OPTIMAL SIZES OF SUSPENSION TUBES IN NITROGEN-FREE HELIUM CRYOSTATS

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An analytical method is proposed for the computation of the optimal size of suspension tubes of nitrogen-free helium cryostats.

For the efficient operation of nitrogen-free cryostats it is necessary that the total heat input to the helium reservoir be determined by the radiation of the working surfaces, and the cold of the evaporating helium be expended completely in cooling the screen and in canceling the heat input along the suspension tube.

A method of computing the optimal size of tubes from the reservoir to the skin is examined below and experimental results are presented. The method is a continuation of the analysis published earlier in [1], where the temperature of the radiation shield T_s and the rate of helium evaporation G were determined.

Represented schematically in Fig. 1 is a cross-section of the tube over which the vapors of the evaporating coolant are raised. The height of the tube can provisionally be divided into three zones, and the optimal length of each can be determined. The upper end of the tube has the temperature of the ambient medium, T_a, and the lower temperature T_B is close to the temperature of liquid helium. The gas temperature in the lower section of the tube equals the temperature of liquid helium T_h. The magnitude of the heat flux along the tube by heat conduction is due to the temperature difference between its ends and the heat exchange between the inner tube surface and the moving gas. To simplify the analysis, let us make the following assumptions: the heat conduction coefficients of the tube material and the gas are averaged in some temperature range in which the physical properties of the gas do not vary. The coefficient of heat exchange between the tube and the gas is also assumed invariant. Then two heat balance equations can be written for zone I [2-4]:

$$\frac{\lambda_T' f_1}{l_1}(T_s - T_B) = Gc_p(T_A - 4{,}2), \tag{1}$$

$$Gc_p(T_A - 4.2) = \alpha' f_2 \Delta T'_{lg}, \tag{2}$$

where

$$f_2 = \pi d l_1; \tag{3}$$

the mean coefficient of heat exchange is

$$\alpha' = \mathrm{Nu}\,\frac{\lambda_h'}{d}; \tag{4}$$

and the logarithmic temperature difference is

$$\Delta T'_{lg} = \frac{(T_s - T_A) - (T_B - 4{,}2)}{2.3\lg\dfrac{T_s - T_A}{T_B - 4{,}2}}. \tag{5}$$

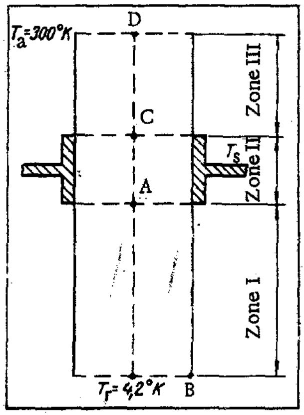

Fig. 1. Cross-section of the suspension tube.

The mode of gas motion in the tube is found from the value of the Reynolds criterion

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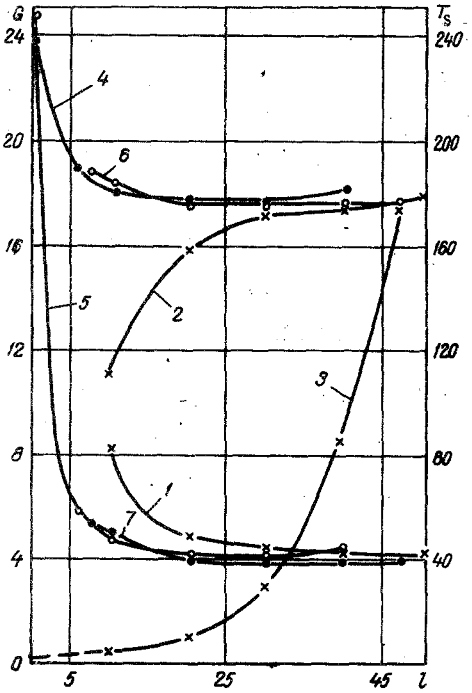

Fig. 2. Dependence of the helium evaporation rate (g/h) and the radiation shield temperature (°K) on the suspension tube length (mm) and the tube temperature profile in zone I.

$$\mathrm{Re} = \frac{wd\gamma}{\eta g}. \tag{6}$$

The value of the criterion Re is small for low rates of helium evaporation and corresponds to the laminar mode of gas motion. The minimum value of Re in circular tubes equals 3.66 for the laminar mode [3].

Three unknowns T_A, T_B and l_1 are contained in (1) and (2). By manipulation we obtain

$$\frac{(T_A - 4.2)^2 \lg \dfrac{T_s - T_A}{T_C - 4.2}}{(T_s - T_B)\left[(T_s - T_A) - (T_B - 4.2)\right]} = \frac{\pi \lambda_T' \lambda_h' \mathrm{Nu} f_1}{2.3 G^2 c_p^2}. \tag{7}$$

Let us solve (7) by successive approximation for T_A by first giving T_B and keeping in mind that the value of λ_h depends on T_A. Knowing T_A, we calculate l_1.

Let us use one heat balance equation

$$Gc_p(T_C - T_A) = \alpha'' f_3 \Delta T_{\lg}'', \tag{8}$$

where

$$f_3 = \pi d l_2;\ \alpha'' = \mathrm{Nu}\frac{\lambda_h''}{d};\ \Delta T_{\lg}'' = \frac{(T_s - T_A) - (T_s - T_C)}{2.3 \lg \dfrac{T_s - T_A}{T_s - T_C}} \tag{9}$$

to describe the zone II. We neglect the temperature difference between the inner surface of the tube and the shield. After manipulation

$$l_2 = \frac{2.3\, Gc_p (T_C - T_A) \lg \dfrac{T_s - T_A}{T_s - T_C}}{\pi \mathrm{Nu} \lambda_h'' \left[(T_s - T_A) - (T_s - T_C)\right]}. \tag{10}$$

The magnitude of the heat input to the site of shield connection to the tube is determined by the difference in the heat flux delivered to the shield from the skin and eliminated from the shield to the reservoir by radiation and through the mechanical coupling. Part of this heat input is canceled by the opposite gas stream in zone I. The rest is taken off in zone II. Assuming $T_B = T_s - 3$, as in [1], we determine l_2.

Analogous reasoning can be carried out for zone III also:

$$\frac{\lambda_T'' f_1 (T_a - T_s)}{l_3} = Gc_p(T_D - T_C); \tag{11}$$

$$Gc_p(T_D - T_C) = \alpha''' f_4 \Delta T_{\lg}''', \tag{12}$$

where

$$f_4 = \pi d l_3;\ \alpha''' = \mathrm{Nu}\frac{\lambda_h'''}{d};\ \ \Delta T_{\lg}''' = \frac{(T_a - T_D) - (T_s - T_C)}{2.3 \lg \dfrac{T_a - T_D}{T_s - T_C}}. \tag{13}$$

After manipulation, the gas temperature at the point D at the exit from the tube can be found from the relationship

$$\frac{(T_D - T_C)^2 \lg \dfrac{T_a - T_D}{T_s - T_C}}{(T_a - T_s)\left[(T_a - T_D) - (T_s - T_C)\right]} = \frac{\pi \lambda_T'' \lambda_h''' \mathrm{Nu} f_1}{2.3\, G^2 c_p^2}, \tag{14}$$

and the value of l_3 from (11).

The method elucidated above was verified experimentally on cryostats of 0.5 liter capacity with one radiation shield. The suspension tube was fabricated from 1Kh18N9T steel. The tube diameter and thickness were 12 and 0.2 mm, respectively. The analysis of the cryostats according to [1] yielded the following initial data: G = 4 g/h, T_s = 178 °K. The values of the tube lengths at different sections along the height were l_1 = 46 mm; l_2 = 22 mm; l_3 = 27 mm, as calculated from (1), (10), and (11) for $T_B - 4.2$ = 0.2 °K.

The influence of the length of each of the zones on G and T_s was investigated. The rate of evaporation was estimated by measuring the volume of the evaporating helium. The temperature of the radiation shield was measured by copper-constantan differential thermocouples. When investigating one of the zones, the other two had the design dimensions. After alternate measurements, the tube length in the zone under investigation, was altered by cutting the subsequent resoldering. The initial tube length was taken 15-20 mm greater than the design value.

The experimental results are presented in Fig. 2 where the length of the zone in mm is plotted along the horizontal and the rate of helium evaporation in g/h on the left vertical and the temperature of the radiation shield in °K on the right vertical axes. It is seen from the graph that a diminution of the suspension tube length below the design value in zone I results in an increase in the rate of helium evaporation (curve 1). A reduction in the radiation shield temperature (curve 2) is observed at the same time. The growth in the rate of helium evaporation is due to the increase in heat flux to the liquid helium along the tube, and the reduction in the shield temperature is due to the more intensive heat exchange because of the change in the temperature heads in the first two zones for a large discharge of gaseous helium.

Actually, the processes described above are accompanied by an increase in the heat input from the skin to the shield by radiation and its diminution from the shield to the reservoir. An increase in the tube length in tube I above some limit is not expedient since this results only in an increase in the size and weight of the cryostat.

Measurements of the temperature profile of the tube (curve 3) permit making a conclusion relative to the value of the difference $T_B - 4.2$. It follows from the graph that the temperature of the tube walls within 10 mm from the lower end will be just 1 °K higher than the temperature of liquid helium. In this case, the heat input to the reservoir by way of the tube will not exceed 3-4% of the heat input by radiation of the working surfaces even in the absence of the opposing stream of gaseous helium. In practice, there is no heat input along the tube for the selected difference $T_B - 4.2 = 0.2$ °K. The heat content of the evaporating helium in nitrogen-free cryostats is more than sufficient to cancel the heat input along the tube in zone I. The temperature at point A was 48 °K, i.e., did not reach the temperature of the tube walls. Upon insertion of a vacuum plug of 11 mm diameter and 25 mm height in the tube, no changes were observed in the evaporation rate and in the shield temperature, which indicates sufficiently efficient heat exchange between the gas and the wall for the gas motion velocities under investigation in small diameter tubes. These results diverge somewhat from the data in [5-7], where it is asserted that the heat exchange between the gas and the wall is not so perfect as is assumed in theory.

The results of investigating the middle portion of the tube are represented by curves 4 and 5. A qualitative contact between the tube and the shield is assured by careful tinning of the surfaces making contact before soldering after having first been fitted to the set size. A change in the contact area was accomplished by soldering additional copper half-rings to the tube. The extreme left points on curves 4 and 5 correspond to a "floating" shield when the suspension tube was wrapped with four layers of 30 μ thick polyfluorethylene resin film to which the shield was attached. As is known from theory, in the case of a "floating" shield the heat input to the reservoir from the skin is halved [3]. It is seen from the figure that a diminution in the contact area to 250-380 mm^2 affects the change in T_s and G negligibly, although it results in their growth. A further diminution in the contact area results in an abrupt rise in both the shield temperature and in the evaporation rate since the passing gas does not succeed in removing heat from the shield for a small contact area. The slight rise in curves 4 and 5 at the length $l_2 > 35$ mm can be explained by the fact that the length of zone III was less than the design length for these measurements.

The dependence of the shield temperature and the evaporation rate on the length of zone III is represented by curves 6 and 7, from which it is seen that the helium evaporation rate increases and the radiation shield temperature rises as the tube length diminishes.

The investigations enumerated above were conducted on cryostats without mechanical connections to the windows in the radiation shield covered by metal washers. An analysis of the results obtained shows that the heat content of the emerging helium is not used completely in single-shield cryostats for nominal tube lengths. The gas leaves the cryostat at a lower temperature than the temperature of the external skin. The temperature at the point D was 260° K in the cryostats investigated. Since there was no heat input to the reservoir along the suspension tube, the evaporation rate was then determined completely by radiation of the radiation shield. The reduced radiativity for the shield-reservoir system, computed by means of the helium evaporation rate, was 0.013. A further diminution in the reduced radiativity because of improvement in the quality of polishing the cryostat surface is technically difficult. The helium consumption by radiation can be reduced by mounting additional shields connected to the suspension tube at definite points since the temperature of the shield nearest to the reservoir will be diminished as the quantity of shields is increased. The heat content of the evaporating helium will then be used more completely. The heat input can also be diminished by mechanical connections in a multishield system. The problem of optimizing suspension tubes in this case should be examined specially.

NOTATION

λ'_T, λ''_T	are the mean heat conduction of the suspension tube material in zones I and III;
λ'_h, λ''_h, λ'''_h	are the mean gas heat conduction in the corresponding zones;
f_1	is the cross-sectional area of the suspension tube;
f_2, f_3, f_4	are the surface area of the suspension tube in the corresponding zones;
d	is the suspension tube diameter;
G	is the rate of helium evaporation;
c_p	is the specific heat of gaseous helium;
Nu, Re	are the similarity criteria;
l_1, l_2, l_3	are the suspension tube lengths in the corresponding zones;
T_A, T_B, T_C, T_h, T_D	are the gas temperature at the corresponding point;
α', α'', α'''	are the mean heat exchange coefficients;
w, γ, η	are the velocity of motion, specific gravity, and viscosity of the gas;
g	is 9.81 m/sec^2;
$\Delta T'_{lg}$, $\Delta T''_{lg}$, $\Delta T''_{lg}$	are the logarithmic temperature difference in corresponding zones;
T_s, T_a	are the temperature of the shield and the outer skin.

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