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Research Paper

Heat transfer correlation of the falling film evaporation on a single horizontal smooth tube

Chuang-Yao Zhao, Wen-Tao Ji, Pu-Hang Jin, Wen-Quan Tao *

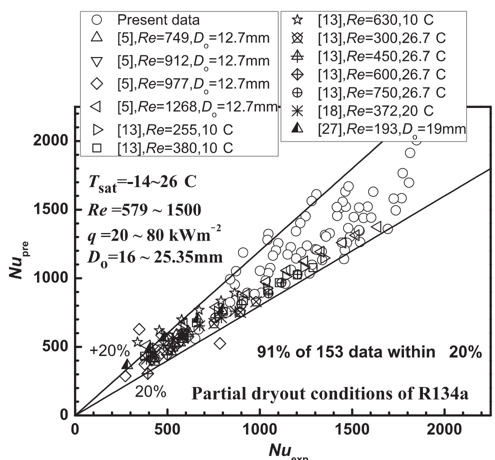
Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- The effects of tube diameter, saturation temperature, film flow rate and heat flux on heat transfer are studied.
- A threshold Reynolds number is proposed to delineate the test data into full wetting and partial dryout regimes.
- The heat transfer correlations for R134a outside a single horizontal tube are developed.
- Comparisons between the predicated results and the experimental data of other refrigerants in literature are conducted.

GRAPHICAL ABSTRACT

For the full wetting regime of falling film evaporation on a single horizontal smooth tube, the proposed correlation fits 94% of the data within ±20%.



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ABSTRACT

The falling film heat transfer of R134a outside a single horizontal smooth tube is experimentally investigated, and the effects of the tube diameter, saturation temperature, film flow rate and heat flux are studied. A threshold Reynolds number is proposed to delineate the test data into full wetting and partial dryout regimes. New correlations based on the present data and some data in literature are fitted for both regimes. The correlation for partial dryout regime fits 91% of the 153 data within ±20%, and the correlation for full wetting regime fits 94% of the 205 data within ±20%. The correlations have also been compared with previous measured data of other refrigerants available in literature. It is found that the predictions for partial dryout regime agree with most of the previous data with a deviation of ±30%.

* Corresponding author. Tel/fax: +86 29 82669106.
E-mail address: wqtao@mail.xjtu.edu.cn (W.-Q. Tao).

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1. Introduction

Falling film evaporation was early used in the ocean thermal energy conversion (OTEC) systems. In recent decades, it has increasingly attracted attentions in applications of seawater desalination, refinery and petrochemical operation, etc. Falling film evaporation shows great potential to replace the flooded evaporation in vapor-compression refrigeration systems for the advantages of higher evaporative heat transfer coefficient, much less refrigerant charge, and the easiness of lubricant return.

The falling film evaporation process is very complicated due to the multitude of influencing factors [1]. According to the latest review, Fernández-Seara and Pardiñas [2] noted that the previous researches disagree with each other about the effects of parameters, and they pointed out that the applicability of proposed correlations is only limited to very specific test conditions. To the authors' knowledge, even for the simplest situation, i.e., falling film evaporation on a single horizontal smooth tube, such a generally-accepted correlation does not exist.

The following is a brief summary of the previous studies on falling film evaporation on a single smooth tube. (1) The major influencing factors on the heat transfer coefficient are film flow rate, heat flux, saturation temperature and tube diameter [3]; (2) the relationship of heat transfer coefficient with film flow rate can be divided into two distinct stages [4]: a plateau stage with full wetting, and a sharply decreasing stage with partial dryout. Under the premise of full wetting the increase of heat flux always has positive effect on nucleate boiling heat transfer because of the increasing nucleate site density [5]; (3) film flow rate usually has positive effect on the heat transfer coefficient; (4) the effects of the saturation temperature and the tube diameter are diverse, some cases positive and some cases negative [3,5–9]. Further studies are needed in this regard.

Up to now, a large number of correlations have been proposed, but it is difficult to apply these predictions in other environments because of their very specific test conditions [2,3]. The work conducted in References 7,10, and 11 shows that the heat transfer coefficient of falling film heat transfer can be correlated with *Re* and *Pr*, as for the conventional convective heat transfer process. The first heat transfer correlation for a single tube was probably put forward by Danilova et al. [12], who worked for the evaporator of refrigeration system by using falling film evaporation process. The most recent publication was given by Chien and Chen [13]. The correlations of falling film evaporation published in these publications for a single tube are listed in Table 1.

By carefully analyzing experimental process and data reduction process [19], we believe that for a fundamental research of falling film heat transfer we should first conduct the simplest case: falling film heat transfer outside a horizontal smooth tube. Even for this simplest case the following five factors may affect the test data. First is how to determine the saturation temperature for data reduction. For example, Roques and Thome [4] took the liquid temperature before distributor as the saturation temperature with 0.5 K subtraction. Different practices [5,13,18] will eventually introduce some uncertainty in the determination of the saturation temperature. Second, the horizontality of the tube is another important factor. Third, the uniformity of liquid distribution on the tested tube greatly affects the test results. Fourth, the test tube should have enough length to guarantee the enough tube-side water temperature difference by which the heat transfer rate is determined. Finally all the measurement instruments should have enough accuracy. All the above five aspects will be dealt with carefully in the later presentation.

In this paper, the falling film evaporation outside a single horizontal smooth tube is experimentally studied, and the effects of tube diameter, saturation temperature, film flow rate and heat flux are investigated. The test ranges are: tubes with diameter of 16.0, 19.05 and 25.35 mm, the saturation temperature of 6, 10 and 16 °C, film Reynolds number of 579–2700, and heat flux of 10–170 kWm^{-2}. In the following presentation the test system will first be introduced, followed by the test procedure and data reduction method. Then the test results will be presented and comparison is made. Finally some conclusions are presented.

2. Experimental facility

The experimental setup is schematically displayed in Fig. 1, from which we can see three circulation loops for refrigerant, hot water and cold water in this system. The detailed description of the three systems can be found in Reference 19.

The evaporator shell is a stainless steel cylinder with an inner/outer diameter of 450/466 mm and an effective length of 1450 mm. The evaporator, condenser and all associated pipes are well insulated by a rubber plastic material with thickness of 40 mm and a layer of aluminum foil.

Special care has been taken to obtain uniform liquid distribution. With the inspiration from the design of Roques and Thome [4], a half tubular overflow box and a guide plate are designed in our liquid distributor, as schematically shown in Fig. 2. The liquid dis-

Table 1
Heat transfer predictions for falling film evaporation on horizontal tube.

	Correlation	Fluid/D_o, mm	Work condition q, kWm^{-2}
[6]	$h_o = 5.169 \times 10^{-11}(rg\rho_l D_o^2)/(\Delta T\mu)(\delta/D_o)(1+\delta')$	Water/20~40	Re: 200 ~ 2500
[8]	$h_o(\nu_l^2/g)^{1/3}/\lambda_l = aRe^{0.10}Pr^{0.65}q^{0.4}$ 8.2×10^{-4} for 25.4 mm, 9.4×10^{-4} for 50.8 mm	Water/25.4~50.8	Γ: 0.135 ~ 0.366 kgs^{-1} q: 30 ~ 80
[12]	$h_o/\lambda_l(\sigma/g(\rho_l \times 10^{-4}\rho_v))^{1/2} = 1.324 \times 10^{-3}(q/r\rho_v\nu_l(\sigma/g(\rho_l-\rho_v))^{1/2})^{0.63}.(P_{sat}/\sigma((\sigma/g(\rho_l-\rho_v))^{1/2})^{0.72})Pr^{0.48}$	R-22, R-12 and R-113/18.0	Re: 135 ~ 2500 q: 0.5 ~ 25
[13]	$h_o = (56.13We^{0.5878}Re^{0.2457}/Bo^{0.1798})h_{nb}+h_{cv}$	R134a/19.0	Re: 184 ~ 750, Pr: 3.45 ~ 3.74, We: 2.3~2.9 × 10^{-3}, Bo: 0.042~0.469
[14]	$h_o(\nu_l^2/g)^{1/3}/\lambda_l = Re^{0.2}Pr^{0.65}q^{0.4}$	Water/50.8	Γ: 16 ~ 3.79 cm^3s^{-1} Pr: 1.3 ~ 3.4 q: 30 ~ 80
[15]	$h_o = h_{nb}+2h_dL_d/\pi D_o+h_{cv}(1-2L_d/\pi D_o)$	–	–
[16]	$h_o = (0.185 + 56.21We^{0.4531}/(Bo^{0.687}Re^{1.3078}))h_{nb}+h_{cv}$	R-123, R-22 R-11, R-134a, R-141b/12.7~19.5	Re: 157 ~ 2500 Pr: 2.54 ~ 5.9 q: 2 ~ 100
[17]	$h_o = 4200P_{red}^{0.22}q^{0.38}M^{-0.5}Ra^{0.2}0.0024Re^{0.91} + h_{dry}(1-0.0024Re^{0.91})$	R134a/19.05	Partial dryout
[18]	$h_o = (0.0152We^{0.2833}Re^{1.2536}Bo^{1.1789})h_{nb}+h_{cv}$	R245fa/19.0	Re: 115 ~ 372, Pr: 6.26 ~ 7.15, We: 1.65~16.8 × 10^{-4}, Bo: 0.044~0.473