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Original Research Paper

Numerical study of nanofluid flow in flat tubes fitted with multiple twisted tapes

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ABSTRACT

In this paper, while numerically simulating the Al_2O_3–water nanofluid flow in flat tubes fitted with twisted tapes, the effects of three different Heat Transfer Enhancement (HTE) methods are also separately evaluated and compared. These three HTE mechanisms include the use of nanofluid instead of the base fluid, use of flat tubes instead of circular tubes and the use of twisted tapes inside the tubes. The obtained results indicate that although all the three mentioned mechanisms improve the heat transfer within the tubes, the HTE due to the use of twisted tapes is greater than that caused by the other two mechanisms. After discovering that the simultaneous use of the three mentioned mechanisms can considerably increase the amount of heat transfer, three different arrangements of the twisted tapes in the nanofluid-containing flat tubes are also evaluated and compared. These three arrangements include the use of one twisted tape, use of two twisted tapes in the same direction and the use of two twisted tapes in different directions. The obtained results indicate that the use of two twisted tapes in different directions leads to the highest amounts of heat transfer and pressure drop in flat tubes.

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1. Introduction

Heat Transfer Enhancement (HTE) in the tubes used in various industrial applications and consequently reducing the volume of industrial equipment is a subject that has been investigated by engineers and researchers for many years. In general, the heat transfer enhancing methods can be divided into active and passive approaches; which the passive method, due to its ease of use and lower cost, has greatly attracted the attention of the researchers and engineers. An important and useful way of passively enhancing the amount of heat transfer in tubes is the use of a nanofluid instead of base fluid. A nanofluid refers to a compound in which solid, and mostly metallic, particles at nano sizes (usually less than 100 nm) are added to an ordinary fluid and help increase the value of the mixture conductivity and thus improve the amount of heat transfer in that fluid. Due to a considerable enhancement of heat transfer and a negligible pressure drop achieved by nanofluids, relative to base fluids, the use of nanofluids has become very commonplace in recent years [1–7].

Another technique for passively enhancing the heat transfer in tubes is using the swirl flow devices such as Twisted Tapes (TTs) which produce secondary recirculation on the axial flow leading to an increase of tangential and radial turbulent fluctuation. This allows a greater mixing of fluid inside tubes. In recent years, the HTE by twisted tape inserts has been considered by several researchers [8–17]. Eiamsa-ard et al. [11] investigated the heat transfer and pressure loss behaviors in a double pipe heat exchanger fitted with regularly-spaced twisted tape elements at several space ratios. Effect of the combined conical-ring turbulator and twisted tape on the heat transfer, friction factor and thermal performance factor characteristics were also studied by Promvonge and Eiamsa-ard [12]. The effects of twist ratio and rotation angle of TTs on the HTE are very important. In recent years several researchers have investigated the effects of rotation angle and twist ratio on the TTs performance [14–17]. Mengna et al. [14] used a converging–diverging tube with evenly spaced twisted tape to investigate the pressure drop and compound heat transfer characteristics experimentally. By varying twist ratio and rotation angle various swirl patterns were generated. It was shown that the heat transfer and pressure drop increase with an increase in twist angle. Wang et al. [15] analyzed the numerical modeling for the optimization of regularly spaced short-length twisted tape in a circular tube. The parameters are given by the spacing between two twisted tapes, twist ratio and twist angle. It was found that the mean heat transfer and flow resistance increase with an increase in twist angle.

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Nomenclature

a	acceleration (m s^{-2})
C_p	specific heat (J kg^{-1} K^{-1})
C	constant in Eq. (14)
D_h	hydraulic diameter of tubes (m)
d_p	diameter of nanoparticles (m)
f	skin friction coefficient
g	gravitational acceleration (m s^{-2})
h	local heat transfer coefficient (W m^{-2} K^{-1})
H	height of flat tube (m)
k	thermal conductivity (W m^{-1} K^{-1})
k_B	Boltzmann constant (=1.3807 × 10^{-23} J K^{-1})
L	length of tubes (m)
Nu	Nusselt number ($= hD_h/k$)
P	pressure (Pa)
Pr	Prandtl number ($= \alpha_m/v_m$)
q''	heat flux (W m^{-2})
Re	Reynolds number ($= VD_h/v_m$)
T	temperature (K)
V	velocity (m s^{-1})
W	width of flat tube (m)
Z	axial coordinate in the tubes

Greek symbols

α	thermal diffusivity ($= k/\rho C_p$)
β	volumetric expansion coefficient (K^{-1})
δ	distance between particles (m)
ϕ	nanoparticles volume fraction
λ_f	mean free path of water molecular (m)
μ	dynamic viscosity (N s m^{-2})
v	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
τ_w	wall shear stress

Subscripts

BF	base fluid
P	plain tube
dr	drift
f	fluid
i	inlet conditions
k	indices
m	mixture
p	nanoparticle phase
w	wall

Abbreviations

STT	Single Twisted Tape
D-Co-TT	Dual Co-Twisted Tapes
D-C-TT	Dual Counter Twisted Tapes
HTE	Heat Transfer Enhancement

One of the other methods to enhance the heat transfer in tubes is the use of flat tubes instead of circular ones. Compared to circular tubes, the flat tubes have higher surface area to cross sectional area ratio, which can be used to increase the compactness and enhance the heat transfer of the heat exchangers. In recent years, a number of researchers have investigated the use of flat tubes instead of circular tubes [18–22].

So far, no analytical, numerical or experimental research on combining the three HTE mechanisms has been carried out; although different combinations of two of these three mechanisms have been investigated. Eiamsa-ard and Kiatkittipong [23] studied the effect of the simultaneous use of twisted tapes and nanofluid on Nusselt number and friction factor. In their experimental and numerical investigations, they evaluated different arrangements of twisted tapes in circular tubes. Ibrahim [24] experimentally studied the simultaneous use of twisted tapes and flat tubes in turbulent flow. Razi et al. [25] experimentally investigated the concurrent use of flat tubes and nanofluid. In their research, the flow regime was laminar and the nanofluid used was CuO–oil. Safikhani and Abbassi [26] numerically studied the effect of using flat tubes and nanofluid together on the flow field of nanofluid. In another research, Safikhani et al. [27] applied multi-objective optimization to optimize the simultaneous use of nanofluids and flat tubes.

Based on our information, no research has been conducted so far on the simultaneous use of three HTE mechanisms: nanofluid, twisted tapes and flat tubes. In this paper, the effect of using the three mentioned HTE mechanisms together on the thermal and hydraulic behaviors of flow are numerically explored. Different arrangements of twisted tapes and flat tubes will be analyzed.

2. Mathematical modeling

2.1. Geometry

The geometries explored in this paper are different combinations of circular tubes, flat tubes and twisted tapes. Fig. 1 shows the schematics of the geometries investigated in this paper. The specifications of the tubes illustrated in this figure have been listed in Table 1. It should be mentioned that the flat tubes have a circumference equal to that of circular tubes [18,19,21,22]. As is indicated in Fig. 1, three different arrangements of twisted tapes will be evaluated in this paper, which include one twisted tape, two twisted tapes in the same direction and two twisted tapes in different directions.

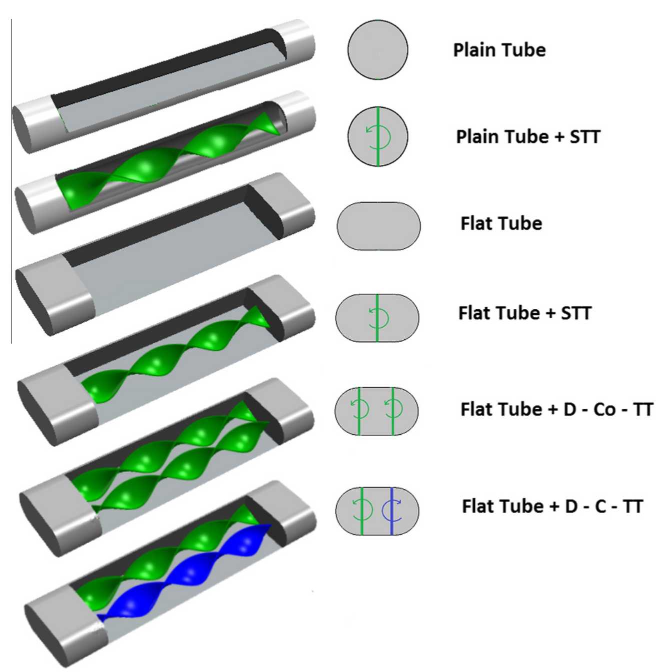

Fig. 1. The details of geometries which will be investigated in this paper.

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