An experimental research on a small flow vortex tube at low temperature ranges

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A small flow vortex tube operating in low temperature below 80 K was developed. Experimental results show that there is still significant separation effect of vortex tube below 80 K for some inert gases. With LN_2 pre-cooling, the lowest temperature of 60.2 K and 3.3 W refrigeration at 67.5 K has been first achieved using a closed-cycle vortex tube refrigeration system. And an interesting inverse temperature effect was found when the cold mass fraction is less than 0.38. These achievements can help thoroughly understand the mechanism of energy separation in the vortex tube and use the vortex tube in some potential situations.

INTRODUCTION

The separation of a gas stream entering into a tube through one or several tangential nozzles into two streams with different stagnation temperatures (the Ranque-Hilsch effect) is a phenomenon which has been investigated long time. Because it has no moving parts and consists mainly of a simple tube, the vortex tube has been used in some special fields [1]. Many works found in open literatures have focused on experimental and analytical investigations of describing the characteristics of the vortex tube. Hilsch [2] and Bruun [3] conducted important experimental investigations on vortex tube. Theoretical and analytical descriptions of the energy separation and the temperature and velocity profiles in a vortex tube were given by Deissler and Perlmutter [4] and Ahlborn [5]. Stephan [6] performed the mathematical investigation of energy separation in the vortex tube. Lewins and Bejan [7] developed the heat-exchanger analogy modeling. Recently, Neills and his colleagues [8] attempted to use vortex tube to replace the traditional expansion instruments in refrigeration system. Using a vortex tube instead of the traditional throttle valve, Luo etc. [9] developed a new mix-refrigerant auto-cascade refrigeration cycle. However, most of them paid attention on the performance of the vortex tube only in normal ambient temperature range, and there are very few articles concerning the characteristic of the vortex tube below 80 K.

The performance of the vortex tube depends on many geometrical and physical parameters. In order to understand the influence of the absolute gas temperature and to apply the vortex tube in low temperature conditions, it is necessary to carry out some experiments at low temperature range. The goal of this work is to investigate the characteristics of a vortex tube at low temperature.

EXPERIMENTAL RESEARCH

A closed-cycle vortex tube refrigeration system has been built in our laboratory (see Figure 1). The compressed gas without any solid particles or lubricating oil is supplied by a diaphragm compressor. The after cooler, LN_2 pre-cooler and several counter-flow heat exchangers cool the high pressure gas to required temperature before entering the vortex tube. The high pressure gas with a temperature less than 80 K expands in the vortex tube and then is divided into cold and hot streams. The cold gas leaves from the central orifice near the entrance nozzle, while the hot gas discharges from the periphery at the far end of the tube. The flow ratio of the cold gas to the hot gas is controlled by a control valve. A copper electric heating coil installed on the cold end of the vortex tube is used to test the refrigeration of the vortex tube. Two returning gases are measured by two rotameters respectively before flowing back to the inlet of the compressor. For the system operating in low temperature, the thermal insulating performance is very important. So the cryostat is placed into a vacuum tank and a high-performance vacuum pump is employed to guarantee a good thermal insulation.

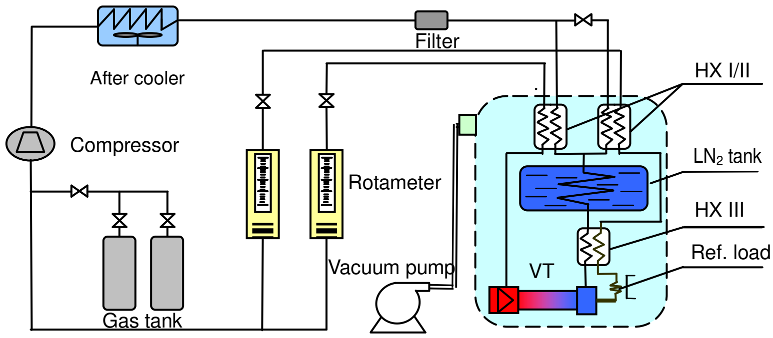

Figure 1 The schematic diagram of the experimental system

The vortex tube investigated in this work (see Figure 2) is built based on our preliminary experiments. It consists of a long conical tube, a vortex chamber, several nozzles, a control valve and some fixing and sealing parts. All parts are made by stainless steel. The essential dimensions are presented in Table 1.

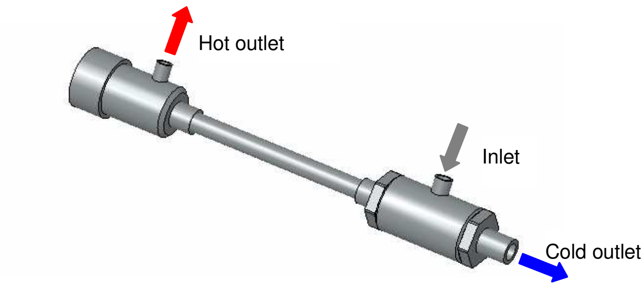

Figure 2 3D appearance of the vortex tube

Table 1 Specifications of the vortex tube

Tube Characteristics	
Length of tube, L(mm)	120
Cone angle of tube	2°32'
Diameter of tube, D(mm)	5
Number of inlet nozzle	2 or 4
Diameter of nozzle, d_n(mm)	0.3
Diameter of orifice, d_c(mm)	3

Two rotameters with an accuracy of ±2.5 % are used to measure the cold and hot flow stream rate, respectively. All temperatures are measured by Pt100 thermometers, which are calibrated in a large temperature range from 52 K to 323 K with an accuracy of ±0.1 K. All temperatures are recorded by a high precision data acquisition system [Keithley Model 2700]. Three manometers with an accuracy of ±0.4 % are used to measure the pressures of the inlet and two outlets.

EXPERIMENTAL RESULTS AND DISSCUSSION

The performance of the vortex tube can be evaluated with following parameters: cold mass flow fraction μ, cold gas temperature difference ΔT_c, hot gas temperature difference ΔT_h, isentropic temperature efficiency η_s and isentropic temperature difference ΔT_s, which can be expressed as follows:

$$\mu = \frac{\dot{m}_c}{\dot{m}_i} \tag{1}$$

$$\Delta T_c = T_c - T_i \tag{2}$$

$$\Delta T_h = T_h - T_i \tag{3}$$

$$\eta_s = \Delta T_c / \Delta T_s \tag{4}$$

$$\Delta T_s = T_i - T_s = T_i \left[1 - \left(\frac{p_c}{p_i} \right)^{(k-1)/k} \right] \tag{5}$$

With $\dot{m}_c$: cold flow mass, $\dot{m}_i$: inlet flow mass, T_i: temperature of inlet gas, T_c: temperature of cold flow, T_h: temperature of hot flow, p_i: pressure of inlet, p_c: pressure of cold outlet.

A series of experiments were carried out at different conditions. Figure 3 shows a typical cool-down curve with LN_2 pre-cooling. It shows that the temperatures of inlet, cold and hot outlets sharply decreased within first 35 minutes after start-up. After about 70 minutes, the temperature of cold end of the vortex tube reached 62 K. And the temperatures of hot and cold ends are less than that of inlet of the vortex tube. The variation of temperatures of inlet, cold and hot gas versus the cold mass flow fraction are shown in Figure 4, which shows a significant temperature separation effect as same as that of the common vortex tube operating in normal ambient temperature. And a surprising and seldom reported abnormal phenomenon was found that when the cold mass flow fraction decreased to about 0.38, the temperature of cold end was higher than that of hot end. We called this “inverse temperature effect”.

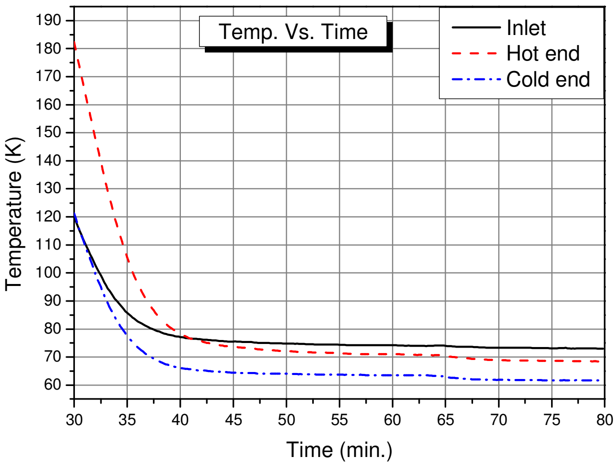

Figure 3 Operating curve

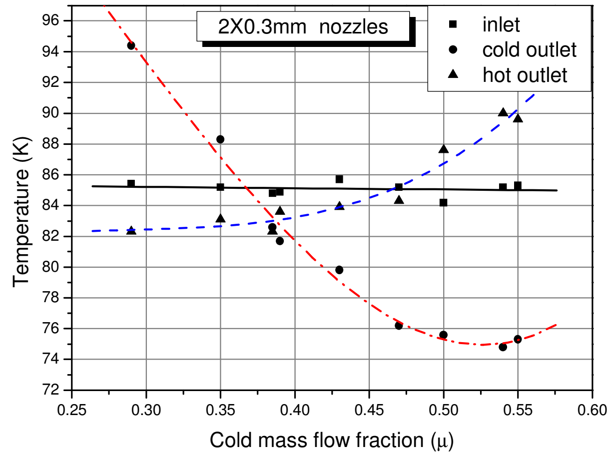

Figure 4 Typical performance at P_i=2.60MPa

The influence of the inlet pressure on the cold and hot gas temperature differences is also investigated by changing the inlet pressure from 1.70 MPa to 2.60 MPa. Figure 5 shows the variations of the cold and hot gas temperature differences versus the cold mass flow fraction at different inlet pressures. As shown in result curves, a higher inlet pressure increases the absolute value of the cold gas temperature difference and decreases the hot gas temperature difference.

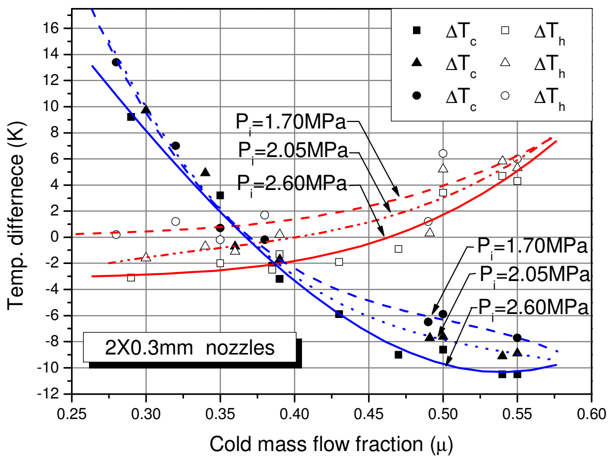

Figure 5 Performance at different inlet pressures

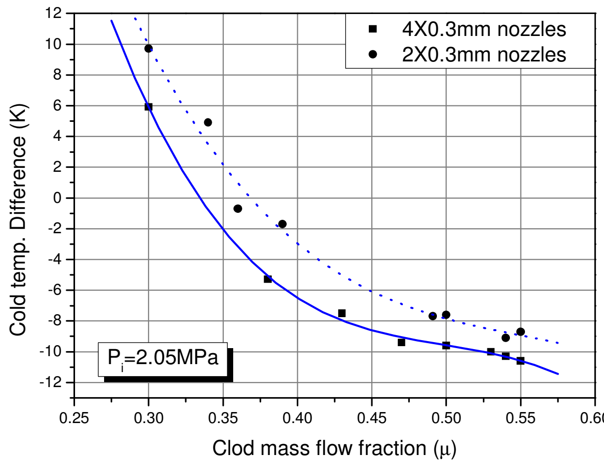

Figure 6 Performance with different inlet nozzles

To study the effect of the inlet nozzle on the performance, two different nozzle types were designed and fabricated. One has two nozzles with inner diameter of 0.3 mm uniformly distributed along periphery, and the other has four equal ones. The variation of the cold gas temperature difference versus the cold mass flow fraction is shown in Figure 6. The result shows that the vortex tube with four 0.3 mm nozzles gives a better performance than the other from the point of the cold gas temperature difference. In order to gain the lowest refrigerating temperature, the entrance with four 0.3 mm nozzles is used.

To know the influence of the substances on the performances of the vortex tube, neon and helium were used in our experiments, respectively. The maximum cold gas temperature difference was measured at inlet pressure of 2.05 MPa. In experiment using neon, the maximum cold gas temperature difference is 9.1 K, which is higher than the 4.9 K attained using helium as working gas. Therefore, neon shows a higher performance for gaining the lowest refrigerating temperature in this experimental system.

Table 2 presents the lowest refrigerating temperatures at differential inlet pressures under optimum conditions. With LN_2 pre-cooling, the lowest refrigerating temperature of 60.2 K and 3.3 W refrigeration at 67.5 K has been successfully achieved by a closed-cycle vortex tube refrigeration system.

Table 2 Lowest refrigerating temperature at different inlet pressures

Inlet pressure P_i (MPa)	Total flow rate (Nm^3/h)	Inlet temp. T_i (K)	Cold temp. T_c (K)	Hot temp. T_h (K)	Efficiency η_s (%)
2.03	8.6	74.0	63.3	70.8	20.0
2.30	9.2	73.0	61.7	68.5	21.8
2.37	9.4	72.5	60.8	67.5	22.8
2.40	9.5	71.6	60.2	66.9	22.7

CONCLUSIONS

A new fabricated vortex tube and closed cycle refrigeration system operating at low temperature were developed. Systematic experiments at different geometrical and physical conditions were carried out to test the performance of the vortex tube at temperature less than 80 K. Such conclusions can be summarized as follows:

1. At the temperature below 80 K, there is still evident temperature separation effect in the vortex tube, this make it possible to use the vortex tube in low temperature range.
2. The pressure of the inlet has a great influence on the temperature separation. Increasing inlet pressure simultaneously decreases the hot and cold temperatures of the vortex tube. And for the cold effect, neon is found better than helium. The four 0.3 mm nozzles configuration gives a better performance.
3. The cold mass flow fraction is a key parameter for the performance of the vortex tube. When μ decreases to less than 0.38, an "inverse temperature effect" will emerge, this provides some new evidences for the thorough understanding of the energy separation mechanism in vortex tube.
4. With LN_2 pre-cooling, the lowest temperature of 60.2 K and 3.3 W refrigeration at 67.5 K has been first time achieved.

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REFERENCES

1. Bruno T.T, Laboratory application of the vortex tube, Journal of Chemical Education (1987) 64 987-988
2. Hilsch R., The use of the expansion of gases in a centrifugal field as a cooling process, Review Sciences Instruments (1947) 18 108-113
3. Bruun H.H., Experimental investigation of the energy separation in vortex tube, Journal Mechanical Engineering science (1969) 11 567-582
4. Deissler R.G., Perlmutter. M, Analysis of the flow and energy separation in a turbulent vortex, International Journal of Heat & Mass Transfer (1960) 1 173-191
5. Boye Ahlborn, Stuart Groves, Secondary flow in a vortex tube, Fluid Dynamics Research (1997) 21 73-86
6. Stephan K., Lin S., An investigation of energy separation in a vortex tube, International Journal of Heat & Mass Transfer (1983) 26 341-348.
7. Lewins Jeffery, Bejan Adrian, Vortex tube optimization theory, Energy (1999) 24 931-943
8. Gregory F.Nellis, The application of vortex tube to refrigeration cycles, The 9th International Refrigeration and Air Conditioning Conference, Purdue, USA (2002) 85-92
9. Luo Er.C, Gong M.Q, etc., A new type cascade refrigeration cycle using mix-refrigerant fraction and vortex tube, Chinese patent, CN00316710.2, (2002)