

DESIGN AND 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 behavior, 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

NOMENCLATURE

ΔT	Difference air temperature, °C
\dot{m}	Mass flow rate, kg/s
\dot{Q}	Heat transfer rate, W
\dot{W}	Compressor isentropic power, W
A	Tube transversal area, m ²
A _e	Inlet transversal area, m ²
COP	Performance coefficient
c _p	Specific heat at constant pressure, kJ/kg.K
d	Diaphragm diameter, m
D	Internal main diameter, m
d _e	Air inlet diameter, m
L	Tube length, m
P	Absolut pressure, kPa
R	Ideal gas constant, kJ/kg.K
T	Temperature, °C
v	velocity, m/s

Greek symbols

δ	Diaphragm dimensionless parameter
α	Outlet cone angle, degrees
ρ	Density, kg/m ³
μ_c	Cold mass fraction

Subscripts

in	Inlet
c	Cold

h Hot

INTRODUCTION

Vortex tube is simple equipment, easy to be manufacturing, reliable, with no moving parts. It works with compressed air input which is separated in two flows in different temperatures, one hot and another cold air flow (www.exair.com, accessed: September 17, 2017). 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 surface (Pinar, Uluer and Kirmaci, 2009). Both secondary flows, hot and cold, leaves vortex tube in the axial direction, in the same or opposite sense, depending on the construction concept applied (Valipour and Niazi, 2011). Despite of having many studies about vortex tube functioning, as the references presented in this work, there is no agreement on physical phenomena which results on flow temperature separation (Xue *et al.*, 2012).

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

THEORY

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, and toward to outlet control valve.

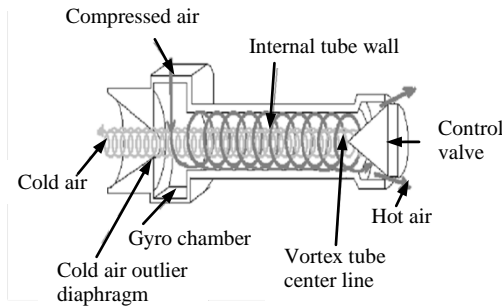


Figure 1. Vortex tube operation scheme. (Gao et al., 2005)

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. In the other hand, another portion from inlet flow is forced backwards in the center 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 is the cold air outlet.

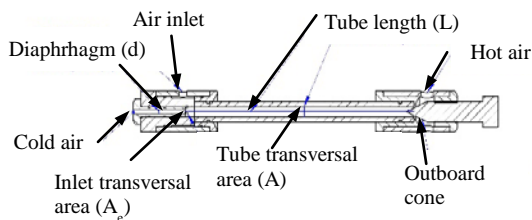


Figure 2. Vortex tube parameters.

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

Table 1. 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 dimensionless parameter (δ), given by ratio between cold air outlet (d) and intake air (D) diameters.	$\delta = 0.5$	Bovand et al. (2014)
Outlet cone angle (α) of most efficiency	$\alpha = 50^\circ$	Aydin and Baki (2006)

EXPERIMENTS

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, it was considered ratios L/D of 12, 15 and 18. Tube diameter was chosen according to aluminum commercial standard dimensions, in which both has $1/2''$ of external diameter and internal o $3/8''$ and $1/4''$, 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
			L (mm)		
9.53	4.76	2.30	114.3	142.9	171.5
6.35	3.18	1.50	76.2	95.2	114.3

Thereafter, the tube was designed by means CAD software Solidworks®, as shows in Fig. 3, with assembled fixing flanges, which allows easy parts changing for each configuration. Fig. 4 shows manufactured tube.

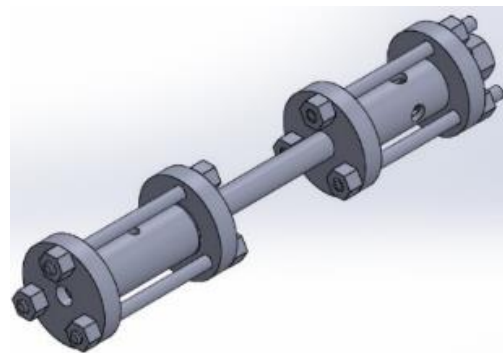


Figure 3. CAD tube design.



Figure 4. Manufactured tube.

Vortex tube testing was performed 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 2.5 bar, 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. 5. 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, control valve, was adjusted by means M12 screw in order to obtain lower temperatures on cold air flow outlet.

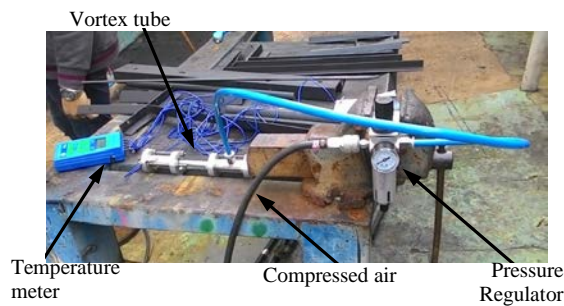


Figure 5. Experimental bench.

The required thermophysical properties were calculated by EES ® software. Vortex tube temperature variations are the most important parameters for this type of equipment, as following:

$$\Delta T_h = T_h - T_{in} \quad (1)$$

$$\Delta T_c = T_c - T_{in} \quad (2)$$

Eq. (1) and (2) shows the difference on hot air temperature (ΔT_h) and difference on cold air temperature (ΔT_c), respectively, 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).

$$\dot{m}_{in} = \dot{m}_c + \dot{m}_h \quad (3)$$

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

$$\dot{m}_c = v_c A_c \rho_c \quad (4)$$

$$\dot{m}_h = 4v_h A_h \rho_h \quad (5)$$

In which, mass flow rates \dot{m}_c and \dot{m}_h , are given by Eq (4) and Eq (5), respectively. v_c and v_h are flow velocities of cold and hot outlets (m/s), respectively; A is diaphragm orifice area (m²); ρ is air density for each air flow (kg/m³). Hot flow rate \dot{m}_h due to constructive shape of the tube which has 4 outlet orifices.

After each measurement, it is possible to calculate cold mass fraction (μ_c) given:

$$\mu_c = \frac{\dot{m}_c}{\dot{m}_{in}} \quad (6)$$

The cold mass fraction, shows in Eq. (6), is one of the important parameters as it indicates the vortex tube performance and the energy separation in the vortex tube (Pinar, Uluer and Kirmaci, 2009).

Performance coefficient (COP) of vortex tube might be determined by the ratio between cold heat transfer rate (\dot{Q}_c) and compressor isentropic power (\dot{W}_c), given by:

$$COP = \frac{\dot{Q}_c}{\dot{W}_c} \quad (7)$$

In which, \dot{Q}_c e \dot{W}_c are given, respectively, by:

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

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

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

RESULTS AND DISCUSSION

Table 3 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 26°C, meanwhile lowest cold temperature was -8.5°C and highest hot temperature was 34°C. During all tests, even at low pressures, it can be observed the air flow temperature separation phenomenon.

Table 3. 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 (°C)	v_c (m/s)	T_h (°C)	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 (°C)	v_c (m/s)	T_h (°C)	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 (°C)	v_c (m/s)	T_h (°C)	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 (°C)	v_c (m/s)	T_h (°C)	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 (°C)	v_c (m/s)	T_h (°C)	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 (°C)	v_c (m/s)	T_h (°C)	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
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Figure 6 shows the behavior of cold temperature difference ΔT_c , given by Eq. (2), 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. 3. Comparison among the ratios L/D, under the same tube diameter, are shown in Fig. 6, the angular coefficients shows that there is the tendency of temperature difference been higher as ratio L/D. From two different tube diameters the 3/8" showed better performance, as it delivers higher ΔT_c for all input pressure.

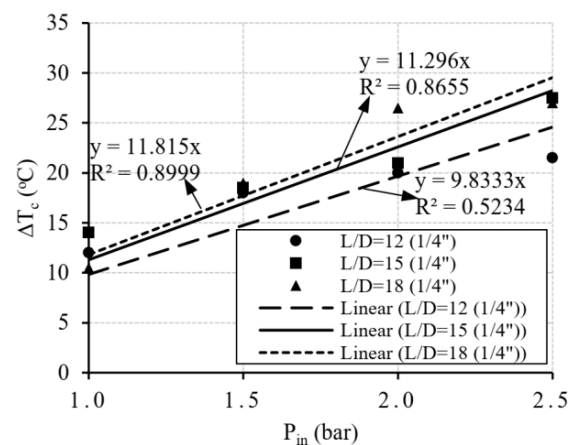
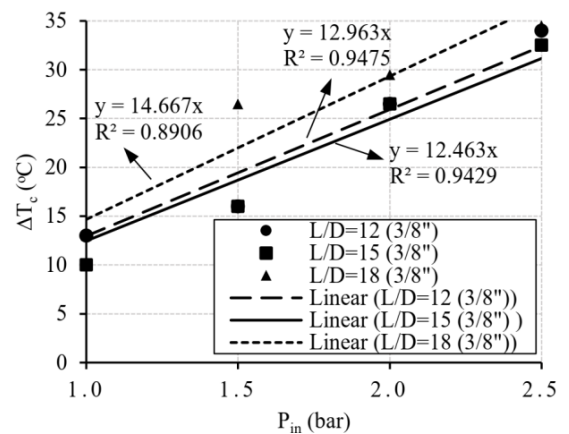


Figure 6. ΔT_c behavior as a function of vortex tube geometric parameters.

Graphic in Fig. 7 shows the behavior of cold mass fraction μ_c in function of equipment configuration available. This is an 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.

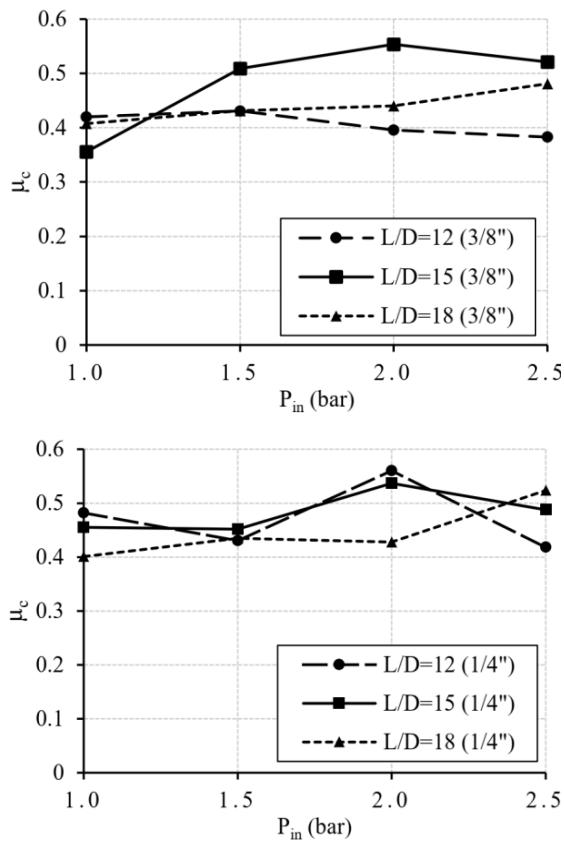


Figure 7. μ_c behavior as a function of inlet pressure and vortex tube geometric parameters.

Graphics in Fig. 8 shows COP for each inlet pressure, as it can be observed in the linearized curves, the higher COPs 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 COPs, for each inlet pressure, when compared to 1/4" 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.

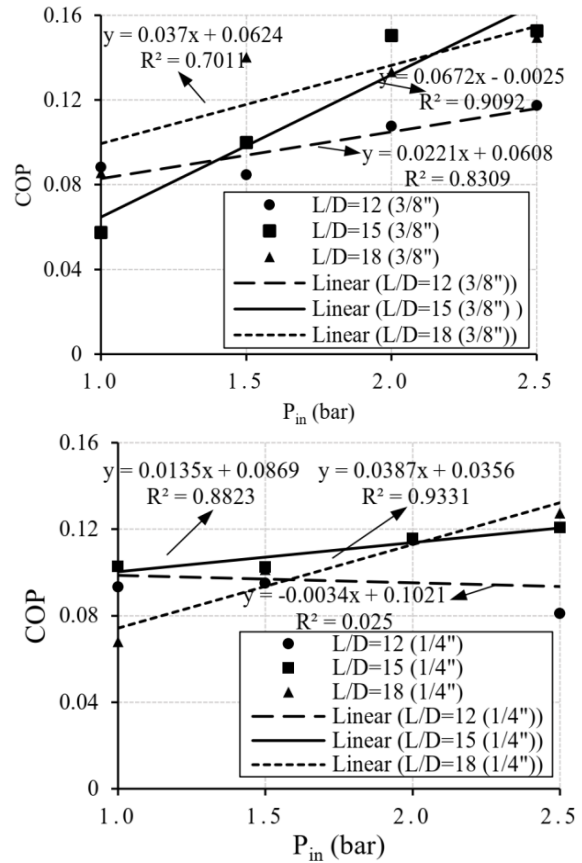


Figure 8. COP behavior as a function of vortex tube geometric parameters.

CONCLUSIONS

Vortex tube is a simple device, easy for manufacturing 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 assemble 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 -8.5°C) and the highest COP (≈ 0.15).

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