International Journal of Heat and Mass Transfer 81 (2015) 804–810

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Film condensation in a large diameter tube with upward steam flow

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A R T I C L E I N F O

Article history:
Received 7 August 2014
Received in revised form 2 November 2014
Accepted 2 November 2014
Available online 19 November 2014

Keywords:
Condensation
Upward steam flow
Vertical tube
Nusselt number
Correlation

A B S T R A C T

Film condensation was considered for upward steam flow at the atmospheric pressure. The experimental data were obtained inside a vertical duralumin tube with the internal diameter of 200 mm and roughness height of 0.14 mm. The film Reynolds numbers and vapor Reynolds numbers were varied within the range of 1–16 and 280–3460, respectively. The obtained experimental data were lower than classical Nusselt prediction. The suggested correlation for the Nusselt number agrees the most of the data within 20%.

1. Introduction

The heat transfer during laminar film condensation inside vertical tubes with upward vapor flow was theoretically investigated in [1–7]. The reflux condensation inside a closed thermosyphon was analytically considered in [8]. In a lot of these works the obtained results were compared with classical Nusselt theory [9] for the case of a quiescent vapor.

Roetzel [1] has developed the model of laminar film condensation inside a tube for the cases of upward and downward turbulent vapor flow. The author of [1] has derived the formulae for the Nusselt number as functions of film Reynolds number, modified vapor Reynolds number, which is defined with difference of vapor velocity and film surface velocity, the viscosity of the condensate and other parameters. The differential pressure drop in [1] was determined as a function of the modified vapor Reynolds number. Seban and Hodgson [2] theoretically investigated laminar film condensation in a tube with upward vapor flow. The authors of [2] noted that the classical Nusselt solution is not applicable to the condensation in the pipe because vapor velocity reduces during the condensation. They [2] also noted that in this case the steam flow rate reduction happened as a result of condensation provides a decrease of shear stress which supports the film. The authors of [2] have presented the numerical solution as well as a variation of the dimensionless edge of liquid film and the film Reynolds number along the tube height. The friction coefficient was evaluated in terms of the vapor Reynolds number. Chen et al. [8] have analytically investigated the reflux condensation in a two-phase closed thermosyphon taking into account the effect of interfacial shear stress and obtained the numerical results as a variation of the dimensionless parameters along the height of the tube. They [8] evaluated the shear stress in terms of the vapor Reynolds number and used the same formulae for the friction factor as Seban and Hodgson [2] with the additional expressions for $Re_v > 4000$. The numerical solutions [8] show that the film thickness increases due to the shear stress and the heat transfer intensity decreases compared to Nusselt's solution. The experimental data of Chen et al. [8] fell below Nusselt prediction at the low film Reynolds numbers. They also noted that shear effects inclusion did not correct the disagreement.

Chen et al. [3] have presented the heat transfer correlation for the Nusselt number for the case of countercurrent film reflux condensation. They determined an interfacial shear stress as a function of the film Reynolds number at a turbulent vapor flow.

Girard and Chang [4] have conducted the phenomenological modeling combining the Nusselt theory extension with a linearized stability analysis of the film flow for the case of a constant heat flux on basis of their experimental study of reflux condensation inside a vertical tube with large H/D ratios (233–506). Chou and Chen [5] have extended the model of Girard and Chang [4] to the case for the convective heat transfer from a tube surface to the isothermal fluid.

The authors of [5] used the same expressions for the friction factor as Chen et al. [8].

Pan [6] has developed a mathematical model on the condensation heat transfer accounting for the mass transfer, vapor velocity

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.001
0017-9310/

Nomenclature

a	component of the roughness width
a_f	film thermal diffusivity
b	component of the roughness width
c_p	specific heat capacity at constant pressure
D	inner diameter of measuring section
g	gravity acceleration
r	latent heat
G	mass flow rate
H	height of measuring section
L	characteristic length
S_m	roughness width
T	temperature
ΔT	temperature difference

Subscripts

f	film
i	inlet of measuring section
l	laminar
lw	laminar-wavy
o	outlet of measuring section
v	vapor

Superscript

—	mean value

Greek letters

α	heat transfer coefficient
Δ	roughness height
ε	condensate and vapor rate ratio, i.e. ratio of condensate mass flow rate to vapor mass flow rate at the inlet of the measuring section
λ	thermal conductivity
μ	dynamic viscosity
μ^*	viscosity ratio
v	kinematic viscosity
ρ	density

Dimensionless numbers

Ga	Galileo number
Ku	Kutateladze number
Nu^*	modified Nusselt number
Pr	Prandtl number
Re	Reynolds number

and interfacial shear and presented the numerical results. He concluded that the effect of the interfacial shear should be especially considered for the upward water vapor flow. Pan [6] has obtained the Nusselt numbers lower than predicted by Nusselt theory. In [6] the expressions for the friction factor were used the same as in [8].

Liao et al. [7] used the heat and mass transfer analogy approach and they have developed a mechanistic model for reflux condensation of flowing vapor accounting non-condensable gases. The shear stress was expressed by the vapor and film Reynolds number.

Only few works [8,10–14] are devoted to the experimental investigations of condensation heat transfer with upward steam flow inside a vertical tube and in a thermosyphon in a case of laminar film flow. All studies (Table 1) were performed for small diameter tubes.

Gross and his co-workers [10,12] investigated the condensation heat transfer, effects of the film Reynolds and Prandtl numbers and interfacial shear stress. In [10] some experimental points for Nu^* at $Re_f < 10$ were significantly smaller than Nusselt prediction. Gross et al. [14] conducted visual study of the formation, structure and frequency of condensate film wave, and also its dependence on the film Reynolds number and shear stress.

Al-Shammari et al. [11] have presented the distribution of the temperature, heat transfer coefficient and heat load along a vertical tube with a counterflow cooling to a vapor flow. Lee et al. [13] have performed reflux condensation experiments in a U-tube and obtained the results which generally agree with the Nusselt prediction.

In papers [15,16] the reviews of investigations of countercurrent condensation in a thermosyphon and tubes are presented. Gross [15] noted that the Nusselt solution was the upper boundary for the experimental data which were smaller than Nusselt predictions by about an order of magnitude in the case of the thermosyphon filled with the water.

Recently Lips and Meyer [16] have presented a review and showed that there are no generally accepted correlations or models for condensation in vertical tubes and that their validity must be examined when new experimental results appear. They [16] also marked that additional experimental investigations are needed for better understanding condensation in vertical tubes at low mass fluxes, particularly for upward vapor flow.

Therefore, the presented examination of literature shows that:

- There are only few experimental investigations of laminar film condensation inside tubes with upward steam flow.
- Experimental values of the Nusselt number fell below Nusselt prediction at a low film Reynolds number ($Re_f < 10$).
- All studies were performed for the tubes with large H/D ratios (10–506).

The purpose of the present paper is to study the laminar film condensation inside a vertical tube of large diameter (0.2 m) and small H/D ratio (1.1) with upward steam flow of small flow rate (0.5×10^{-3}–6.6×10^{-3} kg/s) and develop a correlation for the Nusselt number.

2. Experimental setup

The test facility is schematically drawn in Fig. 1.

Table 1
Experimental investigation of the film condensation with upward steam flow inside vertical tubes and closed thermosyphone.

Authors	Re_f	Re_v	$D \times 10^3$ (m)	H (m)	Tube material
Thumm et al. [10], Gross et al. [12,14]	1.3–2100	0–15000	28.2	0.29–1.7	Brass
Al-Shammari et al. [11]	[a]	8200	28.25	3.0	Copper
Lee et al. [13]	4–68.3	400–6300	16.2	2.8	Steel
Chen et al. [8]	2–24	[a]	14.2	0.9398	Steel

[a] No information.