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Study of heat transfer correlation of two-phase closed thermosyphon

Liqing REN[1], Baixin CHEN[1], Jifu LIU[2]

(1. Dept. of Power Eng., Dalian Univ. of Technol., Dalian 116024, China;
2. Dept. of Energy Sci. and Eng., Harbin Inst. of Technol., Harbin 150001, China)

Abstract: Through the analytical and experimental study of the former results and experiments, it is found that the heat transfer mechanisms and the measure position of saturation temperature are the main factors influencing the heat transfer correlation of TPCT. The heat transfer mechanism of evaporator section is mainly two-phase natural convection. The nucleate boiling heat transfer is deeply suppressed. With water as working fluid, Xin's and Ma's Equs. have good predications. With ethanol as working fluid, Imura's and Groβ's Equs. have good predications. When the working fluid is unknown, Groβ's Equ. can give good predication.

Key words: heat transfer coefficient; heat pipes; pool boiling

0 Introduction

Two-Phase Closed Thermosyphon (TPCT) has been utilized as an effective heat transfer device in thermal engineering field. Many experiments have been done and a lot of correlations have been introduced to predict the heat transfer coefficient of the evaporator section. Some of them are listed below.

Xin[1]:

$$Nu_b = 0.022\,7 Ar^{0.33} Ze^{-0.15} Re_b^{0.408} We^{-0.107} [\rho_g/(\rho_l - \rho_g)]^{-0.227} \tag{1}$$

where subscript "b" stands for bubble.

Imura[2]:

$$h_e = 0.32 \rho_l^{0.65} \lambda_l^{0.3} c_{p_l}^{0.7} g^{0.2} q_e^{0.4} / \rho_g^{0.25} r^{0.4} \mu_l^{0.1} \cdot (p_{in}/p_a)^{0.3} \tag{2}$$

where subscript "e" represents evaporator section, p_{in} is the pressure of the inner of tube.

Groβ[3]:

Based on the natural convection regime

$$Nu = 4(ArFr^{1/2})^{1/3} Pr_l^{1/2} (B_0/10)^n,\ n = 1/2 \text{ for } B_0 \leqslant 10;\ n = 1/6 \text{ for } B_0 > 10 \tag{3}$$

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Liqing REN (1970-), Female, Lecturer; Baixin CHEN (1957-), Male, Professor.

Based on the nucleate boiling regime

$$h_e = h_0 \frac{(p/p_c)^{0.12}}{[-\lg(p/p_c)]^{0.55}} \left[\frac{q}{q_0}\right]^{0.7} \quad \text{where } h_0 = 3.47 \times 10^4 M^{-0.5},\ q_0 = 10^4 \tag{4}$$

Ma[4]:

$$h_e = E(A_c/A)h_{nc} + Sh_{pool} \tag{5}$$

where A_c is the area of convection section

$$E = 0.1Re_b^{0.49},\ S = 1/(1 + 5.7 \times 10^{-7}E^{2.93}Gr^{0.61}) \tag{6}$$

$$h_{pool} = \frac{c_{pl}}{0.0245rPr^{1.7}}\left\{\frac{1}{r\mu_l}\left[\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}\right]\right\}^{-0.33} q^{0.67},\ h_{nc} = 0.17\left(\frac{g\beta\lambda^3}{\nu^2}Pr\right)^{0.25} q^{0.25} \tag{7}$$

Kaminaga[5]:

$$h_e = 22(\rho_g/\rho_l)^{0.4}R^{(1-p/p_c)/5}h_0 \tag{8}$$

where $h_0 = 0.0007\frac{\lambda}{l_m}\left(\frac{p}{p_c}\right)^{0.35}\left(\frac{ql_m}{\rho_g r\nu}\right)^{0.7}\left(\frac{pl_m}{\sigma}\right)^{0.7}$, $l_m = \sqrt{\sigma/g(\rho_l - \rho_g)}$; R stands for the surface roughness (μm).

Because these correlations are presented based on the limited experiments and little is known about the real heat transfer mechanisms of TPCT, there is not a correlation which can be used in wide practical engineering fields till now. Through experimental and theoretical analysis, this study focuses on the recommendation of the formulae which is suitable for different working fluids in order to offer more reliable theoretical basis for engineering.

1 Experimental apparatus

A schematic diagram of the thermosyphon is shown in Fig. 1. The thermosyphon consists of an inner diameter of 20 mm, an outer diameter (d) of 25 mm, 700 mm long steel tube, with a 300 mm evaporator section, a 100 mm adiabatic section and a 300 mm condenser section. Sixteen thermocouples are embedded in 0.48 mm wide, 0.5 mm deep, 10 mm long grooves made on the outer surface of the evaporator and adiabatic section to measure wall temperatures. At the same height there are two thermocouples placed on two diametrically opposite generatrices, thus every eight thermocouples are located uniformly both in height and in circle. The saturation temperature is measured by means of a thermocouple inserted into the adiabatic section from the upper of the tube. Heat is loaded

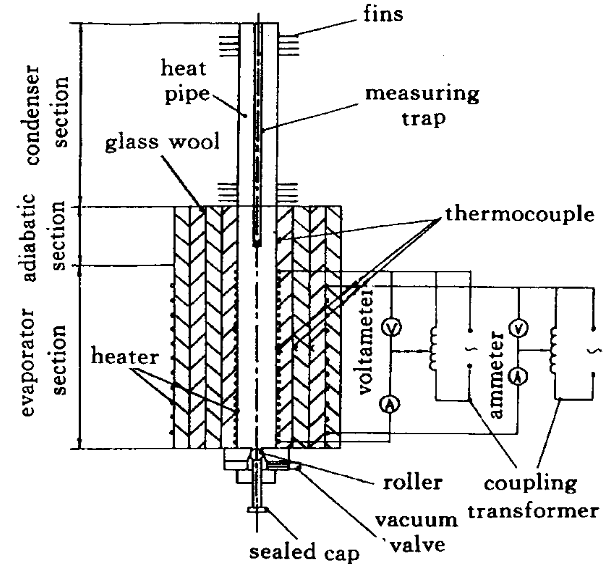

Fig. 1 Schematic diagram of the thermosyphon

through a direct heating method by means of the altering current. The evaporator and the adiabatic section are installed by a glass wool of 50 mm thick, which is divided into four layers. There are two thermocouples that are installed inner and outer wall of the second layer and outside the third layer wrapped uniformly nichrome wire in order to minimize the heat loss. The condenser section is cooled by air through a tunnel whose sectional area is (0. 075 × 0. 3) m^2.

2 Results and analysis

In order to offer reliable theoretical basis, the experimental conditions of these correlations of literatures and this paper are given in Table 1. Figs. 2-3 are the comparison of the experiment values with the calculated heat transfer coefficients using Equs. (1), (2), (3), (5), (8) with water and ethanol as working fluids respectively. The results show that there is difference between correlations and the difference will increase with the increase of heat flux.

Table 1 Experimental conditions of literatures & this paper

	diameter d /mm	filling ratio V /%	inclined angle θ /(°)	working fluid	t_s /℃	q / ($10^4 W\cdot m^{-2}$)	Measure point of t_s	Material of tube
lit. [4]	20,26	20-50	90	water	-	-	adiabatic section	steel
	20	25-30		ethanol				
lit. [5]	28	4. 7-50	90	water	25-105	1. 10-13. 60	in tube	yellow brass
		5-47. 6		ethanol	30-93	1. 10-6. 80		
lit. [6]	2-48	-	5-90	water	10-177	0. 10-24. 50	-	-
	10,20		45,90	methanol	10-66	0. 20-10. 00		
	20-37			ethanol	14-99	0. 06-10. 00		
	5-158		90	R11	23,70	0. 19-6. 70		
	6-68			R113	21-96	0. 10-10. 00		
	24			R22	15-68	1. 10-2. 51		
	40		0-60	R115	56-79	0. 27-4. 69		
	40		0-80	R13B1	16-66	0. 28-1. 59		
lit. [7]	50	45	90	water	70-120	1-7	adiabatic section	yellow brass
	20							
lit. [8]	19. 5	30-75	90	water		1. 90-38. 30	in tube	stainless steel
		30-90		R113		0. 29-3. 94		
		30-90		ethanol		0. 89-11. 60		
this paper	25	26. 3	90	water	68-219	2. 70-6. 92	in tube	carbon steel
		24. 6		ethanol	71-177	2. 41-5. 00		

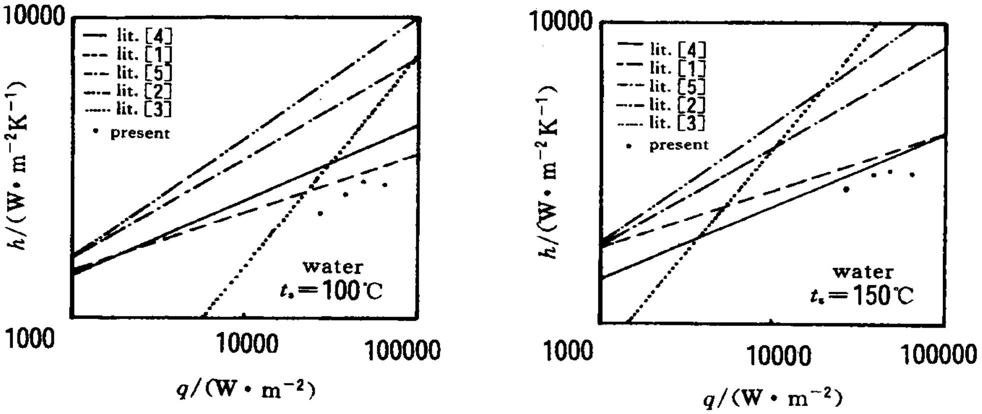

Fig. 2 Comparisons of measured heat transfer coefficients with predictions by literatures

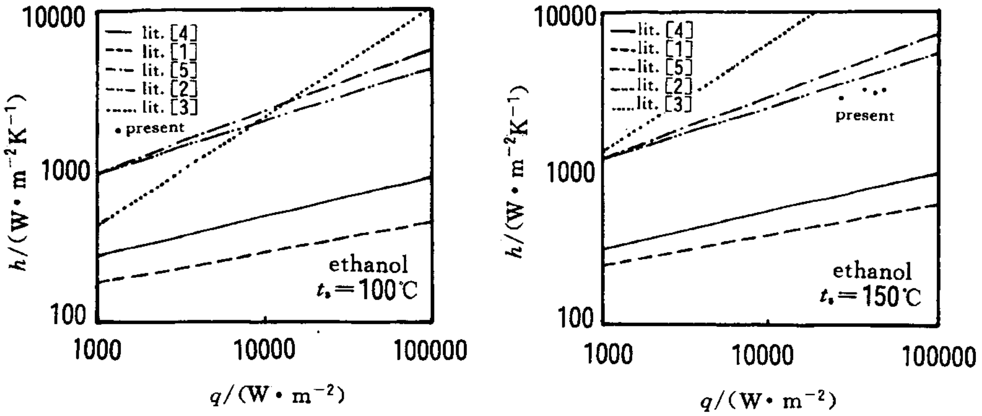

Fig. 3 Comparison of measured heat transfer coefficients with predictions by literatures

The main reasons why there is big difference between these results may be as follows: i)the error of measurement and the error of measuring instruments. ii) the heat loss of operating experiments. iii) the difference of measure point of saturation temperature. In the Xin's and Ma's experiments, the measure points of t_s are all the outer wall temperature of adiabatic section, while Imura's and Groβ's are in tube. It is evident that the real saturation temperature is closer to the latter's. So, the calculated values using Imura's and Groβ's Equs. are bigger than those using Xin's and Ma's Equs. iv) these correlations are based on different heat transfer regimes, which may be the most important reason. Xin's Equ. is based on the two-phase natural convection heat transfer regime with falling filmy evaporation and ascending vapor in centerline. Nucleate boiling in the liquid pool is only considered by bubble Reynolds number Re_b and bubble Nusselt number Nu_b. Imura's Equ. is based on the similar heat transfer regimes and considered working pressure, but neglects the effects of nucleate boiling. Groβ presumd that two-phase natural convection and nucleate boiling are the two main heat transfer regimes. But the determination of incipience of boiling as the borderline between the two regimes has not been successful up to now. In this study, it is found that the calculated values based on Equ. (4) are largely bigger than those using Equ. (3) and the latter one has a better prediction. In addition, the results which are similar to Equ. (3) can also be found in the studies on heat transfer in narrow spaces[6]. So, Equ. (3) is used to be compared in this paper. Ma[4] also finds that the heat transfer regime of the heating section is natural convection enhanced by the agitation of vapor bubbles, while the boiling heat transfer is deeply suppressed. They use EA_c/A and S to modify the natural convection heat transfer and nucleate boiling respectively and present an overall Equ. (5). Kaminaga[5] analyzes several heat transfer correlations and presents a correlation. From the above analysis, it is found that only Kaminaga's Equ. (8) is based on nucleate boiling heat transfer. So, it is believed that the heat transfer regime in the heating zone is mainly natural convection, while the nucleate boiling heat transfer is suppressed. Even so, the prediction of these correlations for different working fluids is very differently shown in Fig. 3. This is because there are many factors in these correlations which largely depend on the limited experimental data.

Owing to the small difference between Xin's and Ma's Equs., Imura's and Groβ's Equs., only the detailed comparisons of Xin's and Groβ's Equs. with the author's experimental results are shown in Figs. 4-7 when water and ethanol are working fluids. From Fig. 2 it can be found that Xin's and Ma's Equs. are both in good agreement with the authors' experimental results when water is working fluid. The biggest deviations are under ± 25% as seen in Fig. 4. The predictions of Imura's and Groβ's Equs. aren't very well. The biggest deviation of Groβ's Equ. is up to 60% as shown in Fig. 5 and Imura's Equ. is higher. With ethanol as working fluid, Imura's and Groβ's Equs. are all in good agreement with the authors' experiments as shown in Fig. 3 and the biggest error is within ± 30% as seen in Fig. 6. On the other hand, Xin's and Ma's Equs. have very large deviation with authors' experiments which can be seen from Fig. 3 and Fig. 7. This is because the Ma's Equ. is based on water which isn't suitable for other fluids. Although Xin's Equ. is based on both water and ethanol, the choice of the factors may be not suitable for ethanol due to the insufficient experimental data.

Generally speaking, Groβ's Equ. has good prediction with both water and ethanol as working fluids as seen in Figs. 5 and 6.

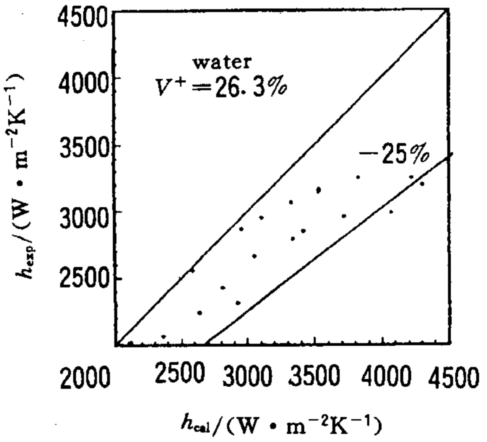

Fig. 4 Comparison of measured heat transfer coefficients with predictions by Equ. (1) in water

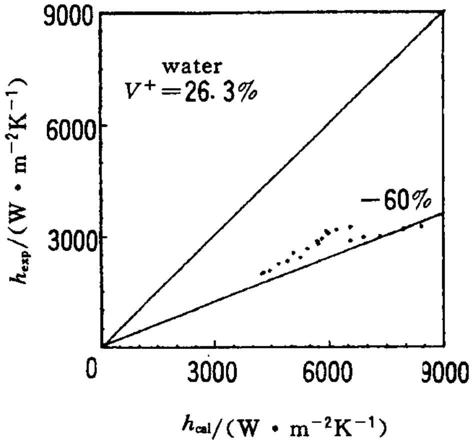

Fig. 5 Comparison of measured heat transfer coefficients with predictions by Equ. (3) in water

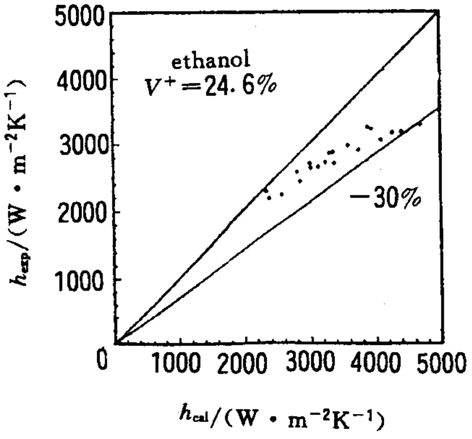

Fig. 6 Comparison of measured heat transfer coefficients with predictions by Equ. (3) in ethanol

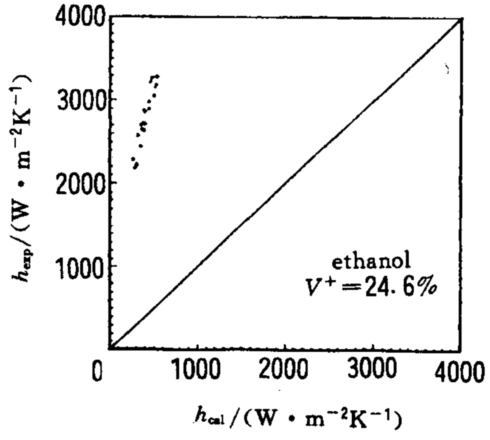

Fig. 7 Comparison of measured heat transfer coefficients with predictions by Equ. (1) in ethanol

3 Conclusions

Heat transfer in the evaporator of the vertical closed two-phase thermosyphon is analyzed with water and ethanol as working fluids. It is found that:

i) Two-phase natural convection heat transfer plays a major role in the heat transfer of evaporator section, the nucleate boiling heat transfer, however, is deeply suppressed.

ii) Xin's Equ. and Ma's Equ. are in good agreement with the authors' experiments when water is working fluild.

iii) Imura's Equ. and Groβ's Equ. are in good agreement with the authors' experiments when ethanol is working fluid.

iv) When the working fluid is unknown, this paper suggests Groβ's Equ.

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两相闭式热虹吸管沸腾换热公式的研究

任丽青[1]， 陈白欣[1]， 刘纪福[2]

（1. 大连理工大学 动力系，辽宁 大连 116024；
2. 哈尔滨工业大学 动力系，黑龙江 哈尔滨 150001）

摘要：通过对国内外几位专家的研究成果以及作者的实验结果进行相互比较与分析，发现换热机理和蒸汽温度测点是影响热管换热公式归纳的主要因素，热虹吸管加热段的换热主要是自然对流，核态沸腾被深深地抑制了. 基于该机理得出的经验关系式中，在以水为工质时，辛明道和马同泽的公式有很好的预测性；而以乙醇为工质时，Groβ 的公式有很好的预测性，Imura 的公式也有一定的参考价值；当工质未知时，建议采用 Groβ 的公式.

关键词：传热系数；热管；池沸腾

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作者简介：任丽青(1970～)，女，讲师；陈白欣(1957～)，男，教授.