STUDY OF WINGLETS VORTEX GENERATORS IN A CIRCULAR TUBE FOR THERMAL ENHANCEMENT

Yunbo Xu, Islam M.D.*
*Author for correspondence
Department of Mechanical Engineering,
The Petroleum Institute,
P.O. Box 2533, Abu Dhabi,
United Arab Emirates
E-mail: dislam@pi.ac.ae

ABSTRACT

Vortex generators/turbulent promoters generate the vortices which reduce the boundary layer thickness and introduce a better mixing of the fluid to enhance the heat transfer. In this research, thermal performance of winglets longitudinal vortex generators (VGs) were investigated experimentally. Delta winglet VGs of different heights and attack angles were inserted inside a 1 m length copper tube. The experiments were conducted with VGs for an air flow range of Reynolds numbers from 6000 to 33000. The influence of the winglet VGs on heat transfer and pressure drop was investigated in terms of the Nusselt number and friction factor. Vortex generators were arranged repeatedly inside the tube 12 rows (N) with same pitch distance (P=L/N) and each row consists of 4 VGs in a circular pattern on the inner surface of the tube. So relative pitch ratio (PR=P/D) is 1.6 and three winglets blockage ratios (B=H/D) are 0.1, 0.2, 0.3 with respect to three winglets heights (H=5mm, 10mm and 15mm). Attack angles of the VGs were maintained 0°, 15°, 35° and 45° for B=0.3. The objectives of the study were to investigate the heat transfer enhancement and to identify the parameter which induces the highest thermal performance augmentation in the circular tube.

Based on the experimental results, the best parameter for thermal performance enhancement (TPE) (η) is for B=0.1, with PR=1.6, β=45°. Nusselt number increased 2 times higher than that of the smooth tube. Friction factor decreased with Reynold number from 0.13 to 0.06.

INTRODUCTION

Vortex generator refers to the components that can generate vortices to improve the thermal performance of heat exchanger, especially for compact heat exchangers. So the size of heat exchanger can be reduced and save more energy. The effect of turbulence promoters on heat transfer has been researched intensively. Vortex generators create longitudinal vortices which do not decay until further downstream and consequently their heat transfer coefficients are higher than other types of VGs with same pressure drops in this region. For tubular heat exchangers, the twisted/helical tapes, wire coils, vortex rings[1] and conical tabulators have been widely used for enhancing the heat transfer [2, 3].

These are widely used in compact heat exchangers, solar collector, mixing biofuel [4], gas turbines [5, 6], and cooling of electrical devices. However, in these applications, gases were used instead of liquids as heat transfer medium.

NOMENCLATURE

A	$[m^3]$	Area of the tube wall
B	[-]	Blockage ratio (H/D)
$C_{p,\,air}$	[kJ/kg·K]	Air specific capacity
D	[m]	Tube inner diameter
f	[-]	Friction factor
H	[m]	Height of the winglet
h	$[W/m^2{\cdot}K]$	Heat transfer coefficient
k	[m]	Air thermal conductivity
L	[m]	test tube length
l	[7]	Delta winglets length
$\dot{m}$	[kg/s]	Mass flow rate
Nu	[-]	Nusselt number
Q	[W]	Heat transfer rate
P	[m]	Ring pitch
ΔP	[Pa]	Pressure drop
PR	[-]	Pitch ratio (P/D)
Pr	[-]	Prandtl number
q	$[m^3/s]$	volumetric flow rate
Re	[-]	Reynolds number
T	[°C]	Temperature (K)
U	[m/s]	Mean axial velocity
VG	[-]	Vortex generator

Special characters

β	[°]	Winglet attack angle
ρ	$[kg/m^3]$	Fluid density
υ	$[m^2/s]$	Kinematic viscosity
η	[-]	Thermal performance enhancement (TPE)

Subscripts

b	Bulk
0	Smooth tube
pp	Pumping power

Therefore, heat transfer enhancement techniques that improve heat transfer rate are of particular interest [7].

There are many researchers devoted to the study of vortex generator regarding its wide use in the heat exchangers. Jaisankar et al. [8] experimentally explored the heat transfer performance of thermosiphon solar water heater system which inserted twisted tapes with spacer and rod at the trail edge. In order to compare the heat transfer performance, three types of twist VGs were used for experiment. Results disclosed that the twist connected with rod VGs indicated better comprehensive thermal performance enhancement than twist fitted with spacer. Gunes et al. [9] experimentally explored the thermal performance of coiled wire inserts while VGs placed separately with different pitch ratios in a tube. The Nusselt number (Nu) and friction (*f*) factor both were found to decrease with the increase of pitch ratio and coil distance. Zhou et al. [10] conducted the experiment inside a rectangular duct with a plate on the bottom to heat the test section by electrical energy. The results showed that curve winglet pair had better thermal performance. Leng et al. [11] investigated the enhancement of heat transfer by spiral coil inserts model in the parallel-plate duct. They reduced the thickness of the boundary layer and enhanced the heat transfer between boundary layer and mainstream. Khoshvaght-Aliabadi et al. [12] examined the thermal performance of plate fin heat exchanger with VGs on the surface where nano fluid was used as working fluid. Experiment and numerical methods were used to study the forced heat convection in laminar and steady state flow with copper based deionized water Nano fluid inside the VGs plate fin ducts. Islam et al [9] have experimentally studied the heat transfer and flow behaviour of a rectangular vortex generators in a narrow channel and obtained better thermal performance. Promvonge et al. numerically studied the thermal performance of 45° inclined baffles on bottom wall [13], 45° [14] and 30 ° [15] inclined baffles on two opposite (upper and lower baffles)walls in a square channel within laminar flow.

As the above literature review shows, previous studies have investigated heat transfer enhancement with twisted tapes, vortex rings and a few studies have concentrated on delta winglets vortex generators in a circular tube with special arrangement. This research attempts to investigate the effect of blockage ratio and attack angle on the heat transfer enhancement and friction factor for delta winglets VGs in a tube.

EXPERIMENTAL SETUP

The experiment was conducted in an open loop facility as shown in Figure 1. Experimental setup consisted of a blower, orifice meter, flow straightener, calming tube and the test section. Test section has a copper tube of 52 mm inner diameter inserted with winglet vortex generators, with length of 1000mm and of thickness 1.75 mm. A blower with a variac transformer is used for the air flow. The straightener can eliminate and reduce mal-distribution of flow during the experiments. For calm section, the length is 1.5m and which is enough to get fully developed flow state before flowing into test section. Pressure drop is measured by a micromanometer which is used to calculate air flow rate. The inlet pressure depends on the flow rate. In the inlet and outlet of the copper tube, there were two pressure taps connected to micromanometer. Copper tube was heated by continually winding flexible electrical wire to provide a uniform heat flux boundary condition which is 694 W/m^2. The electrical output power was controlled by a variac transformer to obtain a constant heat flux along the entire length of the copper tube. The outer surface of the test section was well insulated to minimize convective heat loss to surroundings. The inlet and outlet temperatures of the bulk air were measured by two K type thermocouples located in the inlet and outlet of the test section. The air comes from an air-conditioned room with stable uniform room temperature. So, the inlet temperature profile is uniform and is equal to room temperature. In order to measure the outlet bulk temperature, there is a 0.3m plastic tube downstream of the copper tube which has same diameter with coper tube and also well insulated on the outer surface to avoid heat loss, so that the outlet temperature profile is uniform. So the point measured temperature is equal to bulk temperature. While the other 26 thermocouples were tapped in holes maintaining equal distance throughout tube surface to measure the test section temperatures. All of these 28 thermocouples were connected to DAQs which was connected to a personal computer to acquire the temperature data.

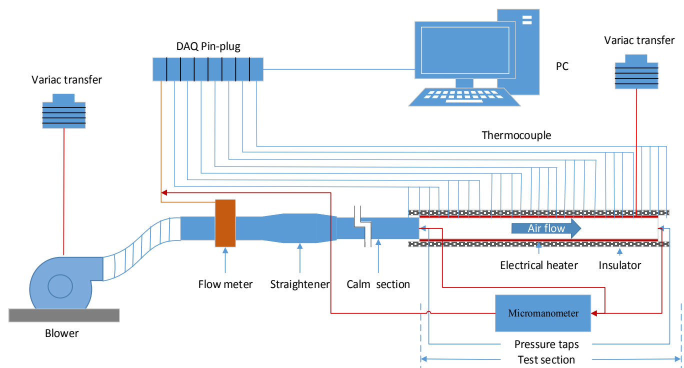

Figure 1 The schematic of the experiment setup

DATA REDUCTION AND UNCERTAINTY

In this study we investigated the thermal performance of VGs. The essential quantities determined were the friction factor and the heat transfer coefficients. The detailed delta winglets VGs is indicated in Figure 2.

The average temperature in the tube surface is measured by 26 thermocouples. Bulk temperature T_b is equal to the average of inlet and out temperature. Average heat transfer coefficient h can be calculated as:

$$h = \dot{m} C_{p,air}(T_o - T_i) / A(\tilde{T}_s - T_b) \quad (1)$$

Average Nusselt number (Nu) based on the tube diameter can be expressed as:

$$\mathrm{Nu} = hD / K \quad (2)$$

Friction factor refers dimensionless pressure drop for internal flow which is calculated by:

$$f = \frac{\Delta P}{(L/D)\rho U^2 / 2} \quad (3)$$

Finally get the thermal performance enhancement (TPE) factor (η)[1], which equals heat transfer coefficient with vortex generator over heat transfer coefficient without vortex generator in the same pumping power:

$$\eta = \frac{h}{h_0}\bigg|_{pp} = \frac{Nu}{Nu_0}\bigg|_{pp} = \frac{Nu}{Nu_0}\left(\frac{f}{f_0}\right)^{-1/3} \quad (4)$$

The average uncertainty of Re is ±4.31%, the average uncertainty of Nu is ±6.25% and the average uncertainty of f is ±7.34%. Experimental test parameters are included in Table1.

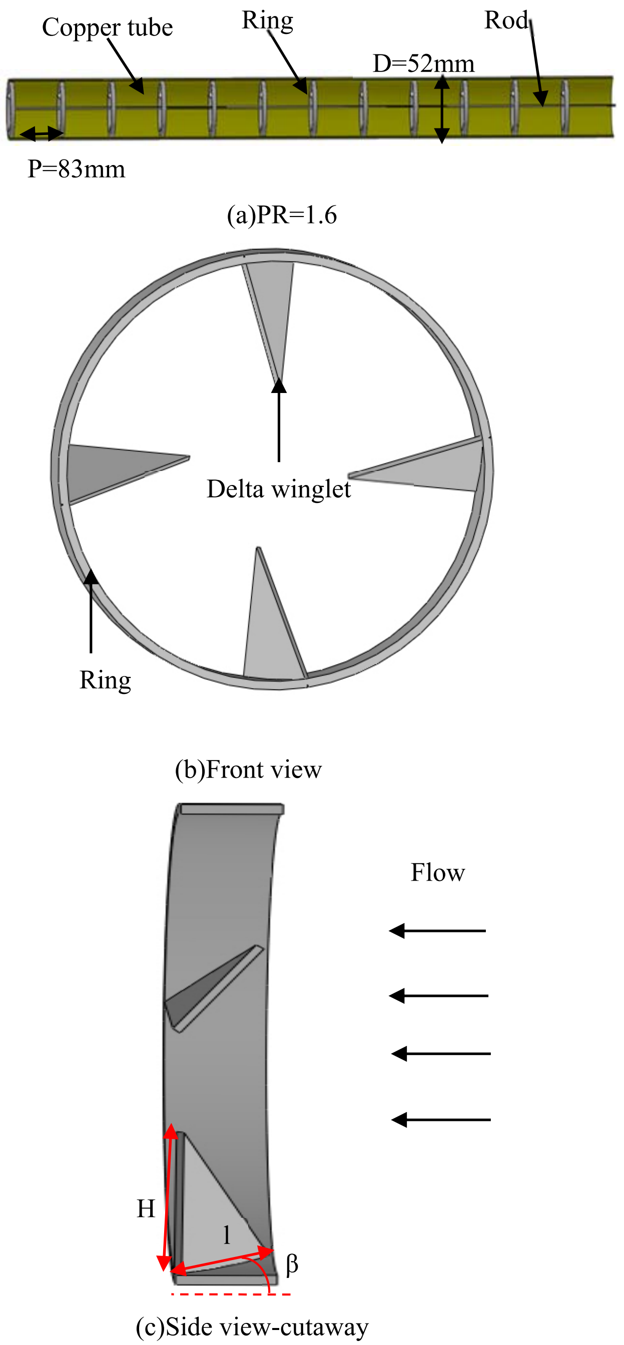

Figure 2 The detailed delta winglets VGs: (β) attack angle, (H) delta winglet height and (l) delta winglet length.

Table 1 Parameters of VGs tested by experiment

Parameters	Values
Tube hydraulic diameter (D)	52mm
Tube length (L)	1m
Number of VGs rows(N)	12
Pitch(P=L/N)	0.083m
Pitch Ratio (PR=P/D)	1.6
VG length (l)	10mm
VG height (H)	5mm, 10mm, 15mm
Blockage Ratio(B=H/D)	0.1, 0.2, 0.3
Attack Angle(β)	0°, 15°, 30°, 45°
Reynolds number (Re)	6000-33000

RESULTS AND DISCUSSION

At this part, the smooth tube is validated, and the effects of VGs on Nusselt number, friction factor and thermal performance are presented.

Validation of smooth tube

In order to verify the reproducibility, the heat transfer and friction characteristics in a smooth wall tube are validated in terms of Nusselt number and friction factor respectively by the empirical correlations. The correlation of friction factor is from Petukhov and Blasius[16] which is indicated in the Equation (5)(6) and Nusselt number is from Gnielinski and Dittus-Boelter[16] which are indicated in the Equation(7)(8). Comparing with Gnielinski and Dittus-Boelter correlations, the average Nu differences are 9% and 3%. Comparing with Petukhov and Blasius correlations, average friction factor differences are 8% and 7%. As the error of Gnielinski and Dittus-Boelter correlations for Nu are 10% and 25% respectively, and current results is within the range of errors, so current results were validated, as indicated in the Figure 3.

Petukhov $$f = (0.790 \ln Re_D - 1.64)^{-2} \quad (5)$$

Blasius $$f = 0.316 Re^{-0.25} \quad (6)$$

Gnielinski $$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \quad (7)$$

Dittus-Boelter $$Nu_D = 0.023 Re^{0.8} Pr^{0.4} \quad (8)$$

These correlations are valid for turbulent, fully developed flow for smooth walls.

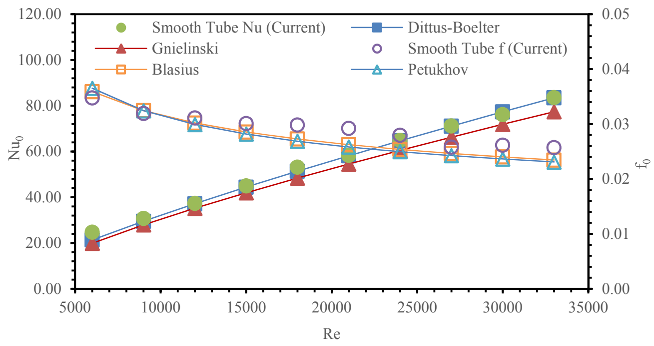

Figure 3 Validation of smooth tube for Nu and *f*.

Effect of VGs on Nusselt number

Figure 4-6 indicate the effects of Reynolds number on the Nusselt number and Nusselt number increments (Nu/Nu_0) which are observed for different cases.

Figure 4 shows that Nusselt number increase with Reynolds number and also found higher than that of smooth tube for all the cases for different blockage ratios. The trend is similar regardless of the blockage ratio.

The Nusselt number ratio, Nu/Nu_0, defined as a ratio of augmented Nusselt number to the Nusselt number of smooth tube plotted against the Reynolds number as indicated in

Figure 5. It is observed that Nu/Nu_0 slightly decrease with Re for all the cases with different blockage ratios, while Nu/Nu_0 is higher for the larger blockage ratio. It is noted that Nu/Nu_0 is higher for B=0.3 than that for B=0.2 and 0.1. This is caused by higher flow blockage of the B=0.3, interrupting the flow and causes stronger turbulence and ultimately better mixing which enhance heat transfer.

Figure 6 which shows that Nu/Nu_0 decrease with Re for the cases of different attack angles. Larger attack angle, β=45° shows higher heat transfer augmentation than that of lower attack angles, (β=0°, 15° and 30°). The reason is that the VGs generate turbulence which reduce the thickness of the boundary layer[3], so heat transfer is enhanced.

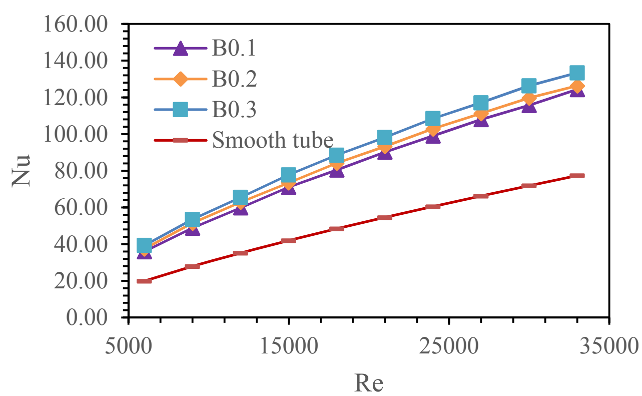

Figure 4 The effect of Reynolds number on Nusselt number for the case of PR=1.6, β=45°.

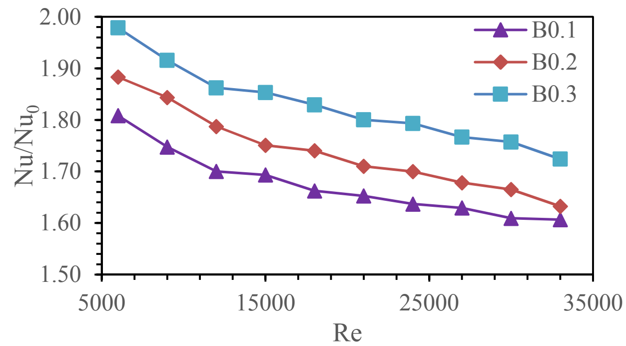

Figure 5 The effect of Reynolds number on $Nu/Nu_0$for the case of PR=1.6, β=45°.

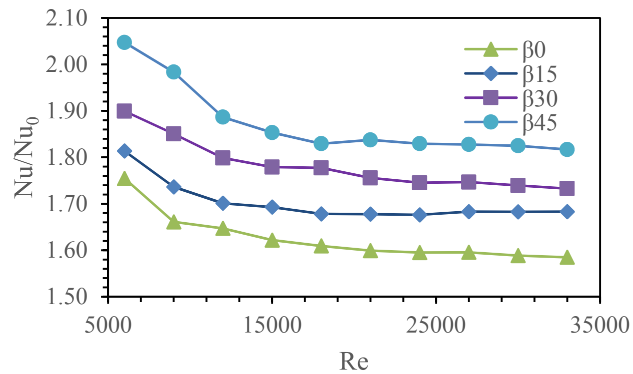

Figure 6 The effect of Reynolds number on Nu/Nu_0 for the case of PR=1.6, B=0.3.

Effect of VGs on friction factor

Figure 7-9 indicate the effects of Reynolds number on the friction factor and friction factor increments (f/f_0) for different cases.

Figure 7 shows that friction factor *f* decrease with Reynolds number (Re). Friction factor is found higher than smooth tube for all the cases with different blockage ratios, while *f* also increase with blockage ratio. This is due to the turbulence that creates fluid interaction leading to the larger friction factor.

Figure 8 shows that f/f_0 increase with Re for all the cases with different blockage ratios, and f/f_0 also increase with blockage ratio.

Figure 9 shows that f/f_0 increase with Re for all the cases with different attack angles, while f/f_0 also increase with attack angle. The reason is that the VGs generate turbulence which increase the friction between the fluid[3], so more dynamic pressure are dissipated which leads more pressure drop.

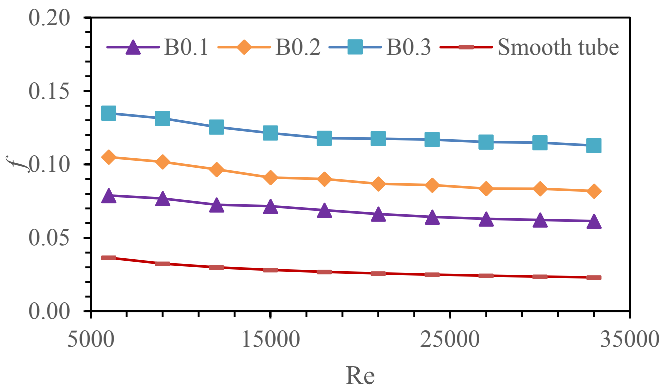

Figure 7 The effect of Reynolds number on friction factor for the case of PR=1.6, β=45°.

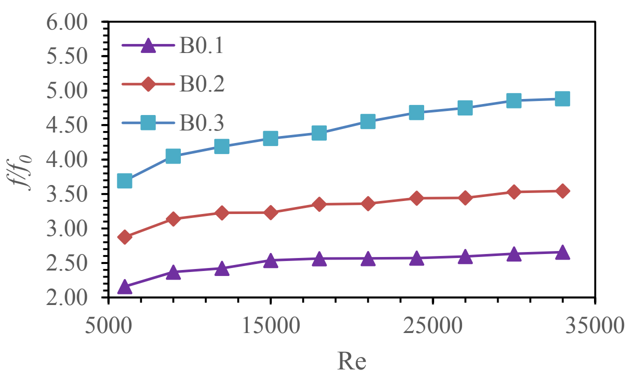

Figure 8 The effect of Reynolds number on f/f_0 for the case of PR=1.6, β=45°.

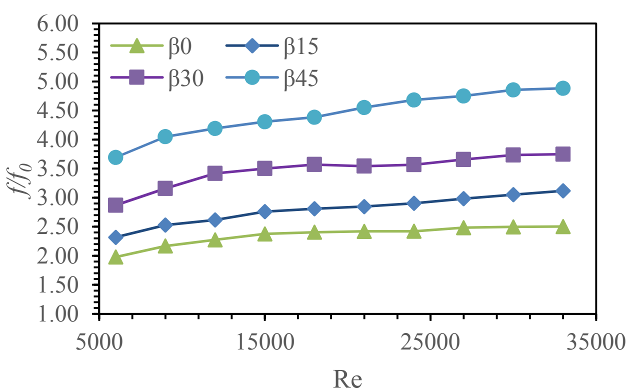

Figure 9 The effect of Reynolds number on f/f_0 for the case of PR=1.6, B=0.3.

Effect of VGs on thermal performance

Figure 10 and 11 indicate the effects of Reynolds number on the thermal performance enhancement (TPE) ($\eta = (Nu/Nu_0)/(f/f_0)^{1/3}$) for different cases. For all the cases, the thermal performance enhancement (TPE) is larger than 1, which means the VGs fitted in the circular tube enhanced the thermal performance. VGs disturb the streamline, swirl the flow, reduced the thickness of the boundary layer. They increase turbulence[3] and enhance the heat convection between the internal fluid and heat conduction of the fluid with tube surface[17].

Figure 10 shows that TPE decrease with Re for all the cases with different blockage ratios, and TPE also decrease with blockage ratio. Figure 11 shows that TPE decrease with Re for all the cases with different attack angles, and TPE also decrease with attack angle. The reason is that f/f_0 increase more than Nu/Nu_0 when increase Re, blockage ratio and attack angle.

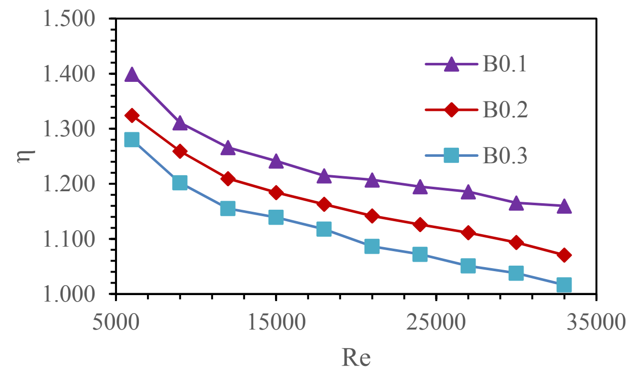

Figure 10 The effect of Reynolds number on thermal performance enhancement (TPE) for the case of PR=1.6, β=45°.

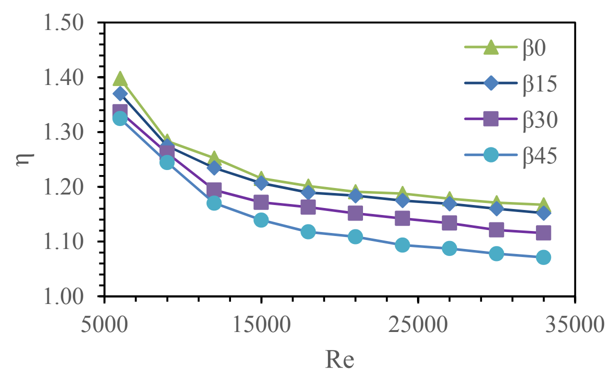

Figure 11 The effect of Reynolds number on thermal performance enhancement (TPE) for the case of PR=1.6, B=0.3.

CONCLUSION

In this research, experiment was conducted for measuring heat transfer and friction factor in a circular tube with VGs for different blockage ratios and attack angles. After a thorough investigation we can summarise as follows:

For the same attack angle and Reynold number, Nusselt number and friction factor are increasing with blockage ratio, the highest Nusselt number increment is 1.98. Thermal performance enhancement (TPE) is decreasing with blockage ratio while the largest TPE is 1.40. For the same attack angle and blockage ratio, Nusselt number increase with Reynolds number from 35.95 to 133.40, while friction factor decrease with it from 0.13 to 0.06, Thermal performance enhancement (TPE) decrease with it from 1.40 to 1.02. So blockage ratio = 0.1 with pitch ratio =1.6, attack angle = 45° and Re = 6000 is the best parameter for thermal performance enhancement (TPE).

ACKNOWLAGEMENTS

The authors would like to acknowledge The Petroleum Institute of Abu Dhabi for the financial support of this research project. Authors are also acknowledges Mr Ming Li and Miss Dai Ying of the mechanical department for their support.

REFERENCES

[1] P. Promvonge, N. Koolnapadol, M. Pimsarn, and C. Thianpong, "Thermal performance enhancement in a heat exchanger tube fitted with inclined vortex rings," *Applied Thermal Engineering,* vol. 62, pp. 285-292, 2014.
[2] P. Promvonge, S. Suwannapan, M. Pimsarn, and C. Thianpong, "Experimental study on heat transfer in square duct with combined twisted-tape and winglet vortex generators," *International Communications in Heat and Mass Transfer,* vol. 59, pp. 158-165, 2014.
[3] P. Promvonge, S. Tamna, M. Pimsarn, and C. Thianpong, "Thermal characterization in a circular tube fitted with inclined horseshoe baffles," *Applied Thermal Engineering,* vol. 75, pp. 1147-1155, 2015.
[4] A. H. Godfrey, "An Investigation into Delta Wing Vortex Generators as a Means of Increasing Algae Biofuel Raceway Vertical Mixing Including an Analysis of the Resulting Turbulence Characteristics," 2012.
[5] W. Li, J. Ren, J. Hongde, Y. Luan, and P. Ligrani, "Assessment of six turbulence models for modeling and predicting narrow passage flows, part 2: pin fin arrays," *Numerical Heat Transfer, Part A: Applications,* pp. 1-19, 2015.
[6] W. Li, J. Ren, J. Hongde, and P. Ligrani, "Assessment of six turbulence models for modeling and predicting narrow passage flows, part 1: Impingement jets," *Numerical Heat Transfer, Part A: Applications,* vol. 69, pp. 109-127, 2016.
[7] H. Ahmed, H. A. Mohammed, and M. Yusoff, "An overview on heat transfer augmentation using vortex generators and nanofluids: approaches and applications," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 5951-5993, 2012.
[8] S. Jaisankar, T. Radhakrishnan, and K. Sheeba, "Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of twisted tapes," *Applied Thermal Engineering,* vol. 29, pp. 1224-1231, 2009.
[9] S. Gunes, V. Ozceyhan, and O. Buyukalaca, "The experimental investigation of heat transfer and pressure drop in a tube with coiled wire inserts placed separately from the tube wall," *Applied Thermal Engineering,* vol. 30, pp. 1719-1725, 2010.
[10] G. Zhou and Z. Feng, "Experimental investigations of heat transfer enhancement by plane and curved winglet type vortex generators with punched holes," *International Journal of Thermal Sciences,* vol. 78, pp. 26-35, 2014.
[11] X.-L. Leng, G.-M. Zhang, Y.-F. Tang, L.-C. Luo, Z. Wu, L.-X. Ma*, et al.*, "Spiral Coil Inserts for Heat Transfer Enhancement in a Parallel-Plate Channel," *Numerical Heat Transfer, Part A: Applications,* vol. 66, pp. 756-772, 2014.
[12] M. Khoshvaght-Aliabadi, F. Hormozi, and A. Zamzamian, "Effects of geometrical parameters on performance of plate-fin heat exchanger: Vortex-generator as core surface and nanofluid as working media," *Applied Thermal Engineering,* vol. 70, pp. 565-579, 2014.
[13] P. Promvonge and C. Thianpong, "Thermal performance assessment of turbulent channel flows over different shaped ribs," *International Communications in Heat and Mass Transfer,* vol. 35, pp. 1327-1334, 2008.
[14] T. Chompookham, C. Thianpong, S. Kwankaomeng, and P. Promvonge, "Heat transfer augmentation in a wedge-ribbed channel using winglet vortex generators," *International Communications in Heat and Mass Transfer,* vol. 37, pp. 163-169, 2010.
[15] S. Eiamsa-ard and P. Promvonge, "Numerical study on heat transfer of turbulent channel flow over periodic grooves," *International Communications in Heat and Mass Transfer,* vol. 35, pp. 844-852, 2008.
[16] P. D. D. F. Incropera, "Fundamentals of Heat and Mass Transfer," 7th edition ed: John Wiley & Sons Inc, 2011.
[17] P. Chu, Y. He, Y. Lei, L. Tian, and R. Li, "Three-dimensional numerical study on fin-and-oval-tube heat exchanger with longitudinal vortex generators," *Applied Thermal Engineering,* vol. 29, pp. 859-876, 2009.