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An experimental study on the effects of a new swirl generator on thermal performance of a circular tube

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ABSTRACT

This study experimentally focuses on the effects of a swirl generator on the thermal performance of a heat exchanging tube. The applied swirl generator is a helically twisted tube with a five-lobe cross section. As the main outcome, the thermal performance of the test tube equipped with the swirl generator are evaluated using the heat transfer rate in the form of Nusselt number and pressure drop in the form of friction factor. Water is used as the working fluid in the experiments performed for different Reynolds numbers from 6000 to 30,000. The different values of twist-angle ($90 \le \theta \le 360$) and length ($2 \le l \le 4$) are investigated as the main geometrical parameters of the swirl generator. The results show that the swirl generator offers an enhancement up to 85% in the Nusselt number and an increase up to 52% in the friction factor. Therefore, the swirl generator presents a thermal performance up to 1.65. This study presents some correlations to predict the Nusselt number and the friction factor of the test tube equipped with the swirl generator.

1. Introduction

Heat exchangers are widely used in numerous industrial and engineering areas, such as the chemical plants, power generation, and air conditioning unites for building and vehicles [1]. Heat exchangers with new creative techniques can help with heat recovery, which is a vital step in addressing energy crisis.

In the last decade, different techniques to enhance convection rate of heat exchanging tubes have been applied [2–5]. Generally, these techniques are classified in three categories. The first class is passive methods such as use of extended surfaces, and fluid additives. The second class is named active methods which normally apply additional forces. The electric field, fluid stirring, vibration of surfaces and fluids, and jet impingement are common examples of active techniques. Finally, those techniques that apply two or more different active or passive methods can be classified as third class called compound methods.

The passive heat transfer enhancement has received more attention in recent years [2]. Passive methods such as twisted tapes, spiral grooved tubes, and swirl flow generators are of general interest to enhance the heat transfer rate. For many different industries, heat transfer enhancement by using a special inlet flow condition, without applying active forcing, is of interest. In these devices, the secondary flows and the existence of self-sustained instabilities, due to turbulent flow oscillations, lead to an increase in the convection rate.

A swirl flow is a fluid flow containing a noticeable tangential velocity component. Considering that swirl flows can provide long residence times and notable fluid mixing, they are broadly attractive for many industrial applications such as fluid mixing, separation, pollution and emission control, combustion, turbomachinery, cyclone separators and etc. In turbulent flows, swirling flows generally lead to an increase in fluctuations of the velocity components. Furthermore, intense mixing between the mainstream and flow near the wall, decrease in the thermal boundary layer thickness, and tangential velocity component are important features of swirling flows. Therefore, the swirling flows can potentially improve thermal performance of heat exchangers [6–10]. Based on the mentioned characteristics of swirling flows, they 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 used in heat exchangers.

As a pioneer study of swirling flows, Kreith and Sonjue [11] performed a theoretical study on a swirling flow generated by a tape-insert. They showed that the Reynolds number directly effects on the decay rate of swirling flow. They mentioned that the increase in the Reynolds number leads to reduction of the decay rate. Kitoh [12] experimentally investigated the physical details of a specific type of swirl flows which is named "free-vortex". It was revealed that the swirl intensity decays exponentially along the tube. Also, the decay coefficient is not constant and depends on the swirl intensity. The experimental findings reported

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Nomenclature

A	surface area (m^2)
D	diameter of the test tube (m)
f	friction factor
h	heat transfer coefficient ($W/m^2 \cdot K$)
k	thermal conductivity ($W/m \cdot K$)
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 ($kg/m \cdot s^2$)
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)
Re	Reynolds number ($= u_{in}D/\upsilon$)
T	temperature (K)

Greek letters

ρ	density (kg/m^3)
υ	kinetic viscosity
η	thermal performance criterion
θ	twist angle
ε	tube roughness (m)

Sub/superscript

ave	average
b	bulk temperature
conv	convective
e	electrical
f	fluid
FL	five-lobe
in	inlet
out	outlet
p	plain tube
SG	swirl generator
w	wall
< >	local-averaged

by Steenberg and Voskamp [13] confirmed that swirling flow exponentially decays in a circular tube and the decay rate decreases by increase of the inlet velocity.

Several researches presented novel types of swirl flow generators to enhance the thermal performance in heat exchanging tubes [14–17]. 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 well-studied swirl generators [1,2]. In an experimental study, Kurtbas et al. [14] investigated the effects of a conical swirl injector on the pressure drop and convection rate in a tube. The results showed that the enhancement rate of heat transfer decreases as the Reynolds number increases. In another experimental research, Khalil et al. [15] investigated the characteristics of flow and thermal fields of turbulent air flow through a sudden expansion pipe at presence of a swirling flow generator. Their results indicated that inserting swirl generators at a sudden expansion pipe increased the rate of heat transfer about 40%. They also proposed some correlations for the friction factor and Nusselt number for the cited conditions.

In an experimental study performed for a turbulent air flow in a pipe with a sudden expansion under a constant heat flux, Zohir and Aziz [16] examined the results of using a propeller and a spring on the flow and thermal fields. 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. [17] investigated the effects of a rotating fan on the heat transfer and flow structures in a circular pipe. They showed that the swirl component gives rise to a noteworthy heat transfer enhancement from a factor of two to 50%.

The aforementioned studies show that implanted swirl generators in heat exchanging tubes lead to a better convection rate. Since the pressure drop is a key parameter for the pumping power and subsequent cost, there are still several steps to be taken to find new devices or techniques to enhance the convection rate with a satisfying change in pressure drop.

The swirl generator investigated in this study is a twisted tube with a five-lobe cross section. To the best of our knowledge, studies addressing the use of this type of swirl injector in the heat exchangers are rare in the literature. The current study investigates the effects of a decaying swirling flow, on convection rate and pressure drop in a test tube under constant heat flux. A large set of experiments has been performed to evaluate the rate of heat transfer and the value of pressure drop along the test tube when Reynolds number varies from 6000 to 30,000. The length ($2 \leq l \leq 4$) and twist angle ($90 \leq \theta \leq 360$) of the device are the most important geometrical parameters. The role of these parameters on the heat transfer rate and pressure drop in the test tube are investigated in details. To check the reliability of the experimental apparatus, the results for the plain tube under constant heat flux are compared with available correlations and benchmarks for turbulent flows in the same operating conditions.

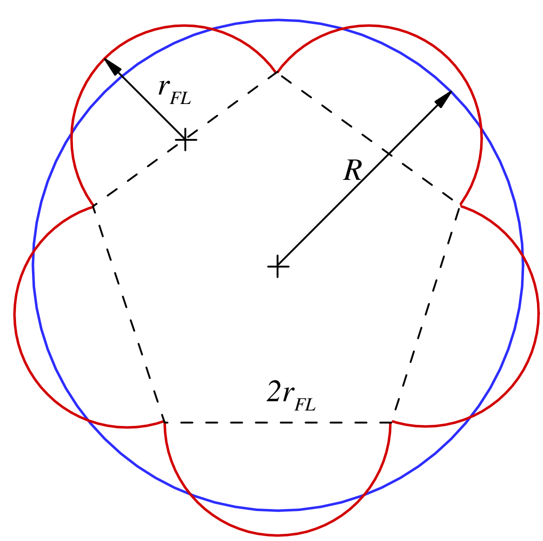

Fig. 1. The cross-sections of the swirl generator (red line) and the plain tube (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)