Application of Porous Solid Nitrogen to Space Borne Cooling Missions

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Summary: A basic experiment of the sublimation heat transfer of solid cryogen has been conducted for its potential applications to cryogenic cooling of onboard instruments. The most serious concern is the separation of solid cryogen from a cooling section caused by local rapid sublimation (dry-out). The condition of the dry-out initiation and the heat transfer performance in the dry-out state was especially pursued in this paper. The order of the effective thermal conductivity of porous solid nitrogen was found to be almost the same as that of pure one and far smaller than that predicted in the sublimation-filtration-condensation (SFC) process. Application of the solid nitrogen to onboard cooling is also discussed.

1. Introduction

In recent years, space borne astronomy has been drastically developed owing to the rapid progress of space technology. Telescopes, detectors and some parts for infrared, ultraviolet and X-ray observations must be cooled down to cryogenic temperatures [1]. Several kinds of liquid and solid cryogens have been utilized as coolants for these purposes, though several kinds of mechanical refrigerators have been proposed to be used in space [2]. Liquid nitrogen and such liquid cryogens with lower boiling temperatures as liquid helium have been successfully used [3, 4, 5]. Solid cryogens have been also used in such cases that cooling down to the liquid helium temperature is unnecessary and that a two-stage cooling system, for example liquid helium as a main coolant and a solid cryogen as an auxiliary one, is employed for longer missions. In fact, there have been a number of missions performed employing solid cryogen as a coolant. Solid ammonia was used as the main cryogen in HEAO-B for X-ray observation which was launched by NASA in 1978, and also in HEAO-C for γ-ray observation in 1979. Both missions were able to perform stable cooling for about one year [2]. Solid nitrogen was applied to cooling infrared detectors aboard a K-10 rocket by the Nagoya University group in 1982. In addition, several astronomical satellites employing solid cryogens have been launched by NASA (Nimbus F and G, and LIMS etc.) [6]. An onboard cooled mission for more than three years is now being planned applying liquid helium II as a main cryogen and solid neon as an auxiliary one [7].

Solid cryogens have some obvious advantages over liquid ones. They are free from any kinds of rapid bulk motions which is usually called sloshing as the acceleration is changing. Moreover, they require no phase separators which separate liquid cryogen from its vapor, and they compose of crucial parts in liquid cryogen systems. On the

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other hand, solid cryogens have a serious weak point. Once large amount of heat is locally loaded, the thermal contact between the cooling section and the cryogen will be lost because of rapid sublimation of the solid cryogen. This state is hereinafter referred to as the dry-out. What is worse, if the dry-out occurs, there would be no ways to recover the initial good thermal contact under the zero gravity state.

However, there have been only a few papers on the basic investigation of solid cryogen, especially no papers on the dry-out. Verkin et al. [8] found that the effective thermal conductivity of porous solid nitrogen was far larger than that of pure one by two or three orders of magnitude. They attributed the phenomenon to the successive sublimation-filtration-condensation processes (SFC) in each pore (just like solid heat pipe processes). Mikhachenko et al. [9] and Verkin et al. [10] studied heat transfer in porous solid cryogen under the condition that the heater was pressurized to the solid cryogen to suppress the dry-out, and determined the heat transfer coefficient. However, it is hard to find any papers on the initiation criterion of the dry-out and the heat transfer in the dry-out state without the boundary pressurization. Thus, the condition of the dry-out initiation and the heat transfer performance in the dry-out state were defined as primary purposes in this experimental study [11]. This was conducted by the use of solid nitrogen converted from liquid by evacuating the vapor. The order of the thermal conductivity of porous solid nitrogen was also attempted estimate to compare with that of SFC phenomenon. Applications of the solid cryogen to space missions were considered in the last section.

2. Theory of Heat Transfer in Dry-out State

The thermal behavior in the dry-out state is considered by reference to Fig. 1, which shows that the solid-vapor phase boundary (the phase boundary) is already apart from the heater surface due to the dry-out. Heaters are sticked on both sides of a base. Several assumptions are introduced for simplicity. The phenomenon is one-dimensional and quasi-steady, what means the temperature of the base (bakelite) is equal that of the heater, $T_H$. Heat transfers through the vapor only by conduction. The heat conducted is wholly consumed upon sublimation of solid nitrogen. Thus, the temperature of the solid nitrogen remains uniformly at a constant, $T_R$. Every physical quantity is also assumed to
be constant. The governing equations are written as follows:

\[
\dot{q} = \kappa_v \frac{T_H - T_R}{l} + C \frac{dT_H}{dt}, \tag{1}
\]

\[
\kappa_v \frac{T_H - T_R}{l} = \frac{d}{dt} (\rho \lambda, l). \tag{2}
\]

The first expresses the heat balance at the heater section and the second at the phase boundary. Here, \( \kappa_v \) is the thermal conductivity of the vapor, \( l \) the distance between the heater surface and the phase boundary. \( \rho \) and \( \lambda \) are the effective density and the latent heat of sublimation of porous solid nitrogen, respectively. The latter is equal to the corresponding value of pure solid nitrogen, while the former is not because of the effect of vapor pores. \( C \) is half of the heat capacity of the base per unit area (heaters on both sides), \( t \) the time, and \( \dot{q} \), the heat generation rate per unit area of the heater, is zero for \( t < 0 \) and is a constant for \( t > 0 \). The initial condition is that \( t = 0 \) and \( T_H = T_R \) at \( t = 0 \). These equations are solved analytically for \( l \) to result in

\[
l^2 + \frac{\kappa_v}{C} lt - \frac{\kappa_v \dot{q}}{\rho \lambda, C} t^2 = 0. \tag{3}
\]

The positive \( l \) should be chosen as the solution,

\[
l = \frac{2}{\rho \lambda,} \sqrt{1 + \frac{4C\dot{q}}{\rho \lambda,} + 1} \dot{q} t. \tag{4}
\]

It is convenient to introduce following two dimensionless quantities,

\[
\xi = \frac{4C\dot{q}}{\rho \lambda, \kappa_v} \quad \text{and} \quad \phi = \frac{\rho \lambda, l}{t} \tag{5}
\]

where the cumulative heat generation from the heater, \( q \), is defined as

\[
q = \int_0^t \dot{q} dt = \xi t.
\]

\( \xi \) is a dimensionless quantity concerning \( \dot{q} \), which indicates the ratio of heat conducted through the vapor to that consumed for temperature rise of the bakelite base. \( \phi \) is another dimensionless quantity concerning the moving rate of the phase boundary apart from the heater surface per unit cumulative heat generation (the moving rate of the phase boundary), which indicates the ratio of heat consumed upon sublimation of the solid nitrogen to \( q \). The solutions are expressed in terms of these by
\[ \phi = \frac{\sqrt{1 + \xi} - 1}{\xi}, \quad (6) \]
\[ C \frac{T_H - T_R}{q} = 1 - \frac{\sqrt{1 + \xi} - 1}{\xi}. \quad (7) \]

These solutions indicate that both of the distance between the heater surface and the phase boundary and the temperature of the heater section vary linearly with the cumulative heat generation provided that \( \xi \) is constant. It is also seen from Eqs. (6) and (7) that the temperature at a point apart from the heater surface is equal to that of the solid nitrogen prior to the arrival of the phase boundary and then linearly rises with the cumulative heat after the boundary reached the point. The rising rate of the temperature at the point is found to be equal to that of the heater temperature. Temperature variations of the heater section and at locations some distances apart from the heater surface are schematically presented in Fig. 2. In the case of \( \xi \) which is small compared with unity, what means that heat conducted through the vapor phase is far larger than that consumed for warming up the base, Eqs. (6) and (7) can be simplified as follows:

\[ \phi \approx 1 - \frac{\xi}{4} \approx 1, \quad (8) \]
\[ C \frac{T_H - T_R}{q} \approx \frac{\xi}{4} = \frac{Cq}{\rho_s \lambda_s \kappa_v}. \quad (9) \]

In this case, it is found from Eq. (8) that the moving rate of the phase boundary is independent of \( \xi \), and from Eq. (9) that the rising rate of the heater temperature is proportional to \( \xi \).

![Fig. 2. Schematic illustration of the theoretical temperature variations at the heater and some distances (x1 and x2) apart from the heater surface.](image-url)
3. **Experimental Apparatus and Procedure**

The cryostat employed in this experiment is seen in Fig. 3. It is composed of two glass dewars, the inner one (φ80-diameter) is utilized for the experimental space of solid nitrogen, and the outer for auxiliary cooling by liquid nitrogen, both of which have longitudinal slits for visual observation. The test section is located in the bottom half of the inner dewar, in which the reference temperature point is also fixed, as shown in Fig. 4. Heaters are made of thin films of stainless steel (45 mm×50 mm×10 μm-thick) and are stucked on both sides of the bakelite base (3 mm-thick). The heater film is notched with 1 mm slits to increase the electric resistance but so as to generate uniformly heat.
Temperatures of the heater section and at several points apart from the heater are measured by copper-constantan thermocouples (0.1 mm-diameter). The reference points of these thermocouples are located at a copper block in the solid nitrogen and its temperature, $T_R$, is measured by another thermocouple. The heater is excited by D.C. current, of which power is determined by the voltage drop across each heater with the four terminal method. The pressure in the dewar is controlled with a pressure regulating valve through which the vapor is evacuated by a rotary pump with a pumping speed of 300 l/min (Fig. 5).

All the data were obtained by a digital data acquisition system and were transferred to a 16-bit-microcomputer system via GP-IB. The transferred data were all recorded on a magnetic tape for further data analysis.

Solid nitrogen is produced from liquid nitrogen by evacuating the vapor, which contains numerous tiny vapor bubbles (porous solid nitrogen). The porosity of porous solid nitrogen is experimentally given by measuring the volume ratio of porous solid nitrogen to liquid nitrogen melted off from the solid to be about 0.27. Thus, the effective density of porous solid nitrogen is found to be about 690 kg/m$^3$.

The experiment started by applying heat stepwise from heaters to solid nitrogen after establishing a specified thermal equilibrium state. Temperature variations were measured at the heater and some points apart from the heater while keeping the vapor pressure at a constant level.

4. EXPERIMENTAL RESULTS

A typical example of the experimental data is shown in Fig. 6, where temperature differences, $T - T_R$, are plotted against the cumulative heat generation, $q$. The saturated vapor pressure, $P$, is 3460 Pa and the reference temperature, $T_R$, is 56 K. It is seen from this figure that the temperatures at point some distances apart from the heater (0.92 mm, 1.72 mm and 3.20 mm, respectively) are almost constant for small $q$, but each of them rises steeply after the solid-vapor phase boundary passes each point. This feature is just as the theoretical prediction illustrated in Fig. 2. The rising rate of each temperature
Fig. 6. Variations of temperature difference $T - T_R$ with the cumulative heat generation $q$. $T_R$ is the initial temperature. $P=3460$ Pa, $\xi=1.34$.

Fig. 7. Variations of temperature difference $T - T_R$ with the cumulative heat generation $q$. Heat loaded intermittently. $P=3460$ Pa, $\xi=1.35$.

approaches to that of the heater temperature at the same value of $q$. Another example is shown in Fig. 7 for comparison, which shows results in the case that heating is interrupted several times otherwise in all the same condition as the previous case. It is found from Fig. 6 and Fig. 7 that the temperature history is almost same for both cases if the envelop of the data in Fig. 7 is compared with the record given in Fig. 6. Thus, it is confirmed that the thermal behavior is predominantly determined by $q$.

The variations of the temperature distribution in the vicinity of the heater are shown in Fig. 8(a) for the same case as given in Fig. 6, and Fig. 8(b) for another case,
respectively, where the abscissa expresses the distance from the heater surface. The thermal condition of both experiments differs only in $\dot{q}$, that is, $\dot{q}=900$ W/m$^2$ for Fig. 8(a) and about the half of this for Fig. 8(b). In these figures, each intersection of two straight lines (one is in solid nitrogen, and another in vapor) indicates a position of the phase boundary for a value of the cumulative heat. It is evident in these figures that the distance between the phase boundary and the heater surface linearly varies with the increase of the cumulative heat generation and the increasing rate of the distance (the moving rate of the phase boundary) for the latter is larger than that for the former.

These rates found in many experiments are converted into the dimensionless moving rates of the phase boundary, $\phi$, by using Eq. (5), which are plotted against $\xi$ in Fig. 9,
where circles represent the experimental data for \( P = 3460 \) Pa \( (T_R = 56 \) K\) and triangles for \( P = 40 \) Pa \( (T_R = 45 \) K\), respectively. The solid line shows the theoretical prediction by Eq. (6). The agreement of the experimental values with the prediction is fairly good. The effects of the vapor pressure, that is, that of the temperature of the solid nitrogen are not recognized here within the experimental error.

The rising rates of the heater temperature in the initial stage (at \( q = 0 \) J/m\(^2\)) are plotted against \( \xi \) in Fig. 10, where circles and triangles are the experimental value and the solid line shows the theoretical prediction by Eq. (7). The experimental values seem to agree qualitatively with the theoretical prediction. The effects of the vapor pressure are not recognized in this case, too. It is seen in this figure that the discrepancy between the experimental values and the theoretical prediction is larger for small \( \xi \). This may be caused by the error of temperature measurement of thermocouples and thus of calculation.
of the rising rate. This kinds of error is not found in Fig. 9. The reason for the difference in the error between Fig. 9 and Fig. 10 is that the measurement of the absolute temperature is not requested in the determination of the moving rate of the phase boundary.

5. DISCUSSIONS

The fact that the experimental results agree with the theoretical prediction as seen in Fig. 9 and Fig. 10 indicates that the heat transfer model assumed to develop the theory is valid. The heat transferred through vapor is, in fact, almost consumed upon sublimation of solid nitrogen at the phase boundary and little heat penetrates into solid nitrogen. It is also pointed out that the moving rate of the phase boundary is still non-zero finite even at the smallest $\xi$ in agreement with the theoretical value. Therefore, it is concluded that the dry-out occurs whatever small heat is applied to solid nitrogen.

It is found that the rising rate of the heater temperature in the initial stage agrees with the theoretical prediction for various cases (see Fig. 10). It is seen from this result that heat conduction really dominates in the vapor for small $q$ when the distance between the heater surface and the phase boundary is small. It is, however, evident from Fig. 6 that the rising rate of the temperature at the heater is not constant on the contrary to the theory (see Fig. 2) and gets smaller with the increase of $q$. The reason for the dependence on $q$ is that the dominant mechanism of heat transfer in the vapor phase changes from the conduction rather to the convection for large $q$ when the distance between the heater
surface and the phase boundary is large.

A rough estimate of the effective thermal conductivity of porous solid nitrogen is attempted to compare with that by SFC phenomenon [8]. The conductivity is calculated in terms of the temperature difference at two points in the solid nitrogen and heat generation rate from the heater for the case shown in Fig. 6. Temperature difference between the 1.72 mm-thermocouple and the 3.20 mm-thermocouple is about 0.6 K for $\dot{q}$ about 900 W/m² over the range of the cumulative heat between $20 \times 10^4$ and $40 \times 10^4$ J/m². The thermal conductivity is roughly evaluated in terms of these values to be 2.3 W/m/K at the temperature of solid nitrogen, $T_N=56$ K. The dependence of the effective thermal conductivity of porous solid nitrogen on the temperature of solid nitrogen derived on the basis of SFC phenomenon model [8] is shown in Fig. 11. The effective thermal conductivity at $T_N=56$ K is about $2 \times 10^2$ W/m/K in this figure, and this value is far larger than that of pure one by three orders of magnitude. The experimental value is also far smaller than that for the SFC phenomenon, though that would be possible maximum thermal conductivity of porous solid nitrogen because little heat out of $\dot{q}$ penetrates into solid nitrogen. Thus, the actual thermal conductivity of porous solid nitrogen is considered to be far less than the figure obtained in this estimate by one or two orders of magnitude, and it is rather closed to pure one ($=1 \times 10^{-1}$ W/m/K). SFC phenomenon, thus, did not occur in porous solid nitrogen at least in the case with zero contact pressure.

6. Space Application

There are two cooling modes in the application of solid cryogen to onboard cooling missions. One is attained by direct contact with solid cryogen (contact cooling), and another is by the forced vapor flow sublimated from solid cryogen (vapor cooling). The latter mode utilizes sensible heat of vapor, which is, in general, smaller than the latent heat. The contact cooling is primarily applied to the onboard detector cooling.

Let's consider an application of solid cryogen to space missions. Eq. (9) can be used to calculate the thermal condition to be imposed on a detector cooled by porous solid nitrogen.

$$T_H - T_N \approx \frac{1}{\rho \lambda \kappa_s} \dot{q},$$

$$= \frac{1}{\rho \lambda \kappa_s} \dot{q}^2 t. \quad (10)$$

Eq. (10) indicates a relation between the permissible temperature rise at the cooling section (the detector), $T_H - T_N$, the heat flux generated from the detector, $\dot{q}$, and the life time of the cooling mission, $t$. If the permissible temperature rise and the life time are specified, the restriction on the heat flux is derived from Eq. (10). For example, if porous solid nitrogen is used as a cryogen ($\rho_s=6.9 \times 10^2$ kg/m³, $\lambda_s=2.7 \times 10^3$ J/kg, $\kappa_s=7.5 \times 10^{-3}$ W/m/K) under the following condition that the permissible temperature
rise; \( T_R - T_k < 10 \) K. and the life time of the mission; \( t = 1 \) Week = \( 6.0 \times 10^5 \) sec, the restriction on \( \dot{q} \) is evaluated as follows;

\[
\dot{q} < 5 \text{ W/m}^2 = 0.5 \text{ mW/cm}^2.
\]

On the derivation of Eq. (10), the rising rate of the temperature is considered to be constant, but it is actually found to be not constant and to get smaller for larger \( q \) as seen in Fig. 6. Therefore, the value gives an optimistic evaluation.

7. Conclusion

Systematic experiment were carried out to investigate the dry-out characteristics of porous solid nitrogen. The following conclusions are arrived from the experimental study. Dry-out occurs whenever heat is applied to solid nitrogen. In the dry-out state, the distance between the heater surface and the solid-vapor phase boundary increases proportionally to the cumulative heat generation from the heater. The experimental results agree with the theoretical prediction derived by the simplified model. Thus, the heat transferred through vapor is almost consumed upon sublimation of solid nitrogen at the phase boundary and little heat penetrates into solid nitrogen. The order of the thermal conductivity of porous solid nitrogen was estimated to be about the same order of pure one. Therefore, there is no phenomenon like SFC in this experiment.

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References

[10] Verkin, B. I., Mikhalchenko, R. S., Getmanets, V. F. and Goncharenko, L. G.: Contact heat transfer