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Estimation of surface emissivity for conduction-cooled metal plates at cryogenic temperatures

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Abstract-- **The relation between surface emissivity and temperature distribution is experimentally and analytically investigated for a conduction-cooled metal plate in vacuum. Experimental set-up consists of a rectangular metal plate placed vertically in a cryostat and thermally anchored to the coldhead of a GM cryocooler at the top. Temperature is measured at a number of locations over the plate with platinum resistors mounted on the plate. A parallel analysis on the balance of heat conduction through the plate and thermal radiation on its surface is performed to numerically calculate the temperature distribution having the same boundary conditions as experiment. By comparing the two results, an average emissivity of the plate is roughly estimated for different metal plates and different surface conditions. The estimated emissivity in present study is less than the listed values for highly polished stainless steel, and meets a fairly good agreement for oxidized copper surface.**

1. INTRODUCTION

Emissivity of a material is a significant physical property defined as the ratio of energy radiated by the surface to the maximum energy radiated by a black body at the same temperature. Since thermal radiation is one of the major sources of cooling load in every cryogenic system [1], it is important to estimate the amount of radiation to cold bodies in terms of reasonably accurate values of emissivity.

Several standard techniques have been developed to measure the thermal radiation and surface emissivity, such as infrared thermometry, bolometer, and direct heat flux sensors [2-5]. In practice, however, an exact emissivity of given surface at cryogenic temperatures is not easy to measure or find even for common cryogenic materials, mainly because radiation is strongly dependent upon the surface condition and the surface temperature [6-8]. This study is proposed to investigate a simple method for estimating the emissivity at cryogenic temperatures from measured and calculated temperature distribution of a conductively cooled plate.

When a metal plate is locally cooled in vacuum by cryogenic liquid or a cryocooler, the plate temperature at a farther location from the cooling source (or heat sink) is higher because of thermal radiation from the surrounding internal wall of cryostat at room temperature.

The temperature gradient in the plate is determined by the relative magnitude of thermal radiation on the surface to heat conduction through the plate. The main idea of this work is an indirect measurement of emissivity through the two-dimensional heat conduction analysis on the plate. This study intends to demonstrate how this idea is practical through a laboratory scale of simple experiments.

2. EXPERIMENT

Fig 1 is the schematic configuration of our experimental apparatus. In order to provide a large surface area for thermal radiation in a tall cylindrical cryostat (400 mm ID, 1125 mm height), a rectangular plate (200 mm x 500 mm x 2 mm) is vertically placed in vacuum-insulated space. The top portion (100 mm) of the plate is bent by 90 degrees and attached horizontally to the bottom of coldhead of a cryocooler. The cryocooler is a single-stage GM (Gifford-McMahon) cooler, and the coldhead connection is made by bolt joints with thermal grease. Selected specifications for the components are listed in TABLE I.

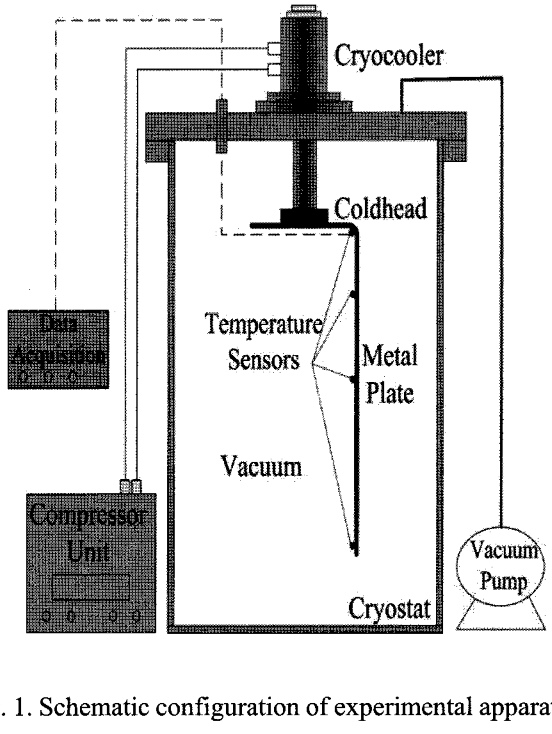

Fig. 1. Schematic configuration of experimental apparatus.

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TABLE I
SELECTED SPECIFICATIONS FOR COMPONENTS OF EXPERIMENTAL APPARATUS

Component	Type (Manufacture: Model)	Specifications
Cryocooler	Single-stage GM (Cryomech: AL60)	60W @ 77K 0 W @ 20K
Cryostat	Vacuum-insulated (Duksung S.I.)	400 mm ID 1125 mm H
Vacuum pump	Mechanical pump (Woosung: TRP-12)	5×10^{-4} Torr 200 L/min
Temperature sensors	Platinum resistor (Lakeshore: PT-103)	ϕ 1.6 mm 12.2 mm L
Data acquisition	Temperature monitor (Lakeshore: 218 S)	8 ch
Metal plates	(a) Polished stainless steel (b) Oxidized copper	200 x 500 x 2 mm

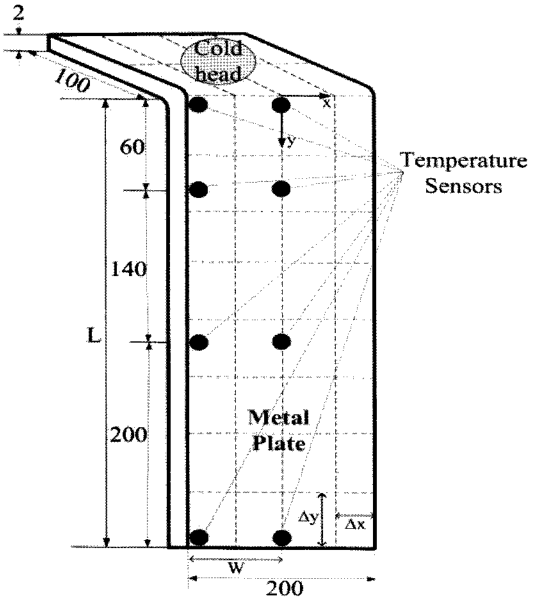
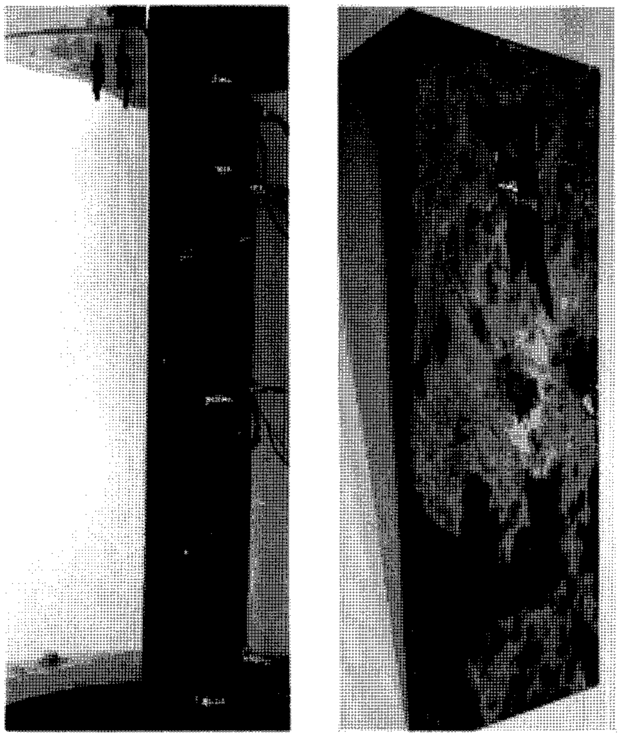


Fig. 2. Dimensions of metal plate and eight locations of temperature sensors. (unit: mm)

Temperature is measured at eight locations as shown in Fig. 2. Since the system is left-right symmetric, temperature is measured only along the centerline and one edge of the rectangular plate. The vertical distance between the temperature sensors is shorter at upper locations, where the temperature gradient should be steeper. The temperature sensors are platinum resistance thermometers (Lakeshore Model PT-103) that have an accuracy of ±0.25 K at temperatures down to 30 K. The platinum resistors with a diameter of 1.6mm are inserted into drilled holes through the plate and attached by cryogenic epoxy. The measured temperature is recorded with an 8-channel temperature monitor (Lakeshore Model 218S).



(a) Polished stainless steel (b) Oxidized copper

Fig. 3. Photographs of metal plates tested in experiment.

Two plates are prepared with the same size, but with different materials and different surface conditions. The first denoted by (a) is a stainless steel plate, both sides of which are highly polished. The second denoted by (b) is an oxygen-free copper plate severely oxidized at experiment. Fig. 3(a) and (b) are the photographs of the two plates tested in this experiment. The polished stainless steel plate is shiny clean like a mirror, and the oxidation of the copper plate is so severe that the surface looks mostly greenish.

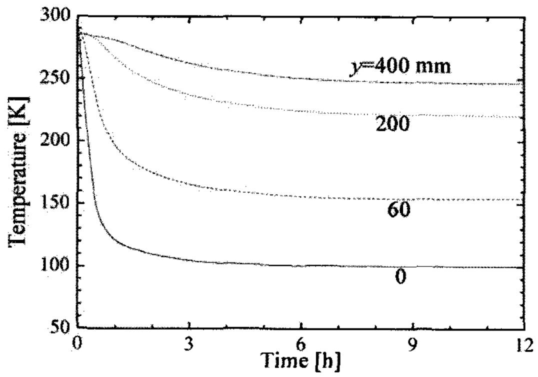
Fig. 4 shows the cooldown history of the two plates at the four vertical locations after the cryocooler is turned on. The top of the stainless steel plate is cooled down to 150 K within 30 minutes, while the bottom temperature decreases gradually for several hours. It is clearly observed that the plate is in steady state after 9 hours of cooldown. The top-to-bottom temperature difference in steady state is as large as 148 K for the highly polished stainless steel plate due to its low thermal conductivity.

On the other hand, the copper plate is cooled down rather uniformly and quickly during the beginning two hours, and then slowly approaches to steady state. The lowest temperature at the top center is 58 K, and the top-to-bottom temperature difference is about 34 K for the oxidized copper plate.

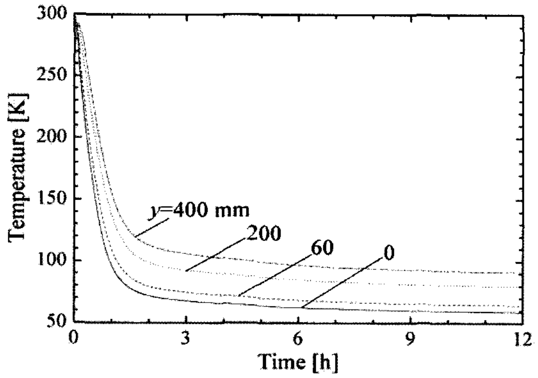
3. NUMERICAL ANALYSIS

Temperature of the metal plate can be determined with a reasonable accuracy by two-dimensional heat conduction equation in steady state.

$$\bar{k}\delta\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+2\sigma\bar{\varepsilon}\left(T_R^4-T^4\right)=0 \quad (1)$$



(a) Polished stainless steel



(b) Oxidized copper

Fig. 4. Cooldown history in experiment at four vertical locations along centerline of metal plate.

where δ is thickness of the plate, and $\bar{k}$ and $\bar{\varepsilon}$ are temperature-averaged thermal conductivity and surface emissivity, respectively. In the radiation term of Eq.(1), σ is Stefan–Boltzmann constant and the factor of 2 accounts for both sides of the plate. It is assumed that the radiation view factor [2] from any plate surface to the surrounding wall of cryostat at room temperature T_R is unity. This assumption is considered later when the analytical results are compared with the experimental data.

Eq.(1) is solved numerically by simple finite difference method. The conduction terms are approximated for a node of mesh shown in Fig. 2 at $x=m\cdot\Delta x$ and $y=n\cdot\Delta y$ as and the radiation terms are expressed in linearized form

$$\frac{\partial^2 T_{m,n}}{\partial x^2}+\frac{\partial^2 T_{m,n}}{\partial y^2} \approx \frac{T_{m+1,n}+T_{m-1,n}-2T_{m,n}}{(\Delta x)^2}+\frac{T_{m,n+1}+T_{m,n-1}-2T_{m,n}}{(\Delta y)^2} \quad (2)$$

$$T_R^4-T_{m,n}^4=4T_M^3\left(T_R-T_{m,n}\right) \quad (3)$$

where T_M is the mean temperature defined as

$$T_M \equiv \sqrt[3]{\left(T_R^2+T_{m,n}^2\right)\left(T_R+T_{m,n}\right)/4} \quad (4)$$

Boundary conditions are imposed in either Dirichlet or Neumann forms. Since the objective of this numerical analysis is to compare the calculated temperature distribution with the measured temperatures, at least one boundary condition needs to match with the experimental value. Here, we select it as the bottom temperature, and the Dirichlet condition is given by

$$T(x,L)=T_L \text{ (from experiment)} \quad (5)$$

The other boundary conditions are the adiabatic relations in Neumann form

$$\frac{\partial T(x,L)}{\partial y}=\frac{\partial T(\pm W,y)}{\partial x}=0 \quad (6)$$

because the radiation on the plate edge is negligibly small.

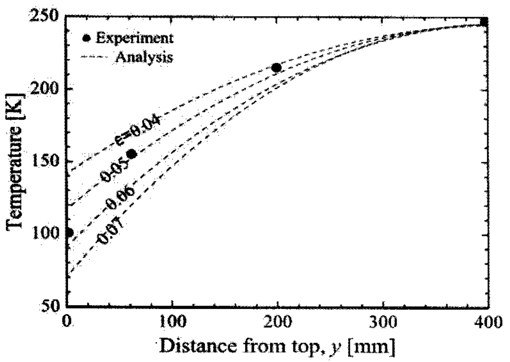
If the average emissivity, $\bar{\varepsilon}$, is given, the system of equations for the nodal temperatures is solved readily with Gauss-Seidel algorithm. In order to treat the implicit term in the mean temperature, T_M, and averaged thermal conductivity, $\bar{k}$, the numerical process starts with initial guesses and is repeated with improved values upon newly calculated temperatures until the convergence criterion is satisfied.

4. RESULTS AND DISCUSSION

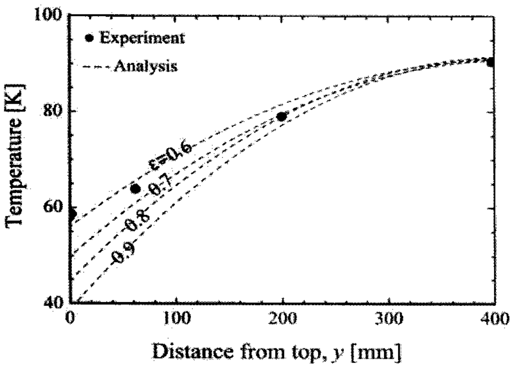
Fig. 5(a) shows the calculated vertical temperature distribution along the centerline of the stainless plate for various values of average emissivity in comparison with the experimental measurement. Any single curve does not fit all the experimental data, mainly because an averaged value of emissivity over space and temperature is assumed in the analysis. It is a reasonable estimation, however, that the average emissivity is in a range of 0.04 and 0.06.

TABLE II compares the emissivity estimated from Fig. 5(a) with the listed values in references. The estimated value is smaller, and we think two major reasons for the difference. First, the stainless steel plate in this experiment is so highly polished that its emissivity may be actually less than typically machined surface. The other reason is that the view factor from the plate to the room-temperature wall is lower than unity (especially for upper portion of the left surface in Fig. 1) due to the horizontal part at the top. This means that the actual radiation effect is smaller or the emissivity from Fig. 5(a) could be an under-estimate. The effect of residual gas in vacuum is negligibly small.

Similar observation and discussion can be made for the oxidized copper plates from Fig. 5(b). The emissivity is estimated as 0.6~0.8 at a temperature range of 60~90 K. This is considered a fair agreement with the listed values, if



(a) Polished stainless steel



(b) Oxidized copper

Fig. 5. Calculated vertical temperature distribution for various values of average emissivity in comparison with experimental measurements.

it is taken into account that the copper plate in experiment is severely oxidized and there is a slight under-estimate due to the reduced view factor as discussed above.

5. SUMMARY AND CONCLUSIONS

The proposed idea to estimate the surface emissivity of a conduction-cooled metal plate is clearly demonstrated with experiment and numerical analysis. Two-dimensional steady-state temperature distribution is obtained over a metal plate in local contact with a cryocooler in vacuum. Temperature measured at several locations is compared with the numerically calculated distribution for various values of emissivity, which provides useful information to estimate the actual emissivity of the metal plate.

Average emissivity of the specific stainless steel plate is estimated 0.04~0.06 at 100~250 K, which is lower than the listed values, mainly because the plate tested in experiment is highly polished. The oxidized surface of copper plate at 60~90 K has a high emissivity of 0.6~0.8, which is well compared within the range of listed values.

TABLE II
ESTIMATED SURFACE EMISSIVITY COMPARED WITH LISTED VALUES IN REFERENCES

(a) Stainless steel plate

	Surface condition	4 K	77 K	300 K
This study	Highly polished	-	0.04~0.06	
[7]	Mech. polished	0.07	0.12	0.16
[8]	Polished	-	-	0.17

(b) Copper plate

	Surface condition	4 K	77 K	300 K
This study	Oxidized	-	0.6~0.8	-
[7]	As received	0.06	0.12	-
[8]	Oxidized	-	-	0.5~0.8

ACKNOWLEDGMENT

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