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Research Paper

Thermal performance enhancement in a heat exchanging tube via a four-lobe swirl generator: An experimental and numerical approach

Mohammad Jafari [a,b,*], Mousa Farhadi [b], Kourosh Sedighi [b]

[a] Faculty of Mechanical Engineering, Lorestan University, P.O. Box 465, Khoramabad, Iran
[b] Faculty of Mechanical Engineering, Babol University of Technology, P.O. Box 484, Babol, Iran

HIGHLIGHTS

- Effects of a new swirl generator on the thermal performance of a tube are studied.
- The swirl generator is a helically twisted tube with a four-lobe cross section.
- Four swirl generator with different twist angles have been used in the experiments.
- The results prove that the swirl generator presents a worthy thermal performance.
- Large Eddy Simulation is performed using pisoFoam solver in OpenFOAM CFD-code.

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ABSTRACT

The effects of a new swirl generator on thermal and flow fields in a heat exchanging tube are investigated experimentally and numerically. The swirl generator is a tube with a four-lobe cross section helically twisted with four different angles (θ = 90, 180, 270 and 360). In the experiments, the heat transfer rate and pressure drop are measured as the main outcomes to extract the role of swirl generator on the thermal performance of the test tube. The experimental study is performed for different Reynolds numbers in the range of 6000–30,000. The experimental results reveal that the swirl generator makes an enhancement up to 87% in the heat transfer rate and an increase up to 48% in the pressure drop. The experimental results are supported by Large Eddy Simulation (LES) of the generated swirling flow. The study applies open-source CFD code named OpenFOAM. It is proved that the swirl generator creates an intense swirling flow at the tube inlet. The numerical results show that the high tangential and axial velocity components, near the tube wall, are the main reason of the better convection rate for the tube equipped with the swirl generator.

1. Introduction

The energy crisis is a global concern in the recent decades. Heat recovery is a vital step in addressing energy crisis challenge. Using heat exchangers with new creative techniques can find a way to profit from heat recycling. Heat exchangers are widely used in numerous engineering areas, such as the chemical plants, power generation, and air conditioning unites for building and vehicles [1]. In recent years, different techniques to enhance performance of heat exchangers have been applied [2–5].

For many different industries, heat transfer enhancement by using a specific geometric characteristic or a special inlet flow condition, without applying active forcing, is a beneficial choice. The passive heat transfer enhancement by affecting the flow characteristics has received more attention in current years [6–10]. From this range of passive methods twisted tapes, spiral grooved tubes, and swirl flow generators are of general interest to enhance the heat transfer rate. In these conditions, the secondary flows and also the existence of self-sustained instabilities, which can develop due to turbulent flow oscillations, lead to increase in the convection rate.

A swirl flow is a fluid flow containing a noticeable tangential velocity component. The tangential velocity component imparts on the flow field and causes helical twists in the streamlines. In turbulent flows, swirling flows generally lead to an increase in fluctuations of the velocity components. Based on the known

* Corresponding author at: Faculty of Mechanical Engineering, Babol University of Technology, P.O. Box 484, Babol, Iran.
E-mail addresses: m.jafari177@gmail.com (M. Jafari), mfarhadi@nit.ac.ir (M. Farhadi), ksedighi@nit.ac.ir (K. Sedighi).

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Nomenclature

A	surface area (m^2)
C_s	Smagorinsky constant
D	diameter of the test tube (m)
f	friction factor
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
l	dimensionless length of swirl generator ($= l/D$)
L	tube length (m)
$\dot{m}$	mass flow rate (m^3/s)
Nu	Nusselt number
P	perimeter (m)
p	pressure (kg/m s^2)
Pr	Prandtl number ($\mu \cdot C_p/k$)
Q	heat transfer (W)
q''	wall heat flux (W/m^2)
R	radius of the test tube (m)
r	radial position (radius) (m)
Re	Reynolds number ($= u_{in}D/\nu$)
S_{ij}	strain rate tensor
T	temperature (K)
υ	tangential velocity (m/s)
x	axial distance from the tube inlet

Greek letters

ρ	density (kg/m^3)
ν	kinetic viscosity
κ	Von-Karman constant (m^2/s)
η	thermal performance criterion
Δ	LES filter width
θ	twist angle (°)
φ	angular position (*rad*)
ψ	LES filter function
τ	wall shear stress(N/m^2)
τ_{ij}	Reynolds stress tensor
ε	tube roughness (m)

Sub/Superscript

ave	average
b	bulk temperature
e	electrical
f	fluid
in	inlet
max	maximum
out	outlet
p	plain tube
ref	reference
SG	swirl generator
FL	four lobe
w	wall
<>	local-averaged
$(\bar{\ })$	Filtered variable. Time-averaged

Abbreviation

CFD	Computational Fluid Dynamics
LES	Large Eddy Simulation
SGS	Sub-Grid Scale

characteristics of swirling flow such as intense secondary flows, thinning of the thermal boundary layer, and mixing of the core and near wall fluids, swirl flows can promote higher heat transfer rate in single phase flows as well as multiphase flows. Swirl generators, belonging to the most applicable group of passive techniques, are widely used in heat exchangers. Twisted tape, twisted duct, screw inserts, propeller vanes and rotating fans are the most common devices used in a wide range of applications. The structure of swirling flow and consequent axial and tangential velocity components are heavily dependent on methods and devices used for generating swirl flows [11].

Several researches presented novel types of swirl flow generators to enhance the thermal performance and to reduce the pressure drop in heat exchanger tubes [1,5]. Propeller-type swirl generators such as vanes, screw inserts and twisted blades, tangential injectors, honeycomb swirl inducers, twisted-tape inserts and also spiral wires or blades placed at the pipe inlet are some of most well-known swirl generators which have been extensively used to induce a decaying swirling flow in circular straight tubes.

Patil and Babu [12] experimentally investigated the effects of twisted tapes and screw tapes on the pressure drop and heat transfer in a heat exchanger. They reported that using these full-length twisted tapes and screw tapes leads to increase of the Nusselt number, respectively about 2.5 and 5 times. Also, the value of friction factor for the twisted tape and screw tape inserts reported to be about 8 and 14 times, respectively, bigger than the friction factor of the plain duct. As it is sensible, equipping the plain tubes with inserted devices results in higher convection performance compared with plain tubes. As a negative point for this type of devices, it should be mentioned that generally they cause higher pressure drops by a factor of three to five. Kurtbas et al. [13] carried out a study on the effects of swirling flow on the rate of entropy generation and exergy loss in a convectional tube. They used a new propeller-type turbulator in their experiments. Their results showed that the convection rate of the equipped tube were bigger than that of a plain tube. The turbulators also presented higher exergy losses. Sarac and Bali [14] presented results of an experimental study on the details of convection rate and pressure drop of a tube equipped with a swirling flow generator. They reported an increase in heat transfer rate from 18 to 163% for the equipped tubed in comparison with the smooth tube. In an experimental study performed for a turbulent air flow in a pipe with a sudden expansion under a constant heat flux, Zohir et al. [15] investigated the effects of a propeller-type swirl generator or a spiral spring on the heat transfer and pressure drop. Their results showed that the rate of heat transfer increases by a factor of 1.69 and 1.37, respectively, using propeller inserts and spring inserts, while by using these devices the pressure drop increases by a factor of 3 and 1.5, respectively. Gorman et al. [16] made an investigation on the effects of a rotating fan on the heat transfer and flow structures in a circular pipe. Their results showed that the swirl component gives rise to a noteworthy heat transfer enhancement from a factor of two to fifty percent.

From the aforementioned researches and a lot of other studies, it has been clarified that implanted swirl generators in heat exchanging tubes presents a better convection rate, though, this enhancement in heat transfer comes with an increase in the penalty pressure drop. Assuming the pressure drop as a key parameter for the pumping power and subsequent cost, there are still a lot of steps to take for finding new devices or techniques to enhance heat transfer with an acceptable change of pressure drop.The applied swirl generator is a twisted tube with a four-lobe cross section.