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International Journal of Refrigeration 30 (2007) 1042–1049

REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration

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Modification and experimental research on vortex tube

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Received 21 July 2006; received in revised form 5 January 2007; accepted 9 January 2007
Available online 30 April 2007

Abstract

Vortex tube (VT) is a simple energy separating device which is compact and simple to produce and to operate. Although intensive research has been carried out in many countries over the years, the efficiency is still low. In order to improve the energy separate efficiency of vortex tubes, three innovative technologies were applied to vortex tubes. A new nozzle with equal gradient of Mach number and a new intake flow passage of nozzles with equal flow velocity were designed and developed to reduce the flow loss. A new kind of diffuser invented by us was installed for reducing friction loss of air flow energy at the end of the hot end tube of vortex tube, which can greatly improve the performance of vortex tube. The experiment results indicated that these modifications could remarkably improve the performance of vortex tube. The developed vortex tube was not only superior to the conventional vortex tube but also superior to that made by two companies in world under big cold gas mass flow ratio.

Keywords: Separation; Tube; Vortex; Experiment; Improvement; Nozzle; Diffuser

Modification et recherches expérimentales sur un tube vortex

Mots clés : Séparation ; Tube ; Vortex ; Expérimentation ; Amélioration ; Tuyère ; Diffuseur

1. Introduction

Vortex tube is a simple device, which can cause energy separation. It consists of nozzle, vortex chamber, separating cold plate, hot valve, hot and cold end tube without any moving parts. In the vortex tube, when works, the compressed gaseous fluid expands in the nozzle, then enters vortex tube tangentially with high speed, by means of whirl, the inlet gas splits in low pressure hot and cold temperature streams, one of which, the peripheral gas, has a higher temperature than the initial gas, while the other, the central flow, has a lower temperature. Fig. 1 shows the schematic diagram of a vortex tube.

Vortex tube has the following advantages compared to the other commercial refrigeration devices: simple, no

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0140-7007/$35.00
doi:10.1016/j.ijrefrig.2007.01.013

Nomenclature

c_p	specific heat capacity (J kg^{-1} k^{-1})	*Subscript*	
F	mass flow rate (kg s^{-1})	x, y	rectangular coordinates
T	temperature (°C)	i	inlet gas of vortex tube
ΔT	temperature difference (°C)	h	hot gas exit
η_c	cold gas mass ratio ($\eta_c = F_c/F_i$)	c	cold gas exit
q	cooling rate per unit mass (kw kg^{-1})		
V	velocity (m s^{-1})		

moving parts, no electricity or chemicals, small and lightweight, low cost, maintenance free, instant cold air, durable (because of the stainless steel and clean working media), temperature adjustable. On the other hand, its low thermal efficiency is a main limiting factor for its application. Also the noise and availability of compressed gas may limit its application. Therefore, the vortex tube becomes a nice device for heating gas, cooling gas, cleaning gas, drying gas, and separating gas mixtures, DNA application, liquefying natural gas and other purposes [1–3], when compactness, reliability and lower equipment cost are the main factors and the operating efficiency becomes less important.

Although the vortex tube effect was known for decades and intensive experiments and correlative investigation had been carried out, the mechanism producing the temperature separation phenomenon as a gas or vapor passes through a vortex tube is not fully understood yet. Several different explanations for the temperature effects in the vortex tube have been offered. Hilsh firstly studied the mechanism of vortex tube and claimed that internal friction lead to the energy separation of vortex tube [3]. Kassener and Knoernschild proposed that the conversion of an initially free vortex into a forced vortex result in a radial redistribution of energy [4]. The theory was supported by the study of some researchers. Stephan and Lin [5] proposed Goertler vortices produced by tangential velocity as a main driving force for the energy separation in the vortex tube. Linderstrom-Lang [6] assumed turbulent transfer of the thermal energy lead to the energy separation of vortex tube. A different theory was developed by Mischner and Bespalov [7]. They explained the energy separation mainly caused by entropy generation in vortex tube. Amitani et al. [8] traced it to the compressibility of the working fluid. But Balmer [9] concluded that the temperature separation phenomenon was not limited to compressible gases and vapors. While each of these explanations may capture certain aspects of vortex tube, none of these mechanisms altogether explained the vortex tube effect.

Now, the efficiency of vortex tube is still very low, and the reason is that the design about the parts of vortex tube is not reasonable enough. We have carried out a lot of work to research how the parts of VT affect its performance by the measure of experiment [10,11]. On the basis of these researches, we proposed three innovative modifications of VT to improve the performance of vortex tube. The

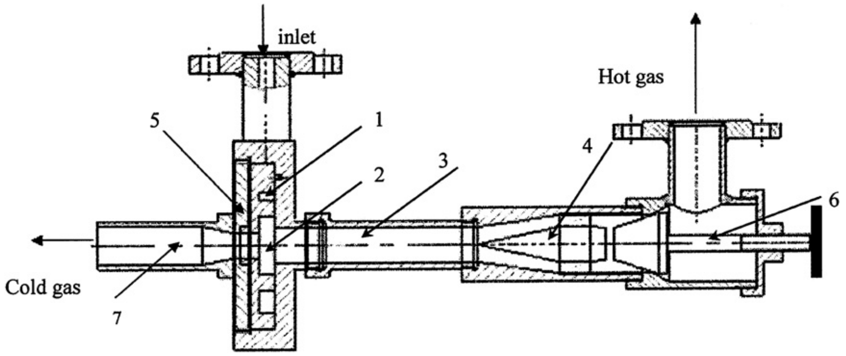

Fig. 1. Schematic diagram of vortex tube. (1) Nozzle, (2) Vortex chamber, (3) Hot end tube, (4) Diffuser, (5) Separating cold plate, (6) Hot valve and (7) Cold end tube.

objectives of this paper are to introduce and verify the modifications by experiments.

2. Three innovative modifications of configuration of VT

2.1. Nozzle intake

In the conventional vortex tube, compressed gas directly enters a circular flow passage with equal section area from a straight pipe (Fig. 2(a)), which can cause a sudden change of flow direction at the joint between the straight pipe and the circular flow passage. The sudden change would lead to the generation of eddies which cause the energy loss. In addition, the compressed gas flow flux decreased after a nozzle, but the area of flow passage keep unchanged, which cause a sudden reduction of flow velocity in the equation area circular flow passage. The sudden change of flow velocity and the eddy generated by the change would also cause the energy loss. In order to reduce the energy loss, a new design with equal gas flow velocity was proposed to keep the constant flow velocity and no sudden change for flow direction in the whole intake flow passage of nozzles. The detailed design is shown in Fig. 2. In the new design, firstly there is a smooth transition from an inlet straight pipe to circular pipe and avoid the sudden change in flow direction. Secondly, the area of circular flow passage decreases with the gas flux decreases, so the flow velocity in the whole circular flow passage can keep a constant flow velocity, which can be seen from the numerical simulation result in Fig. 3.

2.2. Nozzles of vortex tube

It is important to have a high peripheral velocity in the portion of the tube immediately after the nozzle, the curve of nozzle affect the performance of vortex tube. The conventional two types of nozzle are nozzle with normal rectangle and nozzle with Archimedes' spiral, which is that shown, respectively, in Figs. 4 and 5. A new nozzle was designed to minimize the flow loss. The detail of the design was shown in Fig. 6. There is two features in the new designed nozzle. Firstly, the Mach number is the same in the section perpendicular to the axis of nozzle. Secondly, Mach number along the axis of nozzle increases by the same gradient. The two features can be seen from the numerical simulation results in Fig. 7. The nozzle was called Nozzle with equal gradient of Mach number.

2.3. Hot end pipe diffuser of VT

The experimental data which is gained from the experiment with the conventional vortex tube tell us that the airflow is still circumrotating strongly on the outlet of tube, so the friction loss of airflow energy is notable and this energy loss is responsible for the result that the conventional vortex tube has poor COP (coefficient of performance). A diffuser installed before hot valve was designed to reduce the peripheral speed to zero within very short pipe and greatly reduce the ratio of length to diameter. At the same time, the diffuser can also reduce the viscosity loss and residual speed loss. The diffuser was shown in Fig. 8 and the position of diffuser in vortex tube can be seen in Fig. 1.

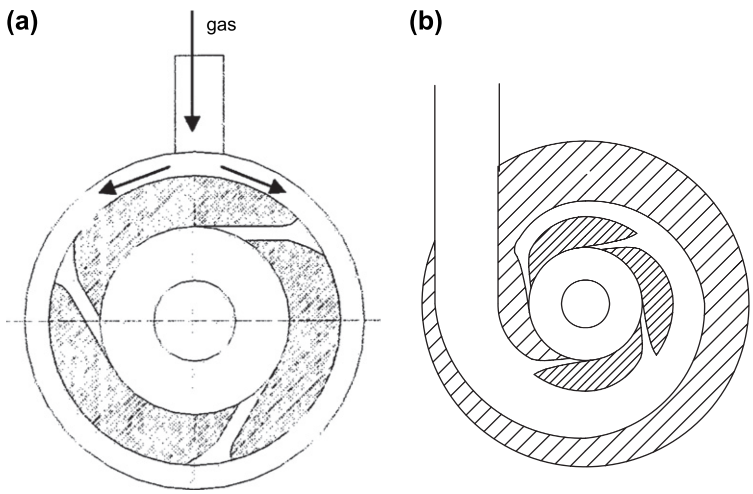

Fig. 2. Comparisons between conventional nozzle and proposed nozzle. (a) Conventional nozzle and (b) Proposed nozzle.

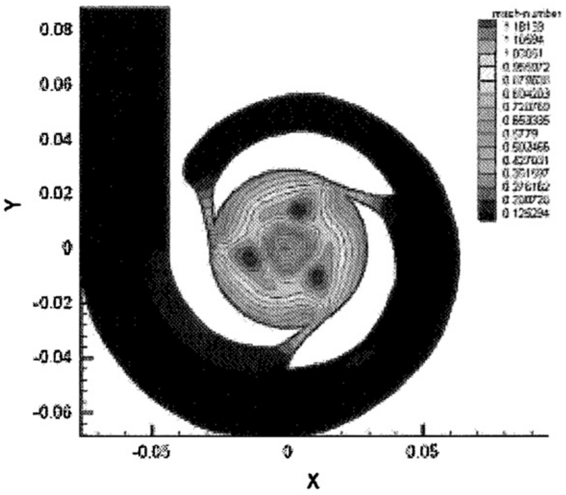

Fig. 3. Mach number distributions in nozzle intake.

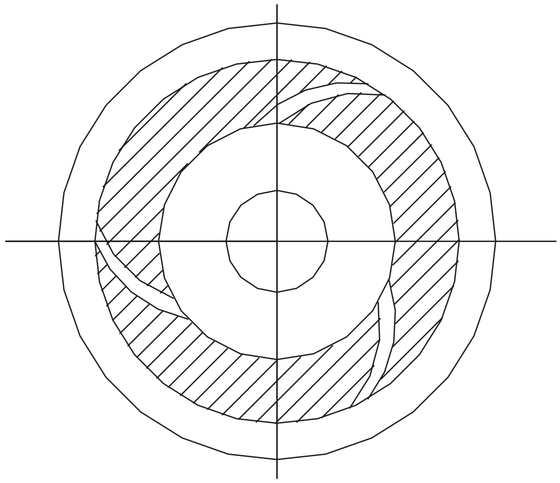

Fig. 5. Nozzle of Archimedes'.

3. Introduction of experimental setup

The schematic diagram of the experimental setup is shown in Fig. 9. The compressed working fluid supplied from the compressor passes through the pressure tank and the thermostatic water cabinet where the temperature of inlet fluid can be regulated. Then, the working fluid is introduced tangentially into the vortex tube where it is expanded and separated into hot and cold air streams. The cold stream in the central region flows out of the tube in the central orifice of cold end tube, while the hot stream in the outer periphery annulus leaves the tube by the exit of hot end tube. The inlet pressure was measured with the manometer in range from 0 to 1.6 MPa and the outlet cold gas pressure with the manometer in range from 0 to 0.1 MPa. The temperatures of the inlet and outlet flows were measured with thermocouples. The mass flow rate of the inlet fluid was measured using a rotameter in range from 1.6 to 16 m^3/h. Two rotameters with different measured range were installed in the cold gas outlet to adapt to the big change of flow rate. The measured range of one is from 0.7 to 7 m^3/h and that of another is from 7 to 70 m^3/h.

4. Results and discussion of the configuration of VT

Before we go, I introduce some basis firstly, in general, the performance of vortex tube was marked by cooling effect (ΔT_c) and heating effect (ΔT_h), which were defined as followed, respectively:

$$\Delta T_c = T_i - T_c, \tag{1}$$

$$\Delta T_h = T_h - T_i, \tag{2}$$

where, T_i is the inlet temperature, T_c is the outlet temperature of cold end, T_h is the outlet temperature of hot end.

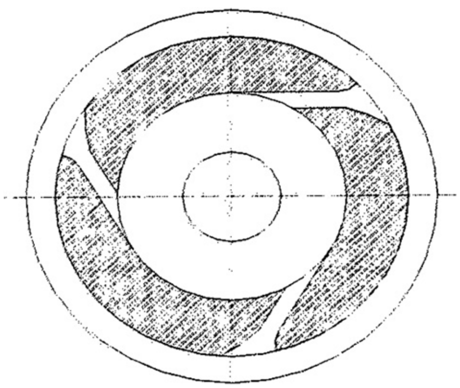

Fig. 4. Nozzle of normal rectangle.

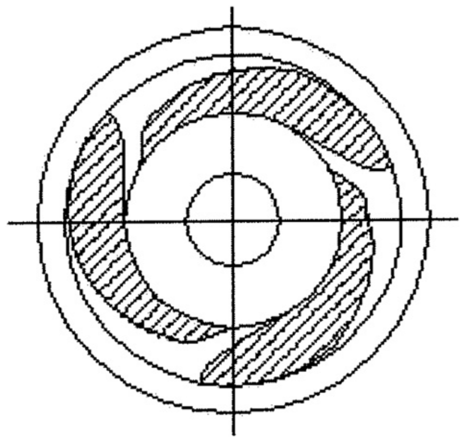

Fig. 6. Nozzle with equal gradient of Mach number.

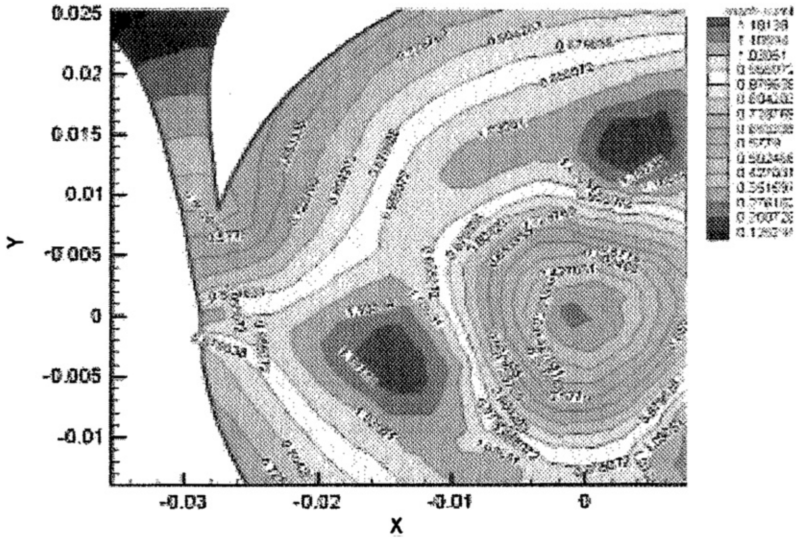

Fig. 7. Mach number distribution in the nozzle proposed by authors.

4.1. Effect on the performance of vortex tube of the nozzle

It is important to have a high peripheral velocity in the portion of the tube immediately after the nozzle. The nozzle curve affects the performance of vortex tube. The two conventional types of nozzles are normal rectangle and Archimedes' spiral nozzles which are that shown, respectively, in Figs. 4 and 5. An improved nozzle, Nozzle of equal gradient of Mach number, was designed by our team and shown in Fig. 6.

We did experiments with the three types of nozzles, respectively, at the same condition that the inlet pressure is 0.4 MPa (absolute) and inlet temperature is 24 °C, the results were shown in Fig. 10. We can see from the curve that the cooling effect of different nozzles varied with the change of η_c and that the improved nozzle had better cooling effect than other two nozzles. For example, in the region where η_c is about 40%, the improved nozzle is about 2.2 °C lower than that of the normal rectangle nozzle and even 5 °C lower than that of the Archimedes' spiral nozzle. Similarly, the heating effect of VT with the improved nozzle is better than that of conventional VT slightly, shown in Fig. 11.

In addition, the two types of conventional nozzle reach the peak of cooling effect when the η_c is 30%, but the improved nozzle reach the peaks at η_c of 40%, this improvement can make the nozzle gain larger cooling rate per unit mass.

4.2. Effect on the performance of VT of diffuser

A contrast experiment between vortex tubes with and without diffuser was carried out, and the results were shown in Figs. 12 and 13, where an exciting advancement can been

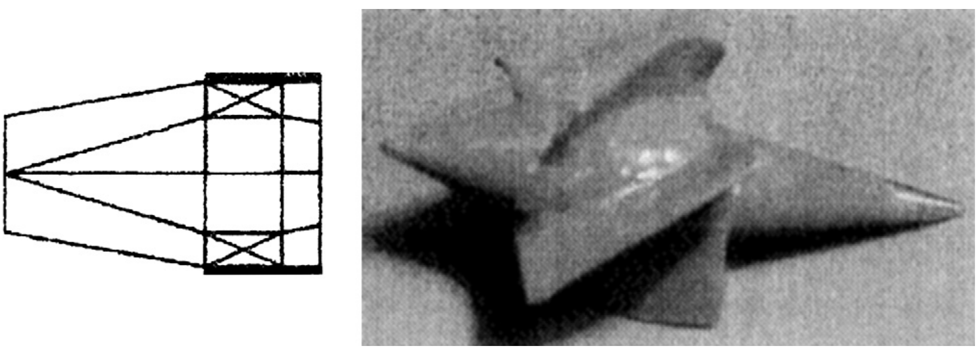

Fig. 8. Picture of the diffuser.

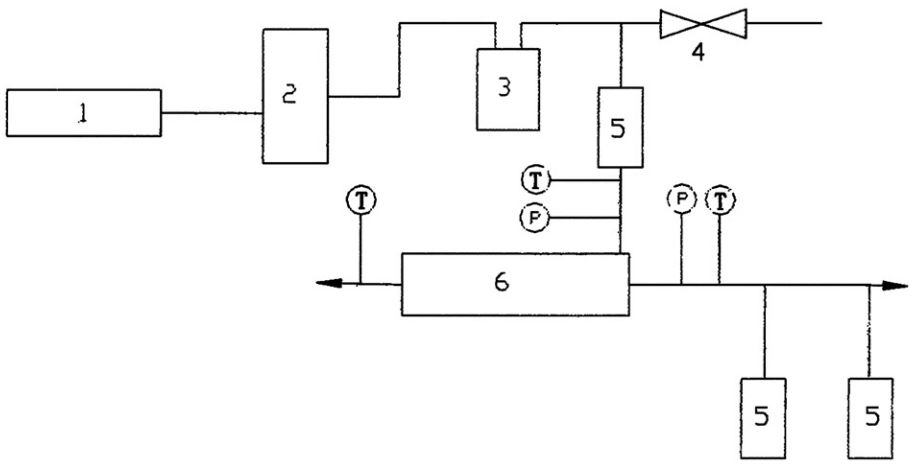

Fig. 9. Experimental system of Vortex tube. (1) Compressor, (2) Pressure tank with filter, (3) Thermostatic water cabinet, (4) By-pass valve, (5) Rotameter and (6) Vortex tube.

seen easily that the cooling effect of the former is lower by 5 °C in maximum than that of latter, and the heating effect becomes a little better too.

4.3. Contrast between the optimized VT and conventional VT

Just like what I said above, various measures have been adopted to improve the performance of vortex tube and proved that these measures are effectual. On the basis of this, lots of influence factors were considered and many disciplinarians were discovered and summarized, then optimization structure parameters of vortex tube were identified now. A vortex tube which combined various measures referred above was developed and the performance was measured.

The comparison of the performance between the developed vortex tube and conventional vortex tube were shown in Figs. 14 and 15. The result indicates that the developed vortex tube has better cooling effect and heating effect than that of original vortex tube in the range of big cold mass fluid ratio.

The developed vortex tube is not only superior to the conventional vortex tube but also is superior to that made in other country of the same type, especially under big cold mass flow ratio, like shown in Fig. 16. We can see from the picture, in the range of $\eta_c > 60\%$, the vortex tube designed by us has better cooling effect and refrigeration capacity per unit mass q. This kind of vortex tube is more suitable for industrial use, therefore, the improvement is significantly.

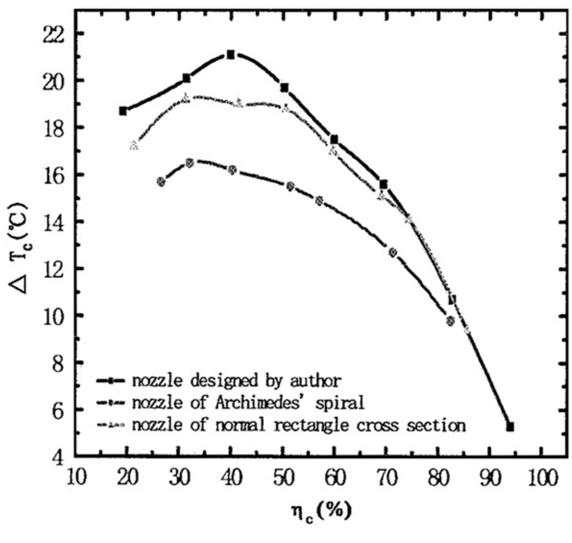

Fig. 10. Effect of various nozzle on cooling effects.

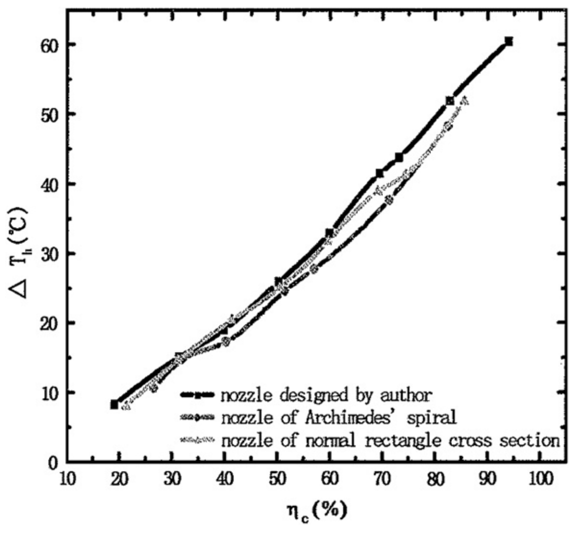

Fig. 11. Effect of various nozzle on heating effects.

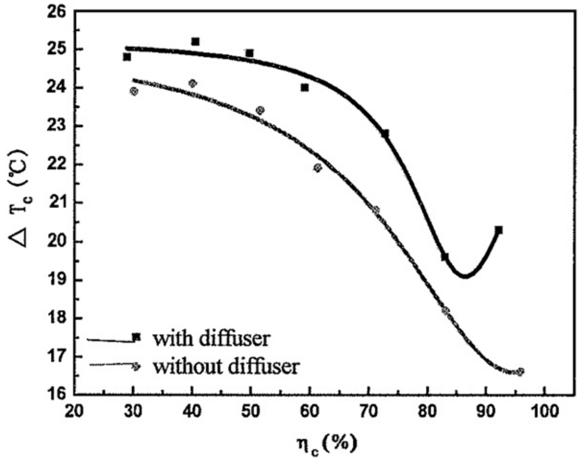

Fig. 12. Effect of the diffuser on cooling effects.

5. Conclusion

Three innovation designs of vortex tubes were done and the performance of modified vortex tube were tested in this paper. The research conclusions can be summarized as follows:

(1) A new nozzle with equal Mach number gradient and an intake flow passage with equal flow velocity were used in the modified vortex tube. The experimental results indicate that the cooling effect of the improved nozzle is about 2.2 °C lower than that of the nozzle with normal rectangle and even 5 °C lower than that of the nozzle with Archimedes' spiral.

(2) A diffuser was designed and installed between the outlet of vortex tube and hot valve aiming to reducing the peripheral speed to zero within very short pipe and greatly reduce the ratio of length to diameter. The experimental results indicate that the cooling effect of the vortex tube with diffuser is up to 5 °C lower than that without diffuser.

(3) A vortex tube which combined various measures was developed, and the experiment with air as medium was carried out as well. The developed vortex tube is not only superior to the conventional vortex tube but also is superior to that made in other country, especially under big cold mass flow ratio.

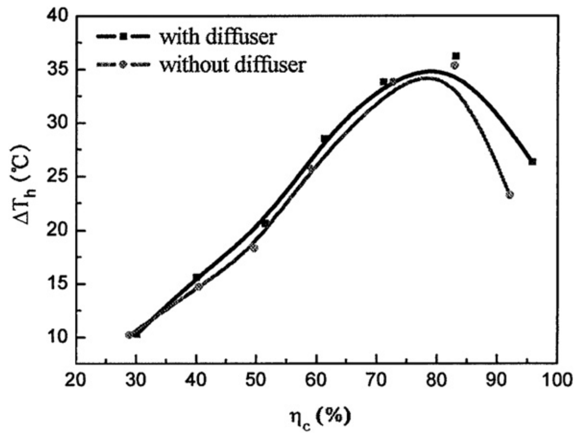

Fig. 13. Effect of the diffuser on heating effects.

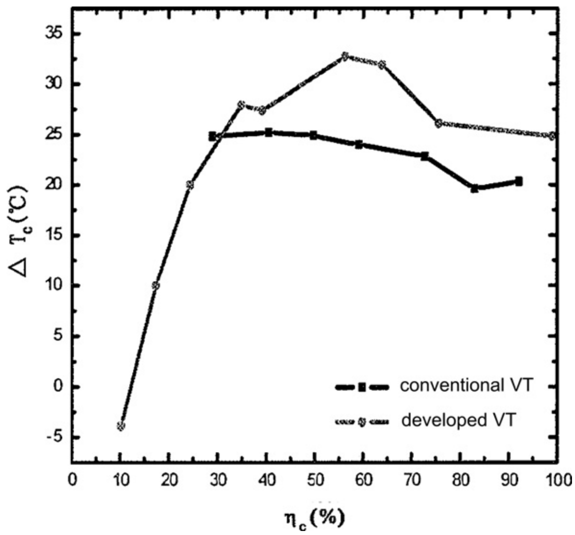

Fig. 14. Comparison between conventional and optimized vortex tube in ΔT_c.

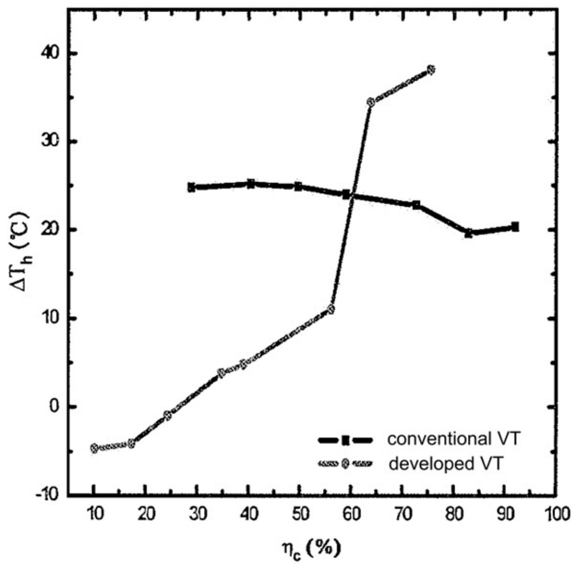

Fig. 15. Comparison between conventional and developed vortex tube in ΔT_h.

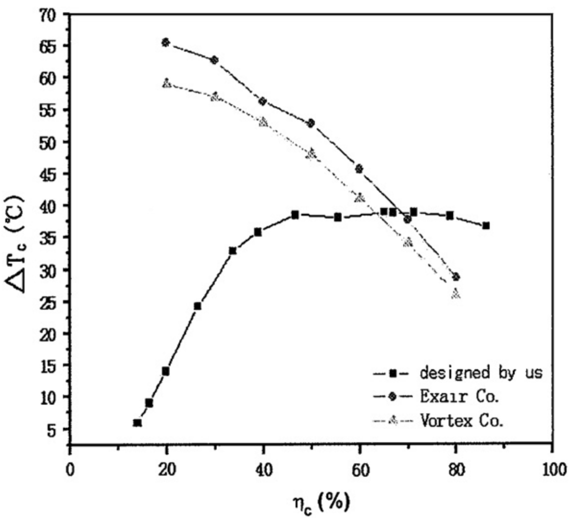

Fig. 16. Comparison between different products in ΔT_c.

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