Study on Characteristics of Steady Flow Condensation Heat Transfer in a Tube under Zero–Gravitation

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In this paper, the annular flow model for in–tube completed condensation is employed to predict the steady flow condensation heat transfer characteristics in a tube under zero–gravitation. In this case, it is proposed that vapor condenses on the liquid film surface. Due to the effect of surface tension, the liquid exists in the form of liquid film ring contacting wall; when the velocity of vapor core decreases to zero, the condensation process ends. Putting forward the physical and mathematical models, the problem is solved and the multi-order equation of the thickness of liquid film is obtained, which includes terms of the pressure gradient along axial direction, the friction force between vapor and liquid on interface. By computational calculation, this model can be used not only to predict the thickness of liquid film, the condensation pressure gradient along the axial direction, but also to determine the Nusselt number, the condensation length and the total flow pressure drop of condensation etc. At the end, the calculation results of the necessary condensation length are compared approximately with those from the experiments, which are obtained on the test set–up placed horizontally in gravitation field, and the deviation is analyzed.

Keywords: zero–gravitation, the annular flow model for in–tube completed condensation, thickness of liquid film, condensation pressure gradient, Nusselt number, total flow pressure drop of condensation, condensation length.

INTRODUCTION

With the rapid development of space technology, it is urgent to develop a new type two phase heat system, which should be smaller, lighter and can transfer more heat for longer distance. In such a system the condensation heat transfer process must be included. So in zero–gravitation field it is very important to predict the characteristics of steady flow condensation heat transfer length inside a condensation tube.

In this paper, it is believed that vapor condenses at the liquid film surface under zero–gravitation environment, due to the effect of surface tension, the liquid can’t leave the vapor–liquid interface into the vapor core. From zero, the thickness of liquid film increases gradually along the flow direction, when the velocity of vapor core decreases to zero, the thickness of liquid film will increase to the radius of condensation tube, then the condensation heat transfer is completed. That is, at steady state the condensation heat transfer in a tube consists of the flowing liquid film ring contacting wall and the flowing vapor core which velocity changes gradually to zero, afterwards there will be single–phase liquid flow heat transfer. The three terms, that is the thickness of liquid film, the axial pressure gradient, the friction force between vapor and liquid, are comprehensively considered along the entire condensation process. From the equilibrium equations of momentum, energy and mass, the multi–
order control equation of liquid film thickness is obtained, including terms of pressure gradient and shearing stress. When calculating the thickness of liquid film and the pressure gradient, the Nusselt number, the axial condensation length and the flow pressure drop can be simultaneously obtained.

In this paper, it is special that the liquid film thickness isn't considered as small term, and the pressure gradient isn't neglected. The leading conclusion from this has significance for designing condenser in zero-gravity: it is not suitable to use larger diameter condensation tube, this differs from the studies of condensation heat transfer in micro-gravity\cite{1,5,6}.

Using this model, it is calculated to find that there is a concave turning point of liquid film thickness along the axial direction, the concave directs down in the beginning, and it will turn upwards near the end of vapor condensation. In 1-gravitation field, it is difficult to find the change of concave direction\cite{5,7}. According to the model proposed, the concave direction will change in zero-gravitation space environment, which will make the condensation characteristics change differently between 1-g and O-g environments.

PHYSICAL MODEL AND MATHEMATICAL MODEL

Physical Model (shown in Fig.1)

1) The working fluid has constant properties and the condensation tube works in zero-gravitation environment;

2) In a condensation tube there is only pure vapor and flowing liquid film ring, i.e. there is no non-condensable gas;

3) The inertial force term of liquid film in the momentum equation is ignored, so is the convection term in energy equation;

4) The temperature at vapor–liquid interface is the saturation temperature $T_s$, and there is no temperature difference, the wall of condensation tube keeps constant temperature $T_w$;

5) The pressure of liquid film and vapor core at each cross section is homogeneous;

6) The surface of the liquid film is in ideal state, there is no oscillation;

7) When the velocity of vapor core decreases to zero, the condensation ends.

Mathematical Model

1) Control equation of liquid film

When flow vapor condenses in a tube, the momentum equation of the liquid film is,

$$\rho_l \left( \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right) = -\frac{dP}{dx} + \rho_l g + \mu \frac{\partial^2 u}{\partial y^2}$$

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Separately the continuity and energy equation of the liquid film are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = a \frac{\partial^2 T}{\partial y^2} = 0 \quad (3)$$

Equation (3) can prove that temperature profile along the thickness of liquid film is linear.

2) Momentum equation of flow vapor

$$\frac{dP}{dx} = -\frac{4\tau_{vl}}{DN} - \frac{d(\rho_u u_v^2)}{dx} \quad (4)$$

In Equation (4), term $-\frac{4\tau_{vl}}{DN}$ is the influence term on pressure gradient due to the friction force between vapor and liquid film, while term $-\frac{d(\rho_u u_v^2)}{dx}$ is that due to vapor inertial force. $\tau_{vl}$, which is the shearing stress between vapor and liquid film, consists of two parts: the one $\tau_f$ is due to the velocity difference between vapor and liquid, the other one $\tau_m$ is due to vapor condensation, which leads to the momentum transfer.

$$\tau_{vl} = \tau_f + \tau_m \quad (5)$$

when $\bar{u}_v > u_{ls}$,

$$\tau_f = \frac{1}{2} C_f \rho_v (\bar{u}_v - u_{ls})^2, \quad \tau_m = \frac{qdx}{h_{fg}} (\bar{u}_v - u_{ls}) \quad (5a)$$

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