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The influence of working gas characteristics on energy separation of vortex tube

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HIGHLIGHTS

- Test device was designed, and R728, R744, R32, R22, R161, R134a were selected as working fluids.
- Performance of the vortex tube for energy separation with different working fluids was studied.
- Thermal diffusivity, kinematic viscosity and thermal conductivity were considered as main factors.
- Isenthalpic throttling effect of working fluids affected the cooling effect of the vortex tube.
- The conditions for the liquefying phenomena using HFCs were evaluated.

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ABSTRACT

Currently, little research has been done regarding the influence of working gases, especially HFCs, on energy separation in vortex tubes. Based on this, a vortex tube performance test device was designed, R728, R744, R32, R22, R161, R134a were selected as working fluids. The inlet pressure of the vortex tube was changed from 0.2 MPa to 1.3 MPa (abs), and the inlet temperature was adjusted to about 12 °C. The performances of the vortex tube with different working fluids were tested. It was found that the temperature separation and outlet pressure increased with the rise of inlet pressure for R728 and R744, but there was an extreme value for R744 when the inlet pressure reached about 1.1 MPa (i.e. when the temperature reached a peak point of about 15 °C), and three fluid characteristics (specific heat ratio, kinematic viscosity, thermal conductivity) were considered as main influencing factors of energy separation. The isenthalpic throttling effect of the working fluids also influenced the cooling effect of the vortex tube. In addition, the wall temperatures of the vortex tube hot end were measured; the phenomena of the cold end of the vortex tube were observed; and the conditions for the liquefying phenomena using HFCs were evaluated.

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1. Introduction

The vortex tube is an effective energy separation device which is structurally simple and has no moving parts [1]. It can separate a high pressure gas into two fluids with distinctly different temperatures, hot and cold [2].

Although Ranque patented the first vortex tube in 1934, Hilsch [3] improved the design of vortex tube and did many experiments to study its principle. He thought that the friction of the vortex gas was the main reason which made the temperature gradient in the vortex tube. Fulton [4] also did research with vortex tubes and agreed with Hilsch's conclusions. In order to understand the inner counter flow of a vortex tube, Bruun investigated the characteristics of gases with different initial velocities, temperatures and pressures, etc. [5]. The experimental results showed that the initial velocity was predominantly tangential. On the other hand, Kurosaka [6] demonstrated through theoretical analysis and experiment that the acoustic streaming induced by orderly disturbances within the swirling flow was caused by the Ranque–Hilsch effect. Ahlborn and Gordon [7] quantified the performance of vortex tube as a thermodynamic machine and developed simple analytic formulas for the temperature and pressure profiles within the tube. In experiments carried out by Wang et al. [8], a vortex tube with six channels was chosen. The results showed that the cooling effect and the heating effect of the vortex tube increased with the increase of the inlet pressure, and the cold mass flow fraction decreased with the biggest cooling and heating effects. Xue [9]

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studied the effect of the angle of rotating flow on the performance and efficiency of the Ranque–Hilsch vortex tube. Dincer et al. [10] conducted the exergy analysis and experimental investigation of a vortex tube with various nozzle cross-section areas. It was found that the exergy efficiency strongly depended on the level of inlet pressure, fraction of cold flow, and the velocity of cold stream.

In the above-mentioned work, many workers had conducted some basic research regarding the performance of the vortex tube for energy separation, and the conclusions were mainly obtained by using air as the working gas. However, the performance of the vortex tube is also influenced by the characteristics of working gases [11]. Based on these considerations, performance experiments of vortex tubes with different fluids (except air which is studied so much as working gas in vortex tube) have been conducted, and some of the outcomes are summarized in Table 1.

As shown in Table 1, it can be seen that these researchers mostly focused on the energy separation effect of different gases (i.e. air, O_2, N_2, He, CO_2). However, some problems still need to be addressed, for example, working gases such as HFCs widely used in refrigeration and air conditioning, have rarely been studied in previous research, and the influence of working gas characteristics on the energy separation in vortex tubes has not been fully discussed.

Table 1
Researches of vortex tube with different fluids.

Year	Researcher	Fluid	Outcome
1957	Martynovskii [12]	Ammonia, CH_4, CO_2	When $Pr_{turbulent} < 0.5$, a temperature reversal occurs: the hot fluid flows from the cold end and the cold fluid flows from the hot end. This phenomenon was not explained.
1971	Williams [13]	Methane-rich mixture	Under a given outlet pressure, low temperature of inlet gas led to the gas being liquefied in the vortex tube, thus decreasing the effect of energy separation.
1979	Collins [14]	Two-phase propane	When inlet pressure $p_{in} = 0.791$ MPa and quality $x < 80\%$, then the temperature separation effect decreased.
1988	Balmer [15]	Water	When inlet pressure $p_{in} = 20–30$ MPa, temperature separation (10–20 °C) could be obtained in the exit, and all outlet temperatures were higher than the corresponding inlet temperatures.
1995	Jin [16]	Two-phase fluid which consisted of water and air	The vortex tube with the liquid also had the effect on energy separation.
1997	Keller [17]	R22, R134a, R744	Simulating the system with R22, R134a and R744, and the COP of the system using R22, R134a and R744 increased by 5%, 10%, 2.5% respectively, while the COP of the system using R22 by the experiment increased by 1.5%.
2003	Poshernev [18]	Natural gas	The outcome was similar to that of Williams [13].
2005	Cao [19]	N_2, Ne, He	The fluid with small coefficient of thermal conductivity enhanced the effect of energy separation in the vortex tube. N_2 had the lowest coefficient of thermal conductivity.
2006	Dincer [20]	O_2, N_2, CO_2	Compared with O_2 and N_2, CO_2 could attain lower temperature of hot fluid and cold fluid.
2006	Aydin [21]	Air, O_2, N_2	The molar mass of N_2 was smaller than that of O_2, thus its energy separation effect was better.

Building on these previous works, the current project will expand the scope regarding the influence of working gas characteristics on the energy separation effect in vortex tubes. In the experiment, the fluids to be evaluated are R728 (nitrogen), R744 (carbon dioxide), R32, R22, R134a and R161. Also, the performance of energy separation in the vortex tube will be obtained when the inlet pressure is changed.

2. Experimental study

2.1. Experimental setup

In this work, a vortex tube test device with different fluids was developed and built, as shown in Fig. 1. The gas from a pressurized gas source, GS, flows into the vortex tube through shut-off valve V0, diaphragm valve V1, heat exchanger EX, and mass flow meter M1, and then it is separated into two temperature fluids in the vortex tube. The cold fluid flows through mass flow meter M2, diaphragm valve V2, and the hot fluid flows through diaphragm valve V3. The inlet pressure of the vortex tube is adjusted by the diaphragm valve V1. The outlet pressures of the cold end and the hot end are adjusted by the diaphragm valves V2 and V3, respectively.

The EX is a concentric tube heat exchanger (outer tube is φ 19 mm × 0.9 mm, inner tube is φ 6 mm × 0.6 mm, total length of heat exchanger is 3.4 m), and water for the heat transfer in the EX comes from tap water which has the same temperature with environment. The inlet temperature of the vortex tube is adjusted by this heat exchanger. The diaphragm valves V1, V2 and V3 are used to adjust the gas pressure. Because of the temperature's influence on the gas pressure, the inlet pressure of the vortex tube is adjusted by V1 and EX together. In the experiment, it is found that the inlet temperature fluctuation (±3 °C) has little influence on the temperature separation effect. The entire apparatus is used for the experiment, and the working gases are discharged into the environment in a controlled manner, and then they are recycled, which makes the experiment environmental friendly. The vortex tube (Model: SCFM3202, EXAIR) is used in this experiment and its main dimensions are showed in Fig. 2 [22]. The measurement devices are placed as showed in Fig. 3. The measurement points of T_{in} and p_{in} are placed between M1 and the vortex tube (outside but near the inlet of vortex tube). The measurement points of T_c and P_c are placed between M2 and the vortex tube (outside and near the cold outlet of vortex tube). The measurement points of T_h and p_h are placed between V3 and the vortex tube (outside and near the hot outlet of vortex tube) and the details of the experimental instruments are showed in Table 2.

The platinum resistance thermometers are obliquely inserted into the brass tube to measure the fluid temperature. Because

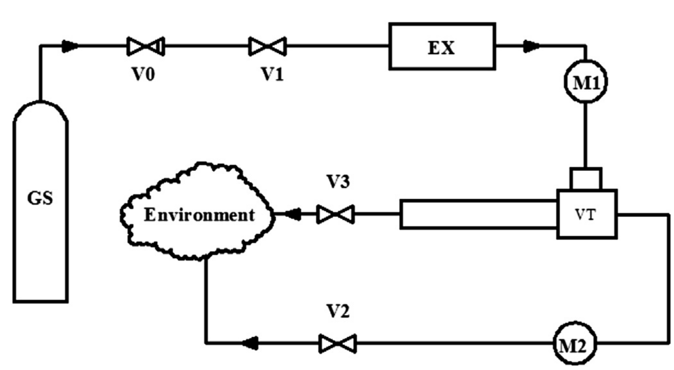

Fig. 1. The experimental apparatus for the vortex tube performance testing.

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