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RANQUE EFFECT AT LOW TEMPERATURES

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Methods and results of experimental research on the Ranque effect at a gas temperature reduced to 80° K.

The separation of a gas stream delivered to a tube through a tangential nozzle into streams with different stagnation temperatures (Ranque effect) is a phenomenon that has not as yet been fully investigated. The problem of the effect of gas temperature T_0 on the performance of the vortex tube is of extreme importance in understanding the mechanics of the effect.

Several investigations [1–3] show an increased difference $\Delta T = T_0 - T_1$ with increase in temperature T_0. However, proportionality between ΔT_1 and T_0 is denied by some authors [3].

In order to elucidate the problem of the effect of the absolute gas temperature, it was decided to carry out an experiment with considerable variation of the temperature T_0 in the absence of heat exchange with the surrounding medium. It was possible to meet both conditions by carrying out the low-temperature experiments in a high vacuum. Lowering of the temperature T_0 from 295° K to the boiling point of liquid nitrogen (~78° K) changes T_0 by a factor of 3.7. As a working medium it is convenient to use helium, which, in this range of temperatures and under moderate pressures, is quite close to an ideal gas.

The experimental apparatus for the low-temperature experiments is shown in Fig. 1. Compressed helium, purified of oil, is fed by a compressor from a closed system. In passing through the tubes of a counterflow heat exchanger, it is cooled by the return stream of helium. Then, after passing through a coil cooled by liquid nitrogen, it enters a receiver from which it is introduced into the vortex tube. The heated stream of helium passes from the vortex tube through a diaphragm and, mixing with the cooled stream, is directed into a heat exchanger. All the low-temperature elements of the apparatus are encased in a vacuum housing, where a pressure of no more than 10^{-3} n/m² is maintained. In order to eliminate radiant heat exchange, the vortex tube and receivers are surrounded with a copper shield with a temperature close to 80° K.

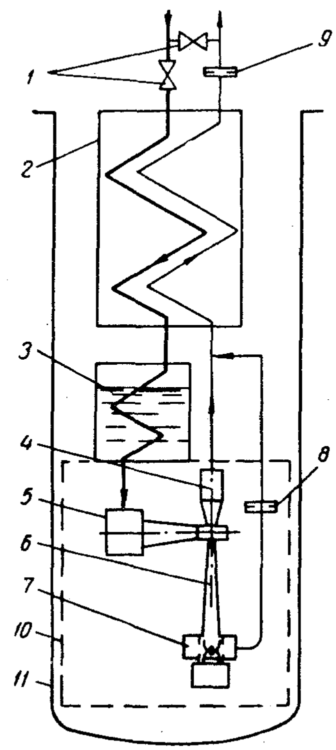

Fig. 1. Layout of apparatus used in the experiment: 1) valves for pressure regulation; 2) counterflow heat exchanger; 3) liquid nitrogen bath; 4, 5) receivers; 6) vortex tube; 7) regulating valve; 8, 9) diaphragms for measuring gas flow; 10) heat shield; 11) vacuum housing.

The vortex tube under investigation consists of the following basic elements: a conical tube with a cone angle of 2° 18', a wall thickness of 1 mm, and a length of 150 mm and with the smallest diameter of 10 mm located near the nozzle; a flat helical insert (Archimedean spiral) with a tapering nozzle entrance, the smallest cross section being 2 × 4 mm (the gas passes to the helical insert through the tapering nozzle with a smooth transition from the circular cross section to a square cross section of 4 × 4 mm); a diaphragm, adjacent to the helical insert, with an orifice 6 mm in diameter and a short conical nozzle (30°) through which the cooled stream exits. All the elements of the vortex tube are made of stainless steel. The heated stream exits through openings in the wall of the conical tube which can be shut off with a valve actuated by compressed helium for the purpose of varying the cold stream fraction X.

The helium flow-rate measurements were made using the upper diaphragm (total stream; measurement error ± 2%) and the lower diaphragm (heated stream; error ±5%). For measuring the temperature differences ΔT_1 and ΔT_2, calibrated copper-constantan thermocouples with their junctions located inside the receivers and the regulating valve were used. The gas velocities in the receivers are low and the temperatures of the exposed junctions are practically equal to the stagnation temperatures. To measure the temperature T_0 in the second receiver, the junction was placed either in melting ice (with $T_0 \approx 80°$ K). The low emf's of the thermocouples at low temperatures were measured with photocompensating instruments. For the purpose of process control, the outgoing signals were registered by recording styluses.

The emf's of the thermocouples at low temperatures were measured with photocompensating instruments. For the purpose of process control, the outgoing signals were registered by recording styluses. The emf's of the thermocouples at $T_0 \approx \approx 300°$ K were recorded directly by a EPP-09 (0.5 class) automatic potentiometer. Calibration errors of thermocouples and measurement errors did not exceed ± 1.5% of the measured temperature differences at low temperature and were less than ± 0.5% at $T_0 \approx 300°$ K. The pressure in the receivers and regulating valve was measured by a standard manometer (0.5 class).

As an internal check on the experiments, use was made of a comparison of the χ values calculated from the conditions of tube heat balance ($\chi = \Delta T_2/\Delta T_1 + \Delta T_2$) with the values obtained by direct measurement of flow rates. The discrepancy between these values did not exceed 10%. In view of the higher accuracy in temperature measurements and good heat insulation, the χ values calculated from the heat balance were accepted as the true values.

The experiments performed showed that, at constant pressure ratio π and the suitable values of χ, a drop in the temperature T_0 from 295° K to 80° K (factor of 3.7) results in a proportional decrease in the difference ΔT_1. The results obtained allow one to assume that, within a broad range of temperatures, there exists the relationship

$$\Delta T_1 (\pi - \text{const},\ \chi - \text{idem}) \approx \text{const}\, T_0 . \tag{1}$$

As is known, the drop in gas temperature ΔT_s during isentropic expansion is also proportional to the absolute temperature of the gas. Relationship (1) points to the desirability of presenting the effect under investigation in the form [2]

$$\Delta T_1 = \eta \Delta T_s = \eta \left[1 - \left(\frac{1}{\pi} \right)^{\frac{k-1}{k}} \right] T_0 , \tag{2}$$

in which the function η, which is usually referred to as the temperature efficiency, is practically independent of temperature (Fig. 2).

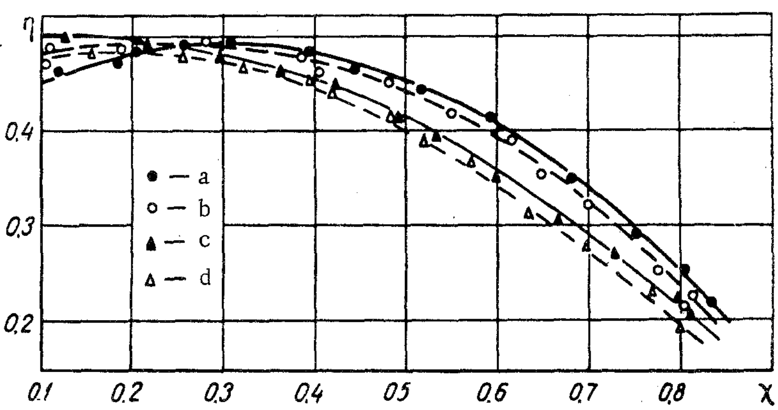

Fig. 2. Temperature efficiency of the vortex tube ($\eta = \Delta T_1/\Delta T_s$): a and c) $T_0 = 295°$ K, $\pi \approx 4$ and 8; b and d) $T_0 = 80°$ K, $\pi \approx 4$ and 8.

In each experiment at selected values of p_0 and T_0, the relationship $\pi = p_0/p_1$ varied somewhat (within 10%) depending on the hydraulic resistance in the cooled stream. Each point in Fig. 2 was calculated from the corresponding value of π.

It is interesting to note the following circumstance. The gas flow through the nozzle at a supercritical pressure ratio may be represented thus:

$$G \approx \text{const}\, p_0 / \sqrt{T_0} . \tag{3}$$

The change in temperature T_0 and the related changes in gas flow ($\sim 1/\sqrt{T_0}$) and gas density ($\sim 1/T_0$) lead to a deformation of the velocity field in the tube proportional to $\sqrt{T_0}$. Therefore, such essential characteristics of the stream in a vortex tube as the Mach numbers and the kinetic energy per unit of gas volume remain unchanged with variation of temperature T_0.

Notation

G—total mass gas-flow through tube; G_1—mass flow of cooled gas; $\chi = G_1/G$—cold stream fraction; T_0, T_1, T_2—absolute gas stagnation temperatures at tube inlet, in the cooled stream, and in the heated stream, respectively; t_s—absolute thermodynamic temperature of gas at the end of reversible adiabatic expansion; $\Delta T_1 = T_0 - T_1$; $\Delta T_2 = T_2 -$

$- T_0$; $\Delta T_s = T_0 - t_s$; $\eta = \Delta T_1/\Delta T_s$ – temperature efficiency of the process in the tube; p_0, p_1, p_2 – gas stagnation pressures at tube inlet in the cooled stream and in the heated stream, respectively; $\pi = p_0/p_1$; $k = C_p/C_v$.

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