Experimental Investigation and Optimization of Vortex Tube with Regard to Nozzle Diameter

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ABSTRACT

The simple counter-flow vortex tube consists of a long hollow cylinder with tangential nozzle at one end for injecting compressed air. Compressed air supplied to the vortex tube is separated into low pressure hot and cold air from its two ends. The exact mechanism of this temperature separation is not known today. Most of the investigators have studied the various operating characteristics of vortex tube based on the cold air fraction. Vortex tubes of different geometrical configurations give optimum performance at different cold fractions.

This paper presents experimental results of the energy separation in vortex tubes for different nozzle diameters keeping all other geometrical parameters constant. It is experimentally evidenced that the nozzle diameter greatly influences the separation performance and cooling efficiency. The most important point revealed in this paper is that there is an optimum nozzle diameter that gives the best performance of vortex tube.

1. INTRODUCTION

A vortex refrigerator is a device with no moving parts (specifically, a tube or pipe) that will convert an incoming compressed fluid stream (such as air) of homogeneous temperature into two streams of different temperature, one warmer than the inlet and one cooler. By injecting compressed air at room temperature circumferentially into a tube at high velocity, a vortex tube can produce cold air and hot air streams. Temperature and airflow rates are controllable by adjusting valve on hot end of the tube. The inlet air is injected circumferentially at one end of the tube and part of the air is removed at the opposite end. As the flow moves toward the warm end, some of the air expands to the central core and exits at the cold end.

Ranque, a metallurgist, first discovered this phenomenon of energy separation in 1931, when he was studying process in a dust separation cyclone. Later, Hilsch a German physicist performed the detailed examination of the vortex effect and improved the design of vortex tube. Intensive experimental and analytical studies of vortex tube began since then and continue even today.

Gulyave A.I. [1], Borisenko et al [2], Raiski et al [3], Takahama et al [4], Parulekar B.B. [5}, Lay J.E. [6], Webster D.S.[7], Y.Soni & W.J. Thomson [8] have done experimental studies on the vortex tube. Alhborn et al [9] has postulated a theory of temperature separation based on heat pump mechanism enabled by secondary circulation flow in vortex tube. M.H. Saidi and M.S.Valipour [10] performed experimental modelling of the vortex tube considering geometrical and thermo-physical parameters. They studied the effects of the diameter of the cold flow line, the humidity of the air at the entrance of the vortex tube and the length of the vortex tube on the performance of the RHVTs, by using a vortex tube with D = 18mm and L = 55.5 x D =1000 mm. They noted that L/D should be between 20 < L/D < 55.5 in RHVTs. Gulyaev [1] recommends a minimum length of 13 times more than that of the diameter. Soni and Thompson [11] deduced an L/D greater than 45 for efficient working.

Singh P.K and et al [11] states that the effect of nozzle design is more important than the cold orifice design in getting higher temperature drops. Balmer [12] has demonstrated that the heat separation, which occurs inside the Ranque–Hilsch a vortex tube is not limited to compressible gases and can be applied for noncompressible fluids as well. Dincer et al. [13] investigated the effect of control valve tip angle on performance of Ranque-Hilsch vortex tube using different inlet pressures. Behera et al. [14] showed from solutions obtained using computational fluid dynamics that this secondary flow could be related to the cold end cross-sectional area. It was concluded that a secondary flow would occur when the cold end cross-sectional area was small. Dincer et al [15] carried out exergy analysis of the vortex tube with regard to nozzle cross sectional area and suggested that the variation of the exergy efficiency increased with increasing pressure and cold fraction.

However till today no exact theory has come up to explain the phenomenon satisfactorily. Thus much of the design and the development of vortex tube have been based on the empirical correlations leaving much scope for optimization of critical parameters.

This paper presents experimental results of the temperature separation in vortex tubes of different nozzle diameters keeping all other geometrical parameters constant. It is experimentally evidenced that the nozzle diameter greatly influences the separation performance and cooling efficiency. The most important point revealed in this paper is that there is an optimum nozzle diameter that gives the best performance of vortex tube.

2. EXPERIMENTAL SET-UP

The schematic of the experimental apparatus and measuring devices which is used for the determination of the energy separation in a vortex tube is shown in figure 1.

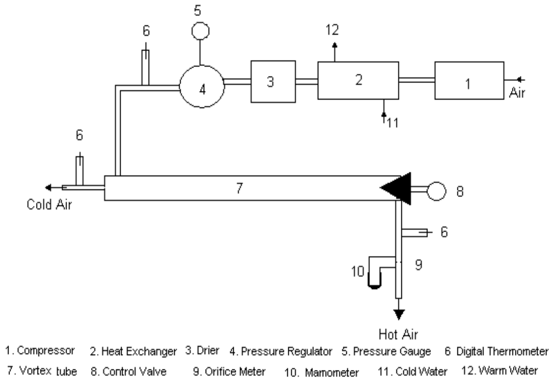

Figure 1. Schematic diagram of the experimental apparatus and measuring devices

Compressed air is passing through the heat exchanger (2) and drier (3). Pressure regulator (4) is used for controlling the pressure of inlet air. Since then it is injected tangentially into the vortex tube (7). The compressed air expands in the vortex tube and meanwhile it is divided into cold and hot streams. The cold air leaves the central orifice near the entrance nozzle, while the hot air discharges the periphery at the far end of the tube. The control valve (8) controls the flow rate of the hot air. The mass flow rates at the hot outlet of the counter flow Ranque–Hilsch vortex tubes can be calculated by standard calibrated orifice meter (9) and manometer (10) fitted to hot exhausts. The inlet temperature, the hot outlet temperature and the cold outlet temperatures of the counter flow Ranque–Hilsch vortex tube have been measured by use of digital thermometers (6) with 0.1 ^oC precision tolerances as shown in Fig. 2. The pressure of inlet gas is measured by pressure gauge (5).

To investigate the effect of nozzle diameter on the operating characteristics of vortex tubes, following geometrical & physical parameters were used as standard.

Tube Diameter, D= 10 mm

Tube Length, L=300 mm

Number of Nozzles, N= 3

Nozzle angle, Φ□ =3^0

Pressure, P =2.0 bar

Orifice diameter, D_o =3.7 mm

The experimental tests of the vortex tube were performed with the variation of each of the above parameters (except tube diameter) one at a time. The pressure of inlet air, Pi was varied from 1.0 bar to 2.5 bar with the increment of 0.5 bar. The tube length, L was varied from 250 mm to 500 mm with the increment of 50 mm. The nozzle angle, Φ was varied from 1.5^0 to 4.0^0 with the increment of 0.5^0. The nozzle diameter, D_n was varied from 2.8 mm to 3.8 mm with the increment of 0.2 mm. The orifice diameter, Do was varied from 2.9 mm to 5.2 mm. Four generators of different number of nozzle intakes (N = 1, 2, 3 & 4) were constructed and examined. Each one of the generators has the same cross-section area. Before starting the experimental studies, the control valve on the hot outlet was kept in fully closed position. Then the compressed air was supplied to the vortex chamber and control valve was gradually opened up to full open position. Thus the experimental tests of the vortex tube were performed with the variation of the cold fraction of air (μ) from 0 to 1.

3. RESULTS AND DISCUSSION

For investigating the optimization effect of nozzle diameter, the maximum temperature drop $(\Delta Tc)_{max}$ for each test is tabulated and plotted against nozzle diameter (D_n) as shown in the figure 2 to figure 6.

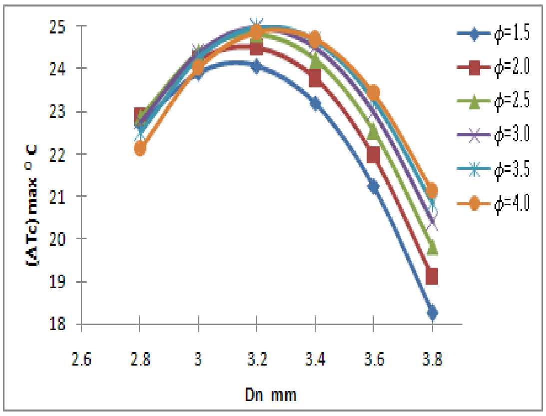

Fig 2 (a)

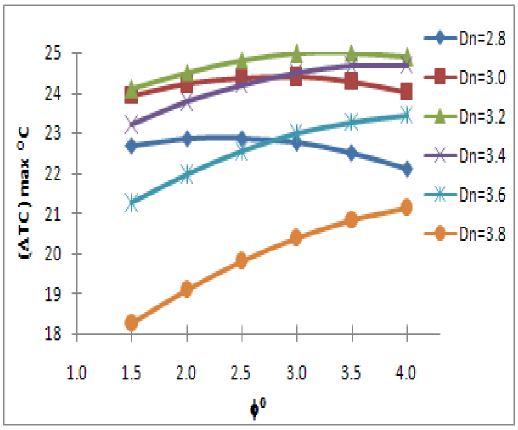

Fig 2 (b)

Fig.2. Effect of Nozzle Diameter and Nozzle Angle on Maximum Temperature Drop

Figure 2 shows the effect of nozzle diameter (Dn) on maximum temperature drop $(\Delta Tc)_{max}$ for variable nozzle angle (Φ) keeping remaining parameters (P, Do, L, Dt, N) constant. From the figure it can be noted that for nozzle diameter greater than 3.4 mm, the maximum temperature drop $(\Delta Tc)_{max}$ increases with increase in nozzle angle (Φ). Whereas for nozzle diameter less than 3.0 mm, the maximum temperature drop $(\Delta Tc)_{max}$ decreases with increase in nozzle angle. But for nozzle angle around 3.2 mm, the maximum temperature drop $(\Delta Tc)_{max}$ is almost constant for nozzle angle ranging from 2.5^0 to 4.0^0. Again it is observed that the peak value of maximum temperature drop $(\Delta Tc)_{max}$ corresponding to all nozzle angles is for nozzle diameter (Dn) around 3.2 mm. Thus for any Φ, Dn=3.2 mm is the optimum value keeping remaining parameters constants.

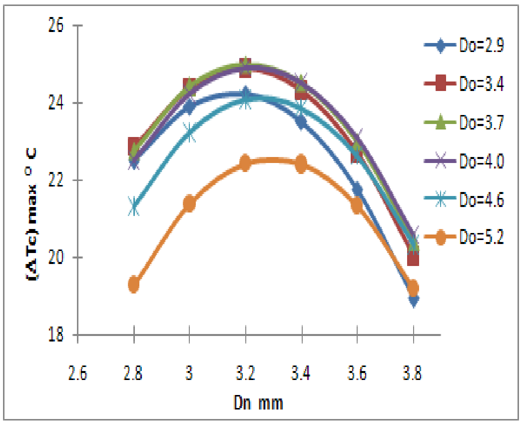

Fig. 3(a)

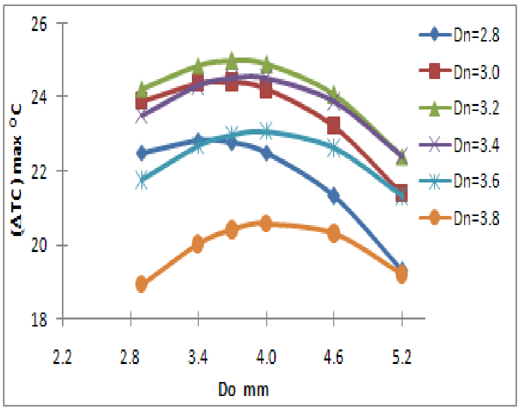

Fig. 3(b)

Fig.3. Effect of Nozzle Diameter and Orifice Diameter on Maximum Temperature Drop

Figure 3 shows the effect of nozzle diameter (Dn) on maximum temperature drop $(\Delta Tc)_{max}$ for variable orifice diameter (Do) keeping remaining parameters (P, Φ, L, Dt, N) constant. From the figure it can be noted that $(\Delta Tc)_{max}$ increases with increase in Do up to certain value, then it attains peak value and finally decreases with increase in Do. For Dn ranging from 2.8 mm to 3.8 mm , it is observed that peak value of $(\Delta Tc)_{max}$ is obtained for Do around 3.4 mm to 4.0 m. For this range of Do, $(\Delta Tc)_{max}$ verses Dn curves merges together at peak value of $(\Delta Tc)_{max}$ for nozzle diameter (Dn) around 3.2 mm. Thus for any Do, Dn=3.2 mm is the optimum value keeping remaining parameters constants.

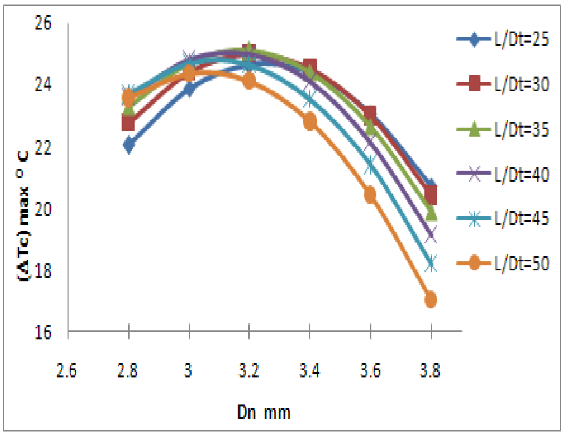

Fig. 4(a)

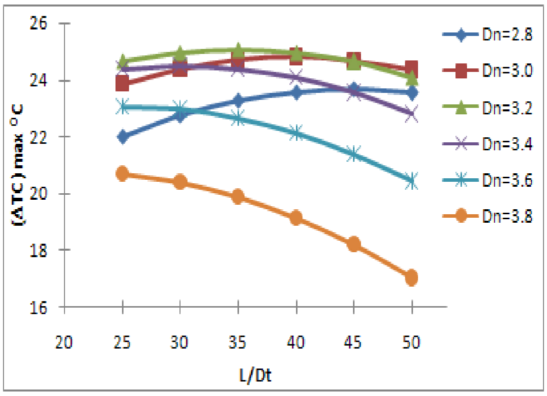

Fig. 4(b)

Fig.4. Effect of Nozzle Diameter and Tube Length on Maximum Temperature Drop

Figure 4 shows the effect of nozzle diameter on maximum temperature drop $(\Delta Tc)_{max}$ for variable tube length keeping remaining parameters (P, Do, Φ, Dt, N) constant. From the figure it can be noted that for nozzle diameter greater than 3.4 mm, the maximum temperature drop $(\Delta Tc)_{max}$ decreases with increase in L/Dt. Whereas for nozzle diameter less than 3.0 mm, the maximum temperature drop $(\Delta Tc)_{max}$ increases with increase in L/Dt. But for nozzle angle around 3.2 mm, the maximum temperature drop $(\Delta Tc)_{max}$ is almost constant for L/Dt ranging from 25 to 50. Again it is observed that the peak value of maximum temperature drop $(\Delta Tc)_{max}$ corresponding to all L/Dt is for nozzle diameter (Dn) around 3.2 mm. Thus for any L/Dt, Dn=3.2 mm is the optimum value keeping remaining parameters constants.

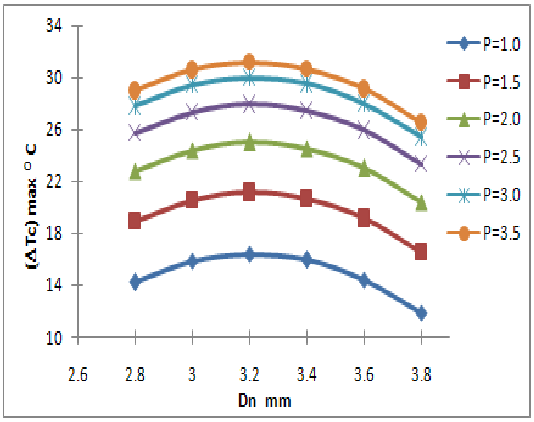

Fig. 5(a)

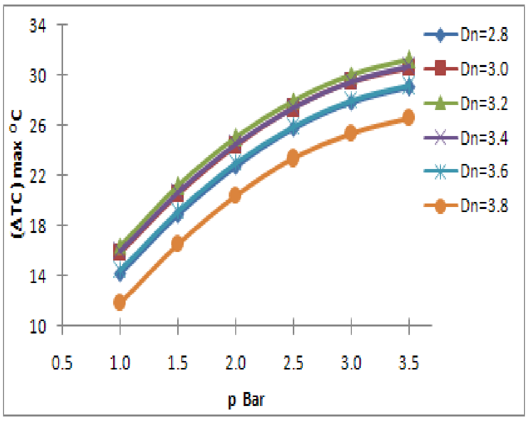

Fig. 5(b)

Fig.5. Effect of Nozzle Diameter and Inlet Pressure on Maximum Temperature Drop

Figure 5 shows the effect of nozzle diameter on maximum temperature drop $(\Delta Tc)_{max}$ for variable pressure keeping remaining parameters (Φ, Do, L, Dt, N) constant. From the figure it can be noted that there are no crossing of the curves, indicating that there is uniform variation in the maximum temperature drop $(\Delta Tc)_{max}$ with variation in pressure P. $(\Delta Tc)_{max}$ increases with increase in P and vice a versa. But the peak value of maximum temperature drop $(\Delta Tc)_{max}$ corresponding to all pressures is for nozzle diameter (Dn) around 3.2 mm. Thus for any P, Dn=3.2 mm is the optimum value keeping remaining parameters constants.

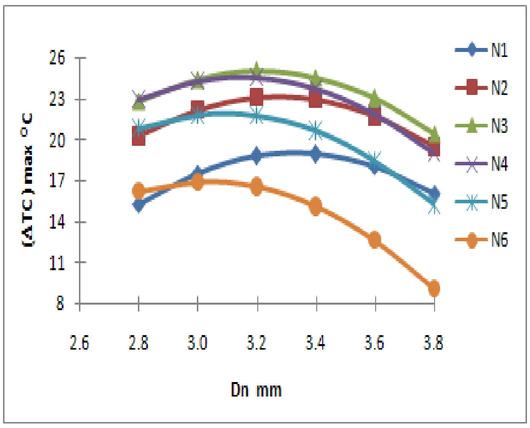

Fig 6 (a)

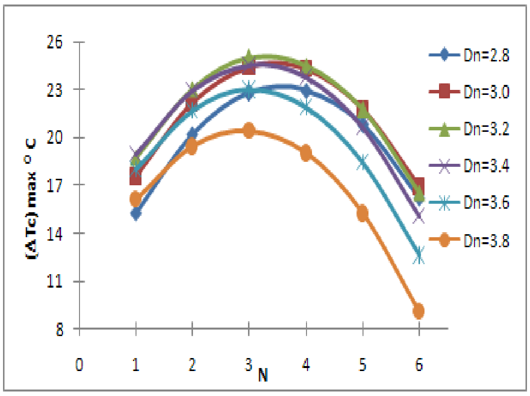

Fig 6 (b)

Fig. 6. Effect of Nozzle Diameter and Nozzle Number on Maximum Temperature Drop

Figure 6 shows the effect of nozzle diameter (Dn) on maximum temperature drop $(\Delta Tc)_{max}$ for variable nozzle number (N) keeping remaining parameters (P, Φ, L, Dt, Do) constant. From the figure it can be noted that $(\Delta Tc)_{max}$ increases with increase in N up to 3, then it attains peak value of N around 3 to 4 and finally decreases with increase in N. For N=3 or 4, $(\Delta Tc)_{max}$ verses Dn curves are nearly flat at peak value of $(\Delta Tc)_{max}$ indicating that nozzle number (N) is more dominating factor than nozzle diameter (Dn) while deciding the vortex tube configuration. But for any N, Dn=3.2 mm is the optimum value keeping remaining parameters constants.

4. CONCLUSION

After the experimentation on the vortex tube with different nozzle diameters, it can be concluded that, nozzle diameter have great influence on the performance of vortex tubes. Cold temperature drop $(\Delta Tc)_{max}$ varies with the variation of nozzle diameter. But there is a unique nozzle diameter that gives the optimum performance for various geometrical parameters like nozzle angle (Φ), orifice diameter (Do), nozzle number (N), tube length (L) and physical parameter like pressure (P). The optimum value of nozzle diameter (Dn) for maximum cold temperature drop $(\Delta Tc)_{max}$ is 3.2 mm.

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