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Low-pressure vortex tubes

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Abstract. The temperature separation effect, which is well known from standard vortex tubes that are driven by compressed air, has been observed in a device where air is sucked into the tube by applying vacuum at the hot and the cold exit ports. Rather than depending on the absolute inlet pressure, the temperature separation was found to be a linear function of the normalized pressure drop $X = (p_0 - p_c)/p_0$ between the inlet and the cold end of the vortex tube.

1. Introduction

A vortex tube is a very simple mechanical device without any moving components, which separates a stream of gas of inlet velocity u_0 into a hot and a cold component. From a gas flow with an inlet temperature $T_0 \approx 290$ K available at an upstream inlet pressure of $p_0 = 3$ bar one can typically obtain a hot stream of $T_h = 320$ K and a cold stream of $T_c = 265$ K. For a given vortex tube the temperature splitting changes with the inlet pressure and the ratio of the cold and the hot mass flows j_c and j_h. The pressures in the hot and cold flows arrange themselves as $p_0 > p_h > p_c$, where the cold gas pressure is generally the ambient pressure $p_c = 1$ atm.

The vortex tube was discovered by Ranque [1] and first described in detail by Hilsch [2]. Vortex tubes are now commercially used [3] for low-temperature applications, e.g. to cool parts of machines, to set solders, to cool electronic control cabinets, to chill environmental chambers, to cool food, to test temperature sensors, and they are also applied to dehumidify gas samples [4].

Recently it has been proposed that vortex tubes could be used as components in refrigeration systems replacing the conventional expansion nozzle in order to increase the efficiency [5]. The coolants in refrigeration systems pass through a thermal cycle in which the pressure may well drop below atmospheric. However all previously reported vortex tubes were operated at high entrance pressures, which ranged from about 2 to 10 atm. In these experiments the pressure never dropped below one atmosphere. It is therefore not experimentally proven that vortex tubes will indeed yield the temperature splitting effect in the intended low-pressure environment. Based on our recent model calculations [6] we conclude that the effect depends on the normalized pressure ratio $X = (p_0 - p_c)/p_c$ rather than on the absolute values of the entrance pressure p_0 and exhaust pressure p_c. It should hence be possible to operate a vortex tube as a suction device with atmospheric intake pressure, provided p_c and p_h are kept below one atmosphere. This has been verified by experiments with a suction vortex tube, arranged as shown in figure 1.

2. Background

In a vortex tube a stream of air is injected tangentially at high speed through one or several nozzles. The air flow separates into a cold component issued from a small hole on the axis close to the inlet plane and a hot component that leaves through a large orifice at the other end. All reported vortex tubes have been given by a gauge pressure in the range of 2–10 atm.

This ‘temperature separation’ has baffled investigators for over 60 years since heat seems to be travelling in the wrong direction, namely from the cold to the hot part of the flow. The working fluid starts in a plenum chamber at practically zero velocity. It gains kinetic energy and loses temperature as it passes through the inlet nozzle into the vortex tube. It splits into a cold and a hot component which each circle around in the tube and eventually emerge either on the hot side or on the cold side of the device. Typically each flow component then passes through a slow down section where it must lose all its kinetic energy. Assuming adiabatic and frictionless flow of an ideal gas, each one of these flow components should emerge with the same temperature, namely the entrance temperature T_0.

Of course no process is truly adiabatic. For instance as the gas speeds up in the entrance nozzle and its temperature sinks below ambient some heat will flow into the gas. We previously modelled this step as an isothermal process [6] and derived limits for the temperature separation. To test if an adiabatic or an isothermal model represents the inlet process more correctly we have recently measured the pressure and the temperature directly in the nozzle throat, and we observed that the flow is more closely adiabatic than isothermal. These results will be discussed in a forthcoming publication.

However, many reported measurements and our own experiments indicate that there is a definite flow of energy from the cold to the hot flow component. This anomalous heat flow is indeed hard to understand. Several different qualitative theories have been offered to explain this strange temperature splitting effect: internal friction with various

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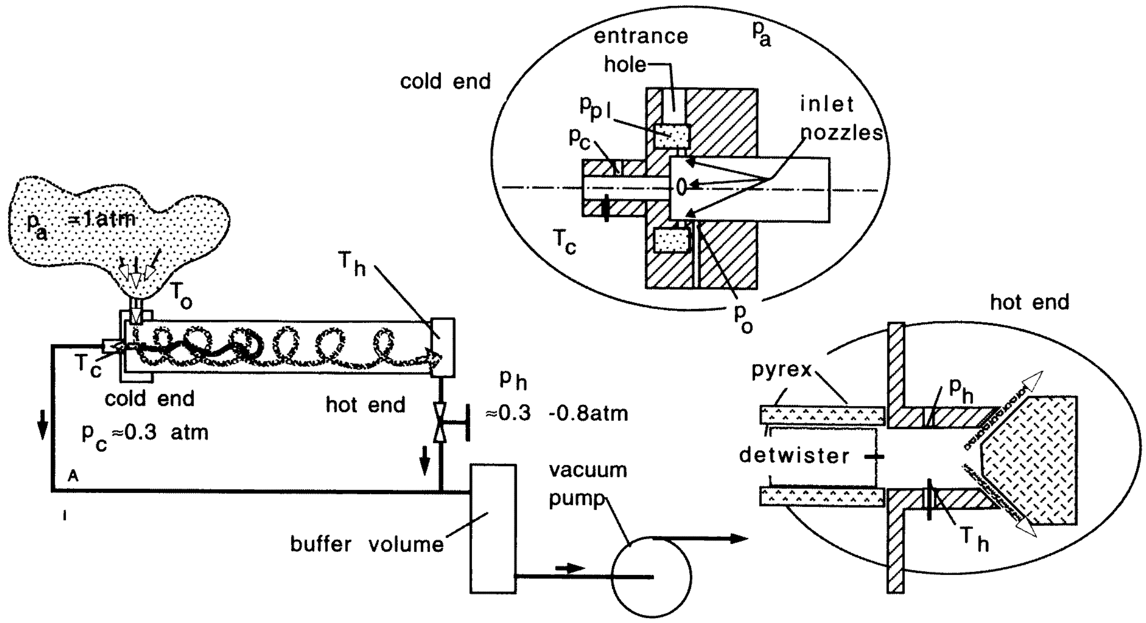

Figure 1. Vortex tube driven by vacuum pump. The insets show the inlet plenum chamber and the hot end.

assumptions about the radial and axial velocity distribution [7]; turbulent heat transfer in a stratified flow [8]; Goertler vortices [9]; compressibility of the working fluid [10]; turbulent transfer of thermal energy in an incompressible flow [11]; effects associated with the particular working fluid [12]; or acoustic streaming processes [13] leading to increased flow velocities which therefore enhance the kinetic energy available for conversion into heat.

For the use of vortex tubes in refrigeration and dehumidification applications the question of how the vortex tube functions is less important than the question of if it works at all below atmospheric pressures. This question has been positively answered by the experiments reported here.

3. Experiments

For the experiments we used a modular vortex tube. It consisted of a Pyrex tube of 25.4 mm inner diameter and 60 cm length, which was held between brass ends containing the inlet–cold gas exit and the hot gas nozzle (see figure 1). Air was drawn through the device by a vacuum pump with plenum chamber, connected directly to the cold end and affixed through a throttle valve to the hot end. This valve allowed one to change the hot gas pressure p_h relative to the cold gas pressure, thereby permitting adjustment of the cold gas fraction $Y = j_c/(j_h + j_c)$ to any desired value between 0.05 and 0.95. For a given vortex tube the cold and the hot exit temperatures are distinct functions of p_0 and Y. By applying suction at the exit holes of the vortex tube air of atmospheric pressure was drawn through an entrance hole into the plenum chamber which supplied the four equally spaced nozzles of the vortex tube, three of which are shown in the inset of figure 1.

The pressures were measured with the help of strain gauge sensors whose electrical signals were recorded by computer. The cold gas pressure was measured a few centimetres downstream of the cold exit port. The hot gas pressure tap was located between a detwister and the hot exhaust valve. We also measured the pressure p_{pl} in the plenum chamber that supplied the four entrance nozzles, and recorded the pressure p_0 inside the vortex tube very close to the entrance nozzles. The pressure at the intake of the vortex tube was always the ambient barometric pressure $p_a \approx 101.3$ kPa. However the pressure in the plenum chamber is somewhat lower. In order to vary the mass flow fraction Y the pressure p_h must be adjusted relative to the cold exit pressure p_c. This was accomplished with the help of the valve shown in figure 1. The vortex tube may hence be considered as a branched flow system where the mass flow ratio $Y = j_c/j_0$ can be adjusted by a single valve in the hot branch. Of course a change of the valve setting also alters the total resistance of the two parallel branches, so that the pressure in the plenum chamber p_{pl} and inside the tube p_0 must also vary when Y is altered. For the desired variation of the mass flow ratio in the range $0.05 \leq Y \leq 0.95$ the plenum chamber pressure adjusted itself in the range 91 to 94 kPa, while the hot and the cold end pressures varied from 33 to 67 and 33 to 58 kPa respectively.

The temperatures at the locations shown in figure 1 were measured with iron–constantan thermocouples, type J gauge 24, inserted into the measuring volumes through Wilson vacuum seals. An ice bath was used at the reference junction of each thermocouple. Data were recorded with a signal processing unit on an XT computer via a DT-2805 12-bit A/D board. The board allowed programmable gains of 1, 10, 100, 500 and an input range of ±10 V. A computer program was written to operate

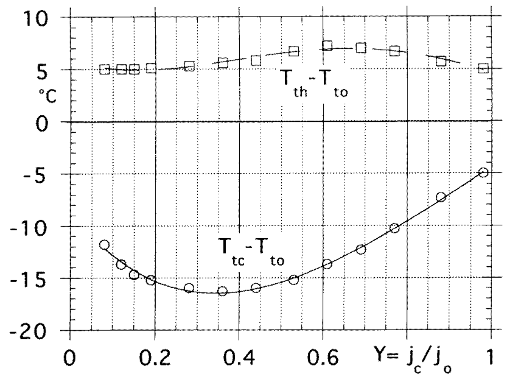

Figure 2. Exit temperatures for vortex tube with atmospheric inlet pressure.

the board. The program allowed real time recording of the measurements on the screen, averaging of the data, selecting of gain and it included user control to save the desired measurements.

Temperature measurements in moving fluids are not as simple as pressure measurements [14]. The actual gas temperature T would be found by a device that moves at the velocity u with the flow, so that it is in thermal equilibrium with the fluid locally. When a probe is inserted into a moving fluid, some of the flow stagnates and the pressure increases on the upstream side of the probe. If the entire flow came to rest, a probe would measure the 'total' temperature $T_t = T + u^2/2c_p$, where c_p is the specific heat at constant pressure. The component $u^2/2c_p$ is sometimes referred to as the 'dynamic temperature' T_d. A probe inserted into a flow only stops the flow partially. To account for this effect a dynamical correction factor $K = 0.75$ for cylindrical temperature sensors has been introduced [14] which permits one to obtain the actual gas temperature T from the temperature T_p measured by the probe using

$$T = T_p - KT_d = T_p - Ku^2/2c_p.$$

For accurate temperature measurements it is hence necessary to know the local flow velocity u at the locations of the thermocouples. Approximate values of u_c and u_h were derived from the known mass flows j_c and j_h [15]. Typically u_c was found to be ≈ 50 m s^{-1}, while u_h was about an order of magnitude smaller.

The vortex tube with atmospheric inlet pressure was operated for a variety of cold gas fractions $Y = j_c/j_0$. The temperature measurements are shown in figure 2.

Clearly the temperature splitting effect is obtained. The cooling is well developed, but it appears as if the heating is not quite as pronounced. We have lately become aware that varying the moisture content of the ambient air will change the thermal capacity of this working fluid significantly and hence contribute to variations of the temperature change ΔT. This effect could easily amount to several degrees and it should be more pronounced in the hot flow component than in the cold stream.

To put the temperature measurements into perspective several high-pressure curves for the same vortex tube are

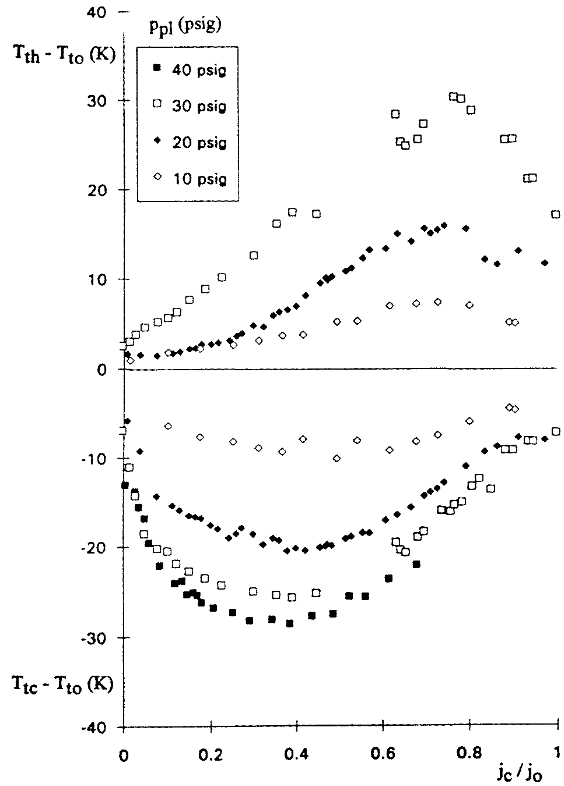

Figure 3. Total temperature separation for vortex tube operated with compressed air.

given in figure 3. For these sets the plenum chamber pressure p_{pl} was held constant. In these measurements the vortex tube was operated with compressed air from a tank that was replenished by a small compressor. Unfortunately this supply had a limited capacity. For the highest pressures of this series (40 psig) there was not enough time to reach thermal equilibrium at the hot end of the tube, owing to the large thermal mass of the hot end valve. For that reason no steady state temperatures T_h could be obtained.

It was predicted from the analysis of reference [6] that the temperature splitting should depend on the normalized pressure drop $X = (p_0 - p_c)/p_c$, rather than on the absolute pressure p_0. For each experimental run the inlet pressure p_0 (measured inside the vortex tube very close to the entrance nozzle) and p_c were recorded, so that X was known. A good figure of merit for the temperature splitting is the maximum (total) temperature difference $T_{th} - T_{tc} = \Delta T_{hc,max}$ between the hot and the cold component. X and $\Delta T_{hc,max}$ are given in table 1 for several entrance pressure conditions. In order to show how well the vacuum values fit into the general scheme $\Delta T_{hc,max}$ is plotted in figure 4 as a function of X.

The value of $X = 0.19$ for 'vacuum' operation falls in the middle of the range of the standard 'compressed air' values. The temperature splitting for vacuum operation, $T_{hc,max} = 23\,^\circ$C, lies well on the line established for the standard experiments.

In conclusion, a vortex tube behaves identically in the above and below atmospheric pressure regimes. Essential

Table 1.

	Vacuum	Compressed air		
Entrance/plenum pressure (Pa)	$p_a = 2.47 \times 10^5$ (= 1 atm)	$p_{pl} = 2.47 \times 10^5$ (= 10 psig)	3.47×10^5 (= 20 psig)	4.47×10^5 (= 30 psig)
$\Delta T_{hc,max}$ (°C)	23	15	33	45
$X = (p_0 - p_c)/p_0$	0.19	0.16	0.24	0.29

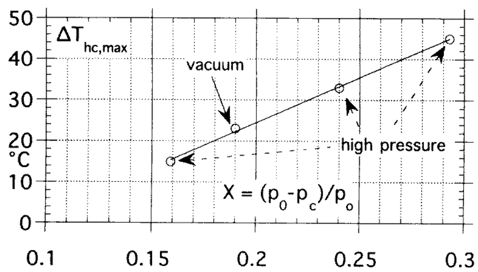

Figure 4. Maximum temperature separation $\Delta T_{hc,max}$ as a function of the normalized pressure drop $X = (p_0 - p_c)/p_0$.

for the temperature splitting is the normalized pressure drop X and not the absolute entrance pressure. This experimental observation allows safe incorporation of vortex tubes in closed cycles that may go below atmospheric pressures for cooling and dehydration applications.

Acknowledgments

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