IJRSET JULY 2017 Volume 4, Issue 7 Pages: 19-28
ISSN 2394-739X
International Journal for Research in Science Engineering and Technology

PERFORMANCE ANALYSISOF VORTEX TUBE REFRIGERATOR

[1] SK.Nayeem, [2] Dr. K. Dilip Kumar
[1, 2] Dept. of Mechanical Engg.,Lakireddy Bali Reddy College of Engg., Mylavaram, AP, India

ABSTRACT: A vortex tube is a Thermo-fluidic device, which generates cold and hot streams from a single injection of pressurized gas. Without any moving parts or chemical reaction within the tube, the interesting phenomenon of energy separation results only from fluid dynamic effects. The main part of a typical counter-flow vortex tube is a straight tube with a tangential injection, through which compressed gas is injected into the tube. There are two exits, located at different ends of a counter-flow vortex tube, or at the same end for a uni-flow vortex tube. A control plug is positioned inside the tube away from the injection point, which has a smaller dimension than the inner diameter of the tube, and this allows the gas to escape from the small gap between the control plug and the tube When the compressed gas is injected into the tube tangentially at a high velocity, two streams with different temperatures will be generated and exhausted from the two exits of the tube. In the present work Vortex tube generator is fabricated with the help of lathe machine, drilling machine and arc welding. Experiment is conducted with pressurized air as inlet from the air-compressor for three different tube lengths (54.61cm, 102.87cm, 119.38 cm) with inlet pressures of 50,100, 120 and 150 lb/in^2. Among three different tube lengths (54.61cm, 102. 87cm, 119. 38 cm) 54.61cm gives lowest temperature outlet(34^{0}c) and hot stream temperature as 38^{0}c with 36^{0}c atmospheric temperature.

1. INTRODUCTION

The phenomenon of generating two streams at different temperatures from a vortex tube with single injection was discovered by Ranque in 1930's, and hence was named as Ranque effect. Without any moving parts or chemical reaction within the tube, the phenomenon results only from the fluid dynamic effects. It is shown in Figure 1.1. that a typical counter-flow vortex tube contains a straight tube with tangential injection, through which compressed gas is injected into the tube, and two exits located at each end of the tube, which allows the streams at different temperatures to be 2 exhausted from the vortex tube. As shown, the tube is completely hollow and there are no other parts inside the tube; hence, the separation of the two streams at different temperatures inside the vortex tube must be based on some fluid dynamic or thermodynamic effects.

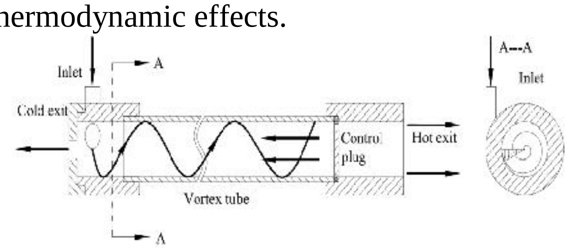

Figure- 1.1 Counter-FlowVortexTube

Lower and higher temperature were generated and exhausted from different ends of the tube. The cold stream was exhausted from the central exit near the inlet and the hot stream was exhausted from the peripheral exit at the other end of the tube. Ranque explained the separating effect in the vortex tube as one, which depended on expansion and compression. In 1947, the German physicist, Rudolf Hilsch, improved the performance of the tube. Due to the contributions of different researchers in developing an understanding of the knowledge of the vortex tube, the vortex tube has been referred to be the Ranque Vortex Tube for the thermal separation relates to the energy transferred from the inner flow to the outer flow. The angular velocity of the inner flow is believed to be higher than the flow in the peripheral region; hence the decrease in the angular momentum of the inner flow is transferred as kinetic energy to the outer vortex during the axial movement of the rotating flow. Then the temperature of the outer layer flow increases due to energy gain, and the temperature of the inner flow drops due to the loss of energy. However, none of these explanations covers all the aspects of the thermal separation in the vortex tube. Furthermore, many of the explanations and hypotheses are contradictory. Due to the complex structure of the internal flow, the reasons for generating hot and cold flows from a single injection into a vortex tube have not been identified and the flow behaviour inside the vortex tube, therefore, remains unclear.

Applications of Vortex Tube:

According to the working process described previously, the vortex tube has many advantages compared with other thermal devices, which has no moving parts, no electrical or chemical input, is small, lightweight, low in cost, maintenance free, and produces instant adjustable cold and hot air. These advantages make the vortex tube an attractive device in many applications, including cooling, heating, dehumidification and mixture separation. For example, fluid cooling is applied to remove the heat generated at the cutting zone during machining, especially, during the machining of very hard materials. The cold air, exhausted at high velocity from the vortex tube, provides both cooling and removal of the chips produced during machining. This completely eliminates or significantly reduces the need for liquid coolant, the latter being more complicated, expensive, and environmentally hazardous.

The vortex tube system has also been used to separate mixtures of gases. Peak oxygen purity of 80% at yields of up to 25% has been demonstrated from compressed air in a recent report, which indicates the potential application of the vortex tube in producing nitrogen and oxygen from a single injection of compressed air.

Williams proposed another potential application of the vortex tube system, i.e. producing ice. He stated that using a vortex tube, the objective of producing ice can be achieved with the additional benefits of producing water and heat, and increasing combustion efficiency and energy storage.

The vortex tube has also been used to dehumidify air or generate water from air. Liew reported that the concentration of liquid increases with increasing humidity of the injected gas.

Therefore, it is reasonable to conclude that when factors such as compactness, energy resources, reliability and equipment cost are to be considered, the RHVT becomes a feasible device for instant heating and cooling, thermal testing, dehumidification, gas liquefaction, ice production, separation of mixtures, DNA applications and other more general purposes. These significant advantages and wide applications have encouraged scientists and engineers to continue doing more research into the mechanism underlying the vortex tube.

The main limitations of using the vortex tube in industry are its low thermal efficiency, and noise. The maximum thermal efficiency of the vortex tube can reach to about 30%, which is lower than other thermal devices. As such, this lower efficiency leads to a narrower industrial application of the vortex tube. Kurosaka reported the acoustic streaming effect in the vortex tube, in which the noise generated by running the vortex tube reached around 125 dB. These drawbacks of the vortex tube may certainly limit its further application.

2. LITERATUREREVIEW

The vortex tube was first discovered by Ranque[1,2], a metallurgist and physicist who was granted a French patent for the device in 1932, and a United States patent in 1934. The initial reaction of the scientific and engineering communities to his invention was disbelief and apathy. Since the vortex tube was thermodynamically highly inefficient, it was abandoned for several years.

Interest in the device was revived by Hilsch[3], a German engineer, who reported an account of his own comprehensive experimental and theoreticalstudies aimed at improving the efficiency of the vortex tube. He systematically examined the effect of the inlet pressure and the geometrical parameters of the vortex tube on its performance and presented a possible explanation of the energy separation process.

After Hilsch[3], an experimental study was made by Scheper[4] who measured the velocity, pressure, and total and static temperature gradients in a Ranque–Hilsch vortex tube, using probes and visualization techniques. He concluded that the axial and radial velocity components were much smaller than the tangential velocity. His measurements indicated that the static temperature decreased in a radially outward direction. This result wascontrary to most other observations that were made later.

Hartnett and Eckert [5,6] measured the velocity, total temperature, and total and static pressure distributions inside a uni-flow vortex tube. They used the experimental values of static temperature and pressure to estimate the values of density and hence, the mass and energy flow at different cross sections in the tube. The results agreed fairly wellwith the overall mass and energy flow in the tube.

Blatt and Trusch[7] investigated experimentally the performance of a uni-flow vortex tube and improved its performance by adding a radial diffuser to the end of the shortened tube instead of a cone valve. The geometry of the tube was optimized to maximize the temperature difference between the cold and inlet temperatures by changing the various dimensions of the tube such as the gap of the diffuser, tube length, and entrance geometry. Moreover, the effects of inlet pressure and heat fluxes were examined.

Linderstrom-Lang [8] studied in detail the application of the vortex tube to gas separation, using different gas mixtures and tube geometry and found that the separation effect depended mainly on the ratio of cold and hot gas mass flow rates.

The measurements of Takahama[9] in a counter-flow vortex tube provided data for the design of a standard type vortex tube with a high efficiency of energy separation. He also gave empirical formulae for the profiles of the velocity and temperature of the air flowing through thevortex tube.

Bruun[10] presented the experimental data of pressure, velocity and temperature profilesin a counter-flow vortex tube with a ratio of 0.23 for the cold to total mass flow rate and concluded that radial and axial convective terms in the equations of motion and energy were equally important. Although no measurements of radial velocities were made, his calculation, based on the equation of continuity, showed an outward directed radial velocity near the inlet nozzle and an inward radial velocity in the rest of the tube. He reported that turbulent heat transport accounted for most of the energy separation.

Nash [11] used vortex expansion techniques for high temperature cryogenic cooling to apply toinfrared detector applications. A summary of the design parameters of the vortex cooler was reported by Nash [12].

3. GEOMETRY AND WORKING MEDIUM

Working medium:

Different working medium have been successfully applied in the vortex tube, including, compressed air, oxygen, methane, and other gas mixtures.

Due to the different temperature of the exhausted fluid from the exits, the vortex tube is found applicable for separating various gas mixtures. The first studies on the separation of mixtures with the RHVT were reported in 1967 by Linderstrom-Lang [28], and later by Marshall [29]. Different gas mixtures, including oxygen and nitrogen, carbon dioxide and helium, carbon dioxide and air, as well as other mixtures, have been used as the working medium inside the vortex tube.

The separation effect was found to be a function of both the cold flow ratio, and the geometrical parameters. The influence of different working mediums on the tube performance has been further investigated and reported, with the media including air, oxygen, nitrogen, and argon. The successful applications of the vortex tube in gas mixture separation, fluid concentration, and gas liquefaction, have also been reported. These successful applications show the diversity of gas, and gas mixtures, which can be used in the vortex tube.

Geometry of the tube

In the investigations on the vortex tube, the tube performance has been found to be sensitive to the geometrical parameters, including the size and shape of the control plug, the size and shape of the injection port, the diameter and length of the tube, the structure of the vortex chamber, the diameter of the cold and hot nozzles, among other factors. Many investigations on these geometrical parameters have been reported, with the aim of identifying the primary factors underlying the energy separation, and also with regard tooptimise the performance of the vortex tube system.

Studies on the effect of the tube geometry were started by Hilsch in 1947.

Based on his experimental results, the friction between the peripheral and internal gas layers was proposed as the reason for the temperature rise within the vortex tube, and these correlated with his experimental results obtained. Later, the influence of the geometry of the vortex tube system on its performance was optimized experimentally. It was found that the optimum operation of the vortex tube could be described by a relationship between the injection area, the tube length and diameter, the cold and hot exits characteristics, and the inlet pressure.

In a vortex tube, the mass flow rate of the injection and the formation of the vortex flow are generally dictated by the inlet nozzle.

Investigations on the injection port, which mainly concern the shape, size and number of the inlet nozzles, have been reported.

Considering the conventional tangential injection port, a new inlet nozzle with equal Mach number gradient and an intake flow passage with equal flow velocity was designed and tested in a modified vortex tube by Wu et al. . The experimental results indicated that the cooling effect of the improved nozzle was about 2.2 0 c lower than that of the normal rectangular nozzle, and 5 0 c lower than that of the nozzle with an Archimedes' spiral design.

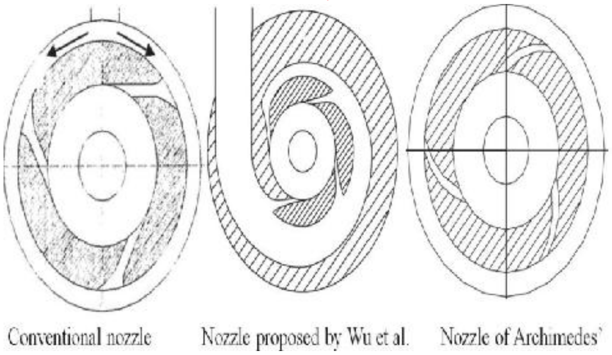

Figure- 3.1 Different type of nozzles

Eiamsa-ard reported an investigation of various geometrical parameters, including a different number of the snail entries, and reported that an increase in the nozzle number and the supply pressure led to a rise in the vortex intensity and thus the energy separation in the vortex tube. Similar observations have been reported in other publications.

The hot end control plug is an important component influencing both the cold and the hot mass flow rates. The influence of the control plug dimensions on the tube performance has been reported, and it was shown that the cold mass flow ratio is dictated by the control plug, and is a determining factor of the temperature of the respective exhausted streams [54]. Moreover, the shape of the control plug has been reported not to be a significant component in the performance of the RHVT due to the small differences observed with different plugs

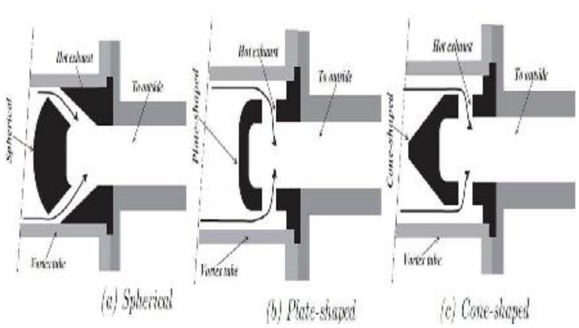

Figure-3.2.Investigationoftheeffectofthecontrolplug

A detwister is a form of vortex stopper, which can be used to block the vortex motion at the exhausts. The applications of the detwister in a vortex tube were reported by Dyskin, who reported positive effects on the tube performance. To improve the tube performance, a diffuser, which exhibits similar effects as the detwister in stopping the vortex motion, has also been placed in the vortex tube. It was reported that the application of a diffuser after the hot exit, improved the temperature rise at the hot end and decreased the temperature drop at the cold end.

4. FABRICATION OF VORTEX TUBE

Simple 2-D geometric diagram is shown in the below fig:3.1. Vortex tube mainly have 4 components 1) Simple circular tube,2) Vortex Generator,3) Cold outlet orifice,4) Control Plug.

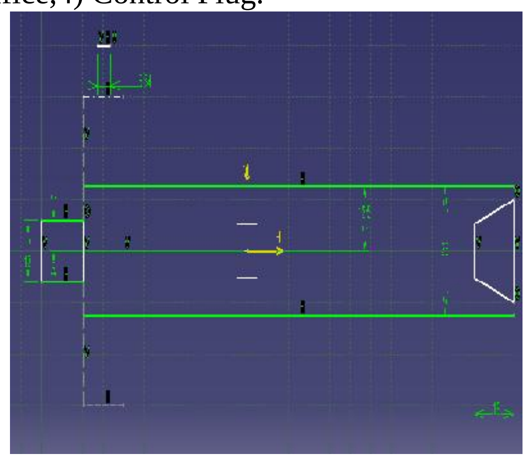

Figure- 4.1 2-D view of vortex tube refrigerator(all dimensions are in mm)

Galvanized iron pipe is chosen for simple circular tube of 25mm internal diameter of maximum length of 119.38cm. A stainless steel ring of 25mm internal diameter is fitted to the outer surface of simple circular tube, and 4holes of 6.35 mm diameter are created with the help of vertical drilling machine.

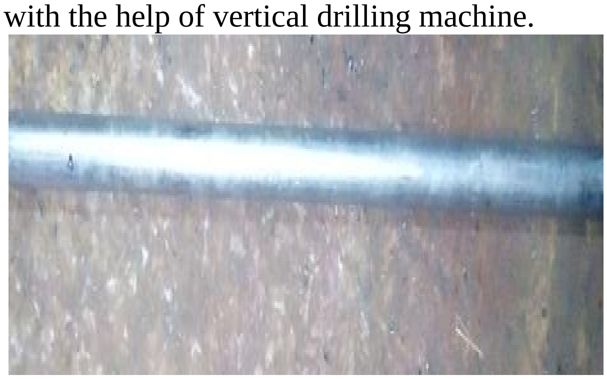

Figure- 4.2 Simple circular tube

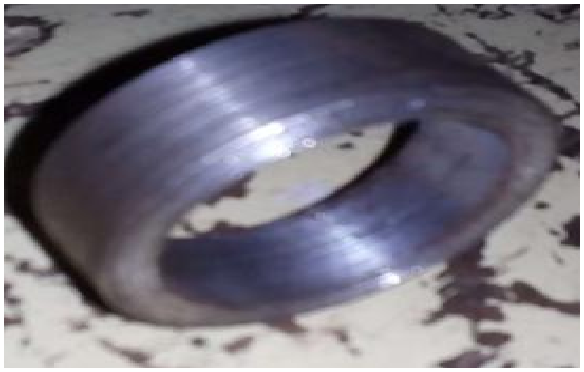

Figure- 4.3 Stainless steel ring

Figure- 4.4: Circular Tube with outer ring

Vortex generator is the major component for generation of vortex flow, it is made of mild steel with 25mm hole for fixing of simple circular tube and 50 mm hole for fixing of cold outlet orifice. It has tangential inlet of 19.05 mm hole on the surface. Vortex generator is shown in below figure 4.5.

Figure- 4.5 Vortex generator

Cold outlet orifice is internal hole 12 mm and has outer diameter of 49mm, it is made of mild steel material in the lathe machine.

Figure- 4.6 Cold nozzle outlet

Control plug is prepared with plastic material and nut. It controls the flow rate at the hot tube side.

Figure- 4.7 Control Plug for flow control

Temperatures are measured at different sections with the help of temperature indicator of range 0^0c to 1000^0c, Thermocouple wire of k-type, 12-pole switch as shown below figures.

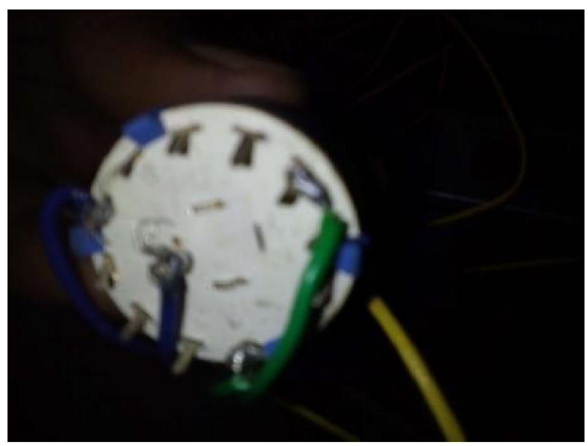

Figure-4.8 12-pole switch

Figure- 4.9 Thermocouple wire

Figure- 4.10 Temperature Indicator

shows complete assembly and connection of all the components and equipment.

Figure- 4.11 Vortex tube refrigerator

5. EXPERIMENTAL SETUP

Experiment is Conductedwith three different Tube Lengths with the help of air compressor: 54.61cm tube length, b) 102. 87cm tube length, c) 119.38 cm tube length

Figure- 5.1. 54.61cm tube length vortex tube refrigerator

Figure- 5.2.102.87cm tube length vortex tube refrigerator

Figure- 5.3.119.38 cm tube length vortex tube refrigerator

Specifications of Air-Compressor

Displacement = 700 CFM Speed = 530 rpm Type = 2-Stroke, 4-Stage air cooled compressor Maximum Pressure =250 psi

Figure- 5.4 Air Compressor

Figure- 5.5Complete setup of Vortex Tube Refrigeration system with compressor connection

6. RESULTS AND DISCUSSION

Temperatures of cold outlet orifice, hot tube outlet and at different lengths of tube are measured with input of 50,100,120 and 150 lb/in^2 inlet pressure. And Graphs are drawn at these pressure inlet for three different tube lengths mentioned in the above section.

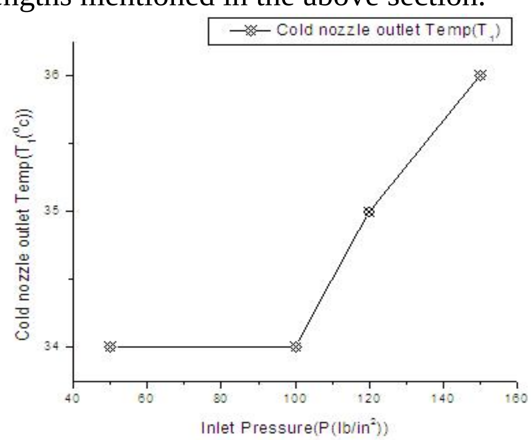

Figure- 6.1 Graph b/w inlet pressure vs cold nozzle outlet for tube length 119.38cm (35^{0}c of atmospheric temperature)

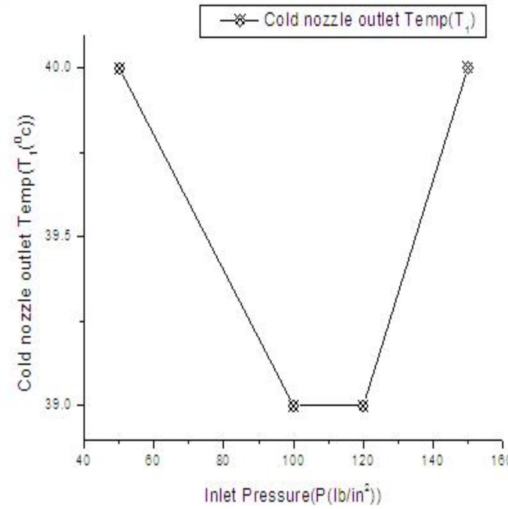

Figure: 6.2 Graph b/w inlet pressure vs cold nozzle outlet for tube length 102.87cm (40^{0}c of atmospheric temperature)

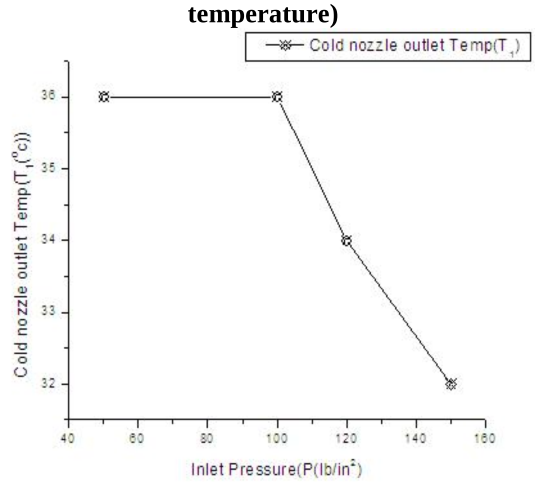

Figure- 6.3 Graph b/w inlet pressure vs cold nozzle outlet for tube length 54.61cm (36^{0}c of atmospheric temperature)

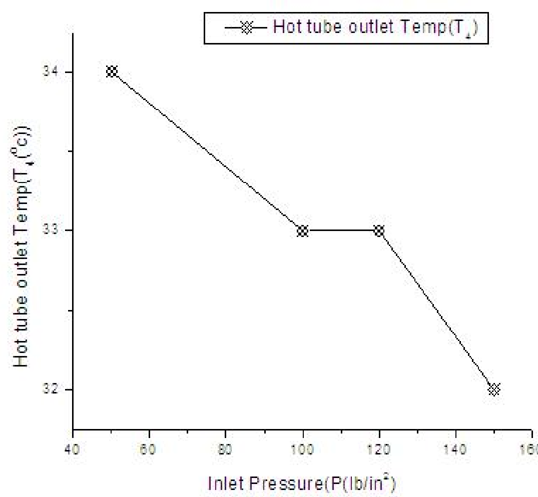

Figure- 6.4 Graph b/w inlet pressure vs hot tube outlet for tube length 119.38cm (35^{0}c of atmospheric temperature)

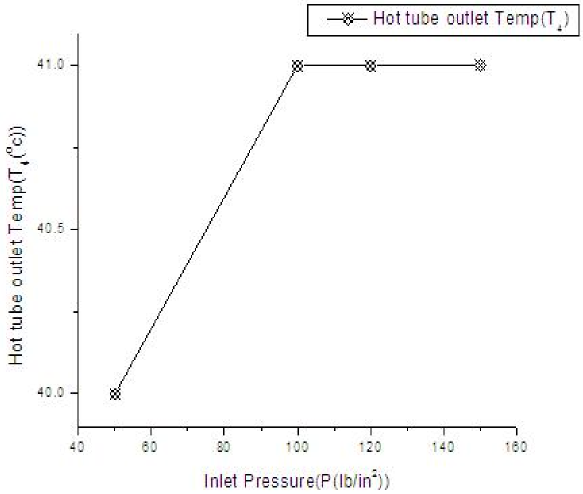

Figure- 6.5 Graph b/w inlet pressure vs hot tube outlet for tube length 102.87cm (40^{0}c of atmospheric temperature)

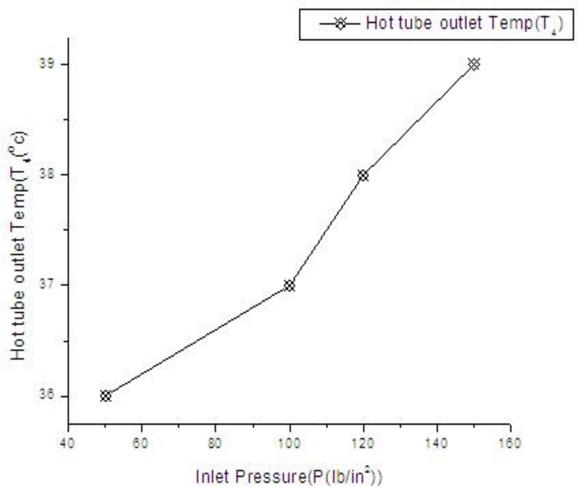

Figure- 6.6 Graph b/w inlet pressure vs hot tube outlet for tube length 54.61cm (36^{0}c of atmospheric temperature)

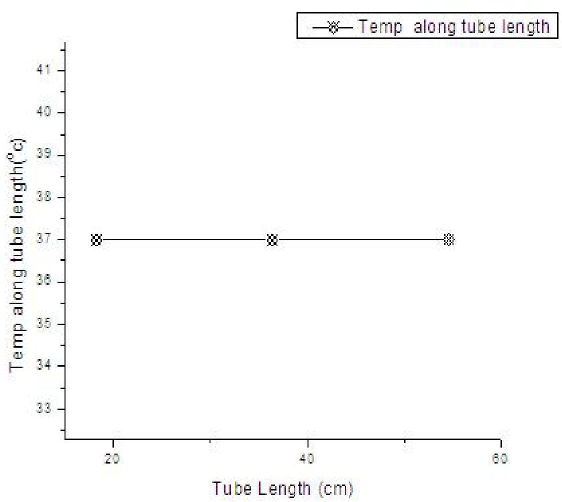

Figure- 6.7 Temperature along the tube length for 54.61 cm at 36^{o}c atmospheric temperature

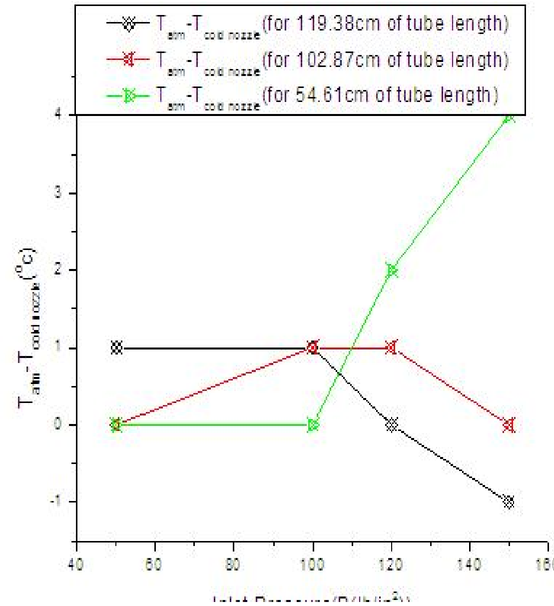

Figure- 6.8 Temperature difference of cold side to atmosphere for three different tube lengths

CONCLUSION

Vortex Tube Refrigerator is constructed and cold, hot outlet streams temp are noted with the help of Digital Temperature indicator. Among three different tube lengths (54.61cm,102.87cm,119.38 cm) 54.61cm gives lowest temperature outlet(34^{0}c) and hot stream temperature as 38^{0}c with 36^{0}c atmospheric temperature.

Also observed that with increasing the length of the tube (for the case of 119.38 cm tube length) hot and cold side exits reversed.

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[1] **S.K. Nayeem** is currently pursuing M.Tech in Thermal engineering at Lakireddybalireddy college of Engineering, Mylavaram. HerecivedB.Tech degree in Mechanical Engineering from Rajiv Ghandi University of Knowledge Technology in the year 2014. E-mail address: saju2927@gmail.com.

[2] **Dr.K.Dilip Kumar** working as *Associate Professor* in Lakki Reddy Bali reddy college of Engineering, Mylavram.HeReceivedPhD from JNTUA.HeReceivedM.tech from JNTUA and Received MBA from Andhra University.HeReceivedB.tech degree from JNTUH. He attended 8 workshops and published 15 international journals.E-mail address: **dilip_011@yahoo.co.in**