Natural Convection Heat Transfer to Liquid Helium in a High Centrifugal Acceleration Field*

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This paper reports experimental results of natural convection heat transfer to liquid helium in a rotating field in the range of 1600 - 3700 rpm. Test surfaces are vertical plates (10 mm width, 5 mm height) with rectangular channels in a radial direction and upward- and downward-facing horizontal plates (8 mm diameter) at radial distances of 0.3 m. The results show that the heat transfer for vertical plates is approximately the same as that for horizontal ones facing upward, independent of the channel gap size in the range of 0.4 - 5 mm and direction of the Coriolis force. The heat transfer can be predicted from the conventional correlation $Nu = 0.13Ra^{1/3}$ in the Ra range of $10^{11} - 10^{13}$, if the film temperature for evaluating properties is substituted for the pseudocritical temperature only when it is above the pseudocritical temperature. The heat transfer for the horizontal plate facing downward is 1/6 - 1/7 of that for the one facing upward, and the Ra exponent of its correlation is 0.2 in the Ra range of $10^{12} - 10^{14}$.

Key Words: Natural Convection, Helium, Heat Transfer, Cryogenics, Supercritical fluid, Rotor, Centrifugal force.

1. Introduction

Liquid helium used in superconductive power generators is at a supercritical pressure because the pressure rises due to its own weight when receiving a large centrifugal force in a rotating field. Natural convection heat transfer of this coolant was subjected to more active research for each of static and rotating fields on the fundamental heat transfer models (for example, a horizontal flat plate), and their behaviors is almost the same as that in natural convection heat transfer of a constant property fluid⁽¹⁾⁻⁽⁶⁾. However, because the influence of the orientation of the heat transfer plate and cooling channel on the heat transfer is not clear, it is unknown whether the knowledge obtained from conventional research can be applied to actual superconductive magnets or not.

Therefore, we made a rotary cryostat, which spins a liquid helium vessel and generates a high centrifugal force field, and conducted experiments

using test pieces having a heat transfer model matching the cooling structure of actual machines. This paper reports the experiment and results.

Nomenclature

a : Acceleration
 D : Representative dimension
 Gr : Grashof number
 N : Speed of revolution
 Nu : Nusselt number
 P : Pressure
 Pr : Prandtl number
 q : Heat flux
 $r_{1,2}$: Radius
 Ra : Rayleigh number
 T : Temperature
 T_f : Film temperature
 T_p : Pseudocritical temperature
 T_{ref} : Evaluation temperature
 x : Cooling channel gap size
 ν : Kinetic viscosity coefficient
 ρ : Density
 θ_c : Coriolis force working angle

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Subscripts

- ∞ : Surrounding fluid
 w : Heat transfer plate

2. Experimental Apparatus

Figure 1 and Table 1 show the longitudinal cross-sectional view of the experimental apparatus and its main specifications, respectively. In the apparatus, test pieces simulating cooling channels of superconductive magnets are built in three test sections standing out radially from the center of the rotor (see Fig. 2).

The root of test sections constitutes a liquid helium (LHe) vessel and is supported by the upper and lower thin-wall torque tubes with rotor shafts. On the outer periphery of the torque tubes, piping for releasing evaporated helium gas (GHe) from the LHe vessel is spirally wound. Due to the coldness of GHe,

Table 1 Main specifications of experimental apparatus

•Rotor	
Overall size	Maximum radius 185mm, Length 1250 mm
	Gas-cooled torque tube
	Helium transfer coupling (use of magnetic fluid seals)
LHe vessel	ID 150 mm, OD 380 mm, Length 120 mm, Volume 7 liters
Test section	3 radial cylinders ($\phi 80$ mm x 180 mm, radius 190 - 370 mm)
Drive motor	1.5 KW DC motor
rotating speed	200 - 3700 rpm
•Vacuum vessel	
Overall size	Diameter 1000 mm, Height 1600 mm
	LN ₂ -cooled radiation shield
Seal	Magnetic fluid seals

Fig. 1 Experimental apparatus

heat conducted from the room temperature section to the LHe vessel is removed so that the heat penetrating to the LHe vessel is decreased. The hollow part at the top of the rotor shaft is provided with coaxial triple tubes constituting LHe supply and GHe release tubes, which are thermally insulated by vacuum. A helium transfer coupling, which is made up of 2 magnetic fluid seals, is installed on the upper rotor shaft end and is capable of supplying LHe and releasing GHe continuously even while rotating. The rotor is supported in the vacuum vessel by room temperature bearings, sealed by magnetic fluid seals and driven by a DC motor with a speed controller. Since the rotor is subjected to heat shrinkage (approximately 1 mm) when cooled, the rotor weight is supported by the upper bearing only and the lower one can slide freely axially. The LHe vessel and the torque tubes are surrounded by a radiation shield cooled by liquid nitrogen in order to minimize heat penetration by radiation. Leads of measuring signal lines from the rotor are taken outside through slip rings mounted on the lower end of the rotor shaft.

The vacuum vessel is made entirely of nickel-plated carbon steel. Pressures down to 1×10^{-3} Pa were provided by means of the oil diffusion pump.

Figure 3 shows the radial cross-sectional view of a test section. Helium circulates in the natural convection loop consisting of a cooling channel and a gap on

Fig. 2 External view of rotor

Fig. 3 Test section

the outer surface of the test piece through buoyancy generated by heat from the heater. The seats of test sections and spacer intervening midway in the cooling loop are provided with sufficiently large cutouts and holes so as not to restrict the circulation flow. Figures 4 and 5 show details of the longitudinal cross-section of the test pieces, and Table 2 gives the main specifications of the heat transfer surfaces. For convenience, the 'horizontal' and 'vertical' in Table 2 mean angles of heat transfer plates to direction of a centrifugal force, which correspond to their centrifugal force. θ_c in Table 2 is the angle of the working direction of the Coriolis force on the vertical plate. It is defined that θ_c is 0° when the Coriolis force is in vertical heat transfer surfaces and a counterclockwise rotation is positive from the axial top view of the experimental apparatus. The heater blocks for heat

Table 2 Heated plate specifications of the test pieces

	Vertical ⁽¹⁾	Horizontal ⁽²⁾
Plate shape	Rectangular Width 10 mm Length 5 mm	Circle Diameter 8 mm
Position	0.300 m	0.295 m (downward face) 0.300 m (upward face)
θ_c	$0^\circ, \pm 90^\circ$	-

(1) in the radial channels with rectangular cross section (length 130 mm, width 10 mm, gaps 0.4, 1 and 5 mm).
(2) opened around heated surface.

Fig. 4 Test piece (vertical plate, $x=0.4, 1.0, 5.0$ mm)

Fig. 5 Test piece (horizontal plate)

transfer plates consist of oxygen-free highly conductive copper (residual resistance ratio RRR=200) with a heater and carbon resistance thermometer (Allen-Bradley Inc., 1/8 W, 50 or 100 Ω). The thermometer is installed 3 mm deep from the exposed part of the heater block to the channel, which is the heat transfer plate. The heat insulating material is Bakelite with glass fiber when the cooling channel gap, x in Fig. 4, is 0.4 mm, otherwise, glass-fiber-reinforced plastic (GFRP) is used.

In the experiment, LHe is accumulated to a certain level in the LHe vessel and the rotating speed is kept constant. Measurements are performed after making sure that each section reaches the steady state. At this state, the heater is turned on and the heat flux and heater block temperature are measured. Temperature differences between the thermometers and heat transfer surfaces are negligible because of the high thermal conductivity of the heater blocks. The voltage and current of the thermometers and the heaters are measured by the 4-terminal method. The rotor speed is detected by an optical tachometer and the LHe level is measured by a superconductive liquid level sensor (Cryomagnetics Inc., Type: 2 D, length: 3 inches). Measurement is performed using a multiple point data logger composed of a digital voltmeter and scanner. The error of the heat transfer coefficient finally obtained is $\pm 10\%$. Table 3 gives experimental conditions.

3. Experimental Results and Studies

3.1 Heat transfer of vertical plate

Figure 6 shows heat transfer characteristics at each speed N when $\theta_c=0^\circ$; i.e., the Coriolis force acts parallel with the heat transfer planes. The heat flux q of the heat transfer plate is a net value without heat loss which is due to leakage from parts other than the heat transfer plate measured beforehand. ΔT_w is obtained by subtracting T_w when not subjected to heat, which is considered to be helium temperature T_∞ , from T_w of the heat transfer surface when heated.

When the speed N is below 1600 rpm, the heat transfer characteristics show hysteresis, i.e., they differ according to whether q increases or decreases. Above 1600 rpm, there is no hysteresis and increasing

Table 3 Main experimental conditions

LHe supply pressure	0.1 MPa
LHe supply temperature	4.2 K
LHe surface radius	0.13 - 0.18 m
Rotating speed	1000 - 3700 rpm
Heating power	0 - 12 W
Heated wall temperature	4.3 - 42 K
He pressure at the heated surface	0.16 - 0.81 MPa

q raises ΔT_w monotonically. Helium pressure P described in Fig. 6 is a value calculated under the following assumption. Helium having a radius of r_1 to r_2 is subjected to an isentropic compression by its own weight where the enthalpy change h is expressed by

$$\Delta h = \frac{r_2^2 - r_1^2}{2} \left(\frac{2\pi N}{60} \right)^2. \quad (1)$$

This assumption has been experimentally proven true⁽⁴⁾. Figure 7 shows an example of the calculated pressures when the LHe level is equivalent to rotor radius 0.15 m. In this figure, the helium pressure is supercritical when N is above 1600 rpm. In actual calculations, 0.15 m is not used but a measured LHe level is.

Before experiments, it was expected that, if rotating speed rose in the supercritical pressure, the centrifugal force would increase and the heat transfer would improve. But, as is evident from Fig. 6, when T_w was as low as 1–3 K, the heat transfer did not depend much on N , contrary to our expectation, and tended to show results similar to those of experiments of horizontal plates facing upward^{(1)–(3)}. The hysteresis of heat transfer characteristics in natural convection of super-

Fig. 6 Experimental results of heat transfer for vertical plates with channels

Fig. 7 Helium pressure vs rotating speed of the rotor

critical helium, pointed out by Eckels et al.⁽⁵⁾, has not been observed in our experiments. Note that these results have not been affected by cooling channel gap size x (0.4, 1 and 5 mm) or Coriolis force working direction ($\theta_c = 0, \pm 90^\circ$). Probably, it is thought that these differences are results of differences in the ratio of heating surface height to cooling channel gap size, i.e., Eckels's ratio (approximately 2600) is much higher than ours (1–12.5).

Next, we tried to apply these experimental results for the supercritical condition into a nondimensional correlation. For physical properties, the temperature is based on a measured value but a pressure is calculated from Eq. (1), because the pressure is hard to measure. Each nondimensional number is defined by

$$Ra \equiv GrPr \equiv \left(\frac{D^3 \cdot a \cdot \rho_\infty - \rho_w}{\nu^2} \right) \cdot Pr. \quad (2)$$

Here D is a representative dimension and is the height (5 mm) for a vertical plate or the diameter (8 mm) for a horizontal plate. First, we defined film temperature T_f , which is an arithmetic mean of T_w and T_∞ , as a reference temperature T_{ref} for evaluating physical properties. The upper half of Fig. 8 indicates results obtained when speed N is 3700 rpm. Considering the magnitude of Ra , the flow may be turbulent. When T_f is lower than pseudocritical temperature T_p at which the specific heat has a peak, Nusselt number Nu and Rayleigh number Ra increase as T_f increases, but, when T_f is higher than T_p , Nu remains almost constant and Ra is reduced. This behavior is the same as laminar flow of supercritical helium⁽⁶⁾. Moreover, when $T_f < T_p$, Nu proves to be proportional to $Ra^{0.4}$.

Fig. 8 An example of nondimensional correlation of experimental results for a vertical plate

These phenomena occur when the pressure is above 0.3 MPa.

When $T_f > T_p$, Ra decreases because, even if T_f rises, most variations of ρ are caused near T_p , and then $(\rho_\infty - \rho_w)/\rho$ is almost constant but ν increases and Pr decreases. The almost constant Nu may indicate that average physical values in the temperature boundary layer, particularly thermal conductivity, are almost the same as at T_p and are almost constant regardless of increasing T_f . T_p support this point, it is necessary to clarify the fluid temperature distribution near the heating surface for natural convection heat transfer, taking into account the pressure and temperature dependencies of the physical properties of helium.

From the above observations, we define reference temperature T_{ref} to be the same value as that for the laminar range⁽⁶⁾.

$$T_{ref} = \begin{cases} T_f & \text{at } T_f < T_p \\ T_p & \text{at } T_f \geq T_p \end{cases} \quad (3)$$

It has been observed that when $T_f \geq T_p$, Nu is almost constant and that Ra is almost constant when ν and Pr are fixed at certain values. Using this T_{ref} definition equation, the experimental results in the upper part of Fig. 8 are rearranged as shown in the lower part of Fig. 8. Nu can be arranged in a form proportional to $Ra^{0.4}$. Thus, using this T_{ref} , all experimental results related to vertical plate have been arranged nondimensionally. The results are shown in Fig. 9. Most experimental results above 0.3 MPa are correlated by the following relation within the range of $\pm 25\%$.

$$Nu = 0.014 Ra^{0.4} \quad (4)$$

Here, the value 0.014 is approximately 33% smaller than the proportionality constant in the equation $Nu = 0.021 Ra^{0.4}$ ⁽⁷⁾ for natural convection heat transfer from a vertical plate.

3.2 Heat transfer of horizontal plate

Figures 10 and 11 show experimental results of

heat transfer characteristics on a horizontal plate. For a horizontal plate facing upward (Fig. 10), the obtained characteristics are almost the same as on a vertical plate. The influence of the rotating speed on heat transfer is much smaller than on a vertical plate. At a subcritical pressure, no experiments have been performed but it has already been proven by Ogata and Nakayama⁽³⁾ that increasing the speed increases the critical heat flux of nucleate boiling. For a horizontal plate facing downward (Fig. 11), the heat transfer is 1/6–1/7 that of a plate facing upward. The influence of the speed on the heat transfer is the same as for the plate facing upward. At a subcritical pressure, the transition from nucleate boiling to film boiling, although not shown, leaves some traces, but is not apparent and the heat transfer characteristics are very similar to those under the supercritical condition except that the heat transfer magnitude is smaller corresponding to the lower speed.

Figures 12 and 13 indicate results arranged nondimensionally in Eqs. (2) and (3). Figure 12 shows results on a horizontal plate facing upward. For reference, Jakob's equation⁽⁸⁾, well known as an equation

Fig. 10 Experimental results of heat transfer for the upward-facing horizontal plates

Fig. 9 Nondimensional correlation results of heat transfer characteristics for vertical plates

Fig. 11 Experimental results of heat transfer for the downward-facing horizontal plates

arranged for natural convection heat transfer from a horizontal plate facing upward, is shown by a solid line. All data, except for a comparatively small region of Ra , are within $\pm 20\%$ of Jakob's expression and the present experimental method proves to be appropriate. The reason that Nu is rather high in a small Ra region may be that the heat transfer enhancement pointed out by Islam and Scurlock⁽⁹⁾, and Khan and Scurlock⁽¹⁰⁾, is produced. Figure 13 shows results arranged nondimensionally for a horizontal plate facing downward. These results are correlated by the following relation.

$$Nu = 1.11 Ra^{0.2} \quad (5)$$

Although the proportionality constant is different, the exponent of Ra is the same as for conventional natural convection heat transfer for the laminar range⁽⁷⁾.

4. Comparison of Results

Figure 14 shows a comparison of results obtained in the present researches and results⁽¹⁾⁻⁽⁵⁾ reported previously, which are rearranged using Eqs. (2) and

(3). Note that, in previous reports, all experiments except those of Eckels et al.⁽⁵⁾ relate to a horizontal plate facing upward. Our results almost match the past reports, and it is shown that the phenomenon⁽⁷⁾ wherein turbulent natural convection heat transfer for a constant property fluid does not depend much on the plate inclination is also recognized with supercritical helium. Note that Nu in data of Khan and Scurlock⁽¹⁰⁾ tends to rise higher than other values as Ra is decreased. The reason is that the range of temperature difference ΔT_w in the experiment performed by them is below 1 K and the heat transfer enhancement mentioned above is produced. The reason why the heat transfer characteristics of Eckels et al.⁽⁵⁾ are much higher than those according to Jakob's correlation may be that not only natural convection heat transfer but also heat transfer enhancement by a duct effect or Coriolis force may be produced. In their experiments, the heat transfer characteristics suffer from hysteresis, and the height of the heat transfer plate of their test pieces is very high.

Fig. 12 Nondimensional correlation results of heat transfer characteristics for the upward-facing horizontal plates

Fig. 13 Nondimensional correlation results of heat transfer characteristics for the downward-facing horizontal plates

Fig. 14 Comparison of experimental results of previous research

5. Conclusions

A cryostat of a rotating liquid helium vessel to generate a high centrifugal force field (4600 G) has been made and an experiment of natural convection heat transfer has been performed for radial plates with cooling channels (i.e., vertical plates) and plates facing perpendicular to centrifugal force (i.e., horizontal plates). It has been found that the heat transfer characteristics of supercritical helium are almost equivalent on the horizontal plate facing upward and vertical plate, that they can approximately be expressed by a conventional empirical correlation for the turbulent natural convection heat transfer by using Eq. (3) and that the heat transfer of the horizontal plate facing downward is $1/6 - 1/7$ that of the plate facing upward.

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