# NATURAL CONVECTION OF SUBCOOLED LIQUID NITROGEN IN A VERTICAL CAVITY

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## ABSTRACT

An experiment to measure the natural convection of subcooled liquid nitrogen between two vertical plates has been performed. The main objective of this study is to confirm the feasibility of our recently proposed design for an HTS power transformer cooled by natural convection of subcooled liquid nitrogen. A liquid nitrogen bath is cooled to nearly the freezing temperature (63 K) at atmospheric pressure by a vertical copper heat transfer plate thermally anchored to the coldhead of a GM cryocooler. A parallel copper plate generating uniform heat flux is placed at a distance so that liquid between the two plates may develop a circulating flow by natural convection. The vertical temperature distribution on both surfaces is measured in steady state, from which the heat transfer coefficient is calculated. The experimental data are compared with the existing correlations for a rectangular cavity where each vertical surface has a uniform temperature. The discrepancy between two data sets is examined by considering that the surface temperatures in this experiment decrease upwards as the cryocooler is located at the top. The formation of multi-cellular flow is qualitatively discussed in terms of the height-to-gap ratio of the cavity and the vertical temperature gradient as determined by the magnitude of heat flux.

## INTRODUCTION

Over the past several years, liquid-nitrogen cooling systems that are continuously refrigerated by a cryocooler have been developed for the HTS (high temperature superconductor) power devices, such as HTS transformers, fault current limiters, and terminals of transmission cables [1-3]. This method has advantages in simplicity of the cooling system and excellent dielectric properties of liquid nitrogen. Yoshida et al. [1], who

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pressurized their system with nitrogen gas, reported the development of subcooled liquid nitrogen system for an HTS transformer, operating at around 65 K. This system consists of two cryostats, where subcooled liquid nitrogen is continuously cooled by pair of GM coolers in a secondary cryostat and circulated through transfer-tubes to the main cryostat by a pump. Yazawa et al. [2] presented the experimental results of a subcooled nitrogen cryostat at 65 K for a 66 kV class AC magnet winding as an initial step for an HTS fault current limiter design. Also, they reported the characteristics on the bubble creation of subcooled liquid nitrogen. Furuse et al. [3] designed a liquid-nitrogen cooling system for HTS power transmission cables and calculated the temperature distribution of a counter-flow subcooled liquid in a duplex tube.

An international collaborative research involving the cryogenics for HTS transformers is underway at the National High Magnetic Field Laboratory. The objective of this project is the design of cryogenic cooling systems for both the power utility applications at KPU (Korea Polytechnic University) and all-electric shipboard at CAPS (Center for Advanced Power Systems). As a beginning step, we have presented a thermodynamic optimization of the operating temperature, aiming simultaneously at compactness and efficiency of HTS transformers [4,5]. Based upon the results of preliminary study, we proposed a new cryogenic design for KPU prototype transformers, operating in the range of 63~66 K by natural convection of subcooled liquid nitrogen, and evaluated its thermal characteristics by performing a relevant heat transfer analysis [6]. Although the proposed cooling system by natural convection has great advantages in compactness, efficiency, and reliability, an experimental test of the concept is crucial to confirming the feasibility of our proposed design.

In order to confirm the feasibility of our new design for transformer cooling, we have designed and constructed a natural convection cooling system experiment. The primary purpose of the experiment, therefore, is simulation of the thermal environment as closely as possible to the prototype of a KPU transformer. In this paper, we describe the natural convection experiment and present the results of cooling liquid nitrogen down to 63 K by a cryocooler and extended surfaces. In addition, the effects of height-to-gap ratio of the vertical cavity and magnitude of heat flux on the heat transfer characteristics of natural convection are investigated. The experimental data should contribute to understanding the natural convection phenomena between two vertical plates whose surface temperatures decrease upwards.

## EXPERIMENTAL APPARATUS

FIGURE 1 shows the schematic overview of the experiment, which consists of cryocooler, and heating and cooling plates immersed in liquid nitrogen. The cryocooler is mounted directly at the top plate of the cryostat and a rectangular shape of 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 cryocooler through a horizontal plate. The experimental apparatus has the same configuration as the recently designed 1 MVA HTS transformer for KPU, except that the electrical heater is used to simulate the AC loss of HTS windings and the vertical cavity between parallel plates replicates the narrow annular gap between HTS windings and vertical sheets of the HTS transformer.

A single-stage GM cryocooler (Cryomech Model AL60) provides the cooling to the experiment. The refrigeration capacity is 38 W at 50 K, which is approximately 1/5th that of the cryocooler selected for the KPU transformer (Cryomech Model AL300). In general,

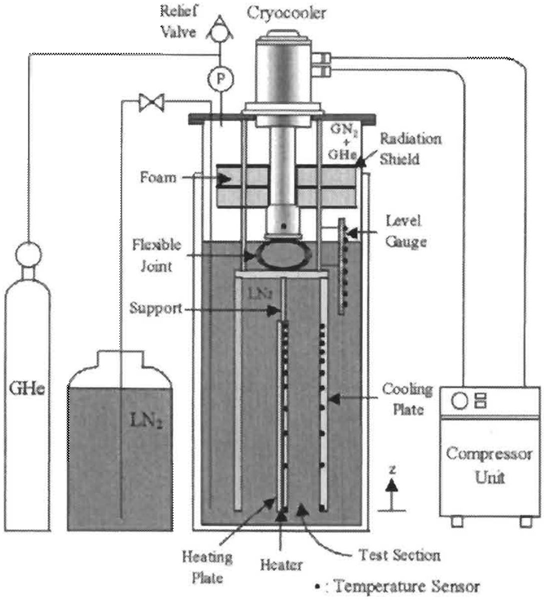


FIGURE 1. Schematic of experimental apparatus

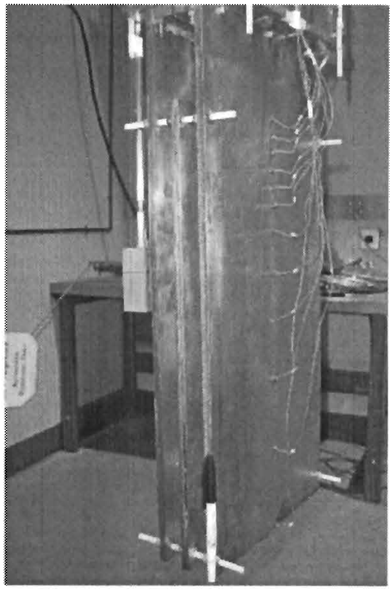

FIGURE 2. Photograph of heating and cooling plates

natural convection correlation can be expressed as dimensionless parameters. However, physical similarity in our situation is rather complicated, because the surface temperatures are not vertically uniform and the flow pattern is influenced by the temperature gradient along the vertical surfaces. Therefore, the same dimensions as KPU prototype, including vertical length, thickness of cooling plate, and gap distance between cooling and heating plate, were chosen. Even though the heat transfer area should be different because of the geometrical constraints, the heat flux is the same since we chose the heat transfer area as

**TABLE 1.** Physical dimensions of KPU transformer and NHMFL experiment

| | | KPU Prototype | NHMFL Experiment |
|---|---|---|---|
| Cryostat | Material | GFRP | Stainless Steel |
| | Diameter | 948(OD)/334(ID) mm | 305 mm |
| | Height | 1200 mm | 1040 mm |
| Cryocooler | Model | Cryomech AL300 | Cryomech AL60 |
| | Capacity @ 77 K | 320 W | 60 W |
| | Capacity @ 50 K | 220 W | 38 W |
| | Input Power | 7.2 kW | 2.0 kW |
| Main Heating Source | Type | AC Loss | DC Heater |
| | Heat Flux | 110 $W/m^2$ * | 100 (80~120) $W/m^2$ |
| | Height | 480 mm | 500 mm |
| | Gap Distance | 50 mm | 40 (20~60) mm |
| Horizontal Copper Sheet | Width | 80 mm | 180 mm |
| | Length | 2200 mm | 255 mm |
| | Thickness (Vertical) | 30 mm | 10 mm |
| | Weight | 47 kg | 4 kg |
| Vertical Copper Sheets | Total Width | 1920 mm | 510 mm |
| | Length (Vertical) | 700 mm | 610 mm |
| | Thickness | 10/8/5 mm | 10 mm |
| | Weight | 93 kg | 28 kg |

* Based on AC loss of 1.0 W/kA-m

approximately 1/5th as of the KPU prototype to match the refrigeration capacity. TABLE 1 lists the physical dimensions of the experimental apparatus in comparison with the KPU prototype.

The two vertical cooling plates are bolt jointed at the top with the horizontal plate so that the horizontal gap distance of the test space can be adjusted. Flexible tinned copper braids are used for connection between the coldhead and the horizontal plate as well as protection of the coldhead from thermal contraction. A Thermofoil™ heater is sandwiched between two identical copper plates and cryogenic epoxy is applied to ensure good contact between the heater and the plates. The heating power is regulated with a DC power supply. The cooling plates are suspended at the top plate of cryostat, and the heating plate is suspended at the cooling plates with gravitational and lateral supports made of threaded GFRP rod.

The coldhead temperature of GM cryocooler and the lower end of the cooling and heating plates are measured with silicon diodes (Lakeshore DT-470-SD). The surface temperatures of cooling and heating plates are measured with E-type (chromel vs. constantan) thermocouples at a number of vertical locations as shown in FIGURE 1, while platinum thermometers (Lakeshore PT103) are used for determining the absolute temperature at the top of cooling and heating plates. As shown in FIGURE 2, the lead wires of temperature sensors are connected through the holes from the opposites directions of the test section to minimize the disturbance of liquid flow. The liquid level is measured with a capacitance level gauge and the temperature distribution near the free surface is also measured with E-type thermocouples. A relief valve set at 105 kPa is installed to maintain the inside pressure constant.

At the initial phase of the experiment, the cryostat is filled with liquid nitrogen and it is cooled down to near its freezing temperature using the cryocooler and the extended heat exchange 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 local and averaged heat transfer coefficients are calculated. Variables in this experiment are the magnitude of heat flux and the gap distance between the heating and cooling plates.

## RESULTS AND DISCUSSION

FIGURE 3 shows the temperature history of the coldhead, top and bottom of the cooling plate, and bottom of the heating plate after the cryocooler was turned on. During the initial cool-down, the temperature decreased almost at a constant rate requiring approximately 9 hours for the coldhead to reach 63 K, the freezing temperature of nitrogen. After this point, the temperature of coldhead dropped quickly to 51 K, while the copper plates in liquid nitrogen remained nearly constant at 63 K, as the liquid begins to freeze on the plate surface. Helium gas was then supplied to maintain atmospheric pressure so that the liquid is in subcooled state. When the heater was on, the temperature of coldhead increased gradually and the temperature difference between the two plates became measurable.

During the preheating period, the heat flux was varied up to 80 W/m$^2$ (20 W), and then set at 80 W/m$^2$ for 10 hours until the cooling system achieved steady state. At this point, the coldhead temperature was 52.2 K. The refrigeration capacity of the GM cryocooler is estimated 42 W at 52.2 K from the performance provided by the manufacturer [7] and measured by our own test, indicating that the total heat loss of the experimental cryostat should be approximately 22 W. The steady temperatures at the top

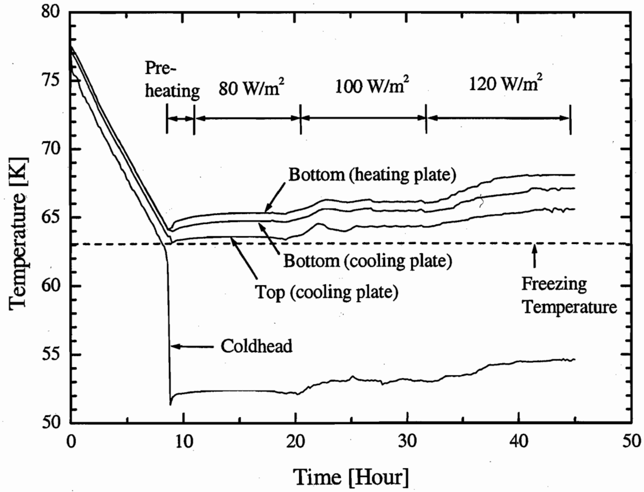


**FIGURE 3.** Temperature history of coldhead, cooling and heating plates when gap distance is 40 mm

and bottom of the cooling plate, and the bottom of heating plate were 63.3 K, 64.6 K, and 65.2 K, respectively. The heat flux was then set at 100 W/m$^2$ (25 W) for the next 10 hours until the system reached steady state. The temperature of the plates increased approximately 1 K due to the 20 W/m$^2$ of the additional heat flux and the steady temperatures of plates were 64.2 K, 65.4 K, and 66.1 K. The same procedure was repeated with an increased heat flux of 120 W/m$^2$ (30 W), where the steady temperatures were 65.6 K, 67.1 K, and 68.2 K, respectively.

The liquid level and pressure inside cryostat can be controlled easily by the pressurization with helium gas. It was extremely difficult to reach a stable equilibrium at the free surface when pressurized with nitrogen gas only, since the heat of vapor condensation must be balanced by thermal conduction in the liquid. In our case, the vertical

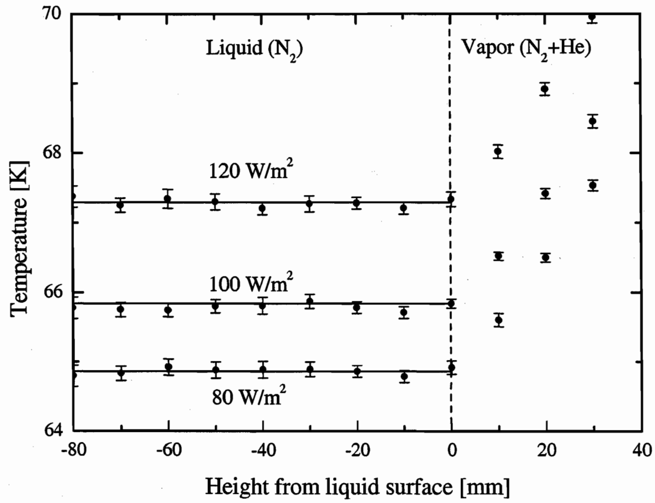


**FIGURE 4.** Vertical temperature distribution near liquid surface when gap distance is 40 mm

temperature distribution below the liquid surface is uniform as shown in FIGURE 4. Yoshida et al. [1] reported around 40 mm of thermal gradient layer beneath the liquid surface of 77 K. The heat leak through this layer is approximately 10 W. In our experiment, the subcooled liquid is in equilibrium with the gas mixture at the free surface. Thus, the temperatures are uniform and there is no conduction loss due to the steep temperature gradient. The temperature below the free surface increases as heat flux increases, with steady temperatures of 64.8 K, 65.9 K, and 67.3 K when the heat fluxes set at 80, 100, and 120 W/m$^2$, respectively. These values are used as pool temperature to calculate the vertical temperature distribution of cooling and heating plates in analytical solutions.

FIGURE 5 shows the measured vertical temperature distribution of the heating and cooling plates at steady state in comparison with analysis [6] for the gap distance of 40 mm. Points are the result of averaging ten individual measurements. The top (z = 500 mm) temperature of cooling plate was matched with the measured value as one of the boundary conditions in analytical solutions. A convective condition was used as the boundary condition at top of heating plate, and natural convection on the outside surface of the cooling plates was considered. The heat transfer coefficient in the analysis was evaluated from the existing correlation for rectangular cavity where each vertical surface has a constant temperature [8,9].

Even though the temperatures of the cooling plate were higher and those of heating plate were slightly lower in the experiment than in the analysis, a fair agreement was observed. The smaller temperature difference between two plates means that the natural convection in the experiment has a greater value of heat transfer coefficient than the existing correlation. As heat flux increases, the temperature of the plates rises, and the discrepancy between experiment and analysis is larger because the vertical temperature gradient is greater.

Though there is a noticeable temperature gradient for z > 400 mm, the vertical temperature distribution of heating plate is almost uniform, because the heating plate has high thermal conductivity. As we mentioned earlier, the heating plate is composed of a Thermofoil heater and two identical copper plates. Therefore, although the heat flux is

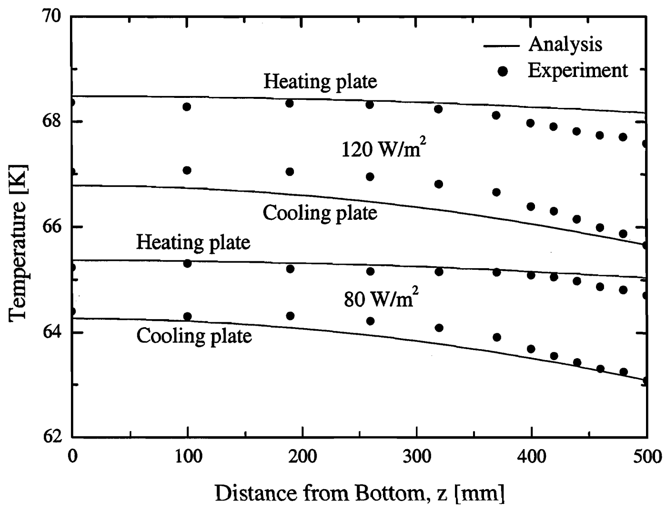


**FIGURE 5.** Vertical temperature distribution of cooling and heating plate when gap distance is 40 mm

increased up to 120 W/m$^2$ and there is a greater vertical temperature gradient at cooling plate, the top (z = 500 mm) temperature of heating plate is still higher than the bottom (z = 0) temperature of cooling plate. So a cellular flow may have been formed in this rectangular cavity. The possibility of various flow patterns depend upon the thermal boundary conditions [10-12] and the flow must be multi-cellular if the bottom temperature of a cooled plate is higher than the top temperature of the heated plate [6]. In our experiment, it should be possible to clearly observe the multi-cellular flow by replacing the heating plate by low thermal conductive material, such as stainless steel or GFRP, and applying a higher heat flux. The temperature discrepancy above z = 400 mm increases our confidence that multi-cellular flow could be occurred.

The averaged Nusselt numbers (Nu) were calculated from the measured temperatures between heating and cooling plates for different gap distance and heat flux. FIGURE 6 shows the averaged Nu as a function of averaged Rayleigh number (Ra) and compared with the existing correlations [8,9]. As the height-to-gap ratio decreases, Nu as well as Ra increases because Nu and Ra are defined based on the gap distance, and are proportional to gap distance and cube of gap distance, respectively.

As the height-to-gap ratio of test section is in the range of 8.3 ~ 25, the measured values of Nu are greater than the existing correlation by approximately 20 ~ 40 %. This is because the surface temperatures in the experiment decrease upward, while the existing correlation are developed for surfaces with a constant temperature. This experimental condition could generate a more active natural convection. Also, there is an additional cooling effect at the top in the experiment. Since the coldhead of cryocooler is located at the top, the liquid above the test section was maintained at a lower temperature than the heating plate. Therefore, the ascending liquid near the top of the heating plate must have returned toward the cold plate at a lower temperature. The existing correlations for the rectangular cavity are based on the adiabatic conditions for the horizontal walls.

For the same height-to-gap ratio, Ra increases with increasing heat flux because it is proportional to the temperature difference between two plates. As shown in FIGURE 5, the temperature difference is larger for higher heat flux. However, the amount of temperature difference in case of higher heat flux is not so much larger than that for the lower heat flux.

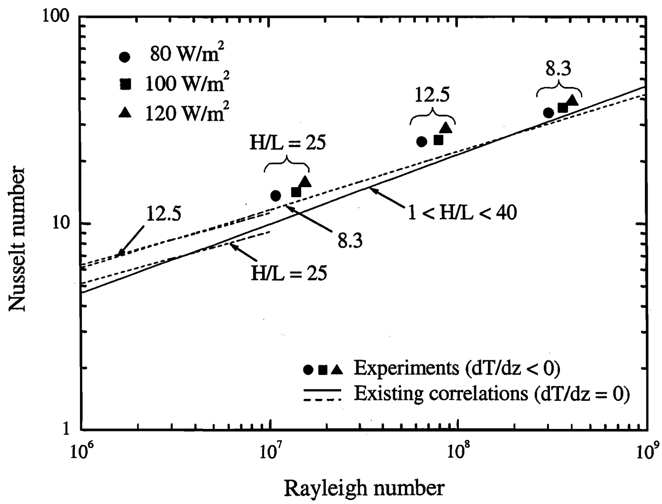


**FIGURE 6.** Average Nusselt number versus Rayleigh number

Therefore, the Nu increases with increasing heat flux in spite of increasing temperature difference.

## CONCLUSIONS

An experiment was designed, constructed, and successfully performed to confirm the feasibility of the subcooled liquid nitrogen system by natural convection. A liquid nitrogen reservoir is refrigerated at atmospheric pressure by vertical copper plates thermally anchored to the coldhead of GM cryocooler. The cold surfaces were continuously maintained below 66 K in subcooled liquid nitrogen for heat fluxes up to 100 W/m$^2$. Pressurization with helium gas was a suitable technique to control the liquid level and eliminate the steep temperature gradient of liquid below the free surface. The heat transfer coefficient of natural convection between cooling and heating plates was greater by 20 ~ 40 % than the existing correlation, mainly because the temperature of the plates decrease upwards. Future work will analyze multi-cellular flow in order to verify this flow pattern in specific thermal boundary conditions.

## ACKNOWLEDGMENTS

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