CFD Simulation of a Small Stirling Cryocooler

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Certificate of approval

This is to certify that the project entitled, **“CFD Simulation of a Small Stirling Cryocooler”** being submitted by ***Mr. Ravindra Kumar*** has been carried out under my supervision in partial fulfillment of the requirements for the Degree of **Bachelors of Technology (B. Tech)** in Mechanical Engineering at National Institute of Technology Rourkela, and this work has not been submitted elsewhere before for any other academic degree/diploma.

Date: 10th may 2013

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CONTENS

ABSTRACT

The application of cryocoolers has advanced in various fields of modern day applications because of adequate refrigeration at specified temperature with low power input, high reliability, long lifetime, and light weight. The demand of Stirling cryocoolers has increased due to the ineffectiveness of Rankine cooling systems at lower temperatures and with the advancement in applications of Stirling cryocoolers, several simulations of such cryocoolers were also developed. These simulations saved a lot of time and money as it could provide an accurate analysis of the performance of the cryocooler before actually manufacturing it. At present, design issues of mini cryocooers are given more serious consideration for its applications in various fields. There are large and diverse applications of cryogenic technology and very often a new application is added to the list. Here, in this project, an attempt has been made to formulate a CFD simulation of a stirling cryocooler. This project deals with a new type of numerical computational fluid dynamic (CFD) approach of making more realistic to the porous media inside the regenerator of a stirling refrigerator. The available commercial software package FLUENT for solving Computational fluid dynamics (CFD) has capable of define a porous media and solve the governing equation for this region. A detailed analysis has been done of the simulation of the cryocooler in the results and discussion section.

LIST OF FIGURES:

CHAPTER -1

INTRODUCTION

Cryogenics is the branch of study that deals with physical phenomena that occurs at very low temperature range, theoretically absolute zero, 0 Kelvin. Cryogenics is a branch of mechanical engineering that has many applications which operates in the temperature below 120 K. **Cryogenics** is the study of the behavior of materials at low temperatures (below −150 °C, −238 °F or 123 K). Cryogenicist is a person who studies elements that have been subjected to extremely cold temperatures. Cryogenicists use the absolute temperature scales rather than the relative temperature scales of Celsius and Fahrenheit.

1.1 CRYOCOOLERS

BRIEF DESCRIPTION-

Cryocooler is a cooling machine which operates in a temperature range less than 120 K with a small refrigerating capacity. There are two types of cryocooler: recuperative type and regenerative type. The former includes the joule Thomson cryocooler and Brayton cryocooler [1]. The latter includes the Stirling type and Gifford- McMahon type cryocooler. These cryocoolers are used for cooling of superconductors and semiconductors, also in the cooling of infrared sensors in the missile guided systems and satellite based surveillance . The cryocoolers can also be used in other applications such as cooling of radiation shields, cryopumps, Super Conducting Quantum Interference Device, liquefying natural gases, Semiconductor fabrication, Magnetometers, SC Magnets etc.

1.2 TYPES OF CRYCOCOOLERS

We can classify Cryocoolers on the basis of operating cycle and heat exchanger.

1.2.1 On the basis of types of operating cycles

Open cycle cryocoolers:

These type of cryocoolers use cryogenic fluids which are in liquid state and either in subcritical or supercritical state and also solid cryogens which are stored as high pressure gas with a Joule- Thomson expansion valve.

Closed cycle cryocoolers:

Closed cycle cryocoolers provide refrigeration effect at very low temperatures and reject heat at very high temperatures. They are basically mechanical cryocoolers. There are few examples of closed cycle cryocoolers like Brayton cycle cryocoolers , Stirling cryocoolers, Joule-Thomson cryocoolers etc. These closed cycle cryocooler uses two working fluids, one which will be working in the cycle and the other one which will be coming in direct contact of the space to be cooled [2].

1.2.2 Types of heat exchangers

1. Recuperative Cryocoolers

Since the direction of flow of the working fluid is unique, these are similar to direct current electrical systems. To maintain the flow direction the compressor and expander have separate inlet and outlet valves. Valves are necessary when the system has any rotary or turbine components.In rotary motion of components there are maximum chances for back flow of the working fluid, so in order to avoid that valves are necessary [3]. Working fluid since forms the important part of the cycle, that’s why the efficiency of the cryocooler depends upon it . Recuperative cryocoolers can be scaled to any size for specific output which is their main advantage. They are classified into valve less and with valves type of cryocoolers. There are few examples of recuperative cryocoolers which can be seen in Fig.2 below [2]. Larger volumes of working fluids can be used in these systems because of steady pressure oscillations; as a result these fluids flow anywhere except for locations where there are larger radiation heat leaks due to additional volumes at the cold end. Due to expansion and cooling of the working fluid inside the cryocooler, there is a possibilities of “pipe cold” at different locations. As the cold end of the cryocooler is separated from the compressor part, vibration of compressor is reduced greatly. As there is a lot of distance between cold space and compressor part of cryocooler so electromagnetic interference is also reduced. There can be traces of oil in the working fluid which are needed to be removed & which can be done from oil removal equipment implanted at the hot end of the cryocooler. Any traces of oil in the working fluid will clog and will freeze the system.

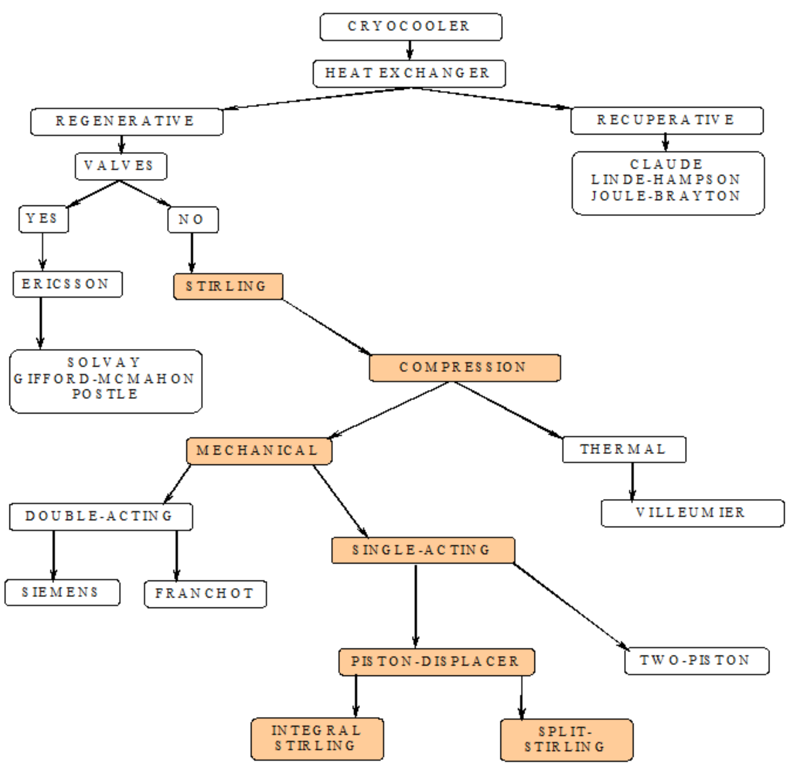

Fig. 1: Classification of cryocoolers

2. Regenerative Cryocoolers

These cryocoolers are similar to alternative current electrical system since the working fluid oscillates in the flow channel .There is oscillatory motion of the working fluid inside these type of cryocoolers in which it oscillates in cycles and while moving through the regenerator part of the cryocooler, working fluid exchanges heat with the wire mesh. The regenerator has a very high heat capacity which stores the heat during one half of the cycle and then in other half it gives it back to the working fluid. These are very efficient because of their very low heat transfer loss but these Cryocoolers cannot be scaled up to large sizes. There are mass flows and oscillating pressures in the cold head and there is a phase relationship between the mass flows and the pressure variations. The oscillating pressure can be generated with a valve less compressor as shown in Fig.2 for the Stirling cryocoolers and pulse tube, or with valves that switch the cold head between a low and high pressure source, which is in a Gifford-McMahon type cryocooler. Gifford- McMahon cryocooler has compressor with inlet and outlet valves which are used to generate high and low pressure in the system. The oil lubrication in the cryocooler is used to install oil removal equipment which can be installed at the high pressure line. The efficiency of the system is greatly reduced by use of valves. They use generally compressors with valves but there can be any type of pressure oscillation in a pulse tube cryocooler. The compressors which are with valves are modified for air conditioning and they are used for commercial applications. Regenerator is the main heat exchanger in regenerative cycles. The incoming hot gas transfers heat to the matrix of the regenerator, where the heat is stored for one half of the cycle and then in the second half of the cycle returning the cold gas, which is flowing in the opposite direction through the same channel, takes heat from the matrix and returns to the matrix at its original temperature (at the start of the cycle). Regenerator is a stacked mesh of wire screens (generally made up of steel) which is having a high heat transfer capacity.

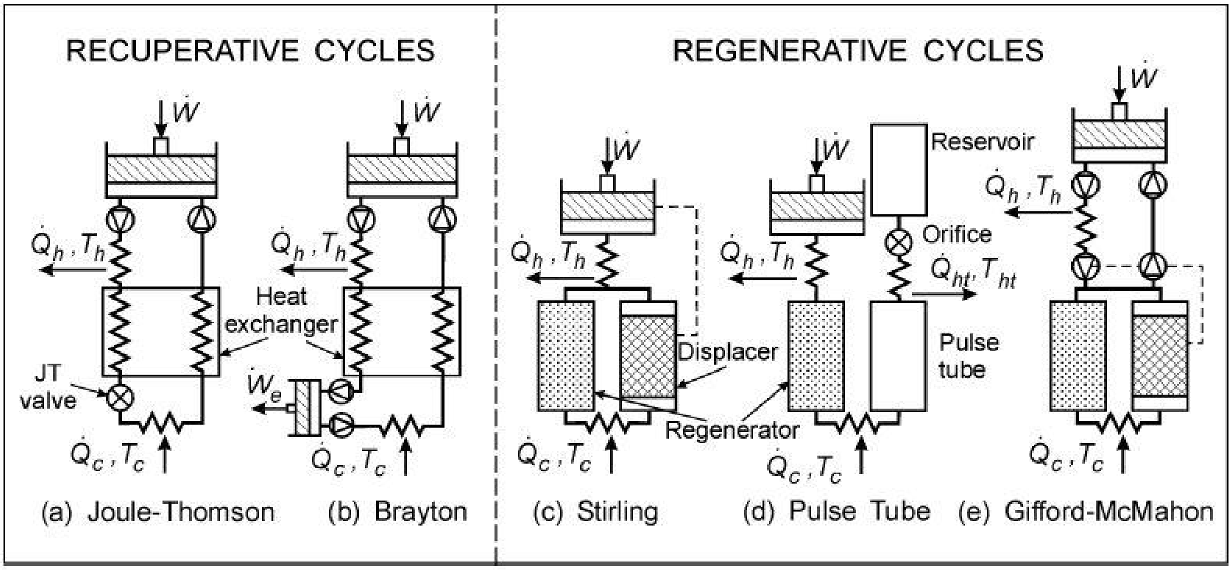

Fig. 2: Different types of Regenerative and Recuperative Cryocoolers

1.2.3 Description of Different Cryocoolers

1. Joule Thomson Cryocooler

The Joule-Thomson cryocoolers works on the principle of expansion of gases from high pressure to low pressure state. This process occurs at constant enthalpy. The expansion occurs with no production of work or heat input, thus, the process occurs at a constant enthalpy. The heat input occurs after the expansion and is used to evaporate any liquid formed in the expansion process or to warm up the cold gas. For an ideal gas enthalpy is independent of pressure at a constant temperature but enthalpy changes with pressure for real gases. Thus, cooling in a JT expansion occurs only with real gases and temperatures which is below the inversion curve. At very low temperatures the cooling increases for a given pressure change and it is maximum near the critical point. Generally argon and nitrogen are used in joule Thomson cryocoolers. To obtain a good cooling effect, 20 M Pa pressure or more than that is used on the high pressure side.Joule Thomson cryocoolers doesn't contain any moving component due to which a rapid cool down rate is obtained in it. Because of their rapid cool down rate Joule Thomson cryocoolers are used in missile guiding systems. When joule Thomson cryocooler operates in an open cycle mode it lasts for few days only till the gas evaporates fully from it. For the heat exchanger miniature finned tubing is used. Through an explosive valve Gas flows from the high pressure bottle and then it gets out to the atmosphere.

When joule Thomson cryocooler works in a closed cycle mode, its efficiency is low because of the clogging by moisture at the small orifice. JT cryocoolers are nowadays used with mixtures of different gases as its working fluid. This mixture of gases lowers the freezing point of fluid as a whole by having gases with higher boiling points.

2. Brayton Cryocoolers

These cryocoolers are also referred as reverse-Brayton cycle as cooling occurs by the expansion of gas and in this process it does work. The total heat absorbed with an ideal gas in the Brayton cycle is equal to the total work produced which is according to the First Law of Thermodynamics. This process is then more efficient than the Joule Thomson cycle and it does not require very high pressure ratio. These cryocoolers are generally used in large liquefaction plants. Turbines with approximately of 6 mm of diameter on shafts of 3 mm diameter are those systems which were reviewed by McCormick *et al.*8 for space applications of cooling of infrared sensors. Turbines which are having speeds of 2000 to 5000 rev/s are generally used in these type of cryocooler system. Centrifugal compressors which are providing a pressure ratio of approximately 1.6 with a low side pressure of 0.1 M Pa are also used with these systems. When operating above 35 K usually Neon is the working fluid which is used in the turbo-Brayton cryocoolers, but for lower temperatures helium is used. Brayton cryocoolers are having very low vibration of their rotating parts in a system with centrifugal compressors and turbo expanders. Low vibration of Brayton cryocoolers make them suitable for use with sensitive telescopes in satellite applications.

3. Pulse Tube Cryocoolers

In a pulse tube cryocooler there is a proper gas motion in phase with the pressure which is achieved by the use of an inertance tube along with a reservoir volume or an orifice to store the gas during a first half cycle. During the oscillating flow the reservoir volume diminishes any pressure oscillations which separate the heating and cooling effect. For a given frequency there is a limit on the diameter of the pulse tube in order to maintain adiabatic process. There are mainly four steps in its cycle of operation. In the first step the piston moves down to compress the gas in the pulse tube. In the second step this heated gas due to its higher pressure it moves into the reservoir and exchanges heat with the ambient through the heat exchanger at warm end of the pulse tube. In the third step then piston moves up and expands the gas adiabatically in the pulse tube. Finally this cold, low pressure gas is pushed through the cold heat exchanger by the gas from the reservoir and this stop when the pressure in the reservoir increases to the average pressure. The incoming high pressure gas is cooled by Regenerator before it reaches to the cold end. The gas in between the pulse tube insulates the two ends as it creates a temperature gradient between these two ends and never leaves its position. The turbulence is minimized by the gas in between the two ends. Pulse tube transfers acoustic power in an oscillating gas system from one end to the other across a temperature gradient with minimum entropy generation and power dissipation. If different changes are made in geometries of pulse tube cryocooler then it increases the lower temperature limit.

1.3 APPLICATIONS OF CRYOCOOLERS

1.3.1 Environmental

- IR sensors for atmospheric studies
- IR sensors for pollution control

1.3.2 Military applications

- IR sensors for night vision and missile guidance
- IR sensors for surveillance which is satellite based
- Gamma ray sensor which is used for monitoring nuclear activity
- Superconducting magnets which is used for mine sweeping

1.3.3 Commercial applications

- Cryopumps
- Industrial gas liquefaction
- For cellular phone base stations Cooling superconductors

1.3.4 Medical applications

- Cooling superconductors for MRI
- Cryosurgery

1.3.5 Transport applications

- Superconducting magnets used for maglev trains

1.4 STIRLING CRYOCOOLER

This is a regenerator type cryocooler. In general there are mainly three configurations of

Stirling cryocoolers viz. alpha, beta & gamma type. cryocooler operates on Stirling cycle. Helium is used as the working fluid in engine. An ideal Stirling cycle consists of two constant volume processes and isothermal processes alternatively. The cycle takes place in anticlockwise direction. The constant volume processes are of heat addition and rejection whereas isothermal processes are of contraction and expansion.

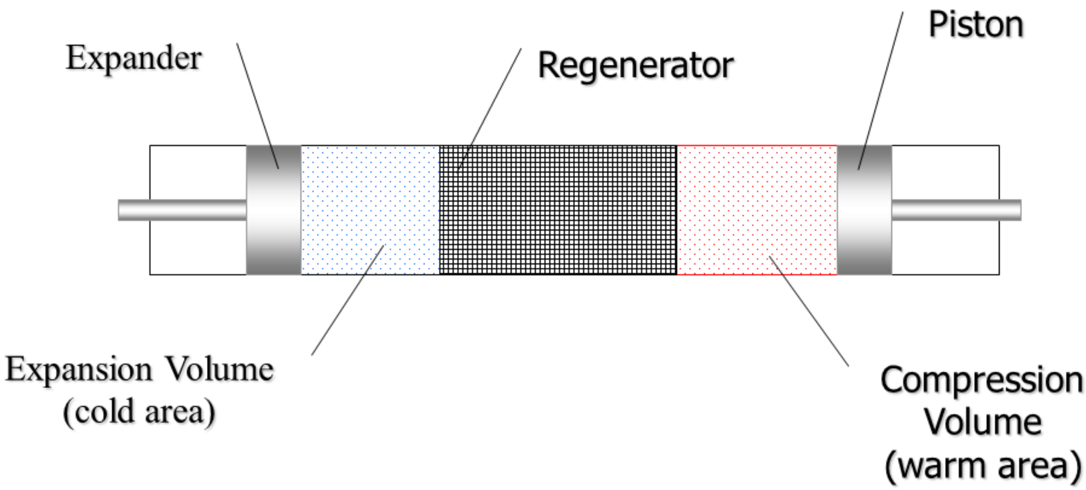

Fig. 3: Schematic representation of cryocooler.

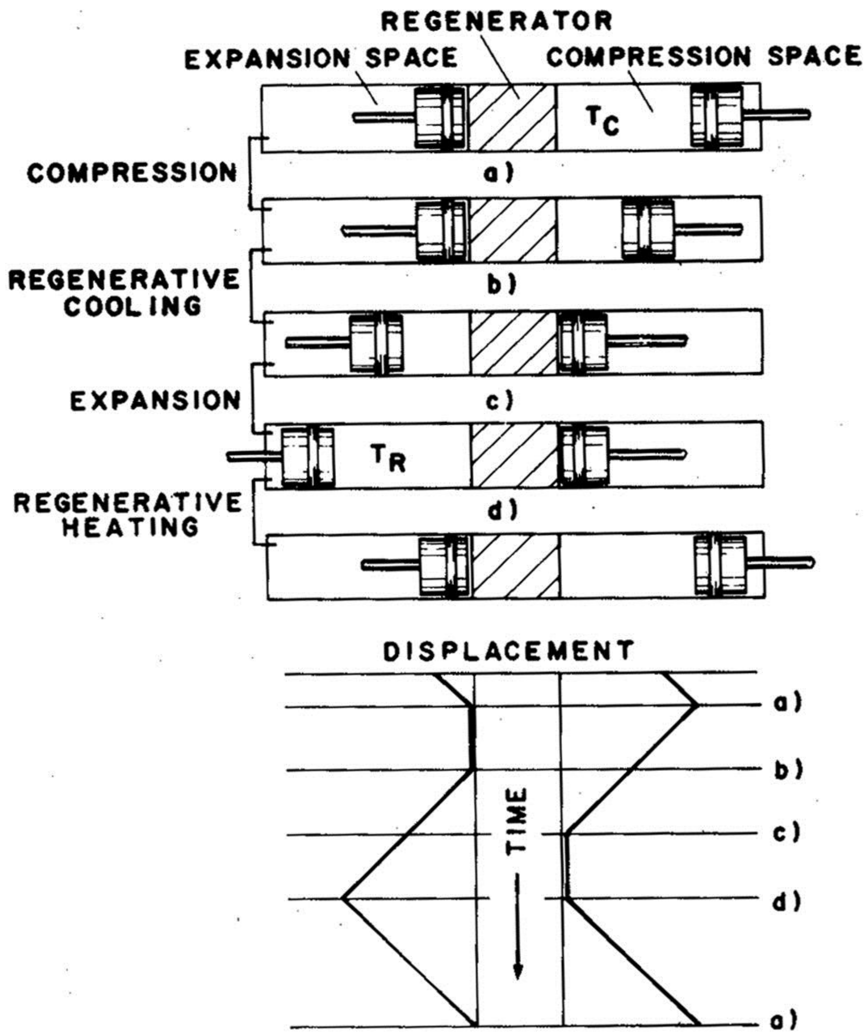

Fig. 4: Displacement-time variation of stirling cryocooler

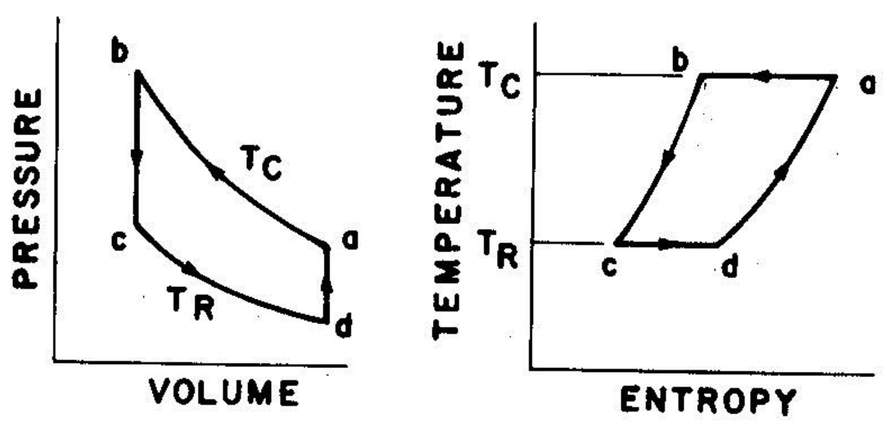

Fig. 5: P-V and T-S diagram of ideal stirling cycle. [3]

(a-b) Isothermal compression

(b-c) Regenerative cooling

(c-d) Isothermal expansion

(d-a) Regenerative heating

These above four processes can be explained as follows:

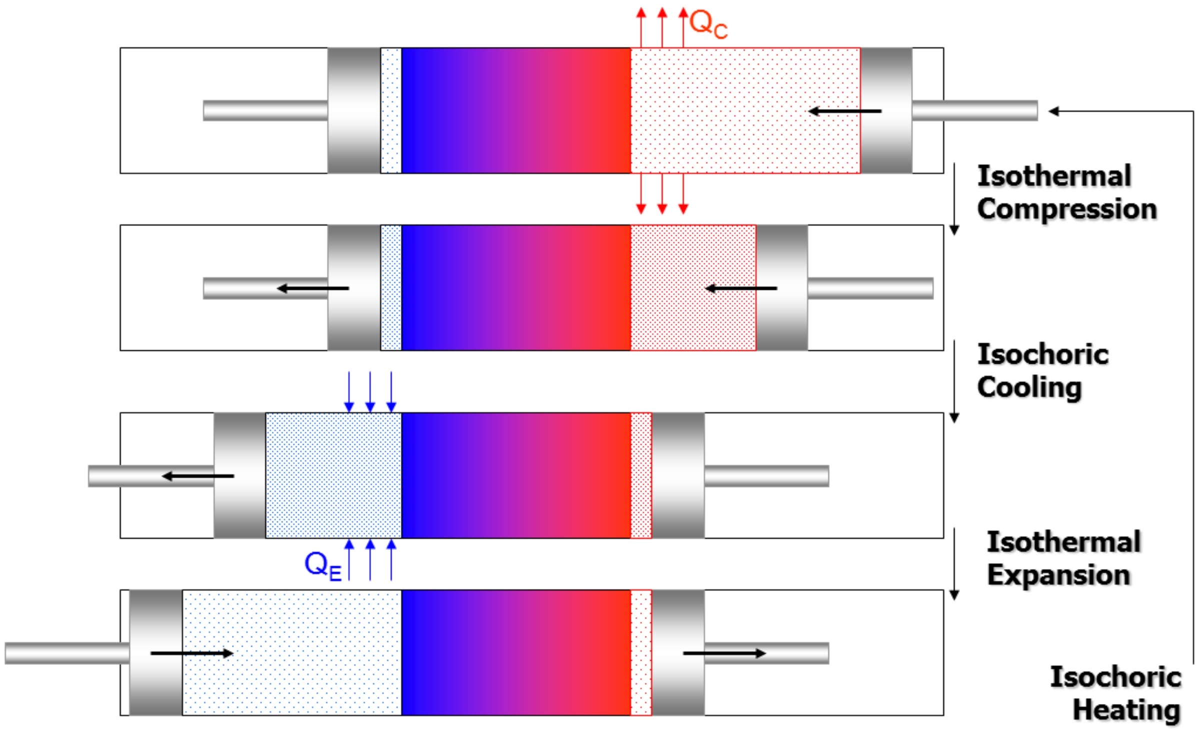

Fig. 6: Systematic representation of thermodynamic process involved in ideal stirling cycle.

Isothermal Expansion:

The gas in the cold heat exchanger space expands as the gas from the hot heat exchanger travels through the regenerator towards the cold end at constant temperature. During this process the fluid exchanges heat with the regenerator as it gives away its heat to regenerator to store it.

Isochoric heat Addition:

Where the cooling effect is to be produced, the cold end is exposed to the space so in this stage gas absorbs heat away from the space by keeping the volume of the cold space constant.

Isothermal Compression:

The gas from the cold end is compressed and then it travels through the regenerator at constant temperature towards the hot end of the cryocooler, during its course it takes away heat which was stored in the regenerator.

Isochoric heat rejection:

The gas in the hot end is now having the heat from the regenerator and the space to be cooled. The gas now in compressed state rejects heat to the ambient space by keeping the volume of the cold space constant.

1.4.1 Description of Stirling Cryocooler

The main components are compressor with piston, transfer line, after cooler, hot heat exchanger, displacer (regenerator) and cold heat exchanger. Regenerator and Piston are the moving components and rest are stationary.

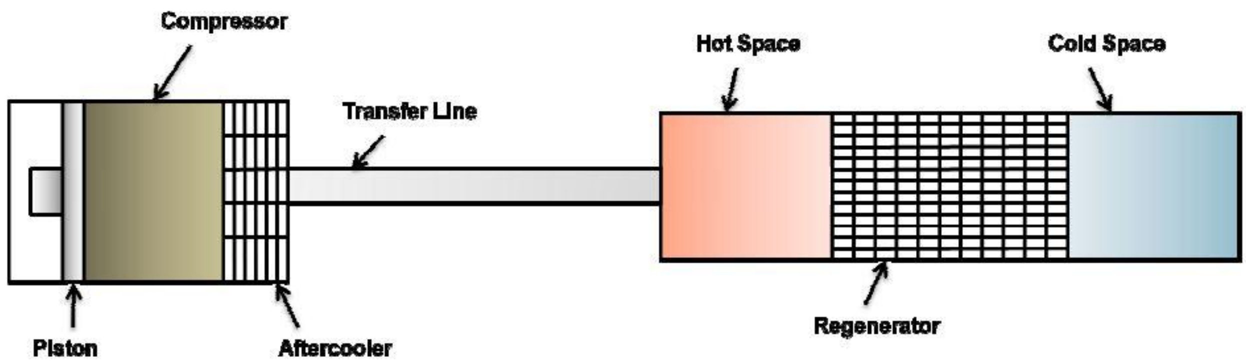

Fig. 7: Stirling cryocooler with Schematic representation [3]

1.4.2 Working of Stirling Cryocooler

From above Fig.7 of Stirling cycle if the gas is at the maximum volume condition, then the gas absorbs heat from the space to be cooled while regenerator remains stationary and piston was moving towards left. Next step the displacer moves to the right and thus forces the fluid to pass through it and while moving it absorbs heat from the regenerator at constant volume condition. Next the piston compresses the working fluid as it moves right and this compression at the hot end is isothermal so heat is given off to the surroundings at the atmospheric temperature. Now the regenerator moves to left thus forcing the fluid to pass through it and during this fluid gives away heat to the regenerator. It also maintains constant volume condition. This is an isochoric heat rejection process. Next the piston moves towards left and thus causing the fluid to expand. A pressure oscillation in the system will cause temperature to oscillate and produce no refrigeration. The motions of two parts are sinusoidal in nature and displacer motion is 90 degrees out of phase from that of piston motion. With this condition the mass flow or volume flow through the regenerator is in phase of pressure [2]. The moving piston causes both compression and expansion of the gas and net power Input which is required to operate the system. The moving regenerator reversibly extracts net work from the gas at the cold end and transmits it to the warm end where it contributes some to the compression work. In an ideal system, with isothermal expansion and compression and a perfect regenerator, the process is reversible [2].

The cooling cycle is split in four steps as shown in Fig.8. When the two pistons are in their most left positions, the cycle starts:

- From a to b. The warm piston moves to the right while the cold piston is remain fixed. Isothermal compression is used at the hot end, so heat Q_a is given off to the surroundings at ambient temperature T_a.
- From b to c. The two pistons move to the right while volume between the two pistons are remain constant. The hot gas enters the displacer with temperature T_a and leaves it with temperature T_L. The gas gives off heat to the regenerator material.
- From c to d. The cold piston moves to the right while the warm piston is fixed. The expansion is isothermal and heat Q_L is taken up. This is the useful cooling power.
- From d to a. The two pistons move to the left with isochoric process. The gas enters the displacer with low temperature T_L and leaves it with high temperature T_a so heat is taken up from the displacer material. Finally the state of the cooler is the same as in the beginning.

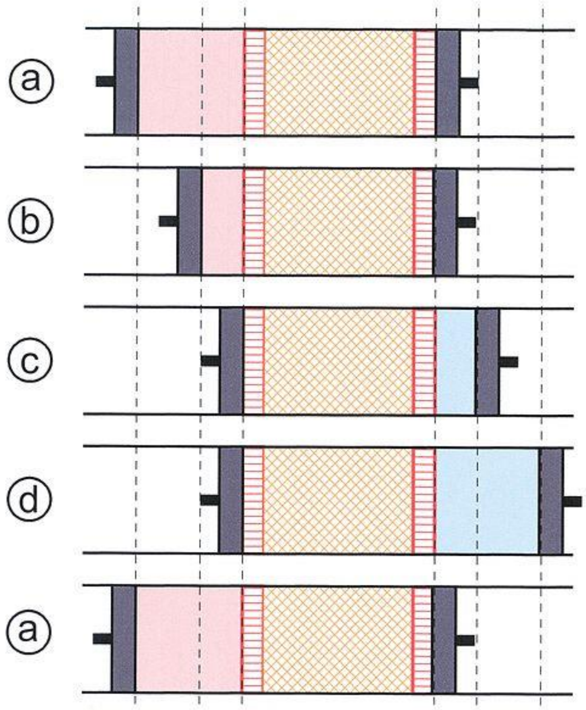

Fig. 8: Four steps involved in cooling cycle.

Let Q_C represents heat being rejected from the compressor during isothermal compression, W_C is the work input which is equal to Q_C and this is given by [4].

$$Q_c = mRT_c \ln\left(\frac{V_{max}}{V_{min}}\right) = W_c$$

Q_e is the amount of heat is being absorbed into the expander during isothermal expansion [4].

$$Q_e = mRT_e \ln\left(\frac{V_{max}}{V_{min}}\right) = W_e$$

Then by definition Carnot efficiency of the cryocooler is

$$\eta = \frac{Q_e}{W} = \frac{Q_e}{W_c - W_e}$$

$$\eta = \frac{T_e}{T_c - T_e}$$

Regenerator:-

- Temporary storage of thermal energy or heat of working fluid.
- To materialize Stirling cryocooler in a real machine it is very important component.
- Compact heat exchanger ; micro channel heat exchanger with high thermal efficiency
- Very large heat transfer area.
- Relative straightforward construction and fabrication for the same heat exchange duty
- Propensity for self-cleaning.

CHAPTER -2

LITERATURE REVIEW

In 1816, Dr. Robert Stirling patented a concept which states that heat can be converted to work on a hot air engine through repeated expansion and compression of the working fluids at various temperature levels. This is the base line of the research done in refrigeration till date. Stirling cryocoolers were introduced to the commercial market in 1950 for the first time as cryocoolers for IR sensors and single cylinder air liquefiers to about 80K. In the 1960s, William Beale invented free-piston Stirling engines acting as power systems and has been in continuous development process since then. The first linear free piston cryocooler was developed at Phillips laboratory Eindhoven. In the 1970s, linear Stirling cryocooler was developed by Dr. G Davey, Oxford University which resulted in developments of various new components such as flexure springs , no contact seals, linear compressor etc [5].

In a typical Oxford type Stirling cryocooler the regenerator comprises of the frequency of piston, long stack of phosphorus bronze discs, and displacer is usually very high in this case and is around 30 to 60 Hz. The working fluid has a very complex oscillatory motion [6].

In the 1980s, The US navy had started a program, in which some new designs for cryocoolers were solicited and which would have a coefficient of performance within a range of 2000 to 10000 W/W [7].

In the year 1997, AFRL, Raytheon and JPL collaborated and developed a Stirling cryocooler operating in the range of 25K-120K [8].

In the same year, a light weight linear driven cryocooler was also developed for cryogenically cooled solid state Laser systems which were developed by Decade Optical Systems, Inc. (DOS Inc.) [9].

Barrett et al. has used a commercial computational fluid dynamics (CFD) software package Tomodel the oscillating flow inside a pulse tube cryocooler. The variation of temperature and velocity vectors is represented by a 2-D axis-symmetric model along with the addition of heat flux at the cold and hot end heat exchangers [10].

Yarbrough et al. have modeled the pressure drop using CFD through wire mesh regenerator. They developed a model with the use of computational fluid dynamics for the prediction of pressure drop through the wire mesh of regenerator which eventually facilitated the development of a cryocooler system model [11].

Anjun et al. have done both the numerical and experimental study to determine the characteristics of transfer of heat for cryogenic fluid helium by analyzing the physical properties which are temperature dependent and found cryogenic gas with temperature-dependent thermo physical properties are quite different from those in the ambient (or atmospheric) condition with constant thermo physical properties [12].

The earlier work done by Martini [13] was taken in practice at the University of Calgary to carry out simulations on these Stirling cryocoolers using codes of computer written in FORTRAN 77 language to create a way to use digital simulation program for CRYOWEISS, microcomputers by Walker et al [14].

The computer program was used to compare it with the experimental results of PPG-1 Stirling liquefier and also predict the results of it. A CFD code, CAST (Computer Aided Simulation of Turbulent flows) was developed by Peric and Scheuerer in 1989 [15]. This program was used for analyzing and computing a two dimensional unsteady state heat transfer phenomena. The code was written in computer language FORTRAN IV. The code was widely accepted but used mainly by the graduate students of Cleveland State University for the simulation and analysis of various components of Stirling machine.

CHAPTER- 3

COMPUTATIONAL FLUID DYNAMICS

3.1 Introduction

Computational Fluid Dynamics deals with the numerical solutions of heat, mass transfer and fluid flow problems by modeling the equations for particular cases and by numerical solution techniques and applying several assumptions by which it provide us the solution. Though the solution obtained through computational modeling can't be considered as the perfect one as there are several discrepancies and unrealistic results that might occur during simulation such as the assumptions, all the situations will go in an ideal condition. So the best way to study about a particular problem or situation is by an experimental method as it gives the actual insight of what the actual situation is. No simulation gives better results than experimental methods but it still has its pros and cons. Experimentations may involve certain errors such as measurement errors which are very much significant when we deal with the micro and nano fluidics. Also cost is another important factor that the researchers or analysers have to consider. There are few experiments which are very costly and thus they are not feasible enough to be performed in the large scale. Some use the scaled methods of experimentation but it also results in the discrepancy in the results. Next method of simulation is the numerical method. This method is the most exact method to get the precise results of literally any fluid flow problems or situations. But the limitation is that it is very much limited and can be applied only to some special cases. So we can see that the computational methods gives better results as compared to the other available options where we have to optimize the cost and time of experimentation by compromising over the results under the safe limits of error. The most straightforward method to solve fluid flow problems or situations , Navier Stokes equation with appropriate boundary conditions in the given problem. CFD simulation provides approximate solutions to the governing equations of fluid motion in the given problem. Application of the CFD simulation to analyze a fluid situation requires the following steps. Firstly, the mathematical equations which are the partial differential equations of second or even higher order which govern the fluid flow are modeled. These equations are then discretized using several discretization schemes based of Finite Volume method, Finite Difference Methods and Finite element analysis. The domain is divided into small grids or cells which are called meshes which can be quadrilateral, triangular or combination of both. Finally the operating conditions boundary conditions and operating conditions are specified in order to get the results based on our requirements. The result is iterative in nature as there are many steps involved and there are several controlling factors such as the least amount where we need our solutions to converge. Less the limit given, more exact will be the solution and more time it will take to solve.

The CFD simulation process contains three steps:

(1) Pre-processor: In this process, geometry of the flow domain is made and the boundaries and zones are given specific types. Then problem is setup by providing the operating conditions and boundary conditions.

(2) SOLVER: In this process the differential equations are discretized and solved through various discretization schemes.

(3) POST PROCESSOR: In this phase the results obtained after the solution are studied and compiled together in order to achieve at a general consent.

3.2 CFD Analysis of Stirling Cryocoolers

Governing Equations:

a. Mass Conservation Equation:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho\vec{V}\right) = 0$$

b. Momentum Conservation Equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}(\lambda + \mu)\nabla.\vec{V} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}\right) + \rho b_i$$

c. Energy Conservation Equation (For incompressible flow):

$$\rho c_p \frac{dT}{dt} = -\left(\frac{\partial \dot{q}_x}{\partial x} + \frac{\partial \dot{q}_y}{\partial y} + \frac{\partial \dot{q}_z}{\partial z}\right) + \dot{q}_h$$

Equilibrium Thermal Model Equations:

For simulations in which the porous medium and fluid flow are assumed to be in thermal equilibrium, the conduction flux in the porous medium uses an effective conductivity and the transient term includes the thermal inertia of the solid region on the medium:

$$\frac{\partial}{\partial t}(\gamma\rho_f E_f + (1-\gamma)\rho_s E_s) + \nabla.\left(\vec{v}\left(\rho_f E_f + \mathrm{p}\right)\right) = S_f^h + \nabla.\left[K_{eff}\nabla\mathrm{T} - \left(\sum h_i J_i\right) + (\bar{\bar{\tau}}.\vec{v})\right]$$

where

E_f = total fluid energy

E_s = total solid medium energy

ρ_f= fluid density

ρ_s = solid medium density

γ = porosity of the medium

K_{eff} = effective thermal conductivity of the medium

S_f^h= fluid enthalpy source term

The effective thermal conductivity in the porous medium, K_{eff} , is computed by ANSYS FLUENT as the volume average of the fluid conductivity and the solid conductivity:

$$K_{eff} = \gamma K_f + (1-\gamma)K_s$$

where

K_f = fluid phase thermal conductivity (including the turbulent contribution,

K_s = solid medium thermal conductivity

The fluid thermal conductivity K_f and the solid thermal conductivity K_s can be computed via user-defined functions.

The anisotropic effective thermal conductivity can also be specified via user-defined functions. In this case, the isotropic contributions from the fluid are added to the diagonal elements of the solid anisotropic thermal conductivity matrix.

3.3 MODELING THE GEOMETRY

3.3.1 GAMBIT:

A two dimensional geometry of Stirling cryocooler is created in GAMBIT. For meshes regular rectangular cells have been taken. In order to reduce the time consumption in simulation an axis-symmetric model has been made. The main components of the design are Piston, transfer line, after cooler, Compressor, hot space, regenerator and cold space. The dimensions of various components are shown in the following table and the subsequent figure which are taken from [16].

Sl. No.	Components	Radius(in mm)	Length (in mm)
1	Compressor	8	9
2	After cooler	8	3
3	Transfer line	1	55
4	Hot Heat	5	5
5	Regenerator	5	45
6	Cold Space	5	7
7	Piston	8	_
8	Displacer /Cold Piston	5	_

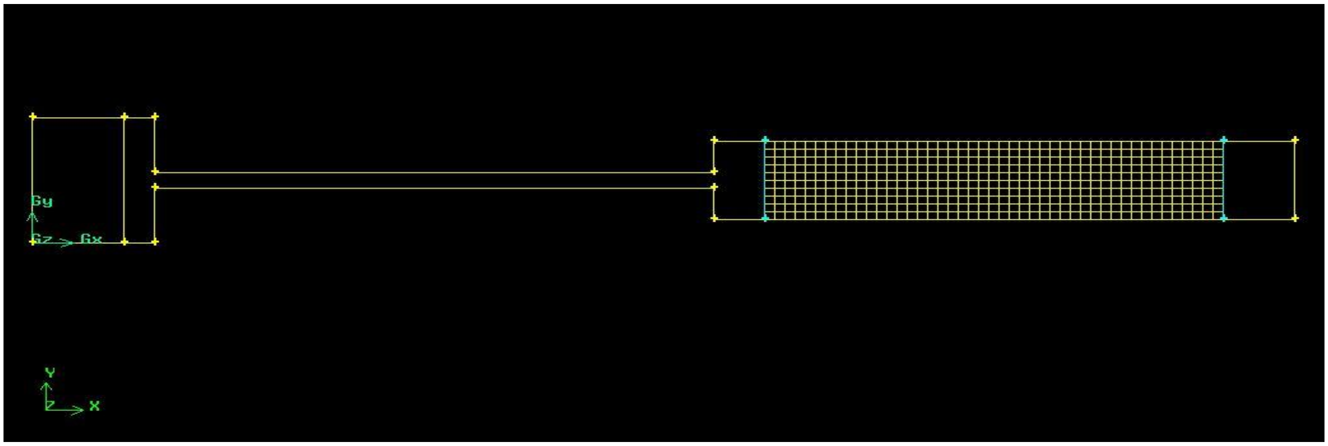

Fig. 9: Stirling cryocooler with Axis-symmetric model developed in GAMBIT

3.3.2 FLUENT

Fluent offers wide variety of freedom to solve any type of flow problems one could possibly come across. It provides tools and accessories to devise new technologies and also to optimize or modify the existing ones. The technology can help us to design complicated simulations to test them how they will be behaving in real world.

3.3.3 SETTING UP THE PROBLEM IN FLUENT:

The mesh file is incorporated in FLUENT after defining zones and proper boundary types to the geometry. The mesh is being read by the FLUENT and the cell sizing came out to be 420 cells, 998 faces, 579 nodes and 1 partition. The whole situation is then designed based on the boundary conditions and operating conditions prevailing in actual conditions for which we are designing the simulation. For this study, the above mentioned cell was scaled by a factor of 0.001 in order to convert the units to mm. The detailed inputs given are listed as :

Details of Solver	
Solver	Segregated
Formulation	Implicit
Space	Axis-Symmetric
Time	Unsteady
Velocity Formulation	Absolute
Unsteady formulation	1^{st} order implicit
Gradient Option	Cell Based
Porous Formulation	Physical velocity
Energy Equation	On
Details of Viscous Model	
Model	k-epsilon (2eqns)
k-epsilon model	standard
Material	Helium, air and steel
Operating Conditions	1 atm

Solution Controls	
Equations	Flow, Energy and Turbulence
Under relaxation factors	Pressure= 0.1 Density- 1 Body Forces- 1
Pressure velocity coupling	PISO
Skewness correction	1
Discretization scheme	
Pressure	PRESTO!
Density	First order upwind
Momentum	First Order Upwind
Turbulent dissipation rate	Second Order upwind
Turbulent Kinetic Energy	Second Order upwind
Energy	Second Order upwind
Solution Initialization	
Computation from	All zones
Gauge pressure	20 atm
Axial Velocity	0 m/s
Temperature	300 K
Turbulent kinetic energy	1
Turbulent dissipation rate	1

Pressure limits	5 atm – 35 atm
Residual Monitors	Convergence criterion
Continuity	1e-06
x-velocity	1e-06
y-velocity	1e-06
energy	1e-06
k	1e-06
epsilon	1e-06

Boundary conditions:

After cooler and hot space were chosen to have isothermal walls while rest of the walls were chosen to be adiabatic with either zero heat flux or a certain heat flux depending upon the case to be simulated. Regenerator and after cooler are considered to be porous zones. The detailed boundary conditions are mentioned below.

• **Piston:** The material was steel and wall was chosen to be an adiabatic.

• **Compressor:** The walls were chosen to be made of steel and were adiabatic. The compressor space was filled with Helium.

• **After cooler:** The walls were chosen to be isothermal, maintaining a constant temperature of 300K. The interior of the after cooler was chosen to be a porous zone. Details of the porous medium are given below which are taken from [17].

Porosity: 0.7

Viscosity: X: 9.433e+09 1/m^2; Y: 9.433e+09 1/m^2

Inertial *resistance*: Y: 76090 1/; m X: 76090 1/m

The void spaces were filled with Helium , the material of the porous zone and the walls were chosen to be steel .

• **Transfer line:** The walls of the transfer line are adiabatic and are made of steel. Its interior is filled with Helium.

• **Hot space:** The walls of the hot space are made of steel and maintaining a constant temperature of 300K. The hot space is filled with helium.

Regenerator: The regenerator is chosen to be a porous medium with the following details [17]

Porosity: 0.7

Viscosity: X: 9.433e+09 1/m^2; Y: 9.433e+09 1/m^2

Inertial resistance: Y: 76090 1/m; X: 76090 1/m

The material of the walls and the porous zone were chosen to be steel and the void spaces were filled with Helium gas.

• **Cold space:** Its walls were adiabatic and space is filled with Helium gas. The material Of walls of the cold space is steel.

• **Displacer:** The displacer is adiabatic in nature and made of steel.

Description of work:

Two UDF for the motion of compressor and cold wall have been compiled for the sinusoidal motion between them with a phase angle of 100 degrees. There are three governing equations for this problem- Flow, Energy and Turbulence . The under relaxation factors are taken in order to get faster and better simulations. The solution was started from all zones with initial gauge pressure of 20 atm. We have been monitoring the temperature of cold fluid and the temperature of cold wall. The time step size was taken as 0.0007.

Initially the solutions were converging at around 100 iterations and 1 second in real time took around 4 days in simulation. So considering the time factor in mind the simulation was run for 15 days at 190 iterations for a real time run for 5 seconds and the solutions till this point converged fully. After the cold fluid temperature dropped to 150K we have reduced the maximum iterations per time step to 50 and then 10 for faster simulations.

The temperature of cold fluid has been dropping exponentially to 70 K where it became asymptote to the time axis at around 73 second's actual time. But the cold wall temperature was still dropping continuously as the temperature of the fluid in contact with it is very less. The reason for such a big temperature drop can be accounted for the fact that we have operated the cryocooler at no load condition so the results obtained so far are under ideal conditions.

Now we are attempting to introduce heat flux of 250mW and see the variation in the minimum temperature achieved by the cold fluid and the refrigeration effect.

3.3.4 Motion of Piston and displacer

The motion of piston and displacer is governed by the User Defined Functions. The sinusoidal motion is considered. The displacer and piston are happened to maintain a phase angle of 100 degree during their motion. The codes were formed after research and some study from the FLUENT UDF Manual [18].

CHAPTER 4

RESULTS AND DISCUSSIONS

There are steady periodic simulations of CFD and results of which are presented and discussed. The geometry of the Stirling cryocooler is made in GAMBIT and the simulations were done in fluent. Various cases were taken into consideration by varying the frequencies, boundary conditions so that an optimum solution can be found. The geometry remains same during the simulations and only the existing conditions were altered. In the first simulation, no load case or adiabatic is taken at the cold end. In the next simulation, we have taken isothermal condition with a heat load of 0.25 W and then isothermal condition with various speeds of reciprocating piston. The simulations with 0.25 load at cold end were done at frequency of 20 Hz. No load condition at cold end means there is no heat flux through cold wall and there was one more case in which there was simulation with heat load of 250 mW at the cold end.

4.1 NO LOAD CASE WITH FREQUENCY OF 20 HZ

In this the simulation with Stirling cryocooler geometry was run and the frequency of displacer and reciprocating piston was kept at 20 Hz. There is no heat flux at the cold end of the cryocooler. The residual monitor plot for this case is shown below in the Fig.9

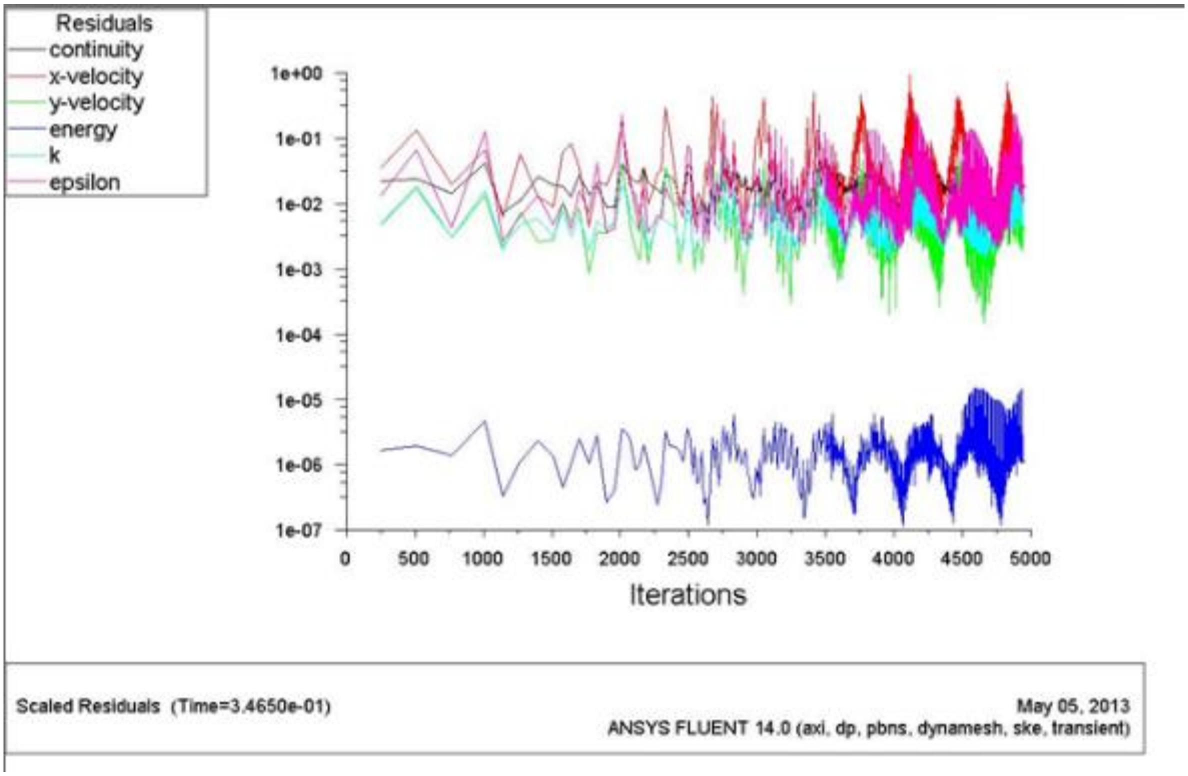

Fig. 9: Residual Monitor Plot for cryocooler with no load condition with 20 hz frequency

4.1.1 COOLING BEHAVIOUR

The cooling behavior of the cold end is like a sinusoidal curve which is constantly decreasing. The temperature of the cold space wall and cold fluid decreases constantly. It looks like as it is given below in Fig.10.

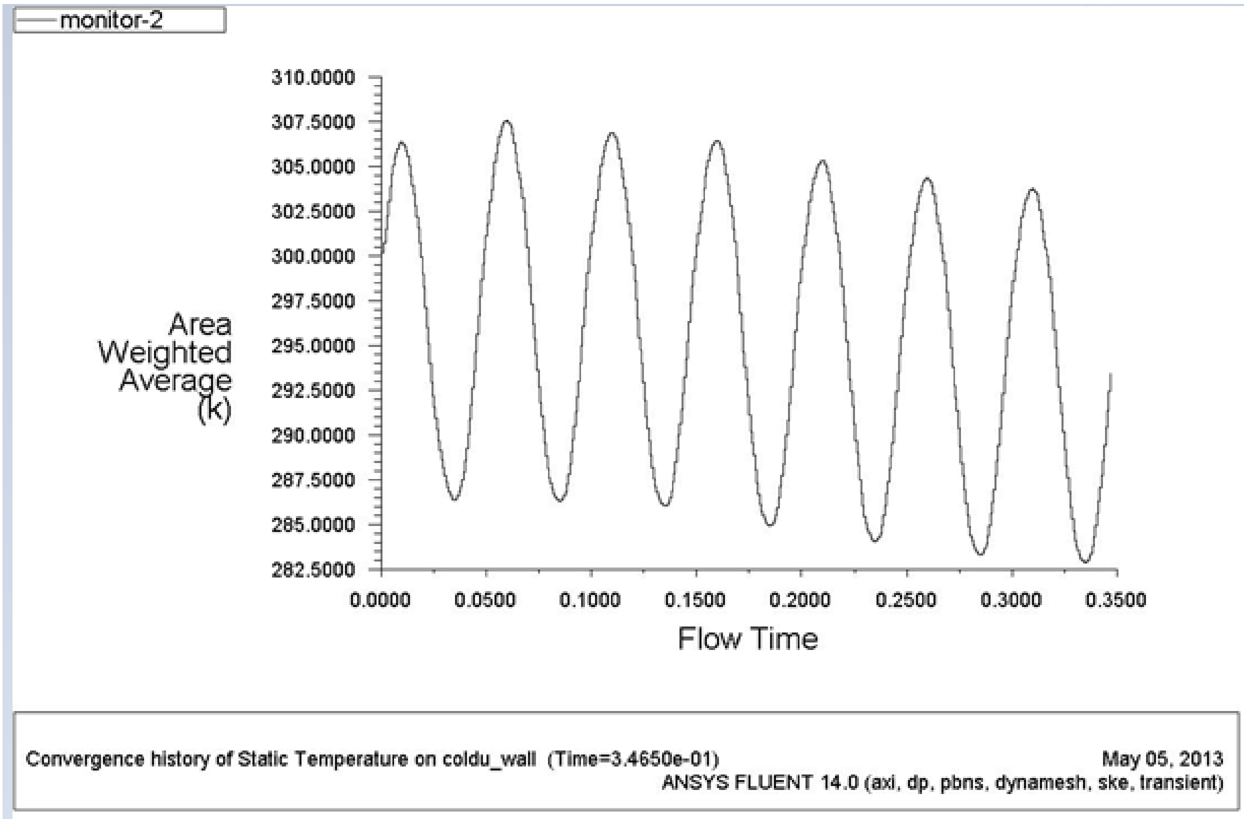

Fig. 10: Sinusoidal variation of temperature of cold space of stirling cryocooler

4.1.2 TEMPERATURE CONTOUR

The temperature gradient in the cryocooler in around 73 seconds of simulation can be seen in Fig.11 given. The maximum temperature is obtained at the compressor end and while the lowest temperature is obtained at the cold end of the cryocooler. The temperature at the left side of the displacer is higher and it gradually decreases as we move towards cold space.

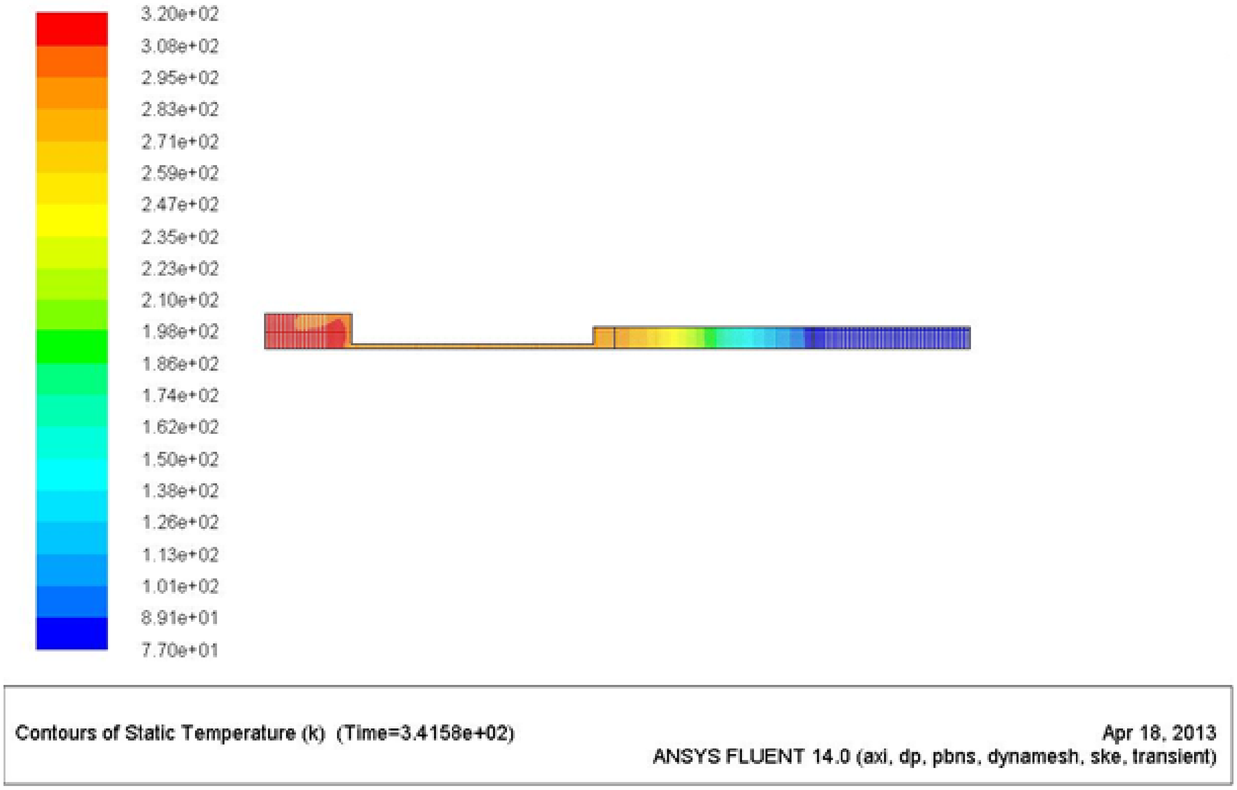

Fig. 11: Temperature contour of cryocooler with no load condition with 20 Hz

4.1.3 TEMPERATURE PLOT

Following figure (Fig.12 below) shows the temperature profile along the Stirling cryocooler length. Compressor position shows the highest temperature whereas the cold space position shows the lowest temperature.

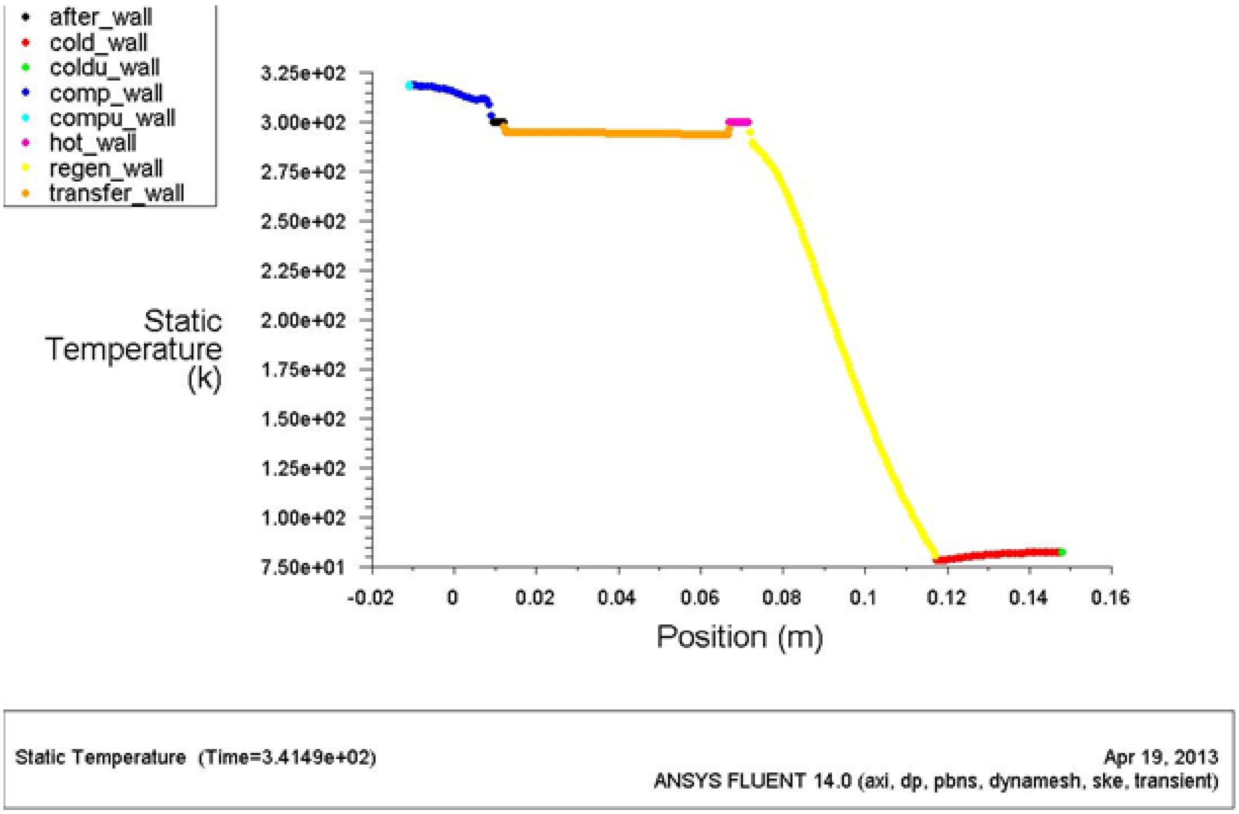

Fig. 12: Temperature plot for Stirling cryocooler at no load with 20 Hz

4.1.6 PRESSURE CONTOUR

The Fig.13 below shows the variation of the pressure along the length of the Stirling cryocooler and it was observed that the pressure decreases along the length of cryocooler.

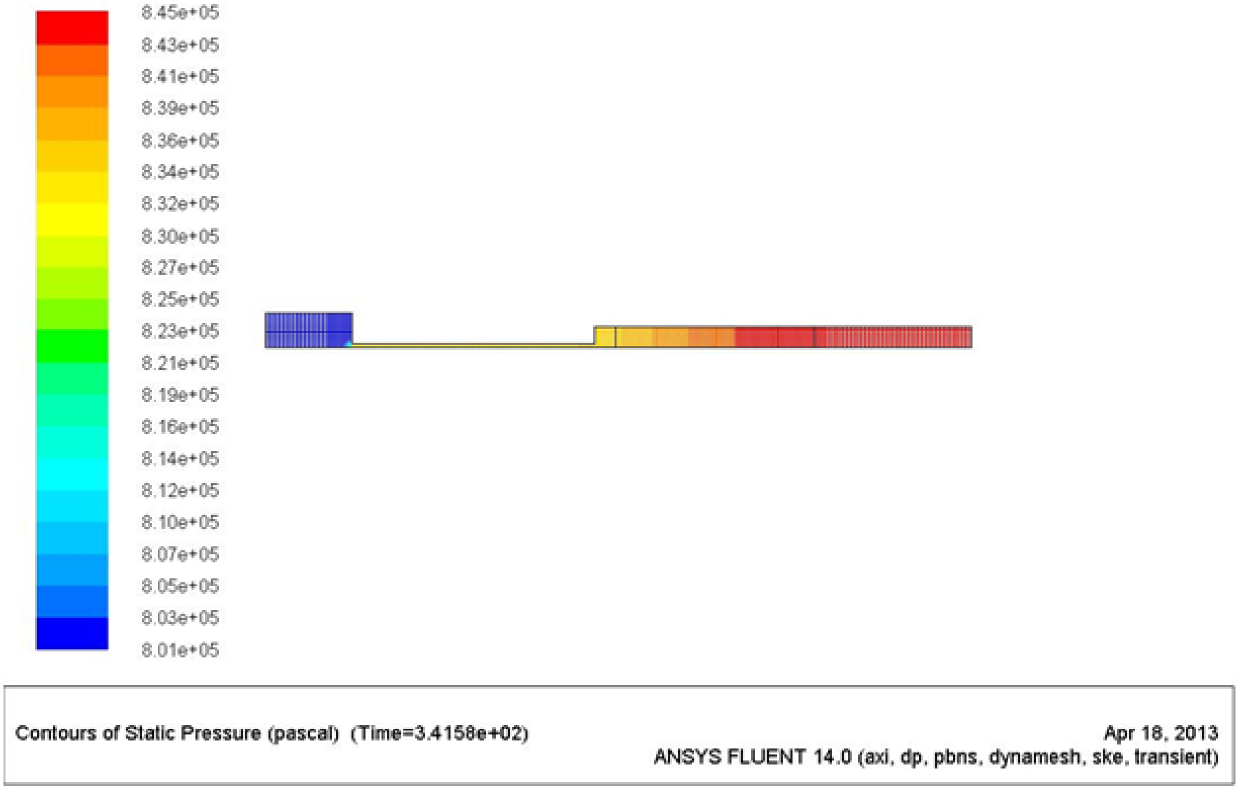

Fig. 13: Pressure contour of Stirling cryocooler at no load at 20 Hz

4.1.7 VELOCITY VECTOR

The plot of Fig.14 below shows how the gas or fluid flow takes place inside the Stirling cryocooler. The arrow marks represent the velocity of the fluid particles and they are plotted in terms of velocity magnitude represented by their colors. The velocity of the fluid through the regenerator is very less Due to the resistance offered to the flow.

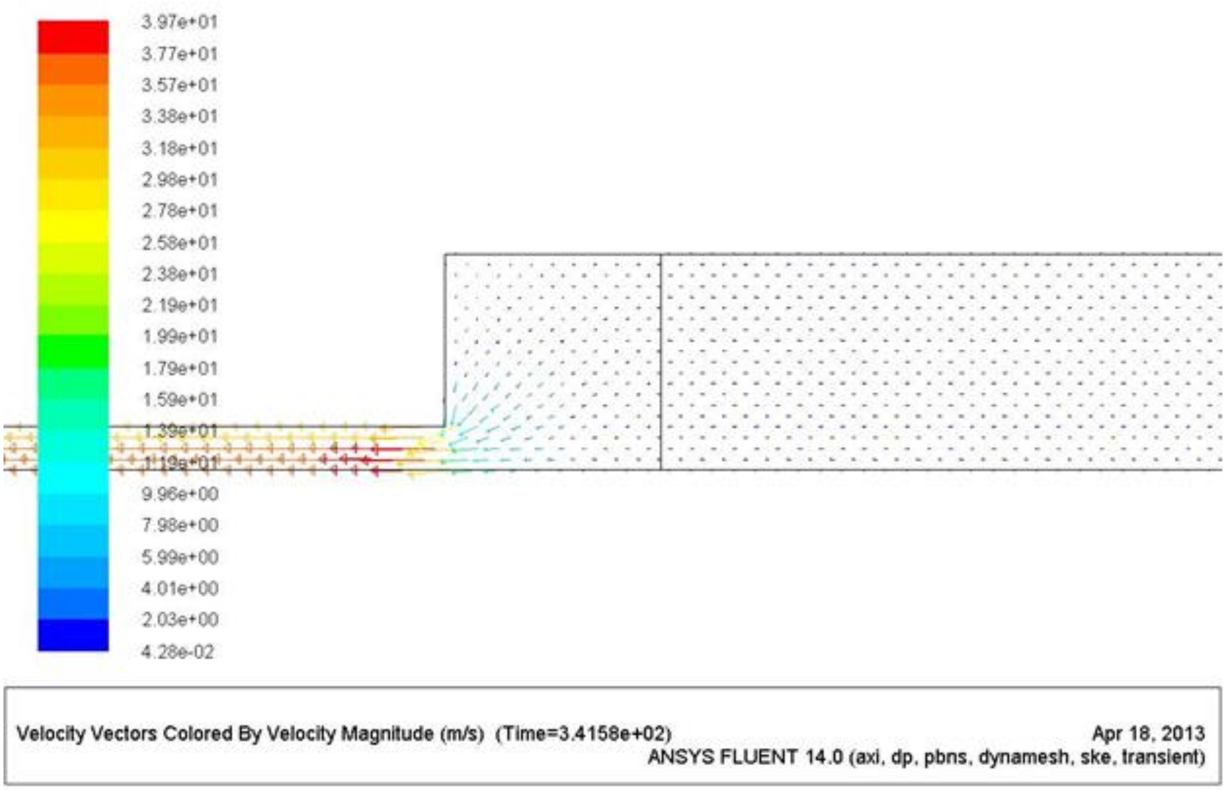

Fig. 14: velocity vector profile of Stirling cryocooler at no load at 20 Hz

4.2 LOAD CASE WITH 20 Hz

4.2.1 RESIDUAL PLOT

In this the residual monitors of each parameter is shown i.e. how it is varying with errors and the time are lying within the range defined before the simulation. This is shown in the Fig.15

below.

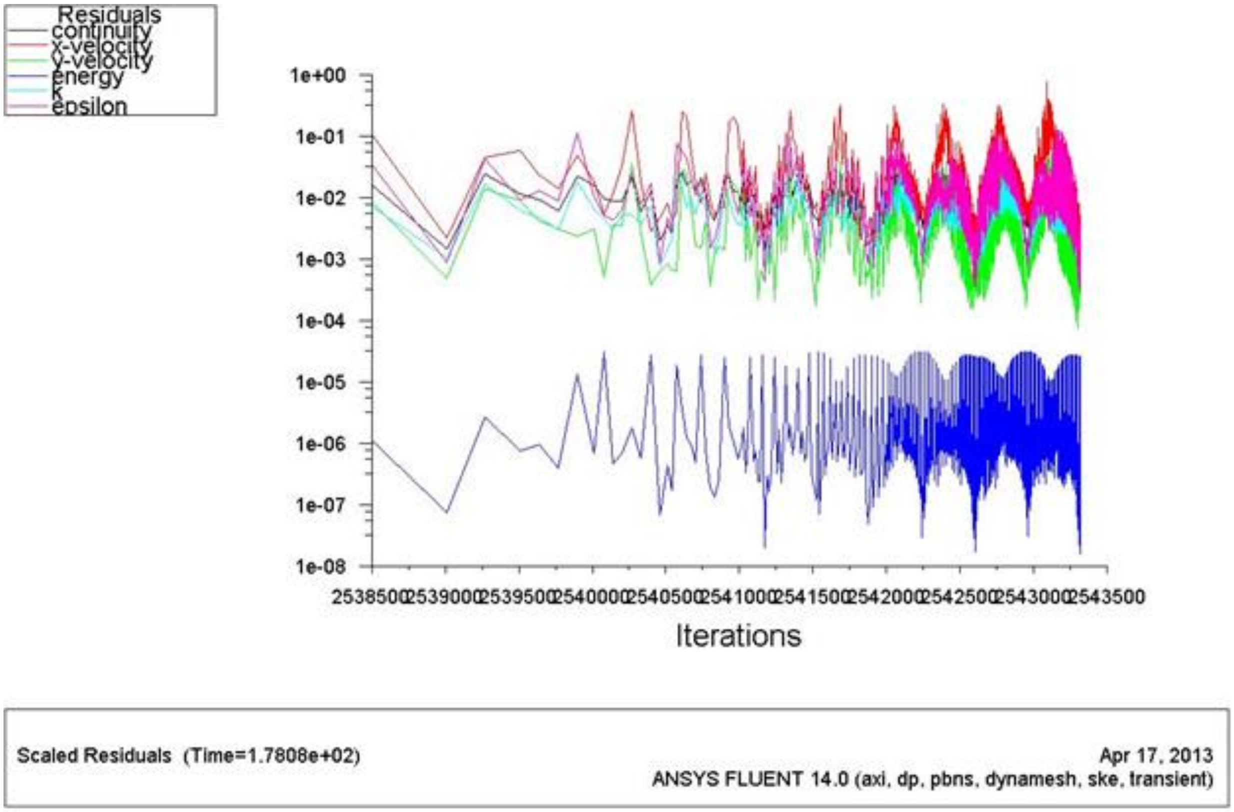

Fig. 15: Residual plot for Stirling cryocooler at 0.25 W load with 20 Hz

4.2.2 PRESSURE AND TEMPERATURE CONTOUR

There are pressure and temperature contours which shows the pressure and temperature values in different region of the stirling cryocooler. The low and high values of pressure and temperature are shown by blue and red colours respectively and in between different colours are used to represent different values. These are shown in Fig.16 and Fig.17 below respectively.

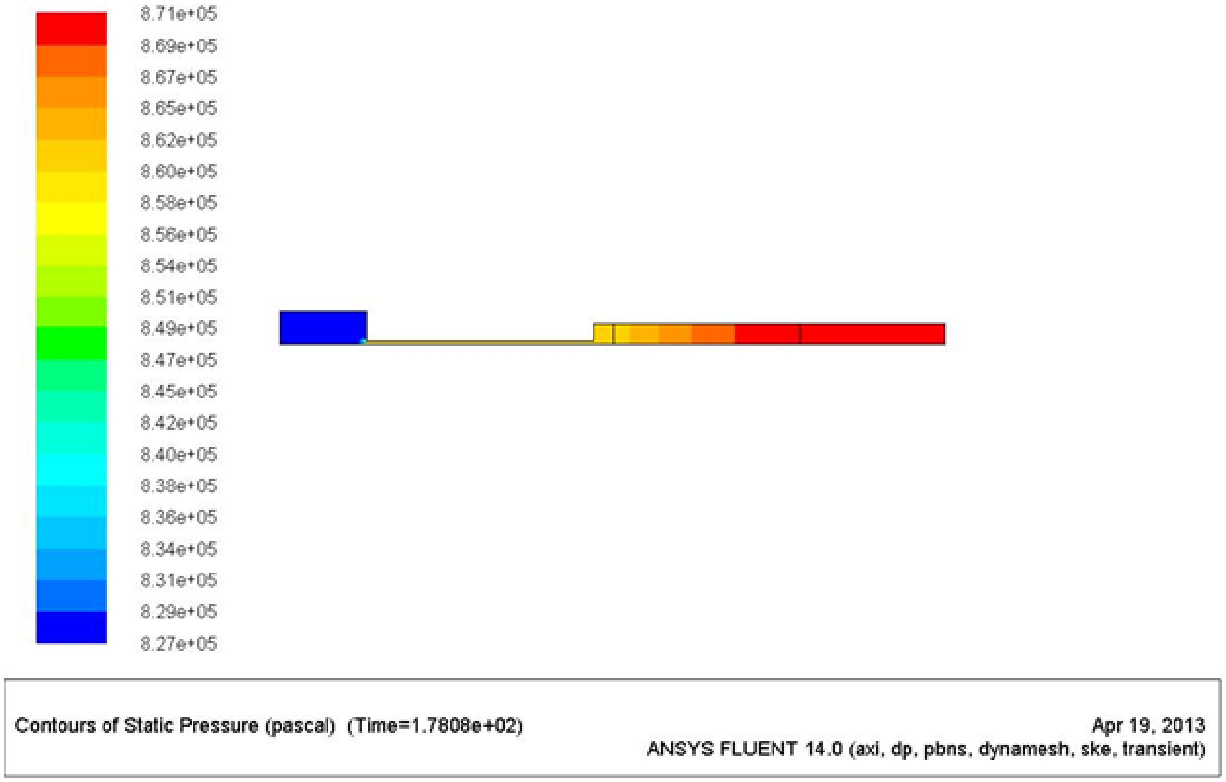

Fig. 16: Pressure contour of Stirling cryocooler with 0.25 W Load

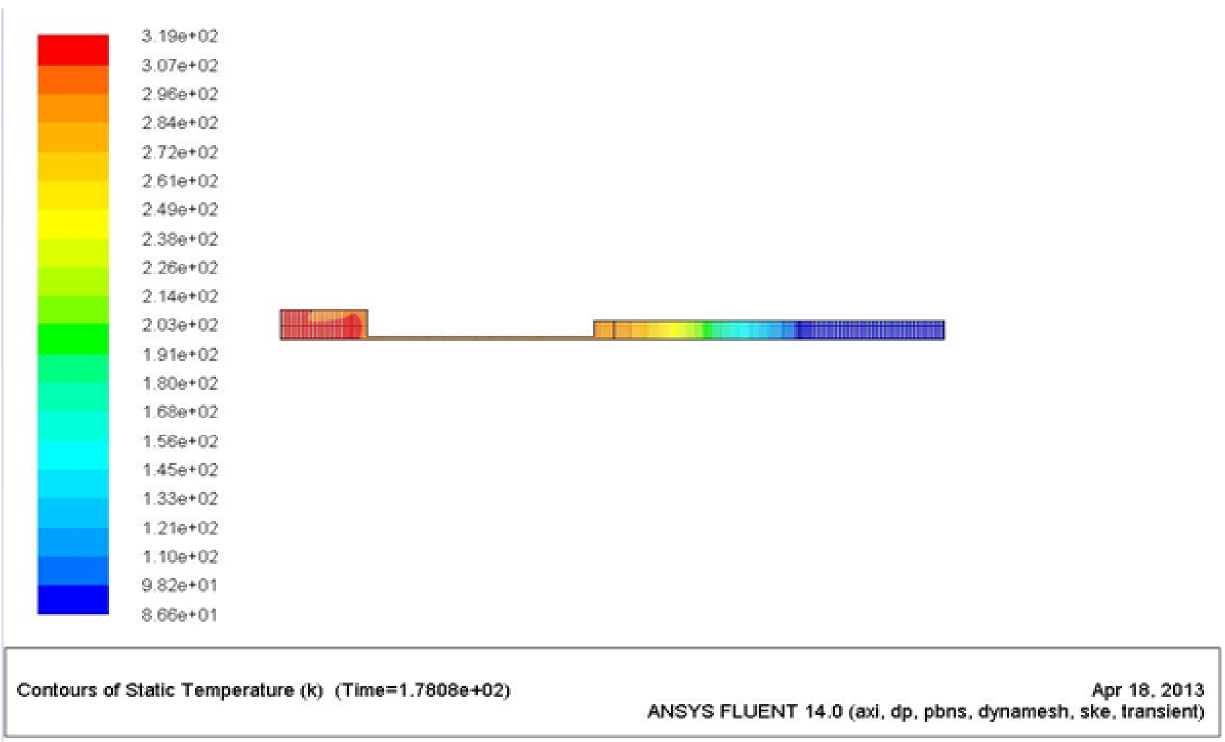

Fig. 17: Temperature contour of Stirling cryocooler with 0.25 W Load

4.2.3 TEMPERATURE PLOT

These are temperature curves which are showing variation of temperature along the axial length of the Stirling cryocooler. The curves are shown in Fig.18 below.

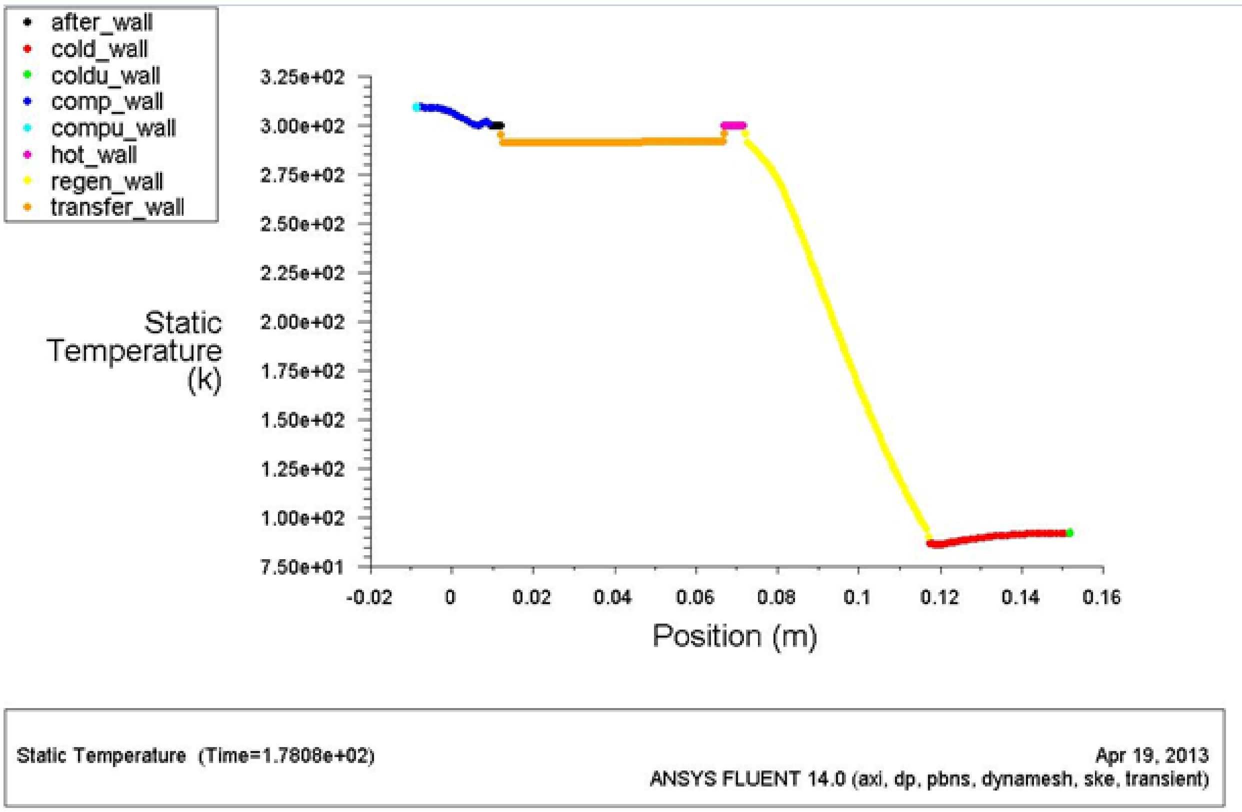

Fig. 18: Temperature plot of Stirling cryocooler at 0.25 W Load

4.2.4 VELOCITY VECTOR

The Fig.19 below shows during simulation how the fluid particles move inside the Stirling cryocooler. The arrows are the directional vectors of the fluid particles and the magnitude of the velocity at each point is represented by different colors whose demarcations are shown in the left side of the figure below.

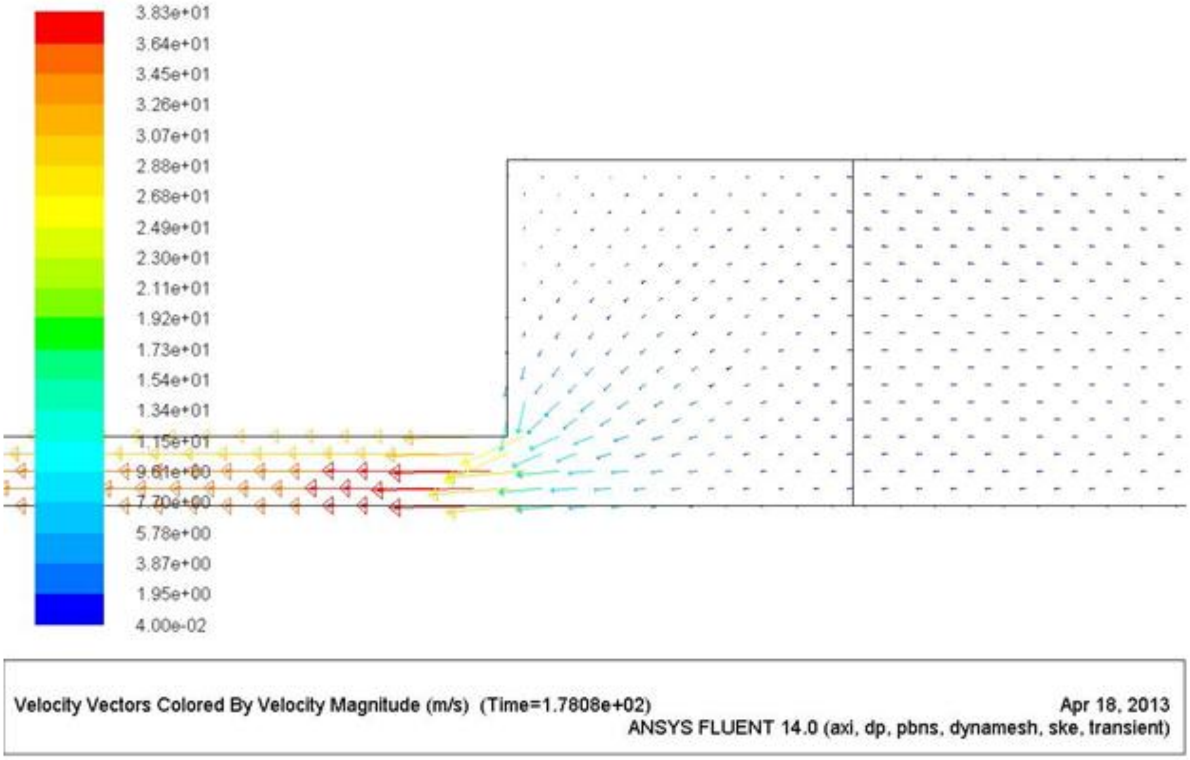

Fig. 19: Velocity vector plot of Stirling cryocooler at 0.25 W Load

CHAPTER -5

CONCLUSIONS

CFD Simulations of the Stirling cryocooler was successfully developed. There were a lot of requirements while simulating a case of cryocooler. The motions of both regenerator and piston were obtained by hooking up UDF'S to the regenerator part and the compressor part. There are different cases of simulations of Stirling cryocooler. For no load case at the cold end the minimum temperature attained was around 70 k with 20 Hz of operating frequency and 80 k with 0.25 W of Load with 20 Hz of operating frequency. The comparison between the two cases shows that the minimum temperature attained is lowest in case of no load but with load condition the minimum temperature increased.

SUGGESTIONS FOR FUTURE WORK

1. There are various areas of cryocooler on which improvements can be done. The most important issue is of losses with Stirling cryocooler. There are various losses like pressure drop losses due to filling of regenerator void volume during pressurization and due to friction across the regenerator then also and depressurization of the regenerator. There is also regenerator thermal loss due to heat transfer to the surrounding by it [19]. There are also acoustic losses and shuttle losses. Shuttle loss is the heat loss due to relative motion between the displacer and it's housing which is due to the temperature difference created between them [20]. Thermal acoustic losses are due to the oscillating flow of the working fluid i.e. helium inside that gap. due to the relative motion of the two walls and due to difference in the heat capacities of the two bounding walls, there is a heat transfer loss [21]. This loss depends upon flow velocities of the working fluid and pressure amplitude.
A proper Schmidt analysis of above mentioned losses can be done and by including their effects in the simulations, results for an optimized geometry of regenerator can be obtained, so that minimum temperature of refrigeration can be obtained while including all the constraints [22].
This can be done by making a non equilibrium model of the case. All the above simulations which are done in this report are in equilibrium model. The thermal conductivity of steel material of regenerator and other parts of the cryocooler also varies with temperature in all the zones [24], so that should also be considered while writing the UDF'S.

2. The simulations which are done in this report are made by moving the last edge of the cold end in an exact phase relationship with that of the piston. But in reality the displacer is moved to and fro inside the cylinder. Also in all the above simulations there is no gap taken between the displacer and the regenerator housing but in actual case there is a gap of very small thickness. So all the above constraints are need to be included and then further simulations can be done for obtaining the results for more practical case. The gap model and displacer motion can be modeled separately first and then after obtaining positive results, they can be brought up together to create a single model for both the cases.

3. The boundary conditions which are taken in the case where there is no load in the cold space are not totally justified. The temperature of the cold wall was taken to be constant but in the actual case the temperature will vary. Also in both the cases of load and no load at the cold space the temperature of the regenerator wall is taken constant but in actual case it will vary due to some heat loss at the regenerator wall. Also the thermal conductivity of the cold space wall and porous material are taken to be constant but in actual case it will vary with temperature, so these can be included and then further simulations can be done.

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