THE EFFECT OF GEOMETRIC PARAMETERS ON THE CHARACTERISTICS OF A CONICAL VORTEX COOLING UNIT

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We present the results of an experimental investigation of a conical vortex cooling unit.

A general view of the installation is shown in Fig. 1. Compressed air enters silica-gel dryer 12 and passes from there to annular receiver 3, from which it passes through the converging section of a nozzle into the coils of the cooling unit. The total pressure (P_{01}) and the stagnation temperature (T_{01}) of the flow are measured in the receiver. The total parameters (pressure P_{0c} and temperature T_{0c}) of the cold flow, after separation, are measured in receiver 2, while the parameters of the hot flow (P_{0h} and T_{0h}) are measured in receiver 4. The weight fraction (μ) of the cold flow is regulated by means of valve 5. The temperature is measured with a copper–constantan thermocouple 0.4 mm in diameter. The pressure is determined with standard manometers (class 0.5) with a scale ranging from 0 to 6 gauge atmospheres, and the flow rates of the inlet and cooling air are measured with Venturi tubes 1. The Venturi tubes are calibrated. The measurement of the cold-air flow rate was checked by calculating the flow rate over the cold-air velocity field at the outlet from the connecting tube. The measurement of the inlet-air flow rate was monitored in similar fashion only for the $\mu = 1$ regime, since the change in the flow rate of the inlet air is insignificant for the constant expansion and pressure ratios which prevail at the cold end of a vortex cooling unit. In all of the experiments the heat was removed from the hot end of the vortex cooling unit by means of free convection, with the exception of the experiments involving tubes variously tapered at the cold ends, these tests taking place with the cooling units thermally insulated. In addition to the thermal insulation, in this case three electrical compensation coils were mounted at the hot end of the vortex cooling unit to offset the loss of the heat evolved from the hot end. The heat flows at the hot end were monitored at three points according to the reading from thermocouples embedded at each point at a distance 12 mm from each other. The weight fraction (μ) of the cold flow in this case was determined from the heat-balance condition for the tube, on the basis of the measured temperature differences:

$$\mu = \frac{\Delta t_h}{\Delta t_c + \Delta t_h}.$$

The test vortex tube had a diameter of 20 mm ($\bar{f} = 0.116$), which was the same as that of the hot end nearest the nozzle cross section; the area of the converging section of the nozzle at the critical cross section was equal to 7.6×4.8 mm^2 (b/h = 1.58) and the length of the hot end was L = 280 mm (L/D = 14). The measurement error did not exceed 5% of the measured temperature difference.

The test was carried out in air at expansion ratios of $\pi = 2\text{-}4$. The results are therefore presented in dimensionless form as the functions $\eta_t = f(\bar{d}, \gamma, \beta)$ and $\eta_e = f(\bar{d}, \gamma, \beta)$. The magnitude of the throttling effect in the investigated range of pressures ($P_1 = 9.8 \cdot 10^4\text{-}29.4 \cdot 10^4$ N/m^2) need not be taken into consideration, since it is insignificant.

The Effect of the Diaphragm Orifice Diameter. We note from numerous studies that the diaphragm orifice diameter exerts considerable influence on the energy and temperature efficiency of a vortex tube. The maximum values of the latter in vortex cooling units with conical hot ends are found at various diaphragm orifice diameters, which is precisely the case with vortex cooling units with cylindrical hot ends [1].

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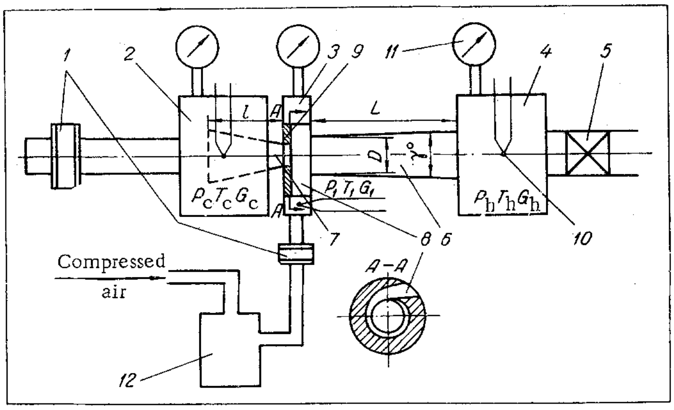

Fig. 1. Experimental installation: 1) Venturi tubes; 2) cold-flow receiver; 3) interflow receiver; 4) hot-flow receiver; 5) regulating valve; 6) hot end of cooling unit; 7) cold end of cooling unit; 8) coil; 9) diaphragm; 10) thermocouple; 11) manometer; 12) air dryer.

The characteristics of the vortex cooling unit were constructed for various diaphragm diameters equal to 8, 9, 10, 11.6, 13, and 14 mm ($\bar{d}$ = 0.4, 0.45, 0.5, 0.58, 0.65, and 0.7, respectively). The taper angle of the hot end was 2.5°, while that of the cold end was 18°, with the latter 250 mm long.

Figure 2 shows the maximum temperature and energy efficiency as a function of the diaphragm orifice diameter $\bar{d}$. In the investigated range of π values the maximum value of the temperature efficiency is found for $\bar{d} = 0.45$; the maximum value of $\eta_{e\,max}$ is found for $\bar{d} = 0.58$.

It should be borne in mind that the maximum value of η_t shifts with an increase in the diaphragm diameter toward the larger values of μ (from $\mu = 0.25$ to $\mu = 0.43$ with $\bar{d}$ increasing from 0.45 to 0.65). The pressure at the hot end (or π_1) declines with increasing $\bar{d}$.

The presence of two optimum diaphragm orifice values for $\eta_{t\,max}$ and $\eta_{e\,max}$ is apparently explained by the fact that the cold axial current varies along the diameter in the nozzle cross section with a change in μ. The diameter $\bar{d} = 0.45$ evidently restricts the cold flow in the nozzle cross section when $\mu = 0.25$, while $\bar{d} = 0.6$ accomplishes the same when $\mu = 0.7$. It is entirely possible that the internal cold flow, in terms of its structure, is also nonuniform, since the values of $\eta_{t\,max}$ diminish with a reduction in $\bar{d} < 0.45$.

Since the cold-flow diameter for an optimum value of $\mu = 0.25$ is $\bar{d} = 0.45$ in the nozzle cross section, when the diaphragm diameter increases to $\bar{d} > 0.45$, the cold axial flow will be accompanied by an intermediate flow whose temperature is higher than that of the axial flow. As a result, the maximum value of η_t diminishes and shifts in the direction of larger μ values by the magnitude of the gas flow rate from the intermediate zone. It should be assumed that for each value of μ there exists a unique value for the orifice diaphragm $\bar{d}$. For practical purposes, we need only two of the above-indicated values of the diaphragm orifice.

The Effect of the Hot-End Taper Angle. To determine the effect of the angle of the hot-end taper on the temperature and energy efficiency of a vortex cooling unit, we carried out tests for hot-end taper angles of $\gamma = 1°15'$; 2°; 3°; 4°; 5° and a constant length (L/D = 14) without any additional fittings at this end. The taper angle of the cold end was $\beta = 20°$ and $\bar{d} = 0.58$. The heat from the hot end of the cooling unit was removed through free convection and radiation. The results are shown in Fig. 3.

The curves show that the maximum value for the energy and temperature efficiency is found at a hot-end taper angle of $\gamma = 3°$ in the investigated range of pressure ratios: π = 2, 3, and 4. This can be explained as follows. With an increase in γ the cross-sectional flowthrough area is enlarged, as a result of which the increase in the gas volume resulting from the elevated temperature of the peripheral flow is offset. The entry of the peripheral hot gas layers into the cold core is thus reduced. This effect is in agreement with the results of [2].

It should be borne in mind that in a counterflow vortex tube the hot peripheral and axial cold flows move in opposite directions along the tube axis, and if the hot flow expands with motion along the axis, the cold flow is compelled to experience compression with motion toward the diaphragm or it must mix with

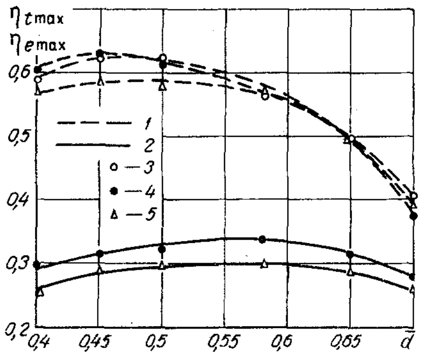

Fig. 2

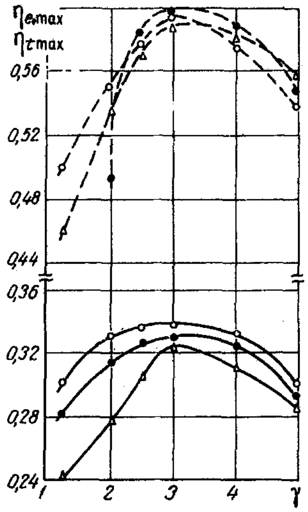

Fig. 3

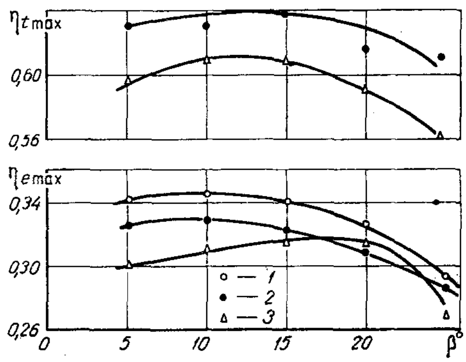

Fig. 4

Fig. 2. $\eta_{t\,max}$ and $\eta_{e\,max}$ vs $\bar{d}$ at $\beta = 18°$; $\gamma = 2.5°$: 1) $\eta_{t\,max}$; 2) $\eta_{e\,max}$; 3) $\pi = 2$; 4) $\pi = 3$; 5) $\pi = 4$.

Fig. 3. $\eta_{t\,max}$ and $\eta_{e\,max}$ vs γ at $\beta = 20°$; $\bar{d} = 0.58$; otherwise as in Fig. 2.

Fig. 4. $\eta_{t\,max}$ ($\bar{d} = 0.45$) and $\eta_{e\,max}$ ($\bar{d} = 0.58$) at $\gamma = 3°$: 1) $\pi = 2$; 2) 3; 3) 4.

the peripheral hot flow, thus reducing efficiency at $\gamma > 3°$. Probably, the expansion of the axial flow with an increase in γ to 3° has a considerably smaller effect than the expansion of the peripheral flow, and this leads to increased efficiency of the cooling unit. In this case, it is doubtlessly the existence of such other factors affecting efficiency – as, for example, the change in the distribution of velocities, pressures, and temperatures – that when $\gamma > 3°$ leads to a reduction in the efficiency of the cooling unit. A more detailed study of this question calls for the measuring of the gas parameters within the vortex tube.

We should take note of the fact that the values of π_1 diminish when μ = const as γ increases. When the taper angle changes from 1 to 3°, the relationship between π_1 and μ can be expressed in the form of a straight line, and beginning with values of $\mu = 0.8$ when $\pi = 4$, the slope of the straight line undergoes a pronounced change, which demonstrates the existence of the two hydrodynamic flow regimes mentioned earlier in [3].

In the taper-angle range between 3 and 5° the function $\pi_1 = f(\mu)$ differs from the linear, although this function, with but slight error, could be expressed in the form of two straight-line segments.

In general form, the function $\pi_1 = f(\mu, \gamma)$ can be expressed by the following approximate relationship when $\mu \le 0.8$ and $\pi = 4$:

$$\pi_1 = (0.07\,\gamma + 0.34)\,\mu - 0.07\,\gamma + 1.52.$$

This relationship is valid when $L/D = 14$, $\bar{d} = 0.58$.

For values of $\mu > 0.8$ the function $\pi_1 = f(\mu, \gamma)$ can be expressed in the following form ($\pi = 4$):

$$\pi_1 = (-0.42\,\gamma + 3.15)\,\mu + 0.35\,\gamma - 0.85.$$

When $\pi = 3$ the values of π_1 can be determined from the relationship

$$\pi_1 = (0.05\,\gamma + 0.12)\,\mu - 0.05\,\gamma + 1.42,$$

where $\mu \le 0.9$, while for $\pi = 2$

$$\pi_1 = (0.02\,\gamma + 0.06)\,\mu - 0.03\,\gamma + 1.24,$$

where $\mu \le 0.9$, while the values of γ should be expressed in degrees. The deviation of the experimental points does not exceed 3%.

The studies showed that the test vortex tube operates efficiently and stably without any additional fittings at the hot end (i.e., a conic throttle, a grid, etc.).

The Effect of the Cold-End Taper Angle. It is demonstrated in [3] that the installation of a diffuser at the cold end of the cooling unit ($\beta = 4°$ and $l = 500$ mm) somewhat increases η_t and η_e. As follows from [10], the tangential velocity component in the nozzle cross section is a substantial quantity relative to the axial component at a diameter of $\bar{d} = 0.5-0.6$.

We can assume without particular error that the cold flow in the cross section of the diaphragm exhibits the same twisting as in the nozzle cross section. The total pressure difference $\pi = P_{01}/P_{0c}$ at our dis-disposal is divided into two parts. The first and primary part of the difference $\pi' = P_{01}/P_h$ represents the gas expansion ratio in the vortex cooling unit, while the second part of the total difference $\pi'' = P_h/P_{0c}$, i.e., the difference at the cold end of the vortex cooling unit, represents the losses at the cold end of the vortex cooling unit. Naturally, the efficient utilization of this second part of the overall difference leads to an increase in cooling-unit efficiency.

However, the problem of an optimum taper angle β has not been completely resolved in the above-cited reference, since in addition to the axial velocity component, the cold flow also involves a tangential component. This provided the impetus for the determination of the effect of β on the efficiency of the cooling unit at a diaphragm orifice diameter close to the optimum ($\bar{d} = 0.58$), and at cold-end lengths $l/d = 11.2$ suitable for practical purposes. The studies were carried out at the thermally insulated hot end. The results are shown in Fig. 4. As we can see from the curves, when $\bar{d} = 0.45$ the maximum value of η_t is found in the range $\beta = 5-15°$ and changes only slightly with increasing β, which is apparently explained by the limited magnitude of the tangential velocity component at $\bar{d} = 0.45$. The energy efficiency η_e when $\bar{d} = 0.45$ undergoes virtually no change with a change in β. When $\bar{d} = 0.58$ the value of $\eta_{e\,max}$ varies with increasing β. The range $\beta = 10-15°$ can be treated as the one that is optimum for the taper angle of the cold end for each of the values investigated. In conclusion, we note the following:

1. The maximum value of the energy efficiency is found with $\bar{d}$ equal to approximately 0.6, while the maximum value for the temperature efficiency is found at $\bar{d} = 0.45$ for all of the investigated values of π. The core of the cold flow in the nozzle cross section is nonuniform. With an increase in $\bar{d}$ the maximum value of $\eta_{t\,max}$ shifts in the direction of larger values of μ.

2. The optimum taper angle for the hot end (from which heat is removed by convection) is 3° for the investigated range of π-values. This angle is optimum both for the maximum energy efficiency and the temperature efficiency.

3. The values of π_1 decline as the taper angle of the hot end (γ) increases and as the diaphragm orifice diameter ($\bar{d}$) increases.

4. The optimum taper angle of the cold end, to achieve $\eta_{e\,max}$ when $\bar{d} = 0.58$ is $\beta = 10-15°$. When $\bar{d} = 0.45$ the effect of the cold-end taper angle within the investigated range is only slight with respect to the efficiency of the cooling unit.

5. A change in the taper angle of the cold end has no effect on the values of π_1.

NOTATION

P_{01} and T_{01}	are, respectively, the pressure and temperature of the stagnated flow at the inlet to the cooling unit;
$\Delta t_c = T_{01} - T_{0c}$	is the gas temperature difference across the cold end of the vortex tubes;
P_{0c} and T_{0c}	are, respectively, the pressure and temperature of the stagnated flow at the cold end of the cooling unit;
P_{0h} and T_{0h}	are, respectively, the pressure and temperature of the stagnated flow at the hot end of the cooling unit;
Δt_s	is the isentropic temperature drop, equal to $T_{01}[1 - (1/\pi)^{(k-1)/k}]$;
k	is the adiabatic exponent which, for air, is equal to 1.4;
μ	is the weight fraction of the cold flow;
$\eta_t = \Delta t_c/\Delta t_s$	is the temperature efficiency of the vortex tube;
$\pi = P_{01}/P_{0c}$	is the gas expansion ratio at the cold end of the vortex tube;
$\pi_1 = P_{0h}/P_{0c}$	is the ratio of incomplete expansion at the hot end of the vortex tube;
γ	is the hot-end taper angle of the vortex tube;
d	is the diaphragm orifice diameter;
D	is the hot-end diameter of the vortex tube, closest to the nozzle section;
$\bar{d} = d/D$	is the relative diaphragm orifice diameter;

L	is the length of the hot end of the vortex tube;
h and b	are, respectively, the height and width of the nozzle;
$\bar{f}$	is the relative nozzle area equal to the nozzle area as a ratio of the lateral cross-sectional area of the hot end, closest to the nozzle;
β	is the taper angle of the cold end;
l	is the length of the cold end.

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