An Experimental Modeling and Investigation of Change in Cold Mass Fraction and Nozzle Numbers on Performance of Counter Flow Vortex Tube

S. S. Mohanty · D. K. Ray

Received: 27 June 2011 / Accepted: 8 April 2012 / Published online: 2 June 2012
© The Institution of Engineers (India) 2012

Abstract An experimental investigation has been performed to realize thorough behavior of a vortex tube system. The vortex tube is a simple device operating as a refrigerating unit without any moving parts. It consists of a principal tube, to which a high pressure gas stream enters tangentially where it splits into two streams: one hot and one cold temperature streams. This paper discusses the experimental investigation of vortex tube performance as it relates to cold mass fraction, and nozzle number. Four different orifices, each with three, four, five and six nozzles respectively, were manufactured and used during the test. The experiments have been conducted with each one of those orifices stated above, and the performance of the vortex tube has been tested with air at inlet pressure of 5 bar and the cold mass fractions of 0.5–0.72.

Keywords Counter flow vortex tube · Cold mass fraction · Heating and cooling effect

List of symbols

Variables

M Mass flow rate (kg/s)
 P Pressure (kPa)
 T Temperature (K)
 ΔT Temperature gradient (K)
 μ_c Cold mass fraction

Subscripts

i Inlet

c Cold outlet
 h Hot outlet

Introduction

The vortex tube, also known as Ranque vortex tube, Hilsch vortex tube, and Ranque–Hilsch vortex tube, is a device that enables the separation of hot and cold air as pressurized air flows tangentially into the vortex chamber through inlet nozzles.

Vortex tube was first discovered in the year 1933 by metallurgist and physicist Ranque, and the German physicist Hilsch [1] improved the design. A vortex tube consists of one or more inlet nozzles, a vortex chamber, a cold-end orifice, a hot-end control valve, and a tube. The vortex tube is a very simple device without moving parts (i.e., diaphragm, pistons, shafts, etc.). In this arrangement a stream of a compressed gas (usually air) is injected tangentially into the vortex tube, which has a diameter D , using one or more nozzles symmetrically located around the tube. A high pressure gas stream enters into the vortex tube, tangentially, and there it splits into two streams: one hot and one cold temperature streams. Cold gas stream leaves the tube through a center orifice near the entrance nozzle, while the hot gas stream flows toward control valve and leaves the tube there [2].

The working principle of the counter flow can be defined as follows: a compressible fluid, which is tangentially introduced into the vortex tube from nozzles, starts to make a circular movement inside the vortex tube at high speeds, caused by the cylindrical structure of the tube, depending on its inlet pressure and speed. A pressure difference occurs between the tube wall and the tube center caused by the friction of the fluid circling at high speeds, though the radial

S. S. Mohanty, *Non-member* · D. K. Ray (✉), *Member*
Department of Mechanical Engineering, C V Raman College
of Engineering, Bhubaneswar 752054, India
e-mail: dwijendrakumarray@yahoo.com

Fig. 1 Schematic representation of counter flow vortex tube

pressure gradient also is partially responsible for the separation of the two streams. The speed of the fluid near the tube wall is lower than the speed at the tube center due to the effects of wall friction. As a result, the fluid in the center region transfers energy to the fluid at the tube wall, depending on the geometric structure of the vortex tube. The cooled fluid leaves the vortex tube by moving against the main flow direction after the stagnation point, whereas the heated fluid leaves the tube in the main direction. The schematic representation of vortex tube is shown in Fig. 1. The energy separation in counter flow vortex tube is shown in Fig. 2.

The vortex tube can be used in many industrial applications such as cooling equipment of computer numerical control (CNC) machine tools, refrigerators, cooling suits, heating processes, etc., because it is simple, compact, light, and quiet. Since it has no moving parts, it does not cause to break or wear the unit and therefore it requires little maintenance.

Experimental Study

An experimental modelling of vortex tube was done and studied by Saidi and Valipour [3] in the year 2003 and then it was modified by Wua, et al [4] in the year 2007. But this study, a counter flow type vortex tube with L/D ratio equal to 16 was used. The material taken for manufacturing was Bright steel (mild steel) [C(.37 % 4 %), Mn(0.60.9 %), Si(0.10.35 %), P(0.04 %), S(0.04 %)] as this material is very easy for machining and for making intricate shapes. The cone valve of three different types having different included angle was designed. Four different orifices with different nozzle numbers [3–6] have been manufactured and used in the experiments.

Fig. 2 Energy separation of counter flow vortex tube

The inlet pressures and the hot and cold outlet pressures of the vortex tube have been measured by use of a pressure gauge. The pressure used in our experiments is 5 bar. The mass flow rates at the cold and hot outlets of the vortex tube have been measured by use of a pitot tube. The temperatures of the pressurized air at the inlet and the cold and hot outlets were measured by use of a thermo couple. It consist of a digital temperature displayer and a K type thermocouple sensor(range-(−99 to 999 °C)). A control valve has been mounted on the hot outlet of the tube in order to adjust the mass flow rate of the hot air. With the help of this valve, cold mass fraction μ_c was being adjusted. Before starting the experimental studies, the control valve on the hot outlet was kept in fully open position and then the air compressor was started and by use of the valve placed on the vortex tube inlet side, the beginning pressure value of 5 bar was reached. The compressed air flow is continued until the constant temperature values have been reached at the cold outlet and at the hot outlet of the vortex tube. During this stage, the mass flow rates and pressures of the air at the cold outlet and hot outlet were measured by using pitot tube and pressure gauges, respectively.

Experimental Setup

Figure 3 represents different components of vortex tube (such as swirl chamber with nozzles, tightening screw, pipe, coupler and conical valves) and Fig. 4 the main assembly of vortex tube.

Figures 5 and 6 show schematic diagram of experimental setup and actual picture of experimental setup.

Results and Discussion

In this study, the performance of the vortex tube with L/D ratio 16 and nozzle number $N = 3, 4, 5, 6$ was tested under

Fig. 3 Different components of vortex tube

Fig. 4 Main assembly of vortex tube

Fig. 5 Schematic diagram of the vortex tube experimental setup. 1 Reciprocating compressor, 2 Vortex tube conical valve, 3 U tube manometer, 4 Vortex tube main pipe, 5 Pitot tube, 6 Pitot tube annular space, 7 Thermo couple digital display, 8 Vortex tube cold orifice, 9 Manometer pipe

Fig. 6 Actual experimental setup

the inlet pressure of 5 bar, $\mu c = 0.50$ – 0.72 conditions with compressed air. The cooling effect (ΔT_c) and the heating effect (ΔT_h) of the vortex tube are defined as follows, respectively:

$$\Delta T_c = T_i - T_c, \quad (1)$$

$$\Delta T_h = T_h - T_i. \quad (2)$$

In general, the performance of the vortex tube was defined as the difference between the heating effect and the cooling effect. Subtracting Eq. (1) from Eq. (2) gives the vortex tube Performance equation as follows [5]:

$$\Delta T = T_h - T_c. \quad (3)$$

The cold mass fraction is one of the important parameters since it indicates the vortex tube performance and the energy separation inside the vortex tube. Cold mass fraction is defined as the percentage of the pressurized air input to that released through the cold end of the tube and can be calculated by using Eq. (4). The cold mass fraction can be controlled by the conical valve, which is placed at the hot end of the tube. This can be expressed as follows [6].

$$\mu c = M_c / M_i \quad (4)$$

where M_i and M_c are the mass flow rates at the inlet of the vortex tube and at the cold outlet, respectively.

The graph between cold outlet temperatures of the air at 5 bar inlet pressure versus cold mass fractions is shown in Fig. 7. For each one of the nozzles used, when the μc was adjusted to 0.578 with $N = 3, 4, 5, 6$ the cold outlet temperatures were measured as follows: 263.4 K, 267.9 K, 274.1 K, 275.2 K respectively. The minimum cold outlet temperature is obtained for $N = 3$.

The graph between hot outlet temperatures of the air at 5 bar inlet pressure versus cold mass fractions is shown in Fig. 8. When the μc was adjusted to 0.711 for each one of the nozzles of $N = 3, 4, 5, 6$ the hot outlet temperatures were measured as follows: 326.6 K, 321.1 K, 317.9 K and 315.5 K, respectively. The cold mass fraction is the maximum cold mass fraction ratio used in this study. But, as shown in Fig. 8, increasing the cold mass fraction ratio also shows an increasing tendency of the hot outlet temperature. And this means that in order to obtain a higher hot outlet temperature the cold mass fraction ratio is to be increased. The maximum hot outlet temperature is obtained for $N = 3$.

Fig. 7 Cold outlet temperatures versus cold mass fractions at $P_i = 5$ bar

Fig. 8 Hot outlet temperatures verses cold mass fractions at $P_i = 5$ bar

Fig. 9 Temperature gradient verses cold mass fraction

When we look at Figs. 7 and 8 again, the hot outlet temperature values changing from maximum to minimum have been obtained for the nozzle numbers of 3, 4, 5, and 6, respectively, while the cold outlet temperature values varying from minimum to maximum have been obtained for the nozzle numbers of 3, 4, 5, and 6, respectively. For testing the performance of the vortex tube the temperature gradient was used, and the performances is shown in Fig. 9 according to cold mass fraction. The temperature gradient between the cold and hot outlets is decreased with increase in cold mass fraction. The temperature gradient is the maximum for $N = 3$ at cold mass fraction of 0.578.

Flow Visualization Using Bromine

Flow visualization shown in Fig. 10 has been done to visualize the flow patterns. In vortex tube the flow pattern is the most important section of study. We used bromine as the chemical which can produce reddish brown colour vapour. This method was not completely successful but we could see the pattern to some extent.

Fig. 10 Flow visualization using bromine

Conclusion

In this study, the experimental data for a counter flow type vortex tube with $L/D = 16$ has been obtained by using the compressed air and with different nozzle numbers $N = 3, 4, 5, 6$ under the pressure of 5 bar and cold mass fractions of 0.5–0.72. According to the experimental results, the minimum cold outlet temperature of 263.4 K and maximum hot outlet temperature of 326.6 K is obtained for $N = 3$. The temperature gradient between the cold and hot outlets is decreased when we take into account the effects of the nozzle numbers. But the maximum temperature gradient is obtained for $N = 3$. It is also seen from the result that the minimum cold outlet temperature (i.e. 263.4 K) has been obtained at decreased cold mass fraction (i.e. 0.578) and maximum hot outlet temperature (i.e. 326.6 K) is obtained at increased cold mass fraction (i.e. 0.711). From the results it is concluded that, the cold outlet temperature (i.e. 263.4 K) which is the minimum temperature obtained in $N = 3$ for a fixed mass flow rate can be used for application in spot cooling of electronic equipments, cooling of cutting tools in manufacturing processes. Similarly the hot outlet temperature (i.e. 326.6 K) which has been obtained in $N = 3$ for fixed mass flow rate when the cold mass is increased can be used for heating applications such as melting the glues, softening the plastics, humidifying the ambient air etc.

References

1. A.F. Hamoudi, A. Fartaj, G.W. Rankin, Performance characteristics of a microscale ranque-hilsh vortex tube. *ASME J. Fluid. Eng.* **130**, 101206–101207 (2008)
2. V. Kirmaci, O. Uluer, An experimental investigation of cold mass fraction, nozzle number and inlet pressure effects of performance of counter flow vortex tube. *ASME J. Heat. Transf.* **131**, 081701–081709 (2009)
3. M.H. Saidi, M.S. Valipour, Experimental modeling of vortex tube refrigerator' center of excellence in energy conversion, school of mechanical engineering, Sharif University of Technology, Iran. *J. Appl. Therm. Eng.* **23**, 1971–1980 (2003)

4. Y.T. Wua, Y. Dinga, Y.B. Jia, C.F. Maa, M.C. Geb, Modification and experimental research on vortex tube. *Intern. J. Refrig.* **30**, 1042–1049 (2007)
5. O. Aydin, M. Baki, An experimental study on the design parameters of a counter flow vortex tube. *Energy* **31**, 2763–2772 (2006)
6. P.K. Singh, R.G. Tathgir, D. Gangacharyulu, G.S. Grewal, An experimental performance evaluation of vortex tube. *J. Inst. Eng. (India) Part MC* **84**, 149–153 (2004)