INFLUENCE OF THE VORTEX ANGLE ON THE EFFICIENCY OF THE RANQUE-HILSCH VORTEX

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ABSTRACT

The phenomenon of temperature distribution in confined steady rotating gas flows is called Ranque-Hilsch effect. The simple counter-flow vortex tube consists of a long hollow cylinder with tangential nozzle at one end for injecting compressed air. Rotating air escapes the tube through two different outlets: a central orifice diaphragm placed near the inlet where the cold portion of air escapes from and a ring–shaped peripheral outlet at the opposite end of the tube where the hot air leaves the tube.

This paper focuses on the performance of the Ranque–Hilsch vortex tube. The flow inside the vortex tube can be described as rotating air, which moves as a spring-shaped vortex track. The peripheral flow moves toward the hot end and the axial flow moves in the opposite direction toward the cold end. The angle between the circular helix and the vertical axis is an important parameter, since it decides the length of the vortex track and peripheral velocity of the flow, which influence the efficiency of the vortex tube. The angle can be called "Ranque angle" or "vortex angle". Various structures were placed in the vortex chamber of a specially designed tube to generate different vortex angles. A series of experiments have been done in order to find the relationship between the vortex angle and the performance of the vortex tube.

Keywords: Vortex flow, vortex tube, Ranque-Hilsch tube, vortex angle.

INTRODUCTION

The Ranque-Hilsch Vortex Tube (RHVT) system is a device that generates separate flows of cold and hot gases from a single compressed air. The Ranque-Hilsch vortex tube was invented by Ranque in 1933 and then improved by Hilsch in 1947. The main part of the vortex tube is a hollow cylinder in which compressed air is injected tangentially at high velocity through a narrow gap. Two nozzles placed on both ends of the tube allow the gas to escape: the cold nozzle port is on the axis of the tube and hot nozzle port is at periphery of the plug. Passing through the vortex chamber, compressed air forms a strong vortical flow in the tube, as shown in Figure 1. The vortical airflow, which is moving towards the hot end, later is forced back by a plug that is placed at the hot end of the tube. The plug adjusts the balance of the amount of the air that is allowed to escape peripherally, which is hot and the amount that is forced back to escape from the centre of the tube, which is cold. The temperature drop between the hot and cold air is a function of the feeding air and geometrical characteristics of the tube.

The first explanation of the flow behavior inside the vortex tube was given by Ranque in 1933. Ranque (1933) explained that the energy separation is due to adiabatic expansion in the central region and adiabatic compression in the peripheral region. Hilsch (1947) was the first to investigate the effect of the geometry on the performance of the vortex tube, in 1947. Subsequently, some research has been done in order to explain this phenomenon, however, the physical mechanism of the process of the cold and hot air

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flows separation has not been completely resolved yet.

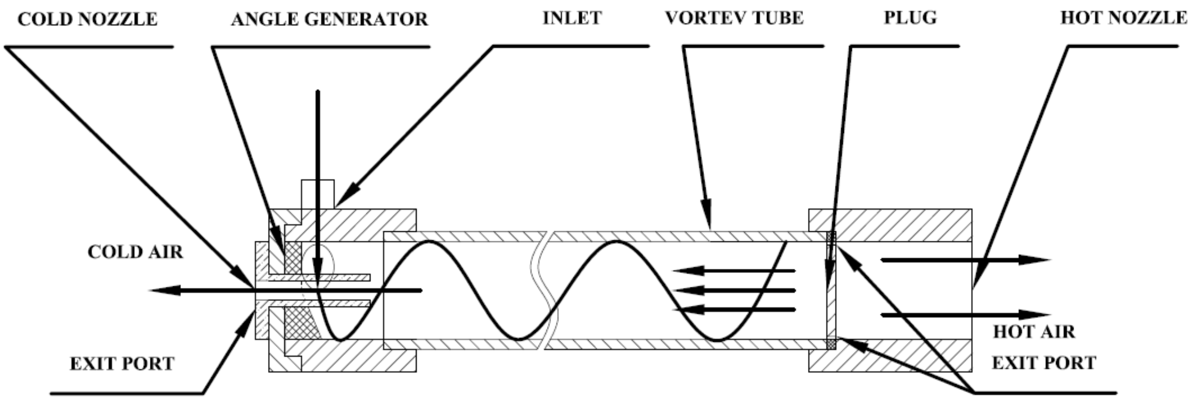

Figure 1. Main structures of the vortex tube and airflow inside the tube

Westley (1955) experimentally optimized the geometrical parameters of the RHVT system. He found that the optimum configuration can be described as a relationship between the inlet area, the tube length, the vortex tube cross sectional area, the cold end orifice area size, hot end plug dimension and the inlet pressure.

Pongjet and Smith (2004) investigated the vortex thermal separation in a vortex tube refrigerator, using two different tubes, insulated and non-insulated. They found that the temperature of the wall is higher than the temperature of the working air when non-insulated tube is used in the experiment. They also located the distance from the inlet on the wall where highest temperature happened along the vortex tube. GAO, Bosschaart, Zeegers, and Waele (2005) measured the flow parameters in the tube. The air velocity inside the tube was measured and the performance of the vortex tube with different parameters like cold fractions, pressures of the injected air and shape of the vortex tube was investigated.

As it is shown in Figure 1, the flow inside the vortex tube can be described as a rotating vortical flow, which moves like a spring-shaped vortex track. The angle between the circular helix and the vertical axis which can be called "vortex angle" or "Ranque angle" has significant effect on the performance of the tube as it decides the peripheral and axial components of the flow inside the tube. Influence of the vortex angle on the performance of the vortex tube which has not been investigated before was studied in this work. Several structures which can be called "angle generators" were placed in the vortex chamber to generate different vortex angles. Then, series of experiments were done in order to investigate the relationship between the vortex angle and the performance of the vortex tube.

EXPERIMENTAL APPARATUS

Experiment setup and the main dimensions of the vortex tube which was specially designed for this experiment are shown in Figure 2. The tube was positioned horizontally on a table. A large tank of compressed air with regulated internal pressure set to 7 bar was used as the source of the working material. A pressure regulator was placed before the inlet nozzle to maintain constant input pressure and measure the input total pressure of the air. An optimized plug, as was suggested in the Arjomandi and Xue's work (2007), was fixed at the hot end to achieve maximum efficiency. The angle generators were fixed in the vortex chamber to be met initially by the injected air when it left the inlet nozzle and flew into vortex chamber. Thus, the injected air formed a vortical flow with a certain vortex angle, which was decided by the angle generator placed in the vortex chamber. A small tube was used to isolate the cold air escaping the cold end from the inlet air, which was fixed at the cold end of the tube. Thus, it could be assumed that direct mixing of the feeding air into the tube and the cold portion of the air leaving the cold orifice did not happen during the experiment.

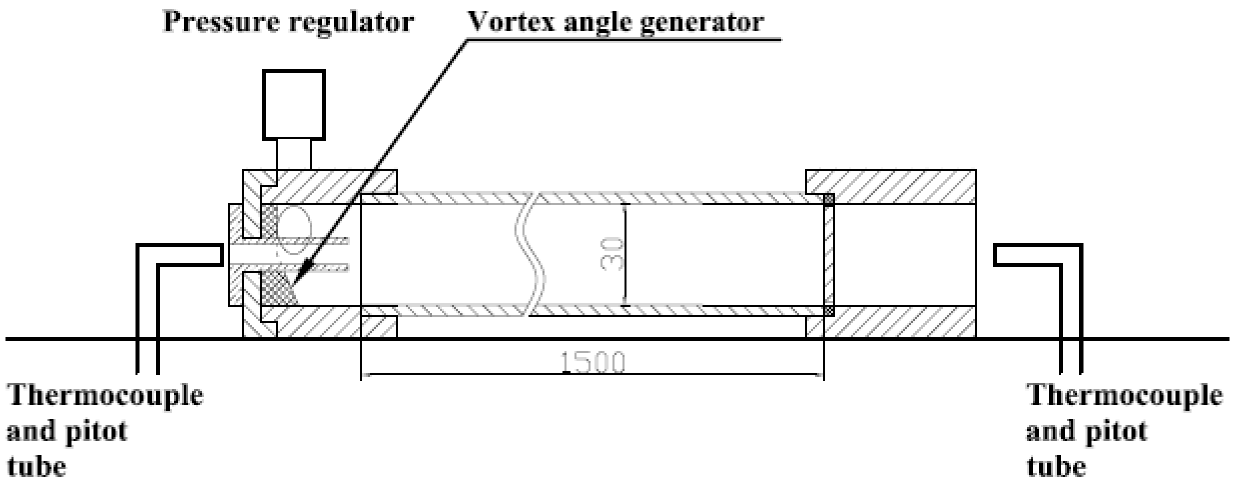

Figure 2. Experimental apparatus for investigation of the vortex angle

Inlet pressure was set at different values before the start of each test (from the smallest value to the largest value), and kept constant in the series of run of different angles. In the experiments, angle generators were changed from the largest angle to the smallest angle in the range. After a series run the inlet pressure was changed to the bigger value and experiments were repeated for the same series of the angle generators. increasing the inlet pressure from the smallest value to the largest and decreasing the angles from the largest angle to the smallest helped to avoid the influence of the remnant heat in the tube and reduced the settling time for measuring the temperature at the hot end, as higher pressure and smaller angle generator produced higher temperature at the hot end of the tube.

Since the air condition in a single day can not change too much, each series test was done in a single day to reduce the influence of the humidity, ambient pressure and temperature changing to an ignorable level. Temperature was measured by a thermocouple and the pressure of the exhausting air was measured by a pitot pipe. Both instruments were fixed at the centerline of the tube ends. In the tests, data were recorded after several minutes after the beginning of each run to allow the air flow to become steady. Enough time was given for settling the tube between sequential tests. Also, where necessary, water was used for cooling the tube in order to avoid the influence of the remnant heat. The temperature of the feeding air was measured before and after each experiment. Because of the large amount of the compressed air in the tank and also short time of each run, the input temperature along each run could be considered as a constant value.

Angle generators were used in this experiment in order to form vortical flows with different vortex angles. The angle generator was designed as an inclined surface, which was attached to a hollow cylinder. The angle generator structure is shown on Figure 3. This structure then was fixed in the vortex chamber immediately opposite the inlet nozzle. The small tube that was used to separate the injected air and the cold air was positioned in the vortex chamber through the cold nozzle and the hollow centre of the angle generator. When the compressed air was injected from the inlet nozzle, it met initially the angle generator, forcing the airflow to align its direction with the angle of inclined surface of vortex generator. Consequently, the air flew toward the hot end with a specific angle. To obtain various vortex angles of the air flow different angle generators were used in this test. Series of experiments were done with a constant input pressure while different angle generators were used; therefore the effects of the vortex angle without the influence of the input parameters were investigated.

The geometrical parameters of the used angle generators are listed in Table 1. All the angle generators have same basement but different angles of the working surface.

Table 1. Size of the angle generators

Number	Size (mm)	Angle (degree)
1	r=5, R=15, H=2.04	2.479
2	r=5, R=15, H=3.15	3.836
3	r=5, R=15, H=4.02	4.876
4	r=5, R=15, H=5.55	6.717
5	r=5, R=15, H=7.15	8.616
6	r=5, R=15, H=10.26	12.283
7	r=5, R=15, H=15.26	17.943
8	r=5, R=15, H=20.06	23.069

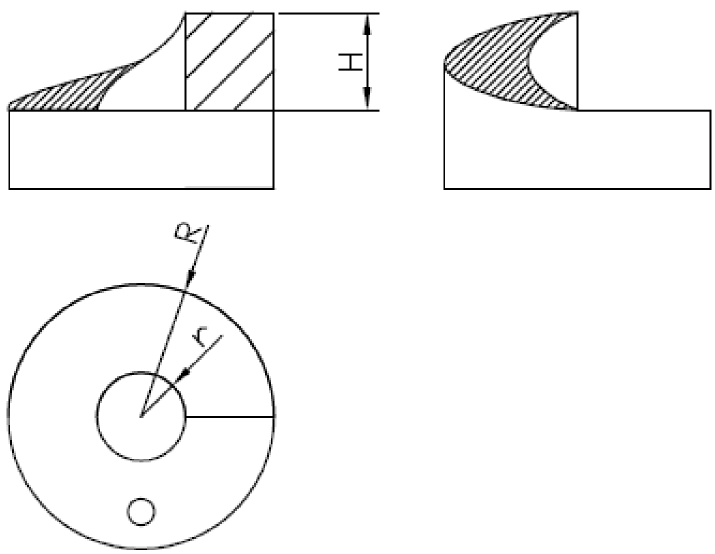

Figure 3. Structure of the vortex angle generator

ANALYSING THE RESULT OF THE EXPERIMENTS

The total pressures, dynamic pressures and the temperature of the input air, and the dynamic pressures and temperature of the exhausting air flow at both hot and cold ends were measured. Analysis of the experimental data shows the following:

In Figure 4 the temperature of the cold air at different input pressures is shown. It is seen that the temperature of the cold air drops when the smaller angle generator is used. In other word, using the smaller angle generator increases the difference between the temperature of ambient air and cold portion of the flow. Moreover, if the angle keeps constant, the temperature drop of the cold air rises with the increase of the input pressure. Since the vortex angle of the vortical flow equals the angle of the angle generator, it is clear that the vortex angle has influence on the temperature drop of the cold air. The temperature drop of the cold air rises with the reduction of the vortex angle or increase of the input pressure. The temperature rise of the hot air at different input pressure is shown in Figure 5. Opposite result can be found in Figure 5 where the temperature rise of the hot air increases with the decrease of the vortex angle or increase of the input pressure. Hence, it is clear that reduction of the vortex angle has positive influence on the temperature separation in the vortex tube. When the input pressure varies between 3 and 4 bar, the temperature of the hot air with small vortex angles is not changing which could be explained as the errors of measurement.

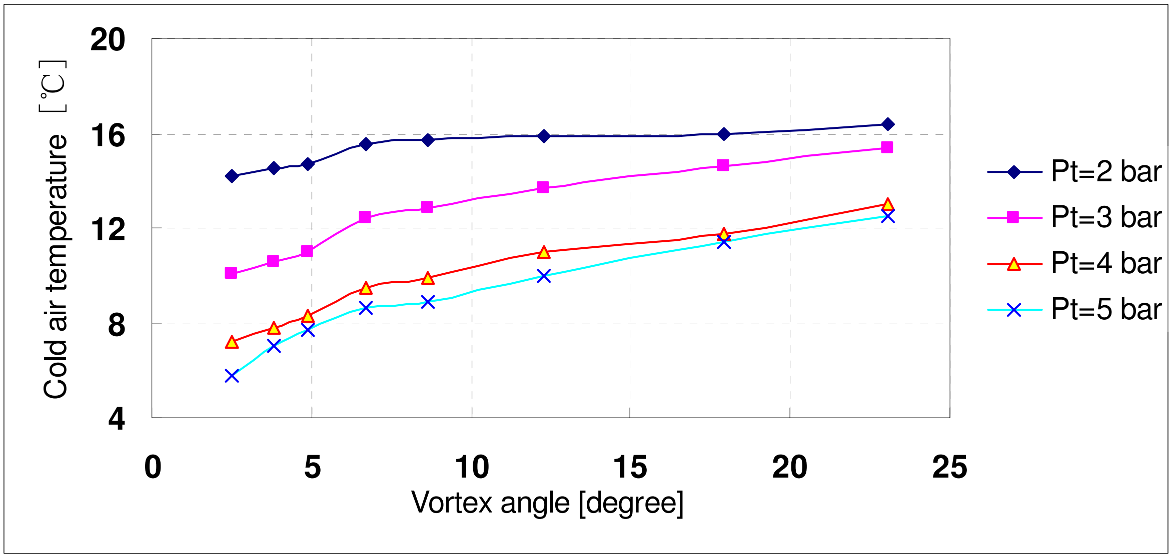

Figure 4. Temperature of the cold air for different vortex angles (Pt is the total pressure of the input air in bar)

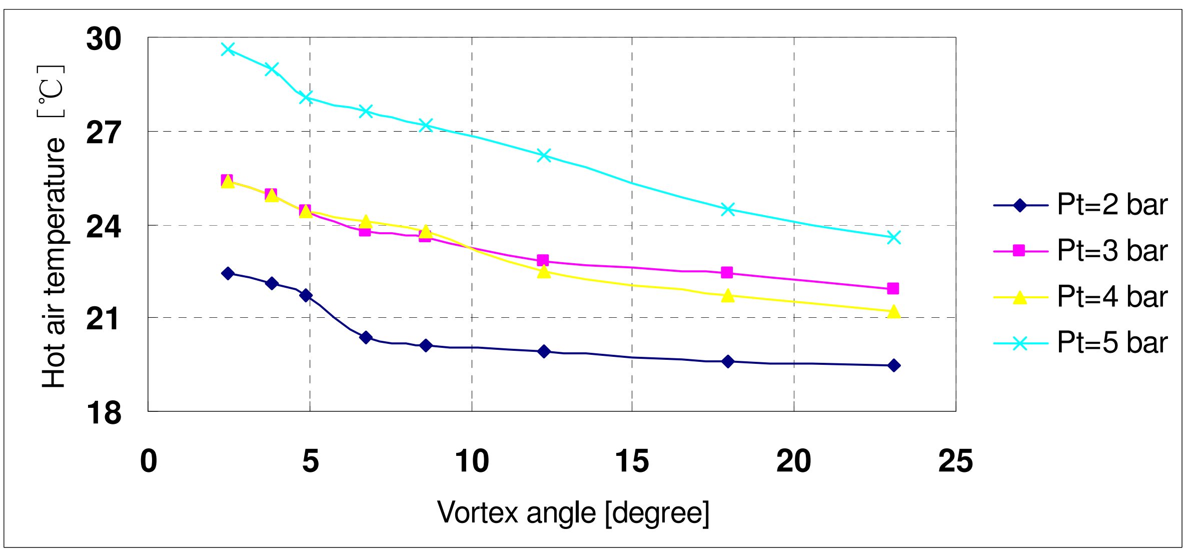

Figure 5. Temperature of the hot air for different vortex angles (Pt is the total pressure of the input air in bar)

For calculation of the thermal efficiency of the vortex tube, the following equation presented in Fulton's work (1950), was used:

$$\eta = \frac{\dot{Q}}{P} = \frac{1}{\Gamma}\frac{\varepsilon \Delta T}{T_{in} \ln \dfrac{p_{in}}{p_c}}$$

Here: η is the thermal efficiency, $\Gamma=(\gamma-1)/\gamma$ where $\gamma=1.4$ is the specific heat ratio, ε is the cold mass fraction and defined as the cold mass flow rate divided by the input mass flow rate, ΔT is the temperature difference, T_{in} is the input temperature, P_{in} and P_c represent the pressure of the input and cold air.

Figure 6 shows the relationship between the heating efficiency of the vortex tube and the vortex angles at different input pressure. Highest heating efficiency happens when smallest vortex angle generator is used in the vortex chamber and highest input pressure is set. For certain input pressure, the heating performance of the vortex tube is better when smaller vortex angle generator is used. For the same vortex angle, the heating efficiency increases when input pressure increases.

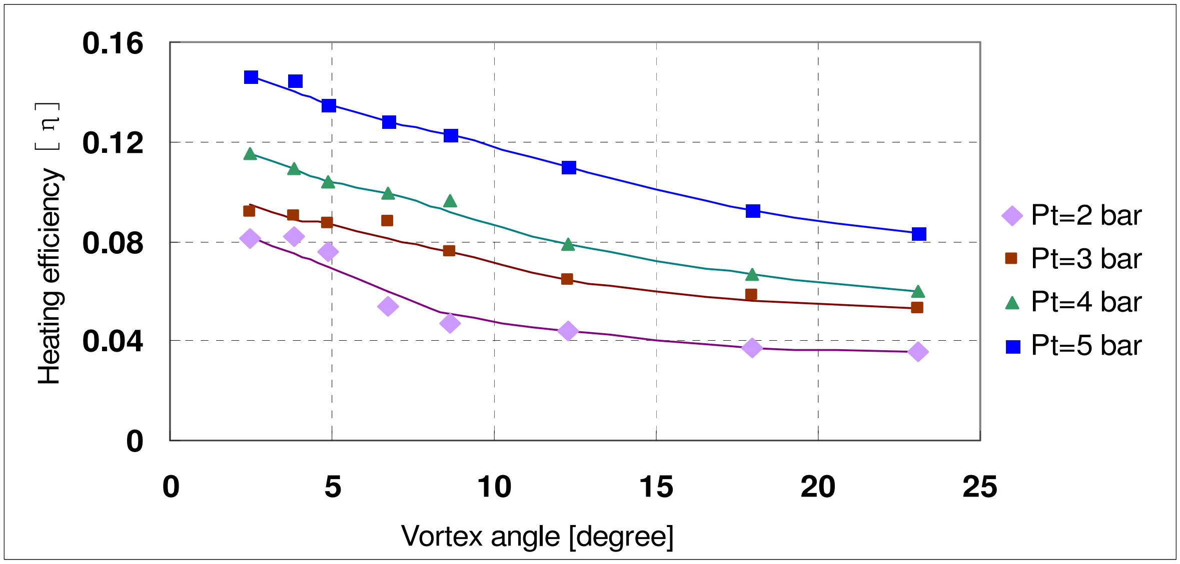

Figure 6. Heating efficiency of the vortex tube versus vortex angle

Cooling efficiency of the vortex tube is shown in Figure 7. The cooling efficiency of the tube for different vortex angle generators and input pressures is comparable with the heating efficiency as a whole. The efficiency increases when vortex angle decreases or input pressure increases.

However, for the input pressure of 2 bars and 3 bars, peak values of the cooling efficiency appear. When the input pressure is 2 bar, the highest cooling efficiency reaches 0.093 with the vortex angle 4.8 degree. And when the input pressure is 3 bar, highest cooling efficiency is 0.156 with the vortex angle 6.7 degree. The relationship between the cooling efficiency and the vortex angle at low input pressure is different from that at high input pressure, which is just a simple direct relationship. This difference of the performance at different input pressure needs more investigation. The point where the peak value of the cooling efficiency at 3 bars input pressure appears does not fit the trendline well and it may be due to the measurement error. For a certain vortex angle, the performance of the vortex tube improves with the rise of input pressure. However, for the input pressure of 5 bars, the cooling efficiency is less than that with 4 bars input pressure. In other words, the cooling efficiency of the vortex tube has best performance at the input pressure of almost 4 bars. When high pressure is set at the input nozzle, stronger turbulence inside the tube reduce the cooling efficiency by increasing more heat than that lower pressure air injected.

The air flow inside the vortex tube can be described as a vortical flow, which has two components, peripheral velocity and axial velocity. The vortex angle shows the relationship between these two types of velocity. The ratio of axial velocity to the peripheral velocity equals the tangent of the vortex angle. Therefore when smaller vortex angle generator is used in the vortex tube, the peripheral velocity is larger, which means that the centrifugal force is larger and the distance of the vortical air travels is longer. According to the compression theory used by Ranque and Hilsch or the inner friction theory used by Reynolds (2005), the temperature separation and the heating efficiency perform well. The cooling efficiency at higher input pressure fits those theories well too. However, when low input pressure is set, the performance of the vortex tube reaches the peak value at certain vortex angle.

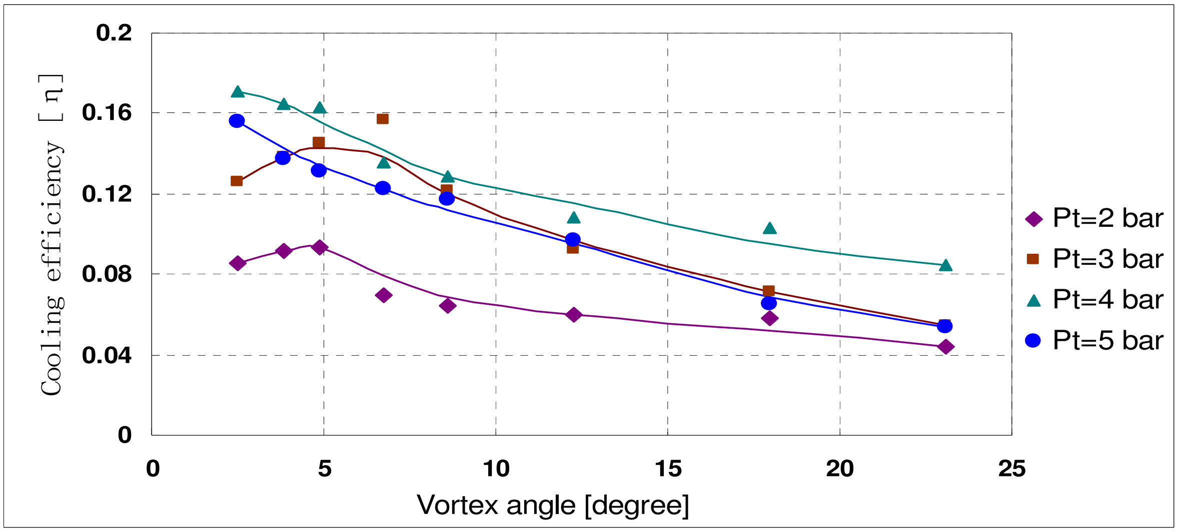

Figure 7. Cooling efficiency of the vortex tube versus vortex angle

CONCLUSION

The purpose of this research is to find the effect of the vortex angle on the performance of the RHVT system. New structure is introduced into this experiment to form different vortex angles, which can be called vortex angle generator.

Different angles are used in the test in order to find the effect of the vortex angle. The vortex angle plays important role in both the temperature separation and the vortex tube performance. Smaller vortex angle gives larger temperature difference, both temperature drop at cold end and temperature rise at hot end. It also gives better performance on the heating efficiency of the vortex tube, and better cooling efficiency except for lower values of input pressure, where peak efficiency appears at vortex angle of about 5 degree. However the existence of the peak value on the cooling efficiency of the RHVT system has not been resolved clearly in this research and more investigation with low pressure injected air is needed. For a certain vortex angle, the better performance of the vortex tube can be seen at higher input pressure and the highest efficiency can be found when the input pressure is around 4 bars. The turbulence introduced by high input pressure reduces the cooling efficiency.

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