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Thermal performance enhancement in a heat exchanger tube fitted with inclined vortex rings

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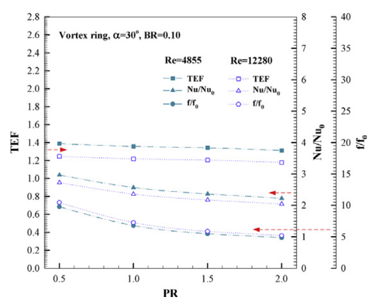
HIGHLIGHTS

- A novel inclined vortex-ring (VR) turbulator is introduced for heat transfer enhancement.
- Influence of VR parameters on thermal performance is examined experimentally.
- Optimum VR parameters are reported.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of inclined vortex rings (VR) on heat transfer augmentation in a uniform heat-fluxed tube has been investigated experimentally. In the present work, the 30° inclined VRs were mounted repeatedly in the tube with various geometry parameters of the VR, three relative ring width ratios (BR = b/D = 0.1, 0.15 and 0.2) and four relative ring pitch ratios (PR = P/D = 0.5, 1.0, 1.5 and 2.0). Air was employed as the test fluid in the tube for the Reynolds number from 5000 to 26,000. The aim at using the VRs is to create counter-rotating vortices inside the tube to help increase the turbulence intensity as well as to convey the colder fluid from the core regime to the heated-wall region. To find an optimum thermal performance condition, the effect of BR and PR values on the heat transfer and pressure loss in the tube is examined. The experimental results show a significant effect of the presence of the VRs on the heat transfer and pressure loss over the smooth tube. The larger BR value provides higher heat transfer and pressure loss than the smaller one while the PR gives an opposite trend. However, the VR at BR = 0.1 and PR = 0.5 yields the best thermal performance.

1. Introduction

Heat transfer augmentation techniques are needed in heat exchanger systems to enhance heat transfer rate and improve their thermal performance. The techniques for heat transfer augmentation can be divided into two main groups. One is the active method requiring extra external power sources such as mechanical aids, surface-fluid vibration, injection and suction of the fluid, jet impingement, and electrostatic fields. The other is the passive method that requires no external power for the systems. In general, the passive method is more popular and it includes a surface coating, wavy surfaces, rough and extended surfaces, convoluted (twisted) tube, additives for liquid and gases, turbulators (coiled wire and conical ring) and vortex/swirl generators. Most inserted devices mentioned above that form an important group of the passive augmentation technique, are frequently used to generate vortex/swirl flow in the thermal system. Insertion of vortex/swirl

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Nomenclature

A	heat transfer surface area, m^{-2}
b	ring width, m
BR	relative ring width or blockage ratio = b/D, e/D
$C_{p,air}$	specific heat capacity of air, kJ kg^{-1} K^{-1}
D	diameter, m
e	rib or baffle height, m
f	friction factor
h	mean heat transfer coefficient, W m^{-2} K^{-1}
I	current, A
k	thermal conductivity of air, W m^{-1} K^{-1}
L	length of test tube, m
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number
Q	heat transfer rate, W
P	pitch length of VR, m
ΔP	pressure drop, Pa
PR	relative ring pitch or pitch ratio = P/D
Pr	Prandtl number
Re	Reynolds number
$\tilde{T}$	mean temperature, K
T	temperature, K
TEF	thermal performance enhancement factor
t	thickness of test tube, m
U	mean axial velocity, m s^{-1}
V	voltage, V
VI	vortex-induced impingement
VR	vortex ring
$\dot{V}$	volumetric flow rate, m^3 s^{-1}

Greek symbols

α	attack angle of VR, degree
ρ	fluid density, kg m^{-3}
ν	kinematic viscosity, N m^{-2}

Subscripts

b	bulk
0	smooth tube
conv	convection
i	inlet
o	out
pp	pumping power
s	tube surface
w	wall

generators in a circular tube is a simple technique for enhancing the convective heat transfer coefficient on the tube side of a heat exchanger due to their advantages of easy fabrication and operation as well as low maintenance. In addition, the performance of those turbulators or vortex generators strongly depends on their geometries. There are many types of vortex generators employed in the heat exchanger ducts/tubes such as helical/twisted tapes [1–3], coiled wires [4–6], circular/twisted-rings [7,8] and angle-finned tapes [9,10].

Yakut et al. [11,12] reported the effect of conical-ring turbulators on the heat transfer, pressure drop, flow-induced vibration and vortices. In addition, the thermal performance for employing the turbulators at constant pumping and entropy generation was evaluated. From the evaluation of entropy generation, the conical-ring turbulators showed the merit as energy saving device only at low Reynolds number since low pressure drop was generated in that flow region. Promvonge [13] studied the insertion effect of the conical ring arrangements, namely, converging conical ring, diverging conical ring, and converging–diverging conical ring on the heat transfer rate, friction factor and thermal performance in a round tube. The study showed that the diverging conical ring offered higher thermal performance than the converging and converging–diverging ones. Durmus [14] investigated the effect of angle arrangement of the conical-ring type turbulators on the heat transfer and friction loss. The investigated results revealed that heat transfer rate as well as friction factor increased with the increase in the conical-ring angle. Promvonge and Eiamsa-ard [15] examined the combined effect of the conical-ring and twisted-tape for heat transfer enhancement in a circular tube. As reported, the use of the conical-ring in common with the twisted-tape provided an average heat transfer rate up to 10% over that of the conical-ring alone. Taslim et al. [16] conducted a measurement of the heat transfer in a V-ribbed square channel with three relative rib height ratios (e/D = 0.083, 0.125 and 0.167) at a fixed P/e = 10 using a liquid crystal technique. Various staggered rib configurations were studied, especially for the angle of 45° and experimental data showed a significant increase in average Nusselt number with increasing the e/D value. Chandra et al. [17] studied the heat transfer behaviors in a square channel with continuous ribs on four walls where ribs were placed superimposed on walls. They found that the heat transfer increases with the increment in the number of ribbed walls and with reducing Reynolds number while the friction factor increases with both cases.

Apart from experimental investigations, the numerical studies on heat transfer enhancement by means of the circular ring turbulators were also reported [18,19]. Ozceyhan et al. [18] numerically studied effect of space between the circular rings on heat transfer rate and friction factor. Similarly, Akansu [19] numerically investigated the effect of pitch spacing of porous rings and demonstrated that the heat transfer rate and friction factor increased with decrement of the ring spacing. Kwankaomeng and Promvonge [20], and Promvonge et al. [21] studied numerically the laminar periodic flow over 30° and 45° angled baffles repeatedly mounted only on one wall of a square channel, respectively. They noted that the heat transfer enhancement for the 45° angled baffle with BR = 0.4 was about 2–3 fold higher than that for the 90° baffle while the friction loss was some 10–25% lower. In addition, they found that a single streamwise main vortex flow created by the angled baffles/fins can help to induce impingement flows on the upper, lower and baffle trailing end walls of the channel. The appearance of the vortex-induced impingement (VI) led to drastic increase in the thermal performance of the channel. In comparison, the 30° baffle/fin performs better than the 45° one due to lower pressure loss. Promvonge et al. [22,23] again investigated numerically the laminar flow structure and thermal behaviors in a square channel with 30° and 45° inline baffles on two opposite walls. Two streamwise counter-rotating vortex flows were created along the channel and VI jets appeared on the upper, lower and baffle leading end walls while the maximum thermal performance was found for the 30° inline baffle case although the 45° inline baffle provides higher heat transfer rate.

From the literature review cited above, the use of wire coil/twisted tape inserts in the tube may not be suitable due to lower strength of the vortex flow, leading to thermal performance in a range of 0.7–1.1. The works in Refs. [20–25] triggered the present work to investigate the heat transfer enhancement in a tube inserted with 30° inclined VRs. In a square duct with wall roughened by repeated angled-baffles (or fins), the baffle-induced secondary flows (or vortex flows) accompanied by enhanced turbulence intensity provide a drastic increase in heat transfer due to the VI effect as reported in