COOLING CAPACITY OF VORTEX TUBES BY CHANGING DIFFERENT CHARACTERISTICS

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Abstract

The improvement of the efficiency and cooling capacity of a simple vortex tube is considered. Three Ranque-Hilsch Vortex tubes, with different diameters and lengths, were developed and manufactured. The vortex tube is an unique device with no working parts and has the ability to deliver hot and cold air simultaneously. It is a simple, low cost device, which is easy to manufacture. Different orifice sizes and nozzle configurations are designed and manufactured to investigate the performance of the three vortex tubes. The ϕ 22 mm vortex tube with a ϕ 7,5 mm orifice and small diameter nozzle gave a better efficiency and an increase in the drop in temperature of the cold air against the different inlet pressures. The maximum efficiency of the ϕ 22 mm diameter vortex tube improved from 8,9% against a cold fraction of 0,630 (with the ϕ 6 mm x 2 tangential nozzle block) to 18,92% against a cold fraction of 0,644 (with the ϕ 3 mm x 4 tangential nozzle block) at an inlet pressure of 500 kPa. The maximum drop in temperature of the cold air improved from 27,0°C against a cold fraction of 0,120 (with the ϕ 6 mm x 2 tangential nozzle block) to 42,3°C against a cold fraction of 0,284 (with the ϕ 4 mm x 2 tangential nozzle block) at an inlet pressure of 600 kPa.

1. INTRODUCTION

The French Metallurgist, M.G. Ranque (1931), found the vortex tube while developing cyclone dust extractors. The vortex tube is a unique device with no working parts and the ability to deliver hot and cold air simultaneously (Lin, Chen and Vatistas, 1990). The vortex tube is ideal for small cooling capacities, for example the cooling of clothing in warm or damp working conditions (Gunter, 1973); the cooling of gas chromatography apparatus to sub-environmental temperatures (Bruno, 1986); and as an aid in compression and de-compression chambers used for diving instruction (Baz and Gilheany, 1988).

2. BACKGROUND

Hilsch (1947) found that the jet of air, injected into the vortex tube, expands from a region of high pressure at the wall of the vortex tube to a region of low pressure near the center of the vortex tube. During this expansion kinetic energy is transmitted to the fluid layers near the vortex tube wall due to the internal friction between the fluid layers. These fluid layers near the vortex tube wall are discharged at a higher temperature. The velocity of the air would increase to a supersonic value from the wall to the center of the vortex tube, in the absence of internal friction. Fulton (1950) descr bed the operation of the vortex tube, which is accepted world-wide, to confirm Hilsch's theory. The air stream leaves the nozzles at high velocity with decreased static temperature and is discharged into the vortex tube. A free vortex ($\omega r^2 =$constant) is generated with a low angular velocity (ω) at the vortex tube wall increasing towards the center of the tube (Althouse, Turnquist, and

Bracciano, 1988). This free vortex reaches the end of the vortex tube and a forced vortex ($\omega =$constant) is generated which moves in the opposite direction (see Figure 1). Figure 1 indicates the flow pattern of the cold and hot air streams through the vortex tube. Free and forced vortex regions are generated inside the vortex tube and the energy separation takes place within the forced vortex (Hartnell and Eckert, 1957). Theoretical analysis shows that the energy separation process occurs as a result of the fluid flowing in the core region to the outer region of the vortex tube (Deissler and Perlmutter, 1960).

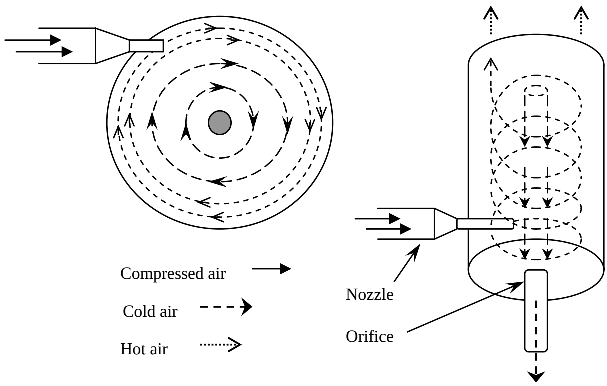

Figure 1: Flow pattern of air streams [Althouse, Turnquist and Bracciano, 1988].

3. METHODOLOGY

The nozzles inject the air tangentially near the wall, resulting in a free vortex (Figure 1). At the right hand side end of the vortex tube (Figure 1) the flow control valve discharge some of the fluid (hot air) to the atmosphere. The remaining fluid flows back upstream (generating a counter stream) through the (previously "empty") center of the tube. The counter stream forms a second vortex (forced vortex) with the same angular velocity of the adjacent fluid layers as formed by the first vortex. The position of the flow control valve determines the quantity of cold and hot air discharged from the tube. Figure 2 shows the construction of the vortex tubes used in the study.

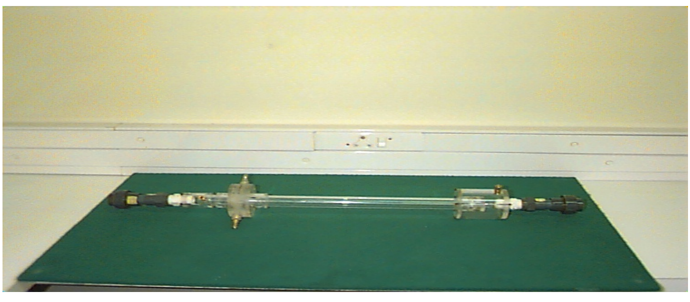

Figure 2: Construction of the vortex tube.

Figure 3 shows a cross-sectional view of the vortex tube to indicate the regions of the free and forced vortex (Fulton, 1950). The principle of the conservation of angular momentum states that the angular velocity of a fluid particle in a free vortex will increase as it moves to the center of the vortex (Bruno, 1986). Since both vortexes are "connected" at the same angular velocity, the inner air stream (that moves upstream) lose internal energy and cools down.

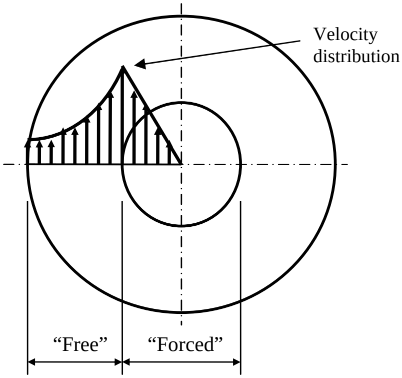

Figure 3: Cross-sectional view of the vortex tube to indicate the "free" and "forced" vortex regions [Fulton, 1950].

The cold fraction (μ) (i.e. the cooling capacity of the vortex tube) is defined by:

$$\mu = \frac{\dot{m}_c}{\dot{m}_o} \qquad (1)$$

Where: $\dot{m}_c$ = mass flow rate of the cold outlet air in kg/s

$\dot{m}_o = \dot{m}_c + \dot{m}_h$ = mass flow rate of the inlet air in kg/s

$\dot{m}_h$ = mass flow rate of the warm outlet air in kg/s

(Fraser, 1982)

The efficiency (η) of the vortex tube is defined as the cooling effect delivered per unit work done required compressing the air and is given by:

$$\eta = \mu \frac{\Delta T_c}{\Delta T_{ad}} \qquad (2)$$

Where: ΔT_c = temperature decrease in the cold air from the inlet air temperature.

ΔT_{ad} = isentropic temperature difference with reference to the inlet air temperature and the pressure ratio across the tube.

(Fraser, 1982)

The temperature of the cold air stream is given by:

$$\frac{T_o - T_c}{T_c} = \frac{\gamma - 1}{2\gamma}\left(\frac{p_h - p_c}{p_c}\right)$$

$$\frac{T_o}{T_c} - 1 = \frac{\gamma - 1}{2\gamma}\left(\frac{p_h - p_c}{p_c}\right)$$

$$\frac{T_o}{T_c} = 1 + \frac{\gamma - 1}{2\gamma}\left(\frac{p_h - p_c}{p_c}\right)$$

$$T_c = \frac{T_o}{1 + \frac{\gamma - 1}{2\gamma}\left(\frac{p_h - p_c}{p_c}\right)} \qquad (3)$$

Where: T_c = temperature of the cold outlet air in K
T_o = temperature of the inlet air in K
p_h = absolute pressure of the warm outlet air in kPa
p_c = absolute pressure of the cold outlet air in kPa

(Ahlborn, Keller, Staudt, Treitz and Rebhan, 1994)

The pressure drop ($p_h - p_c$) in the axial direction is given by:

$$p_h - p_c = \frac{1}{2}\rho u_{cz}^2 \qquad (4)$$

Where: ρ = mass density of the cold outlet air in kg/m^3
u_{cz} = velocity of the cold outlet air at the orifice in m/s

(Ahlborn, Keller, Staudt, Treitz and Rebhan, 1994)

The velocity of the cold outlet air (u_{cz}) at the orifice is given by:

$$\dot{m}_c = \rho A_c u_{cz}$$

$$u_{cz} = \frac{\dot{m}_c}{\rho A_c} \qquad (5)$$

Where: $\dot{m}_c$ = mass flow rate of the cold outlet air in kg/s
A_c = cross-sectional area of the orifice in m^2

The velocity of the inlet air (u_o) at the nozzle outlet is given by:

$$\dot{m}_o = \rho u_o A_o$$

$$u_o = \frac{\dot{m}_o}{\rho A_o} \qquad (6)$$

Where: $\dot{m}_o$ = mass flow rate of the inlet air to the tube in kg/s
ρ = mass density of the air in kg/m^3

A_o = cross-sectional area of the nozzle outlet in m^2

The pressure of the cold outlet air is given by:

$$\frac{p_c}{p_o} = 1 - \left(\frac{\gamma}{2}\right) M_o^2$$
$$p_c = p_o \left[1 - \left(\frac{\gamma}{2}\right) M_o^2\right] \tag{7}$$

Where: p_c = absolute pressure of the cold outlet air in kPa
p_o = absolute pressure of the inlet air to the tube in kPa
M_o = Mach number of the inlet air to the tube
γ = adiabatic coefficient of expansion for air

(Ahlborn, Keller, Staudt, Treitz and Rebhan, 1994)

Equation (7) can be re-written as follows:

$$p_c = p_o \left[1 - \left(\frac{\gamma}{2}\right)\left(\frac{u_o}{a_o}\right)^2\right]$$
$$p_c = p_o \left[1 - \left(\frac{\gamma}{2}\right)\left(\frac{u_o}{\sqrt{\gamma R T_o}}\right)^2\right] \tag{8}$$

The temperature of the cold air depends on the pressure difference ($p_h - p_c$) across the tube, as shown in equations (3) and (4). The pressure difference across the tube is determined by the size of the orifice at the cold air outlet side, as shown in equation (4) and (5). Therefore it was decided to manufacture a ϕ 5,5 mm and ϕ 7,5 mm orifice to show that reducing the orifice diameter, increases the velocity (u_{cz}) and the pressure difference ($p_h - p_c$) for the same mass flow rate. Table 1 shows the dimensions of the different vortex tubes.

Table 1: Dimensions of vortex tubes

Tube	Inside diameter (*D*)	Length (*L*)	*L/D*	Orifice diameter
1.	26 mm	546 mm	21	7,5 mm
2.	22 mm	587 mm	26,7	5,5 mm 7,5 mm
3.	22 mm	410 mm	18,6	5,5 mm 7,5 mm

Figure 4 shows a diagram of the experimental assembling of the vortex tube. The flow meters are Rota meters with viton seals with a capacity of 40-440 l/min. K-type thermo-couples and 10 Bar pressure sensors measures the temperature and pressure respectively at the inlet and outlet positions.

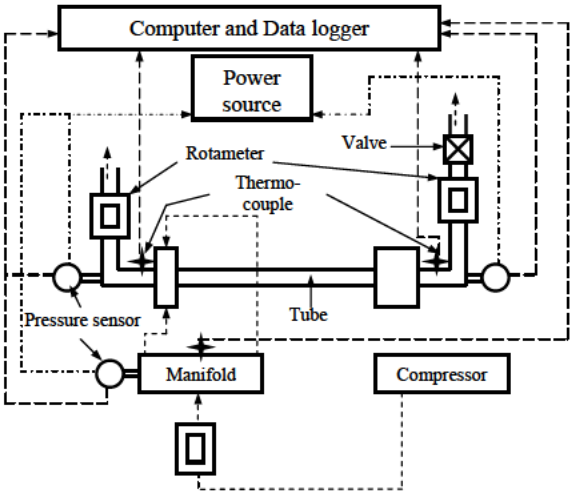

Figure 4: Diagram of experimental assembling

4. RESULTS

4.1 Influence of the tube diameter on the vortex tube

The tests showed with the ϕ 7,5 mm orifice that the two ϕ 22 mm vortex tubes gave better efficiencies and cooling compared to the ϕ 26 mm vortex tube. The efficiency of the ϕ 22 mm vortex tube improved against the different inlet pressures resulting in better cooling of the inlet air. Figure 5 shows the improvement in efficiency with the 3 mm x 4 tangential nozzle block used on the vortex tubes against an inlet pressure of 500 kPa. Figure 6 shows the temperature drop in the cold air (ΔT_c) from the inlet air temperature against different inlet pressures of the vortex tubes with the 3 mm x 4 tangential nozzle blocks.

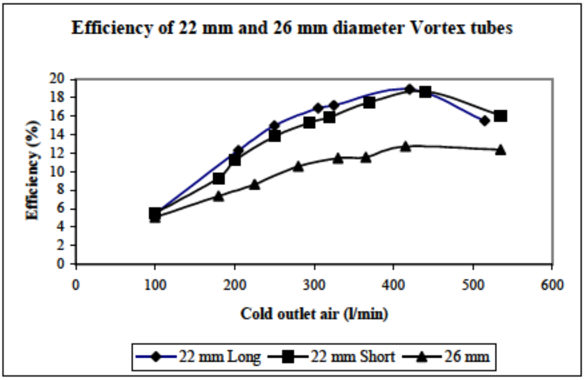

Figure 5: Efficiency of different sizes of vortex tubes.

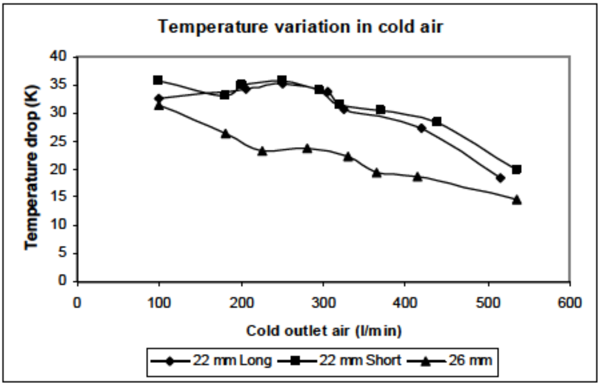

Figure 6: Temperature variations for the different sizes vortex tubes

4.2 Influence of the diameter of the orifice

The influence of the orifice size on the performance of the vortex tubes are shown clearly with the use of the ϕ 7,5 mm and ϕ 5,5 mm orifices. The greater the diameter of the orifice, the smaller the pressure difference across the cold and hot air outlets due to the fact that the velocity (u_{cz}) also becomes smaller, as indicated in equations (4) and (5). Equation (3) shows that the smaller the pressure difference ($p_h - p_c$), the lower the value of the cold outlet air temperature (T_c), which gives a higher cold fraction (μ) and better cooling. Tests conducted against different inlet pressures with the ϕ 7,5 mm orifice on the ϕ 22 mm shorter vortex tube and the ϕ 3 mm x 4 tangential nozzle block confirmed the above-mentioned. Figures 7 and 8 show the improvement in efficiency and the drop in temperature of the cold air (ΔT_c)

from the inlet air temperature with the use of the ϕ 7,5 mm orifice compared to the ϕ 5,5 mm orifice.

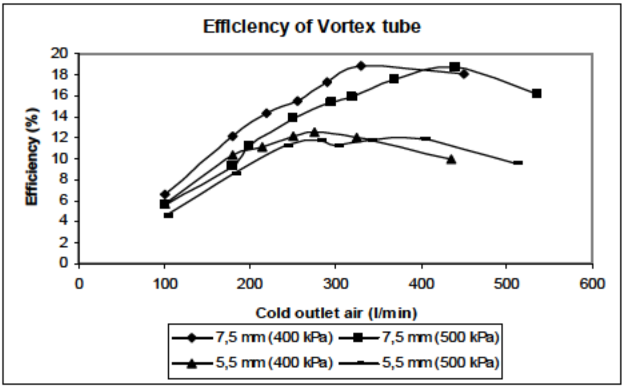

Figure 7: Efficiency of vortex tube with different orifice diameters

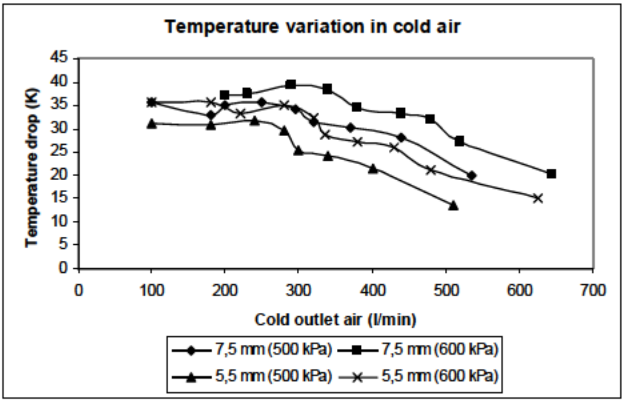

Figure 8: Temperature variations with different orifice diameters

4.3 Influence of the diameter of the nozzle

The influence of the change in nozzle diameter on the performance of the vortex tubes is shown clearly with the use of the ϕ 6 mm x 2, the ϕ 4 mm x 2 and the ϕ 3 mm x 4 tangential nozzle block. Decreasing the nozzle diameter from 6 mm to 4 mm and then to 3 mm resulted in a rise in kinetic energy of the jet of air injected into the vortex tube for the same mass flow rate (equation (6)), consequently improving the performance of the vortex tube (equations (3) and (8)). Tests conducted on the ϕ 26 mm diameter vortex tube with the use of the ϕ 6 mm x 2, the

ϕ 4 mm x 2 and the ϕ 3 mm x 4 tangential nozzle block with the ϕ 7,5 mm orifice against the different inlet pressures confirms the above-mentioned. Figures 9 and 10 show the improvement in efficiency and the drop in temperature of the cold air (ΔT_c) from the inlet air temperature with the use of smaller nozzle diameters.

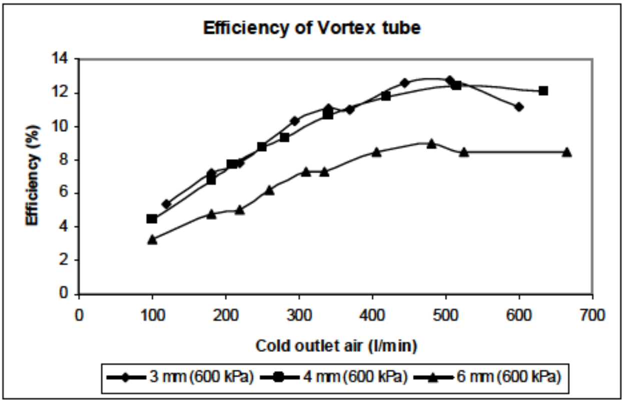

Figure 9: Efficiency of vortex tube with different nozzle diameters

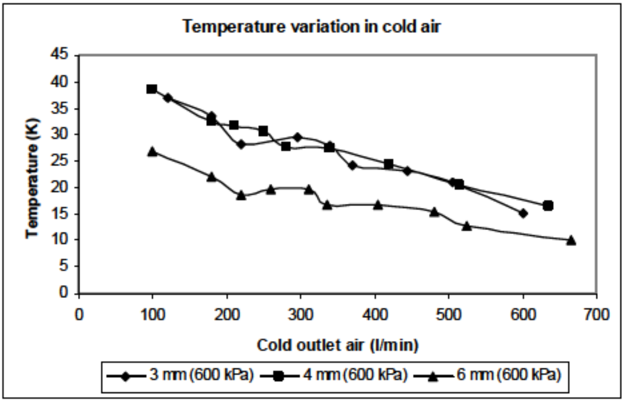

Figure 10: Temperature variations with different nozzle diameters

5. CONCLUSIONS

5.1 Influence of the diameter of the vortex tube

The ϕ 22 mm vortex tube showed the best improvement in efficiency and drop in temperature of the cold outlet air against the different inlet pressures with the different nozzles.

5.2 Influence of the diameter of the orifice

Changing the orifice diameter will change the pressure difference across the cold and hot air outlet ends. The results show that the larger orifice diameter gave much better efficiencies and drop in temperature of the cold outlet air against all the different inlet pressures.

5.3 Influence of the diameter of the nozzle

The influence of the nozzle diameter on the performance of the vortex tube is shown by the use of the ϕ 6 mm, the ϕ 4 mm and the ϕ 3 mm tangential nozzle blocks. Reducing the diameter from 6 mm to 3 mm increases the kinetic energy of the air stream injected into the vortex tube for the same mass flow rate, resulting in improving the performance of the vortex tube. The tests showed that the ϕ 3 mm nozzle gave better efficiencies and drops in temperature of the cold outlet air against all the different inlet pressures.

6. REFERENCES

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