Nucleate Pool Boiling of a Structured Enhanced Tube Used in a Flooded Refrigerant Evaporator

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Key Words : Nucleate pool boiling, Enhanced tube, Alternative refrigerant

Abstract

In this study, pool boiling performance of a structured enhanced tube for a flooded refrigerant evaporator was experimentally investigated. Tests were performed for three different refrigerants(R-11, R-123, R-134a). Compared with the heat transfer coefficients of the smooth tube, the heat transfer coefficients of the enhanced tube were 6.6 times larger for R-11, 6.0 times larger for R-123 and 3.5 times larger for R-134a, which are comparable with the performance of foreign products. The heat transfer coefficients of R-134a was higher than those of R-11 or R-123, both for the enhanced tube and for the smooth tube. At 4.4 ℃ saturation temperature, however, the heat transfer coefficients of R-134a was approximately the same as those of R-11. The effect of the saturation pressure on the boiling performance was similar to that of the smooth tube - the heat transfer coefficient increased as the saturation pressure increased.

Nomenclature

A	:	heat transfer area [m²]
D	:	diameter of the tube [m/s]
h	:	heat transfer coefficient [W/m²K]
L	:	length of the tube [m]
q″	:	heat flux [W/m²]
T_{sat}	:	saturation temperature [K]
T_w	:	wall temperature [K]

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1. Introduction

Flooded refrigerant evaporators are frequently used in centrifugal refrigerators. Figure 1 shows the schematic drawing of the flooded refrigerant evaporator. Refrigerant flows into the bottom of the evaporator at approximately 15% quality, evaporates as it passes through the bundle, and leaves the evaporator as a saturated vapor. Plain tubes had been used for the tube bundle. Recently, however, structured enhanced tubes are widely used because of their superior boiling performance. Enhanced tubes are made by cold-working on the plain tube, and thus, their prices are slightly higher than that of the plain tube. However, they are known to be cost-effective because of the higher heat transfer performance[1].

The enlarged photos of the present enhanced tube are shown in Fig. 2(a). The tube was made from a low integral fin tube having 1654 fins per meter with 1.3 mm fin height, cutting small notches (0.9 mm depth) on the fins, and then flattening the fins by a rolling process. Dimensions of the resultant surface are shown in the figure. Also shown in the figure are the Turbo-B and GEWA-T. The boiling performance of the present enhanced tube is not known yet, while those of foreign products are well documented[2]. The purpose of the present study is to provide pool boiling heat transfer data of the domestic enhanced tube, and compare it with those of foreign products. Refrigerants tested include R-11, R-123 and R-134a.

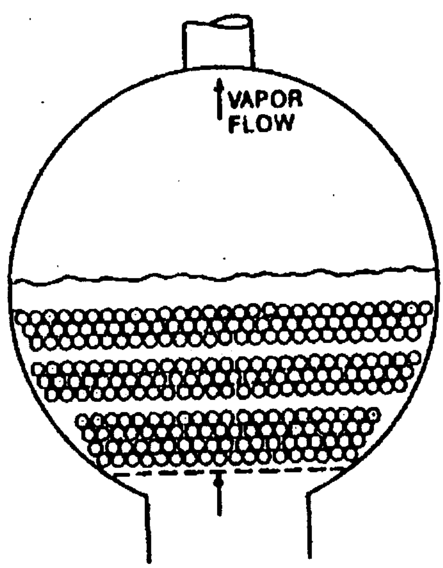
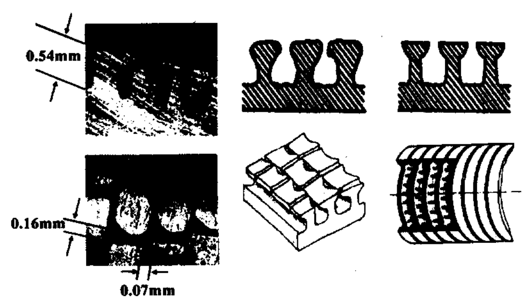


Fig. 1 A sketch of flooded refrigerant evaporator.

2. Experimental Apparatus and Procedures

The test apparatus is shown in Fig. 3. The pool boiling test cell consists of a 150 mm inner diameter and 350 mm long copper tube and two flanges. The test tube was mounted on the copper flange at one end of the test cell, and the sight glass was installed on the other end of the test cell. The vapor generated during the test condensed in the external condenser. The brine from the constant temperature bath circulated in the tube-side of the condenser. Tests were performed at two saturation temperatures (4.4 ℃ and 26.7 ℃). The 4.4 ℃ was chosen because commercial refrigeration chillers operate at the temperature and the 26.7 ℃ was chosen because it is the normal room temperature. The apparatus had a charging line and evacuating line connected to a positive displacement vacuum pump. The detailed sketch of the test tube is shown in Fig. 4. The enhanced tubes were specially made from thick-walled copper tubes of 18.8 mm outer



(a) Present enhanced tube (b) Turbo-B (USA) (c) GEWA-T (Germany)

Fig. 2 A Photograph of the present metal-formed tube along with those from foreign products.

diameter and 13.5 mm inner diameter The length was 170 mm. An electric cartridge heater of 13.45 mm diameter and 180 mm long was inserted into the test tube. Its electric power was controlled by an auto-transformer. The heater was specially manufactured to contain 170 mm long heated section (same length as that of the test tube) and two 5 mm long unheated end sections. To minimize the heat loss, the unheated sections were covered with a teflon cap and a teflon ring as illustrated in Fig. 4. Before insertion, the heater was coated with a thermal epoxy to enhance the thermal contact with the tube.

Four thermocouple holes of 1.0 mm diameter were drilled to the center of the tube. Copper-constantan thermocouples of 0.3 mm diameter per wire were inserted into the holes to measure the tube wall temperature. Before insertion, the thermocouples were coated with a thermal epoxy [Chromalox HTRC] to provide good thermal contact with the tube wall. The thermal conductivity of the epoxy is close to that of aluminum. The vapor temperature was measured at two locations on the upper part of the test cell, and the liquid temperature was measured at 20 mm above the test tube and at 20 mm be low the test tube. During the test, the four temperatures agreed within 0.2 ℃. The test cell pressure was measured using a pressure transducer. When the measured pressure was converted to the corresponding saturation temperature, they agreed within 0.3℃.

Before each test, the test tube was thoroughly cleaned with acetone. Then, the tube surface was conditioned employing the surface aging technique "B" of Bergles and Chyu[3]. The method involved degassing the test tube and the pool at the maximum heat flux (approximately 50 kW/m²) for an hour. The pool was maintained close to the saturation temperature using the constant temperature bath (for 4.4℃ saturation temperature) or the auxiliary heater (for 26.7℃ saturation temperature). The data were taken decreasing the heat flux. Readings were taken 5 to 10 minutes after each power change, at which time a steady state condition was attained. Before reading the data, the auxiliary heater was shut off to minimize the convective effects from the heater. Throughout the test, the liquid level was maintained at 5 cm above the test tube. The heat transfer coefficient (h) is determined by the heat flux (q") over wall superheat ($T_w - T_{sat}$). Calculations of q" and h are based on the envelope area, defined by the heated length (170 mm) multiplied by the tube outside perimeter. The input power to

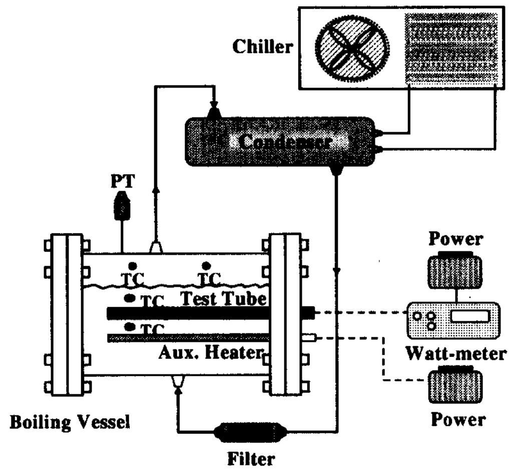


Fig. 3 Schematic drawing of the experimental apparatus.

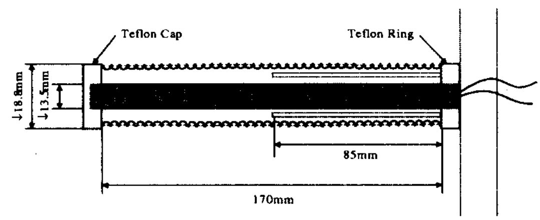


Fig. 4 Detailed sketch of the test tube.

the heater was measured by a precision wattmeter [Chitai 2402A] and the thermocouples were connected to the data logger [Fluke 2645A]. The pressure transducer was also connected to the data logger. The thermocouples and the transducer were calibrated and checked for repeatability. The calculated accuracy of the temperature measurement was ±0.15℃. Tube wall temperature was determined by extrapolating the thermocouple temperatures to the tube wall using Fourier's law.

An error analysis was conducted following the procedure proposed by Kline and McClintock[4]. The uncertainty in the heat transfer coefficient is estimated to be ±3% at the maximum heat flux (50 kW/m²) and ±7% at a low heat flux (10 kW/m²). The heat flux profile in axial direction may not be uniform because of the heat loss at each ends of the heater. A series of tests were conducted changing the thermocouple location in axial direction. The corresponding heat transfer coefficients agreed each other within ±3%. All the tests were conducted with thermocouples located at the center of the tube.

3. Results and Discussion

3.1 Smooth tube

Prior to the tests on enhanced tubes, tests were conducted on a smooth tube. The surface of the tube was emery ground, and the surface profile was measured using a profilometer [Kosaka Lab. SE 3300]. The arithmetic mean roughness height was 0.29 μm. After being ground, the tube was seasoned in a room about a week until a stable oxide film is formed on the surface. This was necessary because the boiling heat transfer coefficient of the just-ground tube was significantly higher than that of the seasoned tube. Several tests conducted for the seasoned tube revealed that the heat transfer coefficients were repeatable.

The boiling heat transfer coefficients of the smooth tube taken at 4.4℃ saturation temperature are shown in Fig. 5. The heat transfer coefficients of R-11 and R-123 are approximately equal while those of R-134a are considerably higher. It is generally accepted that higher the reduced pressure is, higher the heat transfer coefficient becomes. At 4.4℃, the reduced pressure of R-134a is approximately eight times larger than that of R-11 or R-123. The reduced pressures of R-11 and R-123 are approximately the same. The heat transfer coefficients at 26.7 ℃ saturation temperature are shown in Fig. 6. The trend is approximately the same as that at 4.4 ℃. Comparison of the two figures, however, reveals that the heat transfer coefficients at 26.7 ℃ are higher than those at 4.4 ℃. The reason may also be attributed to the lower reduced pressure at 4.4 ℃. The present data are compared with the Cooper[5] correlation (using $R_p = 0.29\,\mu m$) in Fig. 7. Fig. 7 shows that most of the data are predicted within ±10%. The Cooper correlation is known to predict the pool boiling data of re-

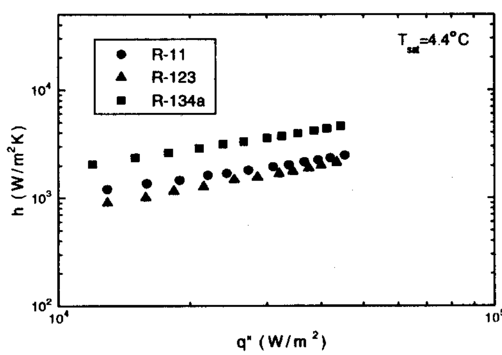


Fig. 5 Boiling heat transfer coefficient of the smooth tube at T_{sat} = 4.4℃.

frigerants reasonably well.

3.2 Enhanced Tube

The experimental heat transfer coefficients of the present enhanced tube are shown in Figs. 8 and 9. Figure 8 shows the heat transfer coefficients at 4.4 ℃ and those in Fig. 9 correspond to 26.7 ℃. Both figures show that, similar to the smooth tube, the heat transfer coefficients of R-11 and R-123 are approximately equal while those of R-134a are considerably higher, and the heat transfer coefficients at 26.7 ℃ are slightly higher than those at 4.4 ℃. Higher reduced pressure may also be responsible. At the normal operating condition of a refrigerant evaporator (4.4 ℃ and 40 kW/m²), the present enhanced tube yields up to 6.6 times higher heat transfer coefficients than the smooth tube for R-11, 6.0 times for R-123 and 3.5 times for R-134a.

In Fig. 10, the heat transfer coefficients of the present enhanced tube are compared with those of Turbo-B and GEWA-T. The figure shows that the heat transfer coefficient of the present tube is higher than that of GEWA-T, and slightly lower than that of Turbo-B. The heat transfer coefficients of Turbo-B and

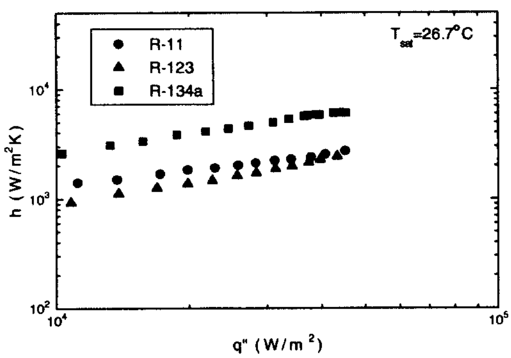


Fig. 6 Boiling heat transfer coefficient of the smooth tube at $T_{sat}=26.7$℃.

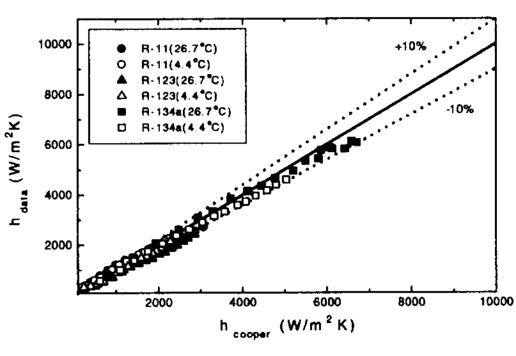


Fig. 7 Smooth tube data compared with Cooper[5] Correlation.

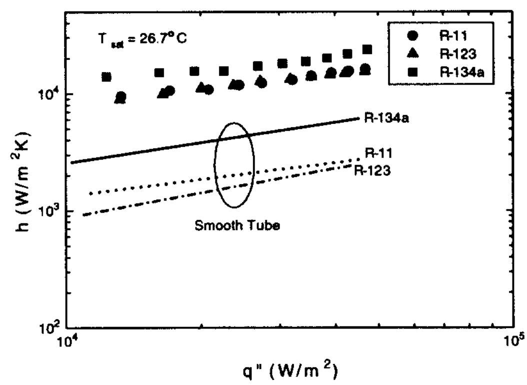


Fig. 8 Boiling heat transfer coefficient of the present enhanced tube at $T_{sat}=26.7$.

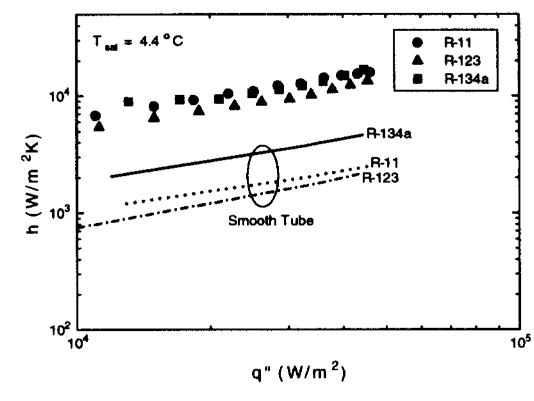


Fig. 9 Boiling heat transfer coefficient of the present enhanced tube at $T_{sat}=4.4$℃.

Table. 1 Curve fits of experimental data in the form $h = c\, q''^{\,n}$

Tube	refrigerant	T_{sat}=4.4℃		T_{sat}=26.7℃	
		c	n	c	n
Present Tube	R-11	24.55	0.604	162.2	0.427
	R-123	16.22	0.622	158.5	0.428
	R-134a	67.61	0.506	398.1	0.373
GEWA-T	R-11	1.50	0.779		
	R-134a	105.5	0.423		
Turbo-B	R-11	830.46	0.298		
	R-134a	304.44	0.389		

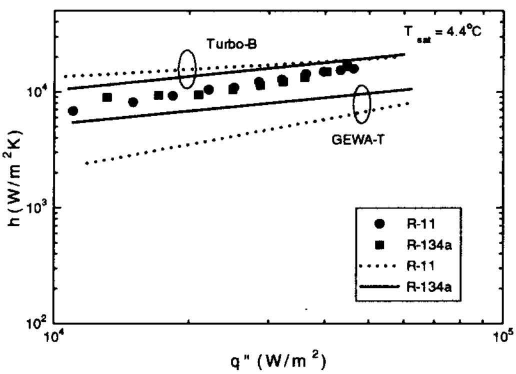


Fig. 10 Boiling heat transfer coefficient of the present enhanced tube compared with those of Turbo-B and GEWA-T at T_{sat} = 4.4℃.

GEWA-T are provided in Webb and Pais[2]. The present data are curve-fitted as a function of heat flux, and the results are provided in Table 1. The curve-fit equations of GEWA-T and Turbo-B are also provided in Table 1.

4. Conclusions

In this study, boiling performance of a structured enhanced tube for a flooded refrigerant evaporator was experimentally investigated. Tests were performed for three different refrigerants(R-11, R-123, R-134a).

(1) Compared with the heat transfer coefficients of the smooth tube, the heat transfer coefficients of the enhanced tube were 6.6 times larger for R-11, 6.0 times larger for R-123 and 3.5 times larger for R-134a, which are comparable with the performance of foreign products.

(2) The heat transfer coefficients of R-134a was higher than those of R-11 or R-123, both for the enhanced tube and for the smooth tube. At 4.4℃ saturation temperature, however, the heat transfer coefficients of R-134a was approximately the same as those of R-11.

(3) The effect of the saturation pressure on the boiling performance was similar to that of the smooth tube - the heat transfer coefficient increased as the saturation pressure increased.

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