EXPERIMENTAL STUDY OF VORTEX TUBE APPLICATIONS AS COOLER AND HEATER

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Abstract: A vortex tube has a number of features that make it attractive for industrial applications. It is a simple mechanical device operating as a cooler and heating machine, using an ordinary supply of compressed air as a power source. In this experimental study of the vortex tube coefficient of performance (COP) as a cooler and heating has been carried out to investigate the parameters affecting. The following constructional parameters were tested and tried to be optimized: the length of the vortex tube, diameter of cold end and number of entrance nozzles.

1. INTRODUCTION

The phenomenon of two gas streams separated without mechanical assistance was discovered by George J. Ranque in 1933 [1] and the subject of a US Patent in 1934. The tube later became known as the Ranque-Hilsch Vortex tube.

The vortex tube creates a helical vortex from compressed air and separates it into two air streams, one hot and one cold. Compressed air enters a cylindrical generator, which is proportionately of larger diameter than the long tube, where it causes the air to rotate. Then, the rotating air is forced to flow down along the inner wall of the tube at speeds reaching a sonic value. At the end of the hot tube, a small or big portion of this air exits through a needle valve (control valve) as the hot air exhaust. The remaining air is forced to flow back through the centre of the incoming air stream at a slower speed. The heat from the slower moving air is transferred to the faster moving incoming air, though here is a higher temperature. This cooled air flows through the centre of the generator and exits through the cold air exhaust port, as shown schematically in figure 1. Cold outlet temperatures can reach as low as -40ºC and hot outlet temperatures can reach as high as 120ºC,

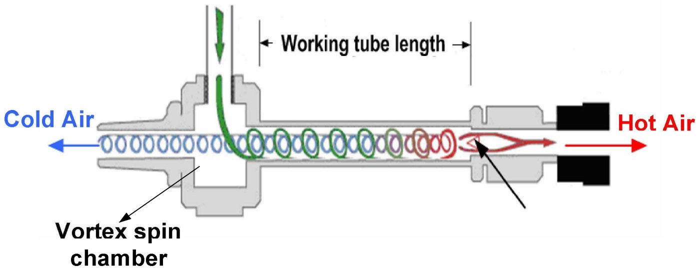

Fig. 1 Schematic diagram of a vortex tube

Hilsch [2] as the first published systematical experimental results by varying the inlet pressure and the geometrical parameters of the tube. Martinovski and Alekseev [3], and Bruun [4] conducted important experimental investigations on vortex tube parameters. Theoretical and analytical descriptions of the energy separation and the temperature and velocity profiles in a vortex tube are given by Folton [5], Deissler and Perlmutter [6], and Young et al [7]. Ahlborn, et al. [8] considered the vortex tube as a refrigeration device which could be analyzed as a classical thermodynamic cycle, replete with significant temperature splitting, refrigerant, and coolant loops, expansion and compression branches, and natural heat exchangers. The effect of various parameters, such as length and diameter on the principal vortex

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tube are considered by Saidi [9] he showed variation of efficiency versus different L/D of vortex tube. Ting-Quan et al [10] they presented experimental results of the energy separation in the vortex tube under different operating conditions showing the temperature changes of the cold and hot streams as a function of the inlet pressure.

The explanation of this phenomenon has been the centre of much research since its discovery. There is still no universally adopted theory that explains the effect of the vortex. The vortex tube is considered to be the result of several simultaneous phenomenons by Ahlborn & Groves [11]. This work will not attempt to further explain or improve the vortex device. There are limited practical applications due to the inherit inefficiency. The coefficient of performance (COP) was calculated. In addition, the lack of available pressurized air is obstacle for a rural application. There are commercially available devices for industrial applications such. As machining spot cooling workers, cold jackets, and electrical cabinet cooling in electrically classified areas, these devices require industrial sized oil free air compressors with low (-40ºC) dew point to achieve optimal performance. Improvement of the vortex device generally results in complication of construction or power [12]. This increase in complexity hinders the physically viability in developing communities.

The purpose of our work was to determine the geometrical and physical viability of using the vortex tube as means for cooler and heater. The vortex tube's design, despite its inefficiency, has the advantage of simplicity, no chemicals, minimal maintenance, low cost, & very low exit temperatures. Our work suggests that the vortex tube cooler is physically viable. Further work must be done to more efficiently produce compressed air in a rural setting. Actual application of the cooler is dependent on the economic, cultural, & climatic viability in the community of its installation.

2. EXPERIMENTAL SETUP

Vortex tubes are classified into two groups according to their flow characteristics: counter flow and parallel flow vortex tube system. In this study, a counter flow vortex tube has been used. The arrangement of experimental apparatus and measuring devices which is used for the determination of the performance of the counter flow vortex tube is shown in figure2. Here, the internal diameter D_{vt} of the vortex tube is 21 mm. Lengths of vortex tube (*L*) are 200 up to 1450 mm made of glass and the number of nozzles (*N*) are 2, 4.

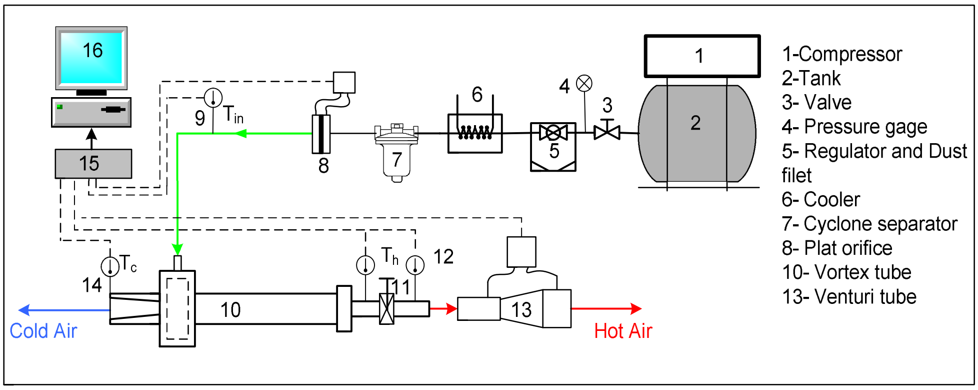


Fig. 2 Schematic diagram of the experimental setup

Flow was controlled by a valve on the hot outlet side. Working fluid was compressed air provided by a rotary screw compressor (800 kPa, $120m^3/h$ and 18.5 kW). Compressed air reached the vortex tube via the nozzles after passing through a humidity eliminating device and a filter. The system was initially brought to a thermal steady state, before the experiments were performed. Pressure and temperature at the entrance, temperatures and mass flow rate at the outlets were measured during the experiments. The mass flow rate of the inlet and the hot outlet air were measured using an orifice and Venture tube respectively. The temperatures of the inlet flow and outlet flows were measured with copper-constantan thermocouples. These experiments were conducted by increasing the pressure at the entrance of the vortex tube from 300 kPa to 600 kPa, and for every run by gradually bringing the valve at the hot outlet side to a fully closed position, from its fully open position. In order to determine the reliability of the experimental results, all data about temperatures and pressures are collected with data acquisition system with the output signals being led to the PC. The program was written in Lab VIEW 7.2 to control the data logging parameters and to display the obtained results.

3. OPERATIONAL CHARECTERISTIES

The operational characteristics of vortex tube may be investigated considering those parameters governing the operation of this device. These characteristics are as follows:

Cold mass fraction

The cold mass fraction is the most important parameter indicating the vortex tube performance and the temperature/energy separation inside the vortex tube. Cold mass fraction is defined as the ratio of cold air mass flow rate to inlet air mass flow rate. The cold mass fraction can be controlled by the cone valve, which is placed at the hot tube end. This can be expressed as follows:

$$\varepsilon = \dot{m}_c / \dot{m}_i \qquad (1)$$

Cold air temperature drop

Cold air temperature drop or temperature reduction is defined as the difference in temperature between inlet air temperature and cold air temperature:

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

Hot air temperature

Hot air temperature is defined as the difference in temperature between hot air temperature and inlet air temperature:

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

Where T_i is the inlet air temperature, T_c and T_h are the cold and the hot air temperatures respectively.

Isentropic efficiency

To calculate the cooling efficiency of the vortex tube, the principle of adiabatic expansion of ideal gas is used. As the air flows into the vortex tube, the expansion in isentropic process occurs. This can be written as follows:

$$\eta_{is} = \frac{T_i - T_c}{T_i\left(1 - \left(P_a/P_i\right)^{(\gamma-1/\gamma)}\right)} \qquad (4)$$

Where η_{is}, P_i, P_a and γ are the isentropic efficiency, inlet air pressure, atmosphere pressure and specific heat ratio, respectively.

Thermal Efficiencies for Vortex tube

The definition of the efficiency of the vortex tube cooler has always puzzled researchers in this field. Only Fulton [5] proposed his definition of the efficiency of the vortex tube as a cooler. This is not sufficient. In this section the definitions of the efficiencies of the vortex tube system are defined. The vortex tube can be used not only as a cooler, but also as a heater. So the definition of the efficiency should consider both effects. For different applications, different efficiencies are used.

The coefficient of performance (COP) of a cooler is normally defined as the cooling power Q_c gained by the system divided by the work power W_p input. So the COP of the cooler, denoted by COP_{cr} is expressed as

$$COP_{cr} = \dot{Q}_c / W_p \qquad (5)$$

Here the cooling power can be calculated according to the cooling capacity of the cold exhaust air (e.g. the heat necessary to heat up the cold exhaust air from the cold exhaust temperature to the applied temperature. Here T_i is chosen.).

$$\dot{Q}_c = \dot{m}_c c_p \left(T_i - T_c\right) \qquad (6)$$

In a conventional refrigeration system, there is a compressor, so the work power is the input power of the compressor. But in the vortex tube system, usually a compressed gas source is used, so it is not easy to define the work power. By analogy the work used to compress the gas from the exhaust pressure up to the input pressure with a reversible isothermal compression process.

$$W_p = \dot{m}_i r_m T_i \, \mathbf{ln}\left(p_i / p_a\right) \qquad (7)$$

as used in [5], can be expressed as:

$$COP_{cr} = \frac{\varepsilon\left(T_i - T_c\right)}{\left(\gamma/\gamma-1\right) r_m T_i \ \mathbf{ln}\left(p_i/p_a\right)} \tag{8}$$

For the heat device, the coefficient of performance is presented as the heating power divided by the work power used. For the vortex tube system, the heating power can be expressed as the heating capacity of the hot exhaust gas.

$$\dot{Q}_h = \dot{m}_{hc} c_p \left(T_h - T_i\right) \tag{9}$$

The work power used by the system is taken the same as used above for the cooler. So the coefficient of performance of the vortex tube as a heat device, denoted as COP_h is:-

$$COP_h = \frac{\varepsilon\left(1-\varepsilon\right)\left(T_i - T_c\right)}{\left(\gamma/\gamma-1\right) r_m T_i \ \mathbf{ln}\left(p_i/p_a\right)} \tag{10}$$

4. RESULTS AND DISCUSSION

In this section, various experiments on the different components of the vortex tube have been done to investigate their influence.

In order to study the performance of the vortex tube, the set-up under various conditions. The following constructional parameters were tested and tried to be optimized: the length of the vortex tube, diameter of cold end and number of entrance nozzles.

Considering the effects of length of principal tube, different tube length have been selected and examined. Figure 3 shows variation of isentropic efficiency various different L/Dvt of vortex tube. It can be shown that for $L/D_{vt} \leq 20$ energy separation decreases leading to decrease in cold air temperature difference and efficiency decreases as well.

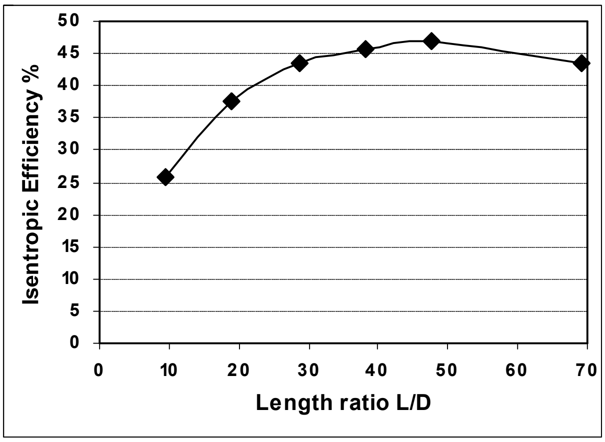


Fig.3 Efficiency versus L/D_{vt} of vortex tube

For $L/D_{vt} \geq 50$ the variation of efficiency with L/D_{vt} is not considerable. Consequently, the optimum value of L/D_{vt} is within the following ranges:

$$20 \leq D/D_{vt} \geq 50$$

To realize the effect of the cold air orifice diameter dc on isentropic efficiency, orifices with five different diameters (6, 8, 10, 12 and 14 mm) were designed, fabricated and examined at different cold air mass fraction. The efficiency various the dimensionless cold air orifice diameter d_c/D_{vt} is plotted in Figure 4. It is shown that for dc < 0.57, increasing dc causes the efficiency to increase and for dc > 0.57, the efficiency decreases. The result is that the optimum value of dc for the maximum cold air temperature difference and efficiency is: $(d_c/D_{vt}) \approx 0.57$

To study the effect of number of entrances nozzle, two types of nozzle were designed and fabricated, having 2 and 4 entrances, with constant inlet cross-sectional area. The efficiency various the cold mass fractions are shown in Figure 5. As the number of entrances in the nozzle increase, flow in the main tube becomes more turbulent due to more interactions of inlet flows. Therefore the cold and hot streams are mixed in the main tube, leading to energy separation, cold temperature difference and efficiency reduction. The result is that the nozzle with two entrances shows better performance than four entrances nozzle from the point of view of cooler efficiency.

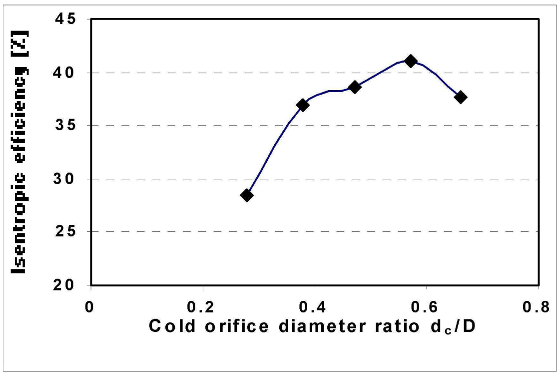


Fig. 4 Efficiency versus the d_c/D

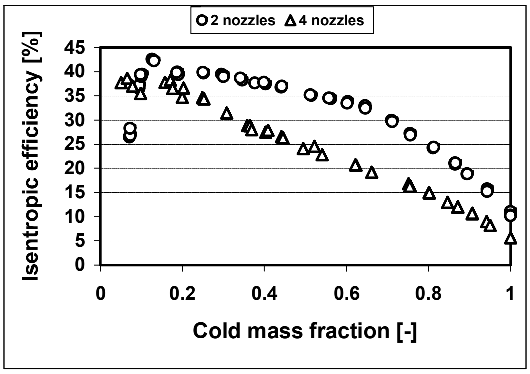


Fig. 5 Efficiency versus the number of entrances nozzle

The performance characteristics of the vortex tubes have been estimated by calculating the coefficient of performance (COP) of this system as a cooler and as a heater for different length tube. The maximum COP of the vortex tube as cooler and heater for various lengths are listed in tables 1 and 2, respectively. They show that the COP's are very small.

Table1. Shows Operating conditions and experimental results of the maximum of COP as a cooler

Length tube[mm]	**200**	**400**	**600**	**800**	**1000**	**1450**
$\dot{m}_{in}$ [kg/s]	0.0404	0.0330	0.0307	0.0328	0.0336	0.0335
CAMR [-]	0.56	0.64	0.65	0.75	0.75	0.75
T_i $[^oC]$	21.3	26.4	27.8	27.9	24.5	27.6
T_c $[^oC]$	-7	-14	-12.7	-18.2	-19.1	-14.5
T_h $[^oC]$	43.4	64.7	82.5	75.8	93.5	94.2
P_{in} [Pa]	606446	616502	556637	548387	564343	562441
P_{atm} [Pa]	96200	97700	97200	97600	97100	97100
COP_{cr} [%]	**0.034**	**0.038**	**0.063**	**0.065**	**0.075**	**0.072**

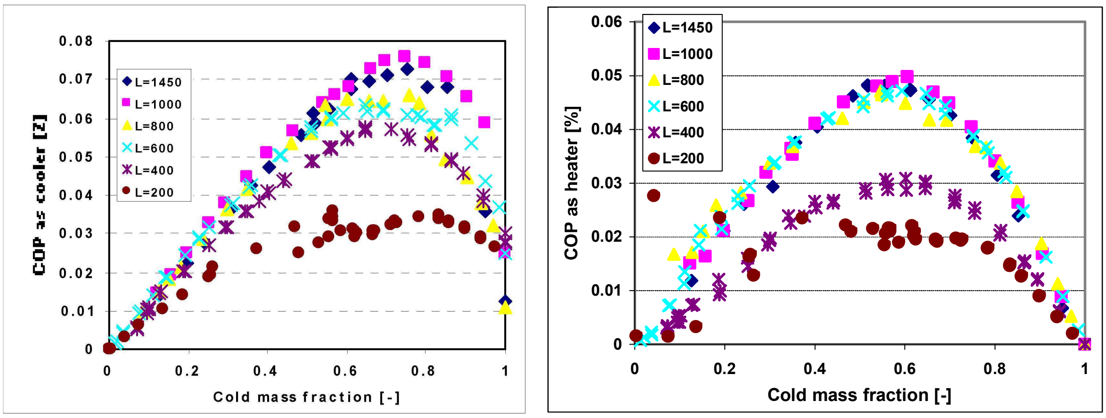
Table2. Shows Operating conditions and experimental results of the maximum of COP as a heater

Length tube[mm]	**200**	**400**	**600**	**800**	**1000**	**1450**
$\dot{m}_{in}$ [kg/s]	0.0394	0.0331	0.0306	0.0328	0.0336	0.0334
CAMR [-]	0.37	0.60	0.59	0.55	0.60	0.52
T_i $[^oC]$	20.8	26.4	27.8	27.9	24.5	27.2
T_c $[^oC]$	-1.6	-14.6	-16.2	-18.2	-19.1	-24.1
T_h $[^oC]$	46.3	61.5	77.1	75.8	93.5	70.4
P_{in} [Pa]	606271	616674	543859	548387	564343	560469
P_{atm} [Pa]	96200	97700	97200	97600	97100	97100
COP_h [%]	**0.023**	**0.030**	**0.047**	**0.047**	**0.049**	**0.048**

Figure 6 showed the Coefficient of performance of the optimize vortex tube length. There was a substantial increase in the COP. The behavior of the COP_{cr} with cold air mass fraction at a six different Length (200, 400, 600, 800, 1000, 1450 mm) to diameter ratio (L/D_{vt}) of vortex tube is depicted in Figure 6 (a). It can be seen that COP_{cr} increases by increasing the length tube up to 1000 mm and it decreases at longer length (1450mm). Also it shows that the maximum COP_{cr} effect occurs as cold air mass fractions between 0.56 and 0.75.

The COP values of the vortex tube for length tube equal 200 to up 1450 mm as a heat machine is shown in figure 6(b). It is observed that the COP_h of the vortex tube as a heat machine increases with increasing the length of the vortex tube up to 1000 mm and then decreases with longer length.

The COP of vortex tube is very low as compared to COP of Carnot cycle. However this is a unique device which produces both heating and cooling effects simultaneously without using any other form of energy than compressed air at moderate pressure. This device can be used effectively in process environments where heating and cooling outputs of vortex tubes can be concurrently used



(a) (b)

Fig.6 Coefficient of performance of the optimized vortex tube for difference length at same operating condition, (a) as a cooler (b) as a heater.

5. CONCLUSIONS

The experimental study of the vortex tube coefficient of performance (COP) as a cooler and heating has been carried out to investigate the parameters affecting. The following constructional parameters were tested and tried to be optimized: the length of the vortex tube, diameter of cold end and number of entrance nozzles.

The result is that the optimum value of L/D_{vt} and d_c/D_{vt} are determined having the maximum efficiency. Nozzle with more number of flow entrances causes cold air temperature and efficiency to decrease. This study showed that the coefficient of performance (COP) of the vortex tube is very low.

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