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Abstract. When using superfluid helium in low-gravity environments, porous plug phase separators are commonly used to vent boil-off gas while confining the bulk liquid to the tank. Invariably, there is a flow of superfluid film from the perimeter of the porous plug down the vent line. For the soft x-ray spectrometer onboard ASTRO-H (Hitomi), its approximately 30-liter helium supply has a lifetime requirement of more than 3 years. A nominal vent rate is estimated as ∼30 μg/s, equivalent to ∼0.7 mW heat load. It is, therefore, critical to suppress any film flow whose evaporation would not provide direct cooling of the remaining liquid helium. That is, the porous plug vent system must be designed to both minimize film flow and to ensure maximum extraction of latent heat from the film. The design goal for Hitomi is to reduce the film flow losses to <2 μg/s, corresponding to a loss of cooling capacity of <40 μW. The design adopts the same general design as implemented for Astro-E and E2, using a vent system composed of a porous plug, combined with an orifice, a heat exchanger, and knife-edge devices. Design, on-ground testing results, and in-orbit performance are described.

1 Introduction

ASTRO-H (Hitomi)1 is the sixth Japanese x-ray astronomy satellite. It was launched on February 17, 2016, and was decommissioned due to loss of the attitude control on March 26, 2016. The soft x-ray spectrometer (SXS)2 onboard Hitomi is an x-ray microcalorimeter operated at 50 mK, providing a nondispersive energy resolution of <7 eV (full width at half maximum) in the 0.3- to 12-keV bandpass. The microcalorimeter is cooled down from room temperature to 50 mK using a dewar, four 2-stage Stirling cryocoolers, a Joule–Thomson cryocooler, superfluid helium-4, and a 3-stage adiabatic demagnetization refrigerator (ADR).3,4 Although the SXS was still in the commissioning phase, it had successfully shown the superb energy resolution on-orbit and provided valuable data sets from aspects of both science and engineering.2

At nominal operation, an average heat load on the helium tank is ∼0.7 mW.3,5 Assuming this heat load and an initial fill level of 30 L, the lifetime of the helium will be ∼4 years. As shown in Table 1, this heat load is lower than any previous space missions using superfluid helium, even compared to values of the two previous x-ray microcalorimeter instruments, the ASTRO-E XRS and the Suzaku XRS2. These two missions planned astronomical observations but were lost due to a rocket failure and a boil-off of the entire liquid helium, respectively. With SXS, we succeeded in conducting the first astronomical observations by an orbiting x-ray microcalorimeter.

To safely vent the small helium gas flow and suppress a superfluid film flow, we employed a porous plug phase separator and a film flow suppression system. The superfluid film flow can lead to a potential loss of the superfluid helium, because the average heat load is tiny. In this paper, we describe design and performance of the porous plug and superfluid film flow suppression system for the SXS.

2 Design

2.1 Overview

The porous plug phase separator and the film flow suppression system are designed based on ASTRO-E XRS and Suzuki XRS2 heritage.15 It consists of four devices as shown in Fig. 1. The design of the system is described in Ref. 15.
Ground tests of bread board model, engineering model, and flight model (FM) systems are described in Refs. 16–19. The design is explained below.

Under zero gravity, a simple vent hole on the top of the tank would not work because the liquid is not always at the bottom. The role of the porous plug is to let helium gas out while retaining superfluid liquid helium in the tank.

At the same time, a small amount of superfluid film flow out of the vent line could influence the helium lifetime, since the gas flow rate is so small. To reduce the film flow, three devices, an orifice, a heat exchanger, and knife-edge devices are included. Without this film flow suppression system, the film flow rate would be $\sim 50 \mu g/s$, corresponding to an effective cooling loss of $\sim 1$ mW.

Requirements for the porous plug and the film flow suppression system are summarized in Table 2. The SXS planned to observe astronomical objects for 3 years with a goal of 5 years. Assuming 30-L superfluid helium, a 5-year lifetime gives an average heat load on the helium tank of 0.59 mW and an average helium flow rate of $28 \mu g/s$. The expected helium tank temperature was 1.15 K. Mass flow rates at the beginning and the end of life estimated by the thermal analysis are 33 and $43 \mu g/s$, respectively. Considering uncertainties of the thermal analysis and safety margin, we required the mass flow rate of $28 \mu g/s$ at 1.15 K. The film flow rate must be $<2 \mu g/s$, to avoid an additional loss of helium.

Two off-nominal cases must be taken into account. In the single cryocooler failure case, we assume that one of the four cryocoolers stops, which results in an increase of the heat load on the helium tank. In this case, the tank temperature should be kept below 1.50 K for the ADR efficiency. Thus, the mass flow rate of 86 $\mu g/s$ is larger than the nominal case must be safely vented at the helium tank temperature of $<1.50$ K.

In the no cryocoolers case, all the cryocoolers are temporarily off (e.g., just after launch). If this situation continues for an unexpected long time, the heat load on the helium tank can reach 73 mW, corresponding to the mass flow rate of 3200 $\mu g/s$. Even in such an emergency situation, the helium tank should be kept below $\lambda$ point ($\sim 2.15$ K) with some margin ($\sim 0.1$ K), to keep superfluid helium in the tank.

We have designed and tested the whole system, to satisfy all the requirements. The principles and design of the four components are as follows.

### 2.2 Porous Plug

A porous plug is a traditional device to separate helium gas from superfluid helium in zero gravity using the thermomechanical
The SXS porous plug is made of stainless steel and has a diameter of 8.9 mm and a thickness of 6.3 mm. A hydrodynamic pore diameter or an equivalent circular opening is 3.8 μm, while the filtration is 0.5 μm, which means that only particles smaller than this would go through the plug. Upstream, the porous plug is attached to the helium tank as shown in Fig. 1(a).

When the superfluid helium goes through this device, it begins to evaporate due to lower pressure downstream. The latent heat of evaporation cools down liquid helium near the outside of the plug. Then, the superfluid helium conducts heat from the tank due to the nonzero size of pores. The temperature difference denoted as ΔT is an important parameter to reduce the film flow out of the porous plug.

### 2.3 Orifice

A narrow tube called an orifice is another critical component to suppress the film flow. Even with the porous plug, the Van der Waals force leads to a film on the walls, and the mobility of superfluid gives rise to film flow. The film flow rate within a tube is limited by the smallest perimeter of the vent line. Therefore, just outside the porous plug, we placed a stainless steel tube with an inner diameter of 1.4 mm, which reduces the film flow down to ~8 μg/s.

Thermal conduction along the tube is strictly limited. If there is a heat flow from the downstream of the tube, the film flow at the downstream can recondensate, leading to a larger film loss. For this purpose, the tube has a length of 117 mm and is made of stainless steel as shown in Figs. 1(a) and 1(b). The thermal conductivity of the tube is then suppressed to ~0.01 mW/K at 1.1 K. When ΔT is 50 mK, the conductive heat would be ~0.5 μW. Since the heat to evaporate the superfluid helium of 1 μg/s is 20 μW, an evaporation of the film flow more than ~0.025 μg/s cannot occur with this tube.

### 2.4 Heat Exchanger

The heat exchanger has a role to evaporate the remaining film flow coming out of the tube. Because the film flow is colder than the helium tank by ΔT as mentioned in Sec. 2.2, almost all the film will evaporate inside the heat exchanger and the latent heat cools down the tank.

The heat exchanger is made of copper for good thermal conductivity and has a hollow shape with a 54-mm diameter and a 5-mm plate thickness. The thermal conductivity between the heat exchanger and the tank is about 50 mW/K. This allows evaporating up to ~120 μg/s of evaporation of superfluid He at 1.1 K assuming a ΔT of 50 mK. This is an order of magnitude larger than the expected film flow out of the tube of ~8 μg/s. It has been shown experimentally that a ΔT > 50 mK results in no mobile film remaining after the heat exchanger and thus no loss of liquid helium.

### 2.5 Knife-Edge Devices

Finally, a pair of knife-edge devices is placed after the heat exchanger to limit the film flow in case the porous plug ΔT < 50 mK. Each of the knife-edge devices has sharp edges with a curvature radius of <100 Å. A surface tension can suppress the film and limit the thickness of <20 Å. Therefore, the edges must be atomically sharp. Also, nested edges are needed to reduce the thermal conductance across each knife-edge. The knife-edge devices can limit the film flow even if the ΔT across the porous plug is unexpectedly small.

We fabricated the knife-edge devices from a silicon wafer by ourselves. The sharp edges were made by using anisotropic wet KOH etching of silicon (110) wafers. A central hole to vent helium gas was made with deep reactive ion etching. Each knife-edge device has a square shape of 10 x 10 mm² with 28 edges and a 1.5 mm through a hole in the center, as shown in Fig. 1(c).

The two devices are glued on other sides of a split flange made of Invar. The thermal conductivity between the two sides must be small for the same reason as the tube. Therefore, the two sides are connected via a small tube with an inner diameter of 0.7 mm and a length of 3.6 mm. The thermal conductivity via the tube is ~0.1 mW/K at 1.1 K, suppressing a recondensation of the film and a subsequent flow.

### 3 Ground Measurements

#### 3.1 Setup

The FM of the SXS porous plug and film flow suppression system was tested before and after it was installed in the FM dewar. Before installation, tests were carried out in a special test apparatus. To immerse the porous plug in superfluid helium, the FM system was set at the bottom of the test helium tank so that the porous plug gets wet. For the same purpose, the tests in the FM dewar were conducted by tilting the dewar. These ground tests are described in detail by Ezoe et al., but we will briefly review the results and introduce an empirical model to estimate the mass flow rate from temperatures of the porous plug and the helium tank.

#### 3.2 Mass Flow Rate

The helium flow rate through a porous plug is a function of the temperature of the superfluid helium and the temperature gradient ΔT across the plug. A hysteresis in flow rate versus downstream pressure is known to exist in porous plugs in general and considered to arise by a movement of a vapor–liquid phase boundary inside the porous plug. The average phase boundary is most probably not reversible but depends on whether the flow rate is increasing or decreasing.

Figure 2(a) shows the mass flow rate through the porous plug and film flow suppression system at fixed temperatures of the helium tank. The flow rate is higher when the tank temperature rises because of a higher vapor pressure of superfluid helium.

### Table 2 Requirements for the SXS porous plug and film flow suppression system.

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat load (mW)</th>
<th>He lifetime (year)</th>
<th>Mass flow rate (μg/s)</th>
<th>He tank temperature (K)</th>
<th>Film flow rate (μg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.59 (0.72/0.91)</td>
<td>5.0 (4.1/3.3)</td>
<td>28 (33/43)</td>
<td>1.15</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Cryocooler failure</td>
<td>1.9</td>
<td>—</td>
<td>86</td>
<td>&lt;1.50</td>
<td>—</td>
</tr>
<tr>
<td>No cryocoolers</td>
<td>73</td>
<td>—</td>
<td>3200</td>
<td>&lt;2.05</td>
<td>—</td>
</tr>
</tbody>
</table>

*Numbers in parenthesis are from the thermal analysis at the beginning of life and the end of life, respectively.*
The flow rate increases as a function of $\Delta T$ since higher $\Delta T$ indicates lower pressure downstream of the porous plug.

At each tank temperature, a lower branch is when the helium flow rate is decreasing and an upper branch corresponds to when the flow rate is increasing. This behavior is similar to other porous plugs used in past space missions. To investigate a hydrostatic head effect, data were also taken at various liquid levels. Higher liquid levels give larger flow rates because the hydrostatic head is not negligible compared to the saturated vapor pressure at low tank temperatures. Data points taken in the component level tests at the lowest liquid level are consistent with those obtained in the FM dewar tests.

At the tank temperature of 1.15 K, the mass flow rate is $\sim 40 \, \mu g/s$ at $\Delta T$ of 50 mK and higher than the requirement of 28 $\mu g/s$ by $\sim 30\%$. However, the saturated vapor pressure of $^4$He is 57 Pa at 1.15 K, while the hydrostatic head at a liquid level of 5 cm is 67 Pa. The extra hydrostatic head will decrease the measured $\Delta T$. This assumption was supported by the fact that a test porous plug showed $\sim 40$ and $\sim 30 \, \mu g/s$ at the liquid level of 7 and 3.5 cm, respectively. We thus concluded that this porous plug will meet the requirement.

The other two requirements were also satisfied. The flow rate at 1.50 and 2.00 K exceeds 86 and 3200 $\mu g/s$, respectively. Even though the hydrostatic head is still not negligible at 1.50 K, where the saturated vapor pressure of $^4$He is 470 Pa, 86 $\mu g/s$ is satisfied with a large margin.

Based on these on-ground data, we constructed an empirical model to predict a mass flow rate $\dot{m}$ in orbit from the helium tank temperature $T_{\text{tank}}$ and $\Delta T$ across the plug. The lower and the upper branches are fitted with a simple linear function: $\dot{m}(T_{\text{tank}}, \Delta T) = A(T_{\text{tank}})\Delta T + B(T_{\text{tank}})$. $A$ and $B$ can be approximated by phenomenological curves as a function of $T_{\text{tank}}$ [At first, we tried a simple power law for the fit of the coefficients $A$ and $B$ but found large discrepancies. Hence, we decided to divide the temperature range below and above 1.30 K and used a polynomial function instead of a power law for $A$ in the lower branch when $T \geq 1.3$ K. The two coefficients are given as follows:

\[
\begin{align*}
A &= 0.050197 T_{\text{tank}}^{-0.093}, & B &= 19.526 T_{\text{tank}}^{3.795} \quad \text{ (upper branch, } T_{\text{tank}} < 1.3 \text{ K)}, \\
A &= 0.033671 T_{\text{tank}}^{4.750}, & B &= 19.656 T_{\text{tank}}^{4.3918} \quad \text{ (lower branch, } T_{\text{tank}} < 1.3 \text{ K)}, \\
A &= 0.0604087 T_{\text{tank}}^{6.707}, & B &= 7.4291 T_{\text{tank}}^{7.946} \quad \text{ (upper branch, } T_{\text{tank}} \geq 1.3 \text{ K)}, \\
A &= 9.65437 T_{\text{tank}}^{2} - 24.304 T_{\text{tank}} + 15.396, & B &= 9.2773 T_{\text{tank}}^{7.3128} \quad \text{ (lower branch, } T_{\text{tank}} \geq 1.3 \text{ K)}.\
\end{align*}
\]

Here, we used only the lowest liquid-level data taken in the component level tests, to minimize the hydrostatic head effect.

Figure 2(b) compares the data points with model predictions. The model represents the data well with a typical error of 10% to 20%. At high tank temperatures and large $\Delta T$ (e.g., 2.00 K and 500 mK), the error seems to become larger but such conditions were not realized in orbit. Because the hydrostatic head is minimized but is not zero, this empirical model can still overestimate the mass flow rate if we compare the model with on-orbit data. Therefore, when we compare the empirical model with the flight data in Sec. 4.1, the smaller mass flow rate model by multiplying the model result by a constant factor is tested as described later.

### 3.3 Film Flow Rate

The film flow out of the porous plug and film flow suppression system was quantitatively measured in the component level tests. We prepared a copper test cell in the downstream of the whole system and added a heat to examine a temperature rise of the test cell.

Figure 3 shows the results. When there is a film flow coming into the test cell, the temperature rise is small. Once all the film flow evaporates, the test cell temperature rapidly rises as a function of the input heater power. This is the same method utilized in the ASTRO-E XRS and the Suzaku XRS experiments.

We took data at a tank temperature of 1.15 K and two different $\Delta T$s (50 and 23 mK). The hydrostatic head was minimized to be 5 to 6 cm. For each data set, we fitted the temperature rise
with a linear function and estimated the heater power necessary to evaporate the film flow. The estimated heat power was 19 and 45 $\mu$W, corresponding to a film flow rate of 0.9 and 2 $\mu$g/s, respectively, assuming the latent heat of superfluid helium at this temperature. Therefore, the requirement for the film flow is satisfied even with a $\Delta T$ of 23 mK.

3.4 Flow Rate Test Before Launch

One day before launch (L-1), a flow rate through the porous plug and film flow system was measured at the Tanegashima Space Center. This test was to confirm that there is no restriction in the vent line and the mechanical valve named V4 is properly closed. The valve V4 allows helium gas to bypass the porous plug and was used to quickly vent the helium tank on-ground. Since V4 should be closed on-orbit, we closed V4 before launch and then measured the flow rate as a final check.

We note that the test configuration is different from the component level tests and the SXS dewar tests as described in Sec. 3.1, because the dewar was on the spacecraft and could not be tilted. However, superfluid helium can crawl up the wall, and the porous plug can be partially wet, causing a $\Delta T$. The flow rate does not obey the empirical model because of this difference. Therefore, we had taken the reference data in the same configuration beforehand.

Figure 4 shows the obtained data compared to those taken in the other past FM dewar tests. The flow rate is as expected from the downstream temperature of the porous plug, which is most probably due to the fact that the downstream temperature of the plug reflects a saturated vapor pressure of helium gas. After this flow rate test, we closed the helium vent valve V5 and stopped pumping on the helium tank with vacuum pumps.

4 In-Flight Performance

4.1 Temperature Profiles

Hitomi was launched on February 17, 2016, 08:45 (UT). The helium vent valve V5 was opened at 08:50. This is the first operation of the SXS after launch and was done during rocket acceleration due to a risk of the so-called castle’s catastrophe. In this launch, we decided not to tilt the dewar, and therefore, the results of the temperature measurement are compared with those obtained from the off-ground tests.

Figure 5 shows the obtained data compared to those taken in the other past FM dewar tests. The flow rate is as expected from the downstream temperature of the porous plug, which is most probably due to the fact that the downstream temperature of the plug reflects a saturated vapor pressure of helium gas. After this flow rate test, we closed the helium vent valve V5 and stopped pumping on the helium tank with vacuum pumps.
which all the superfluid helium may drain off into the space. For
the catastrophe to occur, there would have to be liquid helium
outside the plug where it could reach a heat source. Then, the
thermomechanical effect would work in reverse and pump the
superfluid helium from the tank.

Figure 5(a) shows the temperature profile of the helium tank
(He tank1) and the downstream temperature of the porous plug
(PPI) after the vent valve was opened. $\Delta T$ across the plug
clearly exists, suggesting that the helium liquid is separated
from the gas by the porous plug as designed.

All the cryocoolers were off before launch, causing a con-
tinuous temperature rise of the helium tank. We then turned
on the cryocoolers step by step and the tank temperature
began to decrease. After about one month, the tank temperature
settled down to the thermal equilibrium temperature of $\sim 1.12$ K.
Cyclic temperature rises occur due to ADR recycles. Details on
these initial operations are summarized in other papers.\textsuperscript{3,22}

Estimated helium mass flow rates from the tank temperature
and $\Delta T$ across the plug are shown in the bottom of Fig. 5(a).
Three curves are plotted. Model 1 corresponds to the empirical
model as described in Sec. 3.2. Model 2 is 2/3 (67\%) of the
empirical model to roughly take into account the hydrostatic
head effect. The tank temperature peaks around February 17,
2016, 22:40 (UT). The upper branch model was used before
the peak, while the lower branch model was utilized after that.
For simplicity, we did not use the upper branch model for the
temperature rises due to the ADR recyclers, because the time
intervals are short. Model 3 is estimated from the thermal
temperature model analysis,\textsuperscript{22} in order to reproduce temperature profiles of
the helium tank, internal, and outer shields of the dewar.

Model 2 is closer to model 3 after launch, while model 1 fits
well model 3 as the tank temperature settles down. This may
indicate that the hydrostatic head effect is not a constant factor
but variable depending on the tank temperature, and/or the state
of the liquid and gas boundary inside the plug may be slightly
different from that on the ground.

The spacecraft lost control on March 26, 2016, due to a series
of attitude problems. Figure 5(b) shows a close-up of the last
part of the temperature profiles. As is clear from the data, the
porous plug and the film flow suppression system were working
properly. The tank temperature was decreasing from 1.13 to
1.12 K, while $\Delta T$ was from 36 to 33 mK after the ADR/recycle.

The final tank temperature is consistent with our expectation
but $\Delta T$ is smaller than $\sim 50$ mK by $\sim 15$ mK. The ground
film flow measurement suggests that the film flow rate is $< 2 \mu g/s$
as required with this $\Delta T$. The estimated mass flow rates of models
1 to 3 are $\sim 35, 23,$ and $34 \mu g/s$, respectively. Models 1 and 3
match and coincide with the estimated heat load to the tank of
$\sim 0.7 \text{ mW}$.

4.2 Volume of the Superfluid Helium

Another line of evidence that the porous plug and the film flow
suppression system worked properly after launch is an estimated
volume of the superfluid helium in the tank. Every time the
ADR recycle, the tank temperature rises and falls as a function
of time as seen in Fig. 5(a). This allows a measurement of the
heat capacity of the helium tank and consequently a volume of
the superfluid helium inside it. This is called ADR mass gauge.\textsuperscript{4}

Figure 6 shows the estimated volume compared to those by
integrating the estimated mass flow rates of the three models
since launch. We here assumed an initial fill of 37.0 L from
on-ground estimates. Most of the ADR mass gauge data fall
between models 1 and 3. Therefore, no significant loss of helium
due to the film flow (e.g., a factor of 2 or 3 as expected if there is
no film flow suppression system) would exist, which suggests
that the porous plug and film flow suppression system works.

On the other hand, the mass loss rate inferred from the ADR
mass gauge method was $\sim 20\%$ higher than predicted based
on the thermal model of the cryogenic system (model 1) or
the empirical model (model 3). One possible explanation for
this possible excess vent rate is that the $\Delta T$ across the porous
plug was smaller than anticipated, due for example to a higher
than expected vent line impedance which may lead to an
increase of the film flow, although there remains uncertainties
in the estimations due to the limited lifetime of the spacecraft
and also the resolution of the thermometers of the porous plug.

5 Conclusion

We have developed the SXS porous plug phase separator and
the film flow suppression system. This was a challenge, since
the mass flow rate is smaller than past space missions using
the superfluid helium and also the film flow must be strictly
suppressed. Taking the same approach as the ASTRO-E XRS
and the Suzaku XRS2, the whole system was designed and
fabricated. We tested these components using a special test
apparatus as well as in the flight dewar. The empirical model
of the helium mass flow rate was constructed. The data after
launch suggest that the porous plug and the film flow suppres-
sion system worked.

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