Thermo-Hydraulic Performance of Round Tubes Installed with Double V-Shaped Winglet Vortex Generators: Effect of Blockage Ratio

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***Abstract*— Double V-shaped winglet vortex generators is proposed in the present research enhancing heat transfer and thermal-hydraulic performance factor. The numerical simulation was performed to study the effects of blockage ratios (e/D = 0.05-0.15) and Reynolds numbers (Re = 5000-15,000) on heat transfer rate, flow structure, local heat transfer, pressure loss and thermal-hydraulic performance factor characteristics. The double V-shaped winglets were installed in tandem arrangement on the top and bottom of tubes with constant pitch ratio of p/D = 1.0. Water was employed as the working fluid for Reynolds numbers ranging from 5000 to 15,000 under constant wall temperature boundary conditions. The numerical results demonstrated that the vortex generators induced swirling motion which helped in improving fluid flow mixing, leading to heat transfer enhancement with a moderate pressure loss penalty. Heat transfer and friction loss increased with increasing blockage ratio and Reynolds number while thermal-hydraulic performance factor showed opposite trend. The maximum thermal-hydraulic performance factor of 1.89 was obtained by using the vortex generator with the smallest blockage ratio (e/D) of 0.05 at the lowest Reynolds number of 5000.**

***Index Terms*— Double V-shaped winglet, heat transfer, heat exchanger tube, thermal-hydraulic performance, vortex generator**

I. Introduction

Passive heat transfer enhancement is extensively applied in thermal engineering areas in order to increase the thermal-hydraulic performance, reduce the cost, size and weight of heat exchangers. Longitudinal-vortex motion or swirl motion generating, one of passive techniques is a promising technique in increasing the residence time of the fluid and promoting fluid mixing and also turbulence intensity. Swirl motion can be generated by using insert devices for instance winglet pair, perforated twisted-tapes, double-sided delta-wing tape, tapered twisted tape, circular-ring, wire coil, *etc* [1-8]. Liu *et al.* [9] studied the heat transfer and pressure loss behaviors of a heat exchanger inserted with rectangular winglets in turbulent flow regime (Reynolds numbers ranging from 5000 to 17,000) using water as test fluid. The inserts with different slant angles (10°-35°) and the asymmetric winglet heights (H_2/D = 0.2-0.5) were tested. Their results showed that heat transfer rate and pressure loss increased with increasing slant angle and asymmetric winglet height. For their tested range, heat transfer rate and pressure loss of the tube inserted with rectangular winglets were up to 2.49 times and 12.32 times as compared to those of the plain tube alone. However, thermal-hydraulic performance factor increased first, and then decreased with the increases of slant angle and asymmetric winglet height. The highest thermal-hydraulic performance factor of 1.18 was obtained by using the insert having the slant angle of 30° and asymmetric winglet height of 0.5 at the lowest Reynolds number of 5000. Lei *et al.* [10] investigated the effect of a heat exchanger tube mounted with delta-winglet vortex generators possessing various attack angles (15°-60°) and pitch ratios (1.0-4.0) on heat transfer rate and pressure loss behavior. The use of delta-winglet vortex generators resulted in considerable enhancement of heat transfer with a moderate pressure loss penalty. Their results also showed that heat transfer rate and pressure loss increased with the increasing attack angle and decreasing pitch ratio. Wang *et al.* [11] used the particle image velocimetry to study the heat transfer rate and pressure loss behavior in a heat exchanger tube mounted with multiple vortex generators with various central angles, slice heights and spacing lengths. They found that the multiple pairs of longitudinal vortexes were generated, leading to the increases of the heat transfer rate and flow resistance. They also observed that the heat transfer rate increased

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with the decreasing spacing length, and increasing central angle and slice height. Zhai *et al.* [12] investigated the heat transfer rate and pressure loss characteristics in heat exchanger tube fitted with delta winglet vortex generator pairs arranged in upstream or downstream of flow direction with various pitch ratios (2.4-19.2) in turbulent flow region (*Re* = 5000-25,000). Pitch ratio showed significant influences on the heat transfer rate and pressure loss. The vortex generators with the pitch ratio of 9.6 offered the highest thermal-hydraulic performance factor. In addition, the vortex generators installed downstream of flow yielded higher thermal-hydraulic performance factor than the ones installed upstream flow by around 33%.

From the review made above, passive heat-transfer enhancement devices with vortex generators is one of the popular techniques that is widely studied and geometric parameters of vortex generators are strongly affected heat transfer and pressure loss behaviors in heat exchangers. In the present work, the heat exchanger tube installed with the double V-shaped winglet vortex generators is the case of interest. The aim of this research is to numerically investigate the effect of major factors; blockage ratios (*e/D* = 0.05-0.15) and Reynolds numbers (*Re* = 5000-15,000) on heat transfer rate, flow structure, local heat transfer, pressure loss and thermal-hydraulic performance factor characteristics.

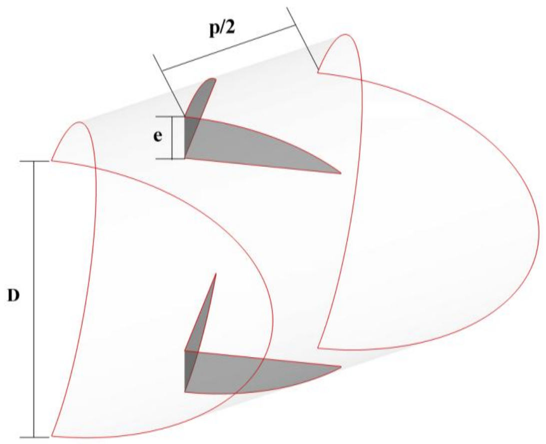


Figure 1. Geometrical details of double V-shaped.

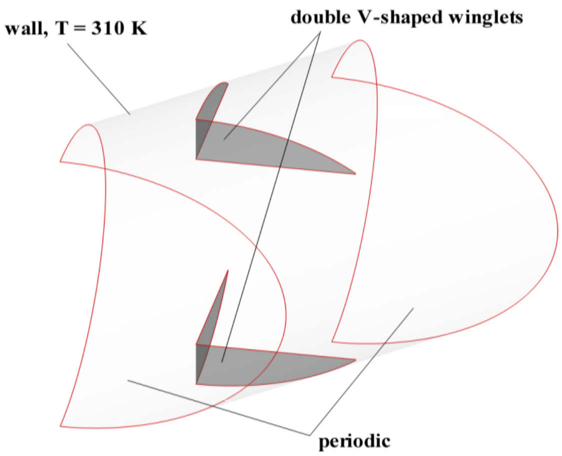


Figure 2. Computational domain.

II. Geometric Details of Double V-shaped Winglets and Boundary Conditions

The geometrical details of the tube flow model installed double V-shaped winglet vortex generators are demonstrated in Fig. 1. The pitch ratio or pitch to diameter ratio (*p/D*) of the double V-shaped winglet was fixed at 1.0. The vortex generators were installed at the top and bottom of tube. The simulation was performed for the vortex generators possessing blockage ratios (*e/D*) of 0.05, 0.1 and 0.15. in the present work, the wall temperature was kept constant at 310 K and no-slip wall condition has been implemented. Water was used as the test fluid, the entry water flow rate is kept constant at 300 K (*Pr* = 0.7). The physical properties of water were assumed to be constant at mean bulk temperature. The periodic boundaries (in which the velocity field repeats itself from one cell/module to another) were applied to the inlet and outlet flow domains as displayed in Fig. 2.

III. Numerical Details

The assumptions for the numerical model applied in the present work are (1) the flow is incompressible and steady three-dimensional, and (2) The body forces, viscous dissipation and radiation heat transfer are ignorable. Based on the assumptions, the continuity, the Navier-Stokes and the energy are the governing equations. In the Cartesian tensor system, these equations can be written as follows:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i' u_j'}\right)\right] \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T)=\frac{\partial}{\partial x_j}\left((\Gamma+\Gamma_t)\frac{\partial T}{\partial x_j}\right) \tag{3}$$

In the present numerical study, the SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm was performed to resolve the flow and pressure equation based on finite volume approach. The discretization scheme for resolved all of the governing equations were the QUICK method. The energy equation and other are considered to be converged when the normalized residual values are less than 10^{-9} and 10^{-5}, respectively. The important parameters (Reynolds number, friction factor, local Nusselt number, mean Nusselt number and thermal-hydraulic performance factor) can be determined as below:

Reynolds number (*Re*) can be determined from

$$\mathrm{Re}=\frac{\rho UD}{\mu} \tag{4}$$

where *D* is the inner diameter.

Friction factor (f) can be expressed as

$$f = \frac{(\Delta P / L)D}{\frac{1}{2}\rho U^2} \tag{5}$$

where U and ΔP are average flow velocity and the pressure drop.

Local Nusselt number (Nu_x) can be determined from

$$Nu_x = \frac{h_x D}{k} \tag{6}$$

where k and h_x are thermal conductivity and local convective heat transfer coefficient, respectively.

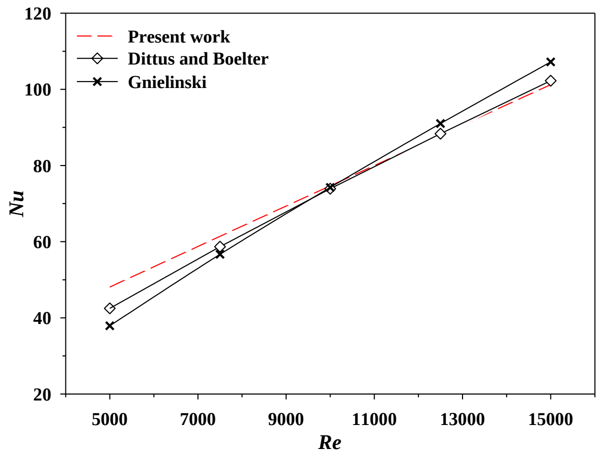
Mean Nusselt number (Nu) can be calculated via

$$Nu = \frac{1}{A}\int Nu_x dA \tag{7}$$

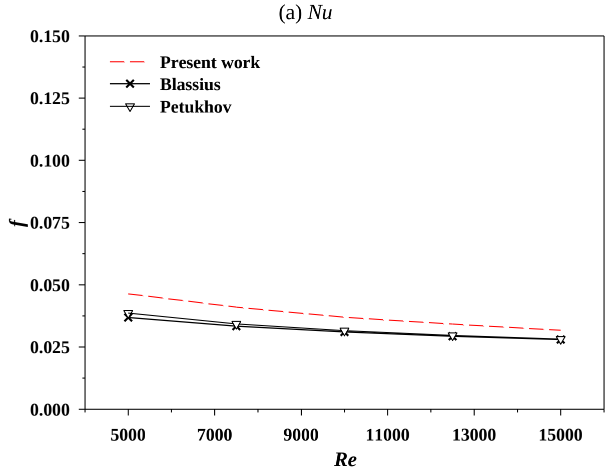
Thermal-hydraulic performance factor (TPF) is defined under the same pumping power.

$$TPF = \frac{(Nu / Nu_p)}{(f / f_p)^{\frac{1}{3}}} \tag{8}$$

where Nu_p and f_p are the Nusselt number and friction factor of the plain tube, respectively.

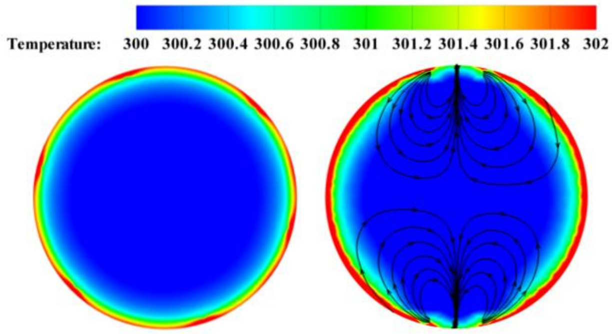


(a) Nu

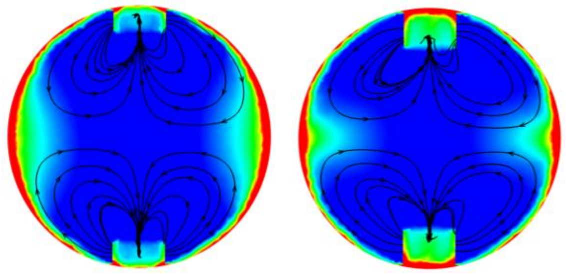


(b) f

Figure 3. Validation test of the plain tube.

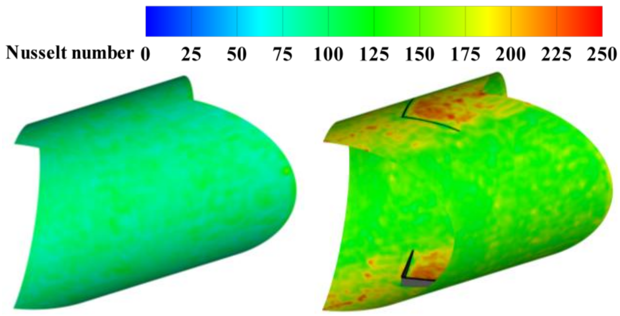


(a) plain tube (b) e/D = 0.05

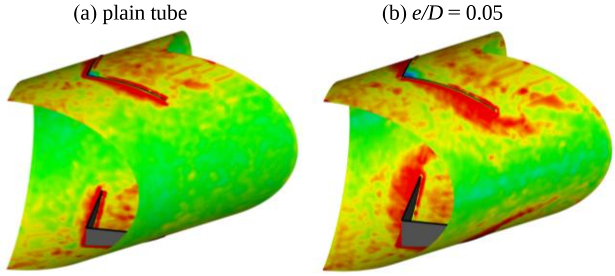


(c) e/D = 0.1 (d) e/D = 0.15

Figure 4. Flow structures and temperature distributions in transverse plane.



(a) plain tube (b) e/D = 0.05



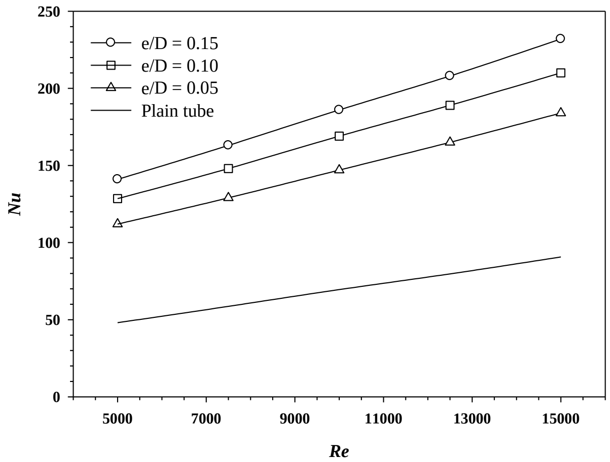
(c) e/D = 0.1 (d) e/D = 0.15

Figure 5. Local Nusselt number distributions of tube installed with double V-shaped winglet.

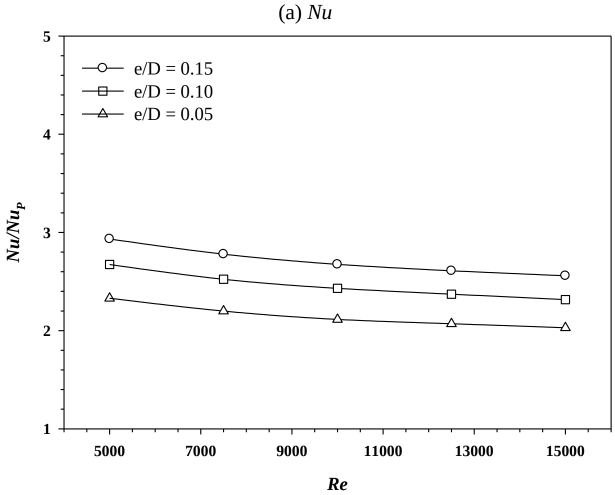
IV. Results and Discussion

Fig. 3 presents the validation test of the plain tube with the previous works. The numerical results indicated that the heat transfer rate (Nu) and friction factor (f) values obtained by using the RNG k-ε turbulent model possessed the minimum deviations of around 10.1% and 6.3%, respectively. Therefore, the RNG k-ε turbulent model was applied for the numerical simulations of the round tubes installed with double V-shaped winglet vortex generators. Fig. 4 displays the flow structures and temperature fields in the tubes installed with double V-shaped winglet vortex generators with different blockage ratios (e/D =

0.05, 0.1 and 0.15) and also the plain tube at Re = 10,000. For the plain tube, the high fluid temperature with high thickness thermal boundary layer (red color contour) was observed near the tube wall region while the low fluid temperature (blue color contour) was observed at the core tube only. The thermal boundary layer was blocked the heat transfer between the fluid and the wall. The thermal layer thicknesses in the tube installed with double V-shaped winglet vortex generators were relatively thinner than those in the plain tube. Evidently, quadruple longitudinal-vortex flows were obviously induced by the vortex generators. The intensity of longitudinal vortex flows was promoted by increasing blockage ratio (e/D) due to the better fluid mixing between the core flow and the one near wall tube. Consequently, the thicknesses of the thermal layers near the wall were significantly reduced.



(a) Nu

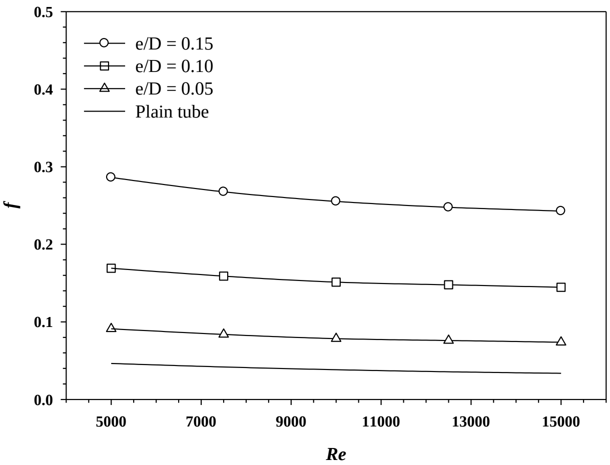


(b) Nu/Nu_p

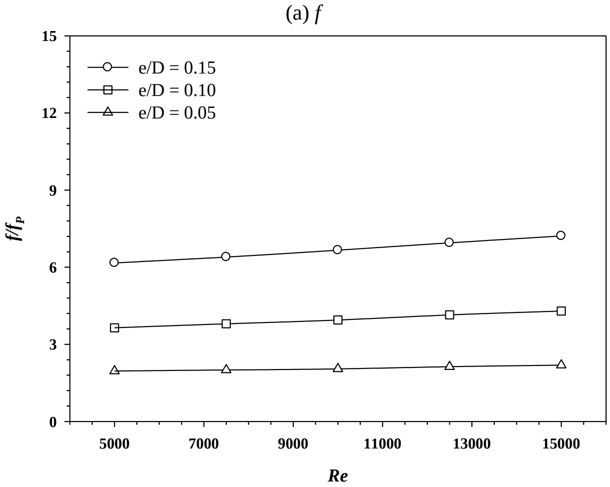
Figure 6. Effect of blockage ratio (e/D = 0.05-0.15) on heat transfer rate.

Fig. 5 demonstrated the local Nusselt number distributions in the tubes installed with double V-shaped winglet vortex generators with different blockage ratios (e/D = 0.05, 0.1 and 0.15) and also the plain tube at Re = 10,000. In the plain tube, local Nusselt numbers were slightly different and mildly changed from core region to wall region, due to the thick thermal boundary layer mentioned above. On the other hand, local Nusselt numbers in the tubes with the vortex generators were changed abruptly from one region to another attributed to the drastic effect of the quadruple longitudinal-vortex flows. The areas impinged by the quadruple longitudinal-vortex flows showed extremely high Nusselt number due to the thermal boundary layer thinning. As blockage ratio (e/D) increased, Nusselt number was increased since quadruple longitudinal-vortex flows became stronger and the thermal boundary layer became thinner.

Figs. 6-8 display the effects of double V-shaped winglet vortex generators on heat transfer rate, friction factor and thermal-hydraulic performance factor. The numerical results showed that the use of the tubes installed with the vortex generators led to the considerable increase in heat transfer rate (Nu) in comparison with that of the plain tube. In addition, heat transfer rate (Nu) tended to increase with the rises of Reynolds number and blockage ratio (e/D). The tubes installed with the vortex generators having blockage ratios (e/D) of 0.05, 0.1 and 0.15 gave heat transfer rate (Nu) up to 2.18, 2.5 and 2.75 times of the plain tube, respectively. In other words, the vortex generators with the largest blockage ratio (e/D) of 0.15 gave higher heat transfer rate than the ones with blockage ratios (e/D) of 0.05 and 0.1 by about 1.1 and 1.26 times.



(a) f



(b) f/f_p

Figure 7. Effect of blockage ratio (e/D= 0.05-0.15) on friction factor.

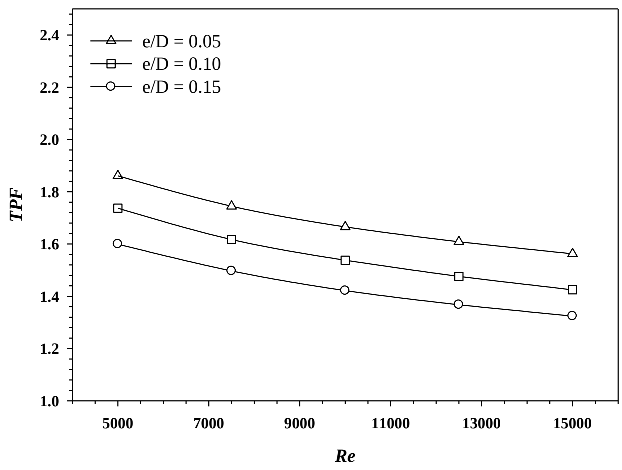


Figure 8. Effect of blockage ratio (*e/D*= 0.05-0.15) on thermal-hydraulic performance factor.

Fig. 7 shows that friction factors (*f*) of the tubes installed with vortex generators were considerably higher than those of the plain tube at the same Reynolds number. Friction factor slightly decreased with increasing Reynolds number but significantly increased with the increase of blockage ratio. The vortex generators having blockage ratios (*e/D*) of 0.05, 0.1 and 0.15 caused maximum friction factors of about 2.08, 3.97 and 6.69 times of that of the plain tube. Fig. 8 shows that thermal-hydraulic performance factors of the tubes installed with vortex generators decreased with increasing Reynolds number. At a given Reynolds number, thermal-hydraulic performance factor increased with decreasing blockage ratio. The maximum thermal-hydraulic performance factor of 1.86 was obtained by using the vortex generator with the smallest blockage ratio (*e/D*) of 0.05 at the lowest Reynolds number of 5000. Although the vortex generator with *e/D* = 0.05 yielded lower heat transfer rate than the ones with *e/D* = 0.10 and 0.15, the vortex generator caused lower friction loss which was a major factor influencing the thermal-hydraulic performance factor in the present work. In addition, the thermal-hydraulic performance factor of the tube installed with the vortex generator having *e/D* = 0.05 was higher than those of the ones with *e/D* = 0.1 and 0.15 by about 1.09 and 1.17 times.

V. Summary

This research attempted to shed light on the heat transfer enhancement mechanism in the tubes installed with double V-shaped winglet vortex generators. The effects of blockage ratios (*e/D* = 0.05, 0.1 and 0.15) of the vortex generators on heat transfer rate, friction factor and thermal-hydraulic performance factor were investigated. The numerical results revealed that the vortex generators with the largest blockage ratio (*e/D* = 0.15) gave the highest heat transfer rate and friction factor which were up to 2.93 and 7.22 times of the plain tube, respectively. However, the maximum thermal-hydraulic performance factor of 1.86 was obtained by using the vortex generator with the smallest blockage ratio (*e/D*) of 0.05 at the lowest Reynolds number of 5000. The results indicated that the lower friction loss was a major factor influencing the thermal-hydraulic performance factor in the present work.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Prachya Somravysin; conducted the research. Boonsong Samutpraphut conducted the research and wrote the paper and analyzed the data. Khwanchit Wongcharee analyzed the data. Smith Eiamsa-ard analyzed the data. Anucha Saysroy wrote the paper and analyzed the data. Varesa Chuwattanakul analyzed the data

All authors had approved the final version.

References

[1] C. Thianpong, P. Eiamsa-ard, S. Eiamsa-ard, “Heat transfer and thermal performance characteristics of heat exchanger tube fitted with perforated twisted-tapes,” *Heat Mass Transf*, vol. 48, 2012, pp. 881-892.

[2] S. Tamna, “Numerical heat transfer investigation in a tube with inclined flower baffles,” *J. Res. Appl. Mech. Eng.*, vol. 2, 2014, pp. 95-102.

[3] S. Eiamsa-ard, P. Promvonge, “Influence of double-sided delta-wing tape insert with alternate-axes on flow and heat transfer characteristics in a heat exchanger tube,” *Chinese J. Chem. Eng.*, vol. 19, 2011, pp. 410-423.

[4] R. M. Sarviya, V. Fuskele, “Heat transfer and pressure drop in a circular tube fitted with twisted tape insert having continuous cut edges,” *J. Energy Storage*, vol. 19, 2018, pp. 10-14.

[5] N. Piriyarungrod, S. Eiamsa-ard, C. Thianpong, M. Pimsarn, K. Nanan, *Chem. Eng. Processing: Process Intensification*, vol. 96, 2015, pp. 62.

[6] S. Ponnada, T. Subrahmanyam, S. V. Naidu, “A comparative study on the thermal performance of water in a circular tube with twisted tapes, perforated twisted tapes and perforated twisted tapes with alternate axis,” *Int. J. Thermal Sciences*, vol. 136, 2019, pp. 530-538.

[7] S. Eiamsa-ard, V. Kongkaitpaiboon, K. Nanan, “Thermohydraulics of turbulent flow through heat exchanger tubes fitted with circular-rings and twisted tapes,” *Chinese J. Chem. Eng.*, vol. 21, 2013, pp. 585-593.

[8] S. Eiamsa-ard, N. Koolnapadol, P. Promvonge, “Heat transfer behavior in a square duct with tandem wire coil element insert,” *Chinese J. Chem. Eng.*, vol. 20, 2012, pp. 863-869.

[9] H. L. Liu, H. Li, Y.L. He, and Z.T. Chen, “Heat transfer and flow characteristics in a circular tube fitted with rectangular winglet vortex generators,” *Int. J. Heat Mass Transf*, vol. 126, 2018, pp. 989-1006.

[10] Y. Lei, F. Zheng, C. Song and Y. Lyu, “Improving the thermal hydraulic performance of a circular tube by using punched delta-winglet vortex generators,” *Int. J. Heat Mass Transf*, vol. 111 2017, pp. 299-311.

[11] Y. Wang, P. Liu, F. Shan, Z. Liu, and W. Liu, “Effect of longitudinal vortex generator on the heat transfer enhancement of a circular tube,” *Appl. Thermal Eng.*, vol. 148, 2019, pp. 1018-1028.

[12] C. Zhai, M. D. Islam, M. M. Alam, R. Simmons, and I. Barsoum, “Parametric study of major factors affecting heat transfer enhancement in a circular tube with vortex generator pairs,” *Appl. Thermal Eng.*, vol. 153, 2019, pp. 330-340.

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