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Measurement and modeling of thermal flow in an enclosed tube containing superfluid helium film

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ABSTRACT

We describe measurements of the thermal conductivity of a vertical tube partially filled with superfluid liquid helium at saturated vapor pressure. The tube was heated from the top while the bottom was maintained at 0.3 K. Thermal conduction through superfluid film creep and vapor reflux has been modeled in the literature and previously measured at $T \geqslant 0.9$ K. From our measurements we assess the validity of the model at the lower temperatures, where significant temperature gradients develop, and consider the effect of ancillary thermal conductances. The work is motivated by the cryogenic requirements for a proposed cryogenic measurement of the electric dipole moment of the neutron.

1. Introduction

Thermal conduction through a vertical tube enclosing superfluid helium liquid and its vapor is a nonlinear process sensitive to the magnitude of the heat flow. As the upper end of the tube is heated a superfluid film will creep from the liquid at the bottom of the tube along the direction of increasing temperature. This upward film flow is counteracted by a reflux initiated by the vaporization of the film at the upper end of the tube. The refluxing vapor then recondenses, releasing its latent heat of condensation at the liquid surface at the bottom of the tube. The vapor flow, and therefore the effective thermal conductivity of the tube is limited by the superfluid film mass flow rate. At large heat fluxes the film flow cannot replenish the vapor and the effective thermal conductivity is limited at the top of the tube. This is the so-called thermal runaway effect [1].

Superfluid film creep to warm surfaces and vapor reflux cause extraneous heat loads in many low-temperature experiments. Consider a container of bulk liquid helium, cooled to $T \approx 0.3$ K by a dilution refrigerator, connected through a tube to warmer parts of the apparatus. The vapor reflux may conduct heat as efficiently as a copper rod, transporting heat to the low-temperature stage of the refrigerator, where it is very costly to remove.

The present investigation is motivated by the design for a new cryogenic measurement of the electric dipole moment of the neutron, the nEDM experiment, which is proposed to be conducted at the Spallation Neutron Source at Oak Ridge National Laboratory [2]. The experiment would involve the production and trapping of ultracold neutrons in a target environment that will include a tank of 1000 L of liquid helium cooled to 0.45 K, as well as several subsidiary volumes at nearly the same temperature. Some of these volumes will enclose free surfaces of liquid at $T \approx 0.3$ K and include tubes connected to warmer parts of the apparatus. In each volume a superfluid film could flow up the walls of the tube, vaporize, and the warm vapor will reflux downward to the cold liquid surface, transporting heat.

2. A model of thermal transport through helium vapor reflux

The enhanced thermal conductivity initiated by the superfluid film was hypothesized by Rollin and Simon [3] to explain mysterious heat flows in a number of experiments. Nacher, Cornut, and Hayden have modeled the heat transport due to refluxing vapor from superfluid ^{3}He–^{4}He mixtures [4,5]. Their model, which can be applied for pure ^{4}He, includes two volumes connected by a vertical thin-walled tube, similar to the experimental apparatus of Long and Meyer [6]. Transverse gradients in temperature and pressure are neglected and the one-dimensional system can be solved to yield equations for temperature and pressure as a function of height z

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above the condensing volume. Any thermal conduction down the walls of the tube, through the superfluid film itself, or through non-convecting gas is comparatively negligible. The model considers no net transfer of atoms or heat between vapor and film along the length of the tube. Therefore vapor and film are in local thermal equilibrium and the chemical potential is uniform in z.

Taking the chemical potential for an ideal gas, Poiseuille's law, and molar flow rates for the film and vapor, the model equations for pressure and temperature gradients in z become:

$$\nabla_z P = \frac{128\eta}{\pi d^4}\frac{\dot{Q}R}{L}\frac{T}{P}, \quad (1)$$

$$\left(\frac{5}{2} - \frac{\mu_4}{kT}\right)\nabla_z T = \frac{128\eta}{\pi d^4}\frac{\dot{Q}R}{L}\frac{T^2}{P^2}. \quad (2)$$

where η is the viscosity, d is the tube's inner diameter, $\dot{Q}$ is the heater power applied at the top, R is the gas constant, L is the latent heat of the bulk liquid, and μ_4 is the chemical potential. Additionally, the derivation of the above equations include an effective viscosity which generates temperature and pressure gradients for cases where the vapor density is low enough that the flow deviates from Poiseuille's law [4].

Following the example of Nacher et al. one can solve Eq. (2) numerically to compute the temperature gradient along a cell with ^{4}He liquid at the base and all heat transported through refluxing vapor. We plot in Fig. 1 the effective thermal impedance ($\nabla_z T/\dot{Q}$) versus temperature. We use the saturated vapor pressure for P as a function of temperature at height z along the tube and set the tube internal diameter to be d = 0.65 cm, as used in our measurements. The result is shown in Fig. 1 along with typical thermal impedances for a copper rod and a stainless steel tube (o.d. = 0.80 cm, i.d. = 0.65 cm). The cell is a good thermal conductor or "heat pipe" at temperatures $\geqslant$0.7 K. Below 0.5 K, however, its thermal impedance is on the same order as that for a stainless steel tube. Thermal conduction along the tube walls can no longer be neglected.

Eq. (2) can be solved for temperature T versus vertical height z for a given heater power applied at the top of the cell. To test the Nacher et al. model at conditions approaching those in the nEDM apparatus, we measured the reflux effect with a base temperature $T \approx 0.3$ K. The diameter of the vertical tube was chosen as d = 0.65 cm due to the limited cooling power from the refrigerator.

Hayden, Cornut, and Nacher reported measurements of pressure gradients caused by the reflux process for pure ^{4}He at $T \geqslant 0.9$ K [7]. They also performed measurements with a ^{3}He–^{4}He mixture with $x_3 \approx 4\%$ at $T \geqslant 0.6$ K. The apparatus consisted of two vertical thin-walled stainless steel tubes of diameters 0.06 cm and 0.31 cm. At their bases the tubes connected to a single reservoir filled with superfluid ^{4}He. The tubes continued upward $\approx$19 cm to where they were thermally anchored at 4.2 K. The pressures were monitored by room temperature pressure gauges. A superfluid film crept up the walls of the tubes to just below the 4.2 K section of tubing. As predicted by their model, they observed pressure gradients due to refluxing vapor with pure ^{4}He at $T \geqslant 0.9$ K.

3. Materials and methods

3.1. Measurement cell

Our film flow test apparatus, pictured in Fig. 2, consists of a series of stainless steel tubes connected by demountable 0.63 cm thick copper flanges. The tubes have an inner diameter of 0.65 cm and the walls are 0.08 cm thick. The base of the cell is attached to a copper plate which in turn is bolted to the mixing chamber of a dilution refrigerator. Copper and stainless parts in the cell were connected with 63Sn–37Pb solder. The two breakable connections along the tube are sealed with indium O-rings. The design is similar to that of Long and Meyer [6,8].

A 500 Ω metal film resistor heater is epoxied to a copper tab at the top plate of the cell. Four 36 AWG phosphor bronze leads con-

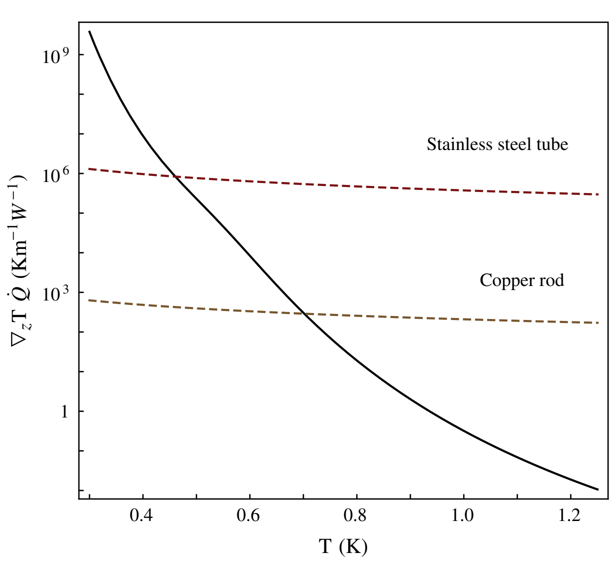

Fig. 1. Effective thermal impedance (K/m W) versus T. This plot is an extension of Nacher et al. Fig. 2 to 0.3 K, using d = 0.65 cm for the reflux tube, and stainless steel instead of Pyrex for comparison. Stainless steel tube wall thickness = 0.080 cm, the solid copper rod has d = 0.65 cm.

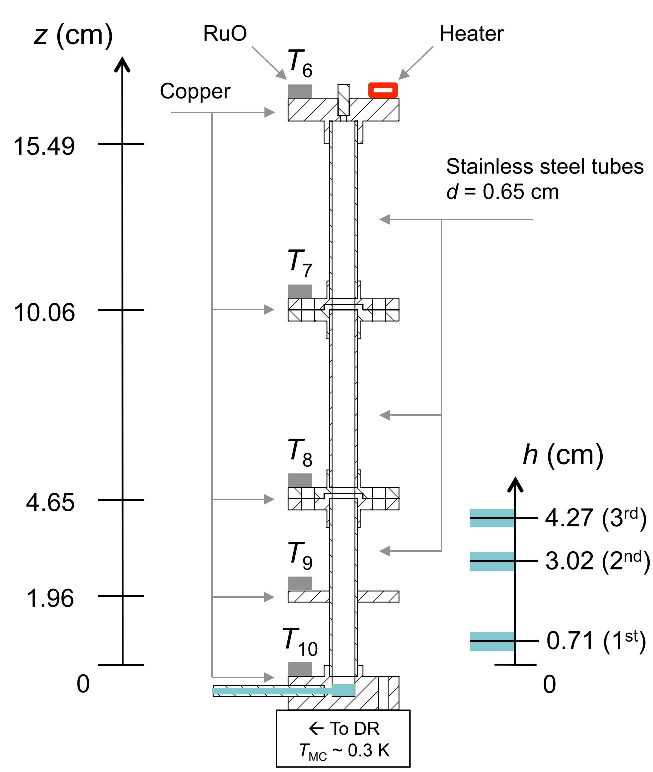

Fig. 2. Diagram of the experimental cell with the h scale on right showing the levels of the three portions of liquid helium that were used (shaded bars denote ±0.25 cm). The z vertical scale on the left notes the effective positions of the resistance thermometers and begins at the top of the bottom copper flange. The RuO thermometers mounted on the copper flanges are labeled T_6(top) to T_{10}(bottom).