International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2014

Experimental study of the Couple Characteristics of the Refrigerants and Vortex Tube

Nian Li
Institute of Refrigeration & Cryogenics, Zhejiang University, Hangzhou, China, People's Republic of, 477792128@qq.com

Zheng Wang
Department of Mechanical Engineering, University College London, London, WC1E 7JE, UK, zheng.wang.13@ucl.ac.uk

Xiaohong Han
Institute of Refrigeration & Cryogenics, Zhejiang University, Hangzhou, China, People's Republic of, hanxh66@zju.edu.cn

Guangming Chen
Institute of Refrigeration & Cryogenics, Zhejiang University, Hangzhou, China, People's Republic of, gmchen@zju.edu.cn

Li, Nian; Wang, Zheng; Han, Xiaohong; and Chen, Guangming, "Experimental study of the Couple Characteristics of the Refrigerants and Vortex Tube" (2014). *International Refrigeration and Air Conditioning Conference.* Paper 1518.
http://docs.lib.purdue.edu/iracc/1518

Experimental study of the coupling characteristics between vortex tube and refrigerants

Nian Li[1], Zheng Wang[2], Xiaohong Han[1], Guangming Chen[1]

1. Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou, 310027 China,
hanxh66@zju.edu.cn
2. Department of Mechanical Engineering, University College London, London, WC1E 7JE, UK
zheng.wang.13@ucl.ac.uk

ABSTRACT

Vortex tube is a simple energy separation device, also known as Ranque tube or Hilsch tube, which can separate a high-pressure stream into two different hot and cold streams. Since its simple structure and unique temperature separation characteristics, vortex tube has been widely used in various industries. In recent years, with the in-depth study of the vortex tube, it has been found that compared with the conventional expansion expander and the throttle valve, the vortex tube is much more structurally simple and efficient, respectively. Researchers have proposed the use of the vortex tube in the refrigeration system in order to reduce the throttling loss and improve system efficiency. This has important implications for improving the performance of the system, to achieve energy saving and emission reduction. However, due to the different physical properties of the different working fluid, energy separation in the vortex tube are not the same. In the existing studies on the vortex tube, the working fluid mainly used air, nitrogen, carbon dioxide and other natural refrigerants, the research about the influence of refrigerants is few.

Due to the fact that the vortex tube is increasingly used in refrigeration and heating system, it is urgent to study the coupling characteristics between vortex tube and refrigerants and find optimal conditions in different systems. The different temperature separation effect of the refrigerants in the vortex tube in the low inlet pressure (300kPa) have been studied in our previous study and three fluid characteristics (specific heat ratio, kinematic viscosity, thermal conductivity) were considered as main influencing factors of energy separation. The influence of different working fluid in high pressure conditions has not been considered, which part of research work in this paper is. The coupling characteristic between vortex tube and refrigerants is studied and the closed loop system is constructed. R134a, R744, R32, R227ea are selected as the working fluids, experiments are carried out in different inlet pressure (500kPa～850kPa), different inlet temperature (308.15K～333.15K), different cold flow ratio (20%～97%). The temperature separation of different working fluids under different conditions are explored and the influences of different characteristics of the working fluids on the temperature separation process are discussed.

These studies can help more profound understand the vortex tube temperature separation process, and also has certain significance on the applications of the vortex tube in the refrigeration system.

KEY WORDS: vortex tube, energy separation, refrigerants

1. INTRODUCTION

Vortex tube is a simple energy separation device, also known as Ranque tube (Rangue, 1934) or Hilsch tube (Hilsch, 1947), which can separate a high-pressure stream into two different hot and cold streams. Due to its simple structure without moving parts and the special temperature separation performance, vortex tube has attracted many scholars' attention and has been extensively researched on its structure, applications and mechanism.

Many scholars have tried to optimize the vortex tube configuration to increase its performance. Aydın and Baki (2006) explored the influence of the vortex tube length, the inlet nozzle diameter and the control valve angle on the vortex tube; Nimbalkar and Muller(2009) studied the optimal geometry of the cold end orifice; Kun Chang *et al.* (2011) focused on studying the influence of the divergence angle of hot tube, the divergent hot tube length and the nozzle intakes number on the vortex tube by using a conical tube. After decades of research and development, the structure of the vortex tube is more perfect, and different structures of the vortex tube can be used to achieve more desirable required cooling, heating, separation and other functions.

With the in-depth study of the vortex tube, it has been found that compared with the conventional expansion expander and the throttle valve, the vortex tube is much more structurally simple and efficient, respectively. Researchers have proposed the use of the vortex tube in the refrigeration system in order to reduce the throttling loss and improve system efficiency (Sarkar, 2009), which has important implications for improving the performance of the system and saving energy. However, different working fluids have different physical properties, energy separation in the vortex tube are not the same. In the existing studies on the vortex tube, air (Aydın and Baki, 2006), oxygen (Kırmacı,2009), nitrogen (Kun Chang *et al*. ,2011), carbon dioxide (Khazaei *et al*.,2012) and other natural refrigerants (Collins and Lovelace,1979) were mainly used as the working fluids, but the research about the influence of refrigerants is few.

Due to the fact that the vortex tube is increasingly used in refrigeration and heating system, it is urgent to study the coupling characteristics between vortex tube and refrigerants, and then find optimal conditions in different systems. Also, although the vortex tube is structurally simple, the inner flow field is very complicated. In order to understand the temperature separation phenomenon and give explanation and theoretical prediction about the vortex tube, different mechanism have been proposed, such as the pressure gradient (Ranque,1933), friction and turbulence (Lay,1959), temperature gratitude (Geolge and Scheper, 1951), acoustic(Kurosaka,1982), the second flow (Ahlborn and Groves,1997)and others. However, there has not been a consensus in the theories. The performance of the vortex tube is also influenced by the characteristics of working gases (Yilmaz *et al*.,2009). The different temperature separation effect of the refrigerant in the vortex tube in the low inlet pressure(300kPa) have been studied in our previous study and three fluid characteristics (specific heat ratio, kinematic viscosity, thermal conductivity) were considered as main influencing factors of energy separation (Han *et al*.,2013).

The influence of different working fluids in high pressure conditions has not been considered, which part of research work in this paper is. The coupling characteristic between vortex tube and refrigerants are studied and the closed loop system is constructed in this artilce. R134a, R744, R32, R227ea are selected as the working fluids, experiments are carried out in different inlet pressure (500kPa～850kPa), different inlet temperature (308.15K～333.15K), different cold flow ratio (20%～97%).

2 EXPERIMENTAL STUDY

2.1 Experimental apparatus

Due to the high pressure of R744 in the gas source, an open-system was used to investigate the couple characteristics between R744 and vortex tube, which was introduced in our previous work (Han *et al*.,2013). Besides, in order to study the coupling characteristics between vortex tube and R134a, R32, R227ea at high pressure, a closed loop device is developed and built. The schematic diagram of the experimental apparatus is shown in Fig.1. Compressed by a compressor, high-pressure refrigerant passes through the oil separator to eliminate lubricant. Then it goes through the pressure regulator valve and the heat exchanger to archive the desired pressure and temperature. After that, it flows through sight glass 1, mass flow meter 1 and into the vortex tube and becomes two streams-cold stream and hot stream. The cold stream flows through mass flow meter 2, sight glass 2, parallel settled diaphragm valve 2 and needle valve 2. The hot stream flows through sight glass 3, parallel settled diaphragm valve 1 and needle valve 1, and then converges with the cold stream. The mixed fluid flows into an evaporator to archive the gaseous state and is sucked into the compressor, and complete the whole cycle finally.

The vortex tube used in this experiment is Model: SCFM3202, EXAIR. The diaphragm valves 1 and needle valve 1 are used to adjust the outlet pressure of the hot end and diaphragm valves 2 and needle valve 2 are used to adjust the outlet pressure of the cold end (diaphragm valves are used for widely adjustment , needle valves are used for accurate tuning). Purity of The refrigerants used in the experiments is above 99.8%.

The measurement devices are showed in Fig. 2. The measurement points of T_{in}, p_{in} and M_{in} are placed between sight glass 1 and the vortex tube (outside but near the inlet of vortex tube). The measurement points of T_{c}, p_{c} and M_{c} are placed between sight glass 2 and the cold outlet of the vortex tube; The measurement points of T_{h} and P_{h} are placed between sight glass 3 and the vortex tube (outside and near the hot outlet of vortex tube). The inlet, hot and cold outlet pressures of the vortex tube are measured by Pressure sensors (Model: PTX7517, Druck, Range :0~2000kPa(abs), Uncertainty:0.15%FS); The mass flow rates at the inlet and cold outlets are measured by using Mass flow meters (Model: CMF025, Emerson, Range:0~30.56g/s, Uncertainty: 0.35%FS); The temperatures of the inlet, hot and cold outlet have been measured by copper-constantan thermocouples (Uncertainty: 0.5K); besides, five thermocouples are arranged 8mm away from each other and attached to the wall of the vortex tube (measuring points marks as 0, 1, 2, 3, and 4.In it, point 0 is closest to the cold end and point 4 is closest to the hot end). Data above are collected by Agilent 34970A. During the experiments, two kinds of temperature measurements (at the inlet and the hot cold outlet measuring points) are used: first, the thermocouples are inserted into the pipe and measuring the center temperature of the fluid; second, and the thermocouples are attached to the wall and when the system is stable, measuring the wall temperature (can be regarded as the temperature of outside region of the fluid).

To study the energy conservation of the experiment, the enthalpy of inlet, hot and cold stream (E_{in}, E_{h}, E_{c}) are calculated in this work, the calculation method is detailed in our previous article (Han *et al.*,2013).

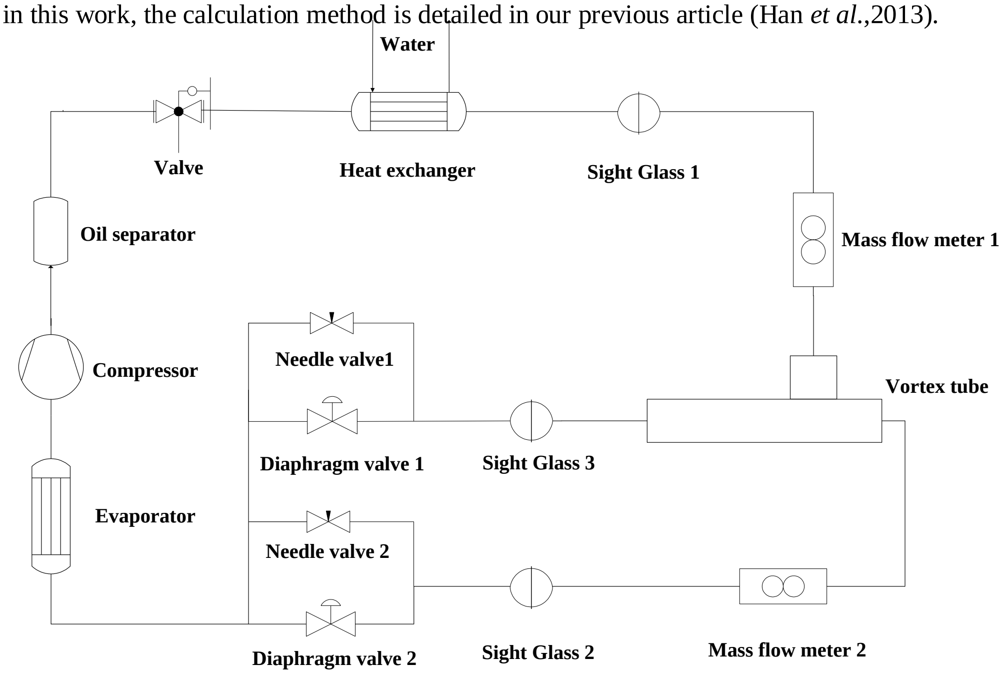


Figure 1: Schematic diagram of experimental apparatus

The purpose of this study is to explore some refrigerants' influence on the energy separation of vortex tube. Firstly, R134a is chosen as the working fluid, and the effect of the cold mass flow ratio μ_{c} ($0 \leq \mu_{\text{c}} \leq 1$) (defined as the ratio of cold stream mass flow M_{c} and inlet stream mass flow M_{in}), the inlet pressure p_{in}, the inlet temperature T_{in} on the energy separation of the vortex tube are explored. Secondly, temperature separation effect using the constant inlet pressure with different fluids（R134a, R744, R32, R227ea）are studied, and the influence of the characteristics of working gases on the performance of the vortex tube is discussed.

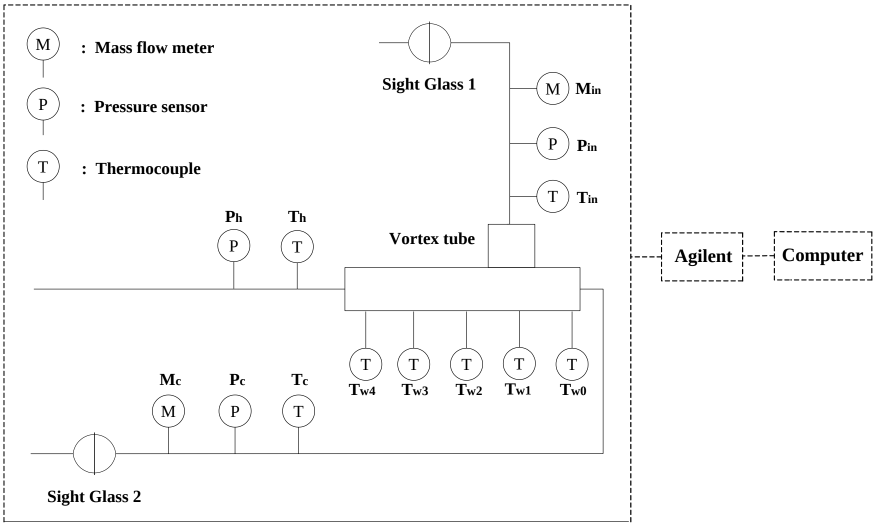
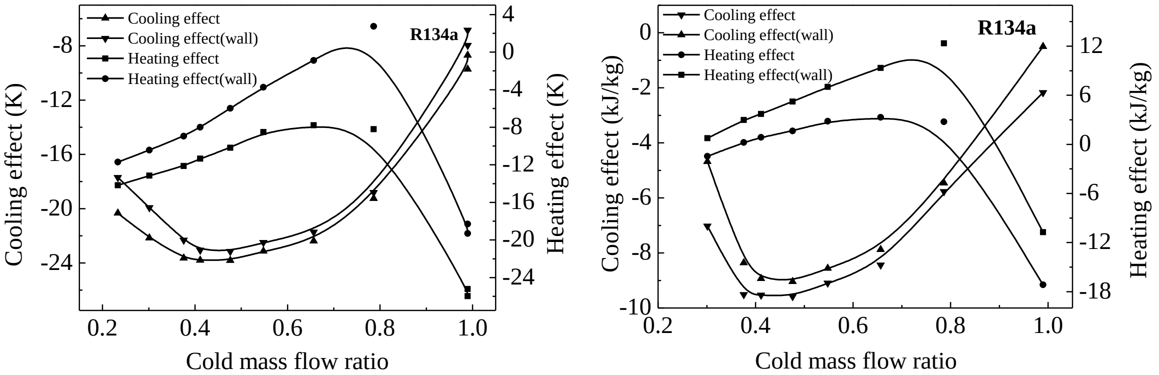


Figure 2: Schematic of the experimental apparatus and measurement

3 RESULTS AND DISCUSSION

3.1 The effect of cold mass flow ratio on the temperature separation of the vortex tube



(a) Temperature difference (b) Enthalpy difference

Figure 3: The effect of cold mass flow ratio on the performance of the vortex tube

During this experiment, the inlet pressure p_{in} of the compressed R134a is constant at 700kPa, the inlet temperature T_{in} is about 313.15K, the hot control valve is kept at a fixed setting, the cold mass flow ratio μ_c is regulated through adjusting the hot and cold outlet pressure p_h and p_c. From Fig.3, it can be observed that with the increasing of the cold mass flow ratio, both the heating effect ΔT_h , ΔE_h and the cooling effect ΔT_c, ΔE_c increased at first, when the cold mass flow ratio reaches certain level ($\mu_c \approx 0.45$), the cooling effect reaches max value and then decreases. Also, when the cold mass flow ratio $\mu_c \approx 0.8$, the heating effect reaches its peak value. This phenomenon is similar to those, in whichair and other gases (Aydın and Baki, 2006) were used as the working fluid. While in this experiment, the heating effect ΔT_h is negative, which means the temperature of the hot outlet stream is less than the temperature of the inlet stream. Through calculating, the enthalpy of the hot outlet stream is larger than the enthalpy of the inlet stream (Fig.3 (b)), and then the whole process satisfies the energy conservation law. When mass flow ratio is large enough ($\mu_c \approx 0.99$), the vortex tube is degenerated into a throttling element and both the cooling and heating effect are negative.

As is introduced above (in section 2), two kinds of temperature measurements are used, and in Fig.3, the cooling effect ΔT_c is better than the cooling effect ΔT_c (wall), while the heating effect ΔT_h is lower than the heating effect ΔT_h (wall) at the same condition. It is considered that in the expansion process at the nozzles, fluid temperature declines sharply and part of the stream exits through the cold outlet directly, thus making the cold outlet temperature much lower than the wall temperature at the cold outlet. The other part of the stream flows to the hot end, and the temperature rise of the fluid is mainly caused by the friction between fluid and wall along the hot tube. The viscosity is one of the mainly factors affecting the performance of the temperature, thus the temperature of the wall is larger than the temperature of the fluid at the hot outlet.

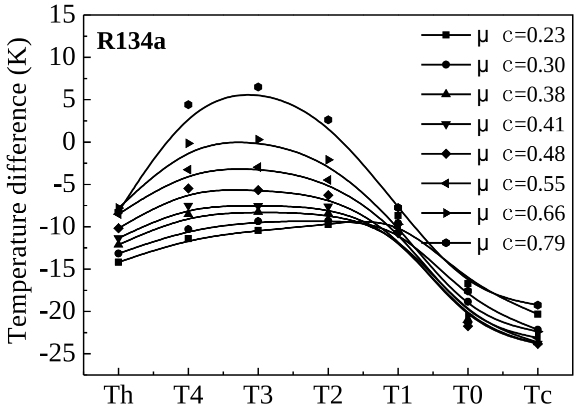
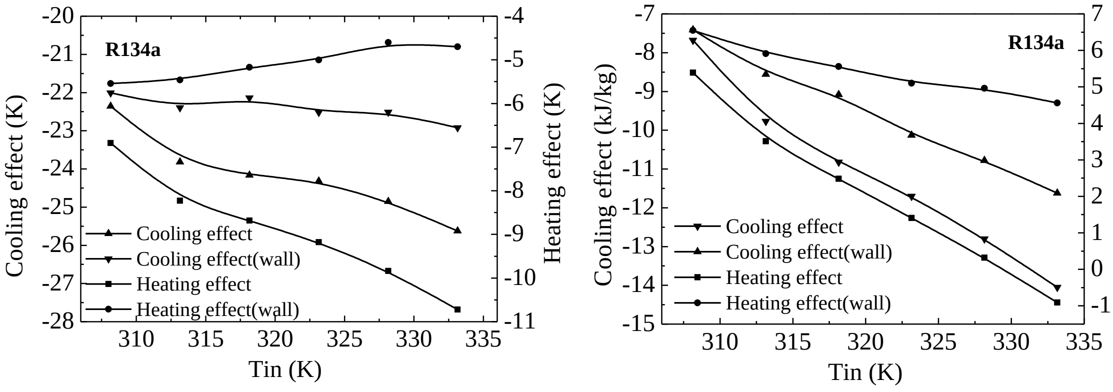


Figure 4: Temperature distribution along the vortex tube at different cold mass ratio

The temperature of the vortex tube gradually increases along the direction of the vortex tube hot ends (Fig .4), but due to the throttling effect of the hot control valve, the temperature of the hot outlet is lower than the temperature of the measuring point 4 (near the hot outlet). On the other hand, with the increase of the cold mass flow ratio μ_c, it can be found that the maximum temperature point (also known as stagnation point) moves to the cold end: when cold mass flow ratio μ_c=0.48, measuring point 4 is the maximum temperature point along the vortex tube; when cold mass flow ratio μ_c=0.79, the maximum temperature point moves to measuring point 3. This potential reason is that there exits turning back flow and multi-circulation in the vortex tube, which make the bifurcation point (Xue *et al.*, 2013), and with the increase of the cold flow ratio, the turn backing flow and multi-circulation move to the cold end, thus making the stagnation point move forward.

3.2 The effect of inlet temperature on the temperature separation of the vortex tube



(a) Temperature difference (b) Enthalpy difference

Figure 5: The effect of inlet temperature on the performance of the vortex tube

During this experiment, the inlet pressure p_{in} of the compressed R134a is constant at 700kPa, the hot and cold outlet pressure p_h and p_c are kept at constant values, the inlet temperature T_{in}, ranging from 308.15 to 333.15K, which is larger than the saturation temperature (299.863K), is regulated by the heat exchanger. . As shown in As is shown in Fig.5, the heating effect ΔT_h decreases with the increase of the inlet temperature T_{in}, and the cooling effect ΔT_c increases with the increase of the inlet temperature T_{in}. The potential reason may be that with the increase of the inlet temperature T_{in}, the cold mass flow ratio μ_c decreases slightly (μ_c=0.429～0.417), which is larger than the cold mass flow ratio obtaining the $\Delta T_{c,max}$ and smaller than the cold mass flow ratio obtaining the $\Delta T_{h,max.}$ Also, with the decrease of the cold mass flow ratio μ_c, the cooling effect ΔT_c increases while the heating effect ΔT_h decreases.

Besides, in this experiment, the cooling effect ΔT_c is also better than the cooling effect ΔT_c (wall), and the heating effect ΔT_h is also lower than the heating effect ΔT_h (wall) at the same condition.

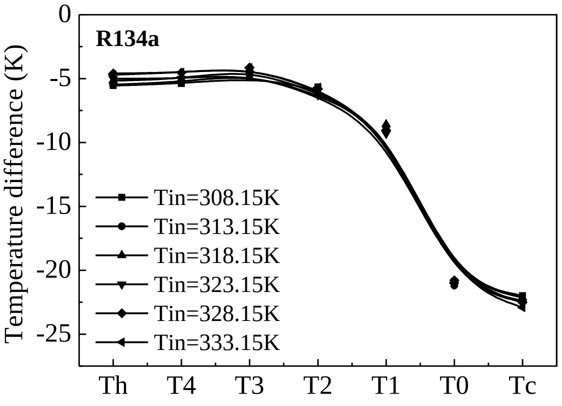
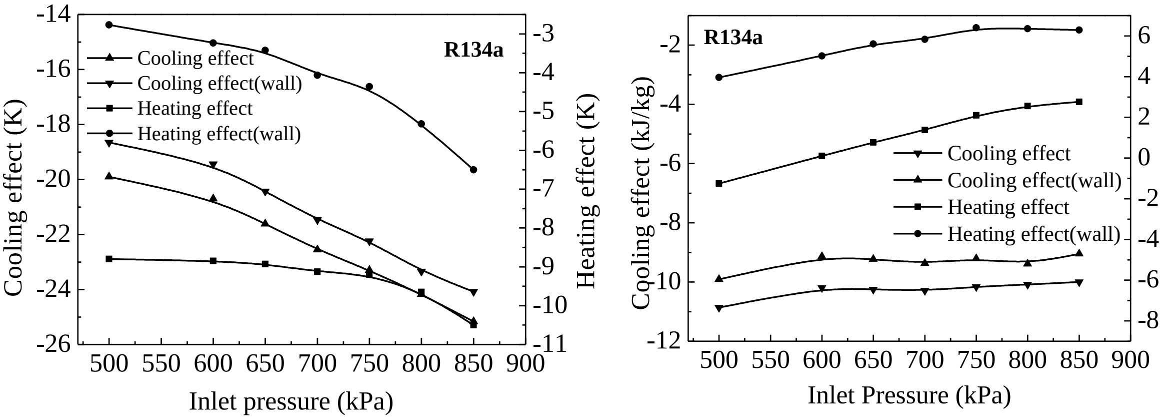


Figure 6: Temperature distribution along the vortex tube at different inlet temperature

Fig.6 shows temperature distribution along the vortex tube at different inlet temperature: the temperature of the vortex tube gradually increases along the direction of the vortex tube hot end, and there exits a temperature decrease at the hot outlet due to the throttling effect of the hot control valve. Besides, the inlet temperature has little influence on the temperature separation performance of the vortex tube.

3.3 The effect of inlet pressure on the temperature separation of the vortex tube

During this experiment, the inlet temperature T_{in} of the compressed R134a is about 313.15K, the hot and cold outlet pressure p_h and p_c are fixed, the inlet temperature p_{in} is regulated by the regulator valve.



(a) Temperature difference (b) Enthalpy difference

Figure 7: The effect of inlet pressure on the performance of the vortex tube

Fig 7 shows the influences of varies of inlet pressure p_{in} on cooling and heating effect of the vortex tube. With the increase of the inlet pressure p_{in}, the cooling effect ΔT_c increases and the heating effect ΔT_h decreases. While in terms of enthalpy, the cooling effect ΔE_c decreases and the heating effect ΔE_h increases. As is discussed in section 3.1, the expansion process at the nozzles mainly contributes to the temperature cooling effect, the larger of the inlet pressure p_{in}, the more intense of the expansion process, more temperature drops, and better cooling effect ΔT_c. But for the heating effect, the temperature rise along the vortex tube reduces with the increase of the inlet pressure, while the enthalpy of heating effect ΔE_h increases.

As is mentioned in section 3.1 and 3.2, the cooling effect ΔT_c is better than the cooling effect ΔT_c (wall), and the heating effect ΔT_h is lower than the heating effect ΔT_h (wall) at the same condition.

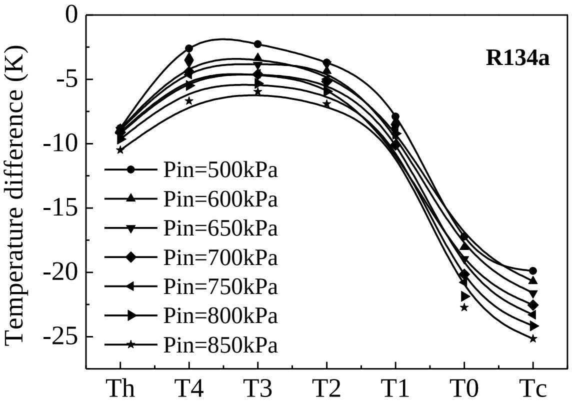


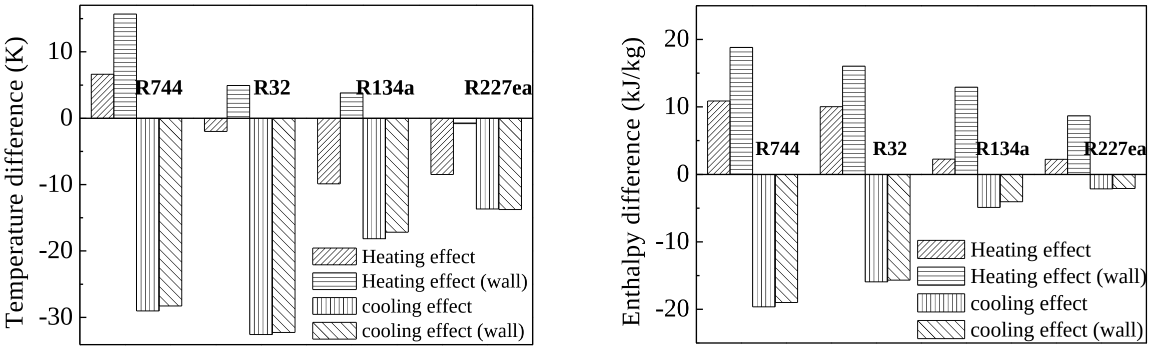
Figure 8: Temperature distribution along the vortex tube at different inlet pressure

At different inlet pressures, temperature distribution along the vortex tube is shown in Fig.8. The temperature difference between the wall and the inlet of the vortex tube gradually increase along the direction of the vortex tube hot ends, and temperature decreases at the hot outlet due to the throttling effect of the hot control valve.

Besides, it can be observed that when the inlet pressure is small (p_{in} =500kPa), compared to the large pressure condition the overall temperature along the vortex tube is larger, and the heating effect ΔT_h is better; when the inlet pressure was large (p_{in} =850kPa), compared to the small pressure condition, the overall temperature along the vortex tube is lower and the cooling effect ΔT_c is better. This is in same to the phenomena in Fig.7(a).

3.4 The effect of working fluids on the temperature separation of the vortex tube

R134a, R744, R32, R227ea are selected as the working fluids, the inlet temperature p_{in} is regulated at 700kPa and the inlet fluid temperature T_{in} is adjusted to about 313.15K. As is mentioned in section 2, the experiment of R744 is conducted in the open-system and experiments of R134a, R32, R227ea are conducted in the closed system.



(a) Temperature difference (b) Enthalpy difference

Figure 9: The effect of working fluid on the performance of the vortex tube

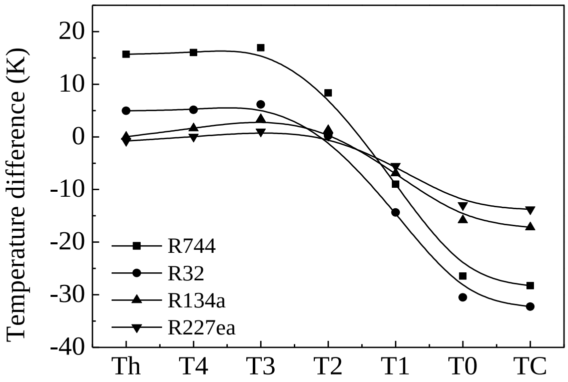


Figure 10: Temperature distribution along the vortex tube of different working fluid

The experimental results are shown in Fig. 9. The heating effect of R744 is greater than that of other working gases, while the heating effect ΔT_h of R32, R134a, R227ea are negative. The heating effect ΔE_h of R32, R134a and R227ea are positive, which meet the energy conservation law. The cooling effect of R744 and R32 are better than that of the other two working fluids.

The temperature distribution along the vortex tube of different working fluid is shown in Fig.10. And the different working gases' characteristics are given by Table 1.

Table 1: The basic properties of different working gases

Working gases	k	z	ν/ $m^2 \cdot s^{-1}$
R744	1.317	0.9699	1.288×10^{-6}
R32	1.314	0.9252	0.879×10^{-6}
R134a	1.197	0.869	0.391×10^{-6}
R227ea	1.168	0.813	0.218×10^{-6}

As is discussed above, the expansion process in the nozzles mainly contributs to the effect of temperature drop in the vortex tube, and this process is affected by the specific heat ratio k, large specific heat ratio of the working fluid contributes to the large temperature drop. In Fig.9 and Fig.10, it can be found that the temperature drop of R744 and R32 are larger than that of R134a and R227ea, which meets the rank of specific heat ratio k in table 1.

The gas compressibility factor z also has influence on the expansion process in the nozzles: under the same expansion conditions, the larger the compressibility factor z, the more dramatic of the expansion and intense of the gas flow in the vortex tube, thus making the temperature separation effect better. As is listed in table 1, the compressibility factors z are 1.317, 1.314, 1.197, 1.168, respectively for R744, R32, R134a, R227ea in descending order, and the temperature difference ΔT is in the same order in Fig.9 and Fig. 10.

The heating effect measured on the wall is larger than that measured in the tube (Fig.9), which means that the temperature rise process is mainly caused by the friction between fluid and wall along the hot tube and the viscosity is one of the mainly factors affecting the performance of the temperature. The kinetic viscosity of R744 is the largest among these fluid and its heating effect is the best. The conclusion agrees with that of our previous work (Han *et al*.,2013).

4. CONCLUSIONS

The effect of the cold mass flow ratio μ_c, inlet pressure p_{in}, inlet temperature T_{in} of R134a on the performance of the vortex tube is explored, energy separation effects of different working fluids are discussed. Conclusions are drawn as follows:

(1) The effect of mass flow ratio on the temperature separation effect when using R134a is similar to those when air and other gases are used. But in our experimental condition, R134a has negative heating effect ΔT_c while has positive heating effect ΔE_c.

(2) When the inlet temperature of R134a is larger than the saturation temperature at the same pressure, the increase of temperature has little influence on the temperature separation effect of the vortex tube.

(3) When the inlet pressure p_{in} of R134a increases, the cooling effect ΔT_c increases while the heating effect $\Delta\ T_h$ reduces gradually.

(4) Comparing the temperature difference of the vortex tube using different working fluids (R134a, R744, R32, R227ea), the specific heat ratio k, compressibility factor z, and kinetic viscosity ν are considered as the main factors affecting the temperature separation process in the vortex tube.

NOMENCLATURE

T	temperature	(K)
p	pressure	(kPa)
μ_c	cold mass flow ratio	
k	specific heat ratio	
z	compressibility factor	
ν	kinematic viscosity	(m^2/s)
△T	temperature difference	(K)
△E	enthalpy difference	(kJ/kg)

Subscript

in	inlet stream
c	cold stream
h	hot stream

REFERENCES

Ahlborn B., Groves S.,1997, Secondary flow in a vortex tube, *Fluid Dyn. Res.*, vol.21,no.2:p.73–86.

Aydın, O. , M. Baki, 2006,An experimental study on the design parameters of a counterflow vortex tube, *Energy*, vol.31,no.14:p. 2763-2772.

Chang, K., et al.,2011, Experimental investigation of vortex tube refrigerator with a divergent hot tube, *Int. J. Refri.*, vol. 34, no.1:p. 322-327.

Collins, R.L., Lovelace R.B., 1979, Experimental Study of Two-Phase Propane Expanded through the Ranque-Hilsch Tube, *J. Heat Transfer*, vol. 101, no.2:p. 300-305..

Geolge, W. , Scheper,1951, The vortex tube: internal flow date and a heat transfer theory. *J. ASRE: Refri. Eng.*, vol.59:p. 985-989.

Han, X., et al.,2013, The influence of working gas characteristics on energy separation of vortex tube, *Appl. Therm. Eng.*, vol. 61,no.2:p. 171-177.

Hilsch, R.,1947, The use of the expansion of gases in a centrifugal field as cooling process, *Rev. Sci. Instrum.*, vol.18, no.2:p. 108-113.

Khazaei, H., Teymourtash A.R. , Malek-Jafarian M., 2012, Effects of gas properties and geometrical parameters on performance of a vortex tube, *Scripta Mater.*, vol. 19, no.3:p. 454-462.

Kırmacı, V.,2009, Exergy analysis and performance of a counter flow Ranque–Hilsch vortex tube having various nozzle numbers at different inlet pressures of oxygen and air, *Int. J. Refri.*, vol. 32, no.7: p.1626-1633.

Kurosaka M.,1982, Acoustic streaming in swirling flow and the Ranque–Hilsch (vortex-tube) effect, *J. Fluid Mech*., vol.124 :p.139–172.

Lay, J.E., 1959, An experimental and analytical study of vortexflow temperature separation by superposition of spiral and axial flow, part II. *J. Heat Trans.-T. ASME* ,vol.81: p.213-222.

Nimbalkar, S.U. , Muller M.R., 2009,An experimental investigation of the optimum geometry for the cold end orifice of a vortex tube, *Appl. Therm. Eng.*, vol. 29, no.2-3: p.509-514.

Ranque, G. J., 1933, Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air. *J. Phys Radium*, vol. 115, no.4:p. 112-114.

Ranque, G.J., 1934, Method and Apparatus for Obtaining from a Fluid Under Pressure Two Outputs of Fluid at Different Temperatures, *US Patent.*,1:952,281.

Sarkar, J.,2009, Cycle parameter optimization of vortex tube expansion transcritical CO2 system. *Int. J. Therm. Sci*., vol. 48,no.9:p. 1823-1828.

Xue, Y., Arjomandi M., Kelso R.,2013, Experimental study of the thermal separation in a vortex tube, *Exp. Therm Fluid Sci.*, vol. 46:p. 175-182.

Yilmaz M., Kaya M., Karagoz S., Erdogan S.,2009, A review on design criteria for vortex tubes, *Heat Mass Transfer*. ,vol.45, no.5:p. 613-632.

ACKNOWLEDGEMENT

The National Basic Research Program of China, Project No. 2010CB227304, financially supports this work. The Fundamental Research Funds for the Central Universities (2013QNA4014) is gratefully acknowledged.