

WIDEDYNAMICRANGE POROUS PLUG FOR s] RTF

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ABSTRACT

The most recent approach to the Space Infrared Telescope Facility (SIRTF) uses a new design concept in which the telescope is launched warm and subsequently cooled to operating temperature on orbit. At launch, the cryostat is at 2 K and the telescope is at room temperature. Cooldown of the telescope will be accomplished initially through radiation to space. Final cooldown to the 5.5 K operating temperature is done with helium vapor. Initially, the helium flow on orbit will be 20 to 30 times larger than required for steady-state operation. The vent line and the liquid/vapor phase separator (porous plug) therefore must accommodate a large dynamic operational range.

For ground testing of IR instruments, the required temperature is 1.5 K. The helium tank temperature for both ground testing and space operations thus needs to be at 1.4 K. We present a discussion of the requirements, a conceptual design, and initial laboratory test results with candidate porous plugs and associated instrumentation. A discussion of possible connections to the design of the Gravity Probe-B cryostat will be presented also.

INTRODUCTION

' Satellites requiring superfluid helium (1 Ic 1 D) for cooling of their infrared detectors have proven their usefulness through astrophysical observations performed in space. One of the earlier successful missions was the infrared Astronomical Satellite ¹(IRAS). The mission lasted 300 days and the temperature of the cryostat (approximately 1.8 K) was controlled through the use of a porous plug as the liquid/vapor phase separator. The design of the venting system allowed a limited range of flow rate, but it was designed sufficiently broad

that the flow-rate variation after the launch was accommodated very smoothly. The temperature stability was very good and no oscillations in the temperature of the cryostat were detected. The Cosmic Background Explorer (COBE) dewar² used a porous plug as the He II liquid/vapor phase separator as well, but the cryostat temperature underwent a number of oscillations. Such temperature oscillations should not occur in the Gravity Probe-B dewar.³ The requirement for the larger range of flow needed for that dewar will be reflected in a ratio of about 1:4, but the same 1.8 K temperature must be maintained.

The European Space Agency so far has produced the largest-volume cryostat for a spacecraft, with a helium volume of over 2100 liters in the Infrared Space Observatory (ISO). That launch is planned for September 1995, from Kourou, using the Ariane 44p rocket.

The currently pursued version of the Space Infrared Telescope Facility (SIRTF), as successor to IRAS and ISO, will use the so-called "warm" launch concept.⁴ The telescope will be warm (ground ambient temperature) at launch and will be cooled in flight both by radiation to space and by the redirected cool helium vapor from the cryostat. The requirements on the porous plug/vent system originate from the need for a large flow after launch and after the telescope shields have cooled by radiation. Therefore, the requirement in particular on the He II liquid/vapor separator is to perform its function within the range of 1.8 ± 0.2 K to 1.4 K, but with a mass flow range of $0.4 \text{ mg} \cdot \text{sec}^{-1}$ to $\sim 11 \text{ mg} \cdot \text{sec}^{-1}$.

The characterization of the candidate stainless-steel porous plug has been explored so far between 2.1 K and 1.6 K with plans to extend tests down to 1.4 K, to determine if only one porous plug could cover the whole range. The indications are that it might, with very careful and precise attention given to characterization in its area, in particular.

TEST APPARATUS AND PROCEDURE

Experimental setup

A schematic illustration of the experimental setup is shown in Figure 1. The porous plug under test is fixed at the bottom of the evacuation pipe with a leak-tight iridium seal. The evacuation pipe is connected to the vacuum pump to simulate the vacuum of space. The temperature of the helium II in the helium bath, T_B , is controlled by a pressure-regulating valve connected to the evacuation pump for the main helium bath. The bath temperature, T_B , and the downstream-side temperature of the porous plug, T_P , are measured by germanium resistance thermometers (GRTs) excited by a 10 microamp DC current. The bath pressure, P_B , and the downstream pressure, P_P , are obtained by reading pressure meters; accurate pressure differences are measured by a precision piezo resistive pressure transducer (ENDEVCO Model 853 IA-15). The volumetric flow rate is measured by a FLOW METER Model HFM 2001 flow meter located at the exhaust side of the evacuation pump. The mass flow rate is obtained by multiplying the measured volumetric flow rate by the density of helium gas under atmospheric conditions. The mass flow rate and the downstream pressure, P_P , are controlled by a control valve.

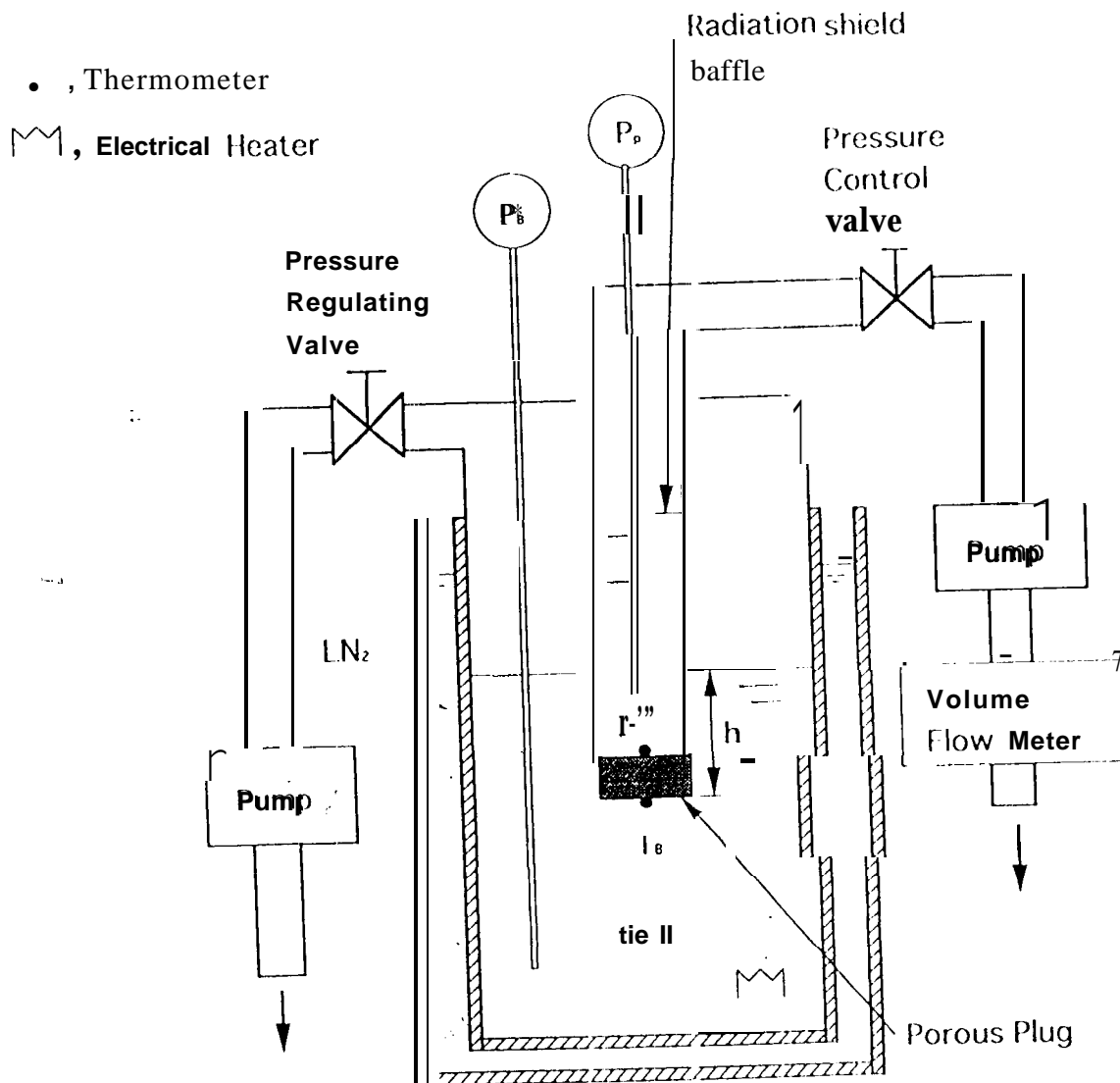


Figure 1. Schematic illustration of He I I experimental setup

Tests of Porous Plugs

A candidate test porous plug is made of sintered stainless steel (Permaflow, Inc.) and has the following parameters:

diameter, d	$=$	25.4×10^{-3} meters
thickness, l	$=$	6.3×10^{-3} meters
porosity, ϵ	$=$	0.21
permeability, κ_p	$=$	3.92×10^{-14} meters ²
mean pore radius	$=$	4.1×10^{-6} meters

where the permeability, κ_p , is measured using helium gas at room temperature. The effective cross-sectional area, A , is 3.84×10^{-4} meters², because the iridium closes some pores on the surface of the porous plug.

Permeability, κ_p , at 1.73 K is measured by using helium gas. In this case, κ_p is obtained from

$$\kappa_p = \frac{\rho_{300} \eta_{1.73} l}{\rho_{1.73} A} \left(\frac{V_r}{\Delta P} \right) \quad (1)$$

Here, the ρ , η , and V_r , represent density, viscosity, and volumetric flow rate respectively. The subscripts 300 and 1.73 indicate the room-temperature and low-temperature (1.73 K) values respectively. In this case, we obtain

$$\kappa_p = 4.4 \times 10^{-14} \text{ meter}^2 \quad (2)$$

This value is almost the same as the value measured at room temperature. The permeability measured also at room temperature using air works out to be $\kappa_p = 3.98 \times 10^{-14}$ meter². Thus, it is found that the permeability does not depend on gas type or on temperature.

Experimental Data and Analysis

Experiments have been carried out to investigate the fundamental characteristics of steady flow through the candidate porous plug. The experimental data for mass flow rate, m , are shown plotted against the pressure difference, ΔP , and temperature difference, ΔT , in Figures 2 and 3. It is found that the mass flow rate becomes smaller as the bath temperature decreases. Three different flow regions can be observed from these figures, and it can be noted that a limit to mass flow rate seems to exist in the high-pressure difference region. In the initial region, the mass flow rate increases even though the pressure difference is very small. We also note that there exists hysteresis in the mass flow rate. When the mass flow rate is increasing, the data yields the upper branch. We call that branch the "nonlinear region". When the mass flow rate is decreasing, it yields the lower branch, which we call the "linear region."

When a phase separator is successfully operated and relatively high pressure and temperature differences are created across the plug, the liquid/vapor boundary may be located somewhere within the porous plug. The experimental data are compared with the equation,

$$m = \frac{A \kappa_p}{l} \left[\frac{\rho_v}{\eta_v} (P_{sat} - P_r) + \frac{\rho S T}{(L + S T) \eta_n} (\rho S \Delta T_2) \right] + m_0(T) \quad (3)$$

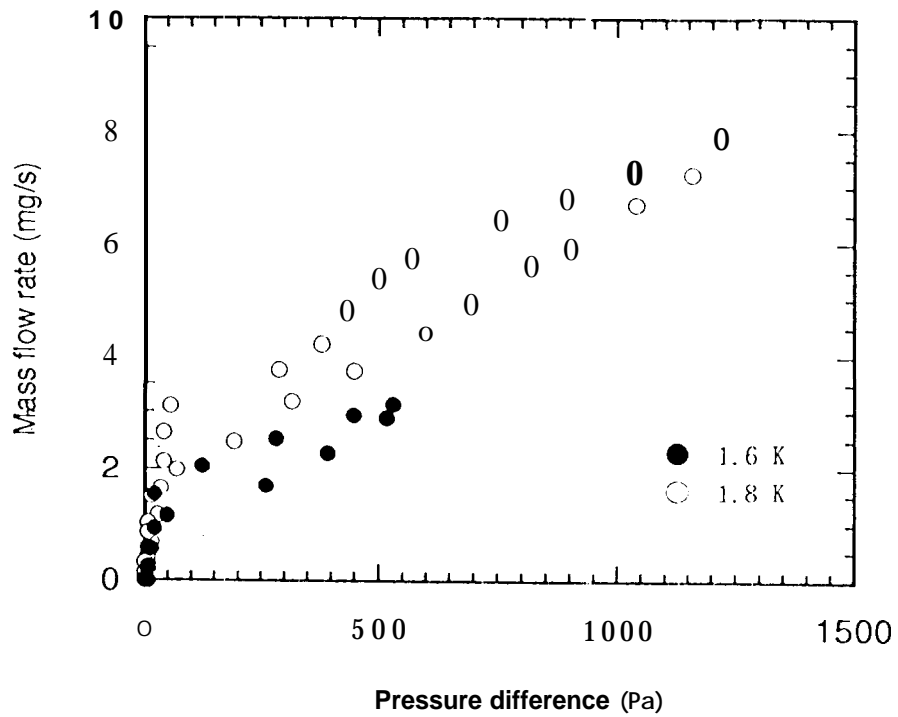


Figure 2. General steady-flow characteristics through porous plug. Relationship of mass flow rate, in $\text{mg}\cdot\text{sec}^{-1}$, to pressure difference, ΔP , in Pa

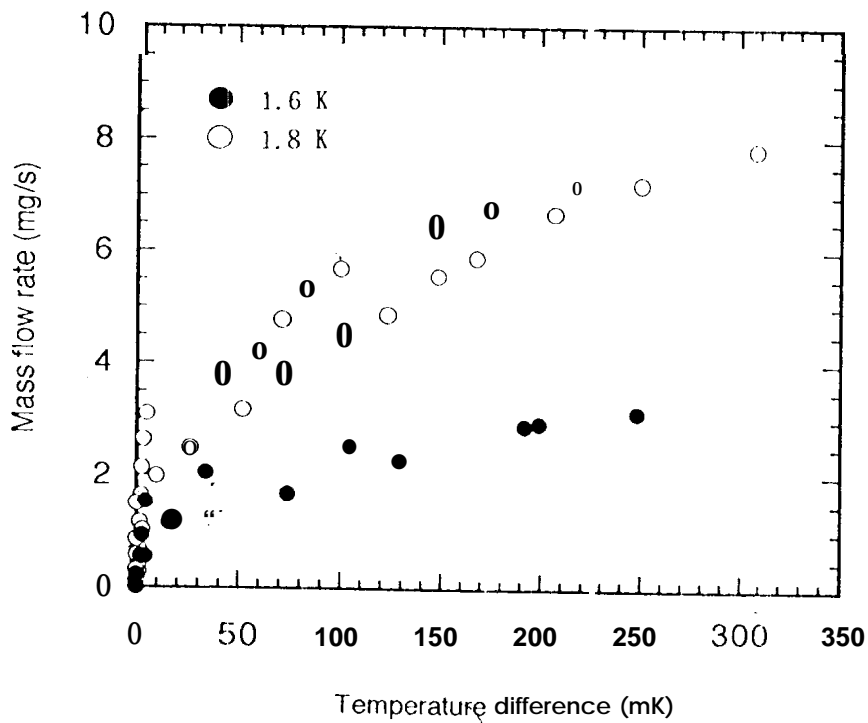


Figure 3. General steady-flow characteristics through porous plug. Relationship of mass flow rate, in $\text{mg}\cdot\text{sec}^{-1}$, to temperature difference, ΔT , in mK

where

$$P_{sat} = P_{bath} + \rho gh + \frac{2\sigma}{R} \cos(\Theta) - \rho S \Delta T_2 \quad (4)$$

Here, P_{sat} stands for the saturation vapor pressure of the liquid/vapor boundary in a porous plug. The ΔT_2 represents the temperature difference between the helium bath and the liquid/vapor boundary in a porous plug and S and L represent entropy and latent heat of vaporization respectively. The subscripts v and n are the vapor and normal fluid component while σ , g , and Θ are the surface tension of He II, the acceleration due to gravity, and the contact angle between liquid and wall for the porous plug. Here, h is the length from the liquid/vapor boundary in the bath to the bottom of a porous plug. The $m_0(l)$ shows an additional mass flow rate caused by radiant heating at the downstream side of the porous plug, which would, in general, be a function of temperature.

Writing the equation in the form shown allows us to consider separately the effects of the liquid and the vapor on the total mass flow rate. The slope of the curve derived from the experimental data in the linear region can be compared with the theoretical prediction shown in Figure 4. The solid line shows the flow conductance of the vapor phase and the broken line shows that of the liquid phase. The experimental data are always located between these two lines, but fall near the solid line. Figure 4 suggests that the effect of the vapor phase is much more dominant than that of the liquid phase in relatively high

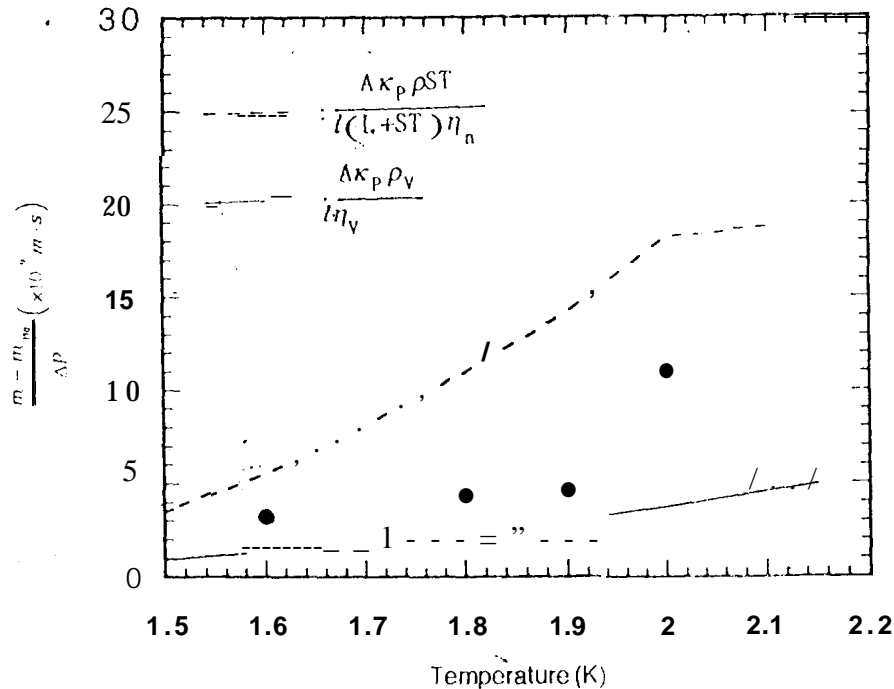


Figure 4. Variation of flow conductance with bath temperature, T_B

pressure- and temperature-difference conditions. This figure also suggests that the hysteresis will become small as the bath temperature decreases. This feature, in fact, is observed in Figures 2 and 3.

We also investigated the initial region, the feature of hysteresis, and the influence of pressure head due to gravity; these results are described in the Summary. A more detailed discussion is presented in Reference 5.

Summary of the Tests

The basic characteristics of a porous plug have been investigated and the following observations have been made:

1. Three different flow regions are observed from this experiment and a limit of mass flow rate seems to exist for the large pressure differences.
2. In the initial region, it can be considered that a liquid/vapor phase boundary is always located at the downstream surface of a porous plug.
3. The nonlinear region and the linear region both exhibit hysteresis. The linear region is relatively stable compared with the nonlinear region. The hysteresis is produced by variations in capillary forces caused by changing contact angles.
4. The effect of the vapor phase is more dominant than that of the liquid phase under relatively high pressure- and temperature-difference conditions in the linear region.
5. The magnitude of hysteresis becomes small as the bath temperature decreases.
6. The effect of hydrostatic pressure due to gravity is understood from simple linear theory. The theoretical predictions show good agreement with experimental (i.e.,

CONCLUSIONS

The current data and the analyses show that the wide dynamic range of the liquid/vapor separator might be accommodated with one unit only. As an additional backup, the heater will be added to the cryostat downstream from the porous plug to assure and/or speed up the telescope cooldown. The requirement for the SIRTIF dewar at launch is that the launch be made with the telescope at ground ambient temperature while the dewar is at a temperature of 1.8 ± 0.2 K. The high flow rate is needed later to cool down the telescope in a reasonably short time, before the parasitic heat is reduced due to the radiation shield's lower temperatures. The long lifetime will be achieved with the small He consumption of ~ 0.4 mg sec⁻¹. The cooldown might require ~ 10 percent of the helium content present at the time of the launch. . .

ACKNOWLEDGMENTS

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

* Supported by the Japan Society for the Promotion of Science. Visiting Postdoctoral Scientist from the University of Tsukuba, Japan

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