§4. Numerical Analysis for Steady-State Heat Transfer from a Flat Plate at One End of a Rectangular Duct in Pressurized He II

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The numerical analysis that perfectly solved the two-dimensional steady-state and transient heat transfer by means of the original two fluid model has not been reported until now. There also have been few studies [1, 2] that estimated whether the analytical models used were adequate or not by comparison with the experimental data for the corresponding conditions, probably because of the lack of experimental data. In this work authors developed a computer code of two-dimensional heat transfer in He II named SUPER-2D based on the two fluid model. They calculated the steady-state critical heat flux in the ducts with the two-dimensional expansion by using the computer code and estimated the adequacy of the numerical model by comparison with the experimental data for the corresponding conditions by Tatsumoto et. al [3].

The heated plate with the width of w, 10 mm and length l, 40 mm is attached to one end of a duct with the length, L, of 100 mm. The other end of the duct is opened to a pool of He II. The inner cross sections of the ducts have the lengths l' equal to l and widths, w', of 10.0 mm, 16.0 mm, 20.0 mm, 22.0 mm, 26.0mm and 35.0 mm. Therefore, the ratio of the cross-sectional duct area to the heated surface area, A_d/A_h, is varied from 1.0 to 3.5.

The numerical calculation was performed on only right half of the analytical system because the system can be regarded as a symmetric problem. The two fluid equations based on Khalatnikov's theory were solved by the finite difference method with a staggered grids system. Time integration was performed explicitly with a time step of 4.0×10^{-7} sec. The length of a grid in the vertical and the horizontal direction was 0.25 mm.

The initial heat flux smaller than the measured CHF for the corresponding conditions was applied uniformly to the heater. When the time variation of the temperature adjacent to the heated surface, $\partial T/\partial t$, converged below 10^{-5} K/sec for a certain duration, the temperature distribution was regarded to be steady-state. The heat flux applied to the heater was set to be 0.04 W/cm^2 higher than the previous value and the calculation was repeated with the time increment. When the temperature adjacent to the heated surface reached λ temperature, the heat flux was defined as the steady-state critical heat flux. The steady-state critical heat fluxes (CHFs) on a flat plate in the rectangular ducts with various A_d/A_h were calculated for the temperature ranging from 1.8 to 2.07 K in pressurized He II at 101.3 kPa.

Figure 1 shows relationship between numerical solutions of critical heat flux, q_{cr}, and ratio of cross sectional duct area to heated surface area, A_d/A_h, with temperature, T_B, as a parameter. They were expressed by means of various solid symbols. The CHFs measured by Tatsumoto et al. [3] were also expressed by using various open symbols for comparison. As shown in this figure, the CHFs for a fixed T_B obtained from the experiment and the calculation rapidly increase, with increase in A_d/A_h up to 2.2. With further increase in A_d/A_h, the increasing rate of CHF tends to become smaller and the CHFs seem to approach a constant value. As the temperature decreases to around 2.0 K, the CHFs rapidly increase. With further decrease in T_B, the increasing rate of the CHF becomes smaller. The CHFs obtained from the numerical analysis are in agreement with those measured by Tatsumoto et al. within 9.0 % difference. The numerical analysis for the two-dimensional problem in He II have been investigated by several workers until now. However, there have been few numerical models that were confirmed to describe experimental data well. The two-dimensional two-fluid model in the present work would be the first one that can describe the experimental data of the steady-state critical heat flux as shown in Figure 1.

Figures 2 shows the typical velocity distribution of the superfluid component, the normal fluid component, the total fluid and the distribution of the temperature in the duct with A_d/A_h=2.0 for bulk temperature of 1.8 K at λ transition. The vortex is generated above the center of the heated surface by the superfluid component coming to flow along the adiabatic bottom. Because of the behavior of the superfluid component, the normal fluid component at first moves to the center of the duct and then expands over the cross-section as shown in Fig.2. Therefore, the temperature rapidly increases near the heated surface. It is observed that the vortex is generated and develops above the boundary between the heated surface and the adiabatic bottom in He II caused by the interaction of the two components mentioned above. It has been considered that there is no net mass flow in He II although the superfluid component and the normal fluid component can flow in opposite direction. The numerical solutions show that the net mass flow is generated in He II for the two-dimensional heat expansion as shown in Fig.2. With further heating, the vortex is separated by the secondary vortex generated at the corner of the duct due to the interaction between the duct wall and the normal fluid component with viscosity. One of the split vortexes is shifted toward the end of the duct by the secondary vortex. The development and the departure of the vortex are repeated until the λ transition occurs. The superfluid component is mainly supplied to the edge of the heated surface along the adiabatic wall and the flow has little disorder. However, it is difficult to supply the superfluid to the center of the heater because of the vortex distribution. The complex disturbance in the normal fluid component impedes the transport of the higher entropy obtained from the heater toward the top of the duct. Therefore, the heat transfer would locally become worse above the center of the heater. The liquid temperature adjacent to the heated surface first reaches the λ temperature at the center of the heater.

On the other hand, the CHFs increase with increase in A_d/A_h because the supply of the colder fluid to the heated surface increases along the sidewall. However, it is assumed that the heat flow expansion from the heater would become saturated for the $A_d/A_h > 2.6$ because of the disturbance of the normal fluid component. The increasing rate of CHFs would become lower with increasing A_d/A_h as shown in Fig. 2.

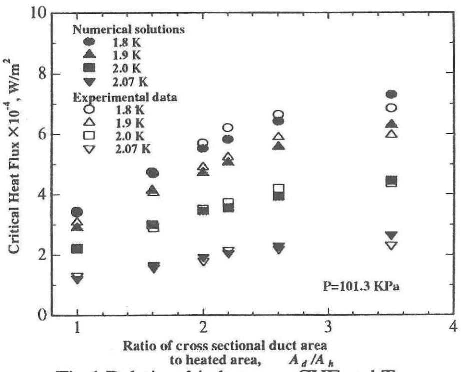
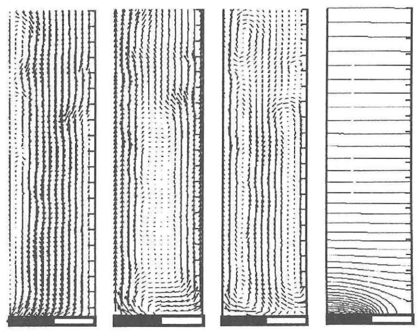


Fig.1 Relationship between CHF and T_B



(a)Superfluid component (b)Normal fluid component (c)Total fluid (d)Temperature

Fig.2 Distribution in a duct with A_d/A_h=2.0 at λ transition for T_B=1.8 K (q_{cr}=5.52 W/cm^2)

References

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