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Continuously Operating ^{4}He Evaporation Refrigerator*

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A simple and compact device was developed to provide continuous, self-regulating refrigeration at approximately 1.3 K. The temperature of the device remains nearly constant, independent of external power, up to a critical power. For a molar flow rate of 10^{-4} moles/sec, the refrigerator can absorb 4.5 mW. Such a refrigerator should be suitable for condensing ^{3}He in a ^{3}He–^{4}He dilution refrigerator.

INTRODUCTION

A NUMBER of continuously operating ^{4}He evaporation refrigerators have been described in the literature[1,2] in which liquid ^{4}He is admitted into a pumped space from a bath at atmospheric pressure, usually through a needle valve. The properties of such refrigerators depend critically on the effectiveness and quality of the needle valve and on the degree of its thermal isolation from the helium bath at 4.2 K.

The present device, which has no valves or moving parts, was developed for the purpose of providing a continuously refrigerated region at a temperature of about 1.3 K for application to a ^{3}He–^{4}He dilution refrigerator. However, it should be applicable to a rather wide variety of experimental problems in which temperatures below the λ point of liquid ^{4}He need be maintained rather constant *in the presence of a variable heat load* for long periods of time.

We assume that a bath of liquid ^{4}He is present, that it is maintained at atmospheric pressure, and that it can be refilled from time to time as necessary. In a standard dilution refrigerator of our design[3] this bath is used to fill, by means of a valve in the ^{4}He bath and a capillary tube, a volume of several hundred cubic centimeters suspended in a vacuum space. This volume, commonly called the ^{4}He pot, is then pumped to achieve temperatures near 1 K which serve to condense ^{3}He for the refrigerator operation and to provide thermal shielding for the colder parts of the apparatus. The volume of the pot is chosen so that it need be filled at minimum intervals of 24 h. The capillary is chosen so that the temperature rise on filling is not sufficient to disturb the equilibrium within the mixing chamber of the refrigerator. Aside from the nuisance of filling the pot and possible perturbations to the dilution refrigerator operation, the pot is a problem from a design standpoint since it requires considerable space, frequently 10 cm or more of vertical height in the cryostat.

The intermittently filled large ^{4}He pot can be eliminated using the simple scheme shown schematically in Fig. 1, in which the volume of evaporating ^{4}He required is only several cubic centimeters. Only the capillary is difficult to design, and here we rely on empirical data. The system also has the important property that when it is pumped at a constant molar flow rate it will maintain a rather constant temperature as a function of power dissipated in the evaporator, from zero up to some critical power.

Referring to Fig. 1 the principles of operation of the device are as follows. When liquid ^{4}He is introduced from the bath at 4.2 K into the evaporator operating near 1 K the resultant heat load is less than half the refrigeration[4] available from the latent heat of evaporation. Thus if the evaporator is initially empty and if there is no external heat load the evaporator will begin to fill. Filling will continue until the level of liquid has risen so high in the pumping line that the rate of introduction of heat by conduction from the main bath compensates for the extra refrigeration available from the latent heat. Even though the liquid level is far up the pumping line the evaporator temperature will be low as a result of the high thermal convection in the superfluid. We note in passing that the details of where the level actually is and how the heat is transferred from the main bath into the pumped liquid are not important. Although a steady state should be obtained, it may be possible that for sufficiently high throughputs there will be instabilities in the rate of evaporation and hence of the temperature. If now an external heat source is applied to the evaporator, e.g.,

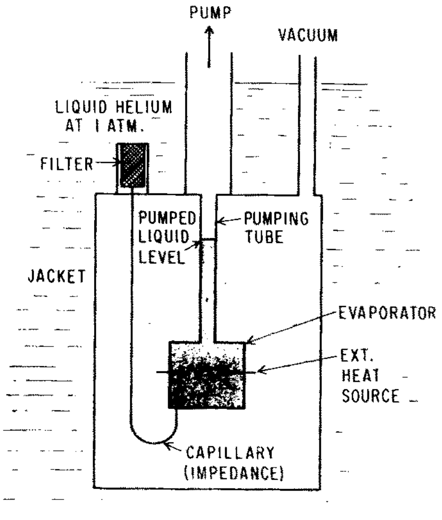

Fig. 1. Schematic drawing of continuously operating ^{4}He refrigerator.

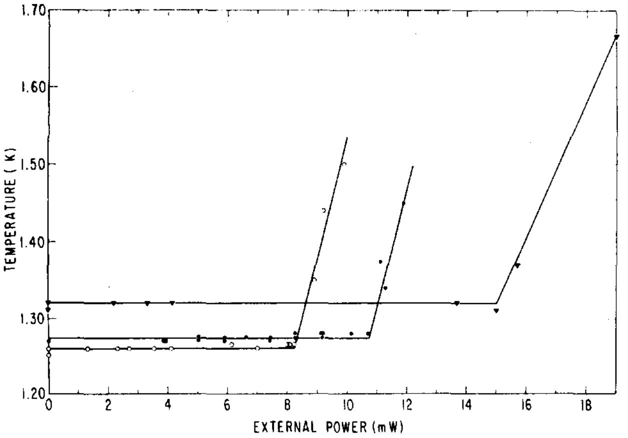

FIG. 2. Temperature of refrigerator as a function of external power for three different impedances. The sudden rise in temperature occurs at the critical power. ▼—$z=0.67\times10^{12}$ cm^{-3}; ●—$z=1.26\times10^{12}$ cm^{-3}; ○—$z=2.00\times10^{12}$ cm^{-3}.

condensation of ^{3}He in a dilution refrigerator, then the rate of evaporation will temporarily increase over the rate at which helium enters through the capillary and the liquid level will drop, thereby reducing the rate of heating of the pumped liquid by the main bath. At equilibrium the pumped liquid level will be lower, the heating of the liquid by the bath will thereby be reduced by an amount equal to the external heating rate, and the liquid will be at essentially the same temperature as before. External heating can be increased until one reaches a critical power. At this power the helium level will be down in the evaporator and the heating by conduction from the main bath will be relatively small. Further increases in the external heating rate lead to a steady change in evaporator temperature until all liquid is evaporated, at which time the evaporator temperature will increase rapidly to some higher equilibrium temperature.

I. DESIGN

The two primary qualities characteristic of the system are the equilibrium temperature of the evaporator shell and the maximum refrigeration capability. A secondary quality is the ability of the refrigerator to withstand short term overloads. This is connected with the volume of the evaporator.

As indicated above the refrigeration available in steady state operation is about half the latent heat of evaporation of liquid ^{4}He at the evaporator temperature. This is verified by our experiments, to be discussed in a later paragraph. The critical power per unit flow rate is approximately 4.5 mW/10^{-4} mole/sec. The required flow rate may be determined using this figure. For a given flow rate the evaporator temperature is determined by the pumping speed. For our application we can obtain suitable results with a mechanical pump of moderate size. The pressure drop in the lines required to drive the flow can readily be made of the same size or smaller than the vapor pressure over the evaporator. Hence the vapor pressure P, the pump speed $\dot V$, and the molar flow rate $\dot n$ are related, at least approximately in practice, by the equation

$$P\approx 0.19\ \text{Torr}\left(\frac{\dot n}{10^{-4}\ \text{moles/sec}}\right)\left(\frac{10\ \text{liters/sec}}{\dot V}\right)\left(\frac{T_a}{300\ \text{K}}\right), \tag{1}$$

where T_a is the ambient temperature in the pump. This pressure is that at the entry to the pump, but it serves to estimate the vapor pressure and hence the evaporator temperature. A pressure of 0.2 Torr corresponds to a temperature of 1.06 K, while a pressure of 1 Torr corresponds to a temperature of 1.27 K. These temperatures are entirely satisfactory for application to a dilution refrigerator.

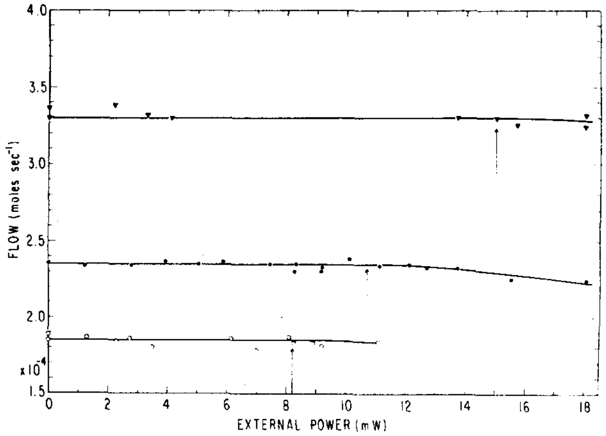

FIG. 3. Molar flow rate as a function of external power. Arrows indicate the critical power. ▼—$z=0.67\times10^{12}$ cm^{-3}; ●—$z=1.26\times10^{12}$ cm^{-3}; ○—$z=2.00\times10^{12}$ cm^{-3}.

The capillary design is not straightforward. We characterize the capillary by a quantity Z, called the impedance factor, which is calculated from measurements at room temperature using the equation[3]

$$Z=(1/\eta)\Delta P/\dot V, \tag{2}$$

where ΔP is the pressure drop required to cause the volume rate of laminar flow $\dot V$ of a gas of viscosity coefficient η. For flow rates in the device of order 10^{-4} moles/sec one can estimate that the capillary should have an impedance factor of about 10^{12} cm^{-3}. We have not attempted detailed calculations, but we expect the flow through the capillary to be highly inhomogeneous. The pressure drops along the capillary from 760 to 1 Torr, so partial vaporization can be expected within the capillary. Since the viscosity of liquid and vapor ^{4}He are comparable at a given temperature and since a pressure drop drives a volume flow rate rather than a molar flow rate, the partial vaporization will lead to a dependence of pressure on distance along the capillary which will be rather like a staircase, with little pressure gradient at the liquid and a substantial pressure gradient at the vapor. The actual flow will be quite complicated, so the capillary size is really determined empirically.

Regarding the refrigeration capability of this device for operation with a dilution refrigerator for which the heat of condensation of ^{3}He must be removed, we note that in steady state operation the heat load will be near the critical value when the ^{3}He and ^{4}He flow rates are comparable. During startup of the dilution refrigerator additional refrigeration should be available in the ^{4}He evaporator, so some factor of safety is required. The experimental values given below should be satisfactory for most cases.

The evaporator should have enough surface area so that the temperature of the copper shell is rather close to that of the helium. An average[5] value for the thermal boundary resistivity to copper at 1.3 K is 10 mK·cm^2/mW, so an area of 10 cm^2 suffices to achieve $\Delta T/T<1\%$ for heat loads up to 10 mW. This means from a practical standpoint that a simple open evaporator cavity will be satisfactory.

Finally we note that for the present device to work satisfactorily it is necessary to prevent plugging of the capillary. This can be effected easily by using adequate flushing technique on cooldown and by putting a suitable filter in the line from the bath to the capillary. We have used sintered copper powder for this purpose.

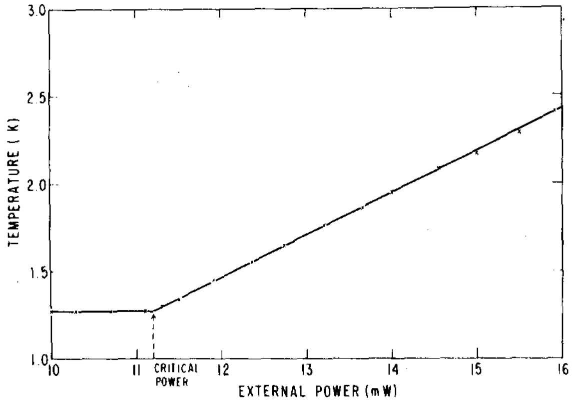

FIG. 4. Determination of critical power during the filling of the refrigerator with ^{4}He.

II. EXPERIMENTAL RESULTS AND DISCUSSION

We present in this section the results of some tests using three different capillaries. The evaporator itself was an open copper cavity of volume 2 cm^3 with an estimated surface area of 8.4 cm^2. The pumping line to the bath was 6.2 cm of 3.2 mm o.d.×0.08 mm wall cupronickel tubing. The mechanical pump used was an Edwards ED-500 with a measured pumping speed of 10 liters/sec. The pumping line itself was 12 mm diameter within the cryostat and 25 mm diameter outside. At room temperature a pressure difference of 3.1 Torr was required to drive 10.7×10^{-4} moles/sec of helium gas through the line when the pressure at the entrance to the pump was 1.9 Torr. The evaporator temperature was measured by means of a calibrated carbon resistance thermometer. Heat was applied electrically.

TABLE I. Characteristics of refrigerator for three different impedances Z.

Impedance	$Z=2.00\times10^{12}$ cm^{-3}	$Z=1.26\times10^{12}$ cm^{-3}	$Z=0.67\times10^{12}$ cm^{-3}
Unfilled quasi-equilibrium T (K)	1.17	1.18	1.26
Equilibrium T (K)	1.26	1.27	1.33
Flow (moles/sec)	1.85×10^{-4}	2.4×10^{-4}	3.3×10^{-4}
Critical power (mW)	8.2	10.7	15
Time for filling (min)	9	5	2.2
$\dot{Q}/\dot{n}$ (mW/10^{-4} moles/sec)	4.4	4.5	4.5
Flow×Z (10^{-4} moles/sec $\times10^{12}$ cm^{-3})	3.7	3.0	2.2

The capillaries were prepared as follows. To achieve $Z=0.67\times10^{12}$ cm^{-3} we used a 2.25 m length of 0.1 mm bore cupronickel tubing. To achieve $Z=1.26\times10^{12}$ cm^{-3} we used 18 cm of 0.25(+) mm bore cupronickel tubing with an 8 cm length of 0.25(−) mm diam bare manganin wire inside; this wire was stretched to approximately 0.23 mm to fit inside the tube. To achieve $Z=2.00\times10^{12}$ cm^{-3} we used a similar technique but with 15 cm of manganin wire. All measurements of Z were made at room temperature.

Evaporator temperatures as function of external power for powers on the whole less than critical power and for the three capillaries are shown in Fig. 2. The correspond-

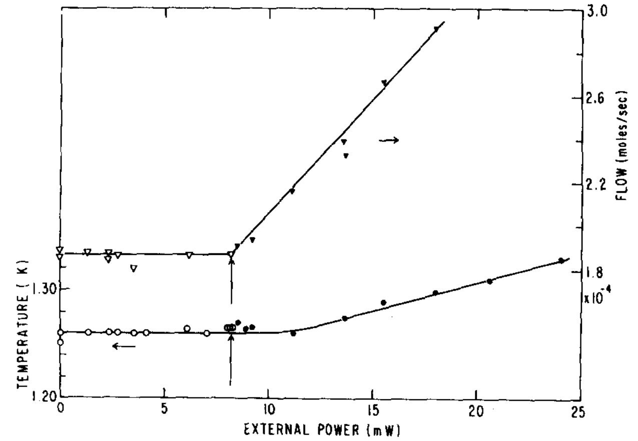

FIG. 5. Temperature and molar flow rate for $Z=2.0\times10^{12}$ cm^{-3} at equilibrium and during overload. ∇—Equilibrium flow; ○—equilibrium temperature; ▼—overload flow; ●—overload temperature.

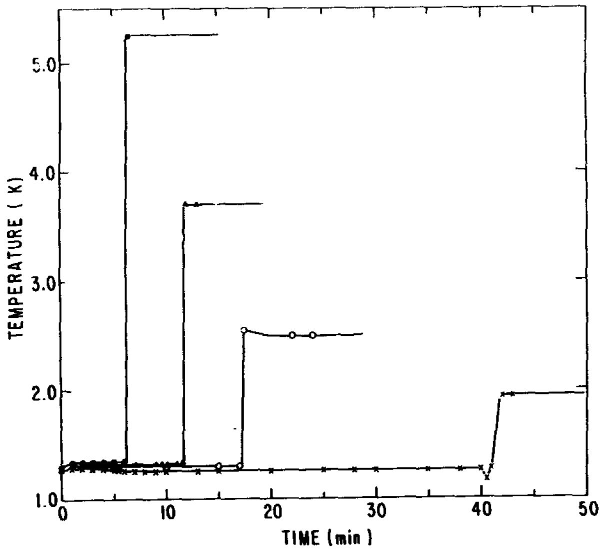

FIG. 6. Overload capability of refrigerator for different external powers. ×—$\dot{Q}=11.1$ mW, $Z=2.0\times10^{12}$ cm^{-3}; ●—$\dot{Q}=28.5$ mW, $Z=1.26\times10^{12}$ cm^{-3}; ▲—$\dot{Q}=20.6$ mW, $Z=1.26\times10^{12}$ cm^{-3}; ○—$\dot{Q}=16.1$ mW, $Z=1.26\times10^{12}$ cm^{-3}.

ing molar flow rates, measured with the help of a wet test meter, are given in Fig. 3. The equilibrium temperatures are adequately independent of the rate of external heating so long as the critical power is not exceeded. The critical power was determined by first increasing the power to a value above critical and waiting for all helium to be evaporated. Equilibrium is then obtained at some temperature and the power is then reduced. The evaporator temperature decreases until the critical power value is reached, below which the temperature remains constant. This is illustrated in Fig. 4 for the 1.26×10^{12} cm^{-3} capillary.

Some of the characteristics of the experiments are summarized in Table I. The critical power per unit flow rate is approximately 4.5 mW/(10^{-4} moles/sec) for all three cases. However, the product of flow rate and room temperature measured impedance factor decreases substantially with decreasing Z, indicating that the flow is complicated.

In regard to the ability of the evaporator to withstand a temporary overload, this depends on evaporator size and the amount of overload. But as an illustration, for the 2.00×10^{12} cm^{-3} capillary, Fig. 5 shows the temperature and flow at equilibrium and during an overload. The temperature and flow points during the overload are constant until the refrigerator runs out of liquid helium. To illustrate how long an overload can be applied, Fig. 6 shows the temperature of the refrigerator as a function of time for various power overloads and for $Z=1.26\times10^{12}$ cm^{-3} and $Z=2.0\times10^{12}$ cm^{-3}. When the refrigerator runs out of liquid the temperature goes up rapidly to some new equilibrium value.

The performance and the simplicity of this refrigerator make it a useful device, in particular for use with a ^{3}He–^{4}He dilution refrigerator where it can be employed to eliminate the above mentioned complications introduced with the use of the standard ^{4}He pot.

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