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Critical Heat Flux and Thermal Quenching of Helium II in Very Long Channels*)

von

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Abstract

Heat-transport experiments with superfluid helium in pipes of 15 - 400 cm length and diameters between 0.3 - 1.0 cm show, that in heat induced counterflow of He II the critical heat flow density, i.e. the heat flux when superfluidity breaks down and vaporization onset starts, is a function of tube length and bath temperature. It is mainly determined by the amount of superheating required for bubble formation. Experimentally it is evident, that the degree of superheat is dependent of hydrostatic pressure and temperature.

Zusammenfassung

Wärmetransport-Experimente mit superfluidem Helium in Kupferrohren mit Längen zwischen 15 und 400 cm und 0.3 bis 1.0 cm großen Durchmessern zeigen das Vorhandensein einer kritischen Wärmeflußdichte, bei der Blasenbildung auftritt und der superfluide Zustand zerstört wird. Der kritische Wärmefluß wird durch die maximal mögliche "Überhitzung" des Helium II bestimmt und ist eine Funktion der Rohrlänge, des hydrostatischen Druckes und der Badtemperatur.

CRITICAL HEAT FLUX AND THERMAL QUENCHING OF HELIUM II IN VERY LONG CHANNELS

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Introduction

The following is a short report of some results concerning heat-transport experiments with superfluid helium in tubes of 15 - 400 cm length and diameters between 0.3 - 1.0 cm.

There were two general reasons for performing this research. The first is a practical one: the people of our superconducting linear accelerator group wanted to know the maximum removable heat from their helically coiled niobium-tubes. These tubes, used as wave-guides and accelerating structures, have a total length of 3 meter and an inner diameter of 0.5 cm. They are cooled by helium II at T = 1.8 K without any mass transfer, i.e. only by the well known "internal convection"-mechanism of superfluid helium. The second one is based on more theoretical questions. These are:

a) Are the thermohydrodynamical equations of the two-fluid model also valid for large scale cooling systems?

b) How can the often stated thermal break-down, or with other words, the limited heat-flux density in heat-induced counterflow of helium II, be explained?

Though there are two publications concerning heat-transport experiments with quite analogous geometries, we repeated the measurements, because the first one of CRITCHLOW and HEMSTEET [1] only dealt with very low temperature differences (in the order of 20 mK) and therefore very small heat-current densities. The second one of PASSOW et al. [2] gave only a rough technical survey and the results presented could not be accepted in general.

Experimental Equipment

All the experiments were carried out in a cryostat and vacuum chamber, as shown in Fig. 1. Two different copper helix tubes were used:

1. Tubes with both ends open to the helium bath.
2. Tubes with only one end open to the helium bath.

Also two kinds of heating have been studied: in the first case heating was carried out with an outer coil wound continuously around the helix tube; and in the second, local heaters were mounted at different places of the tube (for instance: at the closed end or in the middle).

Temperature measurement was carried out with self-made carbon resistances distributed along the tube and calibrated against vaporpressure.

Experimental results and discussion

For turbulent flow the hydrodynamical equations yield the following relation between the temperature-gradient ∇T and heat-current density q [3]:

$$\nabla T = \frac{A \cdot \rho_n}{S} \cdot \left(\frac{q}{\rho_s \cdot S \cdot T}\right)^3 , \qquad (1)$$

where

S : entropy per gram
ρ_s: density of the superfluid component
ρ_n: density of the normalfluid component
A : Gorter-Mellink constant

For numerical calculations we used the values of A as given by VINEN [4].

As you can see from Fig. 2, gradient T has a minimum at about 1.95 K. For $T \leq 1.95$ K it follows, that for a fixed heat-current density grad T is decreasing with increasing temperature and for T $\geq$ 1.95 K grad T increases with rising temperatures. Consequently the temperature distribution along a heated tube looks quite different for bath-temperatures above or below 1.95 K.

Fig. 3 shows some characteristic temperature distributions along the one end-closed helix with the heater at the closed end. It is only one specific example of our numerous measurements for two temperatures with opposite sign of grad T. The solid curves result from step-by-step integration of the relation between grad T and heat-flux density q, where the constant bath temperature is the lower integration limit. The open and block circles indicate the experimentally measured temperatures, which fit the calculated curves quite well. By comparison between the theoretically predicted curves and the experimentally confirmed temperature distributions, two conclusions are evident:

1. Within the experimental occuracy of ± 10 % and the measured temperature range between T = 1.4 K - 2.15 K the equations of the two-fluid model, including the Gorter-Mellink constant A, show no geometrical dependence, i.e. they are valid at least for tubes with a diameter up to 1 cm. The values of A seem to agree with Vinen's data [4] ± 10 %.
2. The two-fluid model is also applicable to superheated metastable helium II.

The second statement has the following meaning: for all liquids exists an equilibrium-state between vapor and liquid. You can estimate the equilibrium pressure change ΔP_D for an temperature increase ΔT on the basis of the CLAUSIUS-CLAPEYRON equation (Fig. 4):

$$\frac{\Delta P_D}{\Delta T} = \frac{1}{T} \cdot \lambda_D \cdot \rho_L \cdot \rho_D \cdot \frac{1}{\rho_L - \rho_D} \approx \frac{\lambda_D \cdot \rho_D}{T}, \qquad (2)$$

with

λ_D: heat of vaporization
ρ_D: saturated vapor density
ρ_L: liquid density.

For superfluid helium under ideal conditions a temperature difference ΔT produces according to LONDON [5] a thermodynamical excess pressure (or fountain pressure) of

$$\Delta P_F = \rho_L \cdot S \cdot \Delta T \qquad (3)$$

For helium the corresponding pressure changes have been indicated schematically in the P-T diagram of Fig. 4. Under the condition that $\Delta P_F > \Delta P_D$, you can see that point representing the liquid state at a higher temperature is always displaced into the unsaturated liquid regime of helium II. Further increase of temperature finally causes a transition across the λ-line between helium II and helium I.

In our experiments - for bath temperatures $T_B < 2.0$ K - we never could heat the helium at the end or in the midde of the tubes up to the λ-point. It was impossible to cross the λ-line, because prior to this event thermal quenching and break-down of superfluidity occured. From the just mentioned considerations one must conclude, that no fountain excess pressure is present in our pipes.

Pressure measurements with a pressure-transducer confirmed these results up to an accuracy of ± 0.1 Torr.

Heating up the helium is therefore simply crossing the equilibrium-line between the liquid and vapor-phase or superheating of the helium inside the tubes, when the liquid state is still existing.
This is illustrated in Fig. 5. The points left to the equilibrium-line represent the liquid state before heating, i.e. they are equal to the bath-temperature. The various degrees of subcooling correspond to different liquid levels above the tubes. The points on the right are the measured temperatures when superfluidity breaks down.

The above mentioned statement, that the two-fluid model is also applicable to superheated metastable helium II, expresses the validity of the hydrodynamical equations between the saturation temperature, i.e. crossing the equilibrium line, and the thermal break-down temperature. In Fig. 3 this can be seen explicitly from the fact, that above the saturation temperature the measured temperatures were in accordance with the calculated ones.

At the thermal break-down temperatures bubble formation and vaporization start. As you can see (Fig. 5) the degree of superheat is dependent of hydrostatic pressure (or subcooling) and of temperature. First theoretical calculations indicate that the amount of superheating (and its temperature- and pressure dependence) perhaps can be explained by a homogenous nucleation process for bubble formation.

Now we can make our last conclusion concerning the limited or critical heat-flow density: the amount of the critical heat-current density q_c or the termal quenching of helium II in finite tubes is only determinate by the maximum possible superheating, i.e. the difference between initial (or bath) temperature and vaporization onset temperature.

In contrast to other investigations [6] no relation between q_c and the ratio L/d (L, d: tube length and diameter) analogous to helium I [7] have been found for our geometries.

The only way the tube length L influences the critical heat-flow density q_c is explained in Fig. 6. The point F in Fig. 6a represent the liquid state inside the tube before heating. The hydrostatic pressure $P_{hydr.}$ results from liquid level high. During heating up F is displaced towards the equilibrium line and the temperature is shifted from T_{bath} to $T_{sat.}$. At $T_{sat.}$ thermal quenching is expected, when no superheating is possible. For different tube lengths (or heater locations) you can find the corresponding saturation heat-flux densities $q_{sat.}$ from the temperature distribution curves in Fig. 6b. You can see for instance, that for a given saturation temperature $T_{sat.}$ two different heat-flux densities follow for two different pipe lengths. If one repeat this for bath temperatures between T = 1.4 K and 2.1 K the curves 1 and 2 of Fig. 6c result, giving the critical heat-flux densities at saturation temperatures.

So we must conclude, that the effect of tube length on the critical heat-flow density q_c is determined by the temperature distribution along the tube or in other words by the strong temperature variation of all parameters to be found in the relation between ∇T and q, equation (1), which from the temperature distributions are derived.

The discrepancies between the saturation heat-flux densities $q_{sat.}$ and the experimentally measured values q_c indicate that superfluid helium can be superheated up to temperatures, which we called vaporization temperature T_{vap}.

In order you get some feeling about the orders of magnitude, some values of the maximum removable heat are given: for a continuously heated helix with a total length of 3.30 m and an inner diameter of 0.5 cm and with both ends open to the helium bath at a temperature of T = 1.8 K you can remove a total of about 0.65 Watt corresponding to a critical heat-current density of about 1.7 Watt/cm^2.

For niobium tubes with quite similar geometries these figures have been fully verified during the first successful operation of the 1. stage of our superconducting proton linear accelerator, when for the first time in the world protons have been accelerated by an superconducting device.

References

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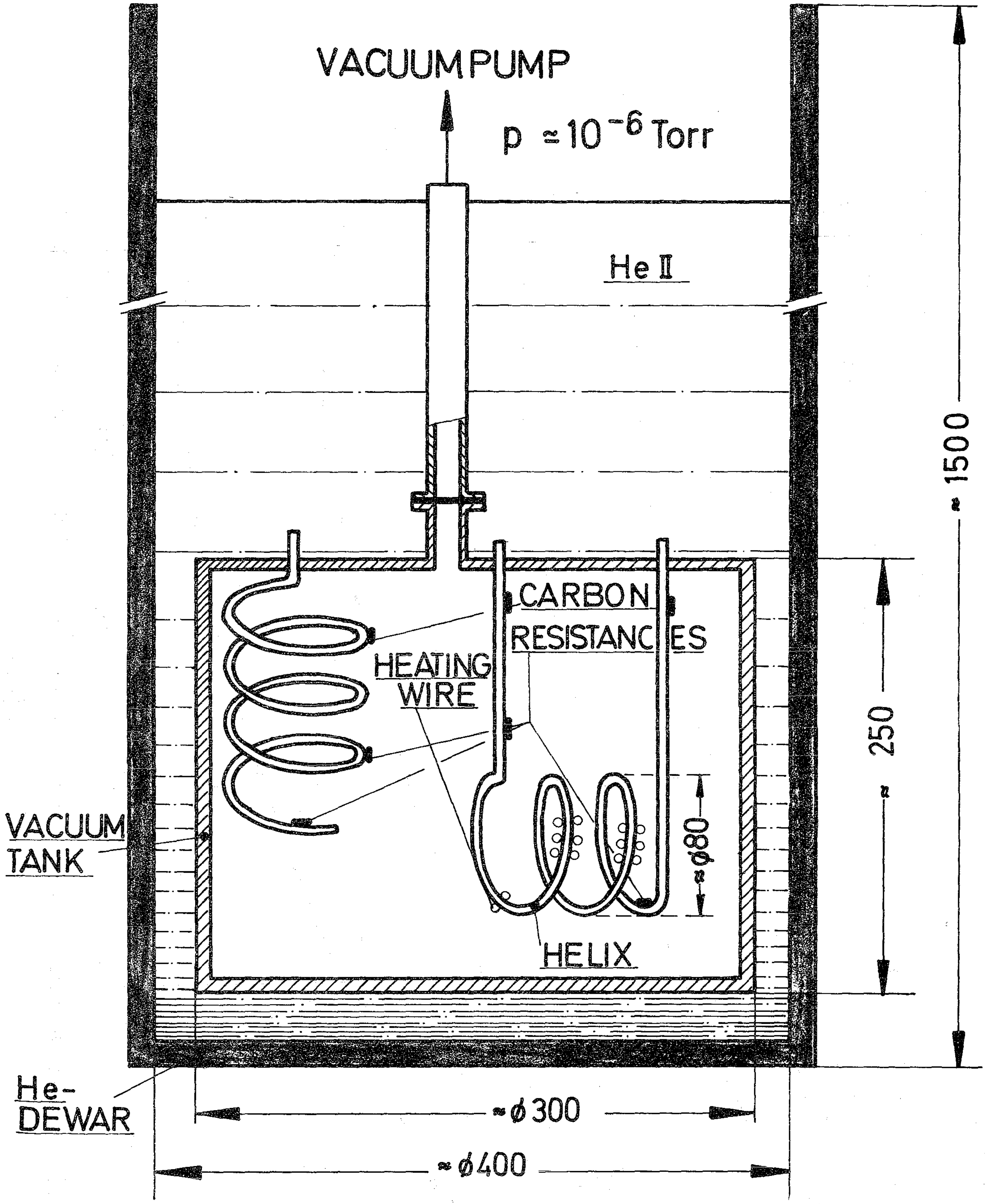
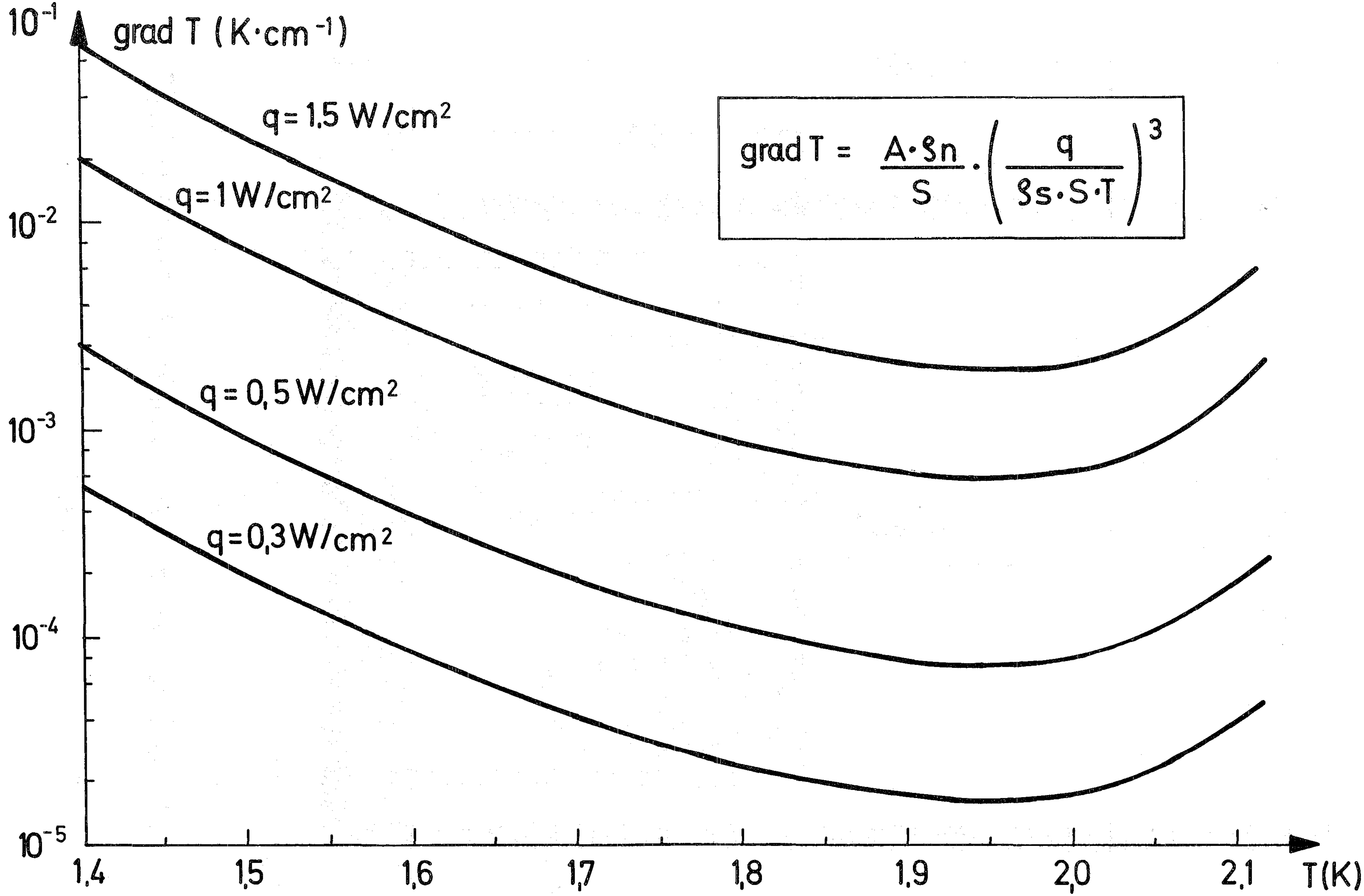


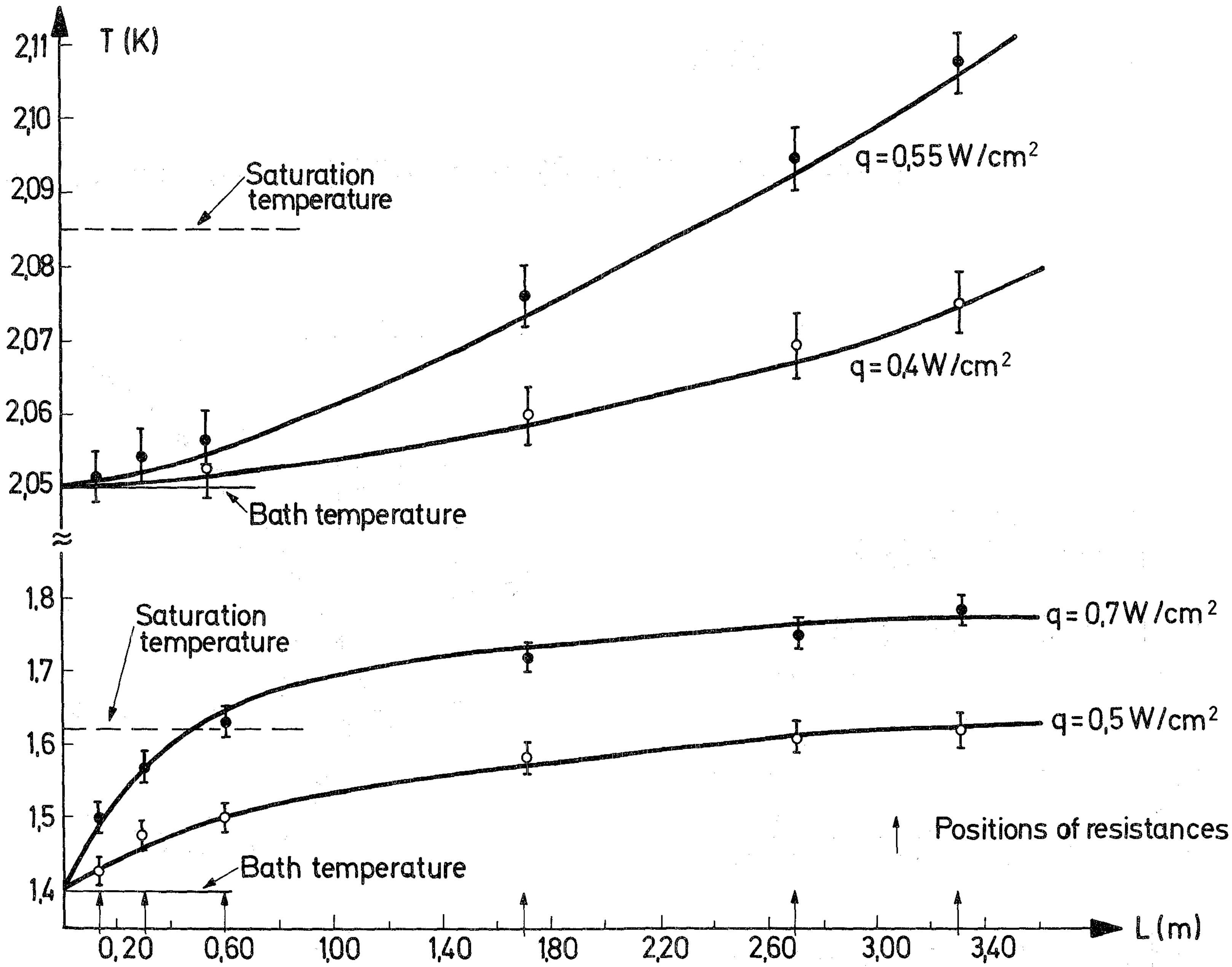
CRYOSTAT WITH VACUUMTANK AND HELICES

FIG.1



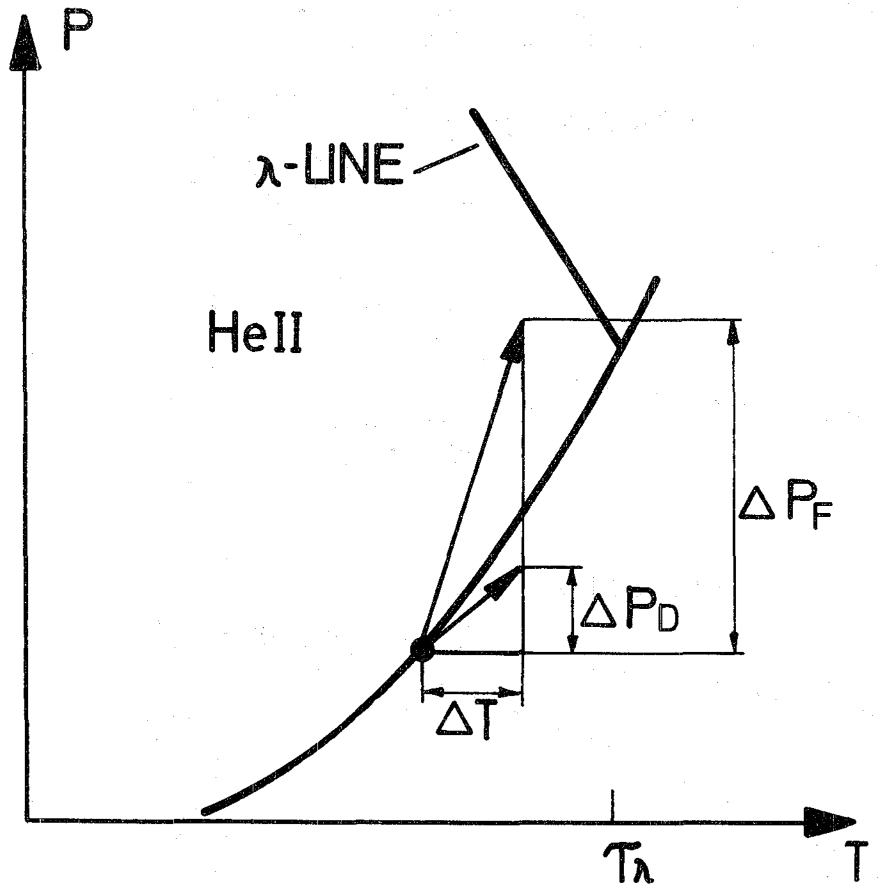
Temperature gradient as a function of heat-current density and temperature

FIG.2



Temperature distribution along the helix (d = 0,8 cm, one end closed) for two bath temperatures and heat-current densities with heater location at L = 3,30 m

FIG.3



CLAUSIUS-CLAPEYRON EQUATION

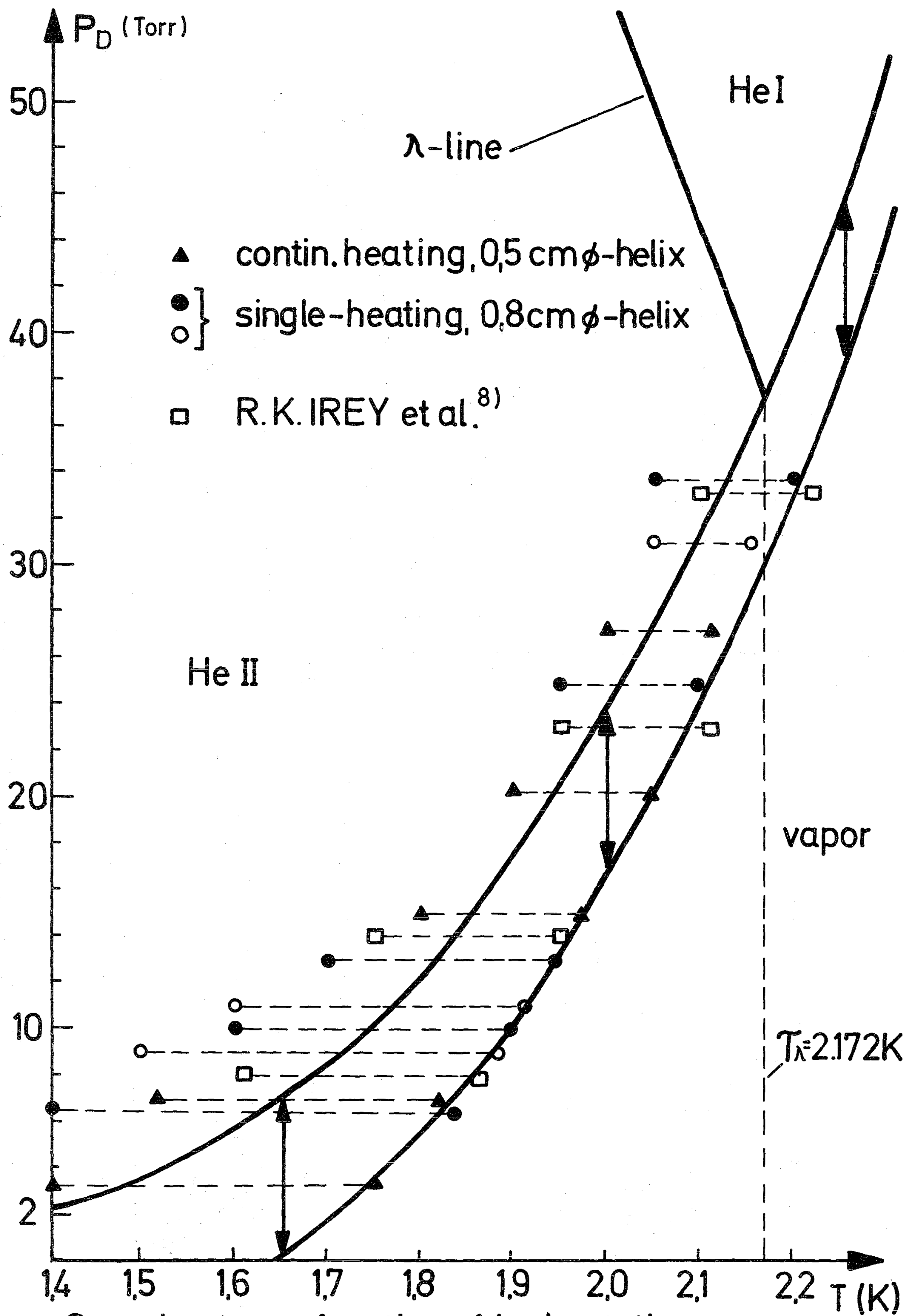
$$\frac{\Delta P_D}{\Delta T} = \frac{1}{T} \cdot \lambda_D \cdot \rho_L \cdot \rho_D \cdot \frac{1}{\rho_L - \rho_D} \cong \frac{\lambda_D \cdot \rho_D}{T}$$

LONDON EQUATION

$$\Delta P_F = \rho_L \cdot S \cdot \Delta T$$

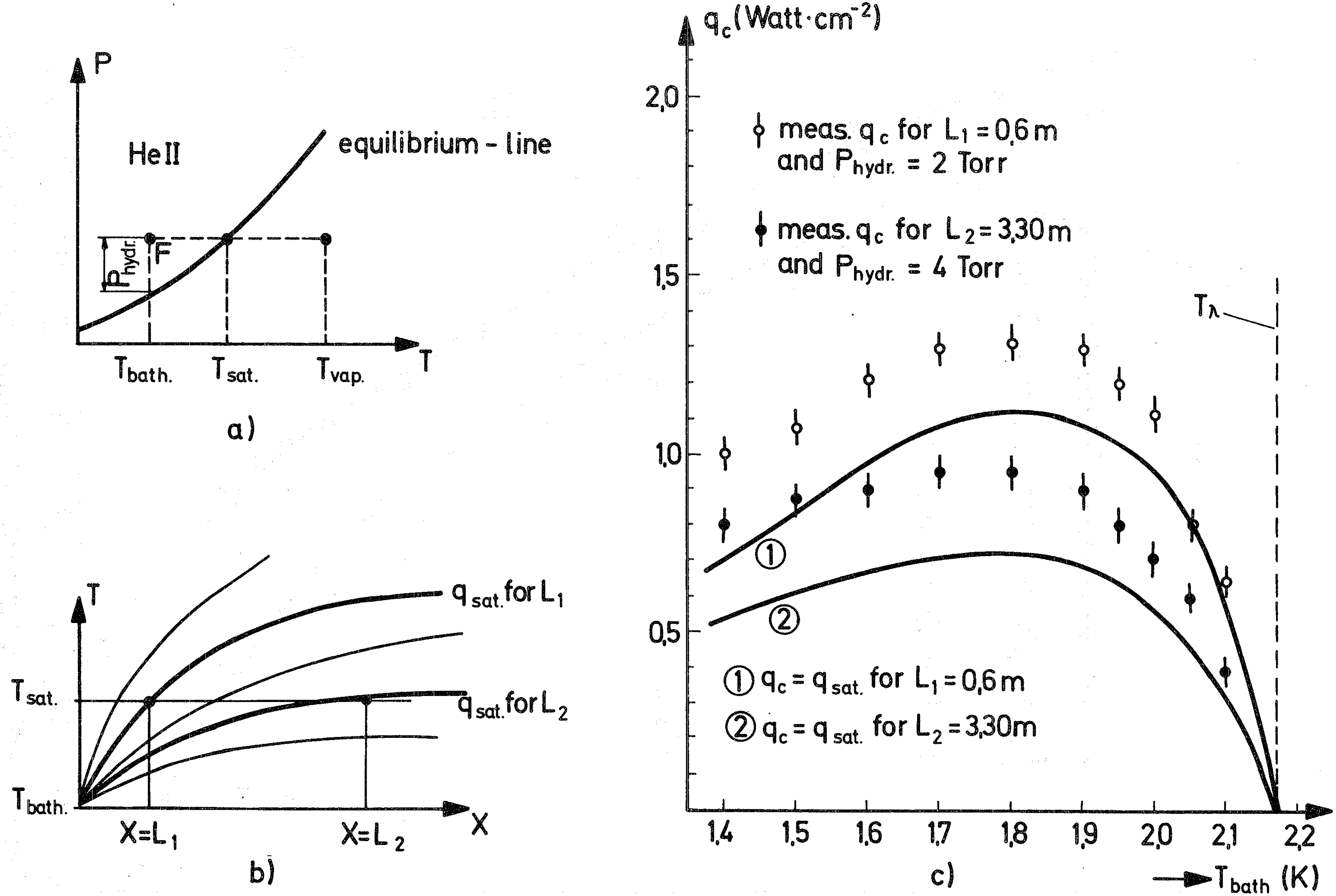
Equilibrium P-T diagram of helium (not up to scale)

FIG. 4



Superheat as a function of hydrostatic pressure and temperature

FIG. 5



CRITICAL HEAT FLOW DENSITIES FOR DIFFERENT TUBE LENGTHS AND BATH TEMPERATURES

FIG.6