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AN INVESTIGATION ON VORTEX TUBE PERFORMANCE BY A PARAMETRIC STUDY

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Abstract. *This paper presents an experimental parametric study of a Ranque-Hilsh or a vortex tube device. A vortex tube is a quite simple moving parts free device that can produce cold air from a compressed air source when it operates as a cooling system. At the same time, the tube can also produce hot air to work as a heat pump. Laboratory tests were carried out in order to learn the main controlling parameters, such as, feeding air pressure, tube lengths and cold and hot air exit cross sections. Experimental results of the tests are presented in this paper. It was found that tube operation has conditions that maximize flow parameters such as cold air mass flow rate and exiting temperature. 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, parametric study, Ranque-Hilsh.

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.

Ranque found out that injecting a compressed air stream perpendicularly and tangentially to a simple hollow cylinder, open on both ends, that two swirling flows developed inside. At the regions near the wall, occurred a high velocity flow having an average temperature superior to that of the intake stream. Near the tube centerline, a jet flew out throughout at a lower temperature. Hilsch 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. Other remarked applications are 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. 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 non-dimensional parameters. Stephan et al. (1983 and 1984) proposed a mechanism based on Goether vortices to describe and model a vortex tube. Hilsch had supposed that the angular velocities gradient could generate friction between the different layers, transporting the heat by shear work. 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 types of vortex tubes: the counter flow vortex tube, in which developed and studied by Ranque and Hilsh, and that has been extensively investigated; 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 made on vortex tubes are related to small internal diameter. 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.

This work aims to investigate a relatively larger internal diameter vortex tube for future application on gas liquefaction processes, so a 27.0 mm internal diameter was constructed and a preliminary parametric study was worked out for the vortex tube behavior investigation.

Considering many aspects revealed by the theoretical and experimental studies aforementioned, this work investigates 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.

2. THEORETICAL MODEL AND CONSERVATION EQUATIONS

The simplest modeling one can develop must, of course, be in accordance with the laws of conservation of mass, momentum, and energy. The present analysis is based on a macroscopic or integral approach carried out over a control volume that envelopes the R-H tube as depicted in Figure 1. The figure shows the schematics of a R-H tube stressing the compressed air entrance, the cold and hot exiting air streams, and the two tube portions, i.e. the hot tube section, labeled L_h, and the cold tube section, L_c.

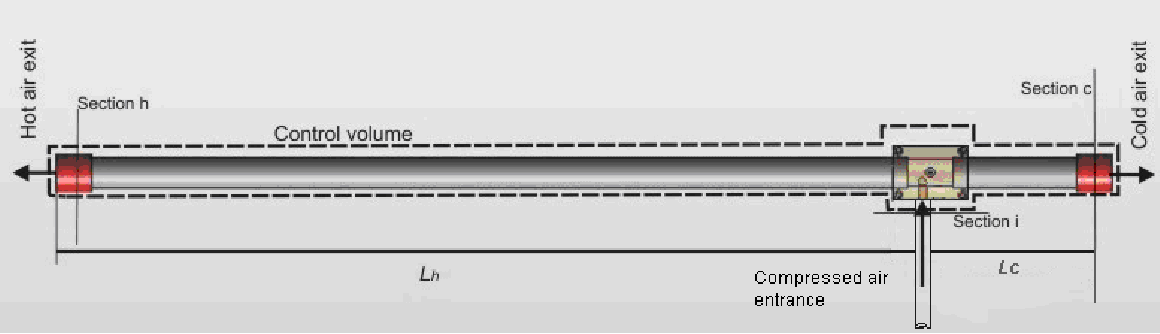


Figure 1. *Control volume enveloping the Ranque-Hilsch tube.*

By assuming a steady state, adiabatic control volume, no shaft power and supposing kinetic and potential energy to be negligible, then the energy and mass balance for the control volume indicated in Figure 1 yields:

$$\dot{m}_i h_i = \dot{m}_c h_c + \dot{m}_h h_h \text{, and} \tag{1}$$

$$\dot{m}_i = \dot{m}_c + \dot{m}_h , \tag{2}$$

where $\dot{m}$ is the mass flow rate, h is the specific enthalpy, and the subscripts i, 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 C_P, and knowing that, it is possible to assume that $h = C_p T$, where T is the temperature, then the eq. (1) can be further simplified to the following form:

$$\dot{m}_i T_i = \dot{m}_c T_c + \dot{m}_h T_h . \tag{3}$$

3. EXPERIMENTAL SETUP

The test rig mounted to the experiments was comprised of two inlet nozzles vortex tube made in aluminum with a hot pipe in cupper material with internal diameter D = 27.0 mm, as can be seen in Fig. 2. The outlet orifices were made in aluminum, being the cold orifice (Fig. 2a) placed coupled to the vortex generator and the hot orifice (Fig 2b) placed at the end of he hot pipe in such configuration that the hot vortex could exit by periphery and the cold vortex could exit by the pipe core.

(a) (b)

Figure 2. *Schematics of outlet orifices: (a) cold orifice (82.81 mm^2), and (b) hot orifice (78.54 mm^2).*

The starting points of this study was the work of Polisel (2005) and Polisel et al. (2005 and 2007), which was a continuation of Staschower´s graduation project (2003), that identified that the main geometrical parameters that dominate the tube operation are hot tube length and hot and cold exits cross sections areas. These, and also other works, showed that the higher the inlet pressure, the greater the temperature difference between hot and cold exits. This work do not included the variation of the number of inlet nozzles, keeping fixed just in one nozzle.

These preliminary experiments were obtained from a test rig with simple assembling procedures, allowing quick modification of the tested parameters. The geometrical parameters tested in this work were:

- Hot tube lengths, L_h (mm): 950, 1144, and 1540;
- Cold orifice cross-section areas, A_c (mm^2): 19.15, 45,18, and 82.81;
- Hot orifice cross-section areas, A_h (mm^2): 34.83, 78.54, and 113.85;
- Inlet pressure, P (kPa): 30, 40 and 50 (except for L_h = 1540 mm)
- Inlet nozzles: 01

The inlet pressurized working fluid was air and temperature was kept constant during all the data acquisition time. The geometrical parameters described above were combined for the verification of its influences on the cold differential temperature.

The inlet, hot and cold outlets pressures were measured with pressure transducers and atmospheric pressure was maintained at the outlets. The outlet hot and cold flow rates were obtained by using an anemometer to measure the air velocity into a well-known tube cross-section area, and the inlet flow rate was obtained from the two mentioned flow rates. Temperatures were measured at the inlet and outlets cross-sections using thermocouples type K.

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.

Table 1. *Experimentally measured variables.*

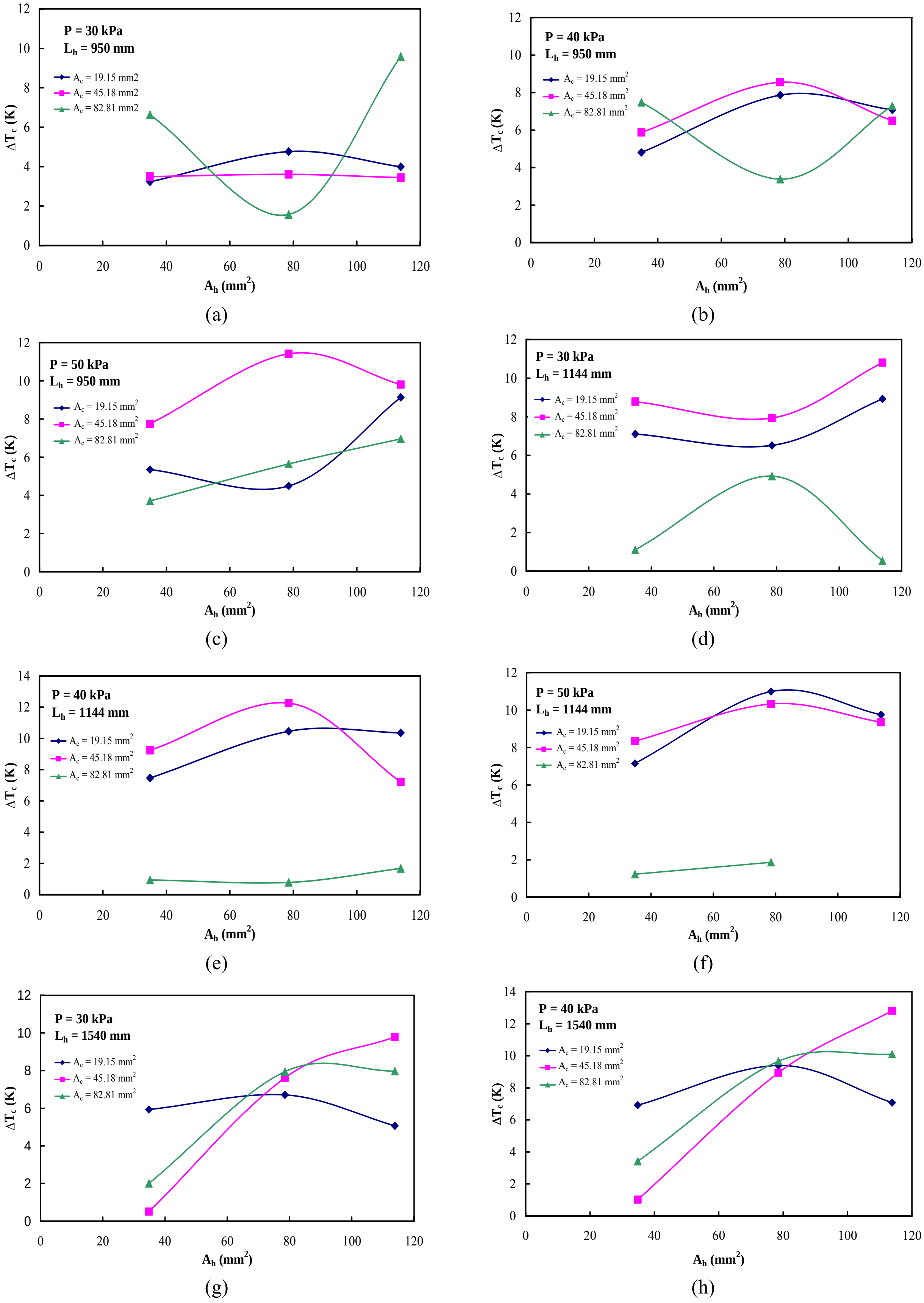
Variable	Technique	Range ± Uncertanty
Pressure	Bourdon manometer	0 – 100 ± 0.1 [kPa]
Temperature	Thermocouple type K	-0.5 - 35 ± 0.1 [°C]
Air flow velocity	Anemometer	0 - 20 ± 0.1 [m/s]

4. RESULTS AND ANALYSIS

The results presented here were obtained for previous parametric studies on the test rig develop in our laboratory. Figures 3a to 3e show a series of graphics of a comparative analysis of the influence of the cold orifice area (A_c) on cold temperature difference, or $\Delta T_c = T_i - T_c$, for many inlet pressure values (P) and hot orifice area (A_h). 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. 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.

The inlet pressure has large influence on cold temperature difference mainly for cold orifice area Ac = 19.15 mm^2 and 45.18 mm^2. The same is not true for the largest A_c = 82.81 mm^2.

The hot tube length that presented best results on ΔT_c = 12.81 (K) was the L_h = 1540 mm, with Ac = 45.18 mm^2 and Ah = 113.85 mm^2.



(a)

(b)

(c)

(d)

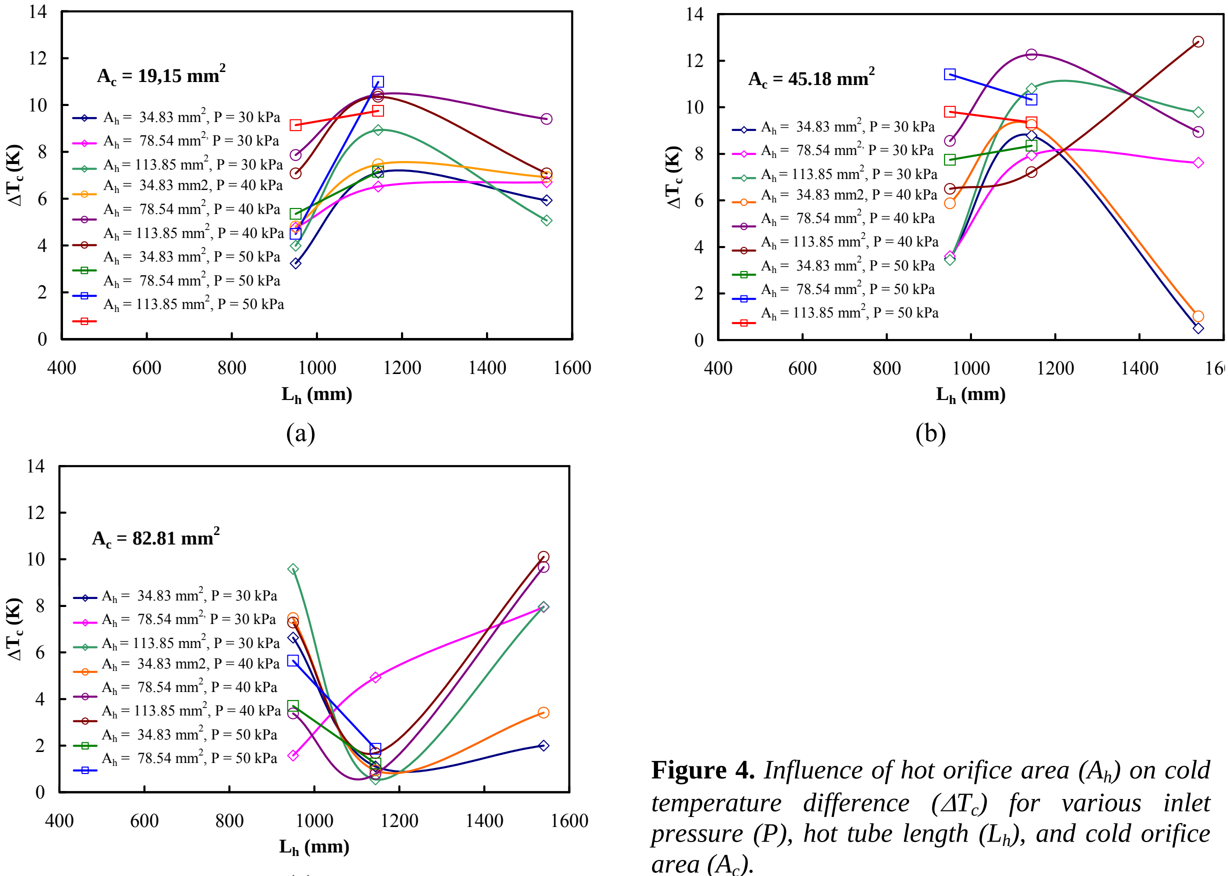
(e)

(f)

(g)

(h)

Figure 3. *Influence of cold orifice area (A_h) on cold temperature difference (ΔT_c) for many inlet pressure (P), hot tube length (L_h), and hot orifice area (A_h).*



(a)

(b)

(c)

Figure 4. *Influence of hot orifice area (A_h) on cold temperature difference (ΔT_c) for various inlet pressure (P), hot tube length (L_h), and cold orifice area (A_c).*

In Figure 4 it is shown the influence of the hot orifice area against cold orifice area (A_c = 19.15 mm^2, 45.18 mm^2 and 82.81 mm^2). Those graphics demonstrate the same effect of inlet pressure and hot tube length on cold differential temperature in a general way. This result, once again shows that optimal operating condition can be achieved by combining properly the geometrical parameters.

Regarding to the hot tube length, results from Fig. 4a show that L_h = 1144 mm present a peak of maximum ΔT_c for all Ah. In Fig. 4b, for high pressure (P > 40 kPa) and high hot orifice area (A_h > 78.54 mm^2) one can note that the cold temperature difference trends to decrease just for L_h = 1144 mm, indicating a bad parameter combination. Analysing the Fig. 4c, its possible to note that the tendency observer in Fig 4b is repeated, but now for most of hot orifice area A_h but not for A_c = 78.54 mm^2. In this case it worked in a reverse way.

4. 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 configurations of cold and hot tubes lengths and exit cross-section areas.

The preliminary study showed that for a 27.0 mm internal diameter vortex tube the parameters configuration influences drastically on vortex tube's performance. 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.

5. NOMENCLATURE

Latin

A_c cold orifice area [mm^2]
A_h hot orifice area [mm^2]
C_p specific heat at constant pressure [kJ/kg.K]
h specific enthalpy [kJ/kg]
L_h hot tube length [m]

$\dot{m}$ mass flow rate [kg/s]
T tempetature [K]

Subscripts
c cold exit section.
h hot exit section
i inlet section

6. ACKNOWLEDGEMENTS

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