Journal of Southeast University (English Edition) Vol. 26, No. 2, pp. 339 – 342 June 2010 ISSN 1003—7985

Pool boiling performance of porous surface tubes under vacuum conditions

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Abstract: Two types of tube bundles are designed, which are, respectively, composed of six tubes arranged in the boiling chamber. The nucleate pool boiling performance of smooth tube bundles and sintered porous surface tube bundles with deionized water as a medium are experimentally studied at atmospheric and sub-atmospheric pressures, respectively. The experimental results indicate that the boiling heat transfer coefficients of the two types of tube bundles increase with the increase in pressure under vacuum conditions as they behave under ordinary pressure. As the pressure varies from 10 to 100 kPa, it also can be seen that the heat transfer coefficient of the sintered porous surface tube is increased by 0. 2 to 4 times compared with the smooth one under the same operating parameters. In addition, the experimental data show that a definite bundle effect exists in both sintered porous surface tubes and smooth tubes under vacuum conditions.

Key words: pool boiling; porous surface tube; heat transfer enhancement

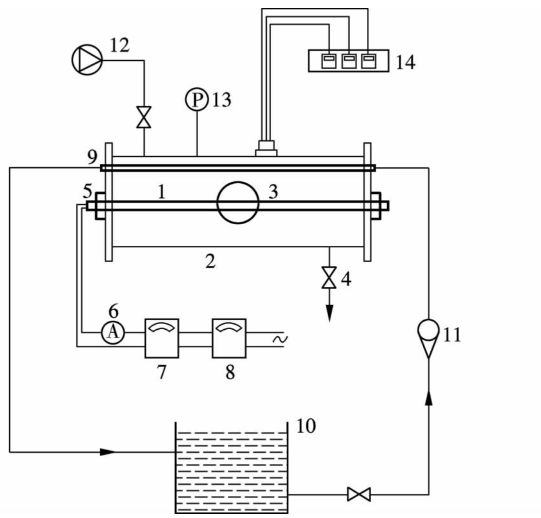
With the development of modern industry, more and more energy saving technologies have been used in various new types of heat exchangers[1]. A kind of high flux tube-and-shell heat exchanger usually used as an evaporator or a reboiler, which has sintered porous surface tube bundles inside. The boiling heat transfer coefficients of the sintered porous surface tubes may be over 10 times greater than those of the smooth tubes[2], and the enhanced heat transfer performance of the porous tubes above atmospheric pressure has been studied[3-5]; however, the pool boiling heat transfer performance of the sintered porous surface tubes under vacuum conditions has hardly been reported in the available literature yet. Accordingly, further research should be carried out in this field.

In this paper, an experimental study of the nucleate pool boiling of deionized water outside horizontal sintered porous surface tube bundles is carried out compared with conventional plain tube bundles. The pool boiling characteristics of porous surface tubes and smooth tubes under vacuum conditions are also analyzed.

1 Experiment and Principle

The thin brass tubes are applied in this testing. The effective length of the tubes is 200 mm and the external diameter is 10 mm. The wall thickness is 1 mm and the thickness of the porous layer is 0. 2 mm. The porosity is about 60% [6].

The testing system is shown in Fig. 1. The electrical heating rod is put into the test tube to heat the liquid out of the tubes. According to the heat transfer equation $\alpha = Q/(A\Delta T) = q/\Delta T$, the boiling heat transfer coefficient α can be obtained. Here, Q is the power of the electric heating rod; q is the heat flux, which can be calculated based on the superficial area of the heating tube; the temperature difference of the boiling heat transfer is equal to the difference between the wall temperature and the main temperature of the boiling solution.



1—Test tube; 2—Boiling room; 3—Sight glass; 4—Vacuum valve; 5—Heating rod; 6—Ammeter; 7—Voltage regulator; 8—Regulator; 9—Cooling tube; 10—Cooling water tank; 11—Flowmeter; 12—Vacuum pump; 13—Vacuum gauge; 14—Temperature measurement system

Fig. 1 System diagram of experimental apparatus

The core component of the experimental device is the boiling room, as shown in Fig. 2. Four smooth tubes are installed in the upper part of the boiling room as a condenser instead of using a separate condenser to reduce the numbers of pipeline joints and the possibility of the leakage. The water vapor generated by the boiling heat transfer makes a condensation directly at the top of the boiling room. Thereby, the vacuum of the boiling room can remain stable.

In the boiling chamber, the distance between the tube centers is 14 mm. Tubes 1 to 4 are porous tubes, and tubes 5 to 8 are smooth tubes, as shown in Fig. 2. As for a single tube, tube 1 and tube 5 are used for comparison experiments. In addition, the other tubes are used for tube-bundle comparison experiments. In order to prevent heat loss, the two ends of the tubes are sealed with asbestos rope, and the entire device is wrapped with heat insulation cotton. Deionized water is used as a medium in the experiments.

Received 2009-11-16.

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Foundation item: The National Natural Science Foundation of China (No. 50706012).

Citation: Wang Xuesheng, Dai Jingjing, Cong Jianli, et al. Pool boiling performance of porous surface tubes under vacuum conditions [J]. Journal of Southeast University (English Edition), 2010, 26(2): 339 – 342.

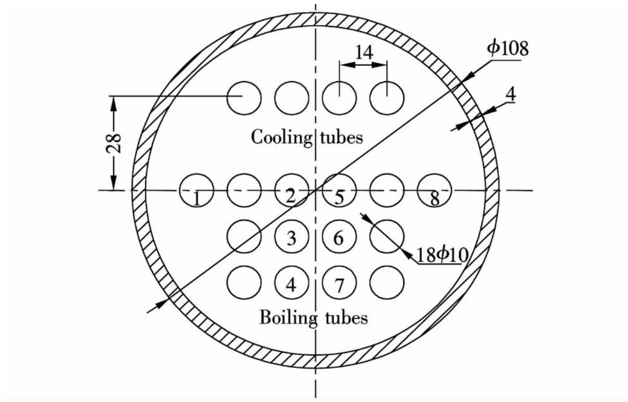

Fig. 2 Schematic of pipe layed in the boiling chamber

2 Results and Discussion

2.1 Effect of heat load on boiling heat transfer coefficient

Deionized water is heated to a boil under three operating pressures (P = 10, 15, 25 kPa) in this study. The relationships between the boiling heat transfer coefficients of the porous tubes and the smooth tubes and the heat load q are shown in Fig. 3.

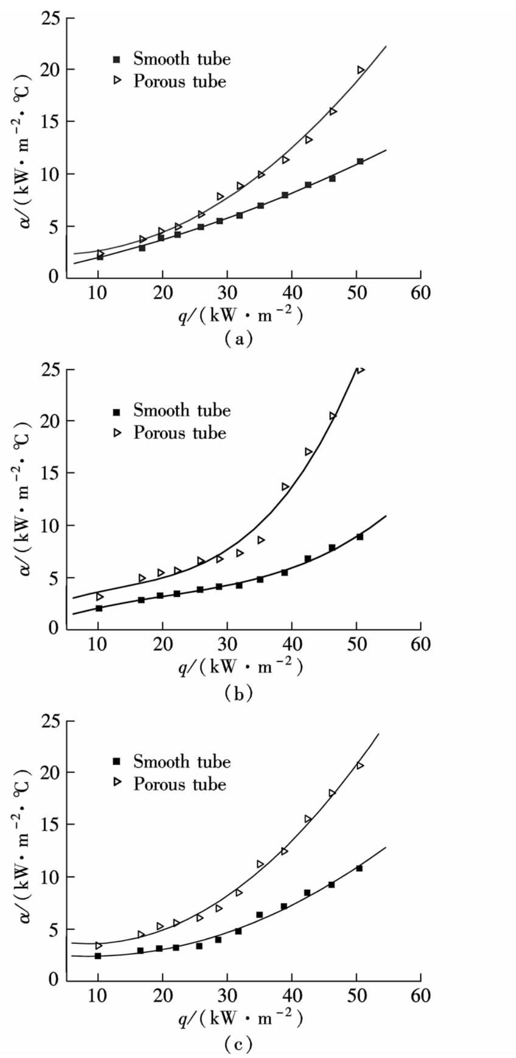

Fig. 3 Relationship between the boiling heat transfer coefficients of porous tubes and smooth tubes and the heat load at different pressures. (a) P = 10 kPa; (b) P = 15 kPa; (c) P = 25 kPa

The boiling heat transfer coefficients of the porous tubes and the smooth tubes increase with the increase in heat load, and the boiling heat transfer coefficients of the porous tubes are greater than those of the smooth tubes, so the sintered surface porous tubes can also enhance boiling heat transfer under vacuum conditions. The enhanced heat transfer mechanism under vacuum conditions is the same as the mechanism at atmospheric pressure. As for the porous tubes, the surface of the sintered surface porous tubes provides a great number of small-size and long-term stability boiling cores.

When bubbling bubbles are generated, the bubble cores first form on the heating wall. Only the vaporization core can grow up to become bubble nuclear when the boiling temperature difference reaches a certain value. Taking the boiling heat transfer data (see Fig. 3) and the morphology (see Fig. 4) into account, it is the bubbles generated by the concave cavities of the porous tube's surface that enhance the boiling heat transfer coefficient of the porous tubes.

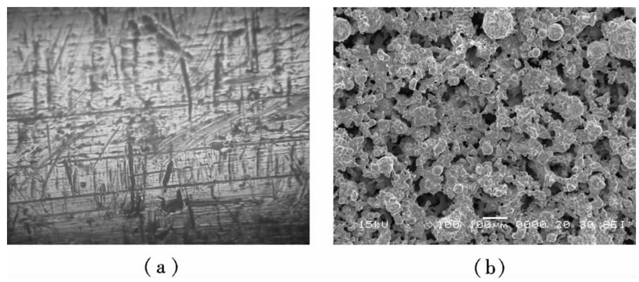

Fig. 4 Plan-view SEM images of smooth tube and porous tube(100 ×). (a) Smooth tube; (b) Porous tube

The results show that the boiling heat transfer coefficients of the sintered porous surface tubes are higher than those of the smooth tubes. The enhanced heat transfer scale factor ε, a ratio of the boiling heat transfer coefficient of the porous tubes to that of the smooth tubes under the same heat flux, increases from 1.2 to 2.2 with the increase in pressure. With the increase in heat flux, ε gradually increases and, meanwhile, with the increase in pressure, ε also increases, as shown in Fig. 5.

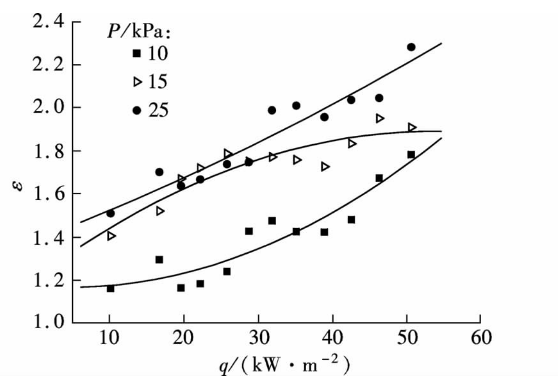

Fig. 5 ε as a function of the heat load

2.2 Effect of vacuum on boiling heat transfer coefficient

The boiling heat transfer coefficients of porous tubes and smooth tubes vary with the vacuum when the heat flux is equal to 50 kW/m^2, as shown in Fig. 6. The experimental results show that at a certain heat flux density, with the decrease in vacuum degree, the boiling heat transfer coeffi-

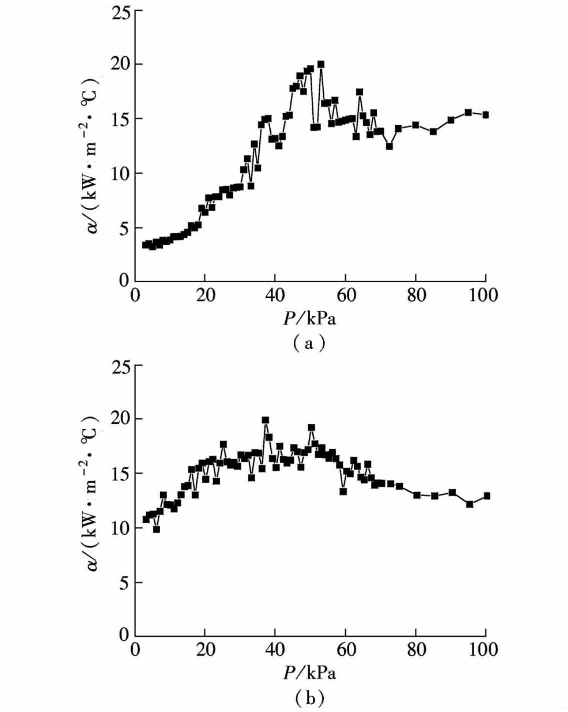

Fig. 6 The boiling heat transfer coefficients at various pressures. (a) Sintered porous surface tube; (b) Smooth tube

cients increase. According to the mechanism of pool boiling heat transfer, the factors that affect nucleate boiling are the overheating degree of the wall and the number of boiling cores. With the increase in boiling pressure, the saturation temperature T_s of deionized water increases correspondingly, and the wall superheat ΔT is reduced, as shown in Fig. 7(a).

According to the equation $\alpha = q/\Delta T$, the heat transfer coefficients increase with the reduction in ΔT when the heat flux density is constant. As shown in Fig. 7(b), in the high vacuum degree range of 0 to 40 kPa, the saturation temperature of deionized water T_s increases significantly with the rise in pressure, and the superheat degree of the wall drops sharply with the increase in pressure as well. It is concluded that the boiling heat transfer coefficient increases fast under the high vacuum degree conditions, and in the low vacuum range or at the atmospheric pressure or at the positive pressure, the pressure influence acts less powerfully upon the saturation temperature of deionized water, so the boiling heat transfer coefficient levels off gradually.

The heat transfer temperature difference of the porous tubes is always below that of the smooth tubes. When the pressure is higher than 50 kPa, the heat transfer temperature difference of the porous tubes is usually below 1 ℃, and the heat transfer temperature difference of the smooth tubes is usually about 3 ℃. It is mainly because the cavity radii of the bubbles generating on the surface of the sintered porous surface tubes are greater than those of the smooth tubes, so the boiling superheat of the porous tubes is less than that of the smooth tubes, and it will bubble at a small boiling heat temperature difference.

The heat transfer coefficients of the porous tubes are higher than those of the smooth tubes, and with the change in vacuum degree, the heat transfer enhancement factor ε increases from 1.2 to 5, as shown in Fig. 7(c). It can be seen

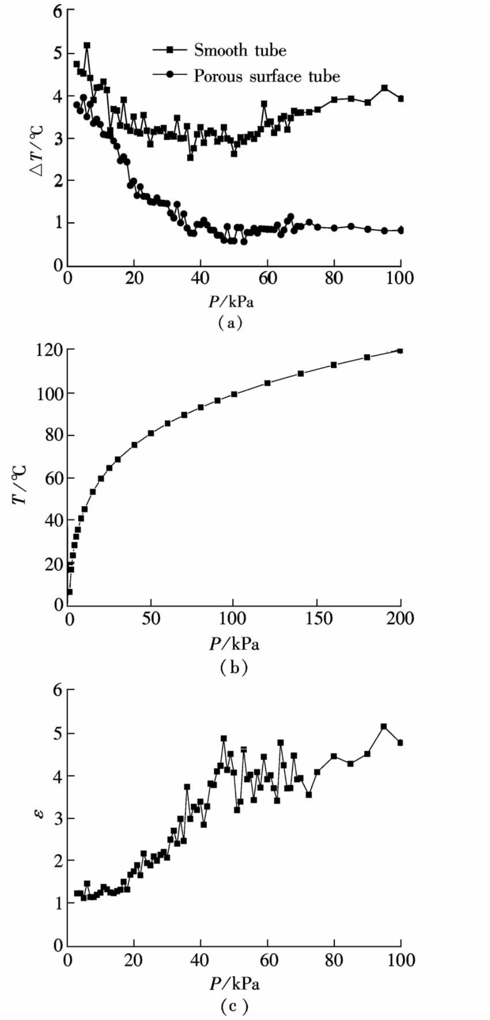

Fig. 7 Variations in temperature difference, saturation temperature and scale factor with pressure. (a) Temperature difference; (b) Saturation temperature; (c) Scale factor

that with the increase in pressure, high-flux pipes have a superior performance. For the smooth surface, the boiling heat transfer coefficient is directly proportional to the 0.3 power of the pressure value. And the boiling heat transfer coefficient of the high-flux pipes is directly proportional to the 0.5 power of the pressure value[7], which is more beneficial in the case of high pressure. In this paper, the enhanced heat transfer performance of the porous tubes applied in adsorption refrigeration is increased by 20%.

2.3 Effect of vacuum on the boiling heat transfer coefficient of tube bundle

Fig. 8 shows the influences of the tube bundle on the boiling heat transfer of porous tubes and smooth tubes when P = 10 kPa. From the figures, the experimental results of pool boiling of water outside both porous and smooth tube bundles show that a definite bundle effect exists under vacuum conditions. That is, while heightening the location of the tube rank, the starting boiling point moves forward and the boiling curve is shifted to up, and the boiling heat transfer coefficient increases. However, the negative effect mentioned in Ref. [8] cannot be found. We can also see from the figures that the heat transfer properties of the porous tubes are significantly higher than those of the smooth tubes.

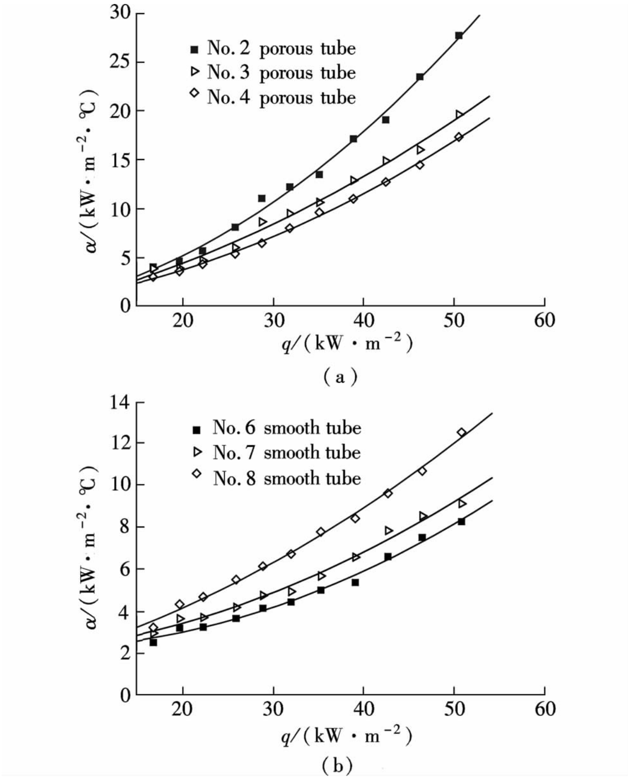

Fig. 8 The tube bundle effect on boiling heat transfer coefficients of sintered porous tubes and smooth tubes with different heat loads. (a) Sintered porous surface tube; (b) Smooth tube

The main reason for the enhanced boiling heat transfer of tube bundles is that there is natural convection induced in the tube bundle. After the bubbles formed in the heating tube divorce from the heated wall, a bubble flow generates between the tubes and makes the liquid flow move upward. Because of the density difference, the liquid in the lower part of the tube moves from the bottom into the tube bundle. The gas-liquid two-phase flow caused by the bubble can reach a higher speed, so the convective heat transfer is enhanced. In addition, some rising bubbles are likely to impact the bubbles growing on the tube wall, thereby encouraging their escaping from the wall, and the boiling heat transfer gets strengthened.

3 Conclusion

Compared with smooth tubes, the boiling heat transfer coefficients of porous surface single tube and tube bundle are studied under vacuum conditions. The results show that with the increase in pressure, the heat transfer coefficients of sintered porous surface tubes (always higher than those of smooth tubes) increase and the enhanced heat transfer factor ε increases from 1.2 to 5 as well.

In the low range of the vacuum, deionized water saturation temperature increases dramatically with the increase in pressure, which causes a sharp increase of the boiling heat transfer coefficient with the change in pressure, and the change rates of the porous tubes obviously exceed those of the smooth tubes.

Also, as a result of natural convection induced in the tube bundle, there is a definite tube bundle effect under vacuum conditions, and the heat transfer performance of porous tubes is significantly higher than that of smooth tubes.

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真空条件下表面多孔管的池沸腾传热性能

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摘要:设计了2种分别由6根管子组成的不同管束排列在沸腾室中. 实验以去离子水为介质,研究了常压及低于大气压下压力对光滑管束和烧结表面多孔管束核池沸腾传热性能的影响. 实验结果表明,在真空条件下这2种管束的沸腾传热系数与在常压条件下一样随着压力值的升高而增大. 在相同的操作参数条件下,与光滑管相比较,当压力值在10~100 kPa之间变化时,烧结表面多孔管的传热系数提高了0.2~4倍. 此外,实验数据还表明在真空条件下烧结表面多孔管及光滑管均存在管束效应.

关键词:池沸腾;表面多孔管;强化传热

中图分类号:TK172