PARAMETRIC STUDY OF A RANQUE-HILSH OR VORTEX TUBE

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Abstract. *This paper presents a parametric study of a Ranque-Hilsh or a vortex tube. A Ranque-Hilsch 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. In actual operation the incoming compressed air stream is split into two streams one of which is cold and the other is a hot one and they exit the device at the opposite tube ends. The theory that fully explains the correct physical phenomenon that takes place inside the tube is yet to be developed. As a consequence, laboratory tests were carried out in order to learn the main controlling parameters. The tests included the following parameters variation: feeding air pressure, tube lengths and cold and hot air exits 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 of 36°C was obtained for 3.5 bar abs inlet pressure. Several experimental data was acquired and optimum performance measures were obtained for this first prototype. To reinforce and expand the gathered knowledge, new tests are under course, including new higher feeding pressure.*

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

1. INTRODUCTION

The thermal energy separation phenomenon, which occurs on a vortex tube, was first observed 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, and 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.

1.1. Aerodynamics and energy separation

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.

To help develop a theory on the vortex tube, laboratory experimental studies have been carried out. At the same time, efforts on the numerical field have also been done in order to learn the working principle.

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 tube lengths and exit cross-sections.

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 Ranque-Hilsh tube as depicted in Figure 1. The figure shows the schematics of a Ranque-Hilsh 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. 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:

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

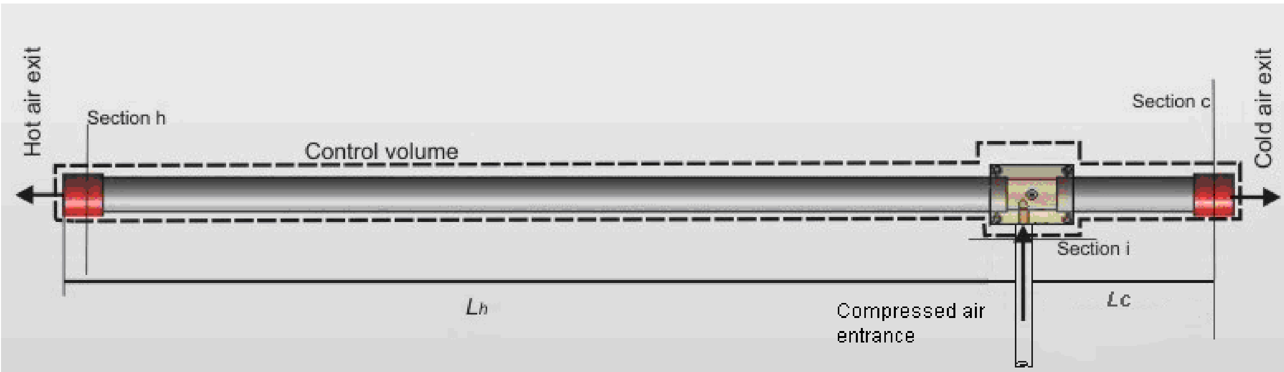


Figure 1. Control volume enveloping the Ranque-Hilsch tube.

Let μ be the *cold to inlet mass flow rates ratio*, defined as:

$$\mu = \frac{\dot{m}_c}{\dot{m}_i} , \tag{4}$$

Then the combination of Eq. (2) with Eq. (3) and the μ definition leads to:

$$\mu = \frac{T_i - T_h}{T_c - T_h} . \tag{5}$$

Thus, by measuring the three air streams temperatures, one can theoretically determine μ. On the other hand, to reduce experimental data, the cold to inlet mass flow rates ratio can be rewritten as:

$$\mu_{meas} = \frac{\dot{m}_c}{\dot{m}_c + \dot{m}_h} = \frac{1}{1 + \frac{\dot{m}_c}{\dot{m}_h}}, \tag{6}$$

where the equation of mass conservation, Eq. (2), has been used, and the subscript "meas" stands for measured. Also, $\dot{m}_c = \rho_c \cdot A_c \cdot V_c$ and $\dot{m}_h = \rho_h \cdot A_h \cdot V_h$, where ρ is the average density and V is the average velocity. Substituting these relations on Eq. (6), we can obtain:

$$\mu_{meas} = \frac{1}{1 + \frac{\rho_c \cdot A_c \cdot V_c}{\rho_h \cdot A_h \cdot V_h}}. \tag{7}$$

Since discharge pressure can be assumed to be the environmental pressure, and recalling that air can be treated as an ideal gas, it can be shown the density ρ is proportional to the reciprocal of absolute temperature, i. e., $\rho \approx 1/T$. So, the Eq. (7) can be written as Eq. (8):

$$\mu_{meas} = \frac{1}{1 + \frac{T_h \cdot A_c \cdot V_c}{T_c \cdot A_h \cdot V_h}}. \tag{8}$$

3. EXPERIMENTAL METHODS

The starting points of this study was the work of Polisel (2005), 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 included also the variation of the number of inlet holes, i.e., the number of compressed air entrances into the vortex tube.

These 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): 300, 400, 500, 600, and 700;
- Cold orifice cross-section areas, A_c (mm^2): 10.0, 19.6, and 28.3;
- Hot orifice cross-section areas, A_h (mm^2): 31.4, 42.4, 56.5, 75.4, and 100.5.

The inlet pressure was maintained in 3.0 bar and the air temperature was maintained constant for all the tests. The geometrical parameters described above were combined for the verification of its influences on the cold differential temperature.

The inlet air flow rate measurements were made by an orifice plate; 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. That technique was chosen so that atmospheric pressure was maintained at the outlets. Temperatures were measured at the inlet and outlets cross-sections using thermocouples. Pressures were measured by using pressure taps with coupled manometers located at inlet and outlets cross-sections.

After collecting the raw data, several parametric curves were plotted according to the experimented parameters. The analysis of these curves allowed selecting the best operational parameters and combination of parameters.

Polisel (2005) showed that the vorticial motion of the fluid inside the tube affected de measured values. To prevent reading errors, it was, thus, installed a corrective rectifying or flow smoothing section in the air flow paths near the exits. This section was made out of several small diameter tubing, glued inside the tube.

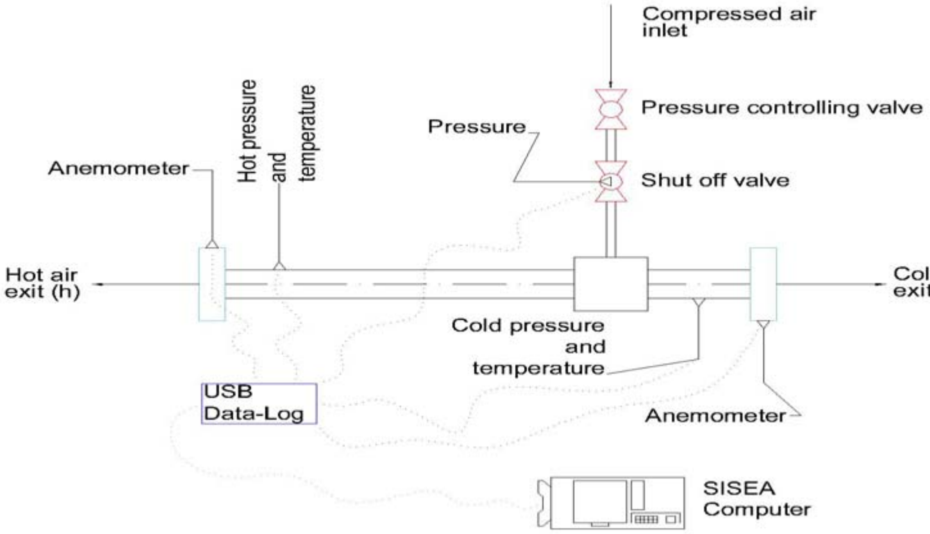


Figure 2. Test rig diagram.

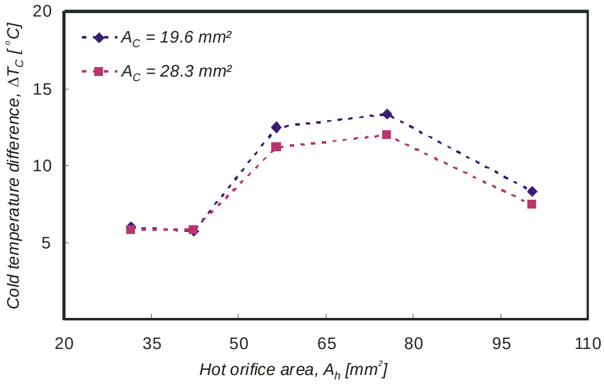
Table 1. Experimentally measured variables.

Variable	Technique	Range
Pressure	Bourdon manometer	0 – 3.0 ± 0.1 [bar]
Temperature	Thermocouple type K	-0.5 - 35 ± 0.1 [°C]
Air flow velocity	Anemometer	0 - 20 ± 0.1 [m/s]

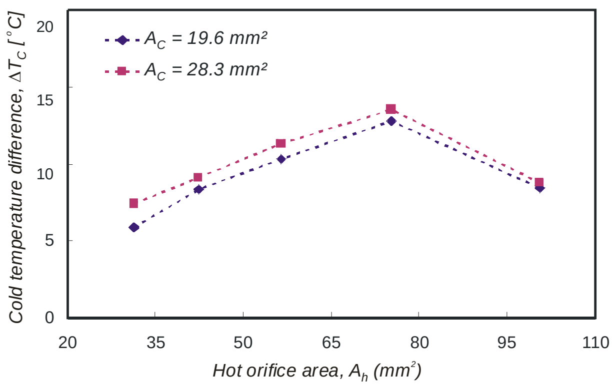
4. RESULTS AND ANALYSIS

Figures 3a to 3e show a series of graphics of a comparative analysis of the cold temperature difference, or $\Delta T_c = T_i$-T_c, with different geometrical parameters for constant injection pressure of 3 bar. Two different values of cold orifice areas (A_c = 19.6 mm^2 and 28.3 mm^2) where used. 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. Other tests revealed also that the best operational condition for the particular R-H tube studied occurred for A_c = 75.4 mm^2, which is not shown in the graphics. 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.

In Fig. 4 it is shown the influence of the hot area. In this case the cold area was the same in all tests (A_c = 19.6 and 28.3 mm^2). The graphics demonstrate that a combination of a high hot area with a long hot tube operates the best. This trend, however, failed the last case (A_h = 100.5 mm^2). This result, once again shows that optimal operating condition can be achieved by combining properly the geometrical parameters.



(a)



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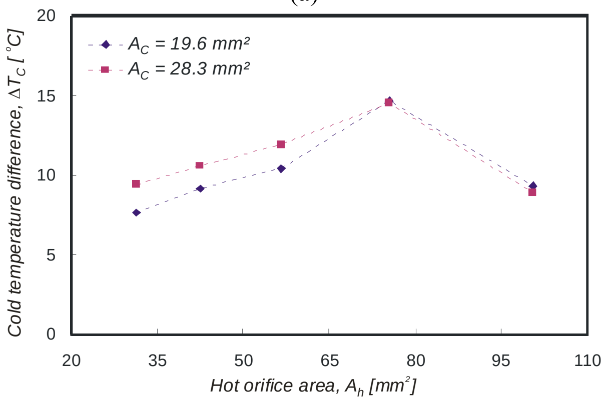

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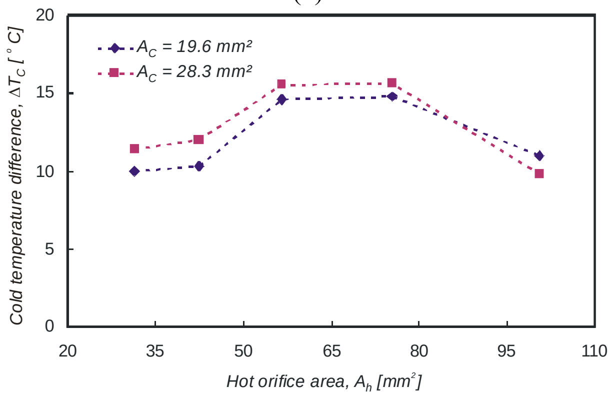

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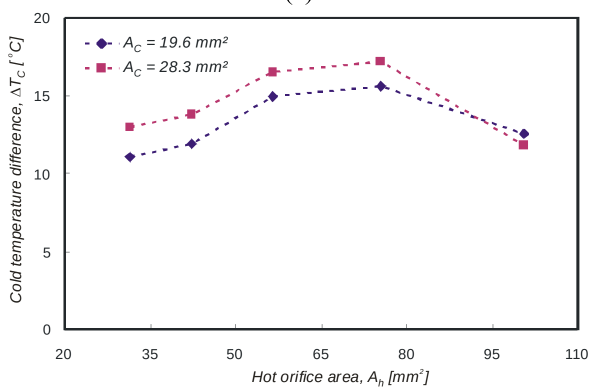

(e)

Figure 3. Cold temperature difference (ΔT_c) versus hot orifice area (A_h) (for A_c = 19.6 and 28.3 mm^2); (a) L_h = 300 mm, (b) L_h = 400 mm, (c) L_h = 500 mm, (d) L_h = 600 mm, and (e) L_h = 700 mm.

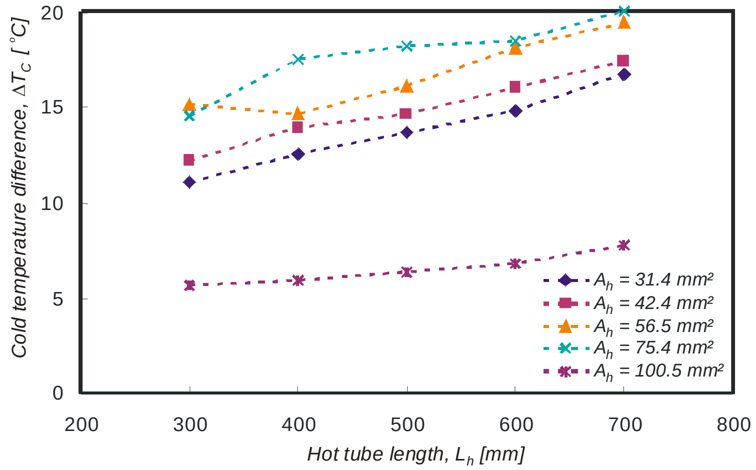

Figure 4. Cold temperature difference (ΔT_c) versus hot tube length (L_h) for several hot orifice area (A_h)

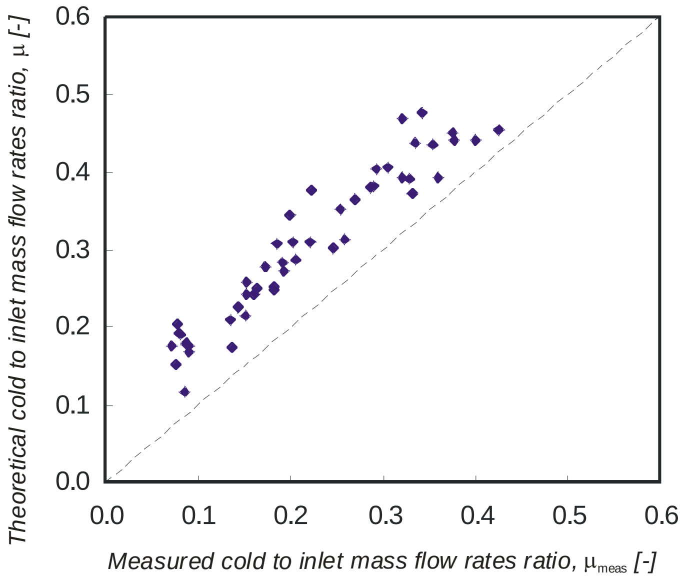

Figure 5. Theoretical versus measured cold to inlet mass flows (μ).

As a last test, it was compared the cold to inlet mass flow rates ratio, μ, according to its definition as in Eq. (4) with the one obtained from the First Law as in Eq. (8). This comparison intended to have a subsequent check on the data. Figure 5 shows the data points and the authors found that there must have some problem with the instrumentation, since it was expected an almost perfect correlation. Further analysis on this point is still on investigation.

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 configurations of cold and hot tubes lengths and exit cross-section areas. The major contribution of this work was to show that the vortex or Ranque-Hilsh tube has optimal operational conditions that result from a certain combination of the geometrical parameters.

6. NOMENCLATURE

Latin

A	area [mm²]
C_p	specific heat at constant pressure [kJ/kg.K]
h	specific enthalpy [kJ/kg]
L	length of the tube [m]
$\dot{m}$	mass flow rate [kg/s]
T	tempetature [K]

Greek

ρ	gas density [kg/m^3]
μ	cold to inlet mass flow rates ratio [-]

Subscripts

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

7. ACKNOWLEDGEMENTS

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