EXPERIMENTAL STUDY WITH REGARD TO THE COOLING OF CRYOGENIC LIQUIDS

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Results are shown of an experimental study with regard to the equilibrium or departure from it during the cooling of cryogenic liquids by vapor evacuation or by paddling with bubbles of an uncondensable gas.

Vapor evacuation or paddling with bubbles of an uncondensable gas are nowadays considered very effective means of cooling a cryogenic liquid. During either of these treatments the temperature of the principal liquid drops as a result of partial evaporation while the vapor is continuously removed.

In the extreme case, the partial pressure of the vapor in a gas bubble during paddling or the vapor pressure above the free surface during evacuation reach the saturation level corresponding to the given temperature of the liquid. Under real conditions, however, the cooling processes may involve departures from equilibrium in a cryogenic liquid. Disregarding such a departure during paddling or evacuation may result in large errors in the design of industrial treatment facilities.

In this article the authors show the results of an experimental study concerning the departure from equilibrium in the processes of cooling liquid nitrogen by vapor evacuation and by paddling with helium, mixed helium–nitrogen, or hydrogen bubbles. The selection of nitrogen as the cooled liquid was dictated by the simplicity of handling it and by the large number of tests needed for establishing the process trends. The experiment was performed in a Dewar glass jar with a 10 liters capacity and with transparent windows for visual observation throughout the volume of cooled liquid. A model VN-2 pump was used for evacuation. Paddling was effected under adiabatic conditions, without a mechanical loss of mass, for which the jar had been specially designed. The temperature of the liquid along the jar height was measured with six copper–constantan thermocouples, while the pressure was measured with a standard vacumeter and a standard manometer. Throughout the experiment the temperature of the liquid was varied from 63 to 77°K while the height of clear liquid in the jar (height of liquid above the nozzle, during paddling) was varied from 100 to 400 mm. The pumping rate during evacuation was varied from 0.78 to 0.02 n · liter/sec; the gas flow rate during paddling was varied from 0.1 to 1.0 n · liter/sec. The equilibrium index with regard to the subcooling process is defined here as the ratio

$$c = p_a/p_s,$$

of the actual nitrogen vapor pressure p_a to its saturation pressure p_s at the temperature of the liquid. The actual nitrogen vapor pressure during evacuation was measured with the vacumeter and the manometer, but during paddling it was determined by interferometry from the nitrogen concentration in the gas mixture at the exit. The temperature drop across the liquid column during the cooling experiment did not exceed 0.1-0.2°C, which was within the error of temperature measurements, and could thus be disregarded for all practical purposes.

It was noteworthy that on the overflow tube reaching almost to the bottom of the jar there appeared vapor bubbles during evacuation throughout the 63-77°K temperature range in the liquid. The buoying bubbles helped to stir the liquid throughout its volume.

The equilibrium index during both paddling and evacuation under our test conditions was somewhat below unity, independent of the pumping rate or the paddling rate, respectively, and a function of the

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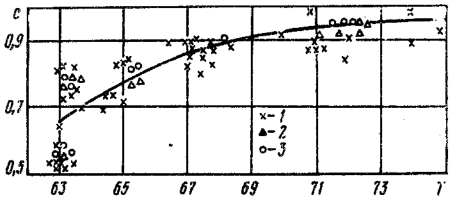

Fig. 1

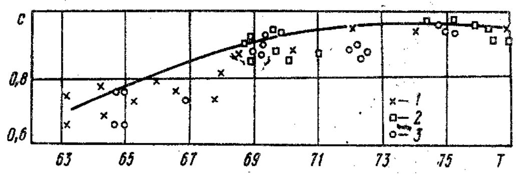

Fig. 2

Fig. 1. Saturation level $c = p_a/p_s$ as a function of the temperature T (°K) of liquid nitrogen during paddling with: 1) helium; 2) helium–nitrogen mixture; 3) hydrogen.

Fig. 2. Equilibrium index $c = p_a/p_s$ as a function of the temperature T (°K) of liquid nitrogen during evacuation at: 1) Q = 0.75 n · liter/sec; 2) Q = 0.35 n · liter/sec; 3) Q = 0.02 n · liter/sec.

temperature of the liquid only. The measured values of the saturation level varying with the temperature of the liquid during paddling and evacuation are shown in Figs. 1 and 2. An analysis of curves approximating the test values indicate that the temperature characteristics of both processes are similar.

The noted departure from equilibrium between liquid and vapor during subcooling has to do with the peculiarities of the heat transfer across the liquid–vapor interface. Thermodynamic equilibrium between liquid and vapor prevails only at their interface. With respect to the entire bulk of liquid, however, thermodynamic equilibrium can prevail only when the heat from the liquid is transmitted sufficiently fast to that interface with vapor. The departure from equilibrium observed in our experiment was due to the thermal resistance building up in the region adjacent to that interface.

LITERATURE CITED

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