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Research Article

Experimental Investigation of performance of Ranque Hilsch Vortex Tube

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Abstract

The Ranque Hilsch Vortex tube is a simple device which can be used to separate hot and cold stream from single injection. It can be used in application such as cooling, heating or mixture separation. As compressed air is injected in to the vortex tube with the help of nozzle which are tangentially attached to the vortex tube, high velocity vortex are formed in the tube. Due to the heat transfer in the vortex tube the cold stream is formed at the center part of tube and hot stream is formed at the periphery of the tube. The behavior of flow inside the tube is of very complex nature. To explain the behavior of flow inside the vortex tube several experimental and numerical investigations have been carried out. This paper discusses the effect on the performance of the vortex tube by varying its number of inlet.

Keywords: *RHVT, Nozzle, Number of inlet, Ranque effect.*

1. Introduction

Vortex tube is a simple device which is used to produce two separate streams i.e. hot and cold stream from single injection of air stream. This device is also called as Ranque Hilisch vortex tube. It consists of a straight tube with a concentric orifice located on a diaphragm near one end, nozzle located tangentially near the outer radius adjacent to the orifice plate. Compressed air enters the tube tangentially through a nozzle forming a swirling motion of air in the tube. It forms strong vortices of flow around the periphery of the tube. The diaphragm prevents motion of the vortex towards left of tube therefore, flow travels towards the right hand side of the tube called hot end. The inlet gas splits into two streams i.e. low pressure stream near the periphery of the tube, while the high pressure stream is formed at the central part of the tube. Hot gas is collected from hot end and cold gas is collected from orifice, thus hot and cold gases are separated.

It has no moving parts. Though it is simple device the thermal efficiency of this device is very low. French physicist named as George J. Ranque invented Vortex tube in 1933; hence it is named after him. In the beginning it was very unpopular due to its very low thermal efficiency; its use was abandoned for several years. However in 1947 the German physicist Rudolf Hilisch modified the design of vortex tube. He had deeply studied and published widely read paper on vortex tube. He stated the functionality of tube as a mechanical device. Since then many researcher have tried to find the way to optimize the efficiency of vortex tube. According to flow direction the vortex tube are classified as uni-flow and counter flow vortex tube. Both types are currently used in the industry. But most widely used is counter flow vortex tube. In the uni-flow vortex tube hot and cold stream flows in the same direction as shown in figure 1. While in the counter flow vortex tube the hot and cold stream flows in the opposite direction as shown in figure 2. Orifice for outlet of cold air is located on the conical valve itself in the uni-flow type vortex tube. But due to the inward turn back motion in the vortex tube it is found that the counter flow type vortex tube is more effective.

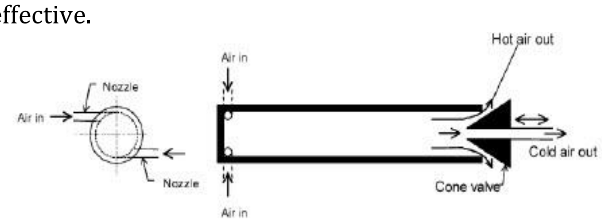

Fig. 1: Uni Flow Vortex Tube

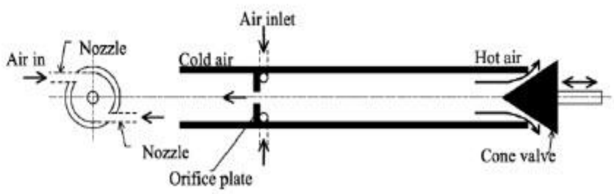

Fig. 2: Counter Flow Vortex Tube

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2. Literature review

The separation mechanism in the vortex tube is not completely understood till a date. Several hypotheses were given for temperature separation in vortex tube by various researchers. These include pressure gradient within the vortex tube, inward turn back of flow, acoustic streaming. The inner part of the flow moves towards the hot end and turns back to central part of the tube. In this part of the tube flow gets expanded due to the low pressure in the central part of the tube and escapes from the cold nozzle at a lower temperature than the injected air (Xeu *et al*. 2013). A Turbulent Flow Instrument named Cobra probe was used to obtain 3-D velocity static pressure and turbulence intensity profiles at different locations along the tube. The three dimensional velocity distributions inside the vortex tube lead to a new understanding of the flow behavior in the vortex tube. It was noted that in the central region of the tube, the rotational vortex at the hot end was transformed to a forced vortex near the injection, and kinetic energy is only transferred outwards from the hot end to the cold end. The locations of the maximum axial velocity indicate the change of the flow structure and support the hypothesis of a multi-circulation as stated in (Xeu *et al*. 2013).

It was observed that for cold fraction lower than 60%, the effect of cold end orifice diameter is negligible and above 60% cold fraction it becomes prominent. It was found that the biggest ΔT values are observed with the plug which has a tip angle of 30° or 60° (Kshirsagar *et al*. 2014). Three innovative technologies were applied to the vortex tubes. A new nozzle and a new intake flow passage for nozzles with equal flow velocity were designed and developed to reduce the flow loss. A new kind of diffuser invented and installed for reducing friction loss of energy in the air at the end of the hot end, which greatly improves the performance of vortex tube (Wu *et al*. 2007). The experiments on the industrial vortex tubes and concluded that vortex tube is more efficient than a simple Joule-Thomson valve. Vortex Tube was developed by Ruhrgas AG and FILTAN GmbH (2000). Temperature separation effect depends on pressure ratio between inlet and outlet of the tubeHigher temperature differences correspond to higher pressure ratios (Gutak A. 2015). To achieve the lowest cold temperature vortex tube should operate at cold stream mass fractions equal 0.2-0.4. The optimum value of splitting air temperature is for length to diameter (L/D) ratio 15 and aspect ratio 1.4 at inlet pressure of 6 bar (Ahmed *et al*. 2014).The optimum L/D ratio can be different it depends upon operating factors, and optimum length of vortex tube is function of geometrical and operating parameters such as inlet pressure and flow rate, increasing the length to diameter ratio of vortex tube beyond 9.3 has no effect on performance of vortex tube (Pourmahmoud and Bramo 2011). The optimum value of cold mass fraction is 0.4 for the maximum temperature separation (Attalla *et al*. 2014). The orifice diameter influences the expansion that take place in the vortex chamber. Experimentation obtained the maximum temperature difference 24.55 for a cone valve angle 10° (Rejin and Thilakan 2012). The inner stream is having a forced vortex flow and the outer stream is having free vortex flow. In a vortex flow as the radius was decreasing the linear velocity of the fluid also decreases hence kinetic energy decreases and this decrease in kinetic energy is converted in heat which is dominant reason for the temperature separation in a vortex tube (Dhangar *et al*. 2015).The performance of the tube is better when the inside surface roughness used is 6.264 μm (Kumar and Sudhir 2014).It was found that the vortex tube with a conical angle of about 2.5˚ have 25% to 30% higher efficiency than the cylindrical tube. Study concluded that the COP of the tube is increased with use of conical angle to the vortex tube. Optimum conical angle for the cylindrical tube is between 2° to 3° (Kumar *et al*. 2014).

3. Working Principle

Compressed air at high pressure is injected in the vortex tube through tangential inlet. Due to high pressure and convergent shape of nozzle flow gets accelerated in to the tube and air rotate with high velocity in the tube. Swirling motion of air starts retarding in the core region of the tube. Flow of air expands in the center part of the tube. Subsequently the spiral flow of air stats moving to the other side of the tube. Out flow of the air is controlled by the hot end valve at the other end. Air comes out from the periphery of the tube. Motion of the air is reversed by the obstruction of the end valve. Center part is pushed to the opposite side of the tube i.e. towards the orifice. Cold stream is collected at the orifice thus flow is separated.

4. Objective of the experimentation

Several hypotheses for temperature separation in the vortex tube are given by various researchers but still not a well-accepted explanation has been given. The main aims of this project work are as follows

- Prepare test rig for the experimentation on the vortex tube
- Observe the temperature of hot air and the refrigeration effects when a different number of nozzles are used.
- To evaluate the COP of vortex tube for constant mass fraction for various nozzle.

5. Design and constructional detail

Design detail of the vortex tube: diameter of the tube D= 20mm; length of the tube L= 300mm; diameter of the orifice= 8mm;

Table 1 Dimension of nozzles

Nozzle	Width (mm)	Depth (mm)
Nozzle 1	10	5
Nozzle 2	8	5
Nozzle 3	8	5
Nozzle 4	6	4

Convergence ratio is kept 2 for all the nozzles.
Material used for manufacturing of vortex tub is aluminum because of low weight and lower machining cost.

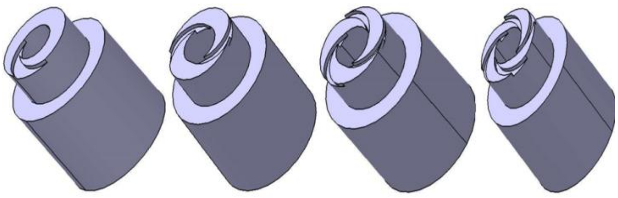

Fig.3 Manufactured nozzle for various number of inlet

6. Experimental setup

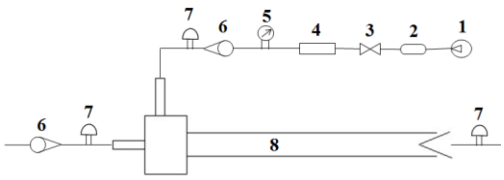

Fig. 4 Layout of the Experimental Setup

Instrumentation used in the experimentation are explained below
Instrument used in the experiment

1 Compressor (2 stage reciprocating) :20 bar
2 Storage tank :165 liters
3 Flow control valve
4 FRL unit :8 bar
5 Pressure gauge :10 bar
6 Rotameter :1-100 lpm, 1-200 lpm
7 Thermocouple : -50°C to 150°C
8 Vortex tube

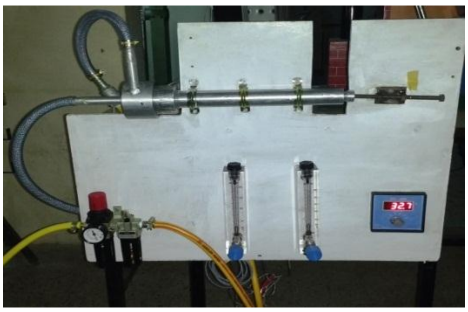

Fig. 5 Test rig for vortex tube

7. Definitions

Cold mass fraction

Cold mass fraction is most important parameter indicating performance of the vortex tube. It indicates the ratio of mass of air leaving orifice to the mass of air injected in the tube.

$$\mu = \frac{m_c}{m_i} \quad (1)$$

Cold air temperature difference
Cold air temperature difference is defined as the depression in the temperature at the cold end.

$$\Delta T_c = T_i - T_c \quad (2)$$

hot air temperature difference
Rise in temperature of air at hot end is known as the hot air temperature difference

$$\Delta T_h = T_h - T_i \quad (3)$$

Power
Power required to drive the compressor is given as

$$P = \left(\frac{\gamma}{\gamma - 1}\right) P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] \quad (4)$$

Refrigerating effect and heating effect
Cooling and heating effect produced vortex tube is given as

$$Q_c = m_c C_p \Delta T_c \quad (5)$$

$$Q_h = m_c C_p \Delta T_h \quad (6)$$

Coefficient of performance
Coefficient of performance is the ratio of cooling effect produced by the vortex tube to the compression work required to compress air

$$COP = \frac{Q_c}{P} \quad \text{Or}$$

$$COP = \frac{\mu C_p \Delta T_c}{\left(\frac{\gamma}{\gamma - 1}\right) R T_i \left[\left(\frac{P2}{P1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (8)$$

8. Result and Discussion

Cold air temperature difference and cold air mass fraction is important parameter defining performance of vortex tube. Obtained results for various nozzles are shown in graph below. Graph for cold air temperature difference vs inlet pressure and COP vs inlet pressure for mass fraction 0.35 and 0.41 is shown in figure. It is clearly visible that the cooling effect increases with increase in inlet pressure. At higher inlet pressure generation of swirling motion is better for similar nozzle configuration due to more tangential velocity.

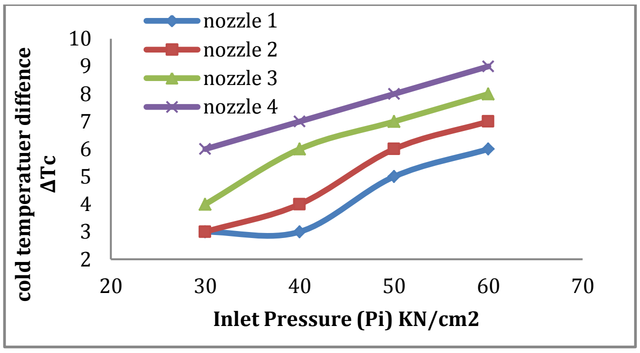

Fig. 6 Variation of cold air temperature difference of various numbers of nozzles for cold mass fraction 0.35

Maximum temperature difference at cold end is shown as 8°C for 4 nozzles, at higher pressure the COP of the vortex tube is low because in increase in compression work for compressing the working fluid, over all cop of the vortex tube is found to be around 0.1

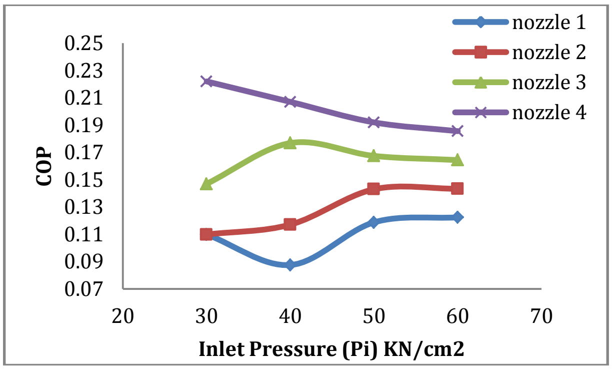

Fig. 7 Variation of COP for various numbers of nozzles for cold mass fraction 0.35

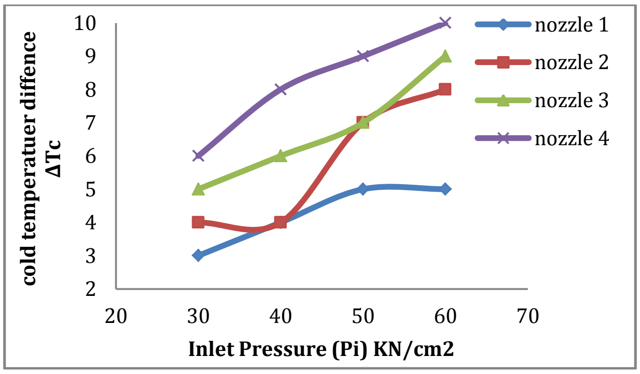

Fig. 8 Variation of cold air temperature difference of various numbers of nozzles for cold mass fraction 0.41

Performance of vortex tube is better at mass fraction 0.41 than 0.35 for nozzle 4. But for low pressure and for nozzle 1 and 2 cop of vortex tube is low mass fraction 0.4. For any mass fraction COP of vortex tube increases with increase in number of nozzle.

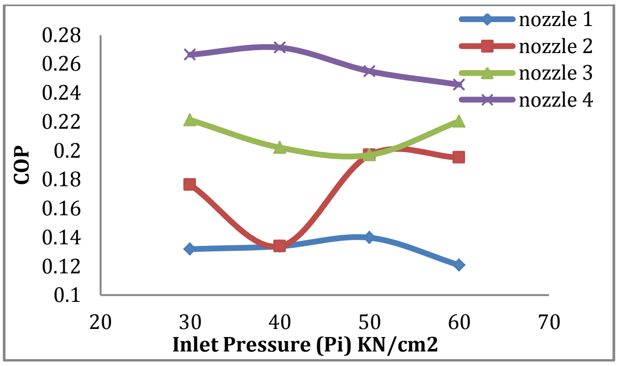

Fig. 9 Variation of COP for various nozzles for cold mass fraction 0.41

Comparison between performances of vortex tube for various nozzles:

As the mass flow increases in the vortex tube the temperature separation increases. Mass fraction exit from cold end is kept constant for single nozzle. Maximum separation for 1 nozzle is 7°C at 6 bar inlet pressure while it increase to 8°C for 4 number of nozzle at 6 bar with increase in mass flow rate. Fig 6 shows the variation in cop for various nozzles. Maximum COP is for 4 number of nozzles.

Conclusions

The influence of number of nozzle is tested experimentally from this study following points are concluded:

a) By increasing the number of nozzle the COP of vortex tube is increased.

b) Though at lower pressure COP of the tube is higher the desired cooling effect is lower at low pressure, hence very low thermal separation

c) By increasing the number of inlet mass flow in the tube can be increased at high pressure for better vortex generation

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