INFLUENCE OF VORTEX-TUBE CONFIGURATION AND LENGTH ON THE PROCESS OF ENERGETIC GAS SEPARATION

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Results are presented of an experimental investigation of cylindrical, diffusor, and step vortex tubes. It is shown that long cylindrical tubes are most effective in a broad range of variation of structural and modal parameters.

No standard viewpoint on the influence of vortex-tube length and configuration on the magnitude of temperature gas separation yet exists in the extensive literature devoted to the vortex effect (the Ranque effect). The determination of the mentioned dependences is essential to a study of the mechanism of vortex temperature separation and of practical recommendations for the use of vortex tubes in a number of branches of industry (refrigeration, gas, aviation, etc.).

Hilsch [1], and afterwards Martynovskii and Alekseev [2], who investigated cylindrical vortex tubes, recommend $L_{opt} = L_0 = 50D_0$ as the optimal (thermodynamically most effective) vortex-tube length. Merkulov [3], who mounted a rectifying crosspiece in a vortex tube, obtained $L_{opt} = 9D_0$. The influence of the rectifier on the diminution of L_{opt} was also noted by Metenin [4]. Hendal [5] proposed the use of diffusor ($\alpha = 2$-$5°$) vortex tubes with a small conical and long cylindrical section to increase the efficiency of temperature gas separation. Gulyaev [6], Metenin [7], Borisenko, et al. [8], who investigated conical vortex tubes, indicate that their thermodynamical efficiency is greater than the efficiency of cylindrical tubes. However, an opposite viewpoint exists. Thus, the authors of [2] remark that long cylindrical tubes are more efficient as compared with diffusor and confusor tubes.

Results are presented in this paper of an experimental investigation of the influence of the vortex-tube length and configuration on the vortex-temperature gas-separation process. The air after the compressor in the experimental setup was dried by silica gel and directed by the entrance nozzles of the vortex tube. The air pressure at the entrance to the vortex tube was regulated by a gate valve. From the vortex tube the cooled and heated air stream was directed to the flowmeter and then ejected into the atmosphere. A change in the relationship between the cold and hot stream discharges was accomplished by the conical valve of the vortex tube.

The pressure, temperature, and discharge of these two streams were measured during the experiments. The total pressure and stagnation temperature of the gas were measured in tanks at the entrance to the vortex tube, at the "cold" and "hot" ends of the vortex tube, and at the appropriate flowmeters.

The "cold" and "hot" tanks were manufactured from ebonite to diminish the heat losses and were washed externally by the emerging air streams. The air pressure was measured by standard manometers. The air temperature was measured by copper–constantan thermocouples, whose "zero" junction was placed in melting ice. A PP-63 potentiometer was used to record the thermocouple readings. The thermocouples were calibrated before performing the experiments. The air temperature was measured to ±0.2°C accuracy. The air discharge was determined by using a diaphragm differential manometer filled with water. The accuracy of measuring the discharge was ±1.5%.

Also measured during the experiments was the static pressure within the vortex tube at the emergence of the air from the entrance nozzles, which permitted a judgment about the presence of the critical escape mode.

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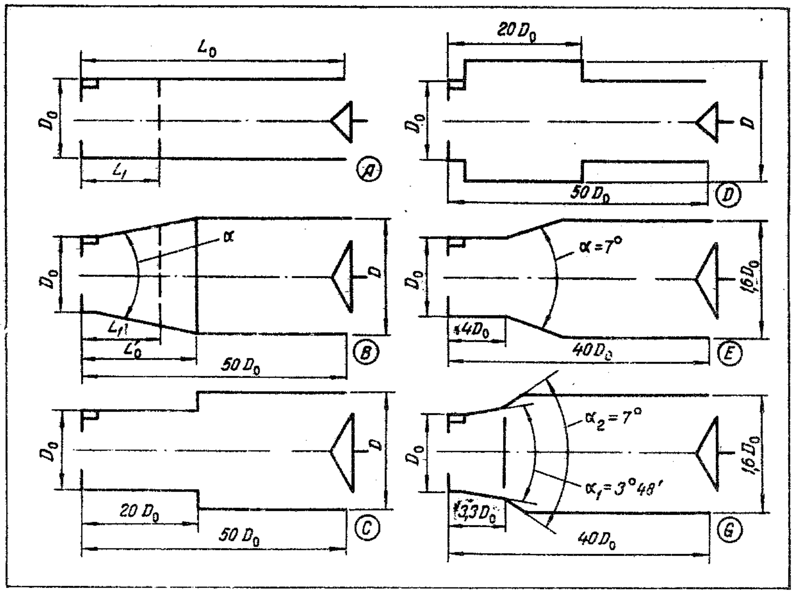

Fig. 1. Configuration of the vortex tubes tested.

The experiments were conducted with ebonite cylindrical and diffusor vortex tubes whose configuration is presented in Fig. 1. The diameter of the initial section of all the vortex tubes studied is $D_1 = 10$ mm. The air was supplied through two rectangular tangential nozzles, whose total area S was 5.55 mm^2 ($\omega = 0.071$). The cooled stream was removed through a diaphragm with a d = 5-mm ($\delta = 0.5$)-diameter hole.

Six cylindrical tubes (Fig. 1A) of different lengths, $L_0 = 5D_0$, $10D_0$, $20D_0$, $30D_0$, $40D_0$, and $50D_0$ and a cylindrical vortex tube of length $L_0 = 40D_0$ with a crosspiece which could be mounted at various distances L_1 from the initial section of the vortex tube, were tested. Moreover, step cylindrical tubes of the configurations C and D were tested.

The diffusor vortex tubes consisted of a diffusor part of length L_0' and a following cylindrical diffusor section. The total length of the diffusor and cylindrical sections was $40D_0$. Diffusor vortex tubes with the apertures $\alpha = 2°$, 3°48', 5°, and 7° were studied. The length L_0' of the diffusor part was varied in the experiments and there was the possibility of moving the crosspieces to different lengths L_1 in the diffusor tube with $\alpha = 3°48'$ and $L_0' = 2.5D_0$.

In conclusion, vortex tubes of variable configuration (types E and G) were tested.

Experiments with cylindrical vortex tubes showed that a change in vortex tube length from $50D_0$ to $20D_0$ does not influence the magnitude of the vortex effect. A further diminution in the length L_0 results in a sharp reduction of the temperature differences. Presented in Fig. 2 are the most characteristic of the results obtained, and in Fig. 3 (the $G_1/G_0 = 0.5$ mode) the dependence $\Delta T_1 - L_0$ in the whole range of vortex-tube lengths studied.

Also shown in Fig. 3 is the change in the temperature differences for a displacement of the rectifying crosspiece in the cylindrical and diffusor vortex tube. It is clearly seen that the change in distance L_1 noticeably influences the magnitude of the vortex effect only in the initial section of the vortex tube. Moreover, a comparison between the thermodynamic efficiency of short ($L_0 < 20D_0$) and long ($L_0 = 40D_0$) vortex tubes with a limiter crosspiece demonstrates the explicit advantage of the latter (for $L_0 = L_1$ = idem).

Represented in Figs. 4 and 5 are the results of tests of diffusor vortex tubes. An analysis of Fig. 4 shows that diffusor vortex tubes are less efficient in a broad range of variation of the modal and structural parameters, than are long cylindrical tubes. When the diffusor aperture is small (α = 2-3°), the thermodynamic efficiency of the diffusor and cylindrical tubes are commensurate for large L_0. As the cone aperture increases further (to α = 5-7°) an abrupt reduction in the vortex effect sets in. The curves in Figs. 4 and 5 are recorded for $G_1/G_0 = 0.5$.

The influence of a change in the length L_0' of the conical section of diffusor vortex tubes on the value of the vortex effect was also studied. It is seen from Fig. 5 that as the length of the diffusor diminishes,

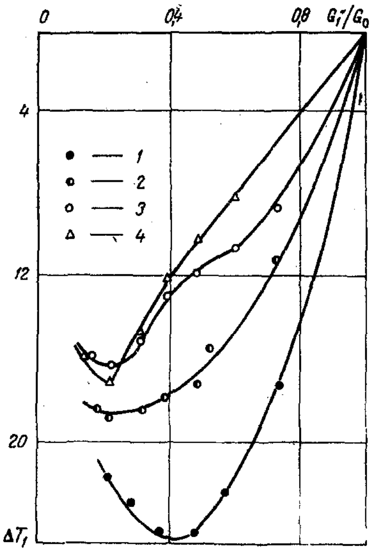

Fig. 2

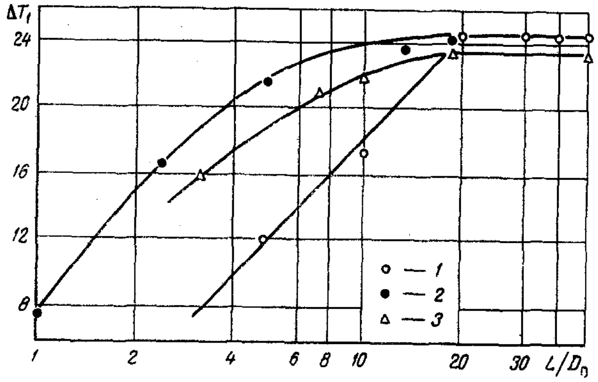

Fig. 3

Fig. 2. Influence of vortex-tube length on the magnitude of the temperature differences ΔT_1 ($P_0/P_1 = 3$): 1-3) cylindrical tube; 1) $L_0 = 40D_0$; 2) $10D_0$; 3) $5D_0$; 4) diffusor tube $L_0 = 5D_0$, $L_0' = 2.5D_0$, $\alpha = 3°48'$.

Fig. 3. Influence of the vortex-tube length on the magnitude of the temperature differences ΔT_1 ($G_1/G_0 = 0.5$, $P_0/P_1 = 3$): 1) dependence on L_0, cylindrical tube; 2) dependence on L_1, cylindrical tube; 3) dependence on L_1, diffusor tube $\alpha = 3°48'$, $L_0' = 2.5D_0$.

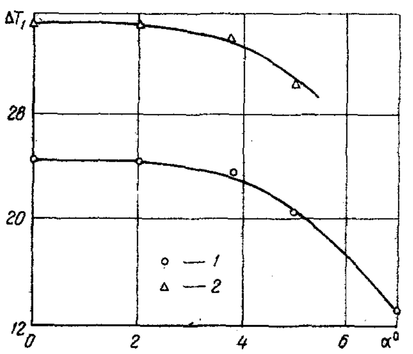

Fig. 4

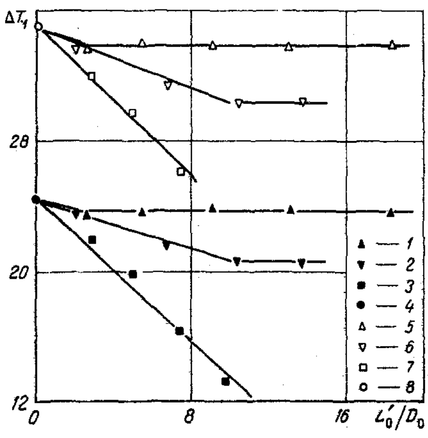

Fig. 5

Fig. 4. Influence of the diffusor aperture angle on the magnitude of the temperature differences ΔT_1 ($G_1/G_0 = 0.5$, $L_0' = 10D_0$): 1) $P_0/P_1 = 3$; 2) 5.

Fig. 5. Influence of the length L_0' of the diffusor section of a vortex tube (configuration B) on the magnitude of the temperature differences ΔT_1 ($G_1/G_0 = 0.5$, $L_0 = 40D_0$): 1-4) $P_0/P_1 = 3$; 5-8) 5; 1) $\alpha = 3°48'$; 2) 5°; 3) 7°; 4) cylindrical tube; 5) $\alpha = 3°48'$; 6) 5°; 7) 7°; 8) cylindrical tube.

the magnitude of the temperature differences increases, approaching values obtained in tests of cylindrical vortex tubes.

Shown in Fig. 6 are the results of experiments with diffusor vortex tubes and with tubes with the configurations of type C and D. The points of curve 1 indicate the invariability of the magnitude of the vortex effect for a sharp step expansion of the helical stream which has first passed through a 20-caliber-long cylindrical part of the vortex tube. Conversely, a step expansion of the cylindrical section of the

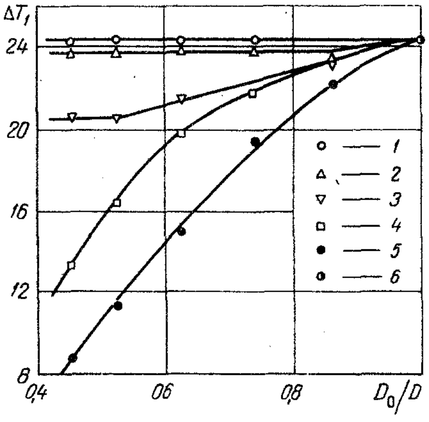

Fig. 6. Dependence of the temperature difference ΔT_1 on the ratio D_0/D ($G_1/G_0 = 0.5$; $P_0/P_1 = 3$): 1) configuration C; 2) diffusor tube $\alpha = 3°48'$; 3, 4) diffusor tube $\alpha = 5$ and 7°; 5) configuration D; 6) cylindrical tube, configuration A.

vortex tube near its initial section results in an abrupt reduction in the vortex effect which will be greater, the greater the diameter D of the expanded section (curve 5).

It should be noted, however, that an abrupt expansion of the vortex tube behind a relatively small section with fixed geometry does not result in an essential change in the magnitude of the vortex effect. Thus, the difference in the quantity ΔT_1 for configuration A ($L_0 = 40D_0$) and E is ~5% in the $G_1/G_0 = 0.5$ mode, and is G ~ 12% for B and G.

Therefore, the most thermodynamically efficient are long ($L_0 \geq 20$) cylindrical vortex tubes. As the absolute length of the vortex tube ($L_0 < 20D_0$) diminishes, the vortex effect is reduced sharply. Experiments carried out with a displaceable crosspiece in a long cylindrical tube showed that the main heat-transfer processes occur in the first 3-5 calibers of the vortex tube.

Diffusor vortex tubes are less efficient than long cylindrical tubes in a broad range of variation of the modal and structural parameters. The thermodynamic efficiency of conical and cylindrical tubes are commensurate for a small diffusor angle ($\alpha = 2$-$3°$); a sharp reduction in the vortex effect sets in for diffusor aperture angles, $\alpha > 5°$.

The efficiency of diffusor vortex tubes grows as the length of the conical section diminishes (for α = const).

These deductions explicitly contradict the results presented in [5-8]. The explanation should be sought in the fact that the diffusor vortex tubes in the papers mentioned were compared with short cylindrical tubes ($L_0 < 20D_0$), and as has been shown above, short cylindrical tubes are substantially less efficient than long tubes with $L_0 \geq 20D_0$.

NOTATION

L_0	is the total vortex-tube length;
L_0'	is the length of the diffusor part of the vortex tube;
L_1	is the distance from the initial section of the vortex tube to the crosspiece;
D_0	is the diameter of the initial section of the vortex tube;
α	is the diffusor aperture angle;
S	is the cross-sectional area of the entrance nozzles;
$\omega = 4s/\pi D_0^2$	is the dimensionless area of the entrance nozzle's cross section;
d	is the diameter of the vortex tube diaphragm hole;
$\delta = d/D_0$	is the dimensionless diameter of the vortex tube diaphragm hole;
G_0	is the mass flow rate of air through the vortex tube nozzle;
G_1	is the mass flow rate of the cold air stream removed through the diaphragm hole;
P_0/P_1	is the ratio between the total air pressure at the entrance to the vortex tube P_0 and the total air pressure at the exit from the diaphragm P_1;
$\Delta T_1 = T_0 - T_1$	is the difference in temperature of air supplied to the vortex tube and the cooled air removed through the diaphragm hole.

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