Experiment on natural convection of subcooled liquid nitrogen

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The natural convection of subcooled liquid nitrogen between two vertical plates is investigated by experiment. A vertical plate is thermally connected to a cryocooler and uniform heat flux is supplied to the other plate so that subcooled liquid in the gap may generate cellular flow. The wall-to-wall heat transfer coefficients are measured and compared with the existing correlations. Good agreement is observed between two data sets, when the heat flux is small. As the heat flux increases, the measured heat transfer becomes greater because of the vertical temperature gradient with the cooling from the top, which generates a multi-cellular flow.

INTRODUCTION

Liquid nitrogen is an excellent cooling media for HTS electric application because of its thermodynamic and dielectric properties as well as low price. Most commercial applications of HTS systems cooled by liquid nitrogen also require refrigeration by a cryocooler in order to eliminate the boil-off and maintain the liquid at the subcooled state. We have proposed a new cryogenic concept for HTS cooling, operating in the range of 63~66 K by natural convection of subcooled liquid nitrogen utilizing a cryocooler [1]. In order to confirm the feasibility of the proposed concept, we designed and constructed a natural convection cooling experiment [2].

In this experiment, liquid nitrogen is cooled to nearly the freezing temperature (63 K) by a vertical copper plate thermally anchored to the coldhead of a cryocooler. As the cryocooler is located at the top, the temperatures of solid bodies including copper plate and HTS magnet decrease upwards which are obviously different thermal boundary conditions from the most studies on heat transfer in a cavity [3-5]. In a previous paper [2], we reported preliminary values for the heat transfer coefficient in a vertical cavity whose surface temperatures decrease upwards. We have now completed measuring the temperature distributions along the vertical surfaces in the cavity for various heat fluxes. In the present paper, the detailed heat transfer characteristics are investigated and the multi-cellular flow patterns with augmentation of wall-to-wall heat transfer are discussed.

EXPERIMENTAL APPARATUS

A schematic overview of the experiment is shown in Figure 1. A single-stage GM cryocooler is mounted directly at the top plate of cryostat and a rectangular shaped heating plate is vertically located at the center of the cryostat. Two parallel cooling plates are positioned at a given distance symmetrically on both sides of the heating plate and thermally anchored to the coldhead of the cryocooler through a horizontal plate.

The two vertical cooling plates are bolt-jointed at the top with a horizontal copper plate. The flexible tinned copper braids are used for connection between the coldhead and the horizontal plate as well as to protect the coldhead from thermal contraction during cool-down. A Thermofoil™ heater is sandwiched between two identical stainless steel plates with 1 mm thickness, and cryogenic epoxy is applied to ensure good contact between the heater and the plates. The heater covers the entire surface and supplies a

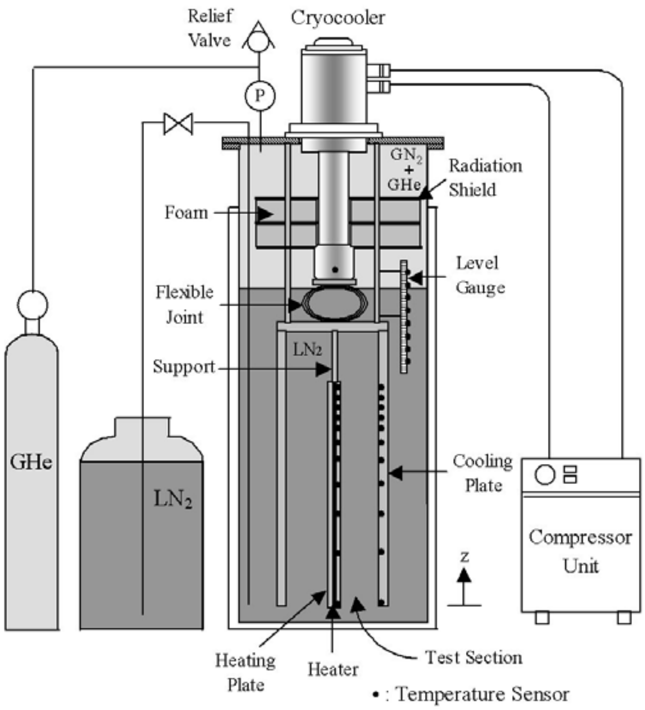

Figure 1 Schematic of experimental apparatus

constant heat flux to the plates. The heating power is regulated with a DC power supply. The cooling plates with 10 mm thickness are suspended at the top plate of cryostat, and the heating plate is suspended with gravitational and lateral supports made of threaded GFRP rod.

The surface temperatures of cooling and heating plates are measured with E-type thermocouples at a number of vertical locations as shown in Figure 1. The lead wires of the temperature sensors are connected through the holes from the opposites sides of the test section. Holes housing for thermocouple beads are located on the vertical centerline on each plate. The sensing beads of thermocouple are dipped in cryogenic thermal grease in order to prevent reaction with the fluid.

At the initial phase of the experiment, the cryostat is filled with liquid nitrogen and cooled down to near its freezing temperature (63 K) using the cryocooler and the extended cooling surfaces. Once the cryostat is cooled down, a uniform heat flux is supplied so that liquid nitrogen between the heating and cooling plates experiences natural convection. The vertical temperature distribution on both plates is measured in steady state, from which the heat transfer coefficients are calculated. The variable in this experiment is the magnitude of heat flux (8~160 W/m^2) for a given gap distance between the heating and cooling plates, L = 60 mm.

RESULTS AND DISCUSSIONS

The measured temperature distributions along the vertical surface of heating and cooling plate are presented with error bar and compared with analysis [1] in Figure 2(a) when the heat flux is 8 W/m^2. The largest value of temperature error is ± 0.025 K at z = 320 mm on heating plate, which is one-order of magnitude smaller than the wall-to-wall temperature difference, approximately 0.2 K. As the heat flux increases, the temperature error maintains within ± 0.025 K while the wall-to-wall temperature difference increases. Therefore, the sensitivity of temperature sensors is quite sufficient for our experimental purpose. In Figure 2(a), the top temperature of cooling plate is matched with the measured value as one of the boundary condition in the analysis. The heat transfer coefficient in the analysis was evaluated from the existing correlations for rectangular cavity [6] where each vertical surface has a uniform temperature. Good agreement is observed between two data sets, because the temperatures of heating and cooling plates are relatively uniform when the heat flux is small.

Shown in Figure 2(b) are the vertical temperature distributions of each plate when the heat flux is 80 W/m^2. A noticeable discrepancy is observed between two data sets, mainly because the heat transfer coefficient evaluated from the existing correlation is assumed constant vertically in the analysis. In the experiment, on the other hand, the heat transfer coefficient is not vertically uniform because of wavy temperature distribution that may result from multi-cellular flow and the details of which are discussed below. Also, the heat transfer is more active in thermal boundary condition of our experiment where the surface temperature decreases upwards, so the heat transfer coefficient is greater than that of the existing correlation. The discrepancy gets larger with increasing heat flux since the natural convection in a vertical cavity is accelerated and the wall-to-wall heat transfer is augmented.

Figure 3 displays the averaged Nusselt numbers (Nu) against Rayleigh numbers (Ra) for all heat fluxes (8~160 W/m^2) and compared with the existing correlations for a rectangular cavity [6] where each vertical surface has a uniform temperature. The height-to-gap ratio for the experimental conditions (H/L) is 8.3. When the heat flux is smaller than 40 W/m^2 or the corresponding Ra is smaller than 1.6×10^8, good agreement is observed between the experiment and correlation because the plate temperatures are

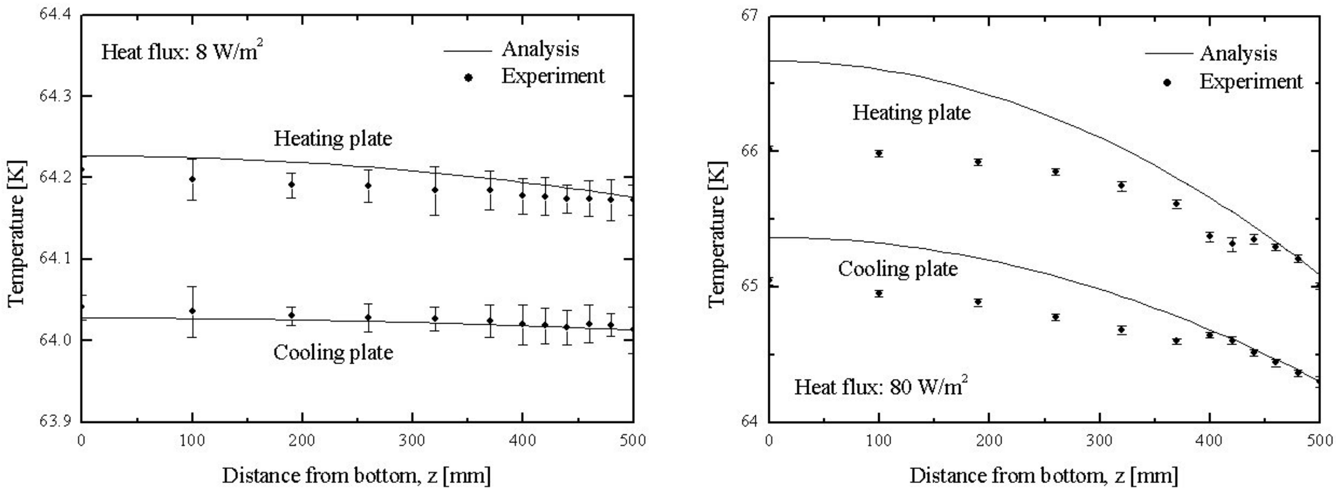

Figure 2 Vertical temperature distribution of heating and cooling plate when the heat flux is (a) 8 and (b) 80 W/m^2

relatively uniform in vertical direction. As the heat flux increases over 40 W/m^2 or Ra exceeds 1.6×10^8, however, the measured heat transfer becomes noticeably greater than the existing correlations. This discrepancy may be explained by the thermal boundary conditions in the experiment where the surface temperatures decrease upwards. Such boundary conditions can cause vertically segregated cellular flows and enhanced heat transfer in the vertical cavity. Once multi-cellular flow occurs the effective H/L ratio is smaller than the actual H/L ratio. Plotted in Figure 3 are correlations for H/L approximately 5 and 3 with the corresponding flow patterns of two and three cellular flow, respectively. These correlations compare more favorably with the experimental data for the high Ra number flows.

The temperature along the streamlines of natural convection is approximately sketched in Figure 4 for the heat fluxes at 8 and 160 W/m^2. When the heat flux is small as shown in Figure 4(a), the surface temperature of each vertical plate is relatively uniform and single cellular flow is formed in the cavity, as the fluid simply ascends along the heating plate and descends along the cooling plate. The heat transfer on the heating plate is active at the bottom and becomes less active along the ascending flow, and the temperature of fluid is getting closer to that of heating plate along the vertical direction. The opposites are true on the cooling plate.

When the heat flux is large as shown in Figure 4(b), however, the temperatures of vertical plates decrease upwards since the cryocooler is located above the vertical plates as shown in Figure 1. The ascending fluid near the heating plate becomes warmer than the surface nearly z = 250 mm, and the heat is then transferred from the fluid to the surface so the density of fluid increases, which makes the cellular flow vertically segregated with the fluid moving downward. The descending fluid near the cooling plate becomes cooler than the surface nearly z = 100 mm, and heat is then transferred from the surface to fluid so the density of fluid decreases, which make the cellular flow vertically segregated with the flow moving upwards.

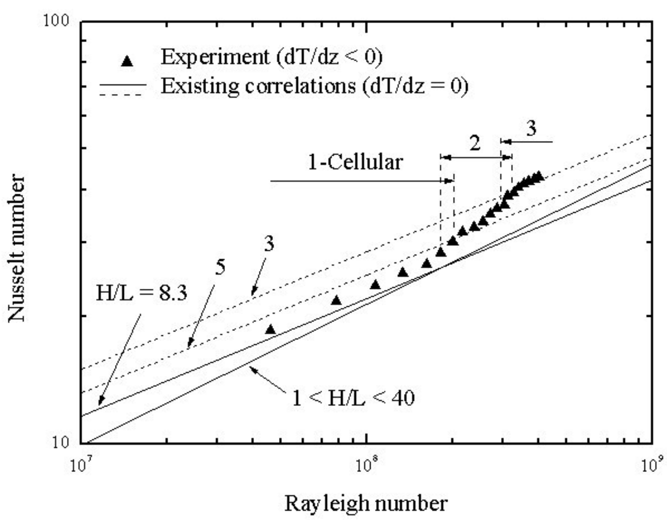

Figure 3 Average Nusselt number versus Rayleigh number

The number of cells in the multi-cellular flow should be related to the vertical temperature gradient and the wall-to-wall temperature difference. A necessary condition for the cellular flow to be vertically segregated is that the minimum temperature on heating plate must be lower than the maximum temperature on cooling plate. As a result, the segregated positions of fluid are near at the local minimum temperature on heating plate or the local maximum temperature on cooling plate. In Figure 4(b) the second cellular flow is segregated nearly z = 420 mm and the third cellular flow did nearly z = 500 mm on the heating plate. Since the cellular flows are overlapping each other, it is hard to tell the exact height of each cellular flow. However, as

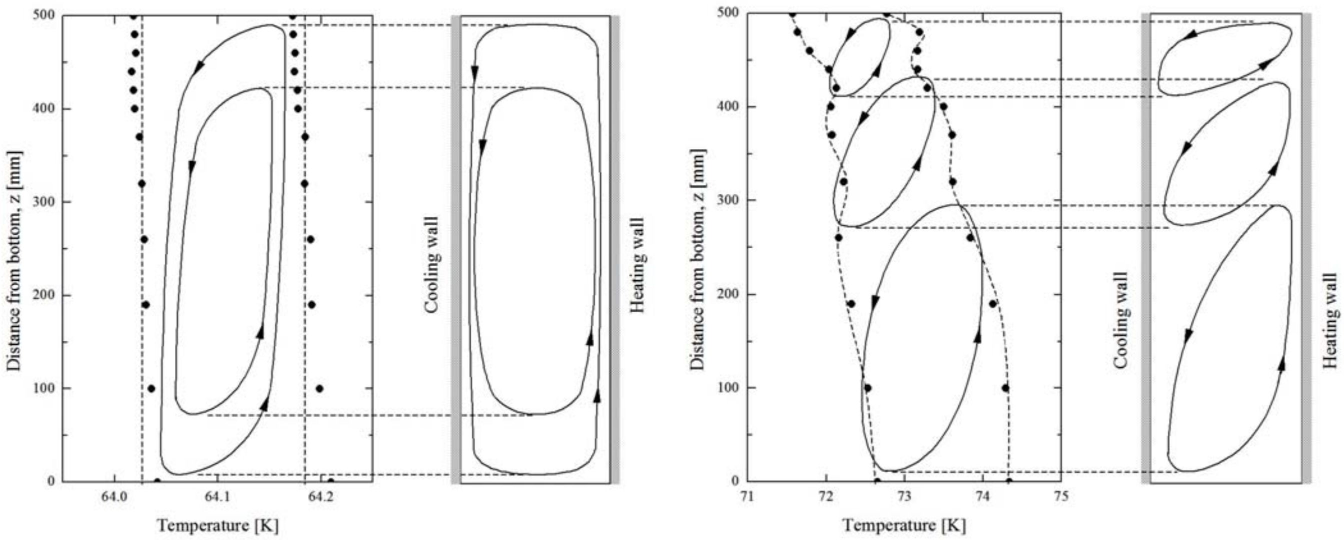

Figure 4 Temperature along streamlines of natural convection when heat flux is (a) 8 and (b) 160 W/m^2

discussed earlier, three cellular flow occurs and the effective H/L ratio is approximately 3 when heat flux is 160 W/m^2.

The multi-cellular flow pattern leads to a wavy temperature distribution along the vertical surface and enhanced heat transfer between top to bottom and plate to plate. As described above the heat transfer is active at the bottom and top when a convection cell is formed in vertical cavity as Figure 4(a). In the multi-cellular flows as Figure 4(b), the heat transfer is active not only at top and bottom but also near at z = 250 and 420 mm, which results in a smaller temperature difference between top to bottom and plate to plate.

CONCLUSION

Experiments were successfully performed to investigate the heat transfer characteristics in a vertical cavity filled with subcooled liquid nitrogen. At high Ra number, the heat transfer coefficients are approximately 20~30 % greater than the existing correlations. The thermal boundary conditions in experiment with surface temperature decreasing upwards may cause vertically segregated cellular flows in the cavity. These multi-cellular flow patterns can lead to the augmentation of wall-to-wall heat transfer by reducing the effective height of the cavity.

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