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Abstract. The Hilsch vortex tube was investigated at low operating pressures (gauge pressures less than one atmosphere). A mathematical analysis by Burkhardt was extended to include this pressure range. Except for differences in magnitude, the experimental results were essentially the same as those previously reported in the literature for high pressure tests. However, because of low flow rates, heat exchanges with the environment had a more pronounced effect. The dependence of Hilsch tube heating or cooling upon the specific heat ratio of the working gas was derived for low operating pressures. This result was experimentally verified for argon and air.

The Hilsch tube (or Ranque, or vortex tube, as it is variously named in the literature) is a relatively simple device for separating a stream of compressed gas into hot and cold components. In recent years it has been marketed for small scale refrigeration applications.

The vortex tube was developed by Ranque (1933) who obtained a United States patent in 1934. The invention remained largely unnoticed until Hilsch (1946) published the results of his significant experiments regarding the dependence of optimum performance upon tube design and dimensions. Numerous investigators have since extended the experimental data, sought applications, and attempted to develop theory. Curley (1951) compiled an extensive bibliography of these studies.

The most noticeable Hilsch tube effect is the large temperature difference that may readily be obtained between the hot and cold gas streams at high input pressures. However, to our knowledge, there are no reports in the literature regarding Hilsch tube phenomena at low input pressures. An investigation by Elser (1951) at one atmosphere (gauge pressure) is the lowest input pressure for which data have been published. Hilsch reports no experiments below 1.5 atmospheres.

The study reported here deals with an investigation of Hilsch tube effects at input pressures less than one atmosphere. It is also concerned with an extension of the Burkhardt theory to include this pressure range.

THEORY

The Hilsch tube consists of a straight length of tubing of radius, r, with a control valve at one end and a concentric orifice of radius, b, at the opposite end. The compressed gas is

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introduced through a tangential nozzle of radius, d, into a spiral chamber adjacent to the orifice plate. The tangential entry and the single spiral turn produce a strong vortex motion in the expanding gas. A fraction, μ, of the entering gas, determined by the valve adjustment, passes through the orifice into the atmosphere. This is the cold gas stream. The hot gas stream is discharged through the valve.

Burkhardt (1948) was the first to advance a quantitative hypothesis for the Hilsch tube phenomena. His theoretical results proved to be in reasonable agreement with the measurements presented by Hilsch (for air). Unlike later investigators, Burkhardt made no attempt to explain the mechanism by which a gas is separated into hot and cold components by the Hilsch tube.

Burkhardt assumed a two stage adiabatic expansion of an ideal gas from an input pressure, P, through the nozzle to a pressure, P_t, inside the tube; then through the orifice to an external (atmospheric) pressure, P_a. Expressions were derived for both critical and noncritical (subsonic) flow through the orifice. Because of the high input pressures used by Hilsch, Burkhardt assumed critical flow through the nozzle for either case.

To obtain a mathematical analysis of the low-pressure investigations reported here, it was decided to extend the Burkhardt theory to include the case of non-critical flow through both nozzle and orifice.

The equation utilized by Burkhardt to obtain the mass flow, G, through a nozzle under non-critical conditions is (as approximated for air)

$$G = 2\alpha A \sqrt{\frac{(P_1 - P_2)\, P_2}{T_1}} \qquad (1)$$

where α is a constant and A is the cross sectional area of the nozzle.

For the special case when the Hilsch tube valve is closed, the mass flow through the nozzle must equal the mass flow through the orifice. Then, by equation (1),

$$2\alpha\pi d^2 \sqrt{\frac{(P - P_t')\, P_t'}{T}} = 2\alpha\pi b^2 \sqrt{\frac{(P_t' - P_a)\, P_a}{T_t}}$$

where T_t is the temperature and P_t' is the pressure in the tube for the closed valve condition. Since there is no hot air flow, $T = T_t$. Thus,

$$d^4(P - P_t')P_t' = b\,(P_t' - P_a)\,P_a$$

or,

$$(P_t')^2 + \left(\frac{b^4}{d^4}P_a - P\right)P_t' - \frac{b^4}{d^4}P_a^2 = 0.$$

The solution of this quadratic equation gives the maximum pressure inside the tube:

$$P_t' = \tfrac{1}{2}\left[P - \frac{b^4}{d^4}P_a \pm \sqrt{\left(P - \frac{b^4}{d^4}P_a\right)^2 + 4\,\frac{b^4}{d^4}P_a^2}\,\right]. \quad (2)$$

The internal pressure for any fraction, μ, of the air mass flowing through the orifice (the cold component) may be approximated by assuming it to be a linear function of the maximum tube pressure, i.e.,

$$P_t - P_a = \mu\,(P_t' - P_a). \quad (3)$$

Burkhardt was able to approximate the temperature, T_c, of the cold gas and the temperature, T_h, of the hot gas by assuming a heat transfer (of an undefined nature) between the gas components in the absence of heat exchange with the environment. The limiting conditions for the heat transfer were expressed as functions of the orifice and tube radii. Thus, Burkhardt derived the relationships:

$$\frac{T_h - T}{T} = \left[1 - \left(\frac{P_t}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[(1-\mu)^{\frac{b}{\gamma}-1} - 1\right] \quad (4)$$

$$\frac{T - T_c}{T} = \left[1 - \left(\frac{P_t}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[(1-\mu)^{\frac{b}{\gamma}-1} - 1\right]\frac{1-\mu}{\mu} \quad (5)$$

Where γ is the ratio of the specific heats. Therefore, it is possible to calculate the heating and cooling effects of a particular Hilsch tube, operated at a given input pressure and temperature, by substituting into the above equations the value of the internal pressure as determined from equations (2) and (3).

Apparatus

A Hilsch vortex tube, Fisher type SS-8, was selected for test use. Performance characteristics at high input pressures, as well as other data, were already available for this instrument. (Detailed drawings and laboratory reports are on file at the Fisher Governor Company, Marshalltown, Iowa.) This model is of the same basic design as those tested by Hilsch except that the spiral chamber was machined in a molded nylon insert. The instrument was modified by the addition of a short length of tubing to the orifice end (cold gas outlet). Also, the two valve outlets were converted to a single outlet with a connecting tube for attachment to a flowmeter. The nylon insert served as an insulator between the hot and cold tubes.

Following the method of Hilsch, thermocouples were attached to the walls of the hot and cold tubes and to the inlet pipe. The assembly was thermally insulated.

Rotameters, calibrated for air, argon, and helium were used to measure the relatively small flow rates associated with low input pressures. All measurements were converted to equivalent air flow rates under standard conditions. Since any obstruction of the orifice (cold gas outlet) greatly reduced efficiency, rotameters were connected only to the inlet pipe and the tube valve (hot gas outlet). Thus, the cold gas flow was obtained by subtracting the hot gas flow from total flow. Input pressure was measured with a mercury manometer.

Experimental Results

Numerous tests were conducted with air as the working fluid. The procedure was to operate the tube at a set input pressure while adjusting the control valve to obtain a suitable sampling of flow ratio values. For each adjustment of the valve, rotameter readings were taken; the temperatures of the hot and cold tubes and the inlet pipe were measured by the thermocouples. From five to fifteen sets of data were thus recorded for each selected input pressure. The temperature change (in degrees Centigrade) of the hot gas, $T_h - T$, and of the cold gas, $T_c - T$, was then computed for each value of the cold gas fraction, μ. (During the test periods, the input temperature rarely varied more than one or two degrees from 22°C.)

The dashed curves in Figure 1 were plotted from the experimental results. They are typical performance curves for low input pressures. In form, they are similar to those published by Hilsch for high input pressures. For example, both indicate that the heating and cooling effects are virtually equal at $\mu = 0.5$. Also, the Hilsch curves show a similar shift of the minimum point (maximum temperature drop) toward smaller values of μ as the input pressure is increased.

The location of the minimum point obviously depends upon heat exchange with the environment. As the cold air fraction is decreased, the temperature of the cold tube wall at first drops, but a minimum point will be reached where the heat absorbed from the surroundings will be balanced exactly by the cooling of the air stream. If the cold air flow is further reduced, the cooling effect can no longer compensate for the heat gained and the temperature of the tube wall will rise. For most Hilsch tubes operated at reasonably high input pressures, the minimum occurs near a cold air fraction of two tenths. By contrast, for an input pressure of 0.10 atmosphere (see dashed curve 1 in Figure 1), the minimum is near $\mu = 0.75$.

Table 1. Cold Air Fractions and Extremal Hilsch Tube Temperatures at Selected Input Pressures

Input Pressure (gauge pressure in atmospheres)	Cold Air Fraction	Extremal Temperature (degrees Centigrade) Hot Tube(T_b–T)	Cold Tube(T_c–T)
0.10	.83	2.0°	
	.75		−1.8°
0.35	.90	6.4°	
	.68		−2.5°
0.55	.93	12.5°	
	.50		−3.8°
0.74	.95	15.8°	
	.35		−4.8°
6.7*	.80	106.0°	
	.30		−34.0°
20.0*	.78	112.0°	
	.14		−54.0°
0.55 (argon)	.96	13.5°	
	.72		−5.0°

* Data from Fisher Governor Company.

There is one notable discrepancy between the low-pressure observations and those of Hilsch at high operating pressures. The experimental curves in Figure 1 show a maximum value for the temperature of the hot tube wall, with a steep temperature decrease as μ approaches unity, i.e., as the hot air flow approaches zero. Hilsch reported no such temperature peaks. Instead, the hot tube curves plotted by Hilsch rise continually with increasing μ, indicating a temperature high at $\mu = 1$, i.e., for zero flow through the hot tube. However, the data presented in Table 1 lend support to the Hilsch results. As the input pressure increases, the maximum point shifts toward higher μ values, with $\mu = 0.95$ at 0.74 atmosphere. This maximum must lie very close to $\mu = 1$ at high input pressures. It is interesting to note that the Fisher Governor Company data, for high input pressures, indicate a nearly constant temperature maximum at $\mu = 0.8$. However, the Fisher data represent temperature readings from thermocouples inserted in the flow streams.

It should be observed that the μ values for the minimum temperatures show a much greater shift with respect to input pressure than do those for the maximum temperatures (Table 1). This is to be expected since the cold air flow tends to be axial while the hot air tends to flow near the tube walls.

Several tests were conducted with gases other than air as the working fluid. The maximum and minimum temperatures produced by argon at an input pressure of 0.55 atmosphere are included in Table 1. Greater temperature changes for both hot and cold components were recorded for argon than for air at the same pressure. Elser reported similar results for air and argon at an input pressure of 6 atmospheres.

Experiments also were conducted using helium. Unfortunately, the supply was exhausted before a full set of results could be obtained. However, the temperature changes for both hot and cold components seemed to be less than that produced by air at the same pressure.

Both Ranque and Hilsch reported that vortex tube performance is poor when humid air is used. Corr (1948) studied the effects of humidity in some detail. We had hoped this would pose no significant problem. The cooling produced by low-pressure operation was, as expected, quite small. In fact, the temperature drop was never enough to produce observable fog or icing. Nevertheless, results were extremely erratic for tests conducted in the spring or fall, evidently because of changes in the effective specific heat of the humid air. Only in the winter, when the dew point in the laboratory was below freezing, were consistent results and optimum performance obtainable. The compressor was equipped with a standard line filter, but apparently this was not effective. Future investigators are strongly urged to employ an efficient humidity control.

Comparison of Theoretical and Experimental Results

The maximum pressure within the Hilsch tube was calculated at selected input pressures from equation (2). (For the Fisher tube: b = 4.37 mm, d = 1.59 mm, and r = 9.53 mm.) For a range of input pressures from 0.10 atmosphere to 0.74 atmosphere, the predicted internal pressure varied from 0.002 atmosphere to 0.012 atmosphere. Thus, absolute values of the internal pressure only slightly greater than atmospheric were indicated for low input pressures.

By the use of equations (4) and (5), temperature changes as a function of the cold air fraction were calculated for selected input pressures. The solid line curves in Figure 1 were thus obtained. A comparison of experimental and theoretical curves reveals the greatest departure at low flow rates, i.e., at $\mu \rightarrow 0$ for

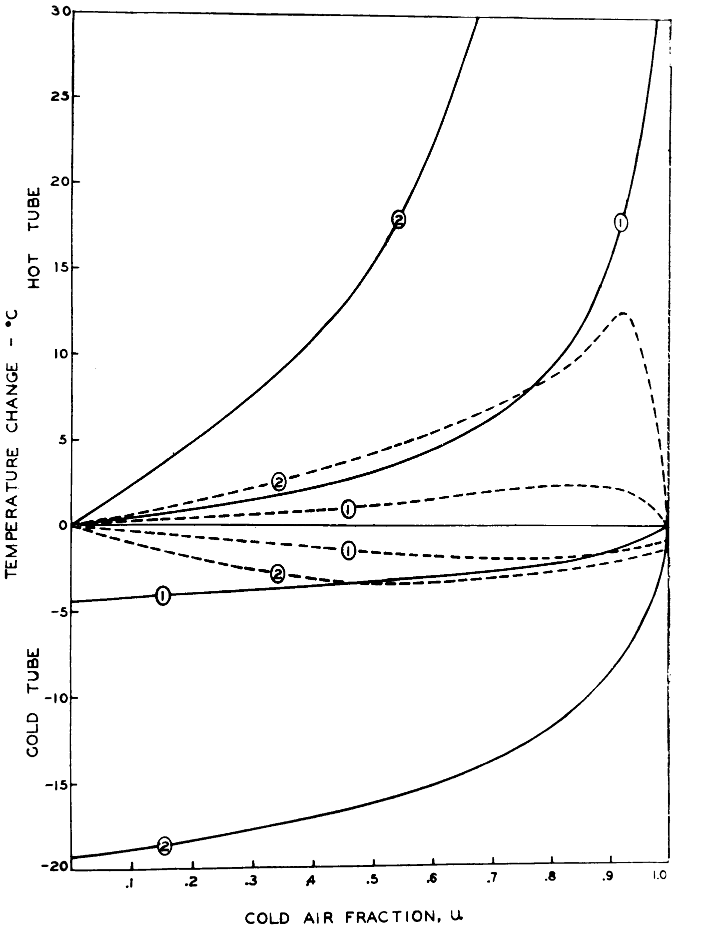

Figure 1. Temperature change vs. cold air fraction. Characteristic curves for Hilsch tube heating and cooling as a function of cold air flow at low input pressures. The dashed curves were plotted from experimental data. The solid line curves represent corresponding theoretical results. Input pressures were (1) 0.10 atmosphere and (2) 0.55 atmosphere.

the cold tube and $\mu \rightarrow 1$ for the hot tube. This is to be expected since Burkhardt assumed no heat exchange with the environment and this effect should be most significant at low flow rates. In fact, for the same reason, the Burkhardt theory is in closer agreement with the Hilsch data than with the low-pressure results. Also, note that actual gas temperatures were calculated whereas the temperatures of the tube walls were measured in the experiments.

An interesting discrepancy, not noted on the scale of Hilsch's results, was the cooling obtained by experiment for total flow through the cold tube. The theoretical curves show $T_c - T = 0$

at $\mu = 1$, because ideal flow had been assumed with the additional constraint that the input and internal temperatures would be equal in the absence of hot air flow. The amount of cooling, about 1°C in magnitude, is too great under these conditions to be attributed to a departure from the ideal gas law, i.e., the Joule-Thomson effect. This phenomenon had been previously noted by Johnson (1947) for high input pressures. However, Green (1959) showed that cooling the outer surface of the hot tube lowered the temperature of the cold air to a significant extent even when the hot air valve was closed. Presumably incomplete thermal insulation around the hot tube should account for the reported anomaly.

The fact that for low input pressures $P_t \approx P_a$ generalizes the results of equations (4) and (5). (Equation (2) had been derived specifically for air.) Accordingly, for any given tube, input pressure, and cold fraction, the temperature changes should depend only upon the specific heat ratio. This conclusion was tested against the experimental results for argon and air at an input pressure of 0.55 atmosphere. For air, $\gamma \approx 1.40$ and $\frac{\gamma - 1}{\gamma} = .286$; for argon, $\gamma = 1.67$ and $\frac{\gamma - 1}{\gamma} = .401$. Using these values in either equation (4) or (5), the ratio

$$\frac{\Delta T_{air}}{\Delta T_{argon}} = \frac{1 - \left(\frac{P_a}{P}\right)^{.286}}{1 - \left(\frac{P_a}{P}\right)^{.401}}$$

is obtianed for equivalent values of μ. This ratio may be approximated by a binomial expansion as follows:

$$\frac{\Delta T_{air}}{\Delta T_{argon}} = \frac{1 - \left(1 - \frac{P - P_a}{P}\right)^{.286}}{1 - \left(1 - \frac{P - P_a}{P}\right)^{.401}} \approx .713.$$

The same ratio was computed from the experimental results by dividing each temperature change for air by the corresponding change for argon at the same cold fraction. The average of these values, for both heating and cooling, was .701, i.e., the heating or cooling of air was only about seven tenths as much as that for argon. However, on the basis of incomplete data, it is our opinion that this test would not have been successful for helium.

Conclusions

Except for differences in magnitude, Hilsch tube phenomena at low input pressures seem to be substantially the same as those observed at high pressures. However, because of low flow rates, effects produced by heat exchange with the environment are more pronounced.

From an extension of the Burkhardt theory to include low operating pressures, the relative dependence of Hilsch tube heating or cooling upon the specific heat ratio of the working gas was plausibly established. This result was experimentally verified for argon and air. The relationship should be tested for other gases.

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