Flow of \( \text{He II} \) through Porous-Plug Phase Separators

By

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Summary: A porous-plug is one of important components for onboard cooling systems which separates the vapor from the liquid helium (\( \text{He II} \)). Flow characteristics through porous-plugs and physical situations of \( \text{He II} \) flow inside plugs are experimentally investigated by examining the temperature distributions inside plugs. It is clarified that \( \text{He II} \) flows ideally, i.e. London’s relation is held, in flows through the most part of a plug and turns into vapor phase near the downstream end of it. The flow of the normal fluid component remains laminar in plugs in any experimental conditions. The liquid-vapor phase boundary is formed just at the downstream end and goes down toward the upstream side as the mass flow rate increases. The thermodynamic states of \( \text{He II} \) are also revealed from these flow characteristics.

1. Introduction

Superfluid helium (\( \text{He II} \)) has some peculiar properties. This can flow without any resistance. Another is the so-called thermal superconductivity, though it is not actually thermal conduction. The apparent thermal conductivity is in effect extremely large because of the internal counterflow. Hence the temperature of \( \text{He II} \) is very uniform, even if external heat is locally applied to it.

Superfluid helium with such thermal property is one of the best coolants to be adopted in various kinds of space cooling missions. Its importance is now increasing more and more, as space borne experiments and observations have been proposed and planned with rapid progress of space technology. Especially in infrared astronomy, it is a great leap to make observations in space, since the absorption and the radiation by the atmosphere limit the observation only to a number of wavelength bands on the ground. In space the infrared observation can be taken quite free from such restrictions. Hence, several infrared observation programs have been planned and some of them have already been accomplished. It should, in addition, be mentioned that the thermal radiation from a telescope at room temperature would be much larger than the infrared signal from astronomical objects and the sensitivity of the telescope be considerably degraded. It is of crucial necessity to cool the telescope down to almost absolute zero. Superfluid helium is most suitable for this purpose because of its extremely low temperature and of its excellent heat transfer capability. It is a key to ensure the higher detectability and the improved performance of infrared telescopes. It is, however, highly possible for such liquid coolant to exhaust together with the vapor in a short time in the zero gravity state. It is necessary to separate the vapor from superfluid helium for a long term containment of \( \text{He II} \) in a vessel under the zero gravity state in space.

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Two kinds of phase separators have been developed and studied. An active phase separator (APS) is made of two concentric cylinders with a small gap (several \(\mu\text{m}\)). The flow rate is controlled mechanically by changing the overlapping length of them. This has been developed and studied by the German Infrared Laboratory (GIRL) group [1, 2]. This group has also made an airborne experiment of an active phase separator [3].

Another is a porous-plug (PP) made of such porous media as compressed alumina and sintered stainless steel. Porous-plugs have been developed and investigated by several groups, the Jet Propulsion Laboratory (JPL) [4], the University of Alabama and the Marshall Space Flight Center (MSFC) group [5, 6], and us [7]. Porous-plugs have been tested experimentally by a rocket [8] and the successful performance of a porous-plug was recently reported utilized in the Infrared Astronomical Satellite (IRAS) [9]. In both phase separators the thermomechanical effect of superfluid helium, which will be mentioned later in detail, is the primary principle of phase separation. Fundamental performance of porous-plug has already been investigated [7], but some features are left to be further investigated for complete understanding. Consequences of such experimental studies on porous-plugs have shown that the flow performance did not always follow the theoretical predictions. There has been even found a non-linear hydrodynamic behavior, which has not been expected in a simple theory. Such discrepancies may be ascribed to the lack of understanding in real physical conditions of \(\text{He II}\) flow inside porous-plugs.

This experimental study aimed at making clear the physical states of flows of superfluid helium and its vapor, and identifying the actual flow through the plug. Some considerations on thermodynamic states of \(\text{He II}\) inside phase separators are also presented. For these purposes, two thermometers were inserted inside each porous-plug in addition to ones employed in the previous study. These thermometers were able to measure the temperature distributions inside the plug.

The next section is devoted to a brief theory of phase separation, and to the experimental setup is Section 3. Experimental results and discussions to clarify the actual flow through porous-plugs are presented in Section 4. In Section 5 thermodynamic state inside plugs is revealed from the results in the last section. Finally some conclusions are derived from this study in Section 6.

2. Theory of Phase Separation

2.1 Thermomechanical Effect

The phase separation for superfluid helium is achieved by the "thermomechanical effect", one of the peculiar properties of \(\text{He II}\). This effect is produced by temperature differences and makes the superfluid component of \(\text{He II}\) flow from a lower temperature part to a higher one. In an equilibrium state with some small temperature differences, \(\Delta T\), the following equation is quantitatively derived first by F. London [10];

\[
\Delta P = \rho S \Delta T,
\]

where \(\Delta P\) and \(\Delta T\) are the pressure and the temperature differences, respectively. The
density and the specific entropy are denoted by \( \rho \) and \( S \), respectively. Eq. (1) may be reduced, regarding \( \rho \) and \( S \) as constants when the temperature difference is small, to:

\[
P_2 - P_1 = \rho S(T_2 - T_1),
\]

(2)

Where subscripts 1 and 2 correspond to the higher and the lower temperature parts. This equation is so-called "London's relation", attained in an ideal situation of He II.

2.2 Theory of He II Phase Separation

Generally accepted for discussions of fluid dynamics of superfluid helium is "two-fluid model" derived by L. D. Landau [11]. He II is assumed as a mixture of two components, that is, the superfluid component and the normal fluid component. They are allowed to make two independent flows simultaneously. Subscripts \( s \) and \( n \) hereinafter denote the superfluid component and the normal, respectively. The equations of motion for each component are derived by R. J. Donnelly [12], ignoring small terms of second and higher order:

\[
\rho_n \frac{dv_n}{dt} = -\frac{\rho_n}{\rho} \nabla P - \rho S \nabla T + \eta_n \nabla^2 v_n,
\]

(3)

\[
\rho_s \frac{dv_s}{dt} = -\frac{\rho_s}{\rho} \nabla P + \rho S \nabla T,
\]

(4)

where \( v \) and \( \eta \) are the velocity and the viscosity, respectively. \( \nabla P \) and \( \nabla T \) denote the pressure gradient and the temperature gradient.

Eqs. (3) and (4) are reduced in the case of the steady flow to be

\[
\nabla P = \eta_n \nabla^2 v_n,
\]

(5)

where using \( \rho = \rho_n + \rho_s \). This means that the normal fluid component behaves as an ordinary viscous fluid.

The net mass flow rate through porous-plugs, \( \dot{M} \), is expressed as the sum of both flow rates of the two components:

\[
\dot{M} = \dot{M}_n + \dot{M}_s = \rho v A = (\rho_n v_n + \rho_s v_s) A,
\]

(6)

where \( A \) is the cross-sectional area of a porous-plug. The heat transfer rate through a porous-plug, \( Q \), is written by

\[
Q = \rho S T (v_n - v) A.
\]

(7)

This expresses that the entropy is transported only by the normal fluid component. This
heat is consumed upon vaporization of He II, if the thermal dissipation may be neglected:

$$Q = \lambda \dot{M},$$

where $\lambda$ denotes the latent heat of vaporization. Eliminating $Q$ from Eqs. (7) and (8),

$$\dot{M} = \frac{\rho S T}{\lambda} (v_n - v) A,$$

is derived. Substituting Eq. (6) into Eq. (9), and using Eq. (5), it finally reduces to

$$\dot{M} = -\frac{\rho S T}{\lambda + S T} \frac{AK}{\eta_n} \varphi P,$$

where $K$ is the permeability of a porous-plug. This formula predicts that the mass flow rate, $\dot{M}$, would be proportional to the pressure gradient, $\varphi P$. It should be emphasized that a formula corresponding to Eq. (10) for the normal fluid component as an ordinary viscous fluid is expressed as:

$$\dot{M}_n = -\frac{\rho_n AK}{\eta_n} \varphi P.$$

Consequently, it is seen that the net mass flow rate, $\dot{M}$, is reduced by a factor of $ST/(\lambda + S T)$ because of the reverse flow of the superfluid component. It must also be noted that above formula is derived under the assumption that the liquid-vapor boundary is located just at the downstream end of a porous-plug, though the boundary is experimentally found to be located inside a plug, not at the end, as mentioned later in detail.

3. Experiments

3.1 Experimental Setup

The schematic diagram of the experimental setup is shown in Fig. 1. The porous-plug is fixed at the bottom of the evacuation pipe which is connected to a rotary vacuum pump (1500 l/min.) to simulate the space. This pipe has a glass-made portion for visual observation of the flow state at the downstream end of the plug. The relative position of the plug to the liquid helium level was kept constant by adjusting the vertical height of the pipe. A control valve was employed to change the pressure difference across the plug.

The temperature of He II in the helium bath, $T_h$, was maintained at a constant with a pressure regulating valve installed between the helium bath and another rotary vacuum pump (300 l/min.) together with a heater in the bath during each run of experiment.

Pressures of the helium bath at the free surface, $P_o$, and the downstream side of the porous-plug, $P_r$, were measured with a capacitance-type high precision pressure
transducer. The temperature in the helium bath, $T_b$, was measured with a carbon resistance thermometer, and that of the downstream side of the plug, $T_r$, with a germanium resistance thermometer. Each thermometer was excited by 1 $\mu$A DC current. The mass flow rate of helium vapor, $\dot{M}$, was converted from the volume flow rate measured with a rotating flowmeter at the exhaust of the vacuum pump.

3.2 Porous-Plugs

In order to insert two extra thermometers inside porous-plugs (as illustrated in Fig. 2), compressed alumina ($Al_2O_3$) seems to be most suitable among a wide range of porous media with low thermal conductivity. These thermometers are employed to measure the temperature distributions inside plugs, which are expected to reveal the actual flow characteristics of $He$ II and its vapor through plugs.

Three porous-plugs including thermometers inside them were tested, whose basic parameters are compiled in Table 1. PP No. 1 has larger cross-sectional area and permeability than those of other two. Though PP No. 2 and No. 3 have approximately the same cross-sectional areas and permeabilities, positions of thermometers inside them are different, that is, PP No. 2 has thermometers in an upstream half of it, while PP No. 3 has in a downstream half. All the thermometers inside plugs are carbon resistance thermometers same as that in the helium bath.
Table 1. Basic parameters of porous-plugs. Positions, $x_1$ and $x_2$, are measured from the upstream end of each porous-plug.

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area $A$ ($\times 10^{-4}$m$^2$)</td>
<td>2.01</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>Permeability $K$ ($\times 10^{-12}$ m$^2$)</td>
<td>15.9</td>
<td>1.96</td>
<td>1.91</td>
</tr>
<tr>
<td>Thickness $t$ ($\times 10^{-3}$m)</td>
<td>10</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Porosity $\varepsilon$</td>
<td>0.375</td>
<td>0.375</td>
<td>0.375</td>
</tr>
<tr>
<td>Position of $T_1$ $x_1$ ($\times 10^{-3}$m)</td>
<td>3.3</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Position of $T_2$ $x_2$ ($\times 10^{-3}$m)</td>
<td>6.6</td>
<td>8</td>
<td>13</td>
</tr>
</tbody>
</table>

3.3 Experiments

A series of experiments was conducted as follows. The temperature of He II in the helium bath, $T_b$, was fixed at a specified one below $T_s$ ($=2.172$ K) by means of the pressure regulating valve and the heater. Each measurement was carried out after the whole system reached a steady state with a certain pressure difference across the plug. Then the two pressures, $P_O$ and $P_P$, the four temperatures, $T_b$, $T_1$, $T_2$, and $T_F$, and the mass flow rate of helium vapor, $\dot{M}$, shown in Fig. 3, were measured. These measurements were repeated at various pressure differences across the plug while keeping $P_O$ and thus $T_b$ constant.

Measured data sets were recorded on cassette magnetic tapes through the microcomputer for further data analyses.
4. Flow Characteristics

4.1 General Flow Feature

The flow characteristics of He II through porous-plugs have been already investigated experimentally [7]. Some typical examples of the relation between the pressure gradient $\nabla P$ and the mass flow rate $\dot{M}$ are presented in Fig. 4 at various $T_0$, where $\nabla P$ is defined by

$$\nabla P = \frac{P_0 - P_P}{t},$$

and $t$ is the thickness of the porous-plug. A hysteresis in this relation is easily found as $\nabla P$ increases and decreases. Each data set at a certain $T_0$ is regarded to consist of three distinct portions according to the magnitude of $\nabla P$. First one is so-called ‘‘creep flow’’ region, where the mass flow rate increases even though there exists little pressure gradient. This flow is exerted only by the superfluid component which is driven by the thermomechanical effect due to parasitic heat into the downstream side. The maximum mass flow rate in this region, $\dot{M}_g$, will be referred to in the following discussion. Next one is on the upper branch where $\dot{M}$ increases non-linearly with $\nabla P$, and the third is on
the lower, where $\dot{M}$ seems to be proportional to $\nabla P$. The upper branch appears while increasing $\nabla P$, and the lower while decreasing $\nabla P$. These features are not expected from the theory. Eq. (10), which just predicts a linear relation between $\dot{M}$ and $\nabla P$. A comparison of the results for the lower branch with Eq. (10) is made in Fig. 5. Fairly large discrepancy is seen, though it seems to become small at lower $T_B$.

Fig. 6 shows some examples of the relation between the mass flow rate, $\dot{M}$, and the temperature gradient, $\nabla T$, defined by

$$\nabla T = \frac{T_B - T_P}{t},$$

(13)

in the same experimental condition as given in Fig. 4. It is easily seen that this relation also has the hysteresis feature. Some data sets at higher $T_B$ above 2.00 K seem, however, to have a different tendency, which is considered to be resulted from the change of the flow state.

Another data plot is presented in Fig. 7 in which $\nabla T$ is plotted against $\nabla P$. This data relation may be compared with London’s relation indicated by a solid line in the figure. Experimental results are found to have much larger slope than the prediction by London’s relation by almost one order of magnitude.

Such dynamic and thermal behaviors which are not explained by the simple theory and the large deviation from London’s relation request some physical reconsideration of actual phenomena inside the porous-plug. It is assumed in the theory that the phase boundary is located just at the downstream end of the plug. But it seems to be most
Fig. 5. Comparison of experimental data with theory in linear region, from Ref. [7].

Fig. 6. Typical example of thermal behavior, $\dot{M}$ vs. $\nabla T$, from Ref. [7].
plausible that the phase boundary moves with the variations of certain physical conditions.

4.2 Temperature Distributions inside Porous-Plugs

Measurements of temperature distributions were attempted to examine experimentally the position of the liquid-vapor boundary inside the porous-plug. It is of course natural that the temperature distributions are affected by the change of the mass flow rate. Shown in Fig. 8 are temperature distributions inside a plug, PP No. 3, as a function of the mass flow rate at three different $T_B$. The position axis in the figure indicates positions of four thermometers measured from the upstream end of the plug. It is observed in these figures that the temperature drops linearly by a few mK in the upstream portion of the plug, $T_B$-$T_1$. At lower $T_B$ such linear temperature drop is seen in the most portion of the upstream side. A large temperature drop up to a few hundred mK occurs in rather thin layer at the downstream end of the plug, $T_2$-$T_B$. It is also seen that the middle portion of the plug, $T_1$-$T_2$, at higher $T_B$ experienced a small temperature drop when the mass flow rate was small, while as the mass flow rate increased the temperature drop became large. The same feature is seen in PP No. 2 data presented in Fig. 9.

These variations of temperature drops are also presented in the form of full-logarithmic plotting in Fig. 10. The mass flow rate is given in $\dot{M} - \dot{M}_0$, where $\dot{M}_0$ which is defined in the last section is physically insignificant and may be subtracted from the mass flow rate $\dot{M}$. It is evident in this figure that the temperature drop in the upstream portion, $T_B$-$T_1$, seems to be proportional to the mass flow rate and to obey London's relation, Eq.
(2).

Now the mass flow rate is expressed as a function of the 'local' temperature gradient, $\nabla T$, by substituting Eq. (2) into Eq. (10) as:

$$\dot{M} = \frac{(\rho S)^T}{\lambda + ST} \cdot \frac{AK}{\eta_n} \nabla T,$$

(14)

where 'local' $\nabla T$ is presented in the form of
Fig. 8. Temperature distributions inside PP No. 3, varied with $\dot{M}$ at various $T_B$: (a) $T_B=2.043\, K$, (b) $T_B=1.999\, K$, (c) $T_B=1.696\, K$.

\[ \nabla T = \frac{\Delta T}{l}, \]  

(15)

and $\Delta T$ is the temperature drop in each layer of the plug, and $l$ the thickness of it. It should be noted that $\Delta T$ is different from $T_B - T_P$ as defined in the previous experiments [7]. Eq. (14) is indicated by a solid line only for the upstream portion, $T_B - T_i$, in this figure.
4.3 Ideal Flow of Superfluid Helium

For the case of a linear temperature drop by a few mK London’s relation is valid. This suggests that an ideal flow of superfluid helium is realized in the upstream portion of the porous-plug. A more detailed comparison of experimental data with Eq. (14) is presented at a lower $T_R$ in Fig. 11. It is clearly shown in this figure that such ideal flow actually occurs in the upstream portion of the plug and that even in the middle portion $He$ II flows ideally. The temperature difference in the downstream portion, $T_2-T_F$, is far
Fig. 11. Temperature differences in each layer compared with theory for each layer (lines in the figure).

Fig. 12. Comparison of experimental data with theory of ideal flow of He II at various $T_0$. 
beyond the scale, though only a few data points for small $\dot{M} - \dot{M}_0$ are given here. Such comparisons of experimental results with the predictions are made at various $T_0$ with all plugs, and the results are shown in Fig. 12, where the slopes $(\dot{M} - \dot{M}_0)/AKFT$ are plotted against $T_0$. It should be mentioned that data points are plotted in the figure when they are well defined to show an ideal flow.

It is concluded from these facts that the ideal flow of He II in which London's relation is held is found in the upstream portion and also in the middle portion under some condition.

On the other hand, the normal component flow is expected to be laminar provided the bulk He II flow remains ideal. A flow of the normal fluid component can be considered by an analogy with an ordinary viscous fluid. The mass flow rate of the normal component, $\dot{M}_n$, is converted from $\dot{M}$ as:

$$\dot{M}_n = \frac{\rho_n v_n A}{\rho} \cdot \frac{\lambda + ST}{ST} \dot{M}.$$  \hspace{1cm} (16)

The permeability, $K$, is expressed in the case of a viscous flow through porous media by [13]:

$$K = \frac{D_p \rho \varepsilon^3}{150(1 - \varepsilon)^2},$$ \hspace{1cm} (17)

were $D_p$ is the mean particle diameter, and $\varepsilon$ the porosity of the medium.

The Reynolds number, $Re$, is defined for such flows by

$$Re = \frac{D_p G \varepsilon}{\eta_n} \cdot \frac{1}{1 - \varepsilon},$$ \hspace{1cm} (18)

where $G$ is given for the normal component flow as;

$$G = \frac{\dot{M}_n}{A}.$$ \hspace{1cm} (19)

The Reynolds number for the flow of the normal fluid component of He II through porous-plug is evaluated by

$$Re = \frac{1}{\eta_n} \cdot \frac{\dot{M}_n}{A} \sqrt{\frac{150}{\varepsilon}}.$$ \hspace{1cm} (20)

The friction coefficient, $F$, is defined by

$$F = \frac{\rho D_p}{G_0} \cdot \frac{\varepsilon^3}{1 - \varepsilon} \cdot \nabla P,$$ \hspace{1cm} (21)
For the normal component flow it is converted, using Eqs. (2), (17) and (19), to

\[ F = \left( \frac{A}{M_n} \right)^2 \rho_n \sqrt{150e^3} \rho ST. \]  

(22)

As Eqs. (20) and (22) are consisted of experimentally measurable quantities and some constants, their relation can be experimentally examined. Logarithmic plots of the friction coefficient, \( F \), against the Reynolds number, \( Re \), for various cases are found in Fig. 13. The solid line is derived from the Blake-Kozeny equation as

\[ F = \frac{150}{Re}, \]  

(23)

which is an empirical equation for cases of laminar flows through porous media. The comparison of experimental data with this equation shows that the flow of the normal fluid component remains laminar rather than turbulent in any experimental conditions. The friction coefficient, \( F \), would be constant independent of \( Re \), if the flow were turbulent. It is physically quite reasonable that the flow of the normal component is laminar in the present situation.

It is now clear as a consequence of above discussions that the ideal flow of bulk \( He \) II occurs in the upstream portion of the porous-plug and the normal fluid component flow is laminar.

4.4 Vapor Flow

It is quite natural to regard that the large temperature drop in the downstream portion of porous-plugs results from the vapor flow. The reason is that there exist significant
discrepancies as seen in Figs. 5 and 7, even though the flow in the upstream portion of the plug remains ideal.

Another series of experiments was attempted to check the above tentative inference. Measurements of temperature distributions were made at such particular situations of porous-plug flows as in the bulk leaking state, in the dryout state and in the vapor state. The position of the liquid-vapor phase boundary inside plugs was forced to shift under these situations, while the other conditions were kept unchanged. The experimental procedure was all the same as that in the usual measurements. Firstly, the porous-plug assembly was entirely immersed in He II so as to be the bulk leaking state. The dryout state is created just in the same manner as in the normal operations of the porous-plug. The hydrostatic pressure, $\Delta P_h$, defined by

$$
\Delta P_h = \rho gh,
$$

(24)
as illustrated in Fig. 14, was altered by shifting the relative position of the plug to the free surface of He II. The porous-plug was located above the free surface in the vapor phase measurement. Results are shown in Fig. 15.

In the case of bulk leak, a uniform temperature distribution inside the plug is seen. This indicates that the plug is not activated in the state. The liquid-vapor boundary gradually goes from the downstream end of the porous-plug toward the upstream side as the hydrostatic pressure, $\Delta P_h$, decreases. It is concluded from the results in the dryout state and in the vapor state seen in the figure that the temperature drop steeply increases when the phase boundary passes through the measuring point. The vapor flow causes the large temperature and pressure drops.

The shift of the phase boundary toward the upstream side was checked by computing numerically the location of the boundary. The usual Darcy's law can be applied in the vapor phase inside plugs as expressed by

$$
\dot{M} = \frac{\rho_v A K}{\eta_v} \frac{\Delta P_v}{l_v},
$$

(25)

\[\text{Fig. 14. Liquid-vapor phase boundary inside the porous-plug.}\]
where the vapor phase is denoted by the subscript \( v \), \( l_v \) is the thickness of the vapor phase and \( \Delta P_v \) the pressure difference across it. The numerical values of \( \eta_v \) are cited from Ref. [14]. The pressure at the liquid-vapor boundary inside the plug may be approximated by the saturated vapor pressure at \( T_B \) with an error of a few mK because of a very small temperature drop in the liquid phase of a plug. Then, the thickness of the vapor phase is computed as follows:

\[
l_v = \frac{\rho_v}{\eta_v} \cdot \frac{AK}{M} (P_{sat} - P_F),
\]

where \( P_{sat} \) is the saturated vapor pressure at \( T_B \). This can be evaluated in terms of measured data. Numerical results are presented in Figs. 16a and b, where \( (\rho_v, \eta_v) \) are evaluated at the mean temperature, \( (T_B + T_F)/2 \). A hysteresis feature is obviously seen at higher temperature \( T_B \) as given in Fig. 16a. It is also seen that the vapor layer is thin when \( T_B \) is low and that at higher \( T_B \) the thickness is large. In Fig. 17 computed position of the phase boundary at each \( T_B \) is presented with the temperature distribution against the mass flow rate. They both qualitatively and quantitatively agree with each other, except a small discrepancy in Fig. 17a.
Fig. 16. Numerical calculations of liquid helium level inside the porous-plug; (a) $T_B = 2.043 \, K$, (b) $T_B = 1.696 \, K$. 

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5. THERMODYNAMIC CONSIDERATION OF POROUS-PLUG PHASE SEPARATION

The state at the free surface is indicated by the point \( a \) on the saturated vapor curve (Fig. 18), at which the pressure and the temperature are \( P_o \) and \( T_o \), respectively. The state at the upstream end is characterized by \( P_h \) and \( T_h \). The temperature \( T_h \) is almost uniform all over the superfluid helium owing to its thermal superconductivity. The pressure \( P_h \) is given in terms of the hydrostatic pressure \( \Delta P_h \) as
Fig. 18. Schematic illustration of thermodynamic states inside the porous-plug.

\[ P_B = P_0 + \Delta P_H. \]  

(27)

This state is indicated by the point b off the saturation curve. The thermodynamic state changes ideally in the liquid phase inside the plug. Point c, the state at the liquid-vapor boundary, \( P_l \) and \( T_l \), is determined by London's relation, Eq. (2). Variation of the state from b to c is entirely determined by London's relation. The pressure at the downstream end of the plug, \( P_P \), is completely determined by such external conditions as the capacity of the vacuum pump and the conductance of the evacuation line. It is not yet evident how the thermodynamic state changes in the vapor phase. Trial computations under the assumption of the isentropic change show a little larger temperature drops than those obtained experimentally. This means that the experimental condition can not be of course completely adiabatic, and the temperature drop in the vapor phase decreases.

It is also found here that the necessary condition for the phase separation in porous-plugs without bulk leakage is

\[ P_P \leq P_l. \]  

(28)

The pressure at the downstream side should be lower than \( P_l \) determined by London's relation which is lower than \( P_0 \).

6. CONCLUDING REMARKS

Flow characteristics of \( He \) II and its vapor through porous-plugs, and the thermodynamic states inside the plug are well understood in this investigation. They are concluded as follows:

(1) Superfluid helium flows ideally and London's relation is valid in the flow through the upstream portion of a plug. The flow of the normal fluid component remains laminar at any experimental conditions.
(2) The liquid-vapor phase boundary moves toward the upstream end as the mass flow rate increases.
(3) Large temperature drops and thus large pressure drops are caused by the vapor flow inside plugs.
(4) One of necessary conditions for accomplishment of complete phase separation is $P_r \leq P_1$.

It should be noted that these conclusions are deduced in the normal operation of the porous-plug, namely, no bulk He II appears at the downstream end of the plug.

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