Condensation heat transfer characteristics of vapor flow in vertical small-diameter tube with variable wall temperature

DU Xiaoze (杜小泽) & WANG Buxuan (王补宣)

Thermal Engineering Department, Tsinghua University, Beijing 100084, China
Correspondence should be addressed to Wang Buxuan (email: bxwang@mail.tsinghua.edu.cn)

Received August 10, 2001

Abstract To explore the condensation characteristics of vapor flow inside vertical small-diameter tubes, the classical Nusselt theory is revised and an analytical model with variable tube wall temperature is established by considering the effect of surface tension exerted by condensate film bending as well as the effect of shear stress on vapor-liquid interface. The effects of various factors including tube wall temperature and gravity on flow condensation in small-diameter tubes are analyzed theoretically to show the heat transfer characteristics. Comparison with the experimental data indicates that the proposed analytical model is fit to reveal the fundamental characteristics of flow condensation heat transfer in vertical small-diameter tube.

Keywords: small-diameter tube, flow condensation, heat transfer characteristics.

Classical Nusselt theory has long been the fundamentals for analyzing condensation heat transfer. Much work has been done concerning laminar film condensation along cooled solid wall, and the assumptions of the Nusselt or revised Nusselt theory have been widely examined. Some semi-empirical correlations for flow condensation were proposed and well used in most of traditional industrial fields.

Since the 1980s in some applied areas such as automatic air conditioners, capillary pumped loop and life-support system in space engineering, heat exchangers have been required to be more compact and more efficient and sometimes have to be minimized due to limited space and high heat flux, meanwhile micro mechanical systems (MMS) and micro electro-mechanical systems (MEMS) have made strict demand on the volumes of cooling installations; that is, heat transfer should be made to take place in a space far smaller than the normal ones. Novel compact heat exchangers have been developed rapidly and exchangers with channel of 0.5—2 mm diameters, prepared with printed circuit technology, have already been put into commercial uses. Such diameters are in a too small scale to fit for Nusselt assumptions and the analytical method of gravity-controlled film flow condensation. The Nusselt theory is facing the challenge of the new technology. Therefore, we have to reexamine the conventional method and remodel the related theoretical analysis.

This work explores the heat transfer characteristics in vertical tube of small-diameter with variable wall temperature. The results reported would help understand the flow condensation heat transfer in small-scale conditions more deeply and promote the correlating applications.

1 Physico-mathematical model

The physical model to be analyzed is illustrated in fig. 1. The inlet saturated vapor with
Fig. 1. Physical model.

temperature $T_s$ and velocity $u_{\phi 0}$ is condensed along the inside tube wall by the countercurrent flow of cooling water surrounding the test tube with radius $R$ and forms falling condensate film of thickness $\delta_i(z)$. Decreasing the tube diameter to some extent, the thickness of downflow condensate film will be no longer negligible as compared with tube diameter. Then, the bending effect of condensate film, and in turn, surface tension on phase change interface may have obvious effect on flow and heat transfer. This may vary various effects on flow condensation. With respect to such a countercurrent annular tube condenser, neither constant tube wall temperature, nor constant wall heat flux condition can be assumed in mathematical modelling. The pressure gradient may also change the fluid properties along the tube. So the basic assumptions we took for proposed analytical model are as follows:

(i) The condensate maintains laminar flow along the tube wall surface in form of stable, annular and smooth film.

(ii) The properties of vapor and phase-change interface will vary along flow path; no effect of non-condensing gas exists.

(iii) The bending condensate film may produce capillary pressure on phase-change interface.

(iv) The local saturated temperature $T_s(p)$ is a function of in-situ pressure, so the vapor will become supersaturated accordingly with $T_v > T_s(p)$ during condensation.

(v) The inertia term in equation of momentum for film flow and the convective terms in energy equation for heat transfer can be neglected.

1.1 The governing equations

For laminar film flow, the governing equations for momentum and heat transfer of condensate can be expressed as

$$
\frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_i \frac{\partial u_i}{\partial r} \right) - \frac{\partial p_i}{\partial z} + \rho g = 0,
$$

with boundary conditions:

$$
u_i = 0, \text{ for } r = R, \quad (2a)$$

$$
- \mu_i \frac{\partial u_i}{\partial r} = \tau_{\delta}, \text{ for } r = (R - \delta_i), \quad (2b)
$$

$$
\frac{2\pi k_i(T_s - T_w)}{\ln(R/(R - \delta_i))} = \frac{dm_{\delta}}{dz} \cdot h_{1i} \left( 1 + \frac{c_v(T_v - T_s)}{h_{le}} \right),
$$

among which $T_s$ is the saturation temperature under in-situ vapor pressure.

Assuming uniform temperature in vapor zone and neglecting inertia terms, the momentum equation of vapor can be expressed as

$$
\frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_e \frac{\partial u_e}{\partial r} \right) - \frac{\partial p_e}{\partial z} + \rho_e g = 0,
$$

with boundary conditions: