EXPERIMENTAL INVESTIGATION THE EFFECTS OF ORIFICE DIAMETER AND TUBE LENGTH ON A VORTEX TUBE PERFORMANCE

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ABSTRACT

Vortex tube is a device which is capable of separating hot and cold gas stream form an inlet gas stream with a proper pressure .Separating cold and hot streams by using vortex tube can be used in industrial applications such as cooling equipment and refrigerators . This device suits for these applications because its light ,simple and more importantly it is compact . Many researches have been carried out in order to identify the factor which affects Vortex tube performance .Here ,an experimental study has been conducted to determine the effect of geometrical parameters on vortex tube performance and air also used as a working fluid .To achieve the maximum proficiency of a vortex tube ,form the data which obtained experimentally , optimum values for cold orifice diameter to the VT inlet diameter (d / D) and the length of VT to its inlet diameter (L/ D) for this experiment proposed.

KEYWORDS

Vortex tube, geometrical parameters, orifice diameter ,tube length, Experimentation,

1. INTRODUCTION

The vortex tube is a device with no moving part with the capability of splitting hot and cold gas stream from a higher pressure inlet gas. Such a phenomenon (splitting of the flow into regions of low and high total temperature)is referred to as the temperature (or energy) separation effect. It comprises the following parts: one or more inlet nozzles, a vortex chamber, a cold-end orifice, a hot-end control valve and a tube. While high-pressure gas is tangentially entered into the vortex chamber through the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls toward the centre of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part goes through the cold end. Part of the gas in the vortex tube reverses for axial component of the velocity and move from the hot exhaust to the cold exhaust. At the hot exhaust, the gas leaves the chamber with a higher temperature, while at the cold exhaust, the gas with the lower temperature in compared with the inlet temperature exists. The vortex tube was first discovered by Ranque [12], a metallurgist and physicist who was granted a French patent for the device in 1932, and a United States patent in 1934. The fisrt reaction of the scientific and engineering communities to his invention was not encouraging . Since the vortex tube was not thermodynamically efficient, it was abandoned for several years .

Hilsch [4] redrew attention to the device , by reported of his thorough experimental and theoretical studies aimed at boosting the efficiency of the vortex tube .The phenomenon which occurs in vortex tube in terms of cold and hot flows can be employed in industrial applications specially in cooling equipment in CNC machines and refrigerators. Vortex tube requires little maintenance because it does not have moving parts. But, its low thermal efficiency is a main restriction factor for its application[1]. In this research numerical and experimental method will be employed to determine the significant factors on vortex tube behaviour with an incompressible flow in order to boost vortex tube energy (thermal) efficiency .Nimbalkar and Muller [9] reported the results of their experiments focusing on various geometries of the ‘‘cold end side” in terms of different inlet pressures and cold fractions. The experimental results showed that there is an optimum diameter of cold-end orifice for achieving maximum energy efficiency. The experiments also showed that for cold fraction $\leq$60%, the effect of cold end orifice diameter is negligible. The results also indicate that the maximum value of performance factor was always achievable at a 60% cold fraction without considering the orifice diameter and the inlet pressure.

Dincer et al. [2] have studied the effects of position, diameter and angle of a mobile plug, located at the hot end side experimentally to achieve the best performance. The most efficient (maximum temperature difference) combination of parameters is obtained with a plug diameter of 5 mm, and angle of 30 or 60 degree centigrade , by keeping the plug in the same position while the air enter into the vortex tube through 4 nozzles. Increasing the inlet pressure beyond 380 kPa did not cause any tangible improvement in terms of performance. Stephan et al.[14] measured the temperature profiles at different positions along a vortex tube axis and came to conclusion that the vortex tube length would have an significant influence on the transport mechanism inside. Saidi and Valipour[13] sowed valuable information on the classification of the parameters which leave effect on vortex tube operation. In their study, the thermophysical parameters like type of gas, inlet gas pressure and cold gas mass the ratio of cold gas mass and the geometrical parameters such as diameter and length of tube chamber, diameter of the outlet orifice and shape of the entrance nozzle, were studied.

Orhan and Muzaffer[10] have performed a series of experiments to examine the effects of the inlet nozzle, and the angle of the control valve on the performance of the counterblow vortex tubes for different inlet pressures. Experiments determined that for higher the inlet pressure, greater the temperature difference of the outlet streams occur. It was also concluded that the cold fraction is an important parameter which affect the energy performance in the vortex tube .The model results are compared with experimental data obtained from a laboratory vortex tube operated with room temperature compressed air. The model indicates that the vortex tube flow field can be divided into three regions that correspond to: hot flow region ,cold flow region and recirculating region.

In this research an experimental study has been conducted to investigate the effects of the VT cold orifice diameter and tube length on the VT thermal separation. Further, the amount of cooling and heating capacity created as air pass through a VT has been calculated. As discussed above, it will have potential applications in refrigerators.

2. THE VORTEX TUBE PARAMETERS

There are a few key parameters that affect the VT thermal behaviour which should be introduced.

2.1. The geometrical parameters

Figure 1 shows a schematic diagram of a counter flow vortex tube which was constructed and used in this study. As shown in Fig.1, the geometrical parameters are inlet VT diameters (D), cold orifice diameter (d), inlet nozzle diameter (δ), conical controlling valve angle (Φ), cold tube length (L_c) and hot tube length (L_h).

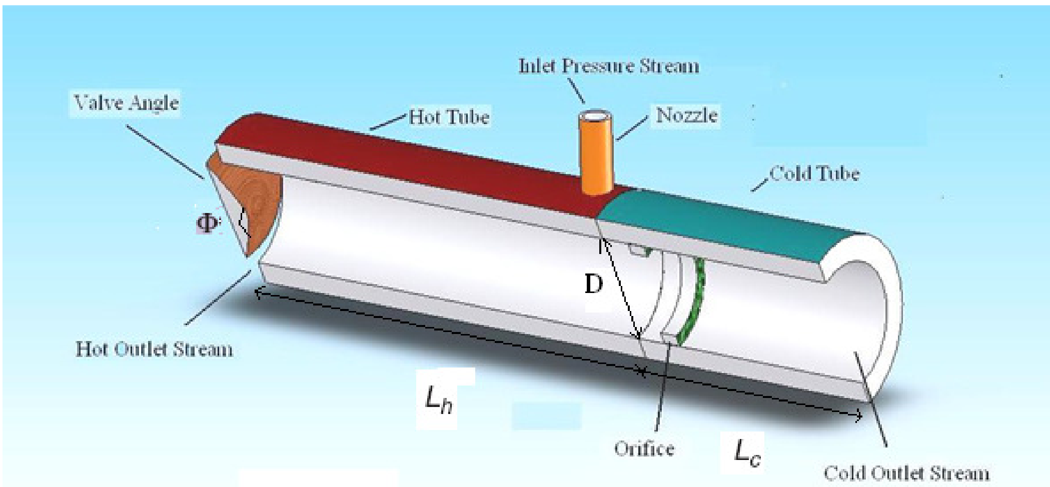

Figure 1. The schematic diagram of a vortex tube

Table 1shows the detailed geometrical parameters dimensions employed in this study. These values are selected according to the optimum values proposed by Eiamsa-ard and Promvonge [3]. As can be seen , the cold orifice diameter was varied from 8 mm to 17.7 mm and hot tube length ranged from 250 to 769 mm.

Table 1. The geometrical parameters and their values.

Parameter	D(mm)	d(mm)	δ(mm)	φ(degree)	L_c(mm)	N	L_h
value	25	8	8	50	50	1	250
		12.1					519
		17.7					769

2.2. The flow parameters

As mentioned by Eiamsa-ard and Promvonge [3], on of the major parameter is cold mass fraction ,defined as:

$$\mu_c = \frac{\dot{m}_c}{\dot{m}_i} \quad (1)$$

where $\dot{m}_i$ and $\dot{m}_c$ are the mass flow rates at the inlet of the vortex tube and at the cold outlet, respectively. The other flow parameters are:

a) The cooling temperature difference (ΔT_c) and hot temperature difference (ΔT_h) are defined as follows:

$$\Delta T_c = T_i - T_c \quad (2)$$

$$\Delta T_h = T_h - T_i \quad (3)$$

where T_i is the inlet stream temperature, T_c is the outlet stream temperature of the cold exhaust and T_h is the outlet stream temperature of the hot exhaust.

b) The performance of the vortex tube is defined as the difference between the heating effect and the cooling effect. Subtracting Eq. 2 from Eq. 3 gives the vortex tube performance equation as follows (Eq. 4):

$$\Delta T = T_h - T_c \quad (4)$$

c) the cooling capacity which is defined as:

$$\dot{Q}_C = \dot{m}_c \Delta h_c = \dot{m}_c (h_i - h_c) \quad (5)$$

For the case of an ideal gas, the cooling capacity may be defined as:

$$\dot{Q}_C = \dot{m}_c \Delta h_c = \dot{m}_c c_p (T_i - T_c) = \dot{m}_c c_p \Delta T_c \quad (6)$$

Considering above definitions, the specific cooling capacity can be derived as follow:

$$q_c = \frac{\dot{Q}_c}{\dot{m}_i} = \mu_c \Delta h_c \quad (7)$$

3. EXPERIMENTAL APPARATUS

Figure 2 shows a diagram of the experimental apparatus . High pressure air from compressor is directed tangentially into the vortex tube. The high pressure gas expands in the vortex tube and separates into cold and hot streams.

The cold gas leaves the central orifice near the entrance nozzle, while the hot gas discharges the periphery at the far end of the tube. The control valve is also being used to control the flow rate of the hot stream. This would help to regulate cold mass friction. Two orifice flow meters constructed according to ISO5167 [5]are employed to measure the mass flow rate of the hot and cold streams. 3 PT100 temperature sensors are installed to measure inlet, hot and cold stream temperatures. 2 pressure transmitters are used to quantify inlet pressure and outlet pressure of hot streams.

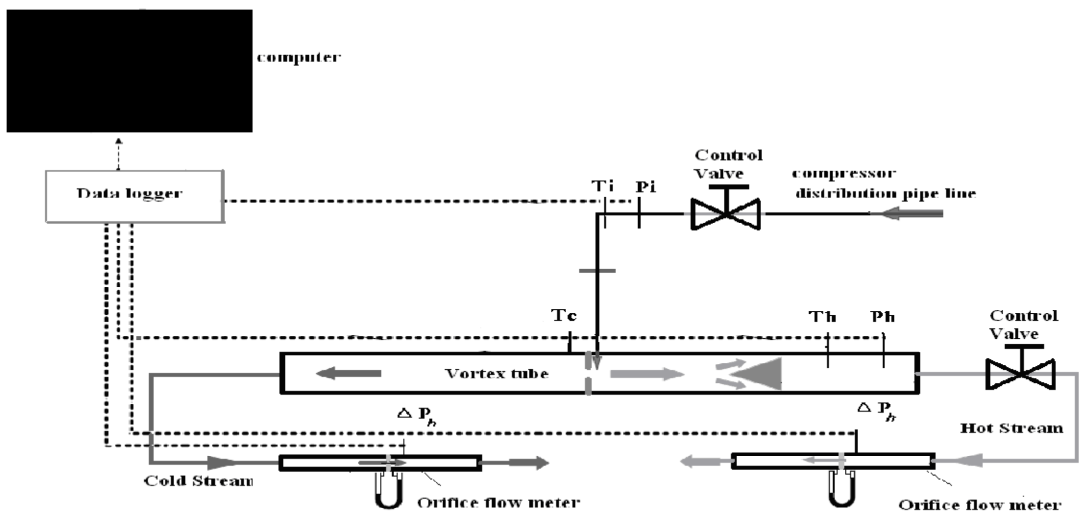

Figure 2. A schematic diagram of experimental layout

Figure 3 shows the experimental test bed has been conducted at Koolab Toos Company to investigate thermal separation of air as working fluid. The inlet pressure did not vary during experiments and was 4 bar. Noting from the figure, the hot length of the VT and hot stream flow meter were painted in red. In other hand, the cold length of the VT and cold stream flow meters were painted in blue. The VT was made from steel with inlet diameter of 25 mm. During the tests, the cold orifice diameter and hot tube length of the VT were varied among 3 available orifices as detailed in Table 1.

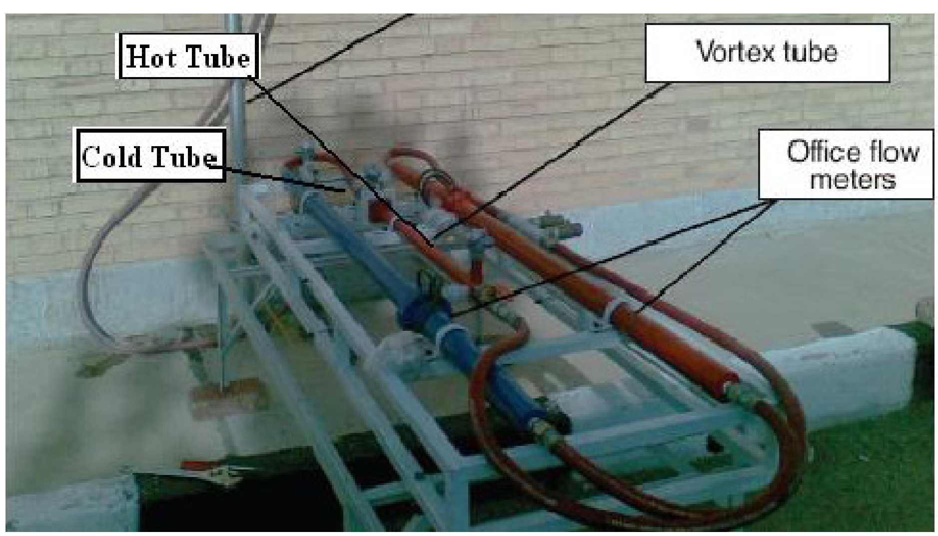

Figure 3. The experimental test bed in operation

4. Error Analysis

The errors associated with temperature measurements are computed in this section.
The maximum possible errors in various measured parameters ;namely ,temperature and pressure ,were evaluated by using the method proposed by Moffat[7]. Errors were estimated from the minimum values of output and the accuracy of the instrument. This method is based on careful specification of the uncertainties in the various experimental measurements. If an estimated quantity, Y ,depends on independent variables like x_i then the error in the value of "Y" is given by.

$$\frac{\partial Y}{Y}=\sqrt{\sum_{1}^{n}\left(\frac{\partial x_i}{x_i}\right)^2} \tag{8}$$

where $\frac{\partial x_i}{x_i}$ are the errors in the independent variables.

∂x_i = Accuracy of the measuring instrument and

x_i =Minimum Value of the output measured

4.1. Error in temperature measurement

PT100 temperature sensors were used to measure the gas temperatures. Temperatures are logged in file with accuracy of $0.1^0 c$. The maximum possible error in the case of temperature measurement was calculated from the minimum values of the temperature measured and accuracy of the instrument. The error in the temperature measurement is:

$$\frac{\partial T}{T}=\sqrt{\left(\frac{\partial T_{PT100}}{T_{\min}}\right)^2+\left(\frac{\partial T_{\log}}{T_{\min}}\right)^2}=\sqrt{\left(\frac{.5}{12}\right)^2+\left(\frac{.1}{12}\right)^2}\approx 0.04=4\% \tag{9}$$

4.2. Error in pressure measurement

Pressure transmitters were used to measure the gas pressure. Pressures directly are logged in file with accuracy 0f 0.01 bar. The error in the pressure measurement is:

$$\frac{\partial P}{P}=\sqrt{\left(\frac{\partial P_{\max}}{P_{\min}}\right)^2+\left(\frac{\partial P_{\log}}{P_{\min}}\right)^2}=\sqrt{\left(\frac{.01}{1.33}\right)^2+\left(\frac{0.01}{1.33}\right)^2}\approx 0.01=1\% \tag{10}$$

4.3. Error in flow rate measurement

Flow measurement has been made using orifice flow meters. Uncertainty analysis was conducted according to the standard procedures reported in ISO5167. The analysis shows that the error in the flow rate measurement is 4.5%.

5. RESULTS AND DISCUSSION

Figure 4 shows the effects of cold orifice diameter on non-dimensional cold temperature differences when L_h= 519mm. It can be seen that the cold orifice with d =8 mm creates the highest cold temperature differences for lower μ_c . At a higher value ofμ_c, cold temperature difference decreases. It should be also pointed out that, there is a specific μ_c (about 0.6) in each case which causes the temperature differences to be maximized.

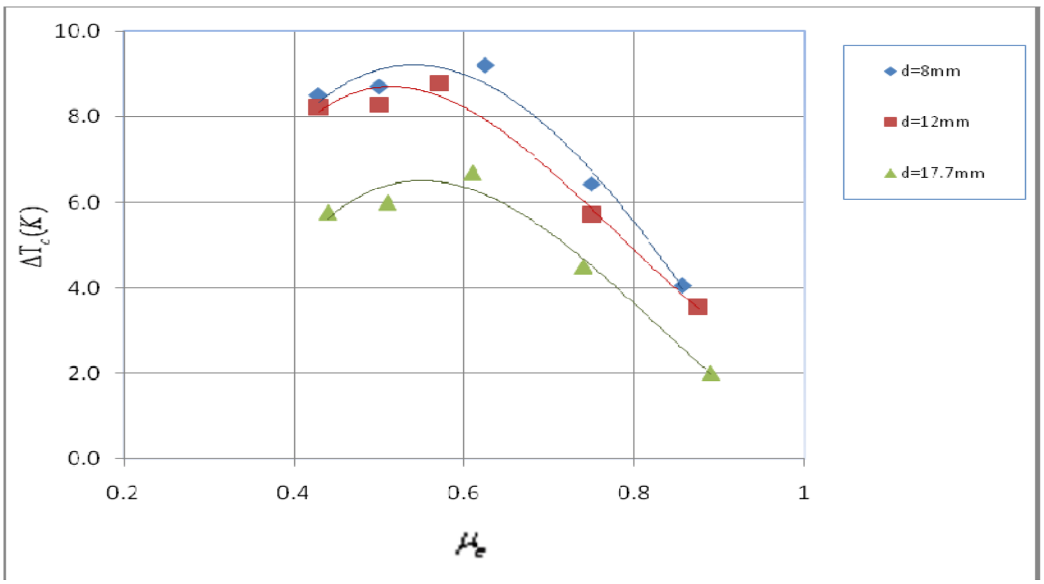

Figure 4. Effect of cold orifice diameter on cold temperature difference

Figure 5 shows the effects of cold orifice diameter on non-dimensional hottemperature differences when L_h=519mm. It can be seen that the orifice with d =8 mm creates the highest hot temperature differences. It should be also pointed out there is a μ_c in each case which cause the temperature differences to be maximized. For the current configuration at $\mu_c \approx .75$the highest hot temperature differences are produced.

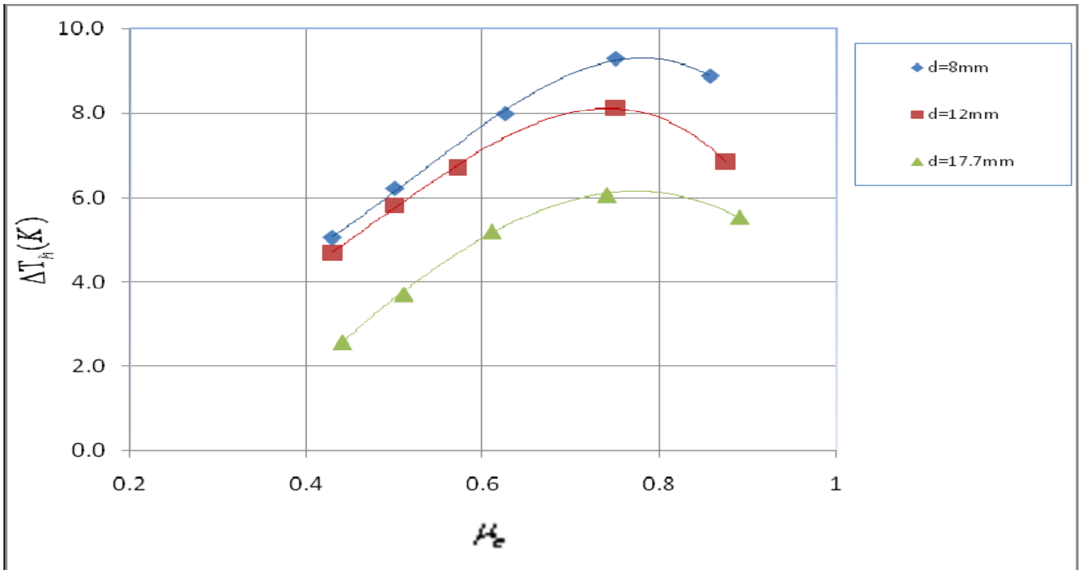

Figure 5. Effect of cold orifice diameter on hot temperature difference

Figure 6 represents the effects of tube length on non-dimensional cold temperature differences when d=8mm. As the graph shows ,the tube with L_h=769 mm creates the highest hot temperature differences. It should be also noticed that there is a μ_c in eachcase which causes the temperature differences to be maximized. For this case ,at$\mu_{c\approx}$.62 the highest hot temperature differences are generated .

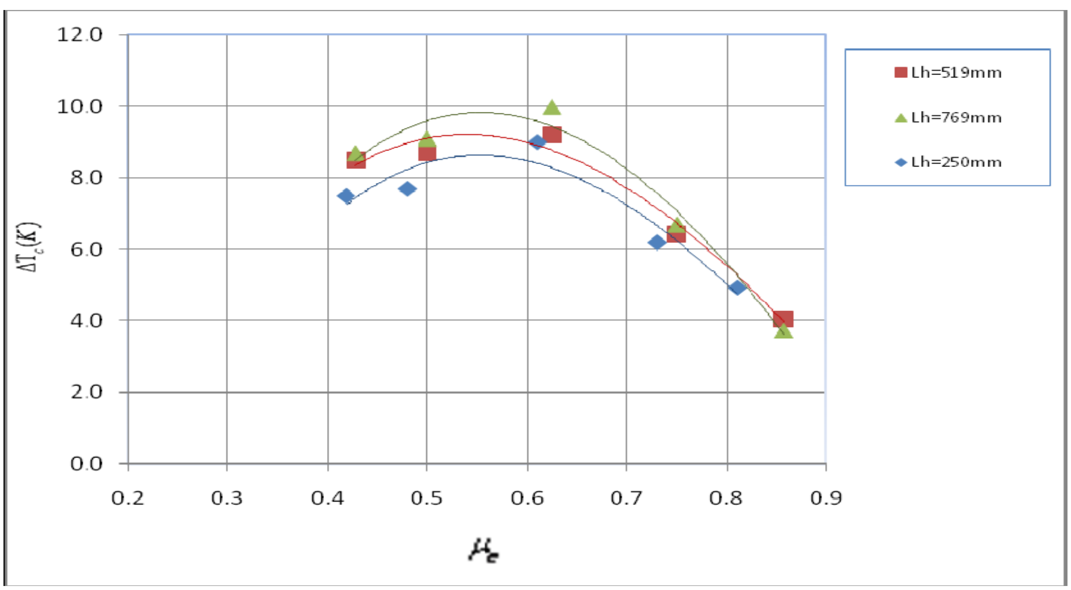

Figure 6. Effect ofL_h on cold temperature difference

Figure 7 indicates the effects of tube length on non-dimensional hot temperature differences when d=8mm. As the graph demonstrates , the tube with L_h=769 mm produced maximum hot temperature differences and at $\mu_{c\approx}$.75the highest hot temperature differences are generated.

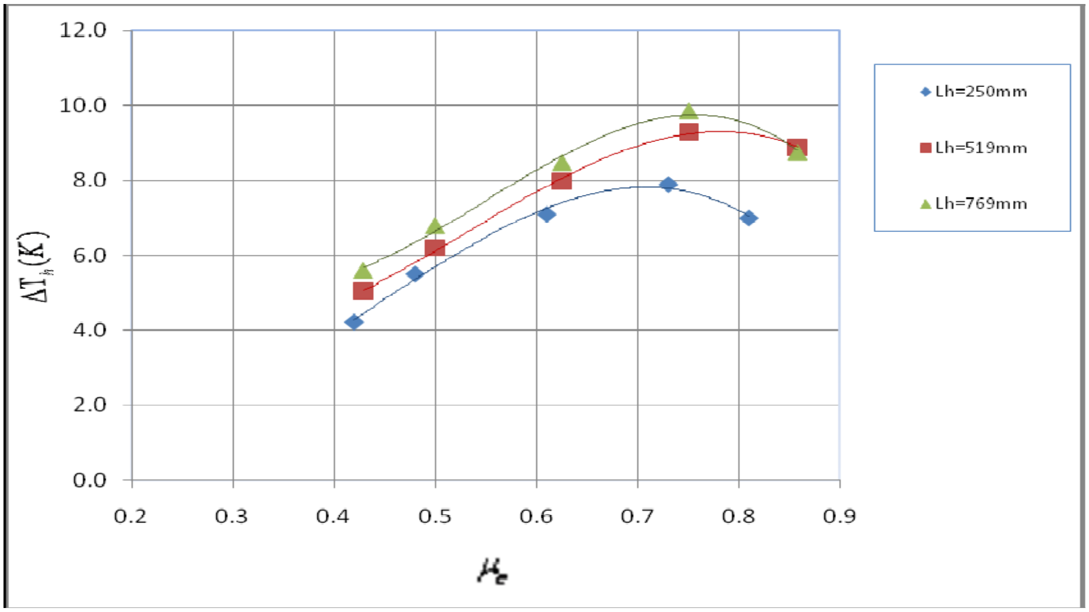

Figure 7. Effect of L_h on hot temperature difference

Figure 8 shows effects of cold orifice diameter on specific cooling capacity when L_h=519. As can be seen , the orifice with d =8 mm produces the highest specific cooling capacity at $\mu_{c\approx}.63$ while the orifice with d =12 mm creates about the same specific cooling capacity at $\mu_{c\approx}.62$. Nikolaev et al.[8] found that the maximum refrigeration capacity of the vortex tube falls within the range from 60% to 70% cold fraction.

Poshernev and Khodorkov [11] mentioned that within their range of input parameters the refrigerating capacity has a distinct maximum at a cold fraction of about 50%–60%. Nimbalkar and Muller [9] mentioned that the maximum value of performance factor was always reachable at a 60% cold fraction irrespective of the orifice diameter. As can be seen from figure 10, our results also show that maximum cooling capacity is encountered at about 65% cold fraction regardless of the orifice diameter.

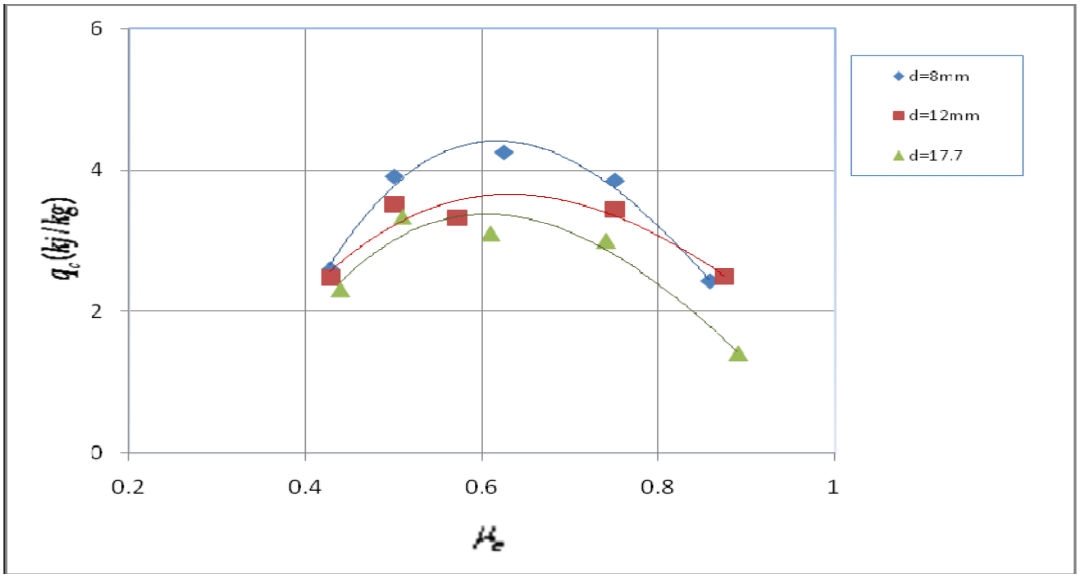

Figure 8. Effect of cold orifice diameter on cooling capacity

Figure 9 shows the effects of hot tube length on specific cooling capacity when d=8mm. The graph indicates that the orifice withL_h=769 mm produces maximum specific cooling capacity at $\mu_{c\approx}$.64 while the tube withL_h=519 mm creates about the same specific cooling capacity. On the other hand ,tube with L_h=250 mmhas the lowest q_c in this regard .

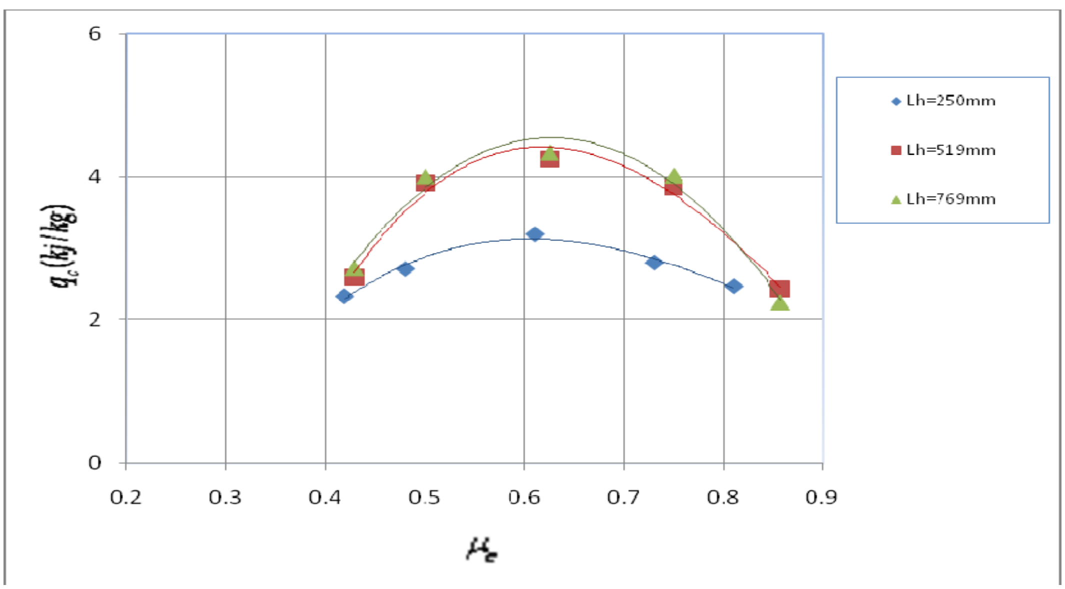

Figure 9. Effect of $L_h$on cooling capacity

6. CONCLUSIONS

An experimental study has been made to offer optimum values for cold orifice diameter to the VT inlet diameter (d / D) and the length of VT to its inlet diameter (L_h/D) for this experiment. The results show that temperature difference is maximized for aspecific orifice diameter .In this regard, d / D = 8 / 25 =.32 andL_h/D= 769 / 25 = 30.76 . As far as cooling capacity and hot temperature difference are concerned ,the study indicates that the aforementioned ratios are same for them .It means that for orifice d=8mm and hot tube length L_h=769mm we can reach the maximum proficiency of a vortex tube for the current study . As for $\mu_c$value , at $\mu_{c\approx}$ .6 we witness the maximum of cold temperature difference and cooling capacity , while for hot temperature difference $\mu_c$is about .7.

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REFERENCES

[1] Cockerill T., (1995)"The Ranque–Hilsch Vortex Tube", PhD thesis, Cambridge University,Engineering Department, Sunderland.
[2] Dincera K., Baskayab S., Uysalc B.Z., Ucguld I. (2009)"Experimental investigation of the performance of a Ranque–Hilsch vortex tube with regard to a plug located at the hot outlet",International journal of refrigeration 32, 87–94.
[3] Eiamsa-ard S., Promvonge P. (2008)"Review of Ranque–Hilsch effects in vortex tubes", Renewable and Sustainable Energy Reviews 12, 1822–1842.
[4] Hilsch R., (1947) "The use of expansion of gases in a centrifugal field as a cooling process", Rev Sci Instrum. 18, 2, 108–13.
[5] ISO-51671, "Measurement of fluid flow by means of pressure differential devices inserted in circular-cross section conduits running full" - Part1: General principles and requirements. & Part 2: Orifice Plates.
[6] Khodorkov L., Poshernev N.V., Zhidkov. M.A. (203) "The vortex tube—a universal device for heating, cooling, cleaning, and drying gases and separating gas mixtures", Chemical and Petroleum Engineering 39, 7-8, 409–415.
[7] Moffat R.J. (1985) Using Uncertainty Analysis in the Planning of an Experiment, J. Fluid. Eng.-T. ASME107, 173-178.
[8] Nikolaev V.V., Ovchinnikov V.P., Zhidkov M.A. (1995)Experience from the operation of a variable Vortex Tube in a gasseparating station, Gaz. Prom. 10, 13.
[9] Nimbalkar S.U., Muller M.R. (2009) An experimental investigationof the optimum geometry for the cold end orifice of a Vortex Tube,Appl. Therm. Eng. 29, 509-514.
[10] Orhan A., BakiMuzaffer (2006) An experimental study on thedesign parameters of a counter-flow Vortex Tube, Energy 31, 2763-2772.
[11] Poshernev N.V., Khodorkov I.L., "Natural-gas tests on a conical vortex tube (CVT) with external Cooling", Chemical and Petroleum Engineering 40, 3-4, 212–217.
[12] Ranque G.J. (1934) "Method and apparatus for obtaining from a fluid under pressure two outputs of fluid at different temperatures". US patent 1:952,281.
[13] Saidi M.H., Valipour M.S. (2003) "Experimental modeling of vortex tube refrigerator", Applied Thermal Engineering 23, 1971–1980, doi:10.1016/S1359-4311(03)00146-7.

[14] Stephan K., Lin S., Durst M., Huang F., Seher D. (1983) An investigation of energy separation in a Vortex Tube, Int. J. Heat MassTran. 26, 341-348

Nomenclature

c_p	heat capacity at constant presure
D	vortex tube inlet diameter
d	cold orifice diameter
h	specific enthalpy
L	vortex tube length
L_h	hot tube length
L_c	cold tube length
P	pressure
T	temperature
ΔT	temperature difference (K)
RHVT	Ranque-Hilsch Vortex Tube
VT	Vortex tube
δ	inlet nozzle diameter
Φ	conical controlling valve angle
$\dot{m}$	mass flow rate
$\mu_c = \frac{\dot{m}_c}{\dot{m}_i}$	cold mass fraction
$\dot{Q}_c = \dot{m}_c \Delta h_c$	cooling capacity
$\dot{q}_c$	specific cooling capacity (kj/kg)

Subscript

1	inlet gas condition of the pressure drop system
2	outlet gas condition of the pressure drop system
c	cold stream
h	hot stream
i	inlet stream