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STUDY OF DIMENSIONAL PARAMETERS INFLUENCE ON VORTEX TUBE BEHAVIOR

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Abstract. *Vortex tube is a thermodynamic device, with no moving parts, applied to separate hot and cold air from compressed air injected into the tube. It has many applications in the industry, for example, among others, it can be mentioned electronic systems cooling, machining processes cooling and environmental chambers. This paper presents the design and tube dimensioning based on parameters and data found in the literature. Therefore, a prototype has been made and tested, which allowed the understanding of the influence of internal tube diameter and width on the hot and cold air temperatures while submitted to compressed air with pressure varying from 1 to 2.5bar. Results of tested configurations indicates that the relation between tube length and diameter (L/D) has small influence on vortex tube behaviour, meanwhile, 3/8" tube diameter shows lowest temperatures on cold flow (-6.5°C, -8.0°C and -8.5°C) and higher COP (≈ 0,15).*

Keywords: *Dimensioning, Vortex Tube, Refrigeration*

1. INTRODUCTION

Vortex tube is simple equipment, easy to manufacturing, with no moving parts and requires almost no maintenance. It works with compressed air which is separated in two flows in different temperatures, one hot and another cold air flow (EXAIR, 2016). It is possible to have temperatures between -46°C and +127°C, with air flow from 3,5 and 250 m³/h and inlet pressure from 1 to 10 bar. (Ginting *et al.* 2016; Exair, 2016; Gao *et al* 2005)

In theory, vortex tube consists in a cylindrical tube in which the high pressure gas is injected in to the chamber in radial direction, tangent to the internal face (Pinar, Uluer and Kirmaci, 2009). Both secondary flows leaves the vortex tube in the axial direction, in the same or opposite sense, depending on the construction concept applied (Valipour and Niazi, 2011). However, there is no agreement on physical phenomena which results on flow temperature separation (Xue *et al.* 2012).

As showed in the Fig. (1), vortex tube operation consists in a compressed air applied in the inlet, crossing internally the tube in a region called gyro chamber, moving tangentially on the tube internal wall, in the direction of the outlet control valve.

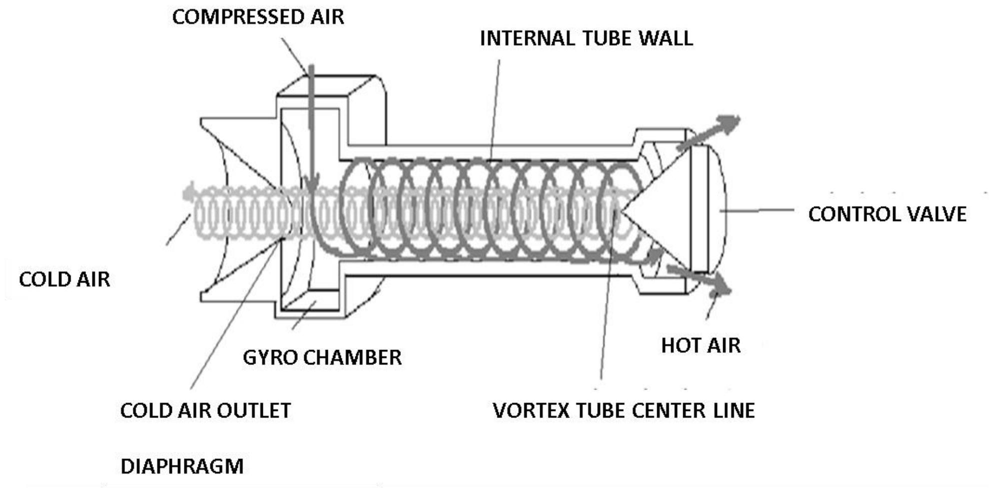

Figure 1. Vortex tube operation scheme. (Gao *et al.,* 2005)

In the outlet, the flow rotation velocity is equal to the inlet, but with less energy compared to the inlet flow, due to lower mass flow in the outlet consequence of the restriction applied by the control valve. This energy loss increases the air temperature in the outlet. However, another portion from inlet flow is forced backwards, by the control valve, in the centre of the tube, and leaves the tube through the diaphragm. This last one is colder than inlet flow, due to the energy balance in the adopted control volume (Valipour and Niazi, 2011).

Parameters available for dimensioning, shown in Fig. (2), are: Inlet transversal area (A_e), tube transversal area (A), tube length (L) and the diaphragm diameter (d), which corresponds to the cold air outlet.

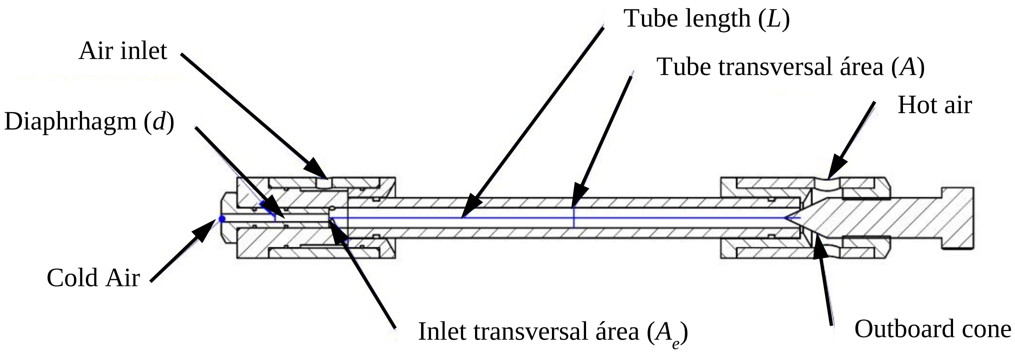

Figure 2. Vortex tube parameters.

Silva (2012) studied the influence of geometric parameter on vortex tube performance. Table (1) summarizes the most important parameters necessary for vortex tube dimensioning.

Table 1. Important parameters for vortex tube dimensioning (Silva, 2012).

Description	**Parameter**	**Autors**
Ratio between orifices aperture area (A_e) and main tube transversal area (A)	A_e= 0,17A	Takahama and Soga (1966)
Ratio between tube length and diameter (L/D)	L/D = 15	Dincer *et al.* (2008)
Diaphragm adimensional parameter (δ), given by ratio between cold air outlet (d) and intake air (D) diameters.	δ=0,5	Bovand *et al.* (2014)
Outlet cone angle (α) of most efficiency	α =50º	Aydin and Baki (2006)

Therefore, proposal of this work was to design a vortex tube based on parameters values found in the literature and evaluate the influence of them on thermic performance of the system in function of inlet air pressure.

2. METHODOLOGY

2.1 Vortex tube

Vortex tube concept chosen was the contrapuntal flow due to its better efficiency. For designing purposes, it was developed a routine in EES software, which was used to define the initial geometric dimensions, based on literature parameters values, Tab. (1).

For main tube dimensioning, initially, it was considered ratio *L/D* value to be 15, and for further studies 12 and 18. Tube diameter was chosen according to aluminium commercial standard dimensions, in which both has ½" of external diameter and internal o 3/8" and ¼", Tab. (2) shows each tube dimensions.

Table 2: Tube parameters and ranges: Internal main diameter (D), cold air outlet diameter (d), air inlet diameter (d_e) and tube length (L).

D (mm)	d (mm)	d_e (mm)	L/D=12	L/D = 15	L/D=18
9,53	4,76	2,30	L=114,3 mm	L=142,90 mm	L=171,50 mm
6,35	3,18	1,50	L=76,20 mm	L=95,25 mm	L=114,3 mm

Thereafter, the tube was designed by means CAD software Solidworks ®, as shows in Fig. (3A), with assembled fixing flanges, which allows easy parts changing for each configuration. Fig. (3B) shows manufactured tube.

(A) (B)

Figure 3. (A) CAD tube design and (B) manufactured tube.

2.2 Experimental Procedure

Vortex tube testing was done for observing thermic separation phenomenon, by means measuring temperatures of outlet cold air and outlet hot air, and comparing them to intake compressed air. Hence, for this purpose, it was chosen penta temperature sensor (Penta III, *Full Gauge*). Flow rates was also measured by means digital anemometer.

Chosen compressed air source was a piston compressor (Schulz, working pressure up to 4bar and nominal flow rate of 8.82 m³/h). Was applied effective pressure from 1 to 2.5bar, regulated by means filter-regulator (FR-1200, Steula).

Experimental bench, assembled with purpose of testing vortex tube performance while varying parameters, is shown in Fig. (4). Thermometers were placed in the compressed air inlet and outlets. One anemometer was placed in the cold air and another in the hot air outlet, in order to measure mass flow rate of both outlets, besides of total flow rate. Outlet cone aperture was adjusted by means M12 screw in order to obtain lower temperatures on cold air flow outlet, which was taken measurements after each aperture adjustment.

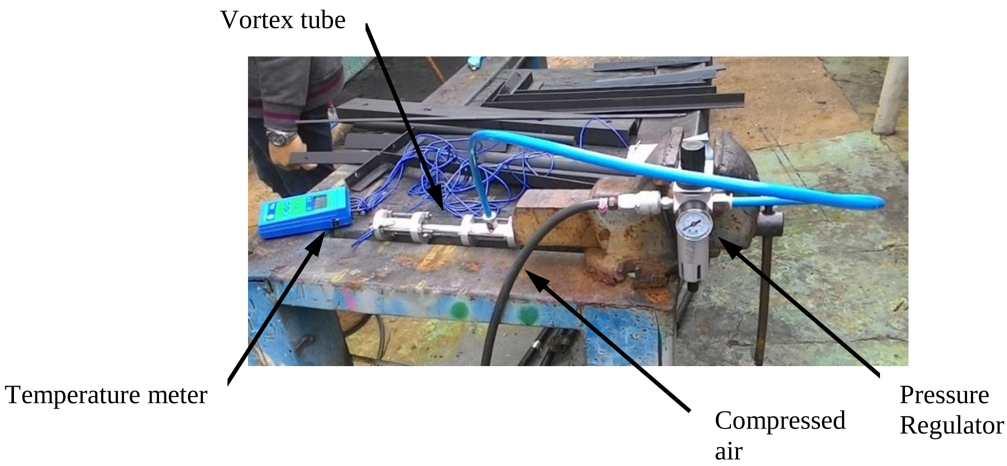

Figure 4. Experimental bench

2.3 Results and Discussion

All needed thermophysical properties were taken from EES ®. Vortex tube temperature variations are the most important parameters for this type of equipment. The difference on hot air temperature (ΔT_h) and difference on cold air temperature (ΔT_c) are given by Eq. (1) and (2), respectively.

$$\Delta T_h = T_h - T_{in} \tag{1}$$

$$\Delta T_c = T_c - T_{in} \tag{2}$$

In which, T_{in} is inlet temperature (°C), T_c is cold air outlet temperature (°C) and T_h is hot air outlet temperature (°C).

Mass flow rate in the inlet ($\dot{m}_{in}$) was found by applying continuity equation by means adding hot ($\dot{m}_c$) and cold ($\dot{m}_h$) outlet flow rates, given by Eq. (3).

$$\dot{m}_{in} = \dot{m}_c + \dot{m}_h \tag{3}$$

In such a way that $\dot{m}_c$ was estimated according to Eq. (4) and $\dot{m}_h$, which, due to constructive shape of the tube which has 4 outlet orifices, it was estimated to be Eq. (5).

$$\dot{m}_c = v_c A_c \rho_c \tag{4}$$

$$\dot{m}_h = 4 v_h A_h \rho_h \tag{5}$$

In which, v_c and v_h are flow velocities on cold and hot outlets (m/s), respectively; A is diaphragm orifice area (m²); ρ is air density for each air flow (kg/m²) is air density for each air flow (kg/m³). Each measurement is possible to calculate cold mass fraction (μ_c) given by Eq. (6).

$$\mu_c = \frac{\dot{m}_c}{\dot{m}_{in}} \tag{6}$$

Performance coefficient (COP) of vortex tube might be determined by the ratio between cold flow cooling rate ($\dot{Q}_c$) and compressor isenthropic power ($\dot{W}_c$), given by Eq. (7).

$$COP = \frac{\dot{Q}_c}{\dot{W}_c} \tag{7}$$

In which, $\dot{Q}_c$ e $\dot{W}_c$ are given, respectively, by Eq. (8) and Eq. (9).

$$\dot{Q}_c = \dot{m}_c c_p (T_{in} - T_c) \tag{8}$$

$$\dot{W}_c = \dot{m}_{in} R T_{in} \, ln\left(\frac{P_{in}}{P_c}\right) \tag{9}$$

In which, c_p is air specific heat at constant pressure (kJ/kgK), R is gas constant (kJ/kg.K), P_{in} is inlet absolute pressure (kPa) e P_c is cold flow outlet absolut pressure (kPa).

3. RESULTS AND DISCUSSIONS

Table (5) shows experimental data measured for certain inlet pressures (P_{in}), from 1 to 2.5 bar, in different vortex tube configuration of ratio *L/D* (12, 15 e 18) and tube diameter (3/8 e 1/4”). Inlet air temperature T_{in} was kept constant at 26ºC, meanwhile lowest cold temperature was -8.5ºC and highest hot temperature was 34ºC. During all tests, even at low pressures, it can be observed the air flow temperature separation phenomenon.

Table 5. Cold air flow temperature (T_c), hot air flow temperature (T_h) and velocity of each flow

L/D = 12 (3/8")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	13.0	6.2	31.5	3.2
1.5	10.0	7.0	32.0	3.5
2.0	-0.5	11.7	33.0	7.1
2.5	-8.0	13.4	33.0	8.8

L/D = 15 (3/8")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	16.0	6.2	30.0	3.2
1.5	10.0	7.0	31.0	3.5
2.0	-0.5	11.7	31.5	7.1
2.5	-6.5	13.4	33.0	8.8

L/D = 18 (3/8")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	13.0	6.2	31.5	3.2
1.5	-0.5	7.0	31.5	3.5
2.0	-3.5	11.7	31.5	7.1
2.5	-8.5	13.4	31.0	8.8

L/D = 12 (1/4")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	14.0	6.2	32.0	3.2
1.5	8.0	7.0	33.0	3.5
2.0	6.0	11.7	33.0	7.1
2.5	4.5	13.4	32.0	8.8

L/D = 15 (1/4")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	12.0	6.2	32.0	3.2
1.5	7.5	7.0	33.0	3.5
2.0	5.0	11.7	34.0	7.1
2.5	-1.5	13.4	33.0	8.8

L/D = 18 (1/4")				
P_{in} (bar)	T_c (ºC)	v_c (m/s)	T_h (ºC)	v_h (m/s)
1.0	15.5	6.2	32.5	3.2
1.5	7.0	7.0	32.5	3.5
2.0	-0.5	11.7	31.5	7.1
2.5	-1.0	13.4	31.0	8.8

Figure (5) shows the behavior of cold temperature difference ΔT_c, given by Eq. (6), in function of effective inlet pressure for the studied vortex tube geometric configuration. Observed behavior indicates that the difference between cold and hot air flow temperature is higher when higher inlet pressure is applied temperature, i.e., lower cold air flow temperature T_c is reached, as observed on Tab. (2). Comparison among the ratios *L/D*, under the same tube diameter, are shown in Fig. (5), the angular coefficients shows that there is the tendency of temperature difference been higher as ratio *L/D*. Performance comparison between two different tube diameters available, 3/8" tube had better results, as it delivers higher ΔT_c for all input pressure.

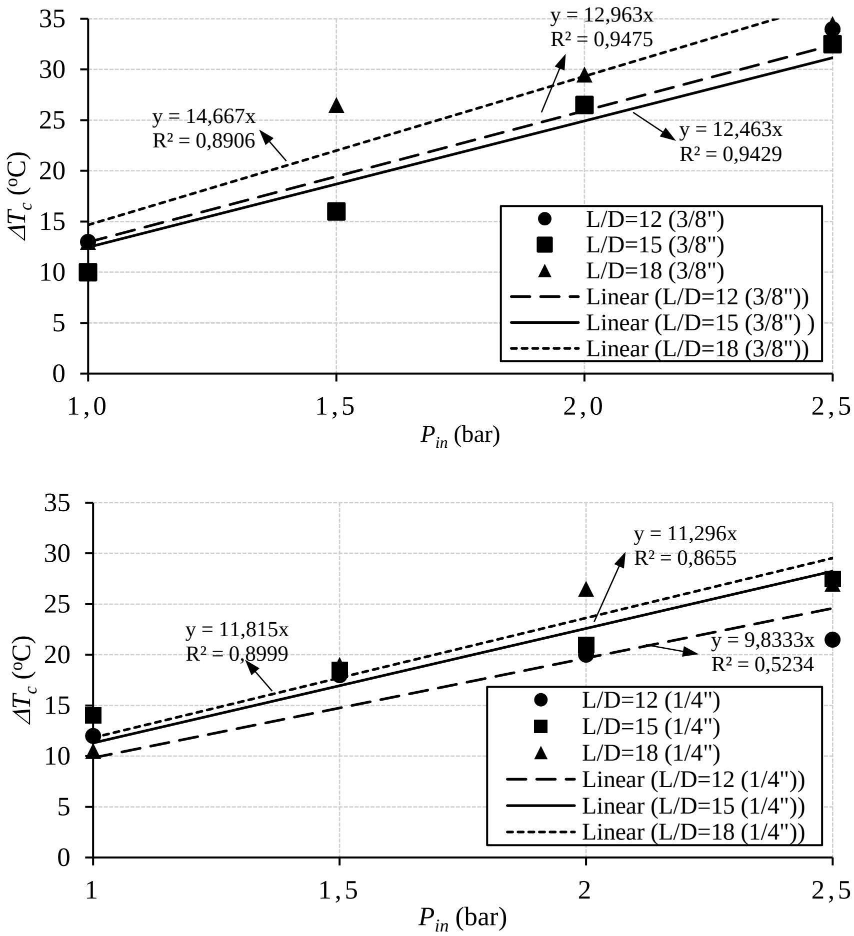

Figure 5. ΔT_c behavior as a function of vortex tube geometric parameters

Graphic in Fig. (6) shows the behavior of cold mass fraction μ_c in funcion of equipment configuration available. This is na important parameter for evaluating vortex tube performance, because it corresponds to the portion of inlet flow at outlet cold flow. For all studied configuration, μ_c values kept between 0,40 and 0,55, mainly due to cone adjustments and inlet pressure values. All these adjustments were done to obtain lower outlet cold air flow. Cold mass fraction μ_c values obtained are aligned with those presented by Mohammadi e Farhadi (2013) who found better results of μ_c between 0,40 e 0,60, for inlet pressure about 2,47 bar.

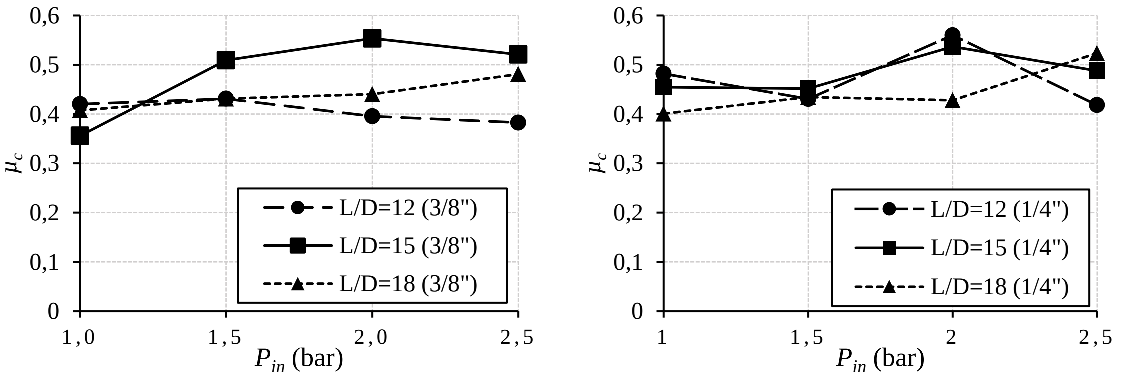

Figure 6. μ_c behavior as a function of inlet pressure and vortex tube geometric parameters

Graphics in Fig. (7) shows *COP* for each inlet pressure, as it can be observed in the linearized curves, the higher *COP*s are obtained at high pressure (*COP* about 0,15 at pressure between 2,0 to 2,5 bar) and tubes diameters of 3/8" also results in higher *COP*s, for each inlet pressure, when compared to ¼" diameter tube. In the same direction, 3/8" tube diameter results in higher ΔT_c. Another evaluated parameter was *L/D*, which has low influence on *COP* and ΔT_c, slightly better results was reached with *L/D=18.*

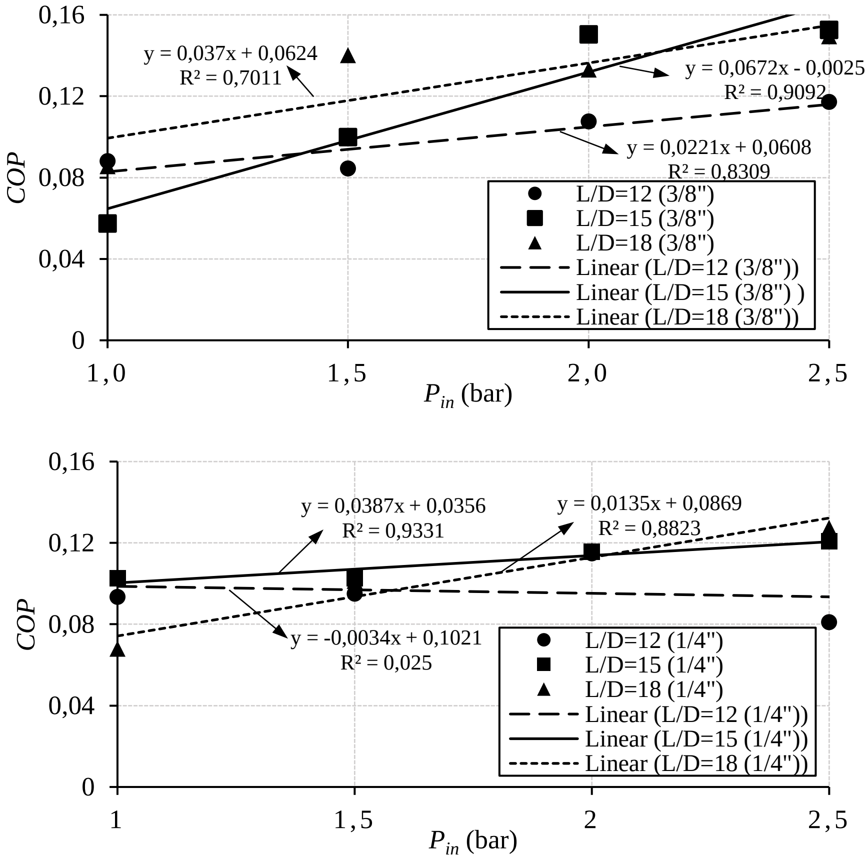

Figure 7. *COP* behavior as a function of vortex tube geometric parameters

4. CONCLUSION

Vortex tube is a simple device, easy for manufactoring and operating, which only needs compressed air source to work. Evaluations performed in this work shows the tube functioning, which splits into two flows, one hot and one cold, the inlet initial flow, even with low inlet pressure values.

The way how it was designed allows modifications in a simple way on the main geometric parameters which has most influence on vortex tube performance, therefore, it is also possible to assembly the equipment for a specific application.

Results of this case of study about evaluating vortex tube parameters configuration indicates that the ratio *L/D* has low influence on vortex tube behavior, meanwhile, tests with tube diameter of 3/8" shows the lowest cold flow (-6,5, -8.0 e -8.5ºC) and the highest *COP* (≈ 0,15).

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6. RESPONSIBILITY NOTICE