A Review on Modeling and Investigation of Chang in Working Parameters on the Performance of the Vortex Tube with CFD Analysis

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ABSTRACT

The vortex tube performance depends on two types of parameters, firstly air or working parameters such as inlet pressure of compressed air, cold mass fraction and secondly tube or geometric parameters such as length of hot side tube, cold orifice diameter, number of nozzles, diameter of nozzle, cone valve angle and also material of vortex tube affects Coefficient of Performance (COP). This paper discusses the experimental investigation of effect of above working parameters on the performance of Ranque Hilsch vortex tube. The paper develops three dimensional flow domain using Computational Fluid Dynamics (CFD) and this CFD and experimental studies are conducted towards the optimization of RHVT. The cast iron material has been used for manufacturing of the vortex tube as it has lower thermal conductivity and less fluid friction losses. In this experimental study the performance of vortex tube has been tested with compressed air at various pressures from 5-10 bar, which supplied through two tangential inlet nozzles. The L/D ratio of hot side tube varied from 10-50.

Keyword: *- Working parameter, Geometric parameter, COP, CFD.*

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1. Introduction

The vortex tube is a mechanical device that separates single compressed air stream into cold and hot streams. It consists of nozzle, vortex chamber, separating cold plate, hot valve, hot and cold end tube without any moving parts. In the vortex tube, when works, the compressed gaseous fluid expands in the nozzle, then enters vortex tube tangentially with high speed, by means of whirl, the inlet gas splits in low pressure hot and cold temperature streams, one of which, the peripheral gas, has a higher temperature the initial gas, while the other, the central flow, has a lower temperature. Vortex tube has the following advantages compared to the other commercial refrigeration devices: simple, no moving parts, no electricity or chemicals, small and light weight, low cost, maintenance free, instant cold air, durable, temperature adjustable. Therefore, the vortex tube has application in heating gas, cooling gas, cleaning gas, drying gas, and separating gas mixtures, liquefying natural gas, when compactness, reliability and lower equipment cost are the main factors and the operating efficiency becomes less important.

Figure1. Vortex Tube

2. Problem Statement

In the present work it is contemplated to experimentally verify the performance of vortex tube in atmospheric conditions for a good range of various working and geometrical parameters to obtain dependence of temperature and refrigeration effect. For this new geometry of helical convergent nozzle is used in which helical nozzle converge from 8mm to 3mm diameter and allowed to escape to vortex diameter 12.5mm tangentially. The intention behind this modification is to pre whirl the air during inlet and also increases the swirl intensity of the air. Different parameters are experimentally tested for 6 no. of nozzles at different pressure i.e.2 bar, 3bar, 4bar, 5bar.

An experimental study has been conducted to evaluate the effect of working parameters such as inlet air pressure, Cold mass fraction (μ) and length of hot side tube (L□) on the performance of Ranque-Hilsch vortex tube. In this work, the counter flow vortex tube has been designed, manufactured and tested. Different parameters were evaluated like temperature reduction on cold side, temperature rise on hot side ,refrigerating effect and isentropic efficiency. The performance of vortex tube has been tested with compressed air at various inlet pressures from 5-10 bar which supplied through two tangential inlet nozzles. The L/D ratio of hot side tube varied from 10-50and cold mass fraction varied from 0.20 – 0.80.

3. Background

The vortex tube was invented in 1933 by French physicist Georges J. Ranque. German physicist Rudolf Hilsch improved the design and published a widely read paper in 1947 on the device, which he called a Wirbelrohr (literally, whirl pipe).The vortex tube was used to separate gas mixtures, oxygen and nitrogen, carbon dioxide and helium, carbon dioxide and air in 1967 by Linderstrom-Lang.Vortex tubes also seem to work with liquids to some extent, as demonstrated by Hsueh and Swenson in a laboratory experiment where free body rotation occurs from the core and a thick boundary layer at the wall. Air is separated causing a cooler air stream coming out the exhaust hoping to chill as a refrigerator. In 1988 R.T.Balmer applied liquid water as the working medium. It was found that when the inlet pressure is high, for instance 20-50 bar, the heat energy separation process exists in incompressible (liquids) vortex flow as well. Note that this separation is only due to heating; there is no longer cooling observed since cooling requires compressibility of the working fluid.

Vortex tube is a simple energy separating device which is compact, simple to produce and to operate. Although intensive research has been carried out in many countries over the years, the mechanism producing the temperature separation phenomenon as a gas or vapour passes through a Ranque-Hilsch vortex tube is not yet fully understood. Numerical simulation of 3D compressible turbulent flow was made using FLUENT software. The temperature distribution in vortex chamber was obtained by numerical simulation and a new explain of vortex tube energy separation mechanism was proposed. In summary, this approach is based on first-principles physics alone and is not limited to vortex tubes only, but applies to moving gas in general. It shows that temperature separation in a moving gas is due only to enthalpy conservation in a moving frame of reference.

4. Objective & Future Scope

The vortex tube (also called the Ranque–Hilsch vortex tube) is a mechanical device operating as a refrigerating machine without moving any parts, is a non-conventional device to achieve refrigeration and hot effect. Being the complex phenomenon, design a proper vortex tube to achieve the desired results is always a challenging task.Vortex tubes of six different configurations are designed and developed, along the objective to study performance assessment of multi nozzle vortex tubes using natural substances. An in house facility is developed to carry out the experimental investigations and measure the performance of the vortex tubes.

1. 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.
2. The Uranium Enrichment Corporation of South Africa. Ltd., (UCOR), developed the process, operating a facility of Pelindaba (known as the 'Y' plant) to produce hundreds of kilograms of HEU. Helicon 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 uranium-235 content of around 3-5%, and 80-93% enriched uranium for use in nuclear weapons. Aerodynamics enrichment processes require large amount of electricity and are not generally considered economically competitive because of high energy consumption and substantial requirements for removal of waste heat. Hence scope is for future development in this case.

3. The simplicity of this apparatus has been alluring to many research workers. The mechanism of this experiment is still obscured. Vortex tube has the potential to be utilized in a compact and separation system that can extract and liquefies oxygen for many purposes including onboard propellant generation for rocket vehicles.
4. The first and foremost important quality of any research or development is its eco- friendly nature, by the virtue of which it fulfills our basic needs without any harm to the nature. The commonly used cooling systems use the gas and liquids which either deplete the ozone layer or contribute in the global warming in the same as $CO2$ does. Many analysts identify carbon-dioxide capture and separation as a major road block in efforts to cost efficiency mitigates greenhouse gas emissions via sequestration. Thus, vortex tube can be used for any type of spot cooling or spot heating application.
5. Scientists have proposed using Vortex tubes to make ice in third-world countries. Although the technique is inefficient, they expressed hope that vortex tubes could yield helpful results in areas where using electricity to create ice is not an option.
6. Over the years, different theories have attempted to explain this effect without achieving any universal agreement. Small size of RHVT presents considerable difficulties towards predicting temperature, pressure and flow field inside it. This is where Computational Fluid Dynamics (CFD) analysis comes to the aid of researches, where scope for researches has increases.

5. Methodology / Research plan

5.1 Theory of Vortex Tube

Theoretical explanation is given by various papers in different way. They have tried to explain as how does the pumping of heat from compressed air temp to high temperature takes place in absence of a mechanical device. When compressed air is passing through the nozzle in the vortex chamber inside the chamber high velocity swirl motion is created. The air moves as a free vortex from the nozzle plane towards the valve end. As it near the valve, the kinetic energy is converted into the pressure energy giving a point of stagnation. But the stagnation pressure is higher than the pressure in the nozzle plane; thereby the reversal in flow takes place. This reversed flow comes in contact with forward moving free vortex, which causes the reversed vortex flow to rotate with it. Heat exchange takes place between these two flows.

5.1.1 Temperature Separation

The vortex tube creates two vortices forced and free. The free vortex fluid particle is moves towards the center of vortex and the angular velocity is fast at the center. In forced vortex particle velocity is directly proportional to the radius of the center vortex and is slower at that placed. In vortex tube outer vortex is free and the inner vortex is forced .The rotational motion of the forced vortex is controlled by free vortex. The turbulence of both the hot and cold air streams causes the layers to be locked together in a single, rotational mass. The inner air stream flows through the hollow core of the outer air stream at a slower velocity than the outer air stream.

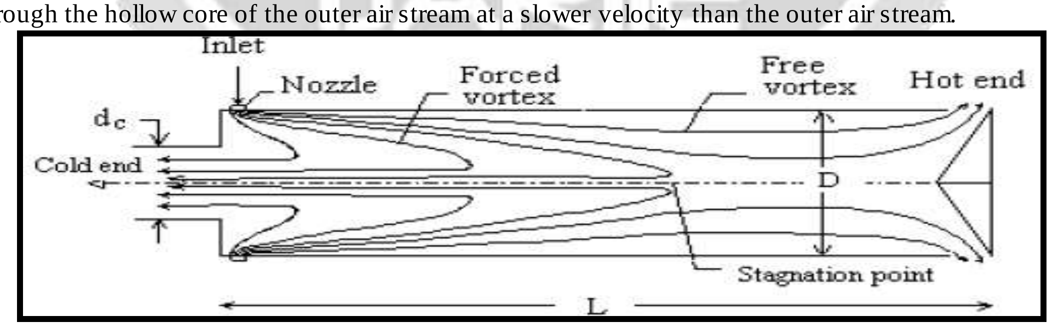

Figure 7.1 Temperature Separation in Vortex Tube

Since the energy is proportional to the square of the velocity, the cold air stream loses its energy by heat transfer. This allows energy to flow from the inner air stream to the outer air stream as heat creating a cold inner air stream.

5.1.2 Humidity Effect

The vortex tube does not separate humidity in between the hot and cold air its remains same as that compressed or input air. The dew point of the air is higher than the temperature then the moisture will condense or freeze. When temperatures are below freezing, the condensation is in the form of snow. This snow has a sticky quality from oil vapour and will eventually collect and block air passages. For continuous operation at low temperatures, use an air dryer or inject an antifreeze mist into the input air. When selecting a dryer, do not use chemical desiccant dyers such as silica gel or molecular sieve types. They tend to heat the compressed air and cause refrigeration losses.

5.2 Refrigeration:

Refrigeration is the science of the producing and maintaining temperatures below that of the surrounding atmosphere. This means the removing of heat from a substance to be cooled. Heat always passes downhill from a warm body to a cooler one, until both bodies are at the same temperature. Not only perishables today many human work spaces in offices and factory building are air-conditioned and a refrigeration unit is the heart of the system.
Before the advent of mechanical refrigeration water was kept cool by storing it in semi porous jugs so that the water could seep through and evaporate. The evaporation carried away heat and cooled the water. This system was used by the Egyptian and by Indians in the south west. Natural ice from lakes and rivers was often cut during winter and stored in caves, straw-lined pits, and later in sawdust insulated building to be used as required. The Romans carried pack trains of snow from Alps to Rome for cooling the emperor's drinks. Though these methods of cooling all make used of natural phenomena, they were used to maintain a lower temperature in a space or product and may properly be called refrigeration. In simple refrigeration means the cooling or removal of heat from a system. The equipment employed to maintain system at a low temperature is termed as refrigeration system and the system which is kept at lower temperature is called refrigerated system. Refrigeration is generally produced in one on the following three ways

1. By melting of a solid,
2. By sublimation of a solid and
3. By evaporation of a liquid.

Most of the commercial refrigeration is produced by the evaporation of a liquid called refrigerant. Mechanical refrigeration depends upon the evaporation of liquid refrigerant and its circuit includes the equipment's naming evaporator, compressor, condenser, expansion valve. It is used for preservation of food, manufacture of ice, solid carbon-dioxide and control of air temperature and humidity in the air conditioning system.

6. Expected Outcome

Performance of a vortex tube, RHVT tube is mainly depends on the design parameters; geometrical parameters, mass flow, reservoir conditions, gas properties, internal flow parameters, and other factors.

- Geometrical parameters - Hot and cold tube length, internal diameter of tube, effective diameter of inlet nozzles, number of inlet nozzles, orientation of inlet nozzles, cold orifice diameter, shape and length of hot end valve, effective diameter of hot flow exit restriction, vortex chamber etc.
- Mass flows-Cold mass fraction, overall mass flow rate, Reservoir conditions, Inlet pressure, inlet temperature, air density at tube inlet etc.
- Air properties-Air viscosity, Air thermal conductivity, heat capacity of air at constant pressure, etc.
- Internal flow parameters-Static pressure at cold exit, static pressure at hot exit etc.
- Other factors-Material of tube, internal roughness etc. As seen in literature, in order to design a good RHVT, the inlet nozzle, the vortex chamber, the cold orifice, the hot and cold tube length, the tube geometry, the tube material, the fluid properties, the cold mass fraction etc., are all relevant design parameters. In this section, the design criteria for vortex tube parameters are discussed.

6.1 Geometric Parameters

- Tube length

It is suggested to have an efficient design tube length should be many times longer than its diameter. The length of the vortex tube affects performance significantly. Optimum L/D is a function of geometrical and operating parameters. The magnitude of the energy separation increases as the length of the vortex tube increases to a critical length. However, a further increase of the vortex tube length beyond the critical length does not improve the energy separation.

- Tube diameter-

In general smaller diameter vortex tubes provide more temperature separation than larger diameter ones. A very small diameter vortex tube leads to low diffusion of kinetic energy which also means low temperature separation. Avery large tube diameter would result in lower overall tangential velocities both in the core and in the periphery region that would produce low diffusion of mean kinetic energy and also low temperature.

- Number of nozzles-

For maximum temperature drop the inlet nozzles should be designed so that the flow will be tangentially entering into vortex tube. The increase of the number of inlet nozzles leads to higher temperature separation. The inlet nozzle location should be as close as possible to the orifice to yield high tangential velocities near the orifice.
Hot flow control valve-The hot-end plug is not a critical component in the RHVT. Optimum value for the angle of the cone-shaped control valve (α) is approximately 35°.

- Tube geometry-

Tapered vortex tube contributes separation process in vortex tubes used for air separation. In divergent vortex tubes, there exists an optimal conical angle and this angle is very small (3°). Rounding off the tube entrance improves the performance of the RHVT.

- Length of vortex tube is one of the most important factors that affect its performance.
- To increase the performance of vortex tube, we have to maintain its L/D ratio and cold mass fraction.
- Nozzle number also effect on its performance, so keep at low.
- Improvement vortex tube cooling capacity by reducing hot tube surface temperature.

The parametric study will be carried for

i) L/D ratio
ii) No. of nozzle
iii) Inlet air pressure and
iv) Material.

6.2 Computational Fluid Dynamics

Definition of Computational Fluid Dynamics

- Computational – mathematical analysis, computing
- Fluid Dynamics - the dynamics of things that flow

CFD - a computational technology that enables one to study the dynamics of things that flow. CFD is concerned with numerical solution of differential equations governing transport of mass, momentum and energy in moving fluid. Using CFD, one can build a computational model on which physics can be applied for getting the results. The CFD software gives one the power to model things, mesh them, give proper boundary conditions and simulate them with real world condition to obtain results. Using CFD a model can be developed which can breed to give results such that the model could be developed into an object which could be of some use in our life.

6.2.1 The Benefits of CFD

There are three reasons to use CFD software: insight, foresight, and efficiency.

6.2.2 Insight

Think of an object which is difficult to produce practically and do some experiment on it. CFD provides the break through. Using the CFD software, one can easily design the object and use the boundary conditions to get output. The simulation thus helps in getting results much easily than constructing the real object.

6.2.3 Foresight

In CFD first we make the model then use certain boundary conditions to get the output. Thus using CFD we can give some real world condition say as pressure or temperature and simulate things to get the output. Many variations can be adopted till an optimal result is reached. All of this can be done before physical prototyping and testing.

6.2.4 Efficiency

The analysis gives better idea of, how the object works. So necessary changes could be brought about to facilitate better production of the product. Thus CFD helps to design better and faster bringing about improvement in each step.

6.2.5 The CFD Process

In the past decades many modelling and simulation software have been developed like PHONICS, FLUENT, SRAT-CD, CFX, FLOW -3D and COMPACT. Generally this software's are based on finite volume method. FLUENT is one of the major software which has helped a lot in modelling fluid and heat transfer problems. Complex geometries can be meshed in 2D triangular or quadrilateral, 3D tetrahedral, hexahedral, pyramid, wedge and mixed meshes. Fluent thus help in simulating the unstructured mesh geometries.

FLUENT consist of two parts, one is GMABIT and the other is FLUENT solver. Gambit is used for designing and fluent solver is used for simulation. Gambit helps in meshing the geometries and coarse and fine meshing can be done as per the flow solutions. Once the meshing is done in Gambit, further modification like setting up boundary condition and executing the solution is done by using Fluent. There are essentially three stages to every CFD simulation process: pre-processing, solving and post processing.

7. Conclusion

We have expected concluded by the vortex tube performance depends on two types of parameters, firstly air or working parameters such as inlet pressure of compressed air, cold mass fraction and secondly tube or geometric parameters such as length of hot side tube, cold orifice diameter, number of nozzles, diameter of nozzle, cone valve angle and also material of vortex tube affects Coefficient of Performance (COP). This paper discusses the experimental investigation of effect of above working parameters on the performance of vortex tube. The paper develops three dimensional flow domain using Computational Fluid Dynamics (CFD) and this CFD and experimental studies are conducted towards the optimization of RHVT.

Future Scope

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.

- Eco- friendly nature
- Vortex tubes could yield helpful results in areas where using electricity to create ice is not an option.
- Recover waste pressure energy

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