OPERATING CONDITIONS OF A RANQUE-HILSH OR VORTEX TUBE

Mariana Lopes Pinto, p.lopes.mariana@gmail.com
SISEA – Alternative Energy Systems Laboratory, Department of Mechanical Engineering, Escola Politécnica, University of São Paulo, Brazil, 05508-900.
Marcelo da Silva Rocha, msrocha@ipen.br
Nuclear Engineering Center - CEN, Nuclear and Energy Research Institute, IPEN – CNEN/SP
Av. Prof. Lineu Prestes, 2242 – Cidade Universitária – CEP 05508-000, São Paulo, SP, Brasil
José Roberto Simões-Moreira, jrsimoes@usp.br
SISEA – Alternative Energy Systems Laboratory, Department of Mechanical Engineering, Escola Politécnica, University of São Paulo, Av. Prof. Mello Moraes, 2231, São Paulo, SP, Brazil, 05508-900, Phone: +55 11 30915684.

Abstract. *This paper presents an experimental parametric study of a Ranque-Hilsh or a vortex tube device to verify the best operating condition regarding to the studied parameters. Laboratory tests were carried out in order to learn how the main controlling parameters, such as, feeding air pressure, tube lengths and hot air stream cross sections affect the global vortex tube efficiency. Experimental results, presented in this paper indicate that tube operating conditions that maximize flow parameters such as cold stream mass flow rate and cold stream differential temperature are mainly related to the inlet air pressure and hot orifice cross-section area. The first experimental results indicated that by correctly adjusting the parameters, temperature difference between the hot and cold exits can be obtained for a restrict exit areas ratio and hot tube length. Several experimental data was acquired and optimum performance measures were obtained for this second generation prototype.*

Keywords*: Vortex tube, Ranque-Hilsh, parametric study*

1. INTRODUCTION

The thermal energy separation phenomenon, which occurs in a vortex tube, was first observed accidently by Ranque (1933) when he was experimenting with his vortex pump. Later, shortly after World War II, Hilsch (1946) brought the device to scientific discussion by showing its cooling capabilities.

In an experimental investigation, Ranque (1933) found out that injecting a compressed air stream perpendicularly and tangentially to a simple hollow cylinder with open on both streams, two swirling flows developed inside, with formation of two different temperatures flow currents in each stream, a hot current, and a cold current. At the regions near the pipe wall, occurred a high velocity flow having an average temperature superior to that of the intake stream. Near the pipe centerline, a jet flew out throughout at a lower temperature. Hilsch (1946) deeply explored the apparatus and proposed the first tentative theory to explain the thermal energy separation.

Presently, the Ranque-Hilsch tube has been widely used in specific applications as a cooling device or heat pump, simply by separating the cold and hot flows and directing them to the desired application. Another remarked application is particle and gas separation or gas cleaning besides many other versatile applications (Khodorkov *et al.* 2003).

An overview on the theoretical propositions to explain the vortex tube phenomenon, one can clearly notice that several and, sometimes, conflicting theories have been conceived to explain how a simple compressed air flow can be heated and cooled at the same time without any external shaft work or interaction with the environment.

A large effort has been devoted to understand the aerodynamics and the energy separation physics for determining maximum efficiency of such device. Since Hilsh (1946) brought up the device to the scientific discussion, many other researchers have been working on the vortex tube (or viscous vortices as some authors prefer) problem to understand how it operates and what are the dominating physical phenomena behind it. The main aspect of that investigation was to suppose that the angular velocities gradient could generate friction between the different layers, transporting the heat by shear work . Regarding that, Pengelley (1957), proposed analytical equations for two-dimensional viscous compressible vortices in which heat transfer was neglected and strictly valid for laminar flow to determine the efficiency of a vortex tube. Lindstrom-Lang (1964) modeled a vortex tube based on turbulent thermal energy transferences with similarities with incompressible fluids. Soni and Thomson (1974) investigated the dependency of a vortex tube performance as a function of geometrical dimensional and dimensionless parameters. Stephan et al. (1983 and 1984) proposed a mechanism based on Goether vortices to describe and model a vortex tube. Ahlborn (1994, 1996, 1997, and 2000) developed models the whole device as a number of thermodynamically cooling cycles powered by the energy of the flow itself.

Constructively, there are two vortex tube configurations: the basic and largely investigated configuration composed by the vortex generator with a straight tube with a hot and a cold stream; and the uni-flow vortex tube, in which flow exits from the hot tube through a concentric cold orifice with the annular hot orifice. Development of a theory on the vortex tube require extensive laboratory experimental studies, at the same time, efforts on the numerical field have also been done in order to learn its working principle. According to Eiamsa-ard and Promvonge (2007), much of recent experimental investigation of vortex tubes has been divided into two main categories: the parametric studies of the effects of varying the geometry of the vortex tube components on the tube performance, and those focused on the mechanism of energy separation and flow inside the vortex tube by measuring the pressure, velocity and temperature profiles at various stations between the inlet nozzle and the hot valve. The effective parameters on temperature separation in the vortex tube can be separated into two groups, the geometrical and thermo-physical parameters.

Most of the experimental studies developed along the last decade made on vortex tubes are related to the global comprehension of the best operating condition by varying the main known parameters, i.e. what are the best configuration that furnishes the highest cold stream differential temperature ΔT_L . According to a large study developed by Eiasma-ard and Promvonge (2007), most of the vortex tubes investigated have internal diameter less than 10 mm, generally used for laboratory investigations and for refrigeration finalities.

Two important works addresses the thermodynamic point-of-view of the vortex tube. The work developed by Ahlborn and Gordon (2000) analyses the vortex tube as an internal thermodynamic refrigeration cycle, presenting an analytic model to estimate the principal temperatures, pressures, and velocity profiles that occurs interlay to the tube. Another recent and important study was developed by Simões-Moreira (2010), in which a thermodynamic analysis was carried out, considering the vortex tube as an air-standard cycle as a way to determine the operating limits according to the conservation laws of mass and energy, as well as the constraint of the Second Law of Thermodynamics.

Recently, some investigations on new geometries has been carried out by Valipour and Niazi (2011), performing a series of experiments to investigate the influence of uniform curvature of main tube over vortex tube performance. Results show that the curvature in the main tube has different effects on the performance of the vortex tube depending on inlet pressure and cold mass ratio.

The starting points of vortex tubes study in SISEA laboratory was performed by Polisel (2005) and Polisel *et al.*, that identified that the main geometrical parameters that dominate the tube operation are hot tube length and hot and cold exits cross sections areas. Many practical aspects have been revealed by the theoretical and experimental studies aforementioned in this investigation, such as the behavior of vortex tube physical parameters aiming to verify which of them more relevant influence the tube performance. Tested parameters include hot and cold outlet orifices areas, hot tube lengths, and inlet pressure.

This work aims to investigate a vortex tube for future application on engineering processes, so a 9.1 mm internal diameter vortex tube was constructed and a parametric study was worked out for the vortex tube behavior investigation.

2. THE VORTEX TUBE

The simplest modeling developed was developed in accordance with the conservation laws of mass, momentum, and energy for a control. The present analysis is based on a macroscopic or integral approach carried out over a control volume that envelope the R-H, with inlets represented by the compressed air inlet, and outlets represented by the hot air and cold air streams. The Figure 1 shows the schematics of a R-H tube assembling with the compressed air inlet, the cold and hot exiting air streams, and the tube portions, i.e. the hot tube section, labeled L_H,. It is possible to note the main physical variables related to the flows, such as temperatures, pressure, and air mass flows.

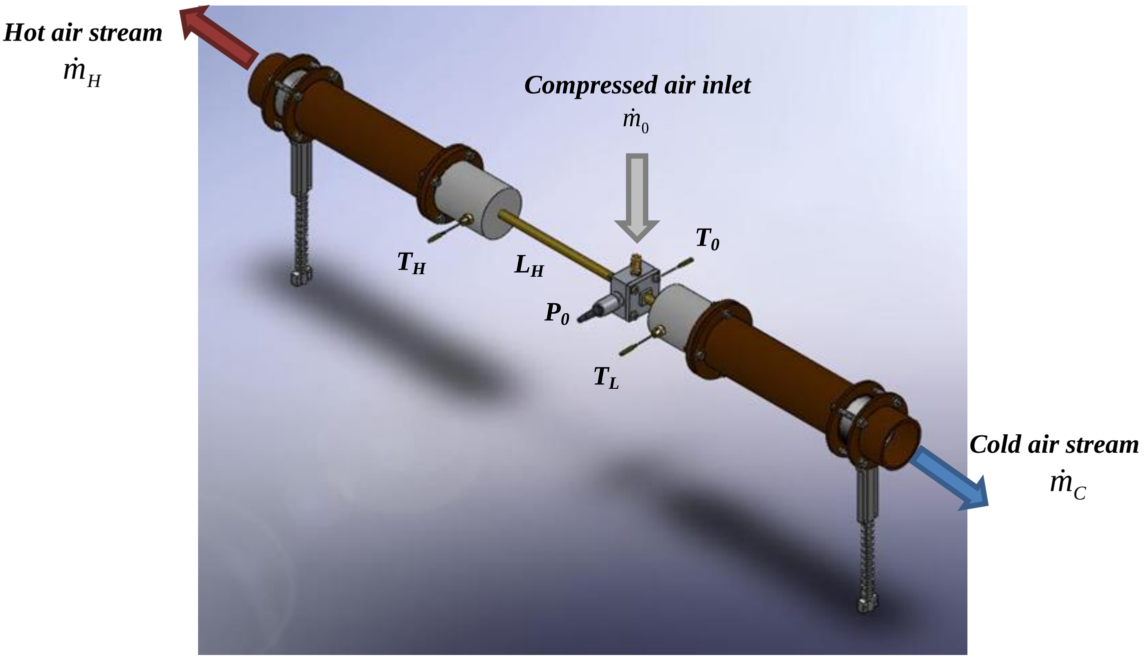

Figure 1. Schematics of the vortex tube assembling.

The analytic model assumes a steady state, adiabatic control volume of the total vortex tube, no shaft power and supposing kinetic and potential energy to be negligible, and then the energy and mass balance for the control volume that involves the entire vortex tube, gives:

$$\dot{m}_0 h_0 = \dot{m}_C h_C + \dot{m}_H h_H \,, \tag{1}$$

$$\dot{m}_0 = \dot{m}_C + \dot{m}_H \,, \tag{2}$$

where $\dot{m}$ is the mass flow rate, h is the specific enthalpy, and the subscripts *0*, *C*, and *H* refer to inlet, cold and hot sections, respectively. Furthermore, by assuming air to be an ideal gas, with constant specific heat at constant pressure *Cp*, and knowing that, it is possible to assume that, where T is the temperature, then the Eq. (1) can be further simplified to the following form of Eq. (3):

$$\dot{m}_0 T_0 = \dot{m}_C T_C + \dot{m}_H T_H \,. \tag{3}$$

Let μ be the cold to inlet mass flow rates ratio, defined as follows in Eq. (4):

$$\mu = \frac{\dot{m}_C}{\dot{m}_0} \,. \tag{4}$$

Both the cold and the hot streams have the same internal diameter that is the same internal diameter of the anemometer used to measure velocities. So, the mass flow rate measured of cold and hot flows from vortex tube were calculated by the expressions of Eqs. (5) and (6)

$$\dot{m}_H = \rho V_H S_A \,, \text{ and} \tag{5}$$

$$\dot{m}_C = \rho V_C S_A \tag{6}$$

where, ρ is the air density (at the velocity measurement point), V_H is the hot stream air velocity, V_C is the cold stream air velocity, and S_A is the internal anemometer area.

The hot to inlet temperature difference is defined as follows in Eq. (7):

$$\Delta T_H = T_H - T_0 \,, \tag{7}$$

and, the cold to inlet difference of temperature can be defined as follows in Eq. (8):

$$\Delta T_C = T_0 - T_C \,. \tag{8}$$

3. EXPERIMENTS AND METHODS

A vortex tube test section has been mounted in order to perform the experiments. The vortex tube projected and built to experimental tests is compounded by two inlet nozzles vortex tube made in aluminum with a hot pipe in copper alloy material with internal diameter D = 9.1 mm. The inlet pressure and temperature of compressed air were measured by a manometer and a T type thermocouple, respectively. The two streams are formed by flow rectification sections in which T type thermocouples, and anemometers were installed to measure temperatures and air velocities, respectively. At hot stream, a nozzle with a total angle of 30 ^{o} made the hot air flow control, and at the cold stream, three different orifices made the flow restriction. All temperature data are acquired by an acquisition data system with an acquisition frequency of 1.0 Hz.

The geometrical parameters tested in this work were:

- Internal diameter of the hot tubes, D (mm): 9.1;
- Hot tube lengths, L_H (mm): 91 (L_H/D = 10), 182 (L_H/D = 20) , 273 (L_H/D = 30), and 455 (L_H/D = 50) ;
- Cold orifice cross-section areas, S_C (mm^2): 12.57, 33.18, and 44.18;
- Hot orifice cross-section areas, S_H (mm^2): 61.82, 64.65, 66.95, and 69.50;
- Inlet pressure, P (kPa): 10, 20, 30, and 40;
- Inlet nozzles: 02.

Tests were carried out as follows: For each test, the geometrical parameters were established and the inlet air pressure was adjusted. The inlet air flow control valve was opened and pressurized air currents flew into vortex tube through inlet nozzles, and kept stable until both inlet, hot, and cold flow temperatures kept constant. So, all data was acquired and noted in a sheet by operator. During the tests, atmospheric pressure was maintained at both streams. The inlet pressurized working fluid was air and temperature was kept constant during all the data acquisition time.

All geometrical parameters described above were combined summing a total of 192 tests.

Parametric analyses were performed by varying the possible combination of cold and hot orifice area, hot tube length and pressures described before. The parametric analysis is resented by using parametric curves plotted according to the experimented parameters. The analysis of these curves allowed selecting the best operational parameters and combination of parameters for the vortex tube analyzed in this work.

Table 1. Variables measurement techniques used.

Variable	Technique	Range ± Uncertainty
Pressure	Bourdon manometer	0 – 100 ± 0.1[kPa]
Temperature	T type thermocouple	-0.5 - 35 ± 0.1 [°C]
Air flow velocity	Anemometer	0 - 20 ± 0.1 [m/s]

4. RESULTS AND DISCUSSIONS

The results presented here were obtained for previous parametric studies on the test rig develop in laboratory. Figures 2 to 5 show a series of graphics of a comparative analysis of the influence of the geometrical parameters over the cold difference of temperature (ΔT_C) for different air inlet pressure conditions. An interesting finding is that in cases the graphics show that there is optimal operation region from the point-of-view of increasing ΔT_C as one can see on discussion below. From the graphics it is also possible to notice that the cold temperature difference can vary significantly depending of a certain combination of the geometrical parameters analyzed in here.

Regarding to the inlet air pressure, it is possible to note its large influence on cold difference of temperature of all test performed. The maximum cold difference of temperature occurred near the highest inlet air pressure, i.e., 30 kPa or 40 kPa, as can be seen in Figs. 2 to 5.

In Fig. 2, cold difference of temperature was observed for all tests performed with a L_H/D = 10. It is possible to note that the maximum ΔT_C = 10.94 ^{o}C occurred for P = 40 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2.

The plotting graphs of Fig. 3, the cold difference of temperature was observed for all tests performed with a L_H/D = 20. It is possible to note that the maximum ΔT_C = 12.09 ^{o}C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2. This is the best configuration of all other configurations tested.

Figure 4 show the cold difference of temperature was observed for all tests performed with a L_H/D = 30. It is possible to note that the maximum ΔT_C = 11.71 ^{o}C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2.

In Fig. 5, the cold difference of temperature was observed for all tests performed with a L_H/D = 50. It is possible to note that the maximum ΔT_C = 10.95 ^{o}C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2.

From all tests performed it is possible to observe that the maximum cold difference of temperature were obtained for a cold stream area, S_C = 12.57 mm^2, and hot stream area, S_H = 64.65 mm^2, instead all other cold and hot areas tested.

Increasing the length of the vortex tube from 10 to 30 cm results in an increase in the temperature drop of the cold flow of 0.7 K, or 2.6%. However, a further increase in length to 40 cm does not change the energy separation; the cold outlet temperature for the 40 cm length vortex tube is the same, to within 0.01 K, as that of the 30 cm length vortex tube. Fig. 10(a) illustrates the streamlines predicted by the numerical model for the 30 cm vortex tube and the rate of work and heat transfer between the hot and the cold region is shown in Fig. 10(b).

This investigation shows that there is a critical geometrical parameter configuration of the vortex tube over which the majority of the energy transfer takes place.

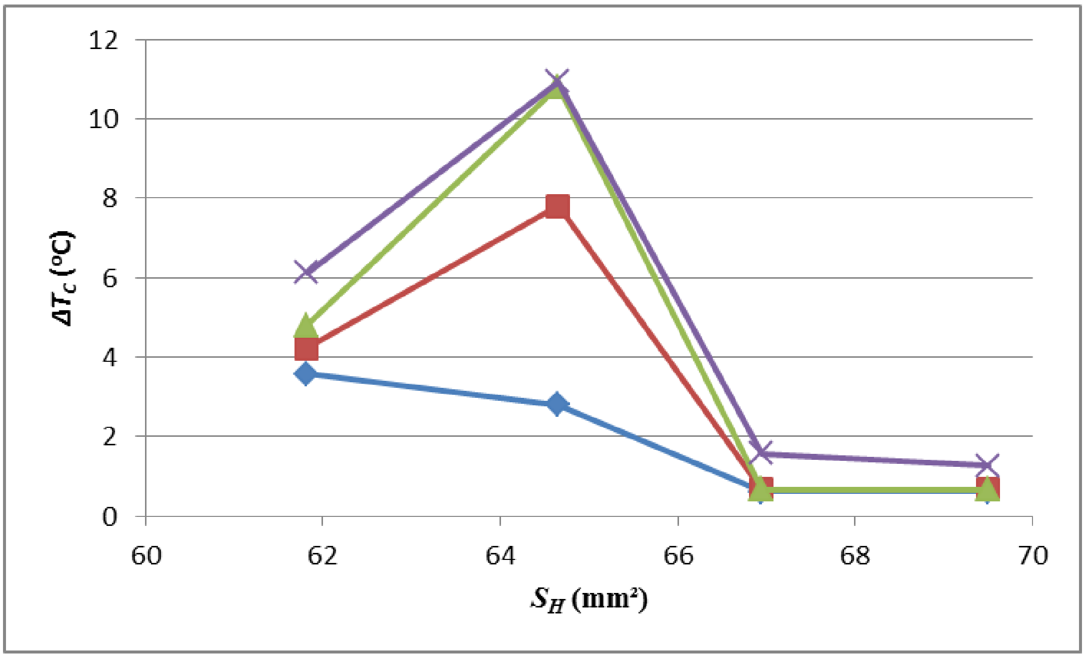

Figure 2. Cold differential temperature (ΔT_C) as a function of hot stream area (S_H) for L_H/D = 10. The maximum ΔT_C occurred for P = 40 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2. Legend: P = 10 kPa (blue), P = 20 kPa (green), P = 30 kPa (red), and P = 40 kPa (purple).

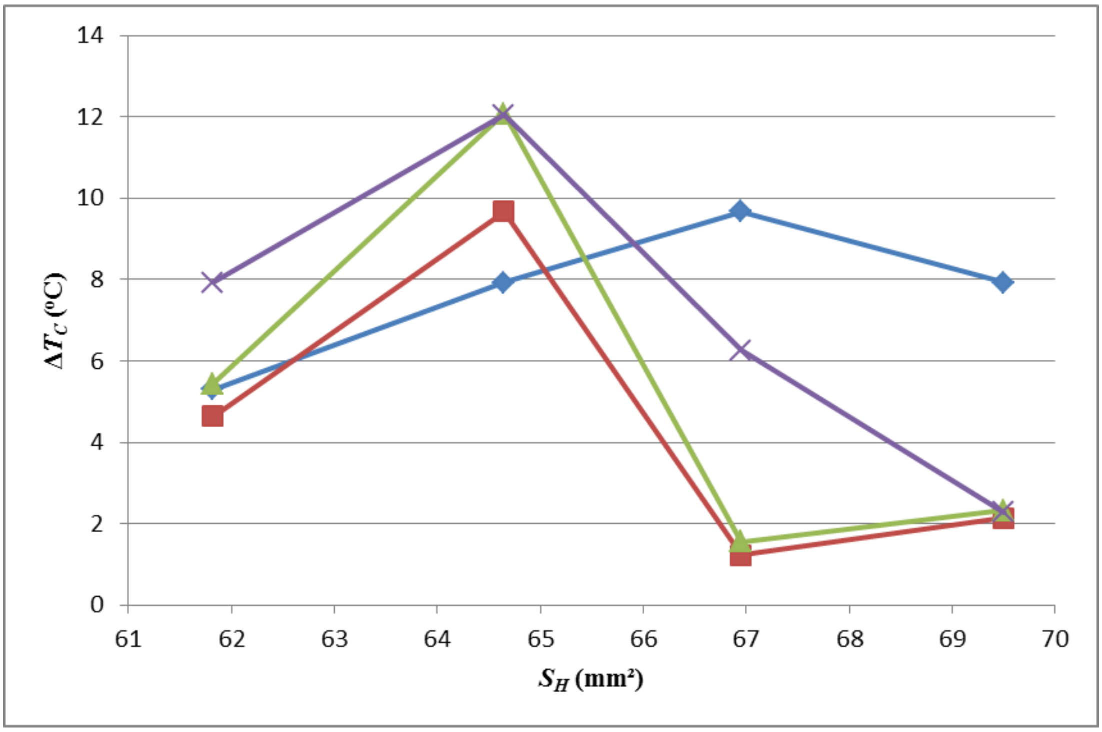

Figure 3. Cold differential temperature (ΔT_C) as a function of hot stream area (S_H) for L_H/D = 20. The maximum ΔT_C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2. Legend: P = 10 kPa (blue), P = 20 kPa (green), P = 30 kPa (red), and P = 40 kPa (purple).

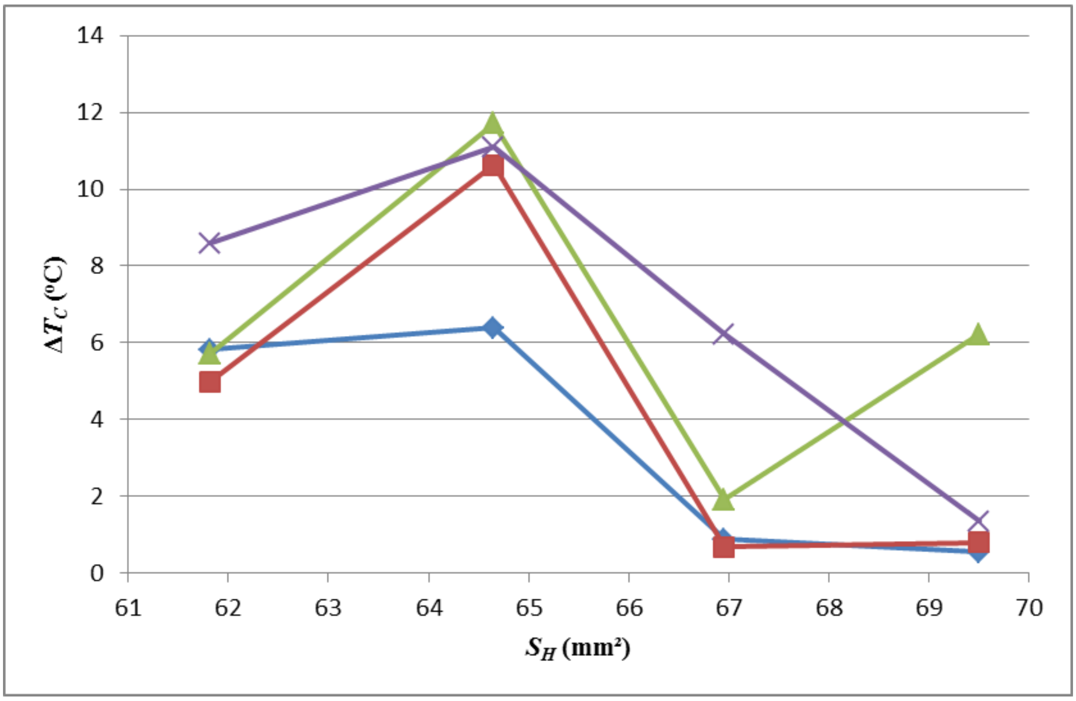

Figure 4. Cold differential temperature (ΔT_C) as a function of hot stream area (S_H) for L_H/D = 30. The maximum ΔT_C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2. Legend: P = 10 kPa (blue), P = 20 kPa (green), P = 30 kPa (red), and P = 40 kPa (purple).

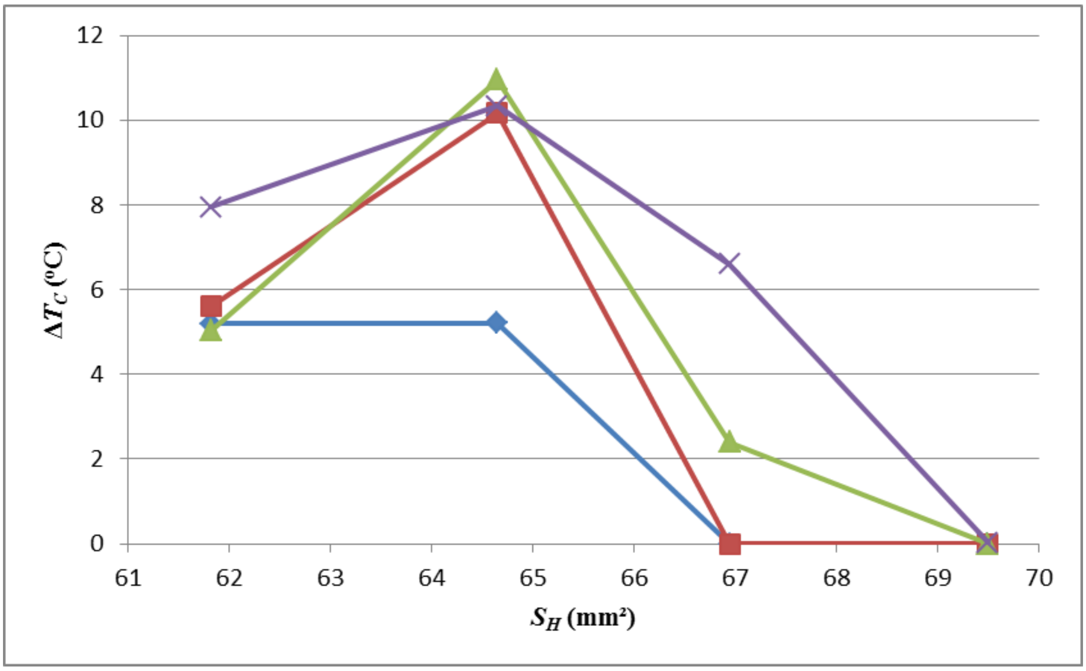

Figure 5. Cold differential temperature (ΔT_C) as a function of hot stream area (S_H) for L_H/D = 50. The maximum ΔT_C occurred for P = 30 kPa, S_C = 12.57 mm^2, S_H = 64.65 mm^2. Legend: P = 10 kPa (blue), P = 20 kPa (green), P = 30 kPa (red), and P = 40 kPa (purple).

5. CONCLUSIONS

An experimental parametric study was carried out with a vortex tube to verify what of the geometrical parameters that influence over cooling capacity of such device. The analysis was made by measuring the cold temperature difference of vortex tube under several physical and geometrical parameter configurations. The preliminary study showed that, for a 9.1 mm internal diameter vortex tube, pressure influences drastically on vortex tube's performance. The minimum cold stream area SC = , and minimum hot stream area SH tested gave the highest cold difference of temperature .A complete study about the application of vortex tube on gas liquefaction needs this kind of support for the best operational configuration. New parameters values must be investigated to define a well posed operational configuration.

6. NOMENCLATURE

Latin
A area [mm²]
Ac cold orifice area [mm2]
Ah hot orifice area [mm2]
Cp specific heat at constant pressure [kJ/kg.K]
h specific enthalpy [kJ/kg]
L length of the tube [m]
mass flow rate [kg/s]
T tempetature [K]

Greek
ρ gas density [kg/m3]
μ cold to inlet mass flow rates ratio [-]
Subscripts
c cold exit section.
h hot exit section
i inlet section

7. ACKNOWLEDGEMENTS

The authors are very grateful for the project and personal financial support by the FAPESP and CNPq.

8. REFERENCES

Ahlborn, B.K., Keller, J.U., Staudt, R., Treitz, G., Rebhan, E., 1994, Limits of temperature separation in a vortex tube, Journal of Applied Physics, Vol. 27, pp. 480-488.
Ahlborn, B.K., Camire, J., Keller, J.U., 1996, Low-pressure vortex tube, Journal of Applied Physics, Vol. 29, pp. 1469-1472.
Ahlborn, B., Groves, S., 1997, Secondary flow in a vortex tube, Fluid Dynamics Research, Vol. 21, pp. 73-86.
Ahlborn, B.K., Gordon, J.M., 2000, The vortex tube as a classic thermodynamic refrigeration cycle, Journal of Applied Physics, Vol. 88, pp. 3645-3653.
Aljuwayhel, N.F., Nellis, G.F., Klein, S.A., 2004, Parametric and internal study of a vortex tube using a CFD model, International Journal of Refrigeration, Vol. 28, pp. 442-450.
Arbuzov, V.A., Dubnishchev, Yu.N., Lebedev, A.V., Pravdina, M.Kh., Yavorskiî, N.I., 1997, Observation of large scale hydrodynamic structures in a vortex tube and the Ranque effect, Technical Physics Letters, Vol. 23, pp. 938-940.
Deissler, R.G., Perlmutter, M., 1960, Analysis of the flow and energy separation in a turbulent vortex, International Journal of Heat and Mass Transfer, Vol. 1, pp. 173-191.
Eiamsa-ard, S, Promvonge, P., 2007, Review of Ranque–Hilsch effects in vortex tubes, Renew Sustain Energy Rev, doi:10.1016/j.rser.2007.03.006
Gao, C., 2006, Experimental study on the Ranque-Hilsch vortex tube, Eindhoven: Technische Universiteit Eindhoven, p. 151.
Hilsch, R., 1946, Die expansion von gasen im zentrifugalfeld als kälteprozeβ, Zeitung fur Naturforschung, Vol. 1, pp. 208-214.
Khodorkov, I.L., Poshernev, N.V., Zhidkov, N.V., 2003, The vortex tube – A universal device for heating, cooling, cleaning and drying gases and separating gas mixtures, Chemical and Petroleum Engineering, Vol. 39, pp. 409-415.
Pengelley, C.D., 1957, Flow in a viscous vortex, Journal of Applied Physics, Vol. 28, pp. 86-92.

Piralishvili, Sh.A., Polyaev, V.M., 1996, Energy separation in a double circuit vortex tube – An experimental investigation, Experimental Thermal and Fluid Science, Vol. 12, pp. 399-410.
Polisel, R.A., 2005, Experimental study of a vortex tube, In Proceedings of ABCM - Brazilian Congress of Mechanical Engineering (COBEM 2005), Ouro Preto, Brazil Vol. 1, p. 8.
Polisel, R.A., Rocha, M.S., and Simões-Moreira, J.R., 2007, Experimental study of a vortex tube, In Proceedings of ABCM - Brazilian Congress of Mechanical Engineering (COBEM 2007), Ouro Preto, Brazil, Vol. 1, p. 8.
Polisel, R.A., Rocha, M.S., and Simões-Moreira, J.R., 2007, Parametric Study of a Ranque-Hilsh or Vortex Tube, In Proceedings of 22nd IIR International Congress of Refrigeration, Beijing, Vol. 1, p. 10.
Ranque, G., 1933, Expèriences sur la dètente giratoire avec productions simultanées d'un échappement d'air chaud et d'un échappement d'air froid, Le Journal de Physique, IV, pp. 112-115.
Sibulkin, M., 1962, Unsteady, viscous, circular flow – Part 3 – Applications to the Ranque-Hilsch vortex tube, Journal of Fluid Mechanics, Vol. 12, pp. 269-293.
Simões-Moreira, J.R., 2010, “An air-standard cycle and a thermodynamic perspective on operational limits of Ranque-Hilsh or vortex tubes”, International Journal of Refrigeration, Vol. 33, pp. 765-773.
Staschower, M. e Rotter, B., 2003, “Estudo de um Tubo de Ranque-Hilsch”, Trabalho de Formatura, EPUSP, São Paulo.
Stephan, K., Lin, S., Durst, M., Huang, F., Seher, D., 1983, An investigation of energy separation in a vortex tube, International Journal of Heat and Mass Transfer, Vol. 26, pp. 341-348.
Stephan, K., Lin, S., Durst, M., Huang, F., Seher, D., 1984, Similarity relation for energy separation in a vortex tube, International Journal of Heat and Mass Transfer, Vol. 27, pp. 911-920.
Valipour, M.S., and Niazi, N., 2011, “Experimental modeling of a curved Ranque-Hilsh vortex tube refrigerator”, International Journal of Refrigeration, In press, doi:10.1016/j.ijrefrig.2011.02.013.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.