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STUDIES OF HEAT TRANSPORT TO FORCED-FLOW HE II*

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ABSTRACT

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Analytical and experimental studies of heat transport to forced-flow He II ~~II~~ are reported. The work is pertinent to the transfer of He II in space. An analytical model has been developed ~~which~~ that establishes a condition for two-phase flow to occur in the transfer line. This condition sets an allowable limit to the heat leak into the transfer line. Experimental measurements of pressure drop and flow meter performances indicate that turbulent He II can be analyzed in terms of classical pressure drop correlations.

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INTRODUCTION

Infrared astronomy in space has become one of the newest applications for He II cryogenics.[1] To date most of the systems designed and tested have relied on the batch process for cooling, where liquid helium is transferred before launch. In orbit, the He II is controlled by using a phase separator consisting of either a porous plug[2] or an actively controlled valve.[3] This technology has received considerable interest and remains an area of active research. Unfortunately, the batch process limits the usable life of ~~the~~ a telescope to about six months, depending on heat loads and on-board inventory.

Because of the finite limitation of batch-cooled systems, there has been a growing interest in developing the technology of He II transfer in space. However, ~~there are~~ a number of problems ~~which~~ must be resolved before this technology can be applied. Included among these problems are: (1) ~~selection of~~ selecting the best method for circulating the He II, ~~i.e.,~~ that is, which type of pumping device; (2) establishing tractable methods for making transfer connections; and

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(3) being able to meter the flow between containers so that the volume transferred can be determined. Proper design calculations related to helium transfer require confidence in the relevant He II fluid dynamics.

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The present paper focuses on two problems relevant to the transfer of He II ~~II~~ in spaceborne cryogenic systems. These are: the analysis of heat leak limitations during He II transfer and a description of current ongoing experiments on heat transport in forced-flow He II.

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HEAT LEAK LIMITATIONS WITH HE II TRANSFER

We consider the problems associated with transfer of He II between two dewars connected by a transfer line. A schematic representation of the physical system is shown in Fig. 1. ~~There exist~~ two helium dewars contain~~ing~~s essentially saturated He II. Fluid is transported from the supply dewar A to the receiving dewar B by means of a low-temperature pump. The head produced by the pump exactly balances the pressure drop in the transfer line. During operation, the transfer line suffers a uniform heat leak Q (W/cm^3 of helium within the transfer line) along its length and a local heat Q_0 (W/cm^2 of helium cross section) at a quick-disconnect fitting near the downstream dewar. Owing to these heat leaks, the local temperature T of the helium in the line exceeds the common saturation temperature T_0 of the two dewars. Because the helium in the transfer line has a higher pressure than the helium in the dewars, it will not vaporize if $(T - T_0)$ is small enough. It is assumed that vaporization of He II and associated two-phase flow is to be avoided.

To formulate the conditions under which the helium does not vaporize anywhere along the transfer line, consider the locus C of its thermodynamic states during transfer (see Fig. 2). This locus represents an idealized case in which the helium leaving the supply dewar, i.e., at the pump exit, is at the same temperature as the helium being delivered to the receiving dewar. In practice, this condition could be obtained by placing a heat exchanger at the pump exit. A further assumption is ~~made~~ that the thermal path back to the supply dewar is not substantially interrupted by the existence of the pump. These assumptions have been necessary in order to formulate an analytic solution; ~~where~~ complex boundary conditions would probably require numerical simulation.

The locus C lies entirely within the liquid region of the phase diagram if its slope at point B, $(dP/dT)_B$, exceeds the slope $(dP/dT)_{sat}$ of the saturation curve at the same point. Now $(dP/dT)_B = (dP/dx)/(dT/dx)_L$, where dP/dx is the uniform pressure gradient in the transfer tube and $(dT/dx)_L$ is the temperature gradient at x = L, the downstream end of the transfer tube. So the condition that prevents the helium from ~~not~~ vaporiz~~e~~ing in the transfer tube is $|dT/dx|_L < |dP/dx|/(dP/dT)_{sat}$.

The temperature T(x) along the transfer tube, from which the temperature gradient $(dT/dx)_L$ can be calculated, satisfies the one-dimensional heat balance equation,[4] < R4

$$\rho v C_p \frac{dT}{dx} - \frac{d}{dx}\left(\frac{1}{f}\frac{dT}{dx}\right)^{1/3} = Q + \underset{\text{zero}}{Q_0}\,\delta(x - \ell) \qquad (1)$$

where δ is the Dirac delta function, v is the flow velocity of the helium in the transfer tube, the volumetric heat capacity of the helium is ρC_p, and $f^{-1/3}$ is the Gorter-Mellink conductance parameter. We seek the solution of ~~equation~~ (1) that obeys the boundary conditions $T = \underset{\text{zero}}{T_0}$ at x = 0 and x = L and for which T is continuous at $x = \ell$, the position of the quick-disconnect fitting.

The solution to ~~equation~~ (1), though straightforward, is complicated, requiring graphical iterative analysis. Accordingly, it is difficult to use it to understand how the largest allowable Q and Q_0 depend on the other parameters of the problem. However, the theory yields a useful bound on the allowable heat leaks Q and Q_0 in which the dependence on the other physical parameters is comparatively transparent:

$$Q + \frac{Q_0}{L} < \left(\frac{\Delta P}{f}\right)^{1/3} L^{-4/3} \left(\left(\frac{dP}{dT}\right)_{sat}^{-1/3} + \frac{1}{L}\left(\frac{Q}{\rho v C_p f}\right)^{1/3}\right) \qquad (2)$$

This bound should be close to an equality when the dimensionless quantity $L^* = (L + Q_0/Q)(f\rho v C_p Q^2)^{1/3}$ is somewhat greater than one. An interesting feature of the bound equation (2) is that it is independent of ℓ, the coordinate of the quick-disconnect fitting.

Calculation of the pressure drop in the transfer line requires some assumptions about the behavior of flowing He II. At present there is only limited understanding of this problem, and further work is in progress. For the purposes of the present calculation, we assume that the pressure drop can be obtained from the classical turbulent flow equation,

$$\Delta P = 2 f \rho v^2 \left(\frac{L}{D}\right) \qquad (3)$$

where f, the Fanning friction factor, is related to the Reynolds number, Re, according to the Blasius equation $f = 0.079 (Re)^{-1/4}$. Such an analysis is qualitatively consistent with He II pressure drop measurements in capillary tubing reported by Johnson and Jones.[5]

Let us consider an example: T_0 = 1.5 K, L = 10 m, tube diameter D = 1 cm, ~~cm,~~ transfer rate = 300 ~~ℓ~~ L/h~~r~~. The slope of the saturation line at 1.5 K is 0.0227 bar/K, the Gorter-Mellink conductance parameter $f^{-1/3}$ = ~~5.15~~ 5.15 $W \cdot cm^{-5/3} \cdot K^{-1/3}$, and the volumetric heat capacity ρC_p = 0.163 $J \cdot cm^{-3} \cdot K^{-1}$. The transfer rate of 300 ~~ℓ~~ L/h~~r~~ corresponds to a pressure drop of 7.98 mbar. When Q_0 = 0, an iterative solution of ~~equation~~ (2) gives Q = 0.523 mW/cm^3, which must be an upper bound for the allowable value of Q. [It is in fact very close to the exact value calculated by solving ~~equation~~ (1)]. If Q is as low as 0.1 mW/cm^3, then, according to ~~equation~~ (2), the allowable heat leak at the quick-disconnect fitting must be less than 0.355 W/cm^2 [which is also very close to the limit calculated by solving ~~equation~~ (1)]. Since the diameter of the tube is 1 cm, Q = 0.523 mW/cm^3 corresponds to a total uniform heat leak of 411 mW, Q = 0.1 mW/cm^3 corresponds to a total uniform heat leak of 79 mW, and Q_0 = 0.355 W/cm^2 corresponds to a local heat source of 279 mW.

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~~The above~~ This calculation points out one difficulty with transfer of saturated He II in space: that of the local vaporization of the helium within the transfer line. Obviously, it is desirable to have a very efficient transfer line. One could possibly circumvent this problem of two-phase flow within the transfer line by placing a valve at the exit, which would provide some additional pressure drop. The fluid in the line would be subcooled, permitting larger temperature excursions without intersecting the phase boundary. At the valve exit, the two phases could be effectively separated in the receiving dewar. This procedure would effectively raise the inlet and outlet pressures by ΔP_v, the amount of additional pressure drop introduced by the valve.

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EXPERIMENTAL STUDIES OF FORCED-FLOW HE II

The underlying assumptions of the preceding ~~above~~ analysis, as well as other concerns about the limitations to He II mass transport, have suggested the need to conduct further experiments. Reported herein are preliminary results from a series of experiments begun at Wisconsin and aimed at furthering our understanding of He II transfer.

We have begun an experiment to study pressure drop and heat transport in flowing He II.[6] The experiment involves both the development of a low-temperature, single-stroke hydraulic pump and measurements on an optimized flow loop. The pump is designed to produce a steady flow rate for a finite period of time. To achieve this condition, two identical stainless steel bellows are coupled to either end of the flow tube. The bellows are set into vertical motion by means of a rack and pinion system connected to a stepped-down DC motor that ~~which~~ provides a range of flow rates. The capacity of the pump is limited by the volume displacement of the bellows, which is 350 cm^3.

The flow tube is designed to allow observation of both the regions dominated by internal convection and those controlled by forced convection. A 2-m-long tube with an inside diameter of 3 mm ~~ID and 2 m in length~~ is wound into a 12-cm-diam~~eter~~ coil. A heater is located at the midpoint, and thermometers are positioned at seven equally spaced locations along the tube length. Also, a turbine flow meter (Sponsler Company) is located in the flow circuit to measure the volumetric flow rate. This measurement is compared to the calculated flow rate as determined by the displacement of the bellows. The absolute pressure is measured at both ~~either~~ ends of the flow circuit using low-temperature pressure transducers (Siemens model KPY-13).

Because of space limitations we consider only the pressure drop and flow rate measurements under isothermal conditions. Plotted in Fig. 3 are pressure drop measurements as compared to the flow rate determined from the bellows displacement speed. This set of data was obtained at near-saturated conditions where the flow tube exit was subcooled only by the hydrostatic head. For v > 20 cm/sec, the pressure drop is well behaved, showing qualitative agreement with the classical turbulent flow expression~~, equation~~ (3). The friction factor f determined from these data is between 0.007 and 0.009, which is about a factor of two larger than that obtained from the Blasius correlation. Also shown in Fig. 3 is the output from the turbine flow meter as it depends on volume displacement. The meter only operated above a minimum flow rate about 1 cm^3/sec, which is apparently common behavior for this kind of device. It also displayed some nonlinearity in its flow rate dependence. Further information concerning this experiment is available in reference ~~ref.~~ 6.

CONCLUSIONS

Based on our present understanding of He II hydrodynamics, we have been able to establish a condition for avoidance of two-phase flow during transfer in a zero-g environment. This condition emphasizes the need for a thermally efficient transfer line. Detailed design will require more numerical analysis. If two-phase flow is unavoidable, it would be possible to have it occur in the receiving dewar by proper location of a Joule-Thompson valve. Thomson

Experiments underway at Wisconsin have supported the assumptions leading to this analysis. Further work is needed to more fully characterize the relevant fluid dynamics issues.

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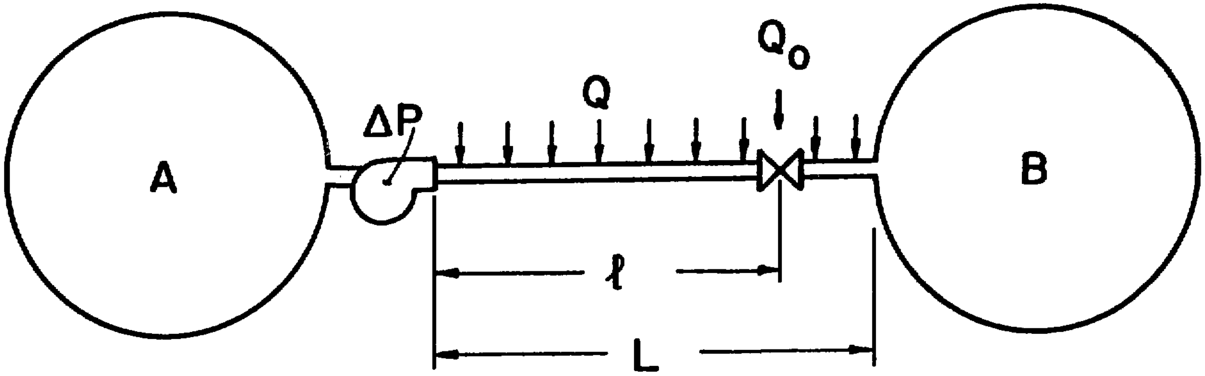
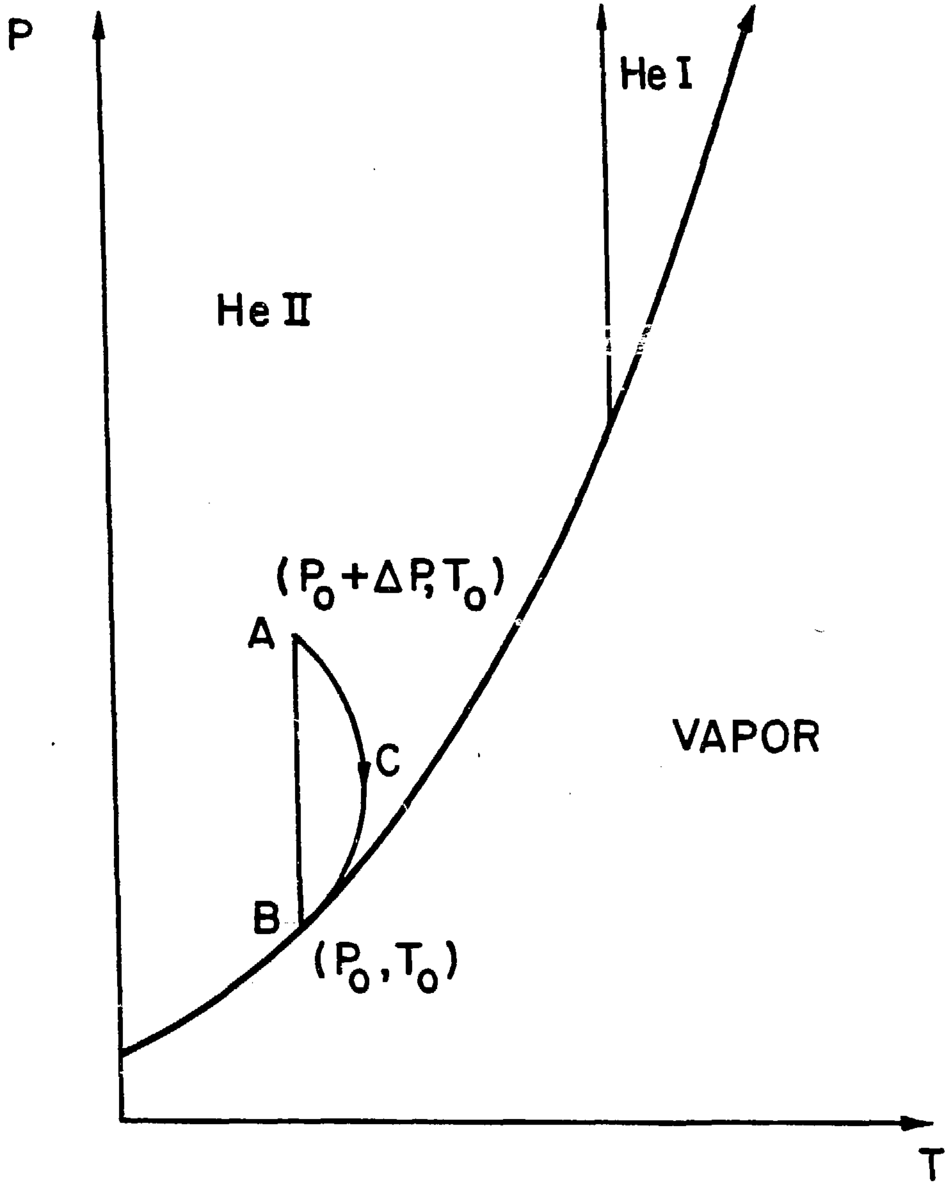
FIGURE CAPTIONS

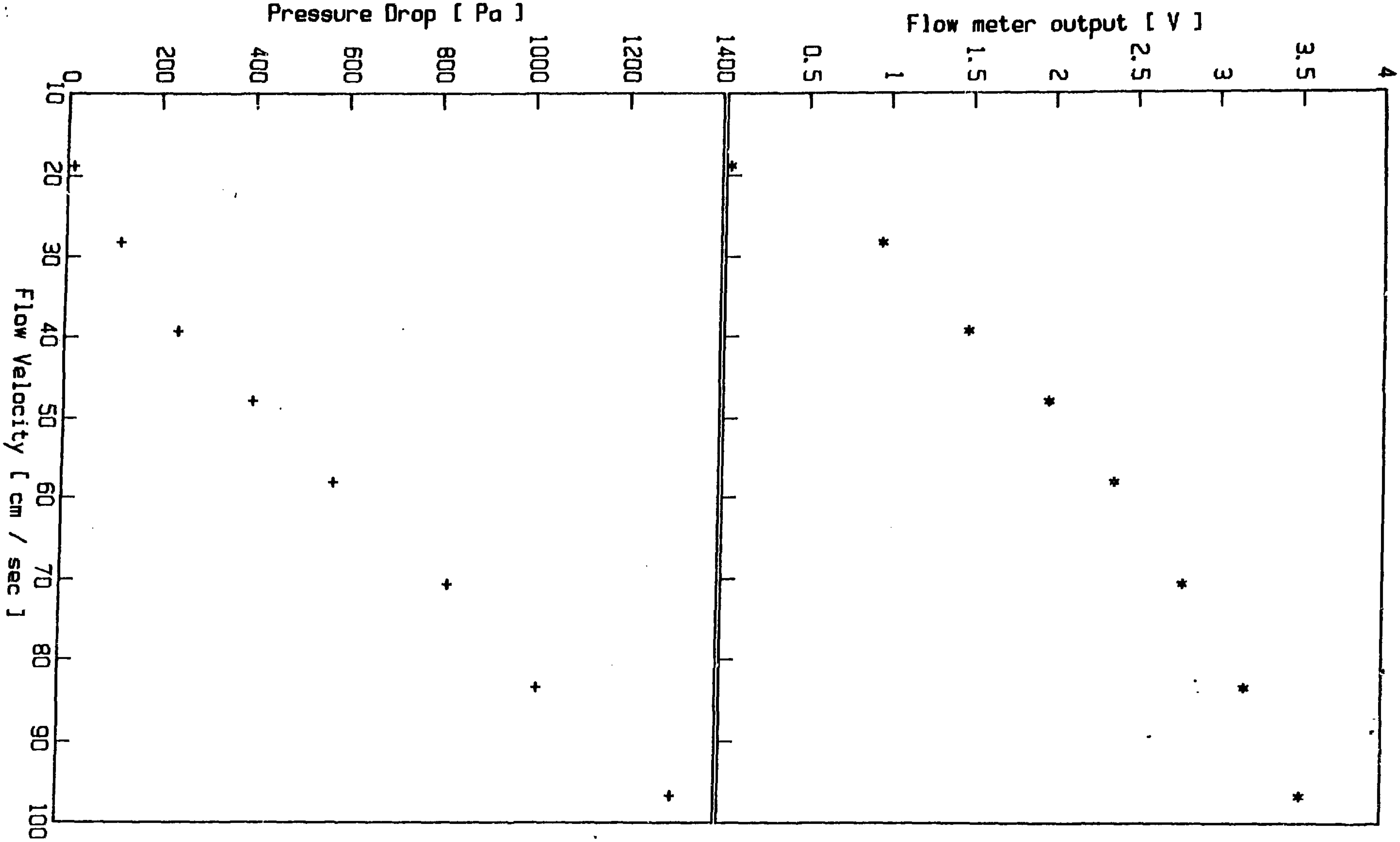
Fig~~ure~~ 1. Schematic representation of He II transfer process.

Fig~~ure~~ 2. Helium phase diagram displaying locus of thermodynamic path during He II transfer.

Fig~~ure~~ 3. Pressure drop and flow meter output during isothermal He II transfer at 1.8 K.


Q_o
ΔP
Q
A
B
ℓ
L


P
He I
He II
$(P_0+\Delta P, T_0)$
A
C
VAPOR
B
(P_0, T_0)
T


Pressure Drop [Pa]
0
200
400
600
800
1000
1200
1400
Flow meter output [V]
0.5
1
1.5
2
2.5
3
3.5
4
Flow Velocity [cm / sec]
10
20
30
40
50
60
70
80
90
100