

Studies on the Effect of Feed Gas Temperature on Ranque-Hilsch Vortex Tube

Rajarshi Kar, Oindrila Gupta, Mukunda Kumar Das

*Department of Chemical Engineering, Heritage Institute of Technology, Kolkata

Abstract- A very interesting phenomenon was observed by G.J. Ranque (1931) and R. Hilsch (1945) when a compressed gas is introduced tangentially into a tube. The tube is fitted with a central aperture orifice at one end (this end of the tube being very close to the tangential entry nozzle) and a throttle valve at the other end (this end being a little far off from the entry nozzle). The shape and size of the nozzle is such that the gas attains maximum velocity of emission as it enters into the tube. In the process of movement of the gas inside the tube towards the throttle end, there develops in the spiraling gas a region of high pressure in the peripheral layers and a region of low pressure in the axis of rotation. Thus a hot stream of gas comes out through the throttle end and a cold stream through the orifice. By manipulating the throttle valve, the amount of gas and also the extent of heating and cooling can be controlled. This very simple device with practically no moving parts is sometimes referred to as Ranque tube, Ranque-Hilsch Vortex Tube (RHVT) or Ranque-Hilsch energy separator.

The RHVT has been used for many decades in various engineering applications. Because of its compact design and little maintenance requirements, it is very popular in heating and cooling processes. Despite its simple geometry, the mechanism that produces the temperature separation inside the tube is fairly complicated. A number of observations and theories have been explored by different investigators concerning this phenomenon. This report goes over some of the major conclusions found from experimental and numerical studies since the vortex tube's invention. One of these studies demonstrated that acoustic streaming caused by vortex whistle plays a large part in the Ranque-Hilsch effect. In addition, thermal and kinetic energy considerations have been used to explain temperature separation. Another study showed that a centrifugal field is generated inside the tube. This field may be utilized in the separation of the gas mixture according to their molecular weights. It is expected that components with higher molecular weights will be concentrated at the periphery of the vortex while those with lower molecular weights at the axis. Therefore it is expected that the stream coming out of the throttle valve will be richer in high molecular weight components and the other stream coming out through the orifice will be richer in low molecular weight components. Thus together with energy separation, there may be separation of mass. So besides being a heat pump, the vortex tube is expected to serve as a diffusion battery. There have also been plenty of numerical analyses that confirm earlier experiments. One fact still remains, however. There is no unifying theory that explains the temperature separation phenomenon inside the vortex tube.

Index Terms- Ranque Hilsch effect, throttle valve, Vortex tube

Nomenclature:

C_p : Specific heat capacity at constant pressure (psig)
 C_c : Cooling capacity (J)
 D : Tube diameter (in)
 H : Standard thermodynamic variable representing enthalpy ($S\text{ kg}^{-1}$)
 ΔH : State variable representing changes in enthalpy ($J\text{ kg}^{-1}$)
 K : Kinetic energy (J)
 m_{in} : Mass flow rate of inlet stream ($g\text{ min}^{-1}$)
 m_h : Mass flow rate of hot outlet stream ($g\text{ min}^{-1}$)
 m_c : Mass flow rate of cold outlet stream ($g\text{ min}^{-1}$)
 P : Pressure of the compressed air in pressure regulator (psig)
 P_a : Atmospheric pressure (mm Hg)
 P_c : Cold outlet stream pressure (mm Hg)
 P_h : Hot outlet stream pressure (mm Hg)
 P_{in} : inlet stream pressure (mm Hg)
 Q : Standard thermodynamic variable representing heat added
 Q_c : Volumetric flow rate of the compressed air at the cold outlet
 R : Ideal gas law constant
 R_{max} : Radius of the tube from tube axis to the tube wall (in)
 S : Entropy ($J\text{ kg}^{-1}\text{ K}$)
 S_{gen} : Entropy generated by the system ($J\text{ kg}^{-1}\text{ K}$)
 ΔS_{total} : Total change in entropy of the system ($J\text{ kg}^{-1}\text{ K}$)
 ΔS_c : Entropy change in the cold stream ($J\text{ kg}^{-1}\text{ K}$)
 T_{ref} : Reference temperature ($^{\circ}\text{C}$)
 T_1, T_{in} ($^{\circ}\text{C}$): Temperature of compressed air after passing through regulator
 T_2, T_h : Temperature of hot outlet stream ($^{\circ}\text{C}$)
 T_3, T_c : Temperature of cold outlet stream ($^{\circ}\text{C}$)
 T_4 : Temperature of the air prior to entering the pressure regulator
 T_5 : Unused temperature meter variable ($^{\circ}\text{C}$)
 $T_6, T_{1/2h}$: Temperature of compressed air halfway down the vortex tube
 U : Internal energy (J)
 V_1 : Volumetric flow rate of the compressed air at the inlet (SLPM)
 V_2 : Volumetric flow rate of the compressed air at the (SLPM)
 W : Work done on a system (J)
 Z : Height of the tube's axis
 Θ : Tube's radial axis
 μ : Fraction of the cold air mass flow rate / total air mass flow rate

Plan of Present Work:

Object: The purpose of the present work is to study the effect of cold fraction at the same temperature on Ranque-Hilsch Vortex Effect.

Plan: It is planned that the cold fraction of the outlet gas will be raised or lowered. For this purpose, the compressed gas

free from oil, water & moisture will be passed through a hot tubular furnace having adequate temperature and pressure controller. Thus we will take a certain number of runs under different cold fractions (μ) and verify our results each time. For different values, we get different temperature differences of our outlets and this will be verified each time.

I. INTRODUCTION

The vortex tube is a mechanical device that separates compressed air into an outward radial high temperature region and an inner lower one. It operates as a refrigerating machine with a simplistic geometry and no moving parts. It is used commercially in CNC machines, cooling suits, refrigerators, airplanes, etc. Other practical applications include cooling of laboratory equipment, quick start up of steam power generators, natural gas liquefaction, and particle separation in the waste gas industry. It contains the following parts: one or more inlet nozzles, a vortex chamber, a cold-end orifice, a hot-end control valve and a tube. When high-pressure gas (6 bars) is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls to the center of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part exist via the cold exhaust directly. Part of the gas in the vortex tube reverses for axial component of the velocity and move from the hot end to the cold end. At the hot exhaust, the gas escapes with a higher temperature, while at the cold exhaust, the gas has a lower temperature compared to the inlet temperature.

A RHVT has the following advantages compared to the normal commercial refrigeration device: simple, no moving parts, no electricity or chemicals, small and lightweight, low cost, maintenance free, instant cold air, durable (because of the stainless steel and clean working media), adjustable temperature. But, its low thermal efficiency is a main limiting factor for its application. Also the noise and availability of compressed gas may limit its application. Therefore, when compactness, reliability and lower equipment cost are the main factors and the operating efficiency becomes less important, the RHVT becomes a nice device for heating gas, cooling gas, cleaning gas, drying gas, and separating gas mixtures, DNA application, liquefying natural gas and other purposes.

The underlying physical mechanism processes that determine the cooling of gas in this device have not been resolved completely in the past. The research on vortex tube generally concerns the following aspects: the compressible fluid dynamics of turbulent and unsteady flow; thermodynamics; and heat transfer. These aspects make the research complicated and challenging. The interest in this research dates back to the work by Westley who states that, "Besides its possible importance as a practical device, the vortex tube presented a new and intriguing phenomenon in fluid dynamics".

II. THEORY

The vortex tube is a mechanical device that separates compressed air into an outward radial high temperature region

and an inner lower one. It contains the following parts: one or more inlet nozzles, a vortex chamber, a cold-end orifice, a hot-end control valve and a tube. When high-pressure gas (6 bars) is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls to the center of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part exist via the cold exhaust directly. Part of the gas in the vortex tube reverses for axial component of the velocity and move from the hot end to the cold end. At the hot exhaust, the gas escapes with a higher temperature, while at the cold exhaust, the gas has a lower temperature compared to the inlet. It operates as a refrigerating machine with a simplistic geometry and no moving parts. It is used commercially in CNC machines, cooling suits, refrigerators, airplanes, etc. Other practical applications include cooling of laboratory equipment, quick start up of steam power generators, natural gas liquefaction, and particle separation in the waste gas industry.

Since the 1930s, the mechanism of the energy separation inside the RHVT system has puzzled researchers. Even now, there is no clear theory that can explain the phenomenon completely. The chamber influence is considered and the compressible flow analysis (gas dynamics) is applied in the analysis of the inlet nozzle. The comparison between the two models shows that MAM agrees better with the measurement than OSCM. At the end, the thermal efficiencies are defined, analyzed, and derived as functions of the inlet and exhaust gas properties.

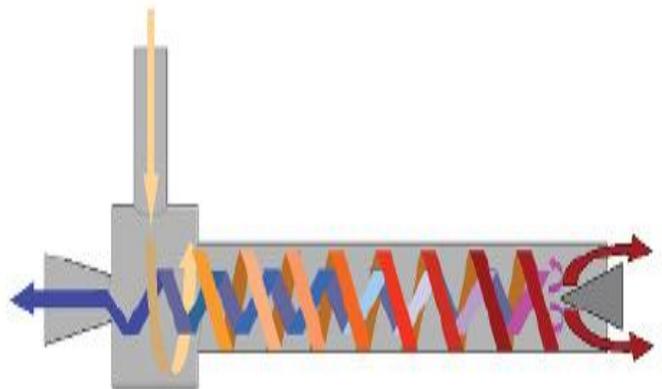
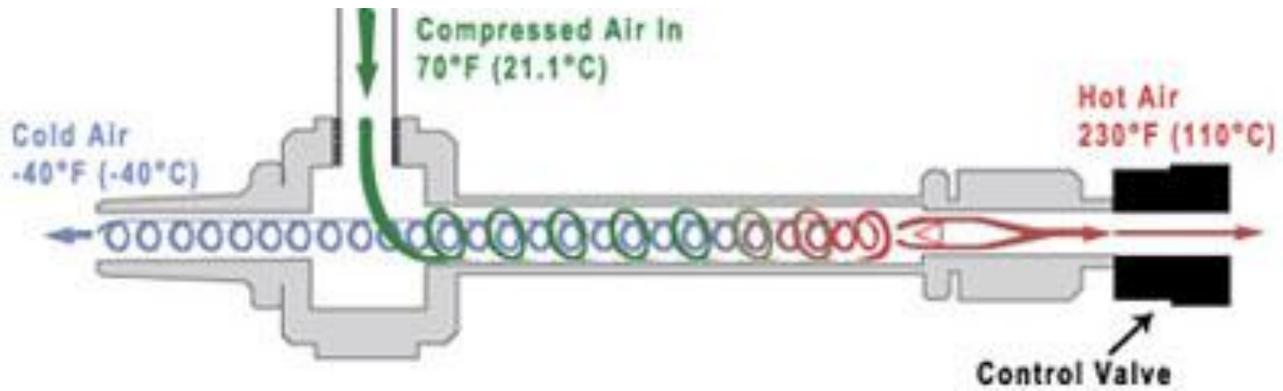
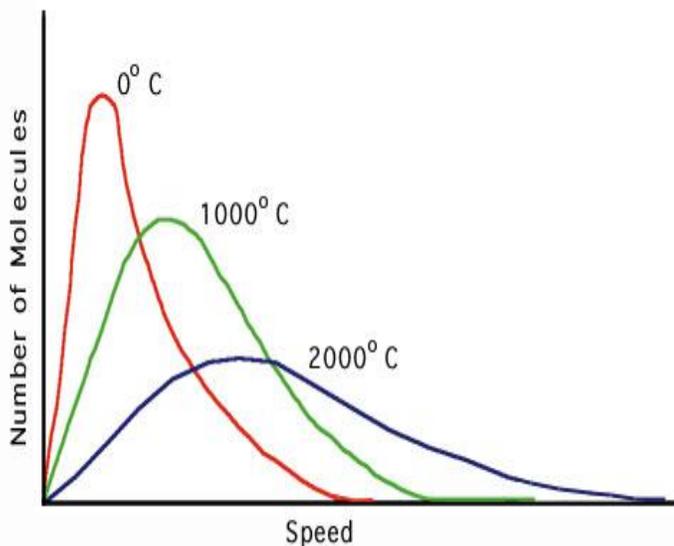


Figure 1: Vortex tube schematic



In the middle section of the tube is the inlet for the compressed air. Note that the inlet is much closer to the cold outlet than the hot outlet. There is a very important aspect of the tube related to this feature which will be discussed shortly. From the above figure, one can see the middle part which says spiral chamber in this part. The spiral chamber is the essential component of the tube because it is the source of hot and cold separation of the gas. How it works is based primarily on the Physics of rotational motion and on Maxwell's law of random distribution. Maxwell's law states the basis of kinetic theory of gases which in turn helps explain the fundamental properties of gases such as diffusion and pressure. Usually the law refers to velocity but can also be applied to molecular momentum. In this particular case, we are focusing on velocities of all the molecules in the spiral chamber. From the law, scientists can create what are known as Maxwell-Boltzmann distribution functions which have importance in physics and chemistry.



An example of such a distribution function is shown above. In this figure, we see three different graphs showing velocity distributions under three different temperature conditions.

The physical mechanism inside an operating vortex tube can be observed physically, but difficult to explain. Compressed air is sent through the inlet nozzle. Swirl generators at the inlet

plane create the vortex motion inside the tube. As the vortex moves along the tube, a temperature separation is formed. Hot air moves along the tube periphery, and cold air is in motion in the inner core. The hot air is then allowed to exit through the cone valve at the far end of the tube, while the cold air outlet is next to the inlet plane. This resulting radial temperature separation inside the vortex tube is also called the Ranque-Hilsch effect, named after its pioneers.

III. TYPES OF VORTEX TUBES

There are two classifications of the vortex tube. Both of these are currently in use in the industry. The more popular is the counter-flow vortex tube. The hot air that exits from the far side of the tube is controlled by the cone valve. The cold air exits through an orifice next to the inlet. Counter-flow vortex tube. On the other hand, the uniflow vortex tube does not have its cold air orifice next to the inlet. Instead, the cold air comes out through a concentrically located annular exit in the cold valve. This type of vortex tube is used in applications where space and equipment cost are of high importance. The mechanism for the uniflow tube is similar to the counter-flow tube. A radial temperature separation is still induced inside, but the efficiency of the uniflow tube is generally less than that of the counter-flow tube.

For this tube, the distribution profile is much different because of the shape of the spiral tube itself. What is known though is that as compressed air enters into spiral chamber, it immediately desires to diffuse based on this diffusion function. The velocity of all molecules will have both a Z-component and a θ component, where Z is the direction along the tube axis and θ is the angular direction above the axis itself. The majority of molecules will diffuse in such a way to create a gas vortex within the tube which expands as the molecules diffuse down the tube. We know that molecules spiraling down the tube far from the tubes Z-axis will have a higher velocity. In other words, the molecules rotating about the tube axis are moving faster as they travel down the tube.

The first law of thermodynamics states that the increase of internal energy of a thermodynamic system is equal to the amount of heat energy added to the system minus the work done on the system by its surroundings. Mathematically, the law is -

$$U = Q - W$$

(Eq 1)

Or written in differential form,

$$dU = dQ - dW$$

.....
 (Eq 2)

In the equations, U refers to the internal energy of the system, Q refers to the heat of the system and W refers to the work done on the system by its surroundings. Applying Eq 1 to the Vortex tube, the thermodynamic law reduces to Eq 3 below -

$$dU = dQ$$

.....
 (Eq 3)

since no work is done on the system. This means that any change in internal energy is related to the change in heat of the system.

One can now understand why the cold outlet valve is much closer to the inlet than the hot outlet valve. As the molecules travel down the tube, they begin slowing down in both Z and θ direction. This slowing is a reduction in the axial convection of the Vortex as it moves down the tube. In other words, the molecule diffusion rate slows down as the gas fills more space and relieves pressure causing a slower propagation of the molecules down the line. As this happens, less kinetic energy is used and converted back to internal energy which in turn increases the temperature of the gas. Since the original radial pressure gradient caused a flow of kinetic energy towards the outer molecules, they have more kinetic energy to convert back to internal energy and hence have higher temperature. This is known as viscous dissipation of kinetic energy.

The reason the cold outlet is closer to the inlet is due to the desire to reduce the effects of viscous dissipation of kinetic energy. The outlet must be close to the inlet because the further away it gets, the more viscous dissipation will occur and hence higher the gas temperature will be. The reason the cold outlet is not directly next to the inlet is to give the system pace to utilize the radial pressure gradient and to transfer kinetic energy to the molecules at the tube wall. The outlet then is logically positioned to remove gas from the center of the tube.

The hot outlet is positioned further from the inlet than the cold outlet is for similar reasons. Instead of getting the air out quickly to keep it cool, the scientist lets it travel farther down the tube warming up by prolonged viscous dissipation of kinetic energy. As the gas travels down the tube, axial convection also decreases, reducing the gradient of temperature of pressure down the tube, to make a more unified stream. By the time the stream reaches the outlet, nearly all of it has the same temperature and has a higher temperature than the inlet due to the increased kinetic energy it had initially. The outlet is drawn from the tube walls to obtain the molecules with maximum high temperature.

IV. MECHANISM OF RANQUE EFFECT

Ranque himself explained the effect in the following manner. According to him, the rotating air stream (in a screw like motion) produces a region of increased pressure near the wall inside the cylinder by adiabatic compression and region of

decreased pressure near the axis. Hence the temperature is increased near the wall and decreased near the axis. Therefore, according to Ranque the diaphragm end which permits the escape of air only from the central region and thereby emits the old stream, the throttle valve however emits the hot stream.

The experimental fact of such separation is also known for fluid in nominal Ranque tubes. Flow heat separation was numerically simulated on the example of laminar self-similar whirled flows in expanding cone-like channels, channels had an injection vector oriented along the porous wall. The mechanism of the process, which has a kinematic basis, is brought to light. The kinematic factor that is exhibited by intense flow swirl conditions stipulates higher inner supply of viscous dissipation heat of fluid kinetic energy compared to its absence (by means of an increased radial speed gradient near the wall in its essence). The implemented mathematical model allowed reconstructing qualitatively the non-monotonic character of excess temperature ($t - t_w$) alteration in the cross section of the channel with cooled walls and heat outflow of the channel, and also its negative values near the real Ranque tube axis. The realized ($t - t_w$) values are conditioned by the recurrent character of transition lines (via convection and thermal conductivity) of heat in the meridional section of the cone channel, those lines coincide at a specific point $r = 0$ from where they start. The results of the self-similar heat task solution also prove the non-monotonic profile of excess temperature and recurrence of transition lines in the case of flat cone-type fluid flow (Hamel flow in flat extending channels). The specific case of stagnation temperature stratification along the channel section in a cone-like whirled flow of viscous gas is discussed.

The final formula of Fluton may be given by the maximum temperature difference that can be obtained at the cold end.

$$(\Delta t_x)_{max} = (1 - 1/2 P_R^*) \cdot \Delta t_x$$

Where Δt_x = Ideal adiabatic temperature difference
 P_R^* = Turbulent analogue of Prandtl criterion

V. DESCRIPTION OF THE APPARATUS

Flow Sheet: Passing it through two cyclone separators, one after the other in series first of all dries the compressed air from the compressor. The drying agent is Silica gel. An auxiliary line provides hot air from the tubular furnace to the driers for regenerating the drying agent. The air stream then passes through the thermostat so that its temperature is more or less constant as it enters the Vortex chamber. The furnace has sufficient heat transfer area for raising the temperature of inlet air. The hot and dry stream at constant temperatures flows into the nozzle of the Vortex tube. A pressure gauge is fitted just before the entrance nozzle of the tube to measure the pressure of the inlet air. The temperature of this air is also noted by means of a thermocouple. Depending on the temperature to be measured, Cu-Constantan was used for lower ranges and Chromel-Alumel for higher ranges. The hot end of the Vortex tube is connected to an orifice meter through a globe valve. After the valve, there is an arrangement for inserting a thermocouple to measure the

temperature of hot air. The cold end stream goes to another orifice meter, its temperature being measured by another thermocouple as required. The tube from the vortex chamber towards the hot and cold end is insulated with thick layers of glass wool and asbestos rope.

VI. SPECIFICATIONS OF THE APPARATUS

The air compressor used for this experiment is a three stage compressor of model 15T2 manufactured by M/S Ingersoll Rand Ltd. There is a maximum capacity of 30 cfm and 600 psig pressure. The construction and the tangential introduction of the gas into the tube is of crucial problem in the experiment. A complete design of the Teflon block containing the nozzle channel, the orifice plate and the drilled hole for Vortex tube as shown in the fig below.

A convergent divergent channel of rectangular cross section (2mm width and 4mm depth) is engraved in the teflon block. A metallic tube (stainless steel) of desired length (50D = 62.5 cm) and diameter (D = 12.5 mm) is threaded into the block and I.D of the hole in the block and the I.D. of the tube are made the same so that the combination will serve as one tube. This is therefore the hot end which is closed by a globe valve. A globe valve may also be replaced by a throttle valve and the effect is found to remain the same.

A thin Teflon plate of 12.5 mm thick now closes the side of the steel block containing the engraved channel permanently. The plate contains an orifice of 6.25 mm dia. The thickness of the plate surrounding the orifice is of 1.56 mm descending uniformly a radius of 6.25 mm. This plate is fixed with a block containing a channel by means of 8 screws of 18.75 mm dia. A thin copper foil serves as the gasket. The 6.25 mm hole on the steel plate is positioned axially to the drilled hole of 12.5 mm and is serving as the centrally aperture orifice. A flanged steel tube is now fixed through the block to channelize the flow through the orifice to serve as the cold end.

For temperature measurements either precision thermometers ranging from -10°C to 110°C and from 0°C to 250°C with graduations of $1/10^{\text{TH}}$ of a degree or by means of digital thermometers.

VII. EXPERIMENTAL PROCEDURE

The compressed air after proper drying is passed through the tubular furnace for raising the temperature of air to a desired value and then it is passed through the nozzle of the vortex chamber. The pressure of the gas is made constant at 650 psig, 100 psig and 150 psig and all observations are made at these three different pressures. Then the globe valve at the hot end is regulated for a particular μ_c . The readings are taken at about μ_c values of .05, .15, .35, .5, .6.75 and .9.

At first the vortex temperature separation was carried at room temperature (about 30°C). The temperature of the inlet air T_i , the hot end stream and the cold stream T_c are noted at 5 min intervals until the cold end temperatures is found to be constant for 10 mins. The pressure readings at the orifice in hot and cold end stream are also noted. The first reading is taken at approximately $\mu_c = .05$. Then other readings are taken at the same

inlet temperature keeping the pressure constant. The process is repeated for 3 different pressures (50 psig, 100 psig & 150 psig)

In this way readings are taken at temperatures of 80°C , 130°C , 180°C , 230°C and 280°C . Then $[T_f = T_i - \text{J.T. cooling at experimental pressure}]$, $\Delta T_c [T_f - T_c]$, $\Delta T_h [T_h - T_f]$ are calculated by calculating m_c and m_h from the manometer readings at the orifices. Four graphs are plotted at each pressure as shown later:

- ΔT_c vs. μ_c
- ΔT_h vs. μ_c
- h_{cold} vs. μ_c
- h_{hot} vs. μ_c

Thus for three different pressures, twelve curves were obtained and the curves are studied.

VIII. APPLICATIONS

The importance of study of Vortex tube can be realized from the possible spheres of its applications.

- Dave Williams has proposed using Vortex tubes to make ice in third-world countries. Although the technique is inefficient, Williams expressed hope that vortex tubes could yield helpful results in areas where using electricity to create ice is not an option.
- There are industrial applications that result in unused pressurized gases. Using vortex tube energy separation may be a method to recover waste pressure energy from high and low pressure sources. **Helikon vortex separation process:** It is an aerodynamic uranium enrichment process designed around a device called a vortex tube. This method was designed and used in South Africa for producing reactor fuel with a uranium-235 content of around 3–5%, and 80–93% enriched uranium for use in nuclear weapons. The Uranium Enrichment Corporation of South Africa, Ltd., (UCOR), developed the process, operating a facility at Pelindaba (known as the 'Y' plant) to produce hundreds of kilograms of HEU. Aerodynamic enrichment processes require large amounts of electricity and are not generally considered economically competitive because of high energy consumption and substantial requirements for removal of waste heat. The South African enrichment plant has apparently been closed.

In the vortex separation process a mixture of uranium hexafluoride gas and hydrogen is injected tangentially into a tube at one end through nozzles or holes, at velocities close to the speed of sound. The tube tapers to a small exit aperture at one or both ends. This tangential injection of gas results in a spiral or vortex motion within the tube, and two gas streams are withdrawn at opposite ends of the vortex tube; centrifugal force providing the isotopic separation. The spiral swirling flow decays downstream of the feed inlet due to friction at the tube wall. Consequently, the inside diameter of the tube is typically tapered to reduce decay in the swirling flow velocity. This process is characterized by a separating element with a very small stage cut

(the ratio of product flow to feed flow) of about 1/20, and high process-operating pressures. Due to the extremely difficult plumbing required to link stages together, the design was developed into a cascade design technique (dubbed Helikon), in which 20 separation stages are combined into one module, and all 20 stages share a common pair of axial-flow compressors. A basic requirement for the success of this method is that the axial-flow compressors successfully transmit parallel streams of different isotopic compositions without significant mixing.

IX. OBSERVATION TABLES

Table I - At about -5 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0			6.0	6.5		24.70	2.08
5	-5.26	-9.23	6.0	6.5	27.75	24.70	2.08
10	-5.26	-9.23	6.0	6.5	27.75	24.70	2.08
15			6.0	6.5		24.70	2.08

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0				4.23		3.8	4.35
5	-5.26	-10.5		4.23	12.13	3.8	4.35
10	-5.26	-10.5		4.23	12.13	3.8	4.35
15				4.23		3.8	4.35

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0			24.7	2.08		6.0	6.5
5	-5.26	-14.8	24.7	2.08	4.62	6.0	6.5
10	-5.26	-14.8	24.7	2.08	4.64	6.0	6.5

15			24.7	2.08		6.0	6.5
----	--	--	------	------	--	-----	-----

Table II - At about 35 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	35.1	19.9	6.0	6.5	69.9	24.70	2.08
5	34.9	18.8	6.0	6.5	71	24.70	2.08
10	34.8	18.5	6.0	6.5	70.6	24.70	2.08
15	34.8	18.5	6.0	6.5	70.6	24.70	2.08
20	34.7	18.3	6.0	6.5	70.4	24.70	2.08

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	33.7	5.3	24.7	2.08	41.5	6.0	6.5
5	33.9	5.9	24.7	2.08	42.5	6.0	6.5
10	34	6.2	24.7	2.08	42.6	6.0	6.5
15	34.1	6.9	24.7	2.08	42.5	6.0	6.5
20	34.1	6.9	24.7	2.08	42.5	6.0	6.5

Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	33.8	7.7		4.23	51.6	3.8	4.35
5	34.5	8.5		4.23	53.5	3.8	4.35
10	35.1	8.9		4.23	55.6	3.8	4.35
15	35.2	9.0		4.23	55.9	3.8	4.35
20	35.2	9.0		4.23	56	3.8	4.35

Table III - At about 55 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	55.1	36.9	6.0	6.5	83.8	24.70	2.08
5	54.9	36.9	6.0	6.5	83.7	24.70	2.08
10	54.9	36.9	6.0	6.5	83.4	24.70	2.08
15	54.9	36.9	6.0	6.5	84.4	24.70	2.08
20	54.9	36.9	6.0	6.5	84.4	24.70	2.08

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	54.8	25.9		4.23	72.3	3.8	4.35
5	54.8	25.9		4.23	72.3	3.8	4.35
10	54.9	26		4.23	73.2	3.8	4.35
15	54.9	26		4.23	73.2	3.8	4.35
20	54.2	25.3		4.23	73.2	3.8	4.35

Condition		End			End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	75.8	41.5	24.7	2.08	82.4	6.0	6.5
5	75.7	40.5	24.7	2.08	80.9	6.0	6.5
10	75.6	39.9	24.7	2.08	80	6.0	6.5
15	75.4	39.6	24.7	2.08	79.7	6.0	6.5
20	75.4	39.6	24.7	2.08	79.7	6.0	6.5

Table V - At about -5 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	54.6	22.3	24.7	2.08	61.6	6.0	6.5
5	55.1	22.5	24.7	2.08	61.8	6.0	6.5
10	55.32	22.6	24.7	2.08	61.8	6.0	6.5
15	55.2	22.6	24.7	2.08	61.9	6.0	6.5
20	55.2	22.5	24.7	2.08	61.9	6.0	6.5

Table IV - At about 75 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	74.7	55.2	6.0	6.5	87.8	24.70	2.08
5	75.3	55.8	6.0	6.5	93.9	24.70	2.08
10	76.0	56.5	6.0	6.5	96.5	24.70	2.08
15	76.0	56.9	6.0	6.5	97.5	24.70	2.08
20	76.4	56.9	6.0	6.5	97.5	24.70	2.08

Tf	Tc	ΔTc	Th	ΔTh	m _c	m _h	h _{cold}	μ _c
-5.86	-9.23	3.37	27.75	33.61	7.8	2.59	212	0.752
-5.86	-10.54	4.68	12.13	17.99	5.065	5.325	183	.488
-5.86	-14.86	9	4.62	10.48	2.48	7.9	162.5	.239

Table VI - At about 35 °C

Tf	Tc	ΔTc	Th	ΔTh	m _c	m _h	h _{cold}	μ _c
34.2	18.5	15.7	70.6	36.4	8.3	2.77	900	.75
34.6	9	25.6	55.9	21.3	5.35	5.7	945	.484
33.5	6.9	26.60	42.5	9	2.62	8.45	481	.286

Table VII - At about 55 °C

Initial Condition		Cold End			Hot End		
Time(t) mins	Ti in °C	Tc in °C	R1 in cm	Cfm	Th in °C	R2 in cm	Cfm
0	75.5	43.7		4.23	88.3	3.8	4.35
5	75.3	43.9		4.23	89.0	3.8	4.35
10	75.1	43.8		4.23	89.2	3.8	4.35
15	75.8	43.6		4.23	89.1	3.8	4.35
20	75.8	43.6		4.23	89.1	3.8	4.35

Tf	Tc	ΔTc	Th	ΔTh	m _c	m _h	h _{cold}	μ _c
54.3	36.9	17.4	84.4	30.1	8.55	2.84	1035	.75
54.2	22	28.2	73.3	11.1	5.5	5.9	996	.482
54.6	22.6	32	61.39	7.3	2.505	8.7	555	.223

Table VIII - At about 75 °C

Tf	Tc	ΔTc	Th	ΔTh	m _c	m _h	h _{cold}	μ _c
75.8	56.9	18.9	97.5	21.7	8.85	2.9	1169	.752
74.2	43.6	30.6	89.1	14.9	5.7	6.05	1195	.485
74.8	39.6	35.2	79.7	4.9	2.785	8.96	683	.237

Initial	Cold	Hot
---------	------	-----

X. SAMPLE CALCULATIONS

J.T. cooling at 50 psig = 0.6 °C

T_f = True feed gas temperature in °C = (Initial feed gas temperature - J.T. Cooling)

= [T_i - J.T. cooling] in °C

T_{f1} = 34.8 - 0.6 = 34.2

T_{f2} = 35.2 - 0.6 = 34.6

T_{f3} = 34.1 - 0.6 = 33.5 and so on

ΔT_c = [T_f - T_c] in °C

Hence, ΔT_{c1} = 34.2 - 18.5 = 15.7

ΔT_{c2} = 34.6 - 9.0 = 25.6

ΔT_{c3} = 33.5 - 6.9 = 26.6

ΔT_h = T_h - T_f

Hence, ΔT_{h1} = 70.6 - 34.2 = 36.4

ΔT_{h2} = 54.9 - 34.6 = 21.3

ΔT_{h3} = 42.9 - 33.5 = 9.0

Similarly, other value of T and T_b were calculated

ΔT_{cop} in °C = $(T_f + T_c)/2$

Hence, T_{1cop} = $(34.2 + 18.5)/2 = 26.35$

T_{2cop} = $(34.6 + 9)/2 = 21.8$

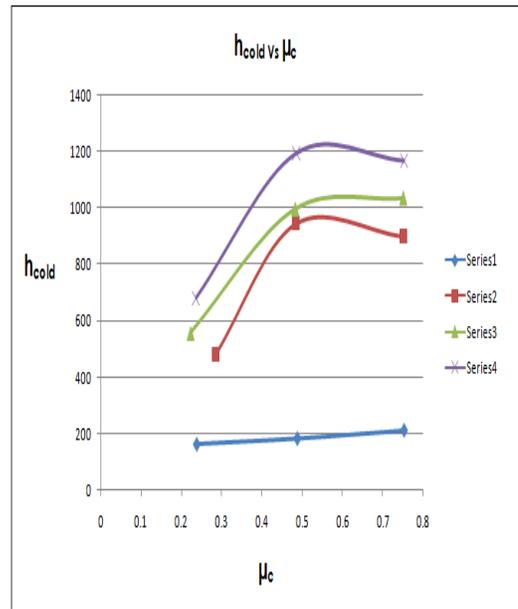
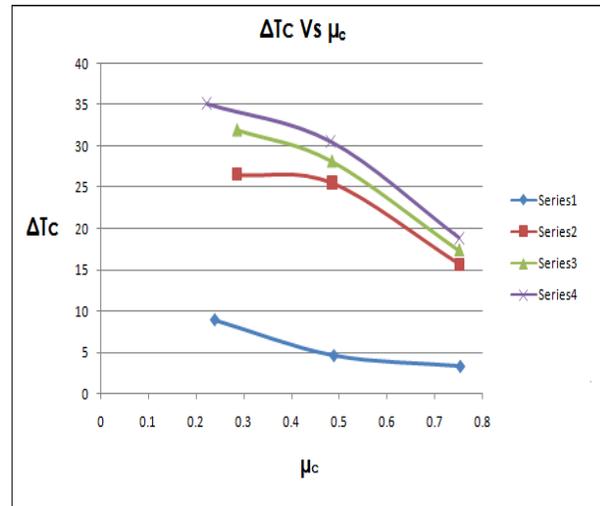
T_{3cop} = $(33.5 + 6.9)/2 = 20.2$

T_{hop} = $(T_h + T_f)/2$

Hence, T_{1hop} = $(70.6 + 34.2)/2 = 52.4$

T_{2hop} = $(55.9 + 34.6)/2 = 45.25$

T_{3hop} = $(42.5 + 33.5)/2 = 38$



XI. CONCLUSION

After performing extensive Literature Survey, which has revealed the huge amount of work done in the field of Ranque-Hilsch Vortex Effect, it shows that this is quite important for academic and industrial purposes. Even after so many works done in this field, there still remain some questions about topics unanswered. Moreover, the fair numbers of applications of this Vortex tube like mass separation of gases, measurement of velocities of airplanes etc. show huge scope of this subject. Performing the cost survey for various instruments, literature survey, collection of information for proceeding on this project and defining objectives has helped us start on a right note on this project.

After completion of our actual experiment, we have obtained our desired results of temperature differences at the two outlets. The obtained temperature difference differences under the current conditions are satisfactory, taking into consideration

the possibility of errors here. So our observations are acceptable within the limits of experimental errors.

XII. DISCUSSIONS

In general the results corroborate the findings of the previous workers. It also confirms that with increases of μ_c , hot end temperature increases continuously and cold end temperature increase continuously. With the increase of μ_c , ΔT_c decreases but below room temperature it decreases in another fashion which is perhaps due to the inaccuracy of temperature measurements. Also ΔT_h value increase with increase of μ_c . the value of μ_c for which minimum temperature of the cold flow can be obtained is about 0.2. The value of μ_c for which maximum temperature of the cold flow can be obtained is about 0.8

The effect of feed gas temperature on the temperature separation at the same pressure (30 psig) is shown .It is observed that with increase of feed gas temperature ΔT_c increases (temperature of the cold flow decreases)and again with increase in feed gas temperature ΔT_h decreases. But it is found that in the case of -5°C the curves are slightly different which is perhaps due to inaccuracy of temperature measurements.

The conclusion drawn above is only approximate because the data taken are not sufficient.

XIII. SUGGESTION FOR FUTURE WORK

The simplicity of this apparatus has been alluring to many research workers. The mechanism of this experiment is still obscure. Vortex tubes have the potential to be utilized in a compact air separation system that can extract and liquefy oxygen for many purposes including onboard propellant generation for rocket vehicles.

Many analysts identify Carbon dioxide capture and separations as a major road block in efforts to cost effectively mitigate green house gas emissions via sequestration.

REFERENCES

[1] Ranque, G.J. J. Phys. Radium, 4, 112, (1933).

- [2] Merculov, A.P. Vortex effect and engineering applications. Moscow, Mashinostroenie, 1969. (In Russian)
- [3] Finko, V.E. Peculiarity cooling and liquation of gas into vortex stream. Journal Technical Physics 53, vol.15 (22), 1989. (In Russian)
- [4] Kotousov, L.S. By liquation of gas into vortex coolers. Journal of Technical Physics, vol.61,iss.2, 1991. (In Russian)
- [5] Saburov, E.N., Karpov, S.V., Ostashev, S.I. Heat exchange and air dynamic of vortex flow in the cyclone units. Leningrad, Leningrad University Pub., 1989. (In Russian)
- [6] Kotelnikov, V.I. High-Efficiency Vortex Pipes. TIEES-96, Trabzon, Turkey, ISBN 975-95505-8-X.
- [7] Ahlborn, B.K., Keller, J.U., Rebhan, E. The Heat Pump in a Vortex Tube. J. Non-Equilib. Thermodyn. 1998, Vol. 23, No. 2.
- [8] Zaslavski, B.I., Yuriev B.V. Study of structure flow in the flat vortex camera. J. Applied mechanic and theoretical physics, 1998, Vol.39, No. 1.
- [9] Gutsol, A.F. The Ranque effect. J. Physical Science Progress, Volume 167, No.6. (In Russian)
- [10] Kotelnikov, V.I. The Vortex Effect in Transfer of Energy. Sustainable Energy and Environmental Technology, World Scientific Publishing Co. Pte. Ltd, ISBN 981-02-2829-5, Singapore, 1996.
- [11] Stiffler A.K., Bakhsh H., A gas jet impacting a cavity. J. Fluid Mech., 1986, vol. 172, pp. 127-141.
- [12] Kurosaka M., Acoustic streaming in swirling flow and the Ranque-Hilsch (vortex-tube) effect. J. Fluid Mech., 1982, vol. 124, pp. 139-172.
- [13] Lavan Z., Fejer A.A., Luminescence in supersonic swirling flows. J. Fluid Mech., 1965, vol. 23, part 1, pp. 173-183.
- [14] Deissler R.G., Perlmutter M., 1960, Int. J. Heat Mass Transfer 1, pp. 173-191.
- [15] Linderstrom-Lang C. U., 1971, J. Fluid Mech, vol. 45, pp. 161-187.
- [16] Sprenger M., Ueber Thermische Effekte in Resonanzrohren. Mitt. Inst. Aero. 21, 18, 1954

AUTHORS

First Author – Rajarshi Kar, Department of Chemical Engineering, Heritage Institute of Technology, Kolkata

Second Author – Oindrila Gupta, Department of Chemical Engineering, Heritage Institute of Technology, Kolkata

Correspondence Author – Mukunda Kumar Das, Department of Chemical Engineering, Heritage Institute of Technology, Kolkata