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THE DEPENDENCE OF CHOKED FLOW AND BREAKTHROUGH ON PORE SIZE DISTRIBUTION IN VAPOR-LIQUID PHASE SEPARATION OF He II USING POROUS MEDIA

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ABSTRACT

Liquid breakthrough and choked flow are important phenomena in the operation of phase separators in space. Breakthrough results in loss of liquid which can reduce the life time of, and potentially terminate a mission. Choked flow limits the amount of liquid boiloff which passes through the phase separator and can result in the warming of the bath temperature. Since the capillary effect plays an important role in both the above phenomena, the distribution of pore sizes in the phase separator governs the critical limits of breakthrough and choked flow. In this paper, the pore size dependence of breakthrough and choked flow in vapor-liquid phase separators will be discussed in detail. The experimental data of various phase separators tested for the Relativity Mission will also be compared to present theory.

INTRODUCTION

Vapor-Liquid phase separation (VLPS) using porous media was studied extensively during the late 70's and early 80's. After the Infrared Astronomical Satellite (IRAS) mission there has been limited effort in the research of the VLPS. The COBE mission[1] raised some uncertainty in the operation of the phase separator as temperature at the downstream of the porous plug was seen to fluctuate with time. The Superfluid Helium On-Orbit Transfer (SHOOT) experiment[2] demonstrated the operation of a high vent rate VLPS system. Recently, the Jet Propulsion Lab conducted experiments[3] on the phase separator to be used for the SIRTF mission. Despite these efforts, there still exists the discrepancy among various theories. Choked flow and hysteresis were not detected in a number of early studies on the VLPS. Whether these investigators overlooked the choked regime is not clear. Moreover, with the same permeability (which has been accepted as a more accurate parameter to characterize VLPS) and dimensions, some plugs tend to choke at higher flowrates than others. We hope that the present paper might shed some light on the theory behind the operation of the phase separator, in particular the pore size dependence of choked flow and breakthrough will be discussed in detail.

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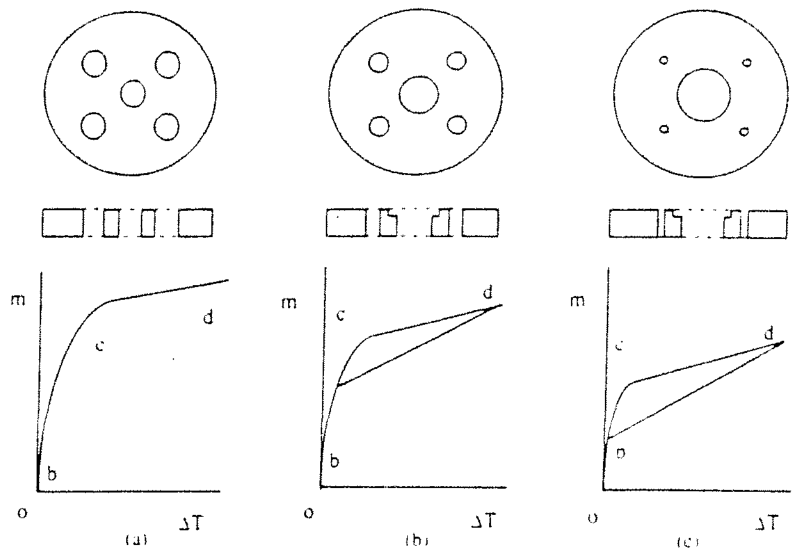

Figure 1. Schematic diagram of the operation of three porous plugs with the same permeability but different distribution of pore size.

THEORY

Vapor-Liquid Phase Separation of He II was studied extensively. The normal operating region or generally know as the linear regime is depicted in Figure 1 as section b-c. The governing equation in this linear regime can be written as[4]

$$m = \frac{\rho^2 S^2 T K_p A \nabla T}{(\lambda + ST)\eta_n} \qquad (1)$$

where ρ is the density. S is the entropy. λ is the latent heat of vaporization and η_n is the viscosity of the normal fluid. K_p is the permeability and A is the area. The choked flow regime was first explored experimentally by Murakami et al[7] and Hendricks[8]. DiPirro[9] offered a simplified model for the choked flow. Lages[10] postulated a more complete theory

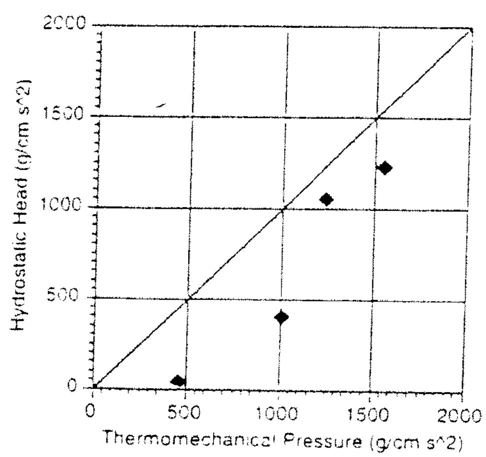

Figure 2. Thermomechanical pressure versus hydrostatic head.

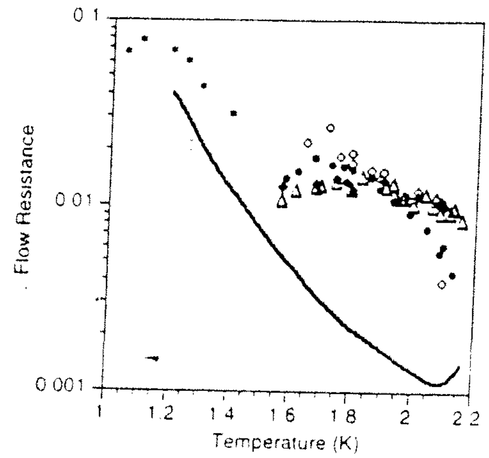

Figure 3. Flow resistance: solid line - Equation 1.
* JPL data (Ref. 4), the rest of the data from Ref. 6.

for choked flow based on the Gibbs free energy analysis, which boils down to DiPirro's equation[9], for pore sizes on the order seen in VLPS. According to DiPirro, the temperature across the porous plug in this regime can be expressed as

$$\Delta T = \frac{\frac{4\sigma}{D} + \rho g h}{\rho S - \left.\frac{dP}{dT}\right|_{[illegible]}} \qquad (2)$$

where σ is the surface tension, h is the height of the liquid and D is the equivalent capillary diameter.

RESULTS AND DISCUSSION

From the experimental data obtained from the Relativity Mission phase separator[[illegible]], one learns the following.

The Breakthrough Regime

In this regime, the thermomechanical pressure is not strong enough to overcome the static pressure (e.g., the hydrostatic head and vapor pressure) across the porous plug. This is represented by section o-b in Figure 1. Three plugs were tested. The first plug has a permeability (K_p) of $3.55\times10^{[illegible]}$ cm². The second plug has a K_p of $1.7\times10^{[illegible]}$ cm². And the third plug has a K_p of $3.8\times10^{[illegible]}$ cm². As expected, the first two plugs are more susceptible to breakthrough. For the the last plug, breakthrough was not detected for flowrates higher than 0.05 mg/s-cm². Figure 2 is a plot of the thermomechanical pressure against the hydrostatic head for the last plug. The data represent the onset of breakthrough. The fact that the thermomechanical pressure is always larger than the hydrostatic head tends to indicate that liquid breakthrough should not have taken place. The liquid detection at the downstream is due to the presence of a thick film.

The Normal Phase Separation Regime

This regime is generally known as the 'linear regime' (represented by b-c in Figure 1). Murakami first reported a discrepancy between the experimental data and the linear equation (Eq. 1). Elliott[4] also pointed out that Equation 1 does not fit the experimental data of JPL for the SIRTF plug, and that an effective viscosity has to be used in place of the actual viscosity. On the other hand, the NASA GSFC group[12] reported that the COBE test data at small flowrates agree with the linear equation. Figure 3 is a comparison between the experimental data in the literature and Equation 1. The flow resistance is defined as

$$R = \frac{\dot{m}}{\nabla P K_p A} \tag{3}$$

Note that the resistance of the above equation is unitless. The fact that most data fall above the curve tends to suggest larger flow resistance than the laminar transport (or linear equation). In Figures 4a and 4b, the mass flow is plotted against the temperature difference on a log-log plot. In both of these plots, the slope of unity is denoted by the dashed line, and the slope of 1/2 is shown by the solid line. They are drawn to guide the eye. Since the Murakami data[6] (Fig. 4a) deviate from the slope of unity, it indicates that the flow is in the transition regime. These data show that the transport in the phase separation is not always in the laminar (or linear regime). Due to the distribution of pore size (as discussed in the next section), some phase separators go from the laminar regime directly into choked flow. Others go from laminar to transition, to turbulent before choking. The 1/2 slope of the JPL data[4] (Fig. 4b) tends to indicate an Ergun type transport as suggested in[5]

$$\nabla P_T = \frac{v_n \eta_n}{K_p} + 1.75 \frac{\rho v_n^2}{(150 \varepsilon^3 K_p)^{1/2}} \tag{4}$$

where ∇P_T is the thermomechanical pressure, v_n is the approach normal fluid velocity, η_n is the normal fluid viscosity, and ε is the porosity.

Choked Flow Regime:

Choked flow is characterized by the recession of the vapor-liquid interface into the porous plug. This regime is represented by section c-d in Figure 1. Since the Relativity Mission requires a large range of flowrates, the authors went through painstaking efforts in searching for the appropriate material to be used for the phase separator. Due to the stringent requirements on the bath temperature control, operation in the choked regime is not recommended. Therefore the maximum massflow of the phase separator is limited by the

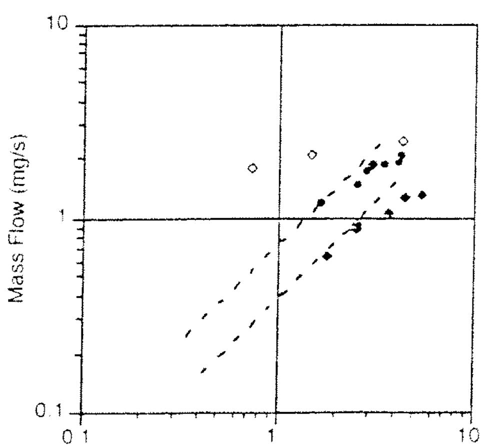

Figure 4a. Data of Murakami[6].

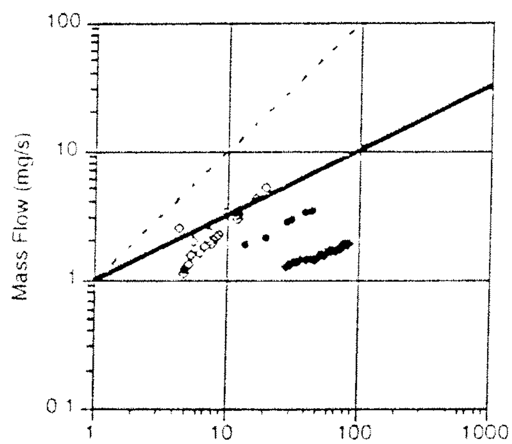

Figure 4b. Data of JPL (Ref. 4)

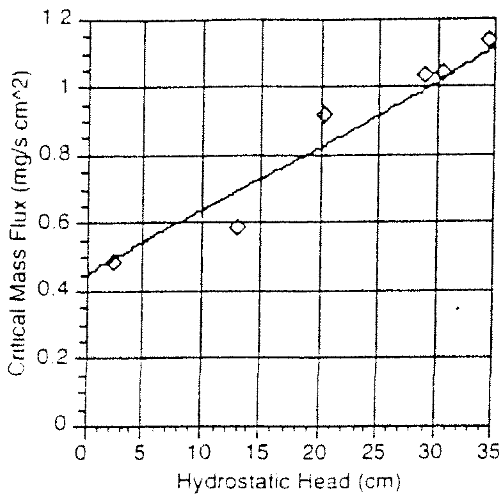

Figure 5a. Lockheed's data (present work)

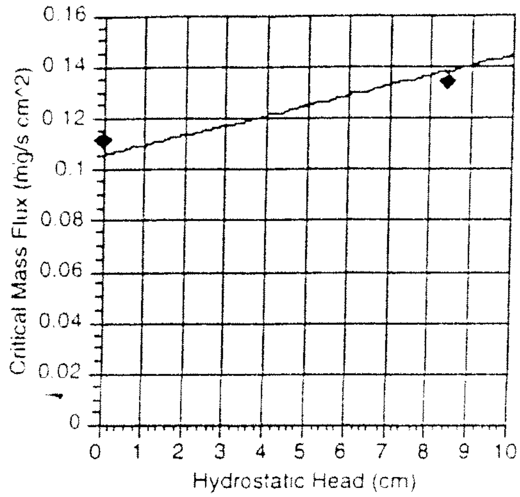

Figure 5b. JPL data (Ref. 4).

critical massflow or better known as the knee[9]. The following lessons are learned from the selection process. Permeability alone is not sufficient in characterizing the critical mass flow (unless the plug has a uniform distribution of pore size). Let's take a look at Figure 1. All three plugs depicted in the figures (a, b, and c) have the same permeability but vastly different distribution of pore size. The plug in Figure 1a has uniform pore size. The transport could go from laminar to turbulent before choking. Also there is little or no hysteresis. This is supported by the data of DiPirro[4] with a glass capillary plug which is supposed to have a uniform distribution of pore size. The plugs in Figures 1b and 1c have progressively larger distribution of pore size. The larger the distribution, the larger the hysteresis loop and the smaller the critical massflow. (The mechanism for hysteresis is very complicated. It is believed to be caused by the varying pore size along the length of the plug which results in the different surface tension during choke and unchoke. Although interconnected pores and superfluid film might also play an important role.) Since the choked flow occurs at much lower flowrates for large distribution of pore size, the transport might choke before the flow turns turbulent or even reaching the transition regime.

The critical mass flux (at the knee) of the phase separator was found to be a strong function of the hydrostatic head. Figure 5a is a plot of the critical mass flux of one of the materials tested for the relativity mission. . This material has a permeability of 3.8 x 10 cm^2 This is obtained by equating Equation 1 and 2 and solving for the critical mass flow as a function of the hydrostatic head. An equivalent capillary diameter D_c = 3.5 microns is used to correlate the data. Since the plug tends to choke at the larger pores, this value of D_c obtained experimentally gives us a measure of the large pores. On the other hand, the average pore size can be deduced from the analog between the Hagen-Poiseuille equation and the Darcy Law

$$D_k = (32K_p)^{1/2} \qquad (5)$$

The present material has an average diameter (D_k) of 1.1 microns. From the difference between D_c and D_k, one can get a feel of the distribution of the pore size. The larger the difference, the larger the distribution and vice versa. Figure 5b shows that a D_c of 3.1 microns is needed to correlate the JPL data, indicatng that the JPL plug (D_k=1.3 microns) has a smaller pore size distribution than the plug tested for the Relativity Mission. Since the bubble point test gives the diameter of the largest pores in a plug, this might be a good way in measuring D_c in Equation 2. While the permeability or D_k is important for the prediction of the transport in the normal operating regime (e.g., Equation 1 or 3), D_c is valuable for calculating the critical mass flow (at the knee) and the size of the hysteresis loop. Note that D_c and D_k could be obtained from the size of the hysteresis loop: D_c on the increasing flow part and D_k on the decreasing flow part.

CONCLUSIONS

The following conclusions can be drawn.

1) Breakthrough Regime:

a) Plugs with large permeability are more susceptible to breakthrough.

b) A thick film is present at the downstream of the phase separator which might set off the liquid level detector to indicate the presence of liquid helium.

2) Phase Separation Regime:

a) The operation in this regime is not always linear

b) The transport in this regime sometimes changes from laminar to turbulent before choking.

c) The Ergun type turbulent transport was detected in some phase separators.

3) Choked Flow Regime:

a) Hysteresis results from a distribution of pore size in the phase separator. Large distribution gives small critical mass flow (at the knee) and large hysteresis loops and vice versa.

b) Like breakthrough, this regime is a strong function of the permeability. The equivalent capillary diameter D_c in Eq. 2 gives a quantitative measure of the large pores in the plug. Because these are the pores that choke first. On the other hand, the $D_k=(32K_v)^{1/2}$ gives the average pore size. If the difference between D_c and D_k is small, the distribution of pore size is small also (Fig. 1a); if the difference between D_c and D_k is large, the distribution of pore size is also large (Fig. 1c).

c) In this regime, permeability alone is not sufficient in predicting the critical mass flow (or the knee). Since the bubbles usually form at the large pores of the plug during a bubble point test. This might be a good way of estimating D_c. A correlation between D_c and the bubble point pressure should be established to characterize plugs used for phase separation.

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