Investigation on Performance Evaluation of Corrugated Low Finned Tubes Oriented for Energy Saving

Bin Ren1,2*, ZhePu1, Xiaoying Tang1,2, Sun Si1, Aini He1,2, Hongliang Lu1,2

1Shanghai Institute of Special Equipment Inspection and Technical Research, Putuo District, Shanghai, 200062, China
2National Heat Exchanger Product Quality Supervision and Inspection Center, Jinshan District, Shanghai, 201518, China
*Corresponding author’s e-mail: renbin_580912@163.com

Abstract. Heat exchangers are the energy facilities that exchange heat in process industries. Corrugated low finned tube is a kind of helically corrugated tube with trapezoidal shape groove. In this paper, the comparison approach is adopted to evaluate the overall performance of corrugated low finned tubes. The heat transfer and friction factor correlations were firstly introduced. Then the overall performance was evaluated for the identical pressure drop and identical pumping power. Finally, the performance evaluation criteria were fitted as the function of Reynolds number, Prandtl number, pitch to diameter ratio and rib height to diameter ratio. The results showed that both the evaluation factors at identical pumping power and at the identical pressure drop are greater than 1.0 over the entire Reynolds number for all the enhanced tubes, indicating that the enhanced tubes have the second best performance oriented from energy-saving.

1. Introduction

Heat exchangers are the energy facilities that exchange heat in process industries, such as petroleum, chemical, power, heating and air conditioning. The heat transfer enhancement is used to reduce heat transfer surface area, reduce temperature difference, increase heat transfer rate and reduce pumping power [1]. The heat transfer enhancement techniques can be classified into three categories: active method, passive method and compound method. The active techniques are more complex compared with the passive techniques because of the need of external power [2].

Corrugated low finned tube (CLFT) is a kind of spirally corrugated tube with trapezoidal profile. Ren et al [3] experimentally studied the heat transfer performance under the turbulent flow condition. Due to the wider spiral protrusion, its heat transfer performance is better than that of ordinary spirally corrugated tube. The effects of tube structural parameter and fluid Reynolds number were also analysed. Ren et al [4] investigated the flow resistance characteristic of corrugated low finned tubes. The results showed that all the enhanced tubes had a larger friction factor than the smooth tube.

It is well known that the ratio of pressure drop increase is often larger than the ratio of heat transfer enhancement under singlephase flow [5]. Numerous researchers have proposed the performance evaluation methods from the perspective of the first and second laws of thermodynamics. Bejan [6] used the second law of thermodynamics to evaluate the irreversibility (entropy generation) associated with simple heat transfer processes. Ji et al [7] used performance evaluation plot to evaluate the...
thermal-hydraulic performance of liquid flow and heat transfer in pipes with internal integral-fins, twisted tape inserts, corrugations, dimples, and compound enhancement techniques. The main purpose of heat transfer augmentation has been changed into energy-saving. So in this paper, the comparison approach is adopted to evaluate the overall performance of corrugated low finned tubes. The heat transfer and friction factor correlations were firstly introduced. Then the overall performance was evaluated for the identical pressure drop and identical pumping power. Finally, the performance evaluation criteria were fitted as the function of Reynolds number, Prandtl number, pitch to diameter ratio and rib height to diameter ratio.

2. Experimental apparatus and object

2.1 Experimental apparatus
The experimental apparatus consisted of the heating water circuit, the test section, the cooling water circuit and the data acquisition system. During the experiment, the volume flow rate of shell side was kept as large as possible to reduce the temperature fluctuation. The volume flow rate of tube side was adjusted with the maximum range (at least six different flow rates). Then the heat transfer performance can be obtained by modified Wilson plot method. The volume flow rates of heating water and cooling water were measured by turbine flowmeter. The inlet and outlet temperatures of heating water and cooling water were measured by thermocouples. And the pressure drops of fluids were measured by pressure difference transmitters.

2.2 Experimental object
Three corrugated low finned tubes were selected from Chinese standard GB/T 24590-2009. These tubes were made of stainless steel tube with 19mm in outer diameter, 2mm in thickness and 1750mm in length. As it can be found in Table, #2 and #3 have the same rib height of e=0.5mm and different pitch of P=6 and 8mm. Tube #2 and #5 have the same pitch of P=6mm and different rib height of e=0.5 and 0.7mm.

| Type | d_o, mm | t, mm | e_o, mm | e, mm | p, mm | L, mm |
|------|---------|-------|---------|-------|-------|-------|
| ST   | 19      | 2     | /       | /     | /     | 1750  |
| #2   | 19      | 2     | 0.7     | 0.5   | 6     | 1750  |
| #3   | 19      | 2     | 0.7     | 0.5   | 8     | 1750  |
| #5   | 19      | 2     | 0.9     | 0.7   | 6     | 1750  |

3. Results and discussion

3.1 Correlations for Nusselt number and friction factor
The fitted empirical correlations for Nusselt number and friction factor [3, 4] are respectively described in Eq. (1) and Eq.(2). The experimental heat transfer and friction factor of tube #3 are compared with the predicted values by the fitted equations and the existing correlations in Figure 1 and Figure 2. These two figures show that the fitted equations can predict the experimental Nusselt number and friction factor very well with the maximum errors of -10% and +5% respectively. In addition, both the correlations proposed by Vicence at al. [8] and Yang et al. [9] overestimate the experimental Nusselt number with the maximum deviation of +20%. Both the proposed correlations underestimate the experimental friction factor with the maximum deviation of -20%. The main reason is contributed to the different structural parameters of the testing tubes.

\[
Nu = 1.121 \cdot Re^{0.638} \cdot Pr^{0.33} \cdot \left(\frac{P}{d_f}\right)^{-0.239} \cdot \left(\frac{e}{d_f}\right)^{0.461}
\]  \hspace{1cm} (1)
0.328 0.979
0.219 2.135
\[ f = 21.335 \cdot Re^{-0.219} \left( \frac{P}{d_i} \right)^{-0.328} \left( \frac{e}{d_i} \right)^{0.979} \] 

Figure 1. Comparison between measured and calculated Nu of tube #3

Figure 2. Comparison between measured and calculated f of tube #3

3.2 Overall performance evaluation

The performance evaluation criteria at identical pumping power and identical pressure drop are adopted, as described in Eq. (3) and Eq. (4). The variations of performance evaluation at identical pumping power are presented in Fig. 3. It can be seen that the evaluation factors at identical pumping power are greater than 1.0 over the entire Reynolds number for all the enhanced tubes. This means that the heat transfer performance can be enhanced with the same pumping power. Moreover, the factors decrease with the increase of Reynolds number. The evaluation factors are highest inside tube #5, indicating that the factors increase with the increase of rib height and decrease of pitch.

\[ \eta_{u3} = \left( \frac{Nu_o}{Nu_i} \right) \left( \frac{f_u}{f_i} \right)^{1/3} \] (3)

\[ \eta_{u2} = \left( \frac{Nu_o}{Nu_i} \right) \left( \frac{f_u}{f_i} \right)^{1/2} \] (4)

Figure 4 shows the variations of performance evaluation at identical pressure drop. It is observed that the evaluation factors at identical pressure drop are greater than 1.0 over the entire Reynolds number for all the enhanced tubes, inferring that the heat transfer performance can be enhanced with
the same pressure drop. According to Fan's classification, the enhanced tubes have the second best performance oriented from energy-saving.

![Graph](image1.png)

**Figure 3. Variation of $\eta^{1/3}$ with $Re$**

![Graph](image2.png)

**Figure 4. Variation of $\eta^{1/2}$ with $Re$**

### 3.3 Correlations for performance evaluation criteria

By fitting the experimental data, the performance evaluation criteria for the identical pumping power and identical pressure drop can be correlated as the function of Reynolds number, Prandtl Number, pitch to diameter ratio and rib height to diameter ratio. The correlations are respectively expressed as Eq. (5) and Eq. (6). Figure 5 and Figure 6 present the comparison between experimental and the predicted evaluation criteria. It can be found that all of the data points from Eq. (5) and Eq. (6) agree well with the experimental values with the maximum deviation of $\pm 5\%$, showing that the correlations can predict the performance evaluation criteria very well. It should be mentioned that the above correlation is applicable with the Reynolds number ranges from 15,000 to 65,000, pitch to diameter ratio from 0.267 to 0.533 and rib height to diameter ratio from 0.020 to 0.047.

\[
\eta_{1/3} = 12.471 \cdot Re^{-0.172} \left( \frac{p}{d_i} \right)^{-0.132} \left( \frac{e}{d_i} \right)^{0.134} \tag{5}
\]

\[
\eta_{1/2} = 6.271 \cdot Re^{0.178} \left( \frac{p}{d_i} \right)^{-0.078} \left( \frac{e}{d_i} \right)^{-0.029} \tag{6}
\]
5

Figure 5. Comparison between measured and predicted $\eta_{1/3}$

Figure 6. Comparison between measured and predicted $\eta_{1/2}$

4. Conclusions
In this paper, the overall performances of corrugated low finned tubes are evaluated by comparison approach. The results showed that both the evaluation factors at identical pumping power and at the identical pressure drop are greater than 1.0 over the entire Reynolds number for all the enhanced tubes, indicating that the enhanced tubes have the second best performance oriented from energy-saving. And the performance evaluation criteria are fitted from the experimental data which can predict the overall performance very well.

Acknowledgments
This work was supported by the 2016 Shanghai Leading Talents Training Program for Professor Xiaoying Tang.

References
[1] Webb, R. L., Kim, N. H. (2005) Principles of Enhanced Heat Transfer, 2nd ed. Taylor & Francis, Boca Raton.
[2] Sheikholeslami, M., Gorji-Bandpy, M., Ganji, D. D. (2015) Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. Renewable and Sustainable Energy Reviews, 49: 444-469.
[3] Ren, B., Si, J., Tang, X. Y., et al. (2019) Experimental investigation on heat transfer performance of corrugated low finned tubes. In: 2019 5th International Conference on Energy Equipment Science and Engineering. Harbin, China.

[4] Ren, B., Pu, Z., Tang, X. Y., et al. (2020) Experimental study on flow resistance characteristic of corrugated low finned tubes. In: 2020 4th International Conference on Advances in Energy, Environment and Chemical Science. Shenzhen, China.

[5] Fan, J. F., Ding, W. K., Zhang, J. F., et al. (2009) A performance evaluation plot of enhanced heat transfer techniques oriented for energy-saving. International Journal of Heat and Mass Transfer, 52: 33-44.

[6] Bejan, A. (1980) Second law analysis in heat transfer. Energy 5: 721-732.

[7] Ji, W. T., Jacobi, A. M., He, Y. L., et al. (2015) Summary and evaluation on single-phase heat transfer enhancement techniques of liquid laminar and turbulent pipe flow. International Journal of Heat and Mass Transfer, 88: 735-754.

[8] Yang, D., Li, H. X., Chen, T. K. (2001) Pressure drop, heat transfer and performance of single-phase turbulent flow in spirally corrugated tubes. Experimental Thermal and Fluid Science, 24(3-4): 131-138.

[9] Vicente, P. G., Garcia, A., Viedma, A. (2004) Experimental investigation on heat transfer and frictional characteristics of spirally corrugated tubes in turbulent flow at different Prandtl numbers. International Journal of Heat and Mass Transfer, 47(4): 671-681.