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Temperature Stratification in a Nonventing Liquid Helium Dewar[1]

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The presence of a large temperature gradient in Dewars used for transporting helium is undesirable because it may be accompanied by unnecessarily high internal pressures when the contents are sealed. In a study of the problems, such gradients were observed in experiments conducted with a 39.7-liter stainless steel Dewar. A method is shown for calculating the pressure rise in the absence of temperature gradients and the results are compared with the observed pressure rise. In some cases curves representing calculated and observed pressure rise intersect. A possible explanation of this situation is given. The destratifying effect of a concentrated heat input and of copper rods is shown.

1. Introduction

For many applications, a greater economy of transportation can be achieved by shipping helium at moderate pressures at or near the liquid density rather than as a warm compressed gas [1].[2] Savings can be realized even though the end use of the product is in gaseous form. The transportation and storage, however, should be accomplished with no loss of helium to keep total costs minimal. An ideal method is one in which the heat input to the Dewar increases the pressure and temperature of the contents rather than causing loss of helium by evaporation.

Temperature gradients may exist in containers of very small heat flux as a consequence of the low thermal conductivity of helium near its normal boiling point, approximately 6.3×10^{-5} cal/cm ° K sec for the liquid [2] and 5.3×10^{-5} cal/cm ° K sec for the vapor [3]. A layer of warm fluid at the top of the container has no tendency to mix. In addition, warm helium anywhere in the container will tend to rise to the top of the container and increase the temperature gradient. For example, at 3 atm, 5.5° K fluid is over twice as dense as fluid at 6.5° K [4]. The practical significance of a temperature gradient in a self-pressurizing system is the difference in the rate of pressure rise as compared to a system in thermal equilibrium.

The object of the experiment to be described was to verify the existence of temperature gradients in a nonventing Dewar and to determine the approximate magnitude of these gradients by experimental measurements.

2. Theoretical Pressure Rise at Thermal Equilibrium

From the first law of thermodynamics, eq (1), and the definition of enthalpy, eq (2), we have:

$$\Delta U = Q - W \tag{1}$$

$$H = U + pv \tag{2}$$

where

Q = heat added to the system,
U = internal energy function,
H = enthalpy function,
W = work done by the system,
p = pressure,
v = specific volume = $\dfrac{\text{container volume}}{\text{total mass of liquid and vapor.}}$

Since the process is one of constant volume and the external work between the system and its surroundings is zero we have:

$$\Delta U = Q$$

$$\Delta H = Q + v\Delta p$$

or

$$Q = \Delta U = \Delta H - v\Delta p \tag{3}$$

A convenient method of expressing eq (3) is a plot of pressure versus internal energy for various specific volumes [4] as shown in figure 1. This process can be illustrated by following an isochor (line of constant volume) for the horizontal distance corresponding to ΔU or Q.

3. Previous Experiments

Previous experiments conducted by Wilson and Robbins of this laboratory with a 2.3-liter capacity Dewar constructed of high thermal conductivity copper, have given pressure rise results which agree with predicted values obtained from figure 1. The copper construction assured that the contents were in thermal equilibrium. The range of specific volumes covered in the experiments were 7.8 to 13.0 liter/kg. The pressure was allowed to rise to 5 atm.

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[2] Figures in brackets indicate the literature references at the end of this paper.

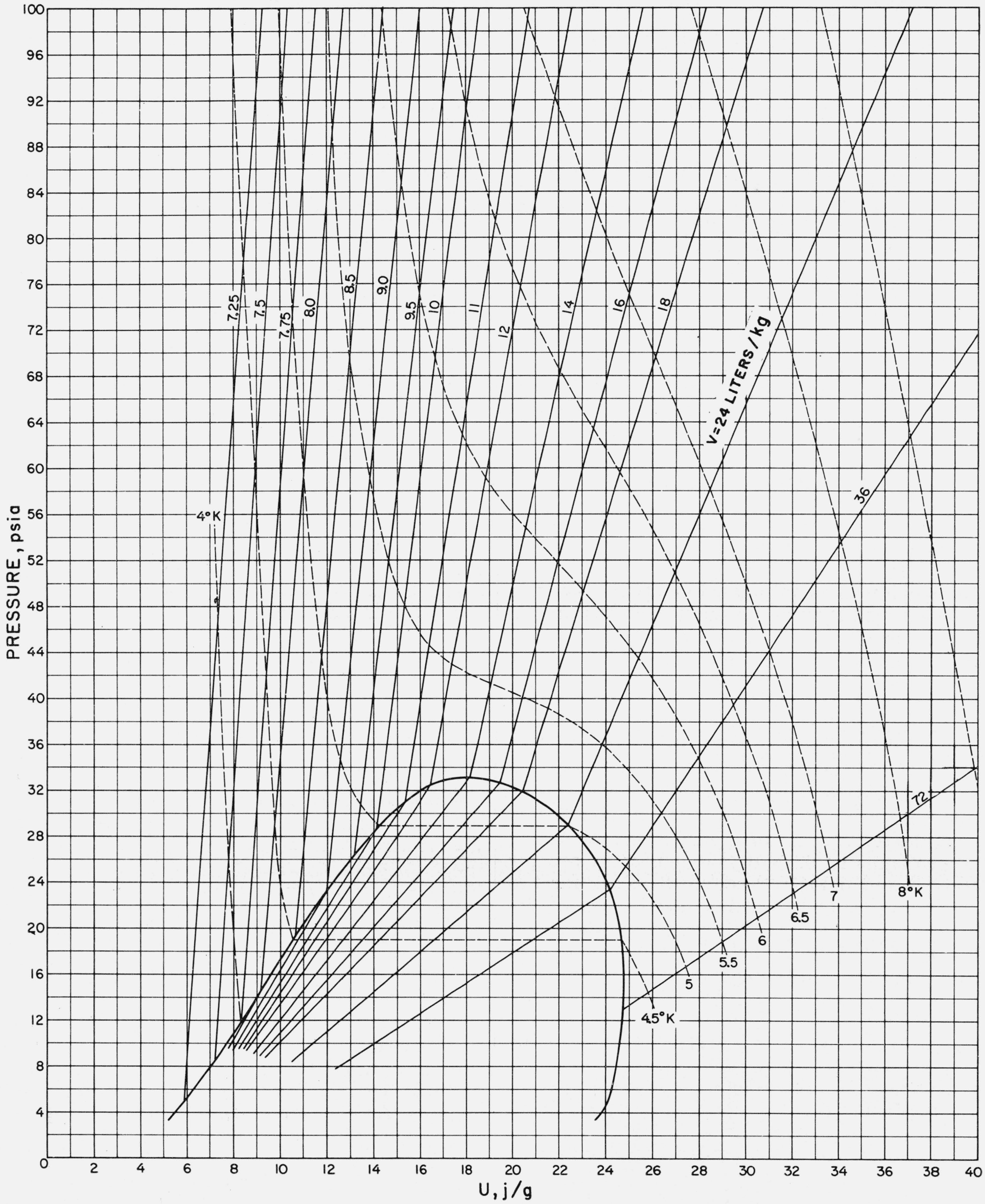

FIGURE 1. *Pressure-internal energy diagram for helium, 0 to 100 psia.*

The Dewar used in these experiments had a fill tube with a temperature gradient from 4° to 76° K. One might erroneously speculate that if a container is filled with liquid helium to a greater level than that corresponding to the critical density, the liquid meniscus might expand into the fill tube. This phenomenon did not occur, undoubtedly as a result of the high compressibility of liquid helium (0.0035g/cm^3/atm at 2.5 atm and 4° K [5]).

It was concluded from the experimental results that the heat input was not affected by a rising liquid meniscus in the Dewar, and that pressure rise as a function of total heat input may be accurately predicted *if the contents are in thermal equilibrium.*

4. Experimental Details

4.1. Description of Apparatus

For the present experiments a Dewar of 39.7-liter capacity (excluding volume in the supporting neck) was constructed from type 304 stainless steel as shown in figure 2. Stainless steel was selected, because of its low thermal conductivity, to reduce vessel wall conduction and thereby minimize effects of the wall on the temperature gradient in the contents. The entire assembly with the exception of the upper 12 in. of supporting tubes was submerged in liquid nitrogen during the measurements. Twelve difference thermocouples (gold plus 2.1 at. percent cobalt versus copper) were installed on the outside of a micarta tube at the vertical centerline and spaced as shown in figure 2. Thermocouple 12 was placed on the sensing bulb of a helium vapor pressure thermometer and was used as the reference for the 11 remaining thermocouples. The thermoelectric emf was measured with a precision Wenner potentiometer. The thermocouples and temperature measuring equipment were capable of an accuracy of better than ±0.1° K in the range of absolute temperatures measured. A resistance wire heater was spiraled around the top and bottom hemispheres to allow a known and concentrated heat flux to be applied.

In experiments 4, 5, and 6, four rods of electrolytic-tough-pitch copper 25-in. long having a combined cross-sectional area of 0.258 sq in. were placed vertically in the Dewar to reduce the temperature gradient.

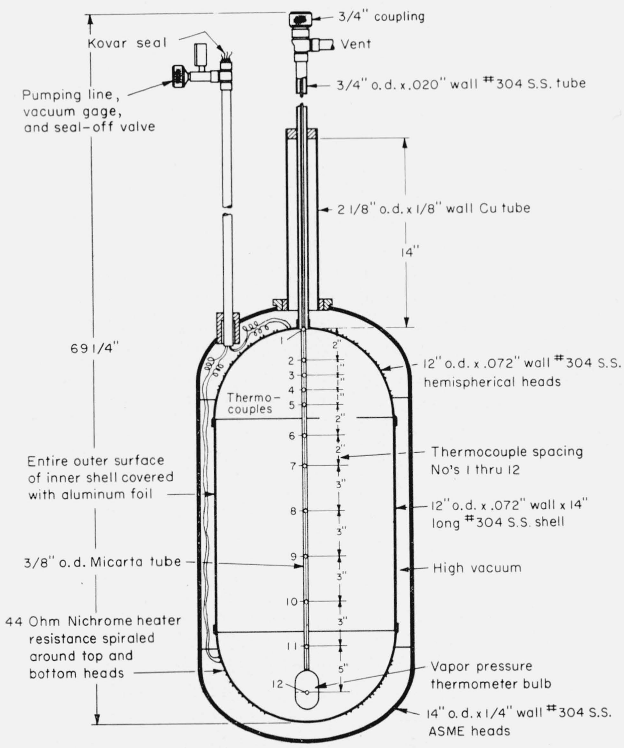

FIGURE 2. *Dewar schematic showing thermocouple positions.*

4.2. Experimental Procedure

The Dewar was filled to various levels with liquid helium. The liquid level was then measured by means of an electrical resistance probe [6] inserted through the neck. The liquid evaporation rate was measured prior to closing the vent to determine the heat input. A correction was calculated for the increased heat input down the neck in the nonventing condition. The system was then sealed and periodic pressure and temperature readings were obtained.

5. Data and Discussion

Six experiments were performed as shown in table 1. In each experiment, the starting conditions were saturated liquid and vapor at 12.2 psia.

TABLE 1

Experiment No.	Liquid volume	Specific volume	Total heat input	Measured time to 50 psia	Theoretical time to 50 psia	Notes
	% full	*l/kg*	*w*	*hr*	*hr*	
1	99	7.8	0.10	15.4	23.2	
2	82	9.23	.10	27.5	60.8	
3	71	10.5	.54	12.5	13.2	Concentrated heat input at bottom.
4	97.5	7.93	.10	24.6	29.4	Copper rods installed.
5	78	9.65	.10	63.4	65.7	Do.
6	81	9.32	.10	55.6	54.8	Do.

Experiments 1 through 5 were terminated after a pressure buildup to approximately 70 psia. Experiment 6 was continued until the pressure reached 160 psia.

Figure 3 shows absolute temperature as a function of vertical position in the Dewar and Dewar pressure for experiments 1 through 5. Temperature readings, taken after the vapor pressure thermometer reference reached the critical temperature (approx 5.2° K) such as shown for experiments 3 and 5, are less accurate because the absolute value of the reference has been extrapolated for values above 5.2° K. Since the majority of data in experiment 6 is above the critical point, temperature readings are not shown.

In each case, essentially all of the temperature gradient existed in the upper one third of the test Dewar. Those thermocouples not plotted were essentially at the reference temperature throughout the test. Thermocouple No. 1 is probably greatly influenced by the heat transferred down the fill tube and is therefore of questionable value.

Dewar pressure as a function of change in internal energy (ΔU) is shown in figure 4 for all six experiments. The calculated thermal equilibrium pressure versus ΔU is also shown for comparison.

Temperature stratification was quite pronounced in all of the experiments performed without the copper rods (see figs. 3 and 4). Comparison of experiments 1 and 2 indicate an increasing temperature gradient and pressure rise deviation from the calculated thermal equilibrium pressure with in-

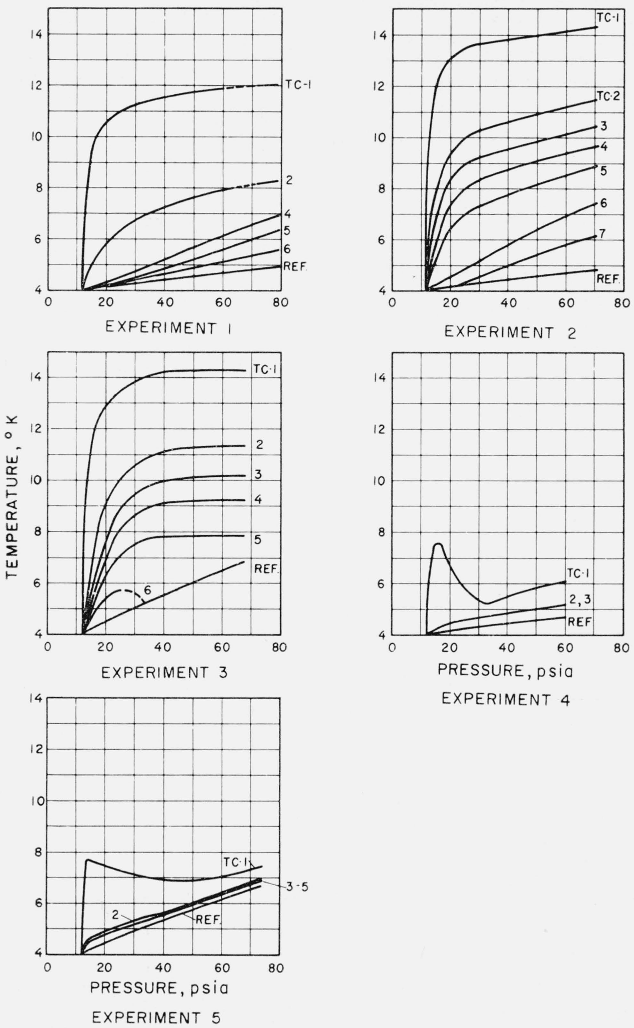

FIGURE 3

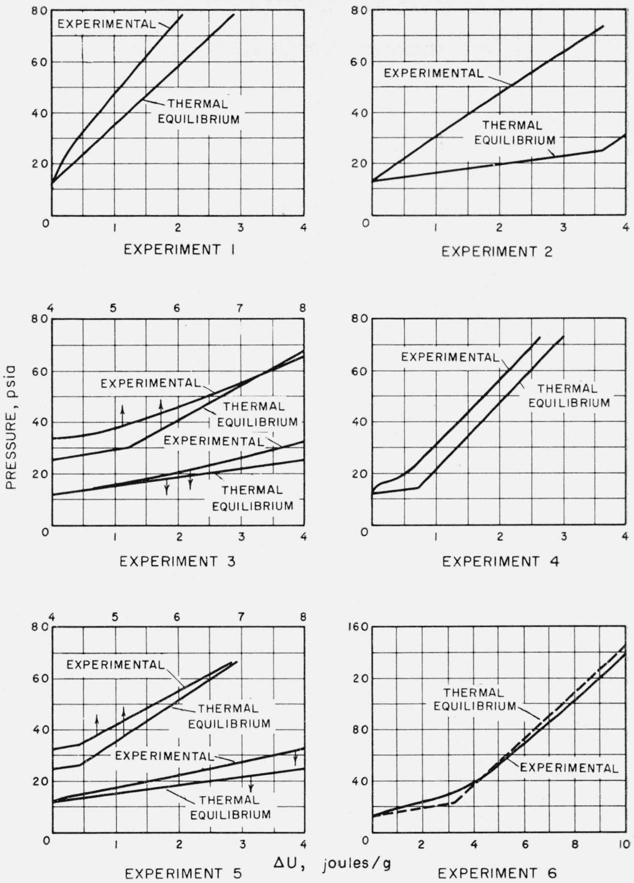

FIGURE 4

creasing specific volumes. Experiment 3 when compared with the trend of experiments 1 and 2 shows that, as would be expected, a concentrated heat input to the bottom of the dewar results in increased convection and therefore reduces the temperature gradient.

The excellent heat conducting characteristic of the copper rods is evidenced by the virtual elimination of temperature gradients in experiments 4 and 5. The experimental pressure rise in experiments 4, 5, and 6 is shown to be in close agreement with the calculated thermal equilibrium curve.

Some of the nonequilibrium pressure rise curves in figure 4 appear to intersect the thermal equilibrium curves. This phenomenon may not be entirely unexpected. As the helium increases in temperature and pressure, the system changes from a two phase gas and liquid system to a single phase fluid. If the single phase fluid was an ideal gas, obeying the ideal gas law, and therefore having a constant specific heat (C_v), it can be shown mathematically that a temperature gradient would not affect the rate of pressure rise in the single phase regime. Thus, it appears that the pressure rise deviation resulting from temperature stratification is possibly a result of the nonideality of the fluid. Consequently, one might speculate that a nonequilibrium pressure rise curve may intersect or become asymptotic to the equilibrium pressure rise curve at some pressure or pressures which would depend upon the magnitude and distribution of the temperature gradient. This speculation is supported by (a) the knowledge that at pressures and temperatures somewhat higher than those investigated, helium tends to obey the ideal gas law, and (b) the behavior of the compressibility factor of helium [4] as shown in figure 5. The compressibility factor Z is defined as PV/nRT. In the constant volume processes under consideration here

$$P = CZT \tag{4}$$

where C is a constant and Z is a function of temperature and pressure. Figure 5 illustrates that at lower pressures Z generally increases with increasing temperature at any one pressure. At higher values of pressure, the situation is reversed; that is, Z decreases with increasing temperature at any one pressure.

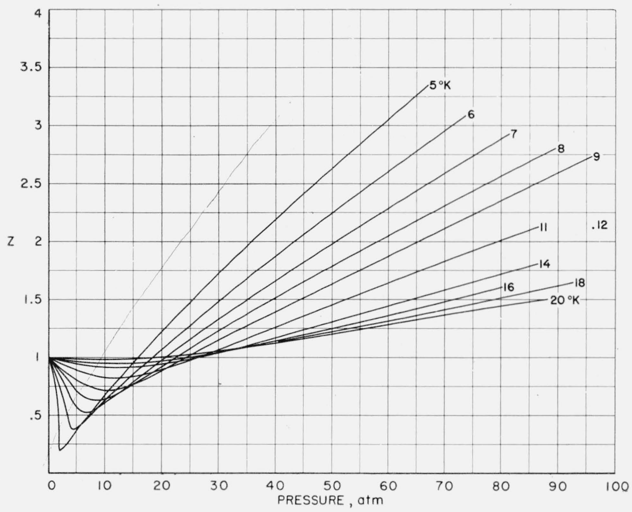

FIGURE 5. *Compressibility factor Z for helium gas.*

The point of intersection may also depend to a lesser extent upon the variation of (C_v) with temperature and pressure. Even though the necessary thermodynamic data are now available, a suitable method of computation of the nonequilibrium pressure rise that would be expected in a container which will support temperature gradients has not yet been attempted.

6. Conclusion

The presence of a good heat conducting material appears to be the most satisfactory method of eliminating temperature gradients and unnecessarily high pressures as well as allowing a pressure rise prediction to be made with the aid of figure 1. It is to be expected that both geometry and the distribution of heat input will influence the stratification tendencies of a Dewar. The use of high conductivity construction materials such as aluminum and copper will greatly reduce this tendency. Very large Dewars may require additional material to conduct heat into the center of the helium mass.

7. References

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