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Research Paper

Experimental study of thermal performance and flow behaviour with winglet vortex generators in a circular tube

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HIGHLIGHTS

- Significant heat transfer enhancement can be achieved with VGs insert in pipe.
- Thermal Performance Enhancement (TPE) decreases with blockage ratio, attack angle, pitch ratio and *Re*.
- The maximum TPE of 1.45 was achieved by the combination of PR2.4-β0-B0.1.
- In the smoke flow visualization, horseshoe vortex, longitudinal vortices were clearly observed.

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ABSTRACT

Vortex generators (VGs) are among the various technologies that have been developed to enhance heat transfer and ultimately increase the efficiency of compact heat exchanging devices. VGs create longitudinal vortices which do not decay until further downstream and consequently increase heat transfer rate with comparatively lower pressure drop. In this research, thermal performance and flow behavior with VGs insert in a circular tube is investigated experimentally. The effects of attack angles, blockage ratios, pitch ratios and arrangements of VGs on the thermal performance were studied. Experimental measurements with and without VGs insert in a tube were conducted for airflows within Reynolds numbers ranging from 6000 to 33,000, with for a constant heat flux on the tube surface. Four Delta winglets VGs were inserted in a circular pattern on the inner surface of a tube with the help of a narrow rod. The different sets of delta winglets were characterized by four attack angles β (0°, 15°, 30° and 45°), three blockage ratios B (0.1, 0.2, 0.3), three different row values, N (4, 8 and 12) and three relative pitch ratios PR (4.8, 2.4 and 1.6).

The experimental results indicate that the Nusselt number decreases with pitch ratio, but increases with Reynolds number, attack angle and blockage ratio. Nusselt number increment (Nu/Nu_0) decreases with Reynolds number and pitch ratio, but increases with blockage ratio and attack angle. Maximum Nusselt number increment (Nu/Nu_0) with the VGs was observed as being almost 2 times larger than that of smooth tube, while the maximum friction factor increment (f/f_0) was 4.8 times larger. Thermal performance enhancement (TPE) decreases with blockage ratio, attack angle, Reynolds number and pitch ratio. The largest TPE obtained was 1.45. In order to understand the mechanism of heat transfer enhancement, details of the flow behavior were also studied with a flow visualization experiment employing a high speed camera and smoke generator.

1. Introduction

Vortex generators (VGs) are components that can generate vortices to improve the heat transfer performance of heat exchanger. There are many applications of VGs inside the circular tube, like mixing and separation of materials, chemical processing plants, thermal power generation plants, nuclear power plants and sewage treatment plants. There are two types of mechanisms for the enhancement of thermal performance by vortex generators. One is active heat transfer enhancement using mechanical force to generate vortices. Another type is passive heat transfer enhancement which does not rely on mechanical force, but on the fluid flow itself with some roughness structure to generate vortices. There are mainly two kinds of vortices that have been widely studied including longitudinal vortices with an axis that is parallel to the main flow stream, and transverse vortices where the axis is perpendicular to the main flow. Previous studies revealed that reattaching flow separated from the VGs and that unsteady flow produced by the Karman vortex both enhance heat transfer, but that reattaching

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Nomenclature

Abbreviations

TPE	thermal performance enhancement
VG	vortex generator

Notations

A	heat transfer area (m^2)
C_p	specific heat capacity (kJ/kg·K)
D	tube inner diameter (m)
f	friction factor
H	height of the winglet (mm)
h	heat transfer coefficient ($W/m^2 \cdot K$)
k	air thermal conductivity (W/m·K)
L	test tube length (m)
l	delta winglet's length (mm)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Q	heat transfer rate (W)
P	ring pitch (m)
ΔP	pressure drop (Pa)
PR	pitch ratio = P/D
Pr	Prandtl number
Re	Reynolds number
$\widetilde{T}$	mean temperature (K)
T	temperature (K)
t	test tube thickness (m)
U	mean axial velocity (m/s)
$\dot{V}$	volumetric flow rate (m^3/s)

Greek symbols

β	attack angle (°)
ρ	fluid density (kg/m^3)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity (N/m^2)
η	thermal performance improvement (TPE)

Subscripts

0	smooth tube
b	bulk
conv	convection
i	inlet
o	outlet
pp	pumping power
s	tube surface

flow behavior persists only for a short distance from the promoter, and promoter itself causes undesirable pressure drop. Recent studies [1–3] have found that longitudinal vortex can last for a long distance far down the VGs, so it leads to more thermal enhancement with same pressure drop. Consequently, longitudinal VGs are more efficient. Therefore, it is not necessary to place many sets of VGs at the downstream which would inevitably increases pressure drop and consequently lower thermal performance. Twisted or helical insert tapes, wire coils, turbulence rings and conical VGs are usually employed to increase the heat transfer performance of the heat exchangers with circular tubes, while, ribs, wings, winglets, and baffles are mainly employed to increase the heat transfer performance of the heat exchangers with ducts, channels or fins.

Usually, the thermal performance of VGs with different shapes, heights (blockage ratios), attack angles, inclination angles, and arrangements are experimentally and numerically studied. Zhou et al. [4] conducted the experiment inside the rectangular duct. The results showed that the jet from the holes could improve the kinetic energy level and then the local heat transfer is enhanced. Withada et al. [5] carried out a 3D numerical simulation to examine periodic laminar flow and heat transfer characteristics in a circular tube with 45°V-baffles on isothermal wall. Effects of tube blockage ratio, flow direction on heat transfer and pressure drop in the tube were studied. They found that a pair of longitudinal twisted vortices (P-vortex) created by a V-baffle can induce impingement on a wall of the inter-baffle cavity and lead a drastic increase in heat transfer rate at tube wall. In addition, the larger blockage ratio results in the higher Nusselt number and friction factor values.

Eiamsa-ard and Promvonge [6] studied the convective heat transfer and friction behaviors of turbulent flow through a straight tape with double-sided delta wings (T-W) in a circular tube. They studied T-W characteristics included T-W with forward/backward-wing arrangement, T-W with alternate axis (T-WA), three wing-width ratios and wing-pitch ratios. The experimental result reveals that for using the T-W, the increases in the mean Nusselt number (Nu) and friction factor are, respectively, up to 165% and 14.8 times of the plain tube and the maximum thermal performance factor is 1.19.

Yakut et al. [7] carried out an experiment to study tapes with double-sided delta-winglets in a circular tube under different geometrical and flow parameters, including angles of attack, winglet heights, pitch arrangements and Reynolds numbers. Kenan used Taguchi experimental-design method and determined the optimum parameters of the turbulator by obtaining the Nusselt number, friction factor, amplitude of fluctuation pressure of the vortices and the vortex-shedding frequency.

Sompol et al. [8] studied an experimental investigation of enhancing convective heat transfer in a heated circular tube with pairs of perforated-delta-winglets placed repeatedly on a perforated-cross-tape (PW-XT). The involved winglet parameters are composed of relative winglet height or blockage ratio, and relative winglet pitch or pitch ratio and those are performed at a single delta-winglet inclination/attack angle, a = 30° and a winglet porosity ratio, Ap /Aw = 0.359 for Reynolds number from 4180 to 26,000 .

Amnart and Jedsadaratanachai [9] studied the improvement of heat transfer rate and thermal performance numerically with punched delta winglet vortex generators, DWVGs, inserted in the middle of the circular tube. The effects of the flow attack angles and the flow directions were investigated numerically for the Reynolds number Re = 100–2000. The numerical results showed that an increase in the flow attack angle results in the increasing strength of the vortex flows. The flow attack angle of 25° results in the highest heat transfer rate and thermal performance, while the flow attack angle of 0° gives the poorest results. The computational results reveal that the optimum thermal enhancement factor is around 2.80 at Re = 2000, α = 25°, with the winglet tip pointing downstream.

Tiggelbeck et al. [10] compared four types of Wing-Type Vortex Generators for Heat Transfer Enhancement in a rectangular Channel Flows experimentally. The heat transfer enhancement and the flow losses incurred by these four basic forms of VGs have been measured and compared in the Reynolds number range of 2000–9000 and for angles of attack between 30° and 90°. Local heat transfer coefficients on the wall have been measured by liquid crystal thermography. Results show that winglets perform better than wings and a pair of delta winglets can enhance heat transfer by 46% at Re = 2000–120 percent at Re = 8000 over the heat transfer on a plate.

Promvonge et al. [11–15] numerically studied the thermal