their studies, it was found that the previous researches mainly focus on the plate heat exchangers [40–44], the shell-and-tube heat exchangers [45,46], the compact heat exchangers [47,48] and the double-pipe heat exchangers [49–51]. The studies dealing with the analysis of nanofluids in the plate–fin heat exchangers are still very limited. Javadi et al. [52] proposed a theoretical investigation on the heat transfer and flow behavior of SiO_2, TiO_2 and Al_2O_3 nanofluids with liquid nitrogen as base fluid in the plate–fin heat exchanger. They found that nanofluids have higher heat transfer and pressure loss in comparison with the base fluid. In addition, their study also indicated that Al_2O_3 nanofluids had the highest overall heat transfer coefficient, while the pressure drop of SiO_2 nanofluids was lowest. Khoshvaght-Aliabadi et al. [53] experimental studied the effects of Cu–water nanofluids on the comprehensive performance of various plate–fin channels. As depicted in their investigations, the increase of Cu nanoparticle could significantly enhance the heat exchange capacity of every plate–fin channels, meanwhile the pressure drop increased at the same time. They also found that the vortex generator channel provided the maximum reduction of surface area. On this basis, a comparative analysis for the typical numerical methods (homogeneous, mixture and Eulerian) was performed to further evaluate the laminar forced convective heat transfer of Cu–water nanofluids in the vortex-generator plate–fin channel [54]. All the results showed that the numerical values obtained by mixture method were more close to the experimental data. Besides, Khoshvaght-Aliabadi et al. [55] also experimentally study the heat transfer enhancement of nanofluids in the corrugated wavy plate–fin channel at a constant wall temperature condition.

According to the above analysis, there is no existing numerical study on the thermal-hydraulic analysis of nanofluids forced laminar convection in the offset strip fins channel. Therefore, in the present study, a numerical analysis is investigated to study the laminar heat transfer and flow characteristics of an offset strip fins channel with the most commonly used nanofluids (Al_2O_3–water) as coolant. Then, the variations of heat transfer, flow and comprehensive performance with the volume fraction of Al_2O_3 nanoparticle and the Reynolds number are analyzed in detail.

2. Mathematical model

2.1. Geometric description and computational domain

Fig. 1(a) shows the flow directions of hot and cold working fluids in a typical cross flow plate–fin heat exchanger. The geometrical parameters and specific terminology of offset strip fins with rectangular cross section can be defined in Fig. 1(b). Considering the symmetrical and periodic features of the offset strip fins channel, the three-dimensional structures as described in Fig. 2 are selected as the computational domain to save computational time without compromising accuracy. In the present study, the computational domain includes some segments of offset strip fins, cover plates on top and bottom of the fins, and working fluid. Many previous investigations found that the flow in the offset strip fins channel could be supposed 'fully developed' when taking 4–5 fin periods [15,17]. Therefore, a proper computational domain length (65 mm) consisting of 13 strip rows is selected to accurately simulate the flow and heat transfer characteristics of offset strip fins channel. Table 1 lists the values of geometrical parameters needed for modeling in this work. Besides, Cu is selected as the material of the fins and cover plates.

2.2. Governing equations and boundary conditions

Normally, the numerical simulation of nanofluids flow can be performed using two different methods which are single and two-phase approach [56–59]. Due to the small size of nanoparticle, many recent researches suggested that nanofluids behaved like a single-phase fluid when the nanoparticle fraction was very low [60,61]. Besides, compared to the two-phase based approach, the single-phase based approach is relative simple to implement while the numerical accuracy remains. Therefore, the single-phase based approach is considered to simulate and describe the laminar flow and heat transfer behavior of nanofluids flowing through an offset strip fins channel under constant wall temperature.

In the present study, the following assumptions are considered [62]:

(1) The flow is a three-dimensional steady-state,
(2) Nanofluids is the incompressible and Newtonian fluid,
(3) The velocity is same for the fluid and nanoparticles, and they are in thermal equilibrium,
(4) All the nanoparticles are uniform in shape and size,
(5) The effects of radiation and viscous dissipation are negligible,
(6) The properties of working fluids are constant.

Please cite this article as: N. Zhao, et al., Numerical investigation of laminar thermal-hydraulic performance of Al2O3–water nanofluids in offset strip fins channel, Int. Commun. Heat Mass Transf. (2016), http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.024