Comparison of Heat Transfer Performance for Condensation in Corrugated Low Finned Tube and Smooth Tube with Air

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Abstract. The existence of air served as non-condensable gas makes it difficult to design effective titanium condenser in PTA plant. In this paper, the heat transfer characteristic for condensation inside corrugated low finned tube and smooth tube in presence of air was compared. The local heat transfer performance was studied by comparing bulk temperature and local heat transfer rate. The effect of non-condensable gas mass fraction on overall heat transfer performance was also analysed. The results indicated that both the bulk temperature and the local heat transfer rate decreased along the axial direction due to the reduction of steam partial pressure and temperature difference. The average heat transfer coefficient and total heat transfer rate decreased with the increase of inlet non-condensable gas mass fraction. And the corrugated low finned tube could reduce the impact of non-condensable gas by reducing the thickness of gas film and condensate film.

1. Introduction
Titanium condensers in pure terephthalic acid (PTA) plants are utilized to condense mixed vapour evaporated from oxidation reactor [1]. Owing to the expansive price of titanium, the effective horizontal condensers are utilized to replace the common vertical condensers from the perspective of economic incentives. Using special-shaped enhanced tubes instead of smooth tubes is the most convenient and practicable heat transfer enhancement technology [2]. In the case of in-tube condensation, corrugated tubes are the most used enhanced tubes [3].

Laohalertdecha and Wongwises [4] investigated the condensation heat transfer and flow performances of R-134a flowing through corrugated tubes. The results indicated that the Nusselt number and two-phase friction factor inside corrugated tubes were significantly higher than those inside smooth tube. Khoelini et al. [5] investigated the effect of inclination on condensation heat transfer performance of R-134a flowing through corrugated tubes. It was showed that at all mass velocities, the largest average heat transfer coefficients were obtained for $\alpha=+30$deg.

As a special kind of corrugated tube, corrugated low finned tube (CLFT) is a type of spirally corrugated tube with trapezoidal concave outside the tube and sinusoidal rib inside the tube. Ren et al [6] experimentally studied the performances of condensation and flow resistance in horizontal corrugated low finned tubes. The result showed that both the heat transfer coefficient and the pressure drop in enhanced tubes were higher than those in smooth tube. The effect of inlet conditions and...
construal parameters were also analysed. And the comprehensive performance was evaluated using the performance evaluation criteria method.

High fraction air in the mixed vapour serves as the non-condensable gas, leading to the difficulty to design this type of condenser. It is well known that small amount of non-condensable gas dramatically reduces the condensation heat transfer performance. Wu and Vierow [7] experimentally investigated the heat transfer and fluid flow performances in a horizontal condenser tube. The results showed that the condensation heat transfer coefficient on the tube top was much larger than that at the bottom. Ren et al [8] established a numerical model based on Liao’s modified diffusion layer theory to investigate the condensation of steam/air mixture. The distributions of temperatures, gas concentrations and heat transfer coefficients were showed along the axial direction.

However, there are few researchers who have studied the condensation mechanism in enhanced tube with non-condensable gas. Only Ren et al [9] investigated the influence of non-condensable gas on condensation heat transfer performance in corrugated low finned tubes. But there is a lack of comparison of heat transfer characteristic between corrugated low finned tubes and smooth tube. So in this work, the comparison of heat transfer performance for condensation in corrugated low finned tube and smooth tube in presence of air was conducted. The local heat transfer characteristic was studied by comparing the bulk temperature and local heat transfer rate. And the impact of non-condensable gas mass fraction on overall heat transfer performance was analysed.

2. Experimental apparatus and object

2.1. Experimental apparatus

The experimental apparatus used here was the same as described in Ren’s paper [1], including steam/air loop, the cooling water circuit, the test section and the data acquisition system. The steam and air were respectively supplied by the boiler and compressor. The test unit was a double pipe heat exchanger. The inner tube could be either the corrugated low finned tube or the smooth tube. The steam/air mixture condensed in the inner tube and the cooling water counter-currently flowed through the annular channel. To study the local heat transfer characteristic, the temperatures of bulk gas and coolant were measured at six axial sites along the condenser tube as shown in Fig. 1. The wall temperature of the condenser tube cannot be measured due to the irregular surface, which was different with Ren’s work. To study the overall heat transfer performance, the inlet and outlet temperatures of the gas mixture and the coolant were also measured by sheathed thermocouples.

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2.2. Experimental object

One corrugated low finned tube was selected from Chinese standard GB/T 24590-2009. This enhanced tube was made of stainless steel with the outer diameter of 19mm, the thickness of 2mm and the length of 1750 mm. After being rolled on a lathe, the rib height was 0.5mm and the pitch was 6mm. This tube was named tube #1. According to the previous research, this tube had the better comprehensive heat transfer.
transfer performance. A smooth tube for contrast was also made of stainless steel tube with the same outer diameter, thickness and length.

3. Results and discussion

3.1. Distribution of local parameters

The distributions of bulk temperature along condenser tube in tube #1 and smooth tube are showed in Fig. 1. The gas mixture temperature is actually the steam saturation temperature. The temperatures both inside tube #1 and inside smooth tube decrease along the axial direction. The reason is that the non-condensable gas fraction increases as steam condensates, resulting in the decrease of steam partial pressure. In addition, the descending rate of temperature in tube #1 is significantly larger than that in smooth tube, which shows that the condensation rate in tube #1 is faster than that in smooth tube.

Figure 2 presents the distributions of heat transfer rate of each measuring section inside tube #1 and smooth tube. It is found that the heat transfer rates decrease along the axial direction inside the two tubes because of two reasons. One reason is that the thickness of liquid and gas layer gradually increases as condensation proceeds, leading to the deterioration of condensation heat transfer coefficient. The other reason is that the temperature difference between gas bulk and wall decreases along the tube due to the decrease of bulk temperature. In addition, the descending rate in tube #1 is larger than that in smooth tube, owing to the higher condensation capability.

![Figure 2. Distribution of gas temperature along the axial direction](image1)

![Figure 3. Distribution of heat transfer rate along the axial direction](image2)

3.2. Variation of heat transfer coefficient
Figure 3 shows the changing curve of average heat transfer coefficient with non-condensable gas fraction. It is clearly that the average heat transfer coefficient decreases with the increase of inlet non-condensable gas fraction both in tube #1 and smooth tube. This is because the thermal resistance in the condenser tube consists of thermal resistance of the gas film and thermal resistance of liquid film. The higher inlet non-condensable gas mass fraction means the higher thermal resistance of gas film, leading to the smaller condensation heat transfer coefficient. Meanwhile, the heat transfer coefficient of tube #1 and smooth tube decreases by 18.04% and 28.37% respectively when inlet non-condensable gas fraction varies from 0.05 to 0.3. This shows that the corrugated low finned tube can lighten the influence of non-condensable gas due to its spiral protrusion.

Figure 4. Variation of heat transfer coefficient with non-condensable gas fraction

3.3. Variation of heat transfer rate

The variation of total heat transfer rate with inlet non-condensable gas fraction is illustrated in Fig.5. It can be found that the higher gas mass fraction leads to the smaller heat transfer rate. This is because both the condensation heat transfer coefficient and temperature difference decrease as gas mass fraction increases. And the heat transfer rate in tube #1 and smooth tube decreases by 16.42% and 21.28% respectively when the non-condensable gas fraction changes from 0.05 to 0.3. This also indicates that the corrugated low finned tube can lighten the impact of non-condensable gas. This is because the spiral protrusions can not only thinning the thickness of liquid film but also reduce the thickness of gas film.

Figure 5. Variation of heat transfer rate with non-condensable gas fraction
4. Conclusions
In this paper, the heat transfer characteristic for condensation in corrugated low finned tube and smooth tube in presence of air was compared. The distribution of local parameters and effect of non-condensable gas mass fraction on overall heat transfer performance were investigated. The results showed that both the bulk temperature and the local heat transfer rate decreased along the axial direction due to the reduction of steam partial pressure and temperature difference. Increasing inlet non-condensable gas mass fraction could decrease the average heat transfer coefficient and total heat transfer rate. And the corrugated low finned tube could reduce the impact of non-condensable gas by reducing the thickness of gas film and liquid film.

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