NUMERICAL SIMULATION STUDY OF ENHANCED CONVECTIVE HEAT TRANSFER IN THE TUBE BASED ON WINGLET VORTEX GENERATOR

by

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In order to enhance the heat transfer effect and improve the energy utilization efficiency of the circular tube under turbulent flow, rhombic and triangular winglet vortex generators are proposed on the basis of rectangular winglet vortex generator. The effects of three vortex generators on flow and heat transfer in the tube are investigated by numerical simulations. The results indicate that, the rectangular and triangular winglets generate two pairs of longitudinal vortices and the triangular winglets generate four pairs of longitudinal vortices due to additional shrinkage regions. The multiple longitudinal vortices increase the mixing between the fluids, raise the temperature in the central region of the tube, and enhance the heat transfer effect. Furthermore, the triangular winglet enhanced tube has the largest direct flow area and the least effect on resistance. The triangular winglet enhanced tube had the best comprehensive performance, followed by the rhombic winglet enhanced tube, and finally, the rectangular winglet enhanced tube. The performance evaluation criterion reached 1.04-1.13, 1.05-1.15, and 1.08-1.21 for the three enhanced tubes in the given flow rate interval. In addition, the effect of inclination angle on the triangular winglet enhanced tube was further investigated, and the results show that the best comprehensive performance of enhanced heat transfer is achieved at an inclination angle of 45°, with a maximum performance evaluation criterion of 1.25.

Key words*: heat transfer enhancement, winglet vortex generator, longitudinal vortex*

Introduction

Energy transfer is an essential part of the energy utilization process, and heat exchangers are the main equipment for heat transfer, which is used in refrigeration, transportation, agriculture and petrochemical [1]. The performance of heat exchangers significantly affects the efficiency of energy utilization. Enhanced heat transfer technology is one of the effective ways to improve the thermal efficiency of heat exchangers, which can achieve energy saving, consumption reduction and efficiency.

Enhanced heat transfer techniques are classified into three categories based on the presence of external energy: active, passive, and composite techniques [2]. Among these

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categories, passive enhanced heat transfer technology stands out as it does not require external power and energy input, and it has been extensively studied and implemented in practical applications. Passive enhanced heat transfer techniques can be further divided into three main categories: tube wall treatments, special-shaped tubes, and built-in inserts. Tube wall treatments involve various methods such as ribs [3, 4], corrugated tube [5], and dimples [6, 7], *etc*. These techniques improve heat transfer while minimizing flow resistance through the heat transfer tube. However, they often incur higher processing and manufacturing costs. With the continuous upgrading of processing technology, these methods will have a wider application space. Special-shaped tubes such as spiral twisted tube [8], helical twisted Multilobe tubes [9] and helical tube [10], can achieve better heat transfer performance than long straight round tubes. These methods are usually used in conjunction with other passive enhanced heat transfer methods. Built-in inserts such as various torsion belts [11], coils [12, 13], and vortex generators [14]. Belts and coils are commonly used in laminar flow conditions but result in higher flow resistance. Vortex generators manipulate fluid-flow to create vortices that erode the fluid near the wall and disturb the core fluid, disrupting the stable boundary-layer and enhancing heat transfer. Specifically, longitudinal vortex generators, which possess a rotation axis parallel to the mainstream direction, have gained significant attention in recent years as a focal point of research into passive enhanced heat transfer technology.

Xu *et al*. [15] numerically studied the heat transfer characteristics of a vortex generator consisting of four uniformly installed triangular wing-type structures in the circumferential direction. The results show that the inclination angle and the blockage ratio have a significant effect on heat transfer and wall friction. Zheng *et al*. [16] introduced a novel self-connected winglet vortex generator for enhancing heat transfer in turbulent gas flow. Numerical simulations validated that the generation of longitudinal vortices enhanced air mixing in the tube and reduced the synergy angle between the flow and thermal fields. Sun *et al*. [17] performed a numerical and experimental investigation on the turbulent flow and heat transfer properties in a circular tube equipped with curved wing vortex generators. The numerical calculations revealed that the trailing edge of the vortex generator generates counter-rotating vortex pairs. These vortices exert a more prolonged impact on the downstream flow field, resulting in a thinner thermal boundary-layer and enhanced fluid mixing. Sun *et al*. [18] introduced a vortex generator consisting of multiple rectangular winglets. Numerical simulations demonstrated that the inclusion of multiple rectangular winglet vortex generators in a circular tube generated multiple sets of longitudinal vortices, which in turn enhanced fluid mixing within the tube. Zhang *et al*. [19] introduced a rectangular winglet vortex generator. They compared the heat transfer enhancement between two configurations: rectangular winglet V-arrangement (V-rwvg) and parallel-arrangement (P-rwvg). The results revealed that P-rwvg generated a single longitudinal vortex, whereas V-rwvg produced multiple longitudinal vortices. Aridi *et al*. [20] used numerical simulation to investigate the impact of using trapezoidal vortex generators on the heat transfer in a concentric tube heat exchanger. The simulation analysis is held on three different cases of vortex generators in different locations. The results show that the trapezoidal vortex generator can induce turbulence at low Reynolds numbers. It enhances heat transfer in all cases and the heat transfer is affected by the position of the vortex generator. Wu *et al*. [14] proposed a new multi-*V*-shaped winglet vortex generator. The effect of the multi-*V*-shaped winglet vortex generator on the heat transfer and flow characteristics is investigated by combining experiments and simulations for a variety of scenarios. The results show that increasing the number of winglets as well as decreasing the row pitch of the vortex generator has a significant effect on improving the heat transfer.

Based on the previous literature, the longitudinal vortex flow generated by a vortex generator enhances fluid mixing in the tube and exhibits significant heat transfer enhancement. In addition, the arrangement of the vortex generator winglets is an important factor affecting the effectiveness of the enhanced heat transfer. This study introduces two additional vortex generator designs: the rhombic winglet vortex generator and the triangular winglet vortex generator, based on the *V*-shaped arrangement of the rectangular winglet vortex generator proposed by Zhang *et al.* [19]. Numerical simulations were employed to investigate the impact of the winglet shape structure of the vortex generator on the flow pattern and temperature distribution within the tube. A comprehensive performance analysis was also conducted in this study and compared with the results of other scholars. Therefore, whether the technology is used in heat exchangers or waste heat recovery, the heat energy utilization rate will be greatly improved. At the same time, due to the effective exchange of heat energy inside and outside the tube, the energy loss in practical applications can be reduced.

Physical model

This paper presents a simplified version of the rectangular winglet vortex generator proposed by Zhang *et al*. [19]. To reduce the complexity of the numerical simulation, the winglets are assumed to be welded onto the inner wall surface of the heat exchanger tube. The proposed rhombic and triangular winglets, based on the rectangular winglet, are shown in fig. 1. Three types of winglets have the same volume. Each winglet, along with the adjacent winglets,

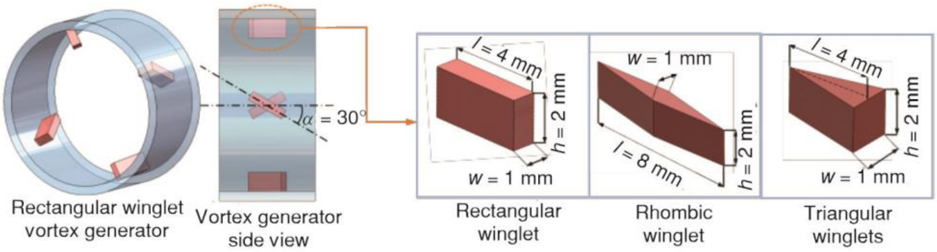

Figure 1. Three types of winglet vortex generator

is arranged in either a *V*-shaped or inverted *V*-shaped configuration around the circumference of the tube, with an inclination angle of $\alpha = 30°$ (the angle between the winglet and the direction of fluid-flow). Figure 2 illustrates the fluid domain model of the heat exchanger tube, comprised of three sections: the upstream section, test section, and downstream section. The fluid domain is 0.58 m long with a diameter of 0.018 m. The length of the test section is 0.4 m, and the vortex generators are evenly spaced at intervals of 0.08 m within this section. The upstream section measures 0.12 m in length, while the downstream section is 0.06 m long. These additional sections ensure that the fluid undergoes full development in the inlet section, generating turbulence and preventing the simulation results from being affected by outlet backflow.

Numerical simulation

Turbulence model and boundary conditions

The numerical simulations were computationally solved using Fluent 2020 R2 software, a professional fluid analysis software, and the following assumptions were made in conjunction with the specific situation of fluid-flow and heat transfer in the heat exchanger tube:
– the liquid water used is an incompressible fluid with constant thermophysical properties,

– the effect of heat radiation on the heat transfer process is not considered,
– the vortex generator is a rigid body, and the effect of vortex generator vibration on the simulation results is ignored,
– the inner wall surface of the heat transfer tube and the wall surface of the vortex generator are no-slip boundaries, and
– ignoring the effects of gravity.

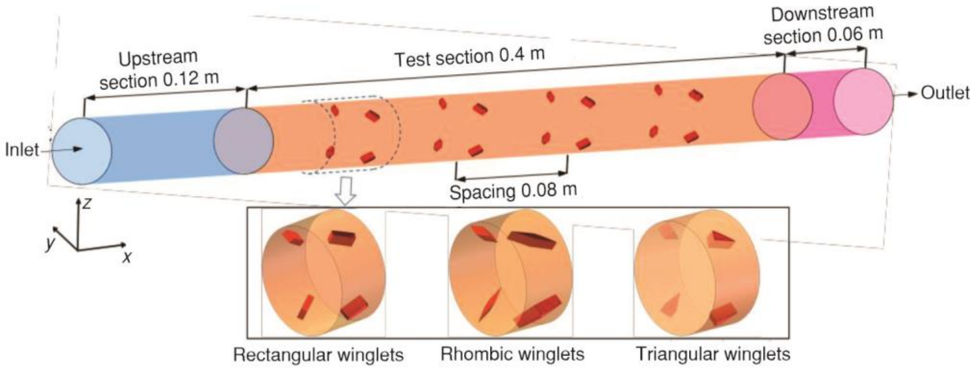

Figure 2. Fluid domain model

The SST k-ω turbulence model is used for the calculation. Simulation using velocity inlet and pressure outlet. The working medium is water, the water velocity u = 0.3-0.7 m/s, the corresponding Reynolds number range is 5374-12539. The inlet temperature is 293 K, the constant heat flux of the tube wall q = 50000 W/m^2. The physical properties of the working medium water: density ρ = 998.2 kg/m^3, specific heat capacity C_p = 4183 J/kgK, thermal conductivity k = 0.6 W/mK, and dynamic viscosity η = 0.001 003 Pa·s.

Definition of calculation parameters

Some of the parameters involved in this paper are defined as: the Reynolds number, Nusselt number, and friction factor, f, are determined as:

$$\mathrm{Re} = \frac{\rho u d}{\eta} \tag{1}$$

$$\mathrm{Nu} = \frac{qd}{(t_w - t_f)\lambda} \tag{2}$$

$$f = \frac{\Delta p 2d}{L\rho u^2} \tag{3}$$

where d is the diameter of the circular tube, t_w – the average temperature of the test section of the tube wall, t_f – the average temperature of the water in the test section, λ – thermal conductivity of fluids, Δp – the differential pressure of the test section, and L – the length of the test section.

The commonly accepted performance comparison metric performance evaluation criterion (PEC) currently used by scientific scholars is defined as:

$$\mathrm{PEC} = \frac{\mathrm{Nu}/\mathrm{Nu}_0}{(f/f_0)^{1/3}} \tag{4}$$

where Nu and Nu_0 represent the Nusselt numbers of the wall of smooth tube and enhanced tube test sections and f and f_0 represent the friction factor of enhanced tube and smooth tube test sections.

Mesh generation and mesh independence verification

Simulation was performed using the Mesh module of ANSYS software to mesh the fluid domain, and the mesh divided was an unstructured mesh as shown in fig. 3. Boundary-layers were added to the fluid domain, and the y^+ values were kept around 1 for all simulations.

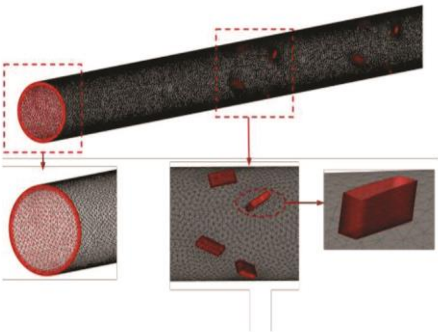

Figure. 3. Fluid domain mesh

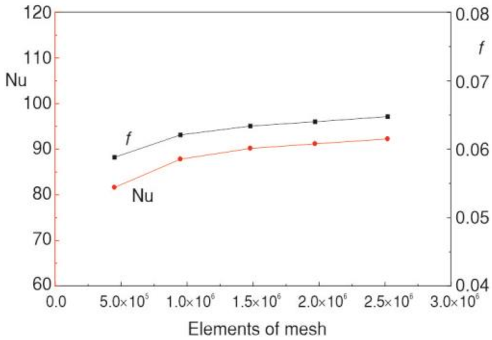

Figure. 4. Mesh independence verification

Mesh independence verification is performed in this paper to eliminate the effect of mesh elements. For u = 0.4 m/s, five different elements of mesh, 4.5×10^5, 9.5×10^5, 14.8×10^5, 19.7×10^5, and 25.2×10^5 were used for the simulation of the rhombic winglet enhanced tube. The calculated Nusselt number and f are shown in fig. 4. Considering the computational accuracy and computational cost, the mesh system of 2 million is dense enough for numerical computation, and the error of Nusselt number for 19.7×10^5 and 25.2×10^5 mesh is 1.08%, and the error off for 19.7×10^5 and 25.2×10^5 mesh is 1%. Therefore, the elements of mesh of about 2 million is chosen for the subsequent mesh division.

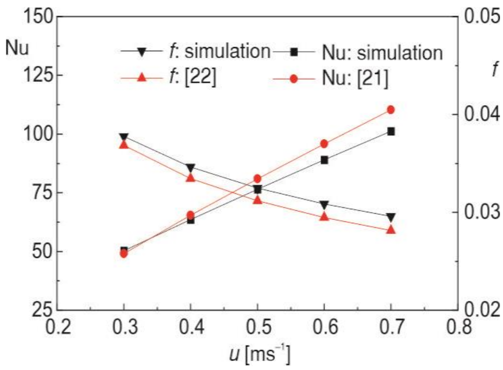

Figure 5. Numerical method validation

Numerical calculation method validation

In order to verify the accuracy of the numerical calculation method, the flow and heat transfer processes in the smooth tube are simulated numerically and the calculated results are compared with the empirical correlation equation. The results are shown in fig. 5. The maximum error of Nusselt number compared with the Gnielinski correlation is 8.92% and the maximum error of f compared with the Petukhov correlation is 5.09%, indicating that the numerical simulation method used in this paper is feasible.

Gnielinski correlation [21]:

$$\mathrm{Nu}=\frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}\left[1+\left(\frac{d}{l}\right)^{2/3}\right],\quad f=(1.8\lg\mathrm{Re}-1.5)^{-2} \tag{5}$$

Petukhov correlation [22]:

$$f = (0.79 \ln \mathrm{Re} - 1.64)^{-2} \tag{6}$$

Results and discussion

Flow field structure and temperature distribution

The analysis of the flow field inside the heat exchanger tube is an important tool to understand the structure of the fluid-flow changed by the vortex generator. The flow field structure and temperature distribution for the smooth tube and three enhanced tubes using vortex generators are given in fig. 6. Longitudinal vortices are generated in all enhanced tubes compared to smooth tube. The flow fields induced by the rectangular and rhombic winglets are very similar, both producing two pairs of longitudinal vortices. The triangular winglets produced four pairs of longitudinal vortices. Two of these pairs have a large area of influence and high strength, while the other two pairs have a smaller area of influence and are weaker. Turbulent kinetic energy (TKE) is a physical quantity characterizing the turbulence and intensity of water flow, and its magnitude determines the ability of turbulence development or decay. The larger the TKE, the more intense the turbulence of water in the enhanced tube and the higher the degree of mixing between fluids. Combined with the TKE cloud, when rectangular winglets are used, the area with higher TKE is mainly distributed near the wall of the tube, when rhombic winglets are used, the core flow area in the center of the tube has higher TKE. This indicates that the vortex caused by the rectangular winglets mainly promotes the mixing effect of the fluid near the wall, while the vortex caused by the rhombic winglets enhances the mixing effect of the core flow region. For the triangular winglets, the area of the region with higher TKE is significantly higher than the former two, and the high turbulent energy region is located near the wall, which indicates that the vortex caused by the triangular winglets perturbs and mixes the fluid near the wall of the tube most intensely.

Figure 6 also compares the temperature distribution clouds on the tube cross section at x = 0.52 m, u = 0.3 m/s. The temperature distribution in all four cases is influenced by the flow field inside the tube. The temperature in the core area of smooth tube is much lower. Vortices initiated by rectangular winglets have vortex cores located closer to the wall compared to rhombic winglets. As a result, a single vortex in rectangular winglet enhanced tube can carry the fluid in the center region towards the wall near the heating for a longer period of time. Rectangular winglet enhanced tube has higher fluid temperatures near the wall. Due to the better mixing effect of the vortex caused by the rhombic winglet on the fluid in the core flow region, the temperature in the central region is higher than using the rectangular winglets. For the triangular winglets, four pairs of longitudinal vortices resulted in the formation of four high temperature zones near the near-wall surface of the tube, with the central region having a lower temperature. This indicates that the vortices induced by the different winglets have a significant effect on the temperature distribution of the fluid inside the tube.

Combined with the analysis of the field synergy principle, taking the rectangular winglets as an example, in region A, the high temperature fluid-flowing near the tube wall is directed to the core flow, and the direction of the velocity vector and the temperature gradient are almost opposite, which leads to poor field synergy. As a result, the heat transfer in this area is poor. In Region B, the low temperature fluid in the center of the tube is brought to heat near the wall, and the direction of the velocity vector and the temperature gradient are almost the same, which improves the field synergy, resulting in the enhanced heat transfer rate. The vortex

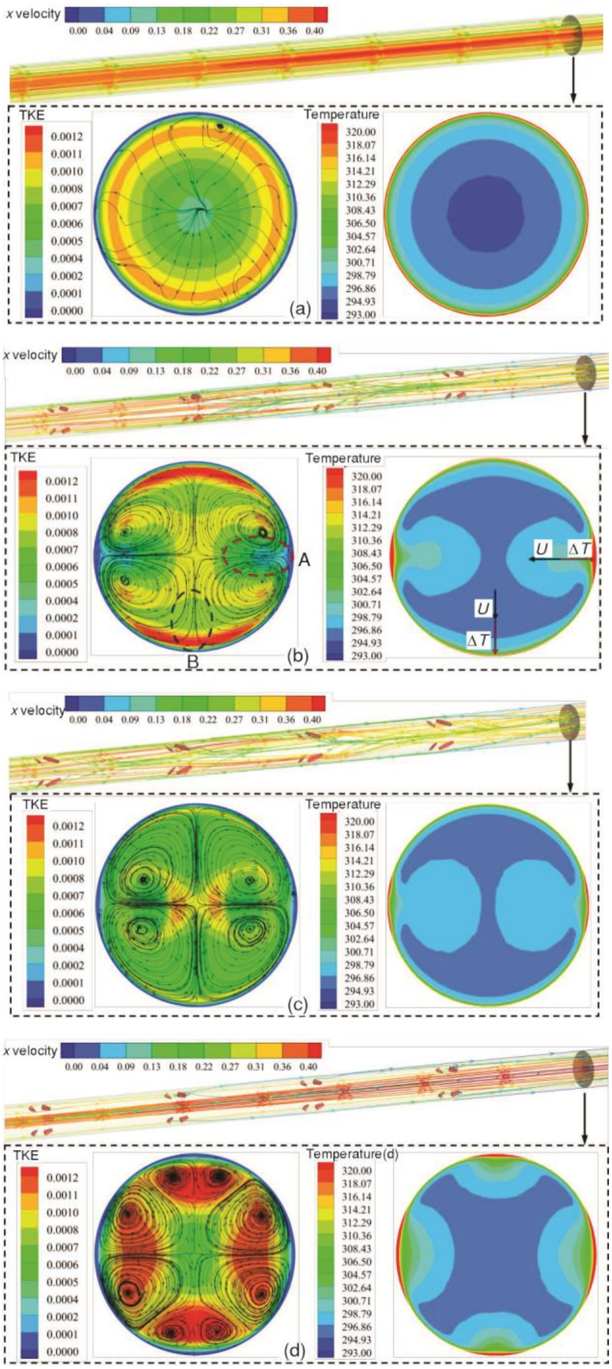

Figure 6. Flow field structure diagram and temperature distribution, x = 0.52 m, u = 0.3 m/s;
(a) smooth tube, (b) rectangular winglets,
(c) rhombic winglets, and (d) triangular winglets

action induced by the three winglets is basically the same, they bring the fluid in the center region of the tube to be heated near the wall, and then bring the heated high temperature fluid to the core flow. Therefore, from the perspective of field synergy, the three types of winglets induced flow fields enhance the heat transfer effect.

It is important to note that the triangular winglets are able to generate four pairs of vortices because they have additional shrinkage regions (Similar to trapezoidal body). The shrinkage region refers to local area contraction due to the winglets. As shown in fig. 7, the winglets are placed at a 30° angle of inclination, thus creating two distinct shrinkage Regions A1. In addition, the structural properties of the triangular winglets result in the formation of two shrinkage regions B1 on their bottom surfaces. A pair of vortices is formed when the fluidflows through the shrinking spatial structure, and the shrinkage region A1 is much larger than the Region B1. Therefore, the two pairs of vortices generated by the shrinkage Region A1 are stronger and exert a greater influence.

Flow and heat transfer characteristics

The variation of Nusselt number and enhanced heat transfer factor, Nu/Nu_0, with inlet velocity for different conditions are given in figs. 8 and 9, respectively. Nusselt number increases gradually with the increase of the flow rate, and the Nusselt number of the test section wall is much larger than that of the smooth tube when using the vortex generator, which indicates that all three vortex generators can improve the heat transfer performance of the heat exchanger tube. In

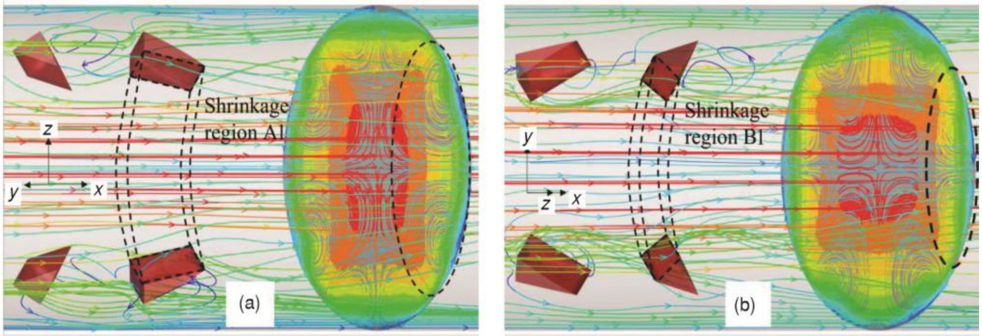

Figure 7. Two shrinkage regions; (a) shrinkage region A1 and (b) shrinkage region B1

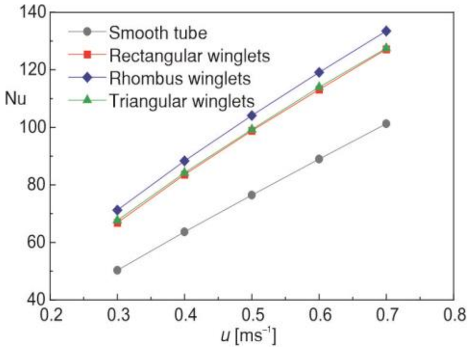

Figure. 8. Effect of three vortex generators on Nusselt number

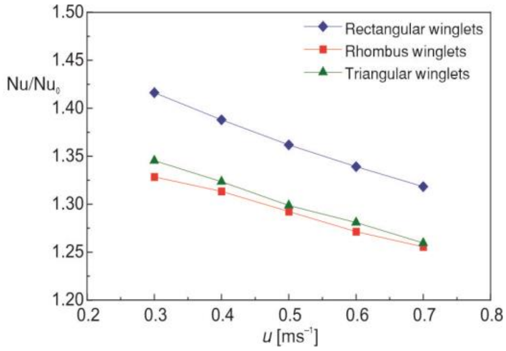

Figure. 9. The Nu/Nu$_0$ of enhanced tube wall

addition, the rhombic winglets have the greatest improvement on Nusselt number of the test section, and the heat transfer performance is improved by 31.8% to 41.6%. The triangular winglets improved Nusselt number slightly more than the rectangular winglets, and these two winglets improved the heat transfer performance by 26.0% to 34.5% and 25.9% to 32.8%, respectively. The reasons for this phenomenon are:

– All three vortex generators form longitudinal vortices in the tube, the longitudinal vortices prolong the flow time of the fluid in the tube, so that the fluid is fully heated.
– The longitudinal vortices bring the low temperature fluid in the core area of the tube to be heated near the wall, and then the heated fluid is brought to the central area, which compress and destroy the original thermal boundary-layer and flow boundary-layer, significantly improves the heat transfer between fluid.
– the rhombic winglets are arranged at an inclination angle of 30°, forming the shrinkage region larger than the other two winglets, the shrinkage region disturbs and affects the fluid for a longer time, generating a higher strength of the longitudinal vortex, better mixing of fluids in the tube, and a higher comprehensive temperature.

The shrinkage region of the triangular winglets is smaller, but its special structure produces two additional shrinkage regions, and these shrinkage regions form a total of four pairs of vortices, and the increase in the number of vortices makes up for the lack of vortex strength and improves the mixing effect of the fluid.

Figure 10 shows the variation of friction factor, *f*, with flow velocity for three enhanced tubes and smooth tube test section. In general, the friction factor, *f*, decreases with the

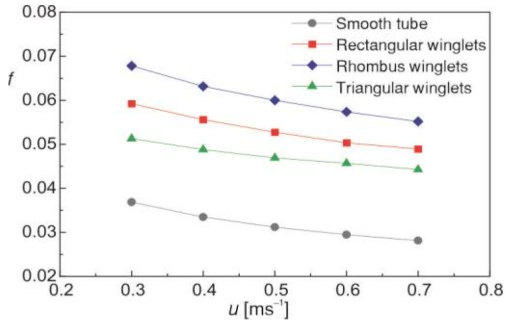

Figure 10. Friction factor of enhanced tube

increase of flow velocity, and the flow resistance in the tube is increased with the use of vortex generators, with the rhombic winglet vortex generator increase the resistance the most and the triangular winglets increase the resistance the least. The reasons for the resistance increase are:
– the longitudinal vortices formed by the three vortex generators enhance the turbulence intensity in the tube, resulting in more dissipation of mainstream kinetic energy and
– all three winglets increase the flow obstruction in the tube, as shown in fig. 11, the direct circulation area in the tube is the smallest when using the rhombic winglet vortex generator, and the direct circulation area is the largest when using the triangular winglet vortex generator, so the triangular winglet has the smallest enhancement of the friction factor.

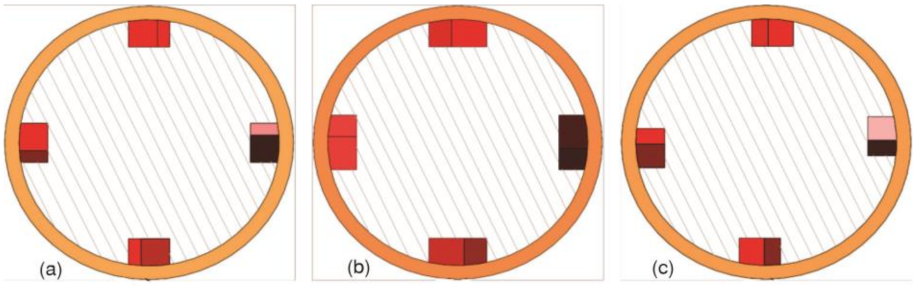

Figure 11. Blockage area; (a) rectangular winglets, (b) rhombic winglets, and (c) triangular winglets

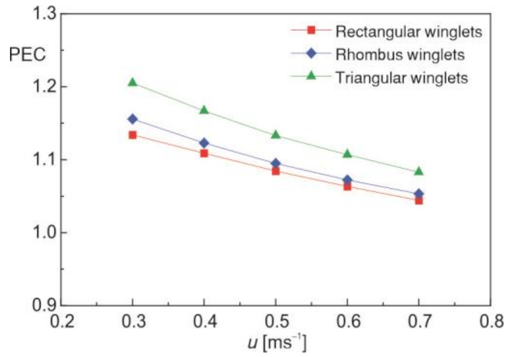

Figure 12. The PEC of enhanced tube

In order to better evaluate the comprehensive performance of heat transfer and flow in the enhanced tube using vortex generators, this paper uses the PEC to evaluate the comprehensive performance. The PEC larger than 1 means the comprehensive performance of enhanced tube is higher than smooth tube, and vice versa is lower than smooth tube. Figure 12 shows the variation of PEC with flow rate when using the three vortex generators. It can be seen that the PEC values of the three vortex generators are larger than 1, where the triangular winglet has the best comprehensive performance, with PEC between 1.08 and 1.21 at the given flow rate, followed by the rhombic winglet. The reasons for this are: although the rhombic winglet vortex generator improves the heat transfer performance the most, the flow blockage is too large and causes excessive flow resistance and the triangular winglet vortex generator improves the friction factor the least, and the multiple vortices formed by the triangular winglet also improve the heat transfer performance better, so the comprehensive performance is the best.

The effect of inclination angle on the heat transfer effect of triangular winglets

Since the triangular winglet vortex generator has the best comprehensive performance of enhanced heat transfer, it is necessary to carry out further research on the triangular winglet. In this paper, the inclination angle of the triangular winglet is changed. The heat transfer in the enhanced tube was simulated at flow velocity u = 0.3m/s and at 0°, 15°, 30°, 45°, and 60° inclination angles. To investigate the effect of the inclination angle on the enhanced heat transfer in the triangular winglet vortex generator, and to determine the best degree of inclination angle.

Figure 13 shows the TKE and velocity vector on the cross section of the tube at x = 0.52 m using five different inclination angles of the triangular winglet vortex generator. The inclination angle α = 0°, the triangular winglet does not form a shrinkage spatial structure, so

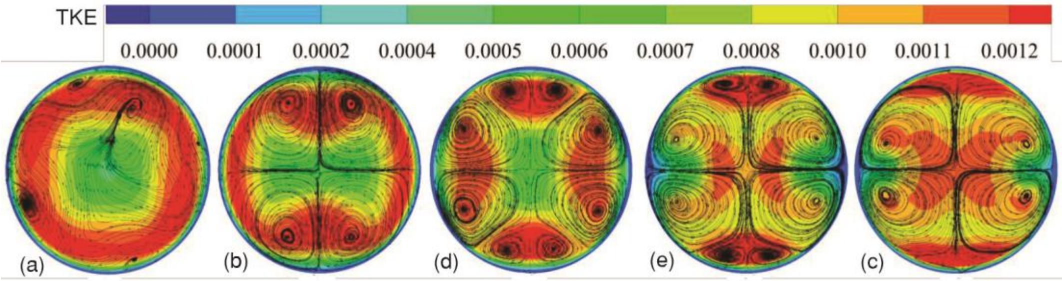

Figure 13. Effect of five inclination angles of triangular winglets on the flow field structure; (a) α = 0°, (b) α = 15°, (c) α = 30°, (d) α = 45°, and (e) α = 60°

there is no longitudinal vortex in the tube, the presence of the winglet only disturbs the flow of fluid. When α = 15°, corresponding to the shrinkage Region B1 in fig. 7 is the formation of longitudinal vortex. This is because the narrow mouth of the shrinkage area B1 is much smaller than the wide mouth, while the narrow mouth of the shrinkage area A1 and the wide mouth of the shrinkage area A1 are not very different, and the fluid-flow through the area A1 is almost unaffected so no vortex is generated. As the inclination angle of the winglet increases, the narrow mouth of the shrinkage region A1 becomes smaller and smaller compared with the wide mouth, while the narrow mouth of the shrinkage Region B1 becomes larger and larger compared with the wide mouth, which leads to the shrinkage Region A1 playing a dominant role in causing longitudinal vortices in the tube, finally, at α = 60°, the shrinkage Region B1 is no longer able to cause longitudinal vortices. For a triangular winglet enhanced tube, the more longitudinal vortices in the tube, the better effect of perturbation and mixing of the fluid in the tube. Only from the flow field structure, longitudinal vortices are formed in both the tapering Regions A1 and B1 at α = 30° and α = 45°, and the effect of enhanced heat transfer should be better in both cases.

In addition, comparing the TKE on the cross section, it can be seen that the region with higher turbulent energy shifts from near the wall to the center of the tube as the inclination angle, α, increases, and the turbulent energy in the center region should be as large as possible in order to ensure that the high temperature fluid near the wall is fully mixed with the low temperature fluid in the center region. At α = 45° and α = 60°, the region of higher turbulent energy is located in the center of the tube. The longitudinal vortices generated by the triangular winglets have a better mixing effect on the core flow in the tube and enhance the heat transfer best.

The effects of the triangular winglet vortex generator with different inclination angles on Nusselt number and f in the test section are given in fig. 14. It can be seen that Nusselt number gradually increases with increasing inclination angle, reaching a peak of 74.25 at α = 45°, and Nu slightly decreases at α = 60°, which corresponds to the previous analysis. In addition, the friction factor, f, increases continuously with the increase of the inclination angle, which is because, the larger the inclination angle is, the larger the blockage area of the triangular winglet is. Combined with the PEC in fig. 15, the comprehensive performance of enhanced heat transfer is also best at α = 45°, with the highest PEC of 1.25.

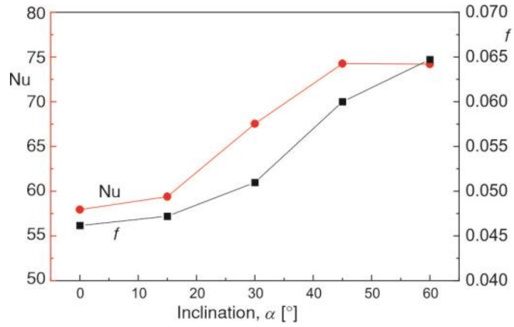

Figure 14. Variations of Nusselt number and *f*

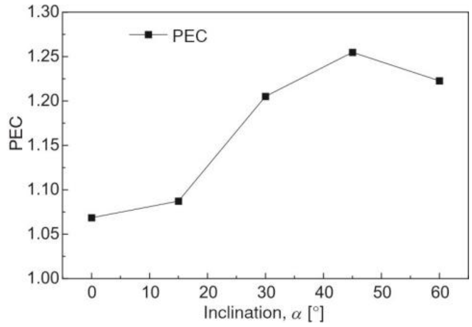

Figure 15. The PEC of five inclination angles

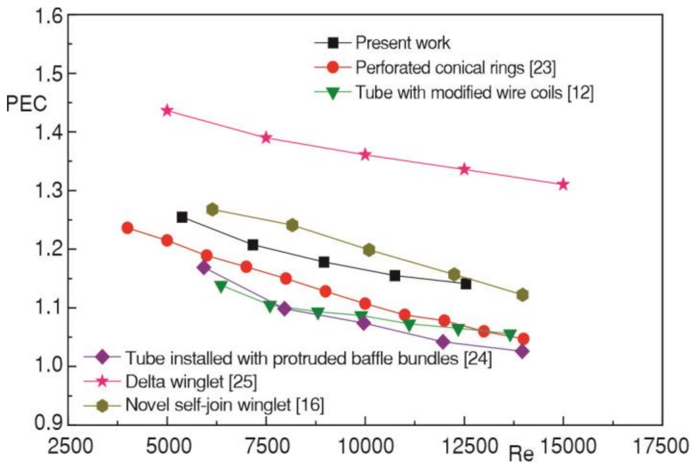

Figure 16. Comparisons of PEC between present work and previous works

Comparison with the results of others' studies

Figure 16 compares the PEC values of the enhanced tube using a triangular winglet vortex generator with an inclination angle of 45° with those of the enhanced heat transfer techniques proposed by other scholars. These studies are perforated conical rings [23], tube with modified wire coils [12], tube installed with protruded baffle bundles [24], delta winglet [25], and novel self-join winglet [16]. The triangular winglet vortex generator proposed in this paper is better than the case of twisted belt and coil insertion. It is a promising technology for heat transfer enhancement. However, there is still a gap compared with the enhanced heat transfer techniques of some scholars. Subsequent studies can further optimize the arrangement method to achieve better results.

Conclusions

The effects of three winglet vortex generators on the flow and heat transfer performance in the tube were studied in the range of flow velocities from 0.3-0.7 m/s, corresponding to Reynolds number 5374 to 12539. The effect of the inclination angle on the enhanced heat transfer of the triangular winglet vortex generator was also studied. The main conclusions can be drawn as follows.

- In this paper, both rhombic and triangular winglet vortex generators proposed based on the rectangular winglet vortex generator form longitudinal vortices. The longitudinal vortex flushes and destroys the boundary-layer, reduced the synergy angle between flow and thermal fields in the tube, and enhances the mixing of core flow and boundary flow. This enhances the heat transfer in the tube.
- The triangular winglets generate multiple longitudinal vortices because the special arrangement of the winglets generates additional shrinkage regions, and the shrinkage region is the key to generate longitudinal vortex.
- All the three vortex generators studied in this paper have the effect of enhanced heat transfer. In terms of comprehensive performance, the triangular winglet vortex generator has the best effect, followed by the rhombus winglet vortex generator and finally the rectangular winglet vortex generator.
- As the inclination angle of the triangular winglet increases, the longitudinal vortex formed in the two shrinkage regions has a greater effect on the flow field inside the tube. At an inclination angle of 45°, four pairs of longitudinal vortices are formed in the tube and the best effect of heat transfer is achieved. When u=0.3m/s, the maximum value of PEC of the enhanced tube reaches 1.25.

Overall, the use of winglet vortex generators enhances heat transfer and improves flow characteristics. It may have a real impact on design and production in various industries. In future work, it is necessary to change the winglet arrangement to improve the comprehensiveness of the work and the value of the study.

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Nomenclature

f – friction factor
f/f_0 – friction factor ratio
Nu – Nusselt number (= hl/λ), [–]
Nu/Nu_0 – Nusselt number ratio
Δp – pressure drop of the test section, [Pa]
q – heat flux, [Wm^{-2}]
Re – Reynolds number (= $\rho ud/\eta$), [–]
t – temperature, [K]
u – velocity, [ms^{-1}]

Greek symbols

η – dynamic viscosity, [$kgm^{-1}s^{-1}$]
ρ – fluid density, [kgm^{-3}]
λ – thermal conductivity of fluids, [$Wm^{-1}K^{-1}$]

Acronyms

PEC – performance evaluation criteria
TKE – turbulent kinetic energy

References

[1] Mousa, M. H., *et al*., Review of Heat Transfer Enhancement Techniques for Single Phase Flows, *Renewable & Sustainable Energy Reviews*, *137* (2021), 110566
[2] Alam, T., Kim, M., A Comprehensive Review on Single Phase Heat Transfer Enhancement Techniques in Heat Exchanger Applications, *Renewable & Sustainable Energy Reviews*, *81* (2018), Part 1, pp. 813-839
[3] Akermann, K., *et al*., Large-Eddy Simulation of Turbulent Heat Transfer in a Multiple-Started Helically Rib-Roughened Pipe, *International Journal of Heat and Mass Transfer*, *154* (2020), 119667
[4] Hasan, M. J., Bhuiyan, A. A., Thermo-Hydrodynamic Characteristics and Entropy Generation in a Tube Heat Exchanger Using Multiple Head Ribbed Geometries, *South African Journal of Chemical Engineering*, 45 (2023), July, pp. 305-314
[5] Hu, Q. X., *et al*., A Numerical Study of Heat Transfer Enhancement by Helically Corrugated Tubes in the Intermediate Heat Exchanger of a Very-High-Temperature Gas-Cooled Reactor, *Nuclear Engineering and Design*, *380* (2021), 111275
[6] Kaood, A., *et al*., Numerical Investigation of the Thermal-Hydraulic Characteristics of Turbulent Flow in Conical Tubes with Dimples, *Case Studies in Thermal Engineering*, *36* (2022), 102166
[7] Yu, J., *et al*., A Simulation Study on the Condensation Flow and Thermal Control Characteristics of Mixed Refrigerant in a Dimpled Tube, *Applied Thermal Engineering*, *231* (2023), 120889
[8] Mashayekhi, R., *et al*., Hydrothermal Performance of Twisted Elliptical Tube Equipped with Twisted Tape Insert, *International Journal of Thermal Sciences*, *172* (2022), 107233
[9] Liaw, K. L., *et al*., Enhanced Turbulent Convective Heat Transfer in Helical Twisted Multilobe Tubes, *International Journal of Heat and Mass Transfer*, *202* (2023), 123687
[10] Kurnia, J. C., *et al*., Laminar Convective Heat Transfer in Helical Tube with Twisted Tape Insert, *International Journal of Heat and Mass Transfer*, *150* (2020), 119309
[11] Chuwattanakul, V., *et al*., Aerothermal Performance Evaluation of a Tube Mounted with Broken V-Ribbed Twisted Tape: Effect of Forward/ Backward Arrangement, *Case Studies in Thermal Engineering*, *41* (2023), 102642
[12] Hong, Y. X., *et al*., Heat Transfer and Fluid-Flow Behaviors in a Tube with Modified Wire Coils, *International Journal of Heat and Mass Transfer*, *124* (2018), Sept. pp. 1347-1360
[13] Yang, Y., Numerical Study on Heat Transfer Characteristics of Molten Salt in a Flat Tube with Circular Helical Wire, *Applied Thermal Engineering*, *227* (2023), 120373
[14] Wu, X., *et al*., A Comparative Study of Fluid-Flow and Heat Transfer in the Tube with Multi-V-Winglets Vortex Generators, *Applied Thermal Engineering*, *236* (2024), 121448
[15] Xu, Y., *et al*., Experimental Study of Thermal Performance and Flow Behaviour with Winglet Vortex Generators in a Circular Tube, *Applied Thermal Engineering*, *135* (2018), May, pp. 257-268
[16] Zheng, N. B., *et al*., Novel Self-Join Winglet Vortex Generators for Enhanced Heat Transfer of Turbulent Airflow in Round Tubes, *International Communications in Heat and Mass Transfer*, *130* (2022), 105806
[17] Sun, Z. Q., *et al*., Experimental and Numerical Studies of Intensified Turbulent Heat Transfer in Round Pipes with Curved Wing Vortex Generators, *International Journal of Heat and Mass Transfer*, *180* (2021), 121823
[18] Sun, Z. Q., *et al*., Investigations of the Turbulent Thermal-Hydraulic Performance in Circular Heat Exchanger Tubes with Multiple Rectangular Winglet Vortex Generators, *Applied Thermal Engineering*, *168* (2020), 114838
[19] Zhang, K., *et al*., Effects of the Configuration of Winglet Vortex Generators on Turbulent Heat Transfer Enhancement in Circular Tubes, *International Journal of Heat and Mass Transfer*, *157* (2020), 119928
[20] Aridi, R., *et al*., CFD Analysis on the Spatial Effect of Vortex Generators in Concentric Tube Heat Exchangers: A Comparative Study, *International Journal of Thermofluids*, *16* (2022), 100247
[21] Gnielinski, V., On Heat Transfer in Tubes, *International Journal of Heat and Mass Transfer*, *63* (2013), Aug., pp. 134-140
[22] Petukhov, B. S., Heat Transfer and Friction in Turbulent Pipe Flow with Variable Physical Properties, *Advances in Heat Transfer*, *6* (1970), pp. 503-564
[23] Nakhchi, M. E., Esfahani, J. A., Numerical Investigation of Different Geometrical Parameters of Perforated Conical Rings on Flow Structure and Heat Transfer in Heat Exchangers, *Applied Thermal Engineering*, *156* (2019), June, pp. 494-505

[24] Eiamsa-Ard, S., *et al*., Parametric Study on Thermal Enhancement and Flow Characteristics in a Heat Exchanger Tube Installed with Protruded Baffle Bundles, *International Journal of Thermal Sciences*, *145* (2019), 106016
[25] Zhai, C., *et al*., Heat Transfer Augmentation in a Circular Tube with Delta Winglet Vortex Generator Pairs, *International Journal of Thermal Sciences*, *140* (2019), June, pp. 480-490

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