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Effect of rotating twisted tape on thermo-hydraulic performances of nanofluids in heat-exchanger systems

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ABSTRACT

Stable TiO_2-H_2O nanofluids are prepared and their stabilities are studied. An experimental set for studying the heat transfer and flow characteristics of nanofluids is established. Heat transfer and flow characteristics of TiO_2-H_2O nanofluids in a circular tube with rotating and static built-in twisted tapes are experimentally investigated and compared. An innovative performance evaluation plot of exergy efficiency is developed and the exergy efficiency of tube with rotating and static built-in twisted tapes filled with nanofluids is analyzed in this paper. The results indicate that the combination of rotating built-in twisted tape and TiO_2-H_2O nanofluids shows an excellent enhancement in heat transfer, which can increase the heat transfer by 101.6% compared with that of in a circular tube. The effects of nanoparticle mass fractions ($\omega =$ 0.1%, 0.3% and 0.5%) and Reynolds numbers (Re = 600–7000) on the heat transfer and flow characteristics of TiO_2-H_2O nanofluids are discussed. It is found that there is a critical Reynolds number (Re = 4500) for the maximum value of relative heat transfer enhancement ratio. The comprehensive performance of the experimental system is analyzed. It can be found that the comprehensive performance index of the experimental system firstly increases and then reduces with Reynolds number, and it can reach 1.519 at best. However, for the performance evaluation of exergy efficiency, the coupling of rotating twisted tape and nanofluids deteriorates the exergy efficiency. Also, it can be found that the exergy efficiency of the circular tube with twisted tape is greater than that of circular tube under the same pumping power and pressure drop, but it shows deterioration under the same mass flow rate.

1. Introduction

With the development of science and technology, the thermal load of the heat exchanger gradually increases. Also, the traditional structure of heat exchanger and working fluid cannot meet the requirement of heat exchanger in a limited heat exchange area. Hence, the heat transfer enhancement technology needs to be improved.

Improving the thermal conductivity of the working medium is one way to enhance the heat transfer. Nanofluids, as a new type of high efficient energy transport medium, have great application values in many fields. Huang et al. [1] added the Au@TiO_2 core-shell nanoparticles into the clean water. It was found that the core-shell structure can improve the photo-thermal conversion efficiency and the evaporation of seawater. Many scholars applied nanofluids to solar photothermal conversion. Chen et al. [2] studied the solar absorption performances of different core-shell nanoparticles. It was found that the core-shell ratios and mixing ratios of nanofluids are two key factors for improving the absorption of solar energy efficiency. Wang et al. [3] applied CNT nanofluids with different concentrations to direct solar steam generation and found that the evaporation efficiency can reach 45% under a solar illumination power of 10 Sun when the concentration of CNT nanofluids is 0.001904 vol%. Liu et al. [4,5] proposed the principle of photonic nanofluids and studied the solar-thermal conversion efficiencies of different types of nanospheres.

Xuan et al. [6] presented a procedure for preparing nanofluids and proposed a theoretical model to calculate the heat transfer performance of nanofluids. Oztop et al. [7] researched the natural convection of nanofluids in rectangular enclosures by numerical simulation. It was found that the heat transfer enhancement of low aspect ratio is much better than that of high aspect ratio. Heris et al. [8] investigated the heat transfer characteristic of Al_2O_3-water nanofluids in a circular tube and found that the heat transfer coefficient increases with nanoparticle concentration and Peclet number. Li et al. [9,10] measured the thermophysical properties of nanofluids and found that metal nanoparticles can increase the thermal conductivity and viscosity of the fluid. Fu et al. [11] analyzed the viscosity of Fe_3O_4 ethylene glycol-water nanofluids

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Nomenclature

A_c	cross-sectional area, m^2
b_i	intercept of straight line
c_1, c_2	coefficient in equation
c_p	heat capacity of nanofluids, J kg^{-1} K^{-1}
c_{pb}	heat capacity of base fluid, J kg^{-1} K^{-1}
c_{pp}	heat capacity of nanoparticles, J kg^{-1} K^{-1}
$C_{Q,P}$	the ratio of heat transfer rate between enhanced and reference surfaces under identical pumping power
$C_{Q,V}$	the ratio of heat transfer rate between enhanced and reference surfaces over the ratio of friction factor between enhanced and reference surfaces under identical flow rate
$C_{Q,\triangle p}$	the ratio of heat transfer rate between enhanced and reference surfaces under identical pressure drop
d	equivalent diameter, m
E	relative heat transfer enhancement ratio
E_1	exergy loss, J
E_Q	heat transfer exergy, J
f	frictional resistance coefficient
h	convective heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity of nanofluids, W m^{-1} K^{-1}
k_i	slope of straight line
l	length of tube, m
Nu	Nusselt number
p	pressure, Pa
P	pumping power, W
$\Delta P/\Delta l$	pressure drop per unit length, Pa m^{-1}
Q	heat absorbed by nanofluids, J
$\dot{q}_l$	heat flux density, W m^{-1}
q_m	mass flow rate, kg s^{-1}
r	outside-radius of tube, m
r'	inner-radius of tube, m
Re	Reynolds number
T_0	temperature of ambient, K
$T(x)$	temperature of fluid, K
$Tw(x)$	temperature of wall, K
T_{out}	outlet temperature of tube, K
T_{in}	inlet temperature of tube, K
T_f	average temperature of nanofluids, K
T_w^*	outside surface temperature of tube, K
$T_w(i)$	temperature of T-type thermocouples, K
T_w	inside surface temperature of tube, K
u	velocity of nanofluids, m s^{-1}

Greek symbols

ω	mass fraction, %
ρ	density of nanofluids, kg m^{-3}
ρ_{pb}	density of base fluid, kg m^{-3}
ρ_{pp}	density of nanoparticle, kg m^{-3}
λ	thermal conductivity of tube, W m^{-1} K^{-1}
ζ	comprehensive performance index

Subscripts

m_1, m_2	exponent in equation
in	import
out	outport
0	circular tube
e	enhanced tube
p	nanofluids
pb	base fluid
pp	nanoparticle
P	under the same pumping power
Re	under the same Reynolds number
V	under the same mass flow rate
Δp	under the same pressure drop
w	wall

considering the effect of particle disaggregation. It was found that nanofluids behaved as Newtonian fluid when the nanoparticles were evenly dispersed in the base fluid. Hong et al. [12] investigated the dynamic concentration of nanofluids in laminar low and proposed an empirical equation to calculate the concentration of nanoparticles in a pipe. It was found that the concentration of nanofluids decreases from the wall to centre in the pipe and it has a maximum value near the pipe wall. Sheremet et al. [13] studied the effects of boundary temperature oscillating frequency on the natural convection of a square cavity filled with alumina-water nanofluids and found that Nusselt number increases with the oscillating frequency of boundary temperature. In addition, Sheremet et al. [14] numerically investigated the natural convection of a triangular cavity filled with micropolar fluid. It was found that the average Nusselt number and fluid flow rate all decrease with the vortex viscosity parameter. Also, Sheremet et al. [15] analyzed the natural convection of Cu-water nanofluids in a cavity and found that heat transfer decreases with Hartmann number. Sheikholeslami et al. [16] researched the natural convection of magnetohydrodynamic nanofluids and found that Nusselt number increases with Darcy number, supplied voltage and Rayleigh number. Sheikholeslami et al. [17] also studied the effect of uniform magnetic field on natural convection of nanofluids in a porous media with sinusoidal hot cylinder and found that temperature gradient decreases with Hartmann number. In addition, Sheikholeslami et al. [18] investigated the effect of nanoparticle shape on heat transfer by means of CVFEM. It was found that Platelet shaped nanoparticles has the highest heat transfer performance.

Rudyak et al. [19] conducted an experiment on aluminum lithium-liquid argon nanofluids with different nanoparticle sizes. It was found that the viscosity of nanofluids increases with the decreasing nanoparticle size. Pendyala et al. [20] and Ilyas et al. [21] applied nanofluids to transformers and obtained that adding CNTs and graphite nanoparticles with different sizes can significantly improve the thermal conductivity of fluid. Kouloulias et al. [22] studied the precipitation of Al_2O_3-H_2O nanofluids and analyzed the natural convection heat transfer characteristics of nanofluids. It was found that Nusselt number decreases with the nanoparticle concentration. Qi et al. [23] conducted an experiment on different rotation angles of enclosure filled with TiO_2-water nanofluids. It was found that the enclosure with rotation angle $\alpha = 0°$ has the highest Nusselt number. Qi et al. [24,25] studied the effects of nanoparticle radius on the natural convection heat transfer by numerical simulation and found that Nusselt number decreases with the increasing nanoparticle radius. Also, Qi et al. [26] investigated the natural convection heat transfer of enclosures with different aspect ratios and found that Nusselt number increases with the aspect ratio of the enclosure. Qi et al. [27] also researched the boiling heat transfer of TiO_2-water nanofluids. The results showed that TiO_2-water nanofluids enhance the heat transfer coefficient by 77.7% at best compared with water. In addition, Qi et al. [28] introduced nanofluids as a working medium to cool the CPU. It was found that Al_2O_3-H_2O and TiO_2-H_2O nanofluids can reduce the temperature of CPU by 23.2% and 14.9% at best compared with based fluid (water) respectively.

Above studies show that nanofluids with a certain mass fraction can play a role in enhancing heat transfer. In order to improve the heat transfer of heat exchanger, enhanced tubes are used instead of smooth tube. In addition, researchers have done some work on the heat transfer