Condensation Heat Transfer Inside a Tube in a Microgravity Environment

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This paper introduces a method for studying condensation heat transfer inside a tube in a microgravity environment. The model assumes laminar flow in the condensate film and an annular flow pattern. The local heat transfer coefficient is then calculated by gravitational acceleration, \( g \), from 0 to 9.8 m/s\(^2\). The model was tested indirectly by measuring condensation heat transfer inside a vertical tube in a normal gravity environment through experiments.

Keywords: condensation, microgravity, annular flow.

INTRODUCTION

Condensation-radiation radiators are very important part of thermal control systems in aerospace applications. Because the condenser works in microgravity, the condensation mechanism and the two-phase flow pattern are different from those in a normal gravity environment. Therefore, theory and correlation formulas obtained from experiments under \( 1 - g \) can not be directly used in microgravity. Further research is needed to understand condensation heat transfer characteristics in microgravity and to develop methods for calculating condensation heat transfer coefficient.

MATHEMATICAL AND PHYSICAL MODEL

Condensate Film Behavior in Microgravity

Conduction is the primary heat transfer channel in the condensate during film condensation, so the thermal resistance is concentrated in the liquid film. The liquid greatly reduces heat transfer coefficient or even halts condensation if the condensate cannot be quickly removed. On earth, gravity not only removes the condensate but also separates the vapor from the liquid. However, gravity has no effect in space. One must use another way to drive the liquid film. Five mechanisms have been proposed to remove the liquid film: suction, centrifugal force, mechanical wipers (they all need energy and reduce reliability of the system), capillary pumping or surface tension forces, and vapor shear stresses.

In microgravity, vapor near the tube wall condenses first. The condensate will then be adsorbed on the tube wall by surface tension, forming a symmetric annular film. Because the vapor velocity is faster than the liquid velocity, there is a clear interface between the two phases. Therefore, the simplest way to remove the condensate is by vapor shear. However, it is unclear whether vapor shear stress can remove the condensate and ensure condensation to be continued.

It is so difficult to study condensation heat transfer in microgravity by experiments that most research now is by theoretics. How to verify theoretical results by experiments is still a problem. Refs. [2,3] studied condensation heat transfer by theoretics, but the results were not tested.

To Proposed Mathematical and Physical Model

Though long-term tests aboard the shuttle or space station will ultimately be required, theoretical study of condenser performance in microgravity is feasible and less costly. But how to examine the theoretical results? Experimental data obtained in normal gravity cannot be used directly, so the gravitational acceleration, \( g \), in the model must be variable not constant. Thus, results can be used in both gravity and micro-
Table 1 Comparison of condensate flow mechanism in micro and normal gravity

<table>
<thead>
<tr>
<th></th>
<th>0 - g (inside tube)</th>
<th>1 - g (inside vertical tube)</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow regime</td>
<td>annular flow</td>
<td>annular flow</td>
</tr>
<tr>
<td>control force</td>
<td>vapor shear stress</td>
<td>gravity, vapor shear stress</td>
</tr>
<tr>
<td>equation</td>
<td></td>
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</table>

Horizontal and vertical directions do not exist in space since there is no gravity. Thus, the model can be tested by a vertical tube experiment on earth.

Assume the condensate film thickness, \( \delta \), is very small compared to the tube diameter, \( d \), and length, \( z \). The condensate film flow is assumed to be laminar, but the vapor flow may be laminar or turbulent. The flow pattern is annular. The vapor is pure which means to neglect the influence of noncondensable gases. The inertia term in the liquid momentum equation and the convection term in the liquid energy equation are neglected. The vapor and liquid properties can be thought approximately as constants. These assumptions can be used in both gravity and microgravity.

As shown in the figure shown in Table 1, the vapor temperature is \( T_v \), the velocity is \( u_v \), the tube wall temperature is \( T_w \), the liquid velocity is \( u_L \), and the liquid film thickness is \( \delta \). The motion of the condensate film is entirely due to vapor shear in microgravity. In \( 1 - g \), the motion is due not only to vapor shear but also to gravity.

(1) momentum analysis

The momentum equation for the liquid film is:

\[
\mu_L \frac{\partial^2 u_L}{\partial y^2} - \frac{dp}{dz} + \rho LG = 0
\]  

(1)

boundary conditions:

\[
\begin{align*}
    y = 0, & \quad u_L = 0 \\
    y = \delta, & \quad \mu_L \frac{\partial u_L}{\partial y} = \tau_\delta
\end{align*}
\]

(2)