Experimental Study of The Energy Separation in Counter Flow Vortex Tube

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Abstract—The present paper investigates an experimental work to study the performance of manufactured counter flow vortex tube incorporated with set of generator nozzles of N = 2, 3, 6 and aspect ratio, AR = 1.4. The effects of inlet air pressure, hot tubes length to diameter and number of nozzles on the splitting air temperature are studied. The study includes evaluation of the COP for the cooling and heating processes. It is found that an optimum value of COPref = 0.24 as well as for COPHP = 0.3 are obtained. The findings encourage using the vortex tube in the applications of cooling and heating processes.

Keywords—vortex tube; cop; energy separtion; Ranque Hilck

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I. Introduction

The vortex tube is a simple device operating as a refrigeration machine without any moving part e.g. rotating shaft or piston cylinder [1]. It is consisted of nozzle, vortex hall, separating cold plate, hot valve, hot and cold end tube [2]. The vortex tube was first discovered by Ranque [3, 4],who was granted a French patent for the device in 1932 and a United States patent in 1934. In 1945, Rudolf Hilsch [5] was conducted an experiment on vortex tube that focused on the thermal performance with different geometrical parameters.

The vortex tube or RHVT can be classified into two types; first is counter flow RHVT and second type is uniflow RHVT [6]. In the counter-flow vortex tube type the cold flow move in the opposite direction with respect to the hot stream, while in the uni-flow type, the hot and cold stream flow in the same direction. In general, the counter flow RHVT was recommended more the uni-flow RHVT for its efficient energy separation. The RHVT is widely applied for cooling and heating applications. The major application is for cooling purpose, e.g. cooling of electric device, cooling of machinery during operation. In spite of its small capacity, the vortex tube is very useful for certain application because it is simple, compact, light, and require no refrigerant [7].
In the recent years it was known that vortex tube is a low cost and an effective solution for many spot cooling problems. The separation mechanism inside the vortex tube remains today not completely understood [8]. Up to date, more than hundred investigations on the energy separation in the RHVT for both numerical and experimental works have been published [9]. For numerical study, numerous investigators have conducted the energy separation in the RHVT by using turbulence modeling. Frohlingsdorf and Unger [10] used the computational code based on CFX along with k-ε model investigated the energy separation inside the vortex tube. Behera et al. [11] used the CFD cod (Star-CD) to investigate the temperature separation in vortex tube. In their study, the effect of the secondary circulation and length of the hot tube on energy separation were also calculated. Shamsoddini and Nezhad [12] were studied the effect of the nozzle number on the flow and power of cooling process of a vortex tube using a three dimensional numerical fluid flow dynamic model. Eiamsaard and Promvonge [13] studied numerically the energy separation in a uni-flow vortex tube using k-ε model. They concluded that the maximum temperature gradients appear in the outer regions close to the tube wall and the separation effect in the core region near the inlet nozzle. Farouk and Farouk [14] used large eddy simulation method to predict the flow and temperature field in the vortex tube. Farouk et al. [15] were computed the temperature and flow field of the species mass fraction in counter-flow vortex tube with nitrogen and helium as a working fluid. The artificial neural networks and employing the experimental data were used to predicate the effect of length to diameter ratio and nozzles number on performance of counter-flow RHVT by Dincer et al. [16].

In same time with the numerical works, many experimental investigations have been completed to study the performance of the vortex tube. Here, some of the experimental works on temperature separation in the vortex tube are explained as follows.

Salid and Valipour [17] investigated the influence of the RHVT diameter and hot tube length, number of nozzle on the cold temperature difference in a counter-flow vortex tube. They observed that the maximum cold air temperature difference was found at tube length to vortex diameter ratio ranged from 20 to 55.5, and cold orifice diameter ratio,β = 0.5, Dincer et al. [18] studied the effects of control valve geometry, plug location and number of nozzle on energy separation under different inlet pressure. Valipour and Niazi [19] investigated the effects of axial curvature and turning angle of main tube on the efficiency of vortex tube under different inlet pressure. Wu et al. [2] presented the effect of the conventional nozzle, proposed nozzle and nozzle of Archimedes on the energy separation of vortex tube. Their results observed that the enhanced nozzle provided a better cooling performance with temperature of cold gas of about 2.2 ˚C and 5 ˚C lower than those presented by the nozzle with a normal rectangle and the with Archimedes coil, respectively. The effect of generator vortex angle of rotating flow on the performance of the RHVT was studied by Xue and Arjomandi [20]. They showed that the maximum cooling efficiency was obtained between vortex generator angles of 4.8 and 6.7˚. Kirmacr [21] investigated the effects of the nozzle numbers and inlet pressures on the energy separation of vortex tube using air and oxygen as working fluids. It observed that the temperature rise between hot and cold fluid reduces with increasing nozzle number. In addition, the cold temperature reductions for using both two working fluids (air and oxygen) increase with the increase of the inlet pressure. The experimental work of Hamdan et al. [8, 22] reported the effect of nozzle parameters on the energy separation of the vortex tube. Their results indicated that the maximum energy separation was achieved with tangential nozzle orientation while the symmetry/asymmetry of nozzles has a minimal effect on the performance of the energy separation. Singh et al. [23] reported the effect of different parameters such as nozzle number, hot end area and mass fractions on the performance of RHVT. They showed that the effect of nozzle geometry was more important than the cold orifice design in getting high temperature separations. Gao et al. [24] used a special pitot tube and thermocouple techniques to measure the pressure, velocity and temperature distribution inside the vortex tube which the pitot tube has only a diameter of 1 mm with one hole. They observed that rounding off the entrance can be improved and extended the secondary circulation gas flow and enhanced the system performance. Aydin and Baki [7] studied experimentally the temperature separation in a counter-flow vortex tube with various geometrical and thermo-physic parameters. In their work the geometry of tube was optimized to maximum the temperature difference between the inlet and cold temperatures by change the various dimensions of the tube such as the diameter of the inlet nozzle and the angle of the control valve.

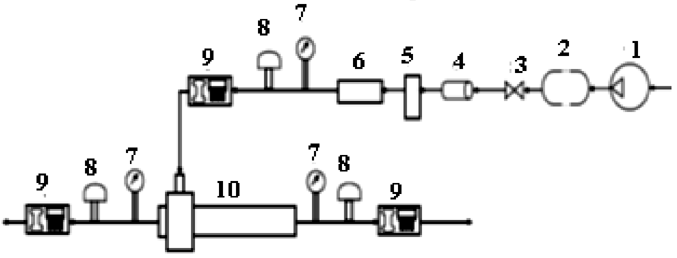
From the above cited literature clearly indicates that the energy separation and the efficiency of a vortex tube are significantly affected by the various geometrical parameters. In the present study, investigated and conducted to provide some new insight into the energy separation of the vortex tube under different operating parameters. Effect of number of nozzles , ratio of hot tube length to diameter, L/D and inlet air pressure on the splitting air temperature are studied. The COP in cooling and heating are evaluated and hence their effects on the splitting air temperature are also studied.

II. EXPERIMENTRAL WORK

A. Experimental set-up

The counter flow vortex tube (VT) and the arrangement of the experimental system are shown in Fig. 1. The experimental setup shows locations of vital instruments used for measuring pressures, temperatures and flow rates. Fig.2 shows the system of the fabricated VT. The compressed air is supplied from the compressor (2) through a pressure vessel (3) followed by a control valve (4) to control the pressure at the inlet to the vortex tube and the second control valve at the exit of the vortex tube. Filter separator (5) is followed the pressure vessel to separate the water droplet incoming from the pressure vessel. A pressure regulator valve with gauge (6) is placed before the vortex tube to maintain a constant input pressure. Two pressure transmitters (7) are placed at the inlet and exit of the vortex tube. The temperatures at the inlet and outlet of the vortex tube are measured with resistance temperature detector (8). The volume air flow is measured using air flow meter (9). All measured data are collected by Data acquisition incorporated with the VT system. In this study six different lengths of hot tubes L varied as 75mm, 97.5mm, 112.5 mm, 150mm, 187.5 mm , 225 mm , 7.5 mm have been used with inner diameter D equal to 7.5mm. Fig. 3 shows a photo of the VT system.

A stream –tek generators kit model GNMD-KIT were used and are incorporated into the fabricated VT system. The set of stream – tek generators have different aspect ratio ranged from 0.6 to 2.4. Fig. 4 shows a stream –tek generator of model GNMD-KIT of number of nozzles, N = 6. Three generator nozzles of N= 2,3, 6 are used in the experiments.



1. Electric motor **2. air compressor** **3. Pressure vessel**
4. Control valve **5. Filter separator** **6. Pressure regulator valve with gauge**
7.Pressure transmitter **8.Resistance transmitter** **9. Air flow meter (vortex type)** **10. Vortex tube**

Fig. 1 Schematic diagram of the VT system

Fig. 2. Fabricated Vortex Tube with different tube length

Fig. 3 Photo of the experimental set-up

N = 6

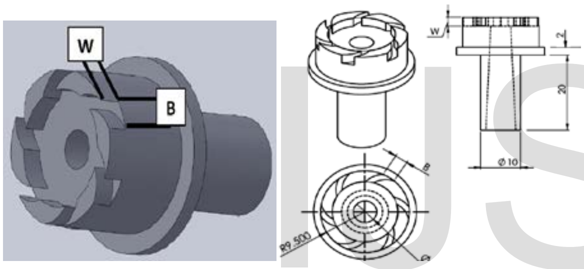


Fig. 4 stream –tek generator kit model GNMD-KIT

A. Procedure

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 being used to control the flow rate of the hot stream. This would help to regulate cold mass fraction. During the experiments, measurements are performed including pressure, temperature and flow rates at the inlet of vortex tube and the exit of hot tube.

B. Data reduction

- The splitting air temperature,($T_h - T_c$) represents an important parameter for the performance of the VT in the energy separation and expressed by :

$$\text{The splitting air temperature} = T_h - T_c \tag{1}$$

where T_h = hot air temperature (exit from hot tube side)K

T_c = cold air temperature (exit from cold tube side)K

Cold fraction, CF, represents the parameter which governs the temperature separation and is expressed by :

$$CF = \dot{m}_e / \dot{m}_i \tag{2}$$

Where $\dot{m}_e$ = mass flow rate of cold air, kg/s

$\dot{m}$ = mass flow rate of inlet air, kg/s

- The vortex tube can be used as a cooler or a heater . The performance of VT in cooling and heating processes is measured using the followings equations:

- In the case of VT for cooling process, VT is called refrigerator (ref) and COP for the refrigerator is defined as follow [8]:

$$COP_{\text{ref}} = \frac{\text{Cooling Load}}{\text{Isothermal Compression Energy}}$$

$$COP_{\text{ref}} = \frac{\dot{m}_c Cp(T_i - T_c)}{\dot{m} R T_i \ln(P_i / P_{atm})}$$

$$COP_{\text{ref}} = CF\left(\frac{Cp}{R}\right)\frac{(1 - T_c/T_i)}{\ln(P_i / P_{atm})} \tag{3}$$

In the case of VT for heating process, VT is called heat pump and COP for the heat pump (HP) is defined as follow:

$$COP_{\text{HP}} = \frac{\text{Heating Load}}{\text{Isothermal Compression Energy}}$$

$$COP_{\text{HP}} = \frac{\dot{m}_h Cp(T_h - T_i)}{\dot{m} R T_i \ln(P_i / P_{atm})}$$

$$COP_{\text{HP}} = (1 - CF)\left(\frac{Cp}{R}\right)\frac{(T_h/T_i - 1)}{\ln(P_i / P_{atm})} \tag{4}$$

Where : C_p = specific heat , kJ/kg K

P_i = inlet pressure , bar

P_{atm} = atmospheric pressure, 1 bar

$\dot{m}_c$ = cold mass flow rate , kg/s

$\dot{m}_h$ = hot mass flow rate , kg/s

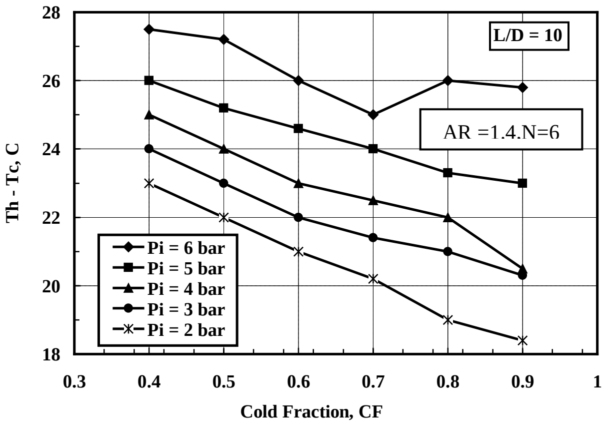
T_i = inlet air temperature , K

III. RESULTS AND DISCUSSION

The performance of the VT manufactured using set of generators of model GNMD-KIT is studied experimentally. These are included the effect of aspect ratio, number of nozzles and inlet pressure on the energy separation. The COP for both heating and cooling is evaluated.

A. Effect of L/D

Fig.5 shows the effect of L/D on the splitting air temperature at conditions of inlet air pressure varied from P_i = 2,3,4,5, 6 bar and aspect ratio AR = 1.4.In general, it is noted that the splitting air temperature increases with decrease of cold fraction and with increase of inlet air pressure as shown in Figs (5) a,b,c,d,e and f. The higher values for (T_h –T_c) are of inlet L/D = 30 as shown in Fig.5.f. An optimum value of the splitting air temperature equal to 37^{o}C is obtained at conditions of P_i = 6 bar, AR = 1.4 and L/D = 30.



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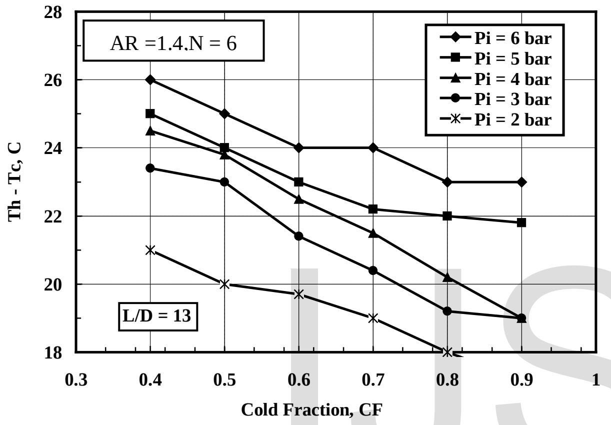

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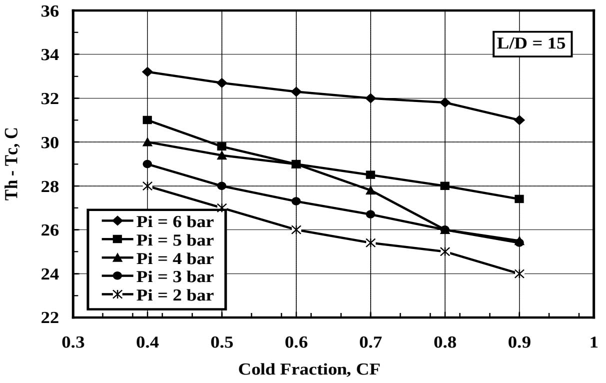

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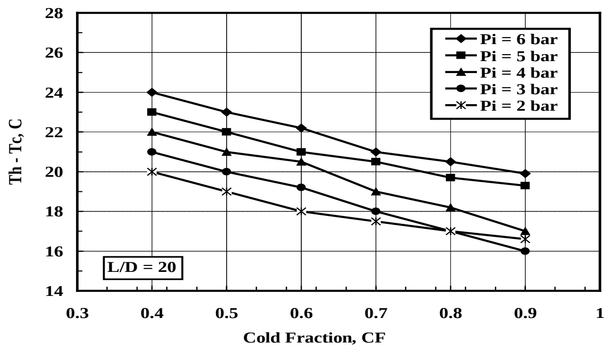

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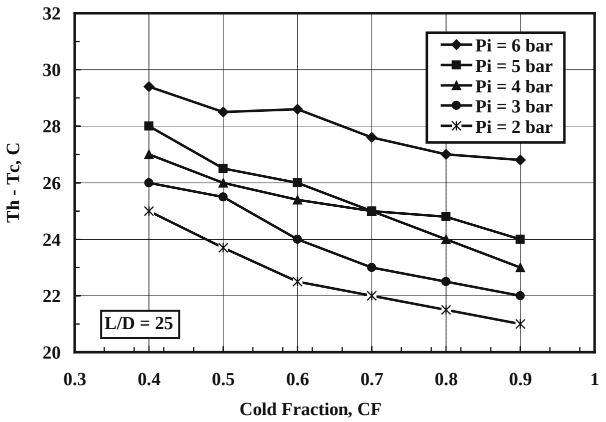

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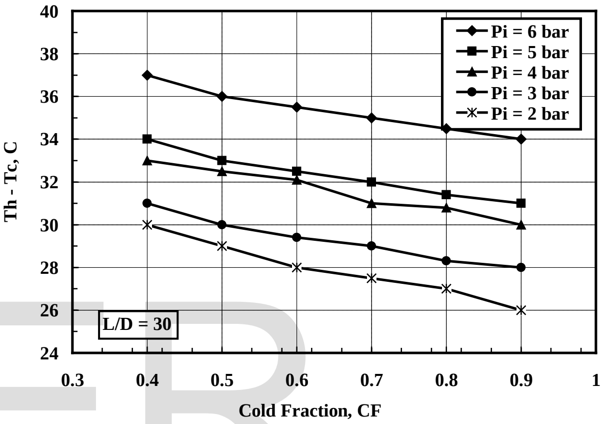
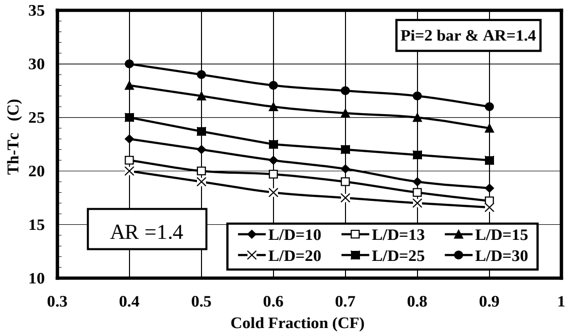


(f)

Fig. 5 Effect of L/D

B. Effect of inlet air pressure

Fig. 6 shows the effect of inlet air pressure on the splitting air temperature at conditions of L/D varied from 10, 13, 15, 20, 25,30 and AR = 1.4. In general, the results shows that the splitting air temperature increases with increase of L/D as shown in Figs (6) a,b,c,d and e. This result is compatible with Attalla et al. [25]. The highest value of splitting air temperature can be obtained at L/D = 30 as shown in Fig.6e.



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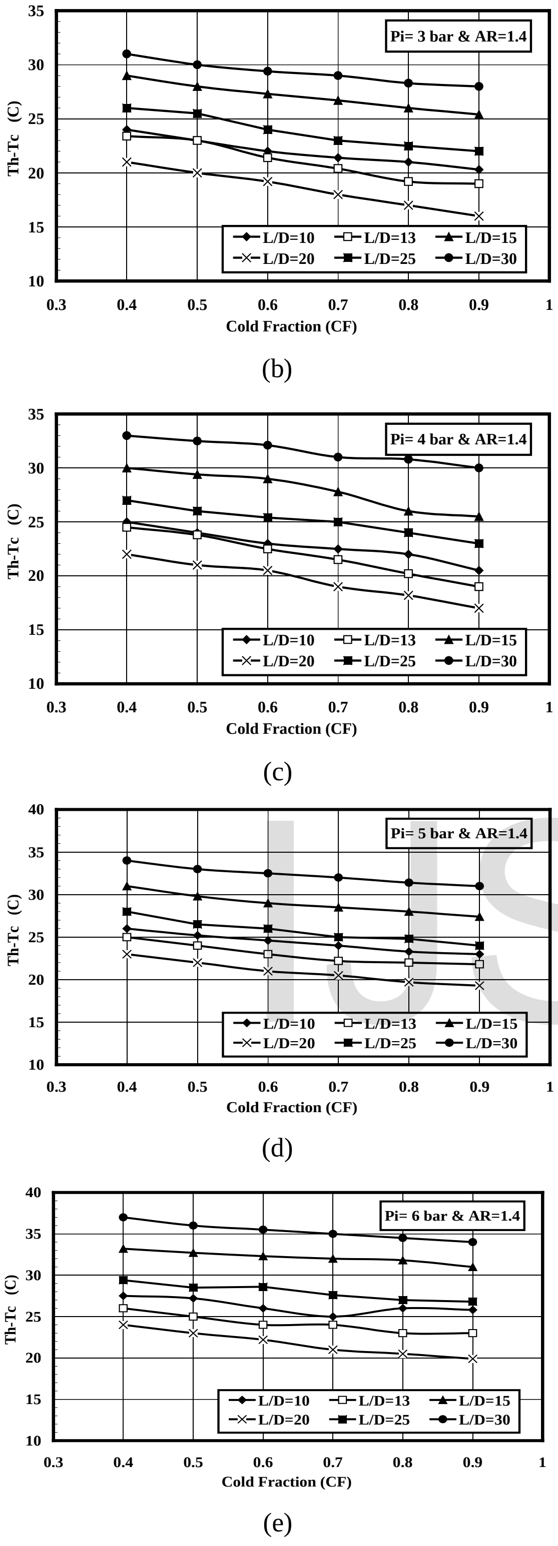

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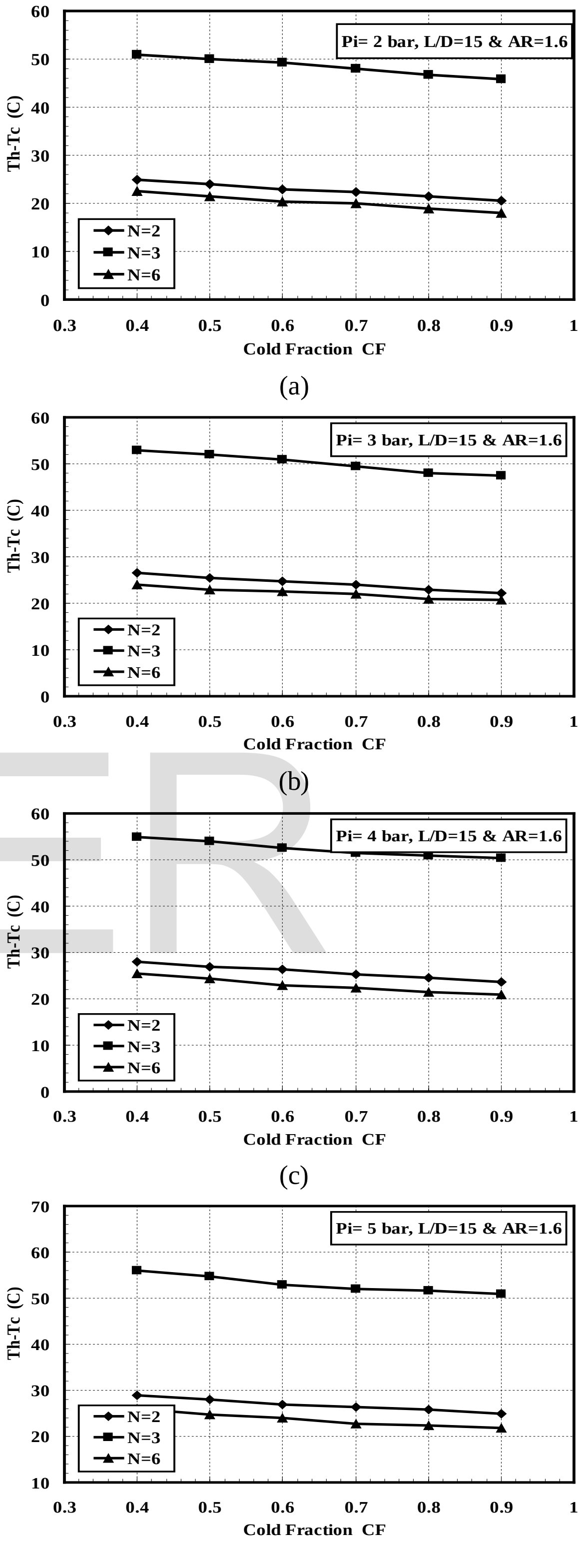
Fig. 6 Effect of inlet air pressure

C.Effect of nozzle

Fig. 7 shows the variation of cold fraction with the splitting air temperature (T_h –T_c) for different number of nozzles, N =2,3,6 , L/D = 15 and AR = 1.6. In general, the (T_h – T_c) increases with decrease of cold fraction. As shown in Fig.8, the higher values of (T_h – T_c), the higher values of nozzle number 3. The highest value of (T_h – T_c) equal to 56.5^{o}C is for nozzle number, N = 3 and P_i = 6 bar.



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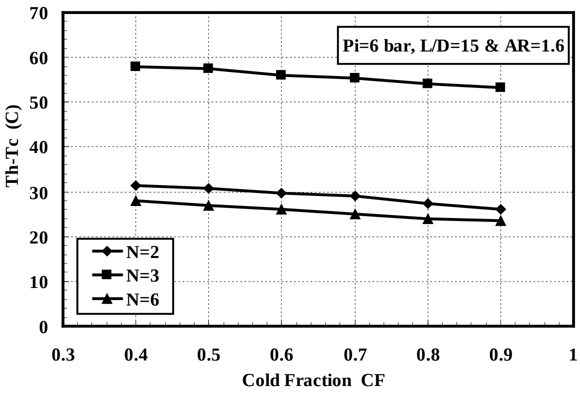

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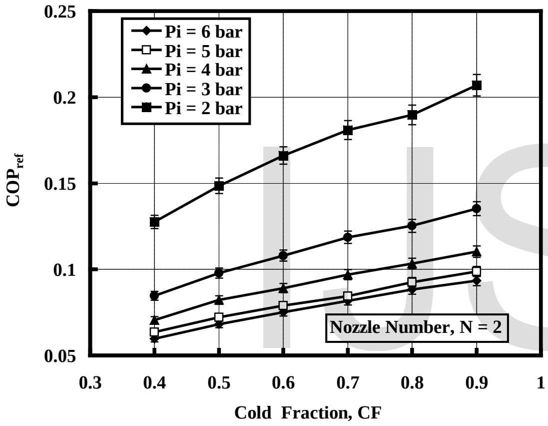
Fig. 7 Effect number of nozzles.

E. Variation of COP_{ref}

Fig.8 shows the variation of cold fraction with COP_{ref} at inlet pressure varied from Pi= 2bar to 6 bar, N =2,3,6 , AR = 1.6 and L/D= 15.



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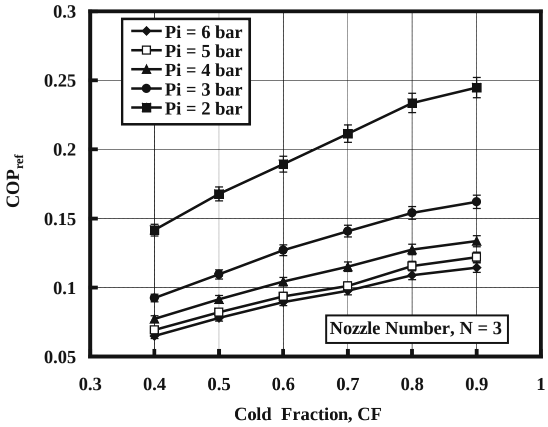

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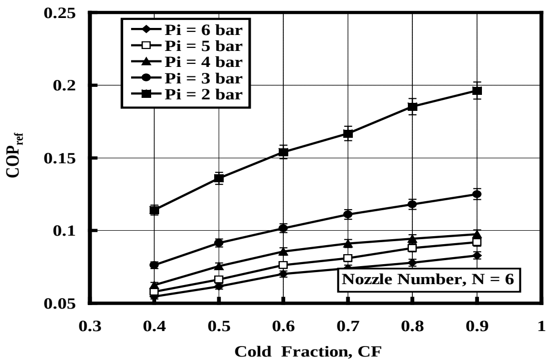

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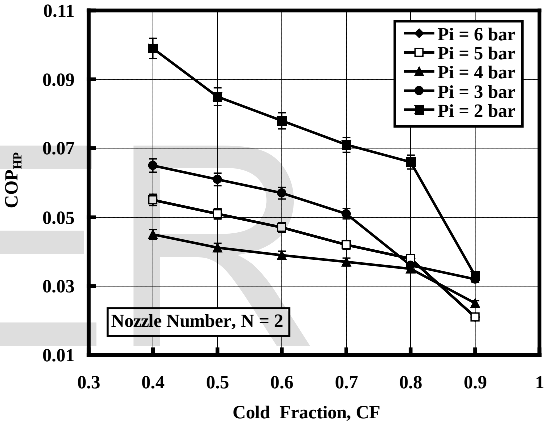
Fig. 8 Variation of cold mass fraction with the COP_{ref}

F. Variation of COP_{HP}

Fig.9 shows the variation of cold fraction with COP_{HP} at inlet pressure varied from P_i= 2bar to 6 bar, N =2,3,6 , AR = 1.6 and L/D= 15.



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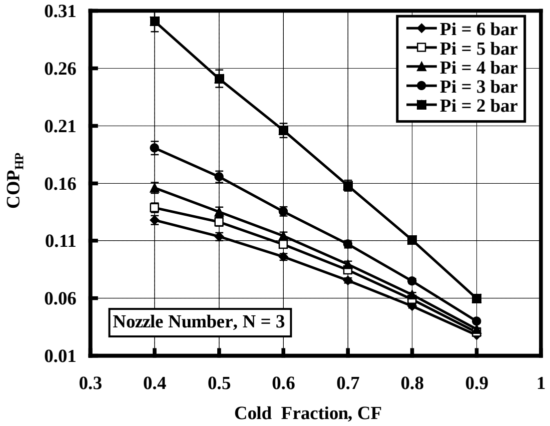

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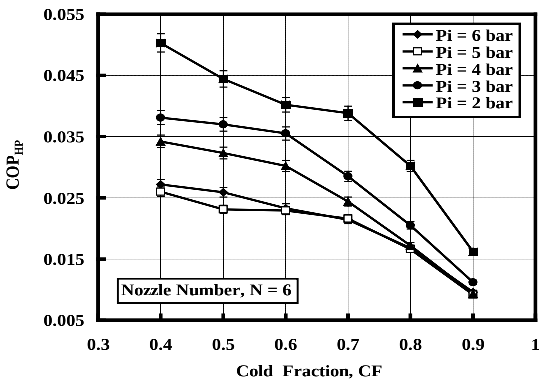

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Fig. 9 Variation of cold mass fraction with the COP_{HP}

IV. CONCLUSIONS

An experimental study is performed to test the performance of the manufactured vortex tube using different hot tubes of length 75,97.5,112.5,150,187.5 and 225 mm with inner diameter , D =7.5mm. A set of generators of model GNMD-KIT are incorporated to the fabricated vortex tube with number of nozzles, N = 2, 3 , 6 and aspect ratio, AR = 1.4,1.6. The main conclusions obtained from this study are as follows:

- An optimum value of the splitting air temperature = 37oC at Pi = 6 bar, L/D = 30 and AR = 1.4.
- An optimum value of the splitting air temperature = 58 at N = 3, Pi = 6 bar, L/D = 15 and AR = 1.6.
- An optimum value of te COP_{ref} = 0.30 at Pi = 2 bar, L/D = 15, N = 3 and AR = 1.6.
- An optimum value of the COP_{HP} = 0.24 at Pi = 2 bar, L/D = 15 , N = 3 and AR = 1.6.

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