International Communications in Heat and Mass Transfer 71 (2016) 234–244

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Heat transfer and nanofluid flow characteristics through a circular tube fitted with helical tape inserts

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ARTICLE INFO

Available online 17 December 2015

Keywords:
Heat transfer enhancement
Helical tape insert
Nanofluid
Forced convection

ABSTRACT

Numerical investigations are performed using finite volume method to study laminar convective heat transfer and nanofluids flows through a circular tube fitted with helical tape insert. The wall of tube was subjected to a uniform heat flux boundary condition. The continuity, momentum and energy equations are discretized and the SIMPLE algorithm scheme is applied to link the pressure and velocity fields inside the domain for plain tube. Four different twist ratios of 1.95–4.89, two different types of nanoparticles, Al_2O_3 and SiO_2 with different nanoparticle shapes of spherical, cylindrical and platelets, and 0.5–2.0% volume fraction in base fluid (water) and nanoparticle diameter in the range of 20–50 nm were used to identify their effect on the heat transfer and fluid flow characteristics through a circular tube fitted with helical tape insert geometries. The results indicate that the four types of nanofluid achieved higher Nusselt number than pure water. Nanofluid with Al_2O_3 particle achieved the highest Nusselt number. For all the cases studied, the Nusselt number increased with the increase of Reynolds number and with the decrease of twist ratio of helical tape insert.

1. Introduction

Heat exchanger application in industrial and engineering purposes is quite popular. The need for analysis of heat transfer rate, efficiency and pressure drop with respect to long-term performance and economic aspects of the equipment, led to a complicated design procedure. Higher pumping cost which is caused by the rise of pressure drop is the price that should be paid along with the improvement in the heat transfer rate by insert technologies and this is the reason to implement optimization on any methods or augmentation device which is about to be utilized in the heat exchanger between the benefits of higher heat transfer rate and higher frictional losses [1].

In general, methods of heat transfer enhancement are classified into three broad categories which are explained herein under.

1.1. Active method

In this method, the enhancement of heat transfer is caused by some external power input. Reciprocating plungers, use of magnetic field, surface vibration, fluid vibration, electrostatic fields, suction or injection and jet impingement are some examples which bring enhancement with some external power [2].

1.2. Passive method

In passive methods, surface and geometrical modifications which are applied to the flow passage and implementation of inserts or additional devices are used to augment the heat transfer rate. Inserts, swirl flow devices, treated surface, rough surface, extended surfaces, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids are some of the examples for passive method [3].

1.3. Compound method

Compound method is the combination of any two methods of augmentation which is implemented at the same time like a rough surface with twisted tape swirl flow device or fluid vibration [4]. This literature review is focused on the passive method pipe heat exchanger. One of the applicable ways to enhance heat transfer rate in the convective heat transfer is to increase the effective surface area and residence time of the heat transfer fluids and it's the main principle of passive methods to generate the swirl and disturb the boundary layer to increase the effective surface area, residence time and the heat transfer coefficient. There are several passive methods to enhance the heat transfer performance but in this article the most popular and related ones are mentioned:

- Displaced enhancement devices: This insert method is applied to perform forced convection. It displaces the fluid from the heated area to the cool area or from the bulk fluid in the middle of the duct with the fluid at the surface and indirectly improves the energy transfer.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.12.010

Nomenclature

A	Cross-Section Area, m^2
A	Component of Vector
C_P	Specific Heat, kJ/kg K
D_h	Hydraulic Diameter
d_p	Nanoparticle Diameter, m
d_f	Equivalent Diameter of a Base Fluid Molecule
F	Darcy Friction Factor
h	Average Heat Transfer Coefficient, W/m^2 K
K	Thermal Conductivity, W/m K
M	Molecular Weight of Base Fluid
N	Avogadro Number, mol^{-1}
N	Direction Normal to the Surface Element
Nu	Nusselt Number
P	Pressure, N/m^2
ΔP	Pressure Drop
PEC	Performance Evaluation Criteria Index
q''	Heat Flux Rate Per Unit Channel Length, W/m^2
Re	Reynolds Number
T	Temperature, K
T_0	Reference Temperature, 293 K
T_{in}	Inlet Temperature, K
U	Flow Velocity Component, m/s
$\bar{u}$	Velocity Correction, m/s
u^*	Initial Guessed Velocity, m/s

Greek symbols

ρ	Density of Fluid, kg/m^3
μ	Dynamic Viscosity, $N.s/m^2$
$\varnothing$	Nanoparticle Volume Fractions
β	Fraction of the liquid volume that travels with a particle material

Subscripts

0	Plain tube
eff	Effective
f	Base Fluid
nf	Nanofluid
P	Particle
W	Wall
In	Inlet
M	Mean
i, j	Components
B	Bulk

- Swirl flow devices: The axial flow's secondary recirculation and production of the superimposed swirl flow inside a channel are the main purpose of swirl flow devices and they include helical strip, cored screw and twisted tape inserts and they are both applicable in single and two phase flow heat exchangers.
- Coiled tubes: Coiled tubes are more conventional in smaller heat exchangers. Secondary flows are produced to augment the heat transfer coefficient.
- Additives for liquids: Addition of solid particles, solvable additives and bubbles in single phase fluids reduces the surface tension and increases the heat transfer.

Besides the theoretical and experimental approaches, the numerical simulation has established itself as the most practical and viable alternative to study and understand different engineering problems. However, numerical simulations would not be possible without the recent developments and improvements in computers in terms of memory size and computing speed [5].

Conventional fluids, such as water, engine oil and ethylene glycol are normally used as heat transfer fluids. Although various techniques are applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Improving the thermal conductivity is the key idea to improve the heat transfer characteristics of conventional fluids. Since a solid metal has a larger thermal conductivity than a base fluid, suspending metallic solid fine particles into the base fluid is expected to improve the thermal conductivity of that fluid. The enhancement of thermal conductivity of conventional fluids by the suspension of solid particles, such as millimeter- or micrometer-sized particles, has been well known for more than 100 years [6].

The metal strips which are twisted inside the flow with necessary dimensions and shape are called twisted tape inserts. Since twisted tape inserts enhanced the heat transfer rates very significantly with low friction factor increase and pumping power requirement they are quite popular in heat exchangers [2–4,7–28].

The main objective of inserting twisted tapes in a channel or tube is to add some swirl flow to the bulk flow and disturb the boundary layer which leads to enhance the convective heat transfer due to the change of surface geometry repeatedly. These tapes can also cause the boundary layer to be thinner and improve the heat transfer coefficient by changing the geometry of the twisted tape. The classification of twisted tapes is based on the most commonly used ones:

- Typical twisted tape: which has the length equal to the length of tube they used inside [8,10,12,14,18].
- Varying length, alternate-axes and pitches twisted tape: which has different length compared to the tube length such as 1/2 of tube, 1/4 of tube and 3/4 of tube length [11,17,21]; or different pitches and spaced tapes which are assembled to each other along the tube [23,25,26].
- Multiple twisted tapes: which is the implementation of more than one twisted tape which is coupled with each other along the tube length [12,26].
- Twisted tapes with rod and varying spacer: which used rod and spacer on twisted tapes to help enhance the heat transfer [12,17,20,29].
- Twisted tape with attached fins and baffles: which used attached baffles on twisted tape with some intervals to achieve more enhancement [12,22,23].
- Twisted tapes with slots, holes and cuts: which used specified slots and holes to amplify the turbulence and create more heat transfer enhancement [24–27,30,31].
- Helical left–right twisted tape with screw: which arranged left rotating and right rotating helical inserts consequently and sometimes with the addition of screw element to improve the heat transfer [20,21,28,32].
- Tapes with different surface modifications: which used the insulation materials or surface dimple materials to avoid the fin effect [16,30,33,34].

The following literatures listed in Table 1 have studied the effect of twisted tape inserts on the heat transfer rate with various shapes, angles and inserting locations.

1.4. Experimental work

Several experimental works have been carried out to inspect the effects of different twisted tape inserts including regular twisted tapes, regularly spaced twisted tapes, varying length twisted tapes, tapes with different cut shapes tapes with baffles and tapes with different surface modifications. The effect of regular twist tapes on the enhancement efficiency of a solar water heater was studied by Kumar and Parsad [8]. It