Discussion of Heat Transfer to Liquid Helium on Surface Orientation Dependence*)

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The surface orientation dependence of heat transfer characteristics in liquid helium was discussed based on previous studies. Judging from their discussions and experimental data, the critical heat fluxes of our measurements come from the upper limit of the heat flux in the regime of continuous vapor columns and patches. To compensate the surface orientation dependence, we modified the gravitational force term in a theoretical equation for the critical heat flux with a horizontal surface. Then, the evaluations by the modified equation were compared with our experimental results. Film boiling heat transfer coefficient with the variation of surface orientation was also discussed based on two-phase boundary layer treatment of free convection film boiling. It was confirmed that our experiments were consistent with the theory.

Keywords: LHe heat transfer, surface orientation dependence, polished copper surface, critical heat flux, film boiling heat transfer coefficient

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1. Introduction

Heat transfer to liquid helium has been studied for the stability analysis of pool boiling superconducting magnets. Some applications, for example, the Large Helical Device (LHD) in the National Institute for Fusion Science (NIFS), etc, their conductors were wound with angular variation because of their complicated configurations. Heat transfer performance from a conductor surface is important to realize a stable superconducting magnet [1]. To date, the surface orientation dependence of liquid helium (LHe) heat transfer has been studied [2–4]. Small discrepancy exists among the measurements because of variations of their experimental conditions. We have also studied the dependence of LHe heat transfer on surface orientation for LHD construction [5, 6]. Useful information for the stability analysis of helical coils was provided. However there were discrepancy between our measurement and others, too.

Heat transfer has been measured on various liquids. Some theoretical and empirical equations have been proposed to express each property. The nucleate boiling heat transfer from a horizontal surface to liquids was discussed based on theory [7]. The regions of isolated bubbles and continuous vapor columns and patches were separately considered. The heat fluxes at the upper limits of the two regions were predicted and agreed with experimental data. Finally, an equation succeeded to express Critical Heat Flux (CHF) with a horizontal surface. On the other hand, film boiling heat transfer in LHe was discussed based on two-phase boundary layer treatment of free convection film boiling [8]. The dependence of film boiling heat transfer coefficient on surface orientation was successfully expressed using an equation.

In this paper, we focus on the equation for CHF and propose the modified equation to compensate the variation of heat transfer surface orientation. The expected CHFs with various surface angles are compared with those of our experimental results. In terms of film boiling heat transfer, it is confirmed whether our experimental results follow the equation of the previous study. Finally, the surface orientation dependences of CHF and film boiling heat transfer coefficient of LHe heat transfer are discussed.

2. Experiment

For heat transfer measurements in LHe under atmospheric pressure, a polished copper surface was employed. Its details were described in reference 6, and therefore, just a brief explanation on the experiment is done in this paper. Figure 1 shows the sample with the mechanism changing the surface orientation to simulate the angular variation of a superconductor. The heat transfer surface was 18 mm in width and 76 mm in length. It was covered by a Glass Fiber Reinforced Plastic (GFRP) holder except for the heat transfer surface. The surface temperature was measured by AuFe-Chromel thermocouples attached in a 1 mm depth from the surface. The orientation was varied from a horizontal (upward), 0° via vertical, 90° to downward, 180° surface.

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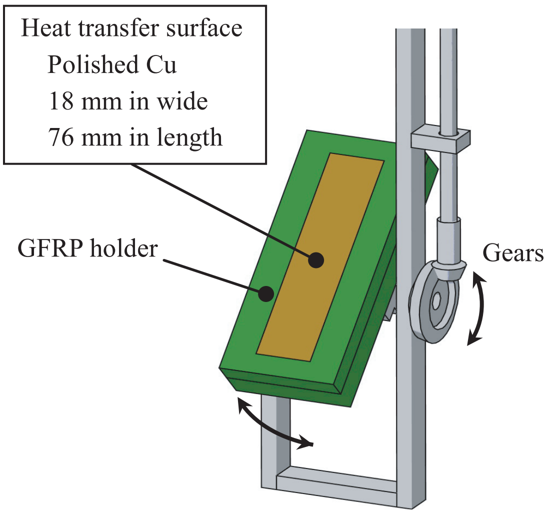

Fig. 1 Sample with the mechanism changing the surface orientation.

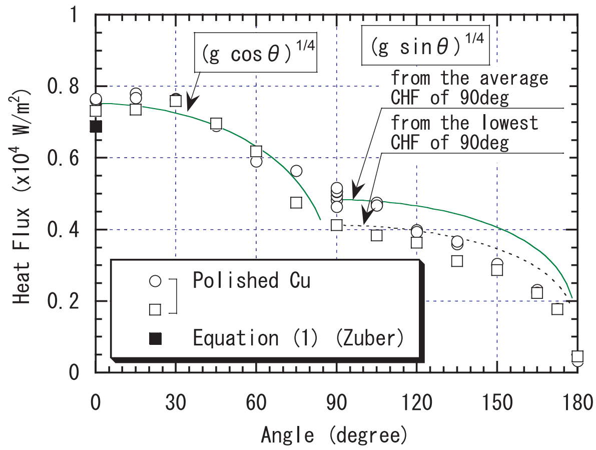

Fig. 2 Dependence of CHF on surface orientation. Two marks; ○ and □ mean different measurements with a re-polished Cu surface.

3. Discussions on Surface Orientation Dependences

3.1 Critical heat flux

The upper limit of the heat flux for a horizontal surface in the regime of continuous vapor columns and patches is expressed as

$$q_{\mathrm{CHF}} = \rho_{\mathrm{v}} h_{\mathrm{LG}} \frac{\pi}{24}\left[\frac{\sigma g\left(\rho_{\mathrm{L}}-\rho_{\mathrm{v}}\right)}{\rho_{\mathrm{v}}^{2}}\right]^{1/4}, \tag{1}$$

where q_{CHF}, ρ, h_{LG}, σ and g are CHF, density, latent heat of vaporization, surface tension and gravity, respectively [7]. Subscripts: L and v are liquid and vapor, respectively. Equation (1) predicts CHF. The expected CHF of LHe heat transfer was calculated and results in 6900 W/m^2. Our measurements are consistent with it as shown in Fig. 2 and support the theory. It was confirmed that the CHF is decided by the upper limit of the heat flux in the region of continuous vapor columns and patches.

To compensate the surface orientation dependence of CHF, the gravity term in equation (1) is changed to g·cosθ in the range of an angle from 0° to less than 90°. The CHFs with angle variation are briefly calculated using the following correlation:

$$q_{\mathrm{CHF}}(\theta) = q_{\mathrm{CHF}}(0^{\circ}) \cos^{1/4}\theta. \tag{2}$$

Figure 2 shows the comparison between the expected CHFs based on the average CHF of a 0° surface and our experiments. Equation (2) can express the surface orientation dependence of CHF for an upward surface. As the angle is close to the vertical, the heat transfer process might be altered to a vertical surface heat transfer, and therefore, the equation is not applicable for the angle of ~ 90°. There would be hardly any difference of heat transfer between this angle range and the vertical. On the other hand, a downward surface starting from the vertical has the different heat transfer mechanism from the upward surface. Bubbles must flow up along the heat transfer surface. This situation is close to that for the narrow channel heat transfer whose CHF depends on the critical quality in terms of a two phase flow [9,10]. The quality is a function of the bubble flow velocity. The rising velocity of a spheroidal babble is in proportion to g$^{1/4}$ [7]. Buoyant force of a He bubble must be affected by the component of the gravitational force along the surface. Finally, the CHF with the surface orientation of 90° to 180° might depend on (g·sinθ)$^{1/4}$. The dependence of CHF on surface orientation might be expressed as

$$q_{\mathrm{CHF}}(\theta) = q_{\mathrm{CHF}}(90^{\circ}) \sin^{1/4}\theta. \tag{3}$$

According to equation (3), the expected CHFs are compared with our experiments. Based on the average CHF of a 90° surface from several measurements, our estimation is overestimated. However, the variation tendency on the orientation dependence is consistent with that of our measurements. In terms of our measurements, obvious discrepancies existed in the CHF measurements especially at the surface orientation of 90°. If the lowest CHF is applied for the estimation, the predicted CHFs are consistent with the measurements. Judging from our discussions, the dependence of CHF on surface orientation can be described by the equations.

3.2 Film boiling heat transfer

Film boiling heat transfer coefficient was discussed based on two-phase boundary layer treatment [11]. Heat transfer coefficient, $h(\theta)$ was proposed to express the equation [8]:

$$h(\theta) = h(90^{\circ}) \sin^{1/4}\theta. \tag{4}$$

Our experimental data of $h(\theta)$ with the temperature difference of 1.5 K are compared to those by the equation as

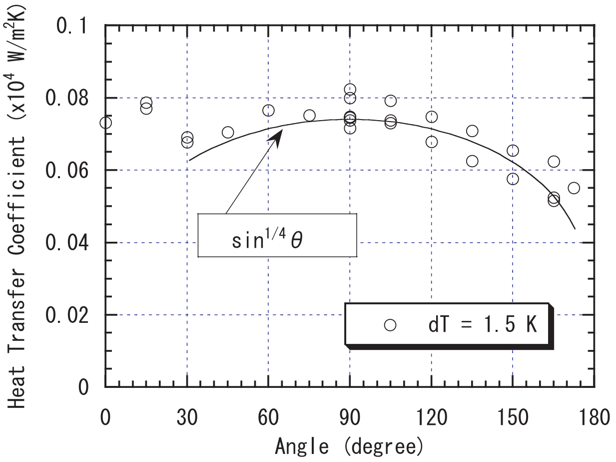

Fig. 3 Dependence of film boiling heat transfer coefficient on surface orientation.

shown in Fig. 3 and are consistent with the theory. As described in reference 8, around the angle close to the horizontal surface, experimental results do not follow the equation.

4. Conclusions

The dependence of heat transfer characteristics on surface orientation was discussed based on the previous studies. The CHF with a horizontal surface in our measurement is predicted by the theoretical equation come from the upper limit of heat flux in the region of continuous vapor columns and patches. We modified the gravitational force term in the equation to compensate the surface orientation effect. The calculations were compared with our experiments. Just modifying the gravitational force term realizes to express the surface orientation dependence of CHF. Film boiling heat transfer coefficient was also discussed according to the previous description on its surface orientation dependence based on two-phase boundary layer treatment of free convection film boiling. It was confirmed that our experiments support the theoretical model.

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