CFD SIMULATION OF A SMALL STIRLING CRYOCOOLER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

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In

Mechanical Engineering

By

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CERTIFICATE

This is to certify that the project entitled "CFD Simulation of a small Stirling Cryocoolers", being submitted by Mr. Amrit Bikram Sahu, in the partial fulfillment of the requirement for the award of the degree of B. Tech in Mechanical Engineering, is a record of bonafide research carried out by him at the Department of Mechanical Engineering, National Institute of Technology Rourkela, under our guidance and supervision.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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CONTENTS

ABSTRACT

The application of cryocoolers has skyrocketed due to various necessities of modern day applications such as adequate refrigeration at specified temperature with low power input, long lifetime, high reliability and maintenance free operation with minimum vibration and noise, compactness and light weight. The demand of Stirling cryocoolers has increased due to the ineffectiveness of Rankine cooling systems at lower temperatures. With the rise in applications of Stirling cryocoolers, especially in the field of space and military, several simulations of Stirling cryocoolers were developed. These simulations provided an edge to the developers, as it could provide an accurate analysis of the performance of the cryocooler before actually manufacturing it. This saved a lot of time and money. In this project, an attempt has been made to develop a CFD simulation of a small Stirling cryocooler. A detailed analysis has been done of the simulation of the cryocooler in the results and discussion section. A comparison has also been made between the cooling curves in no load and a 0.5W load case. An attempt has also been made in determining the optimum frequency of operation of the proposed model of Stirling cryocooler by comparing the minimum cool down temperature attained by them.

LIST OF FIGURES:

CHAPTER 1

INTRODCUTION

1.1. CRYOCOOLERS:

Cryocooler can be simply defined as a refrigeration machine that provides refrigeration in a temperature range of 0K – 150K. Recent development of technologies, especially in the domain of space and military applications, has significantly increased the application of cryogenics.

1.2. TYPES OF CRYCOCOOLERS:

Cryocoolers can be classified on the basis of types of operating cycle and on the basis of type of heat exchanger.

1.2.1. Types of operating cycles:

- *Open cycle cryocoolers*:

These are cryocoolers that use stored cryogens either in subcritical or supercritical liquid state, solid cryogens or stored as high pressure gas with a Joule- Thomson expansion valve.

- *Closed cycle cryocoolers*:

Closed cycle cryocoolers provide cooling at cryogenic temperature and reject heat at very high temperatures. They are also known as mechanical cryocoolers. A few examples are Stirling cryocoolers, Brayton cycle cryocoolers, closed cycle Joule-Thomson cryocoolers etc.

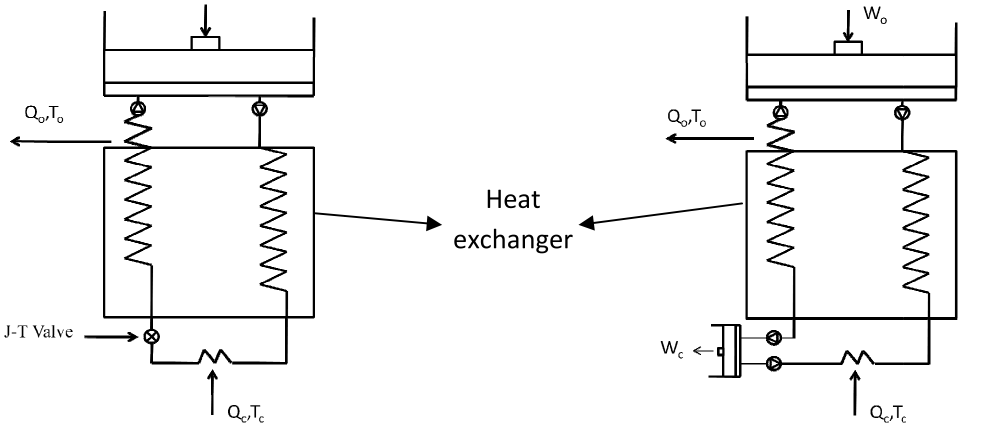
1.2.2. Types of heat exchangers used:

- *Recuperative cryocoolers*:

These are analogous to DC electrical systems since the direction of flow of the working fluid is in one direction only. Due to this reason, the compressor and expander have separate inlet and outlet valves to maintain the flow direction. Valves are necessary unless the system has any rotary or turbine elements. The performance of these cryocoolers primarily depends upon the type of working fluid or refrigerant used. One of the main advantages of these cryocoolers is that it can be scaled to any size (i.e. even upto the order of few MWs). They can be further classified into valveless and with valves cryocoolers. A few examples of recuperative cryocoolers can be seen in Fig.1.

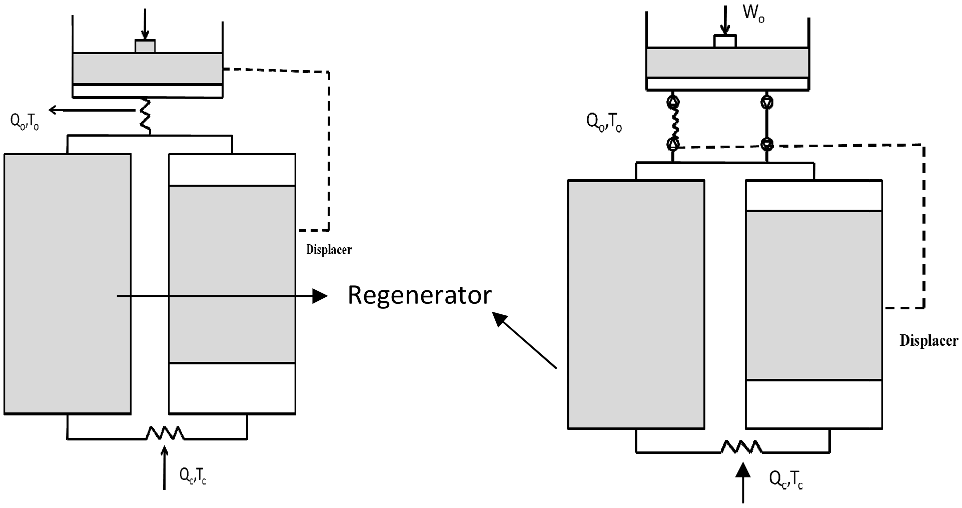
- *Regenerative cryocoolers*:

These cryocoolers are analogous to AC electrical system since the working fluid oscillates in the flow channel. The compressor and expander do not need any valves since there is a single flow channel. The regenerator, which has a very high heat capacity, stores the heat for half a cycle and then releases it back to the working fluid. These cryocoolers cannot be scaled up to large sizes, however, these are very efficient because of very low heat transfer loss. Liquid helium is commonly used as working fluid in these types of cryocoolers. Fig.2 shows a few examples of regenerative cryocoolers.



(a) Joule-Thomson **(b) Brayton**

Fig. 1 Examples of recuperative type cryocoolers



(a) Stirling **(b) Gifford Mc Mahon**

Fig. 2 Examples of Regenerative type cryocoolers

1.3. APPLICATIONS OF CRYOCOOLERS:

1.3.1. Military applications*:*

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

1.3.2. Environmental:

- IR sensors for atmospheric studies(satellite based)
- IR sensors for pollution control.

1.3.3. Medical applications:

- Cooling superconductors for MRI
- Cryosurgery

1.3.4. Commercial applications:

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

1.3.5. Transport applications:

- Superconducting magnets for maglev trains

1.4. STIRLING CRYOCOOLER:

Stirling cryocoolers are regenerator type cryocoolers which work on the basis of Stirling cycle. An ideal Stirling cycle consists of two isothermal process and two constant volume processes as seen in Fig. 3. The detailed explanation of Stirling cycle has been done in the following section.

1.4.1. Stirling cycle:

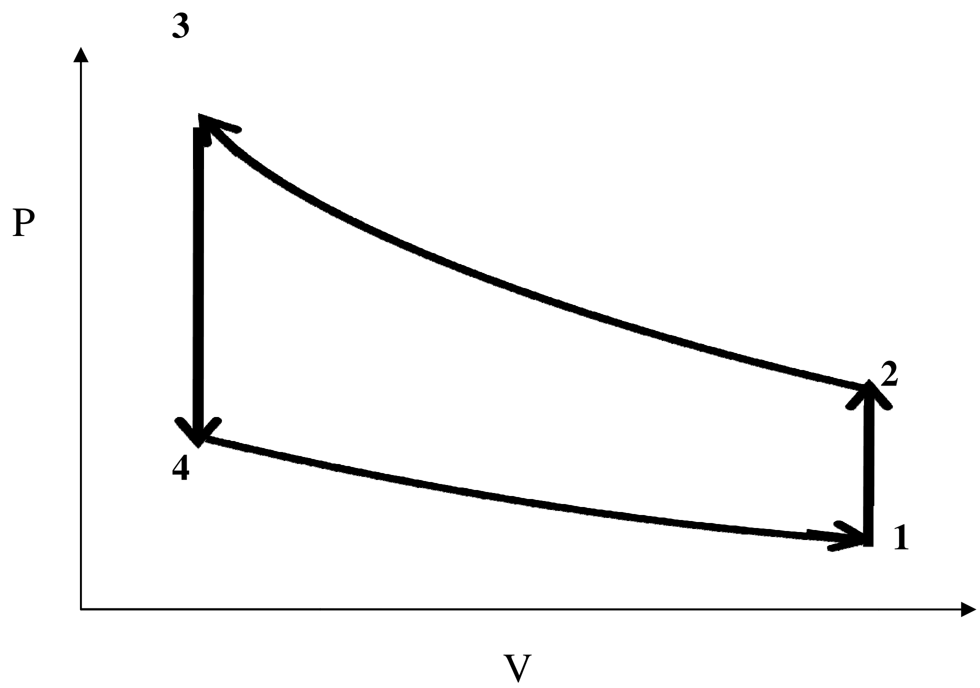


Fig. 3 Thermodynamic processes of an ideal Stirling cycle

An ideal Stirling cycle has two isothermal process and two constant volume processes. Fig. 3 shows a reverse Stirling cycle on the basis of which a Stirling refrigerator works. The Stirling cycle can be explained by four thermodynamic processes.

- *Isothermal Expansion*:

  The expansion space and associated heat exchanger are maintained at a constant temperature while the gas undergoes isothermal expansion owing to the expansion in volume of the cryocooler.

- *Isochoric Heat Addition*:

  The gas passes through the regenerator where it gains much heat because of lower enthalpy of gas than the regenerator.

- *Isothermal Compression*:

  The piston compresses the gas and the gas undergoes isothermal compression where the temperature of compression space and associated heat exchanger are maintained constant.

- *Isochoric Heat Rejection*:

  The gas passes back through the regenerator, losing heat to it, owing to higher enthalpy of gas than the regenerator.

1.4.2. Design of Stirling cryocooler:

The layout of a typical Stirling cryocooler has been shown in Fig. 4. The main components of the Stirling cryocooler are Piston, Compressor space, Aftercooler, Transfer line, Regenerator, Cold space and Hot space. Piston and Regenerator are the moving components of the cryocooler while rest is stationary. The Piston and Regenerator follow a reciprocating motion that is achieved by crank shaft mechanism coupled to a motor. The Piston and regenerator reciprocate with the same frequency as that of the driving motor. A phase difference of 90^o is usually maintained between the motion of Piston and Regenerator. This phase difference in the motion is the main cause of cooling effect produced. Detailed explanation of the cooling effect produced has been explained in the following section.

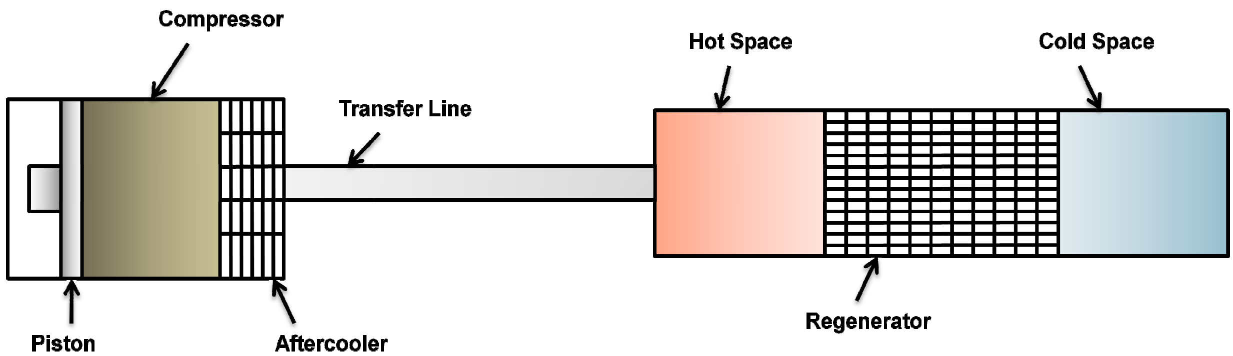


Fig. 4 Schematic representation of a Stirling cryocooler

1.4.3. Working of a Stirling cryocooler:

A Stirling cryocooler works on the basis of the Stirling cryocooler. An ideal Stirling cycle consists of two isothermal processes and two constant volume processes as shown in Fig.3. A schematic representation of a Stirling cryocooler has been done in Fig.4. The step by step working of the Stirling cryocooler has been described in the Fig.5

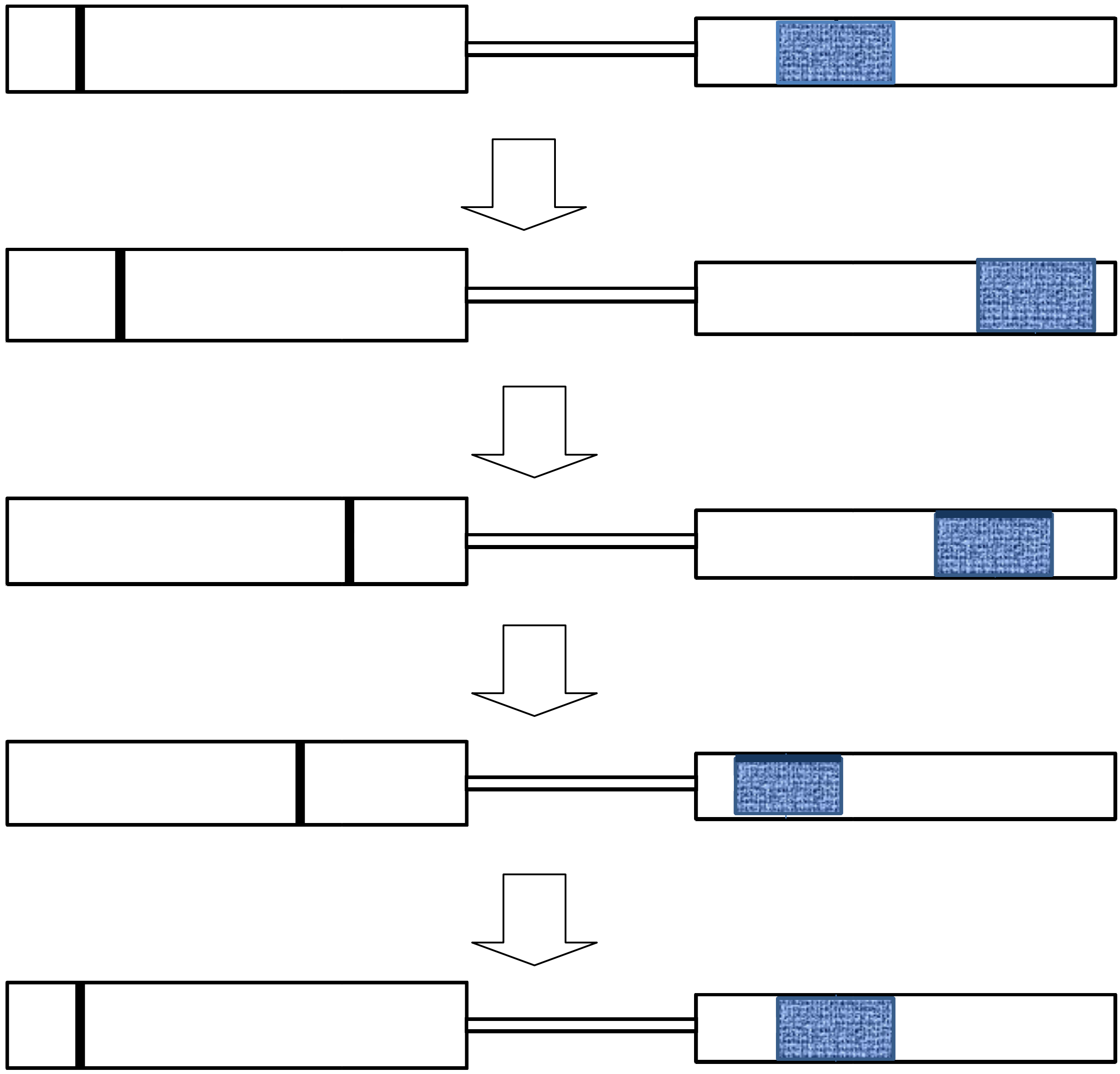


Fig. 5 Step by step process of the working of a Stirling cryocooler

Let the Stirling cryocooler be in the state of maximum volume at initial time. This position refers to state 1 in Fig.3. In this state the working fluid is at least pressure and minimum temperature and is present at the cold space. In the next step, the regenerator moves significantly forcing the fluid to pass through it while the piston stays almost stationary, thus maintaining a constant volume. Since the temperature of the fluid in cold space is lower than the temperature of regenerator, when the fluid passes through the regenerator it absorbs heat from the regenerator. Since the volume is almost constant, temperature rises and hence its pressure also rises which takes it to state 2. This is the constant volume heat addition process. Next the piston moves to compress the working fluid to minimum volume state and the maximum pressure state while the regenerator remains almost stationary. The fluid is at maximum temperature and is present in the hot space now and is in state 3. In the next step, the regenerator moves towards left thus forcing the hot fluid to flow through it. Since the temperature of the fluid is much higher than the regenerator temperature, it loses heat to the regenerator mesh and thus there is a decrease in pressure at constant volume. This is represented by state 4 in the Fig.3 . Now, the piston moves toward left causing expansion and hence, the temperature of the working fluid reduces and comes back to state 1. This is the state of minimum temperature. The expansion process causes the cooling effect. This cycle repeats itself in the Stirling cryocooler to reach a steady state and a minimum temperature state.

CHAPTER 2

LITERATURE SURVEY

2.1. EARLIER MODELS OF CRYOCOOLERS DEVELOPED:

As mentioned in the earlier sections, cryocoolers are now being widely applied in the areas of infrared detectors, superconductor filters, satellite based applications, Cryopumps etc. Stirling cryocoolers were introduced to the commercial market in 1950s for the first time as single cylinder air liquefiers and cryocoolers for IR sensors to about 80K. In early1960s, William Beale invented free-piston Stirling engines acting as power systems and have been in continuous development process since then. The first development of linear free-piston Stirling cryocooler was achieved at Philips laboratories, Eindhoven. Another significant linear Stirling cryocooler unit was developed by Dr. G. Davey, Oxford University. Oxford-split Stirling cryocooler have been developed since its invention in Oxford University in the year 1970s which resulted in developments of many new components such as no contact seals, flexure springs, linear compressor etc[1]. In an Oxford type Stirling cryocooler, the regenerator always contains a long-stack of phosphor-bronze discs, frequency of piston and displacer is very high (30 – 60 Hz) and the oscillating motion of the working fluid is very complicated [2]. Nowadays Oxford-split Stirling cryocoolers are largely found in space and flight based applications. In 1980, the US navy started a program, in which new designs for cryocoolers were solicited which would have a coefficient of performance within a range of 2000 to 10000 W/W. In addition to this, programs were received from NBS- Boulder where development of a nylon and fiberglass Stirling cycle cryocooler had begun under ONR support [3]. Over the last few decades, there have been rapid developments in the field of miniature free piston free displacer Stirling cryocooler. In 1997, AFRL, Raytheon and JPL together developed flight based Stirling cryocoolers whose operating range was 25K – 120K. It provided refrigeration upto 3W at 60K and 1.5W at 35K[4]. A light weight linear driven cryocooler was also developed for cryogenically cooled solid state Laser systems was developed by Decade Optical Systems, Inc. (DOS Inc.) in the year 1997[5]. It has been ascertained that all mechanical cryocoolers gained a sufficient amount of cooling capacity with unprecedentedly low amount of power consumption for the cooling requirement of large telescopes and other applications [6].

4.2.1. LITERATURE REVIEW OF SIMULATIONS OF STIRLING CRYOCOOLERS:

With the rapid development in the cryocooler design and functioning over the past 60 years, it became highly essential to develop computer based simulations for them. These simulations could provide a detailed analysis of the cryocooler's functioning and various characteristics before actually developing it, which in turn saves a lot of time and money. With this intent, the work for development of computer based simulations for cryocoolers began. Analysis of the ideal Stirling cycle was done by Schmidt (first order approach). He made assumptions such as steady state procedure with ideal regenerators and no pressure drops during the isothermal processes. The second order approach was largely developed by Martini, in which he further analyzed by adding realistic losses to the model developed by Schmidt. Realistic losses included pressure drop loss, shuttle loss, pumping loss, static heat loss, regenerator ineffectiveness [7]. He applied decoupled independent correction to account for various losses which have been thoroughly described in Martini's 1982 Stirling engine design manual [8]. During later half of the decade, this analysis of Martini was adopted for carrying out Stirling simulations at the University of Calgary which was later written in FORTRAN 77 language to create an easy to use digital simulation program for microcomputers, namely CRYOWEISS by Walker *et al* [7]. This program was used for predicting results of PPG-1 Stirling liquefier and for comparing it with experimental results. Under an Independent Research program at Lockheed's Research and

Development Division, a third order split-Stirling refrigerator model was developed. Continuous System Simulation Language (CSSL) was used for programming the model. The model had 90 nodes, maximum of which were found in the regenerator region [9]. This model was validated against experimental results for the Lucas Stirling refrigerators, carried out by Yuan et al [10]. Later, a dynamic model of a one-stage Oxford Stirling cryocooler was developed that could predict the dynamic processes and performances for the given structure dimensions and operating conditions [1].

A CFD code, CAST (Computer Aided Simulation of Turbulent flows) was developed by Peric and Scheuerer in 1989, for predicting two-dimensional flow and heat transfer phenomena. The code was written in FORTRAN IV. This code was used by several Cleveland State University graduate students to simulate various Stirling machine components. The development process of the CAST code has been explained in detail by Ibrahim *et al* [11]. In this case, Fluent has been used to simulate the Stirling cryocooler problem.

CHAPTER 3

COMPUTATIONAL FLUID DYNAMICS

3.1. COMPUTATIONAL FLUID DYNAMICS

3.1.1. Introduction:

During the last three decades, Computational Fluid Dynamics has been an emerged as an important element in professional engineering practice, cutting across several branches of engineering disciplines. CFD is concerned with numerical solution of differential equations governing transport of mass, momentum, and energy in moving fluids. Today, CFD finds extensive usage in basic and applied research, in design of engineering equipment, and in calculation of environmental and geophysical phenomena. For a long time, design of various engineering components like heat exchangers, furnace etc required generation of empirical information which were very difficult to generate. Another disadvantage of these empirical information is that, they are applicable for a limited range of scales of fluid velocity temperature etc. Fortunately, solving differential equations describing mass transport, momentum and energy and then interpreting the solution to practical design was the key to the whole designing process. With the advent of computers, these differential equations were solved at a speed that increased exponentially and hence the applications of CFD became widespread.

3.1.2. Governing equations:

The three main governing equations are mentioned below:

- *Transport of mass*:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial(\rho_m u_j)}{\partial x_j} = 0 \quad (1)$$

- *Momentum equation*:

$$\frac{\partial(\rho_m u_i)}{\partial t} + \frac{\partial(\rho_m u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu_{eff}\frac{\partial u_i}{\partial x_j}\right] - \frac{\partial p}{\partial x_i} + \rho_m B_i + S_{u_i} \quad (2)$$

- *Energy equation*:

$$\frac{\partial(\rho_m h)}{\partial t} + \frac{\partial(\rho_m u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{k_{eff}}{C_{pm}}\frac{\partial h}{\partial x_j}\right] + Q''' \quad (3)$$

3.1.3. Steps in a typical CFD problem:

- The physical domain is specified according to the given flow situation.
- Various boundary conditions, fluid properties are defined and appropriate transport equations are selected.
- Nodes are defined in the space to map it into the form of a grid and control volumes are defined around each node.

- Differential equations are integrated over a control volume to convert them into an algebraic one. Some of the popular techniques used for discretization are finite difference method and finite volume method.
- A numerical method is devised to solve the set of algebraic equations and a computer program is developed to implement the numerical method.
- The solution is interpreted.
- The results are displayed and post process analysis is done.

CFD can be broadly divided in to 3 elements as shown in Fig. 6:

- *Preprocessor*:

During preprocessing, the user

- Defines the modeling goals
- Identifies the computational domains
- Designs and creates the grid system

- *Main Solver*:

The main solver sets up the equations required to compute the flow field according to the various options and criteria chosen by the user. It also meshes the points created by the preprocessor which is essential for solving fluid flow problems. The process broadly includes selecting proper physical model, defining material properties, boundary conditions, operating conditions, setting up solver controls, limits, initializing solutions, solving equations and finally saving the output data for post process analysis.

- *Post processor*:

It is the last but a very important part of CFD in which the results of the simulation is examined and conclusions are drawn. It allows user to plot various data in the form of graphs, contours, vectors etc. Global parameters like Nusselt number, friction factor Reynolds number etc can be calculated and data can be exported for better visualizations.

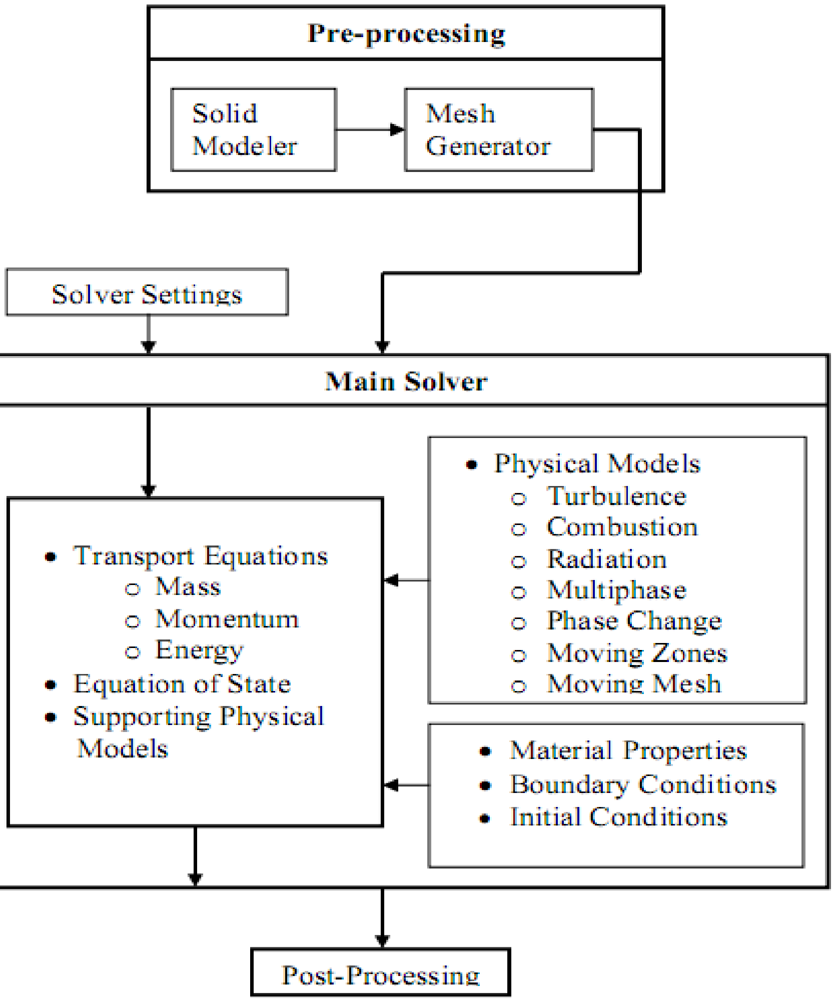


Fig. 6 Layout of the structure of a CFD program

3.2. FLUENT & GAMBIT:

3.2.1. Introduction:

Fluent is a computer program that is used for modeling heat transfer and modeling fluid flow in complex geometries. Due to mesh flexibility offered by Fluent, flow problems with unstructured meshes can be solved easily. Fluent supports triangular, quadrilateral meshes in 2D problems and tetrahedral, hexahedral, wedge shaped meshes in 3D.

Fluent has been developed in C language and hence, provides full flexibility and power offered by the language. C language provides facilities like efficient data structures, flexible solver controls and dynamic memory allocation also. Client- server architecture in Fluent allows it to run as separate simultaneous processes on client desktop workstations and computer servers. This allows efficient execution, interactive control and complete flexibility of the machine.

Fluent provides a interactive menu driven interface. This interface is written in a language called Scheme, a dialect of LISP. Through this interface, Fluent provides all functions required to compute the solution and display the results.

User can create geometry and grid using Gambit. The grid formation can be either triangular, quadrilateral, tetrahedral or a combination of all. Gambit provides flexibility to the user in generating grid by providing various parameters like interval size, number of grids, or the shortest edge %. The user has to define the type of edges/faces to be either wall, internal, velocity inlet etc and the volumes to be either fluid or solid. After creating the geometry and defining its various parts properly, it is exported to FLUENT for simulations.

Once the grid is created by user in Gambit, it is read into Fluent. Fluent performs all the remaining operations required in order to solve the problem like defining the boundary conditions, materials for the system, refining the grid, initializing various parameters etc. It also provides post processing features of the results. Fluent uses unstructured meshes which reduces the time user spent in generating meshes, simplifies the geometry modeling and mesh generation process, models more complex geometries than that possible by using multi-block structured meshes and lets user adapt the mesh to resolve the flow field features. Fluent can handle triangular and quadrilateral meshes in 2D and tetrahedral, hexahedral, pyramidal and wedge shaped meshes in 3D space.

3.2.2. Modeling details:

- *Gambit*:

The geometric modeling and nodalization of various parts of Stirling cryocooler has been done using GAMBIT. Due to the symmetry of the model, as can be seen in Fig. 7, a 2D axisymmetric design was developed. Uniform sized quadrilateral meshes has been used to mesh the model as can be seen in Fig. 8. The main components of the design are Piston, Compressor, Aftercooler, Transfer line, Hot space, Regenerator, Cold space and Displacer. Piston and displacer are the only moving parts of the cryocooler while the rest parts are stationary. The dimensions and zone and boundary setting of the model have been illustrated in Table 1.

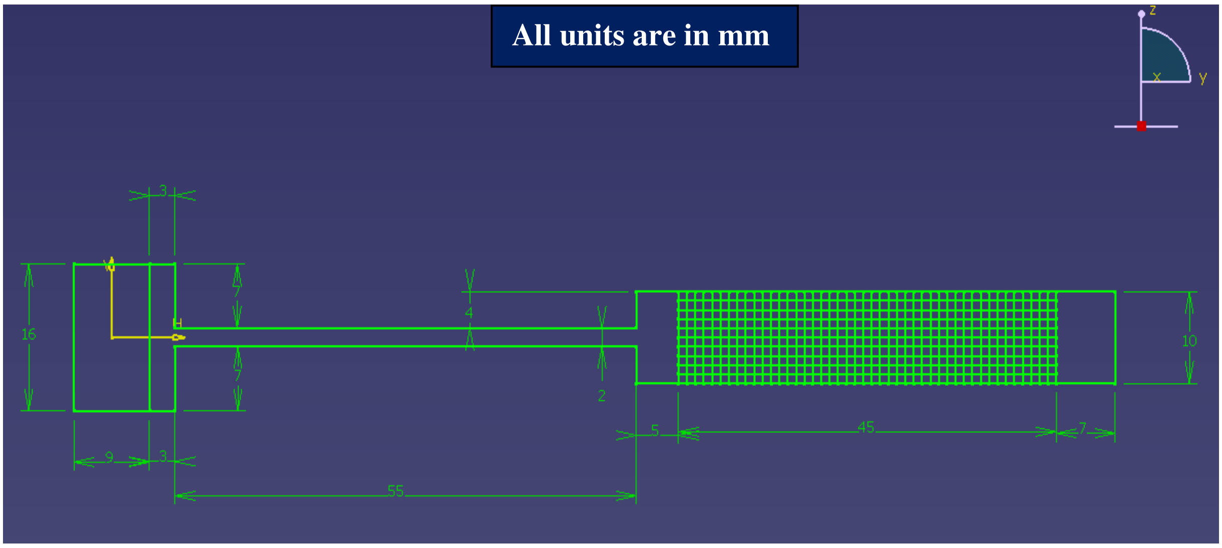


Fig. 7 A layout of the model of the simulated Stirling cryocooler with its proper dimensions

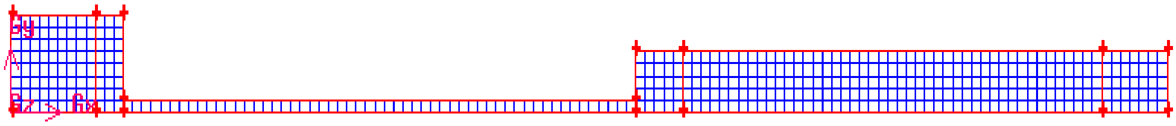


Fig. 8 Axisymmetric model of the Stirling cryocooler developed in GAMBIT

Sl. No.	Components	Radius(in mm)	Length(in mm)
1.	Compressor	8	9
2.	Aftercooler	8	3
3.	Transfer line	1	55
4.	Hot space	5	5
5.	Regenerator	5	45
6.	Cold space	5	7
7.	Piston	8	-
8.	Displacer/ Cold Piston	5	-

Table 1. Dimensions of the various components of the proposed model of Stirling cryocooler

- *Fluent*:

After creating and defining the grid of the model in GAMBIT, the mesh file is read into the main solver, i.e. FLUENT. The grid is them checked to assure that all the zones are present and all dimensions are correct. Skewness and swap tests are also done on the grid. Then, a proper scale is chosen according to the actual model of which simulation is to be done and all the units are assigned. For this study, the above mentioned grid was scaled by a factor of 0.001 in order to bring the units to mm.

3.2.3. Defining the model:

Before iterating, the model properties such as Fluent solver, materials, thermal and fluid properties besides model operating conditions and boundary conditions have to be defined to solve the fluid flow problems. The conditions specified in this case have been mentioned below.

- *Solver*:

Segregated solver, implicit formulation, axisymmetric space, unsteady time.

- *Viscous model and energy equation*:

k- epsilon set of equations and energy equation were selected.

- *Materials*:

Helium (ideal gas) as working fluid and Steel for the frame material.

- *Operating conditions*:

Operating pressure was chosen to be 101325 Pa.

- *Boundary conditions*:

Aftercooler 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. Aftercooler and regenerator were chosen to be porous zones. The detailed boundary conditions have been mentioned in the next page.

- Piston: The piston was chosen to be an adiabatic wall and it material was steel.
- Compressor: The walls were chosen to be made of steel and were adiabatic. The compressor space was filled with Helium.
- Aftercooler: The walls were chosen to be isothermal, maintaining a constant temperature of 300K. The interior of aftercooler was chosen to be a porous zone. Details of the porous medium are given below.

Porosity:	0.69		
Viscosity:	X: 9.433e+09 $1/m^2$	;	Y: 9.433e+09 $1/m^2$
Inertial resistance:	X: 76090 $1/m$	;	Y: 76090 $1/m$

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

- 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 isothermal maintaining a constant temperature of 300K and is made of steel. The hot space is filled with helium.
- Regenerator: The regenerator is chosen to be a porous medium with the following details

.

Porosity:	0.69		
Viscosity:	X: 9.433e+09 $1/m^2$	;	Y: 9.433e+09 $1/m^2$
Inertial resistance:	X: 76090 $1/m$	;	Y: 76090 $1/m$

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

- Cold space: The space is filled with Helium and its walls are adiabatic in nature. The material of the cold space walls is steel.
- Displacer: The displacer is made of steel and is adiabatic in nature.

- *Limits*:

Pressure: 15atm to 25atm

- *Pressure velocity coupling*: PISO

- *Under relaxation factors*:

Pressure: 0.2; Momentum: 0.4; Energy: 0.8

- *Discretization*:

Pressure: PRESTO

Density, momentum, energy were chosen to be First Order Upwind.

- Convergence criterion for continuity, x-velocity, y-velocity, k was chosen to be 0.001 and energy was chosen to be 1e-06.

In order to avoid complications and divergence during the iteration process, a complementary motion was applied to displacer instead of the regenerator which kept the volume of hot space constant but the volume of cold space varied with time.

3.2.4. Defining motions of piston and displacer:

Separate UDFs were written in C language for defining the reciprocating motion for piston and displacer. These UDFs were built and loaded in Fluent and they were coupled with their respective zones (piston and displacer in this case). Various parameters like frequency and amplitude of reciprocating motion could be entered in the UDFs. In order to modify the meshing of the model to compensate the changes brought due to the reciprocating motion of various parts, dynamic meshing option was selected in which resmeshing and layering parameters were defined. In order to verify the motion generated by the UDFs and to determine a proper time step, mesh motion was done several times before running the actual simulation.

CHAPTER 4

RESULTS & DISCUSSIONS

Numerous simulations were run by varying different parameters like frequency of reciprocating motion, boundary conditions etc and comparing the results to find an optimum condition. No changes were brought in the design of the cryocooler during the simulation processes. Four cases of no load condition were run with frequencies of 20 Hz, 30Hz, 40Hz and 50 Hz. No load condition represents a case where no heat flux is given at the cold end of the cryocooler. One more case was run, in which a load of 0.5W was applied at the cold end condition. The results have been shown and discussed in the following sections.

4.1. NO LOAD CASE WITH FREQUENCY OF 30HZ:

A simulation of the Stirling cryocooler was run. The frequency of reciprocating motion of the piston and displacer was specified to be 30Hz. No heat flux was applied to the cold end of the Stirling cryocooler. The residual monitor plot for the above simulation is shown in Fig. 9. The residual monitor shows no signs of divergence.

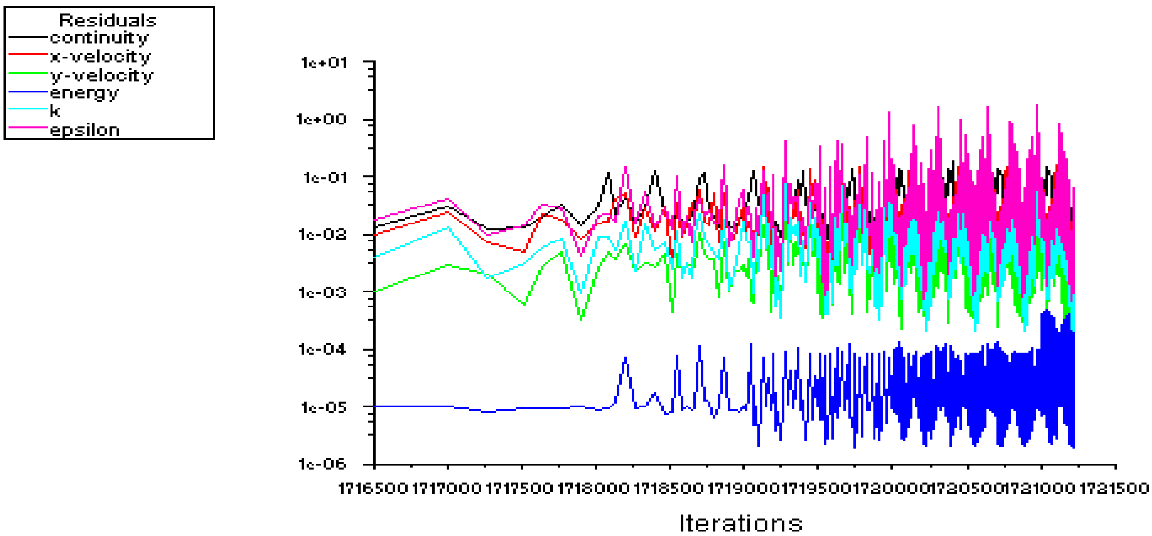


Fig. 9 Residual monitor plot of a CFD simulation of Stirling cryocooler

4.1.1. Cooling behavior:

Fig. 10 shows the trend of decrease in temperature at the cold end. The temperature is observed to follow a gradually descending sinusoidal wave.

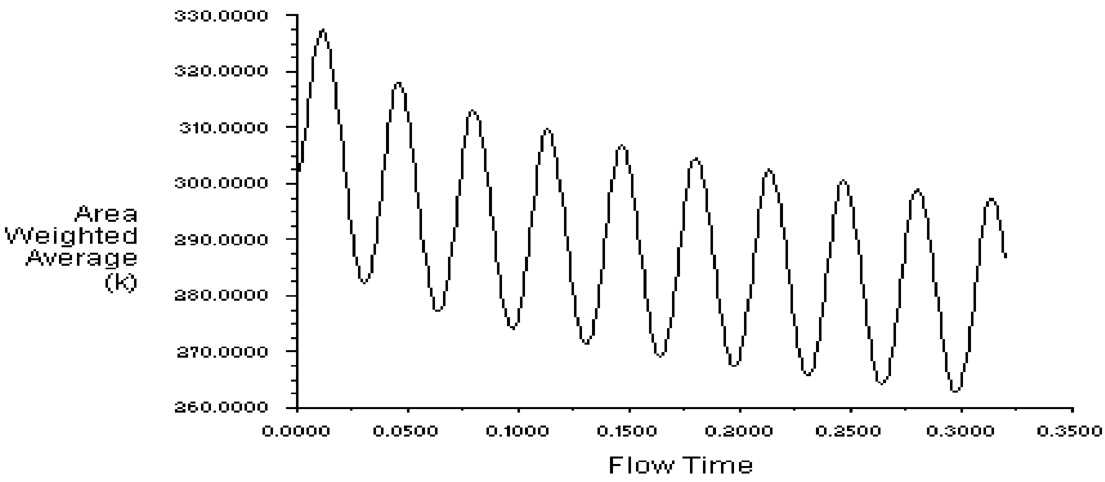


Fig. 10 Sinusoid behavior of temperature at cold space of the cryocooler

4.1.2. Pressure behavior:

Fig. 11 clearly shows the sinusoidal variation of pressure in compressor space generated mainly due to the reciprocating motion of the piston.

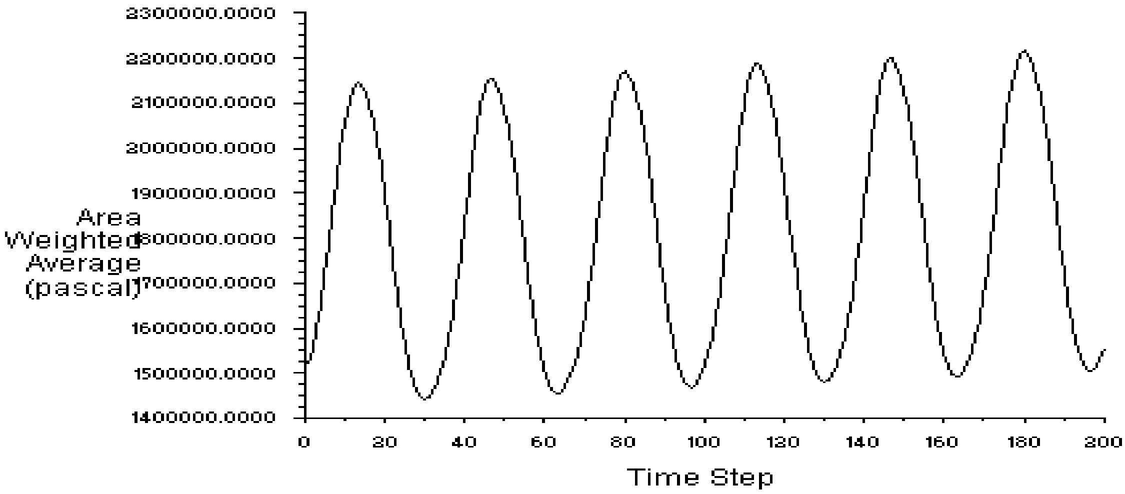


Fig. 11 Sinusoidal pressure variation at the compressor end during a simulation

4.1.3. Cooling curve:

The temperature of the cold end begins to drop initially at a greater slope initially but gradually the slope decreases and the system reaches a steady state. The cooling curve can be seen in Fig.12 The simulation was run for 172.5 seconds.

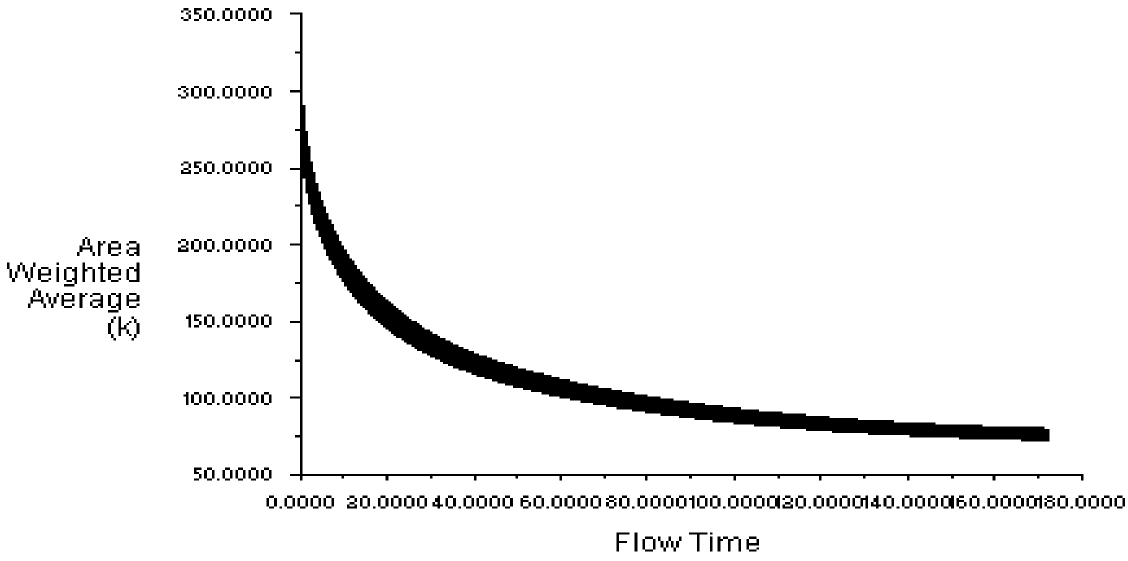


Fig. 12 Temperature vs Flow time plot in a simulation of Stirling cryocooler with no load condition, frequency: 30 Hz, phase difference: 90^0

4.1.4. Temperature contour*:*

The temperature gradient in the Stiring cryocooler after 172.4 seconds of simulation can be seen in Fig. 13. The highest temperature is observed at compressor end while the lowest temperature is observed at the cold end of the cryocooler. The temperature profile of the regenerator, whose ends are marked by red vertical lines, can be clearly observed in Fig. 14. The temperature on the left side of the regenerator is higher and it gradually decreases linearly as we move towards right (i.e. towards the cold space).

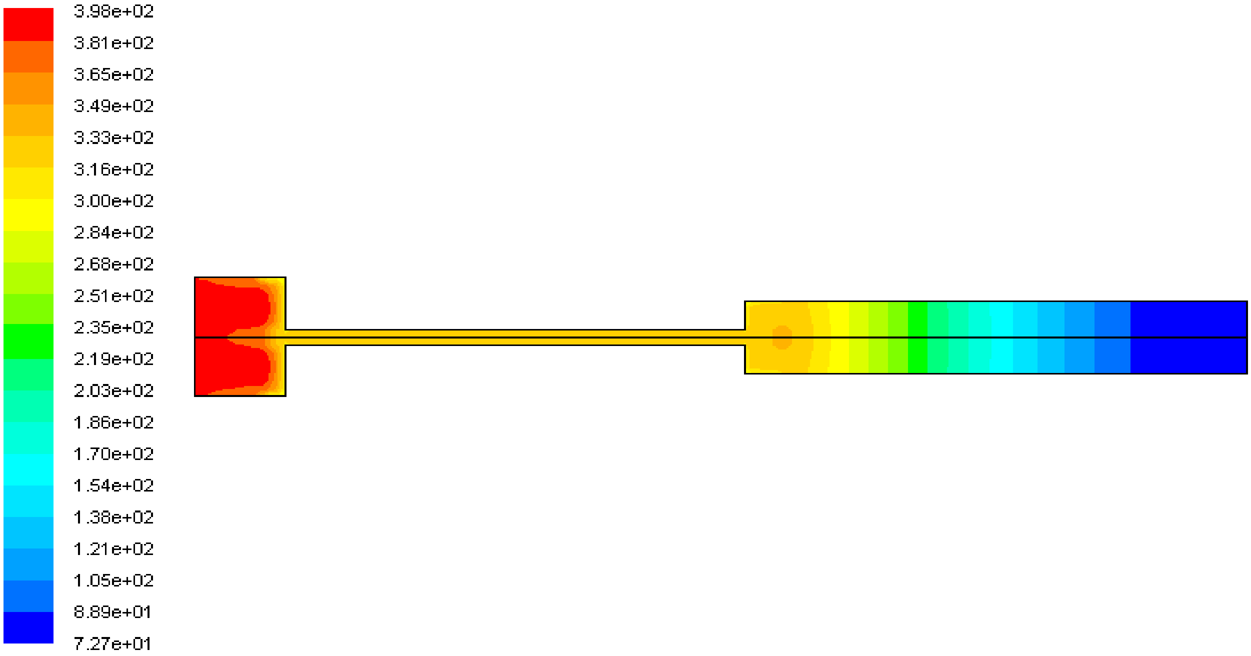


Fig. 13 Temperature contour of the Stirling cryocooler with no load condition, frequency: 30Hz, phase difference: 90^{0}, t: 172 s

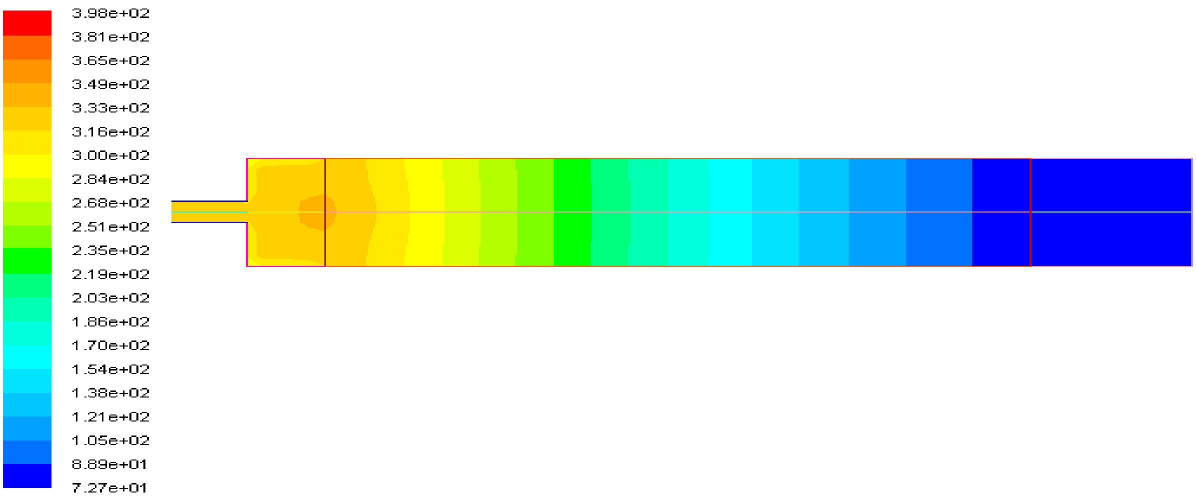


Fig. 14 A closed shot of regenerator temperature profile

4.1.5. <u>Temperature plot</u>:

A temperature plot was drawn as shown in Fig. 15 showing temperatures at different positions such as piston, compressor wall, aftercooler wall, regenerator, displacer etc at particular instant of time. The time at which the temperature plot is drawn, is 172.4 seconds. It can be clearly observed that the temperature at the piston and compressor wall is highest while the cold space is at the lowest temperature. X-axis values represent the distance of the nodes from the leftmost end of the cryocooler.

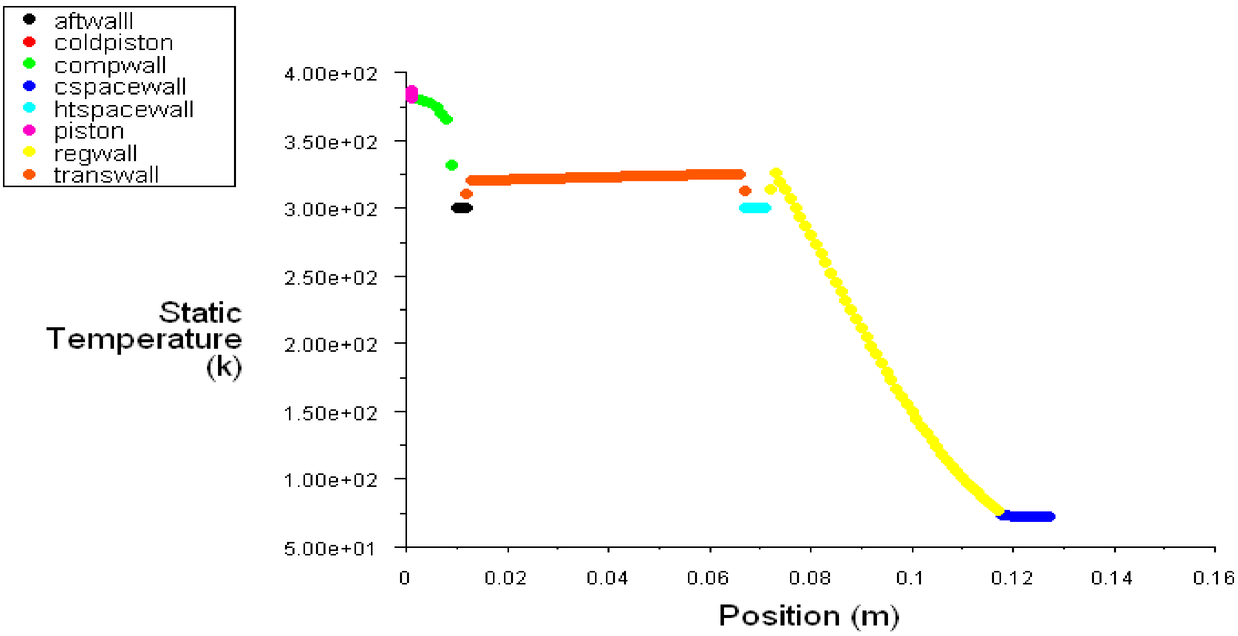


Fig. 15 Temperature plot at different positions of the Stirling cryocooler after 172.4 sec of simulation with no load condition; frequency: 30 Hz, phase difference: 90^0

4.1.6. Velocity vector:

It can be clearly observed from Fig. 16 that there is no recirculation in the flow of the working fluid through the regenerator. The arrow marks represent the velocity vectors of the fluid at various nodes and their color represents the magnitude of velocities. Due to resistance offered to the flow, the velocity of fluid through the regenerator very less.

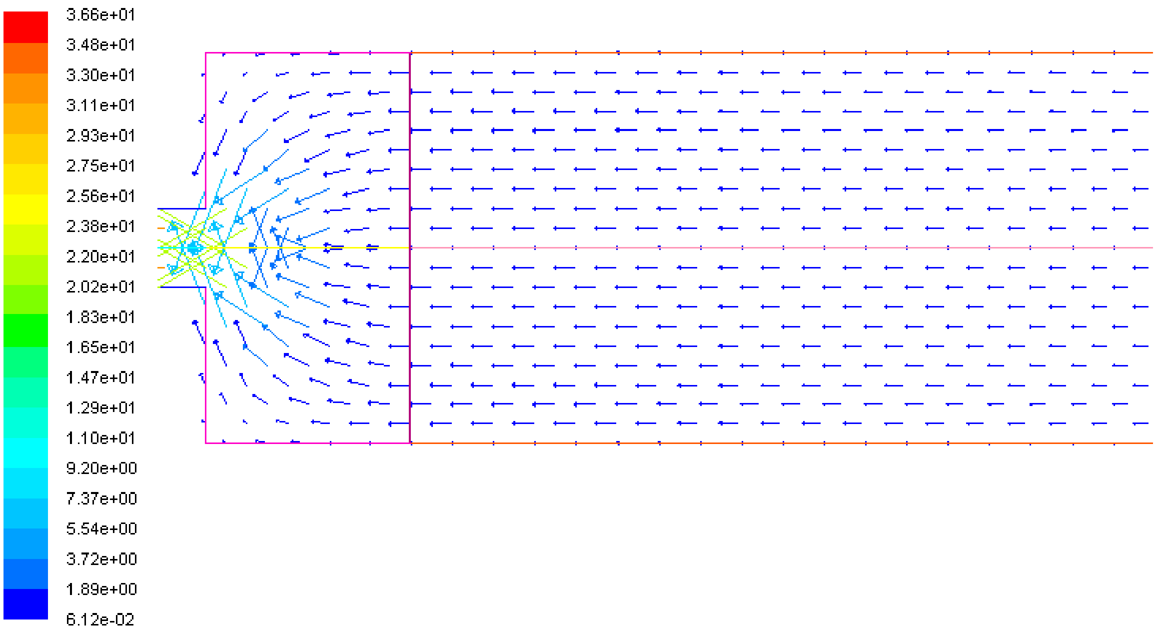


Fig. 16 Velocity vector diagram of fluid through regenerator

4.2. COMPARISON OF COOLING BEHAVIOR IN NO LOAD CASE AND 0.5W LOAD CASE:

In order to observe the effect of a cooling load, applied to the cold space, on the cooling behavior of the cryocooler two cases were compared. In both the cases the frequency of reciprocating motion was chosen to be 40Hz. In the first case, no cooling load was applied to the cold space which represents the no load case. In the second case, a cooling load of 0.5W was applied which was achieved by providing an appropriate flux rate at the cold space walls, while defining its boundary conditions. Fig. 17 clearly shows that the minimum temperature achieved at cold space walls, in the no load case is lower than that achieved in the 0.5W load case. Due to the cooling load, the initial temperature of the cold space walls is a bit greater than the no load case. The minimum temperature reached in the no load case was around 80K while in the 0.5W load case, the minimum temperature attained was approximately 90K.

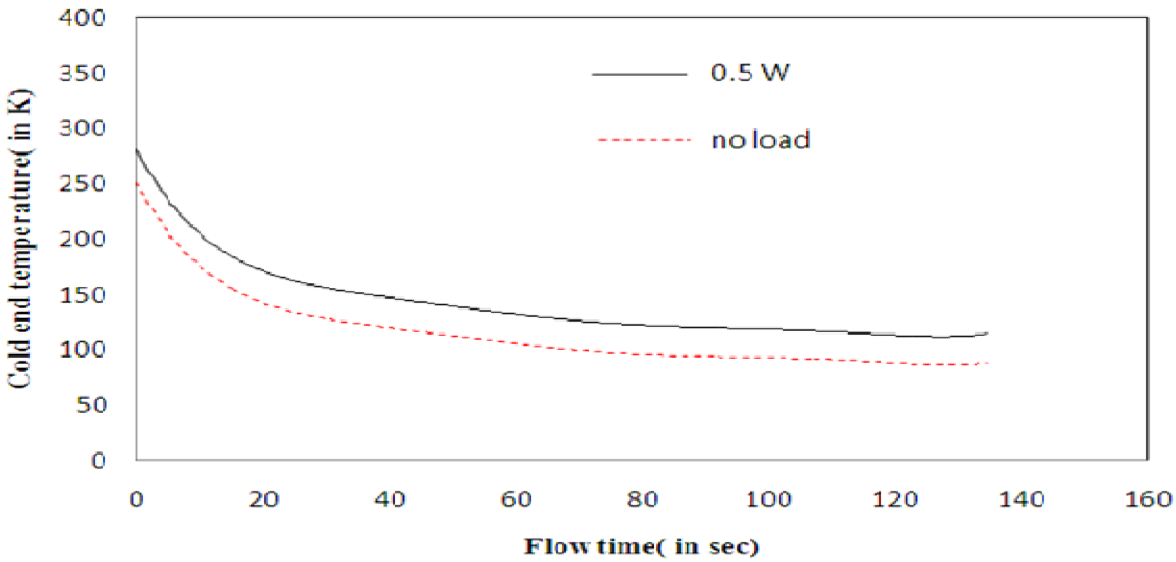


Fig. 17 Cold space temperature vs flow time plot for a no load condition and 0.5W load condition, frequency: 40Hz, phase difference: 90^0

4.3. DETERMINING THE OPTIMUM FREQUENCY:

In order to find the optimum frequency of operation, four cases were studied. All the cases had no load conditions, and only the frequency of reciprocating motion was varied. The four frequencies chosen were 20Hz, 30Hz, 40Hz and 50Hz. The minimum temperatures attained after steady state of the cryocooler have been plotted in Fig. 18. Fig. 18 shows the trend of minimum temperature attained at cold end and a frequency around 30Hz shows the least temperature. So, the optimum frequency for the above design was concluded to be approximately 30Hz.

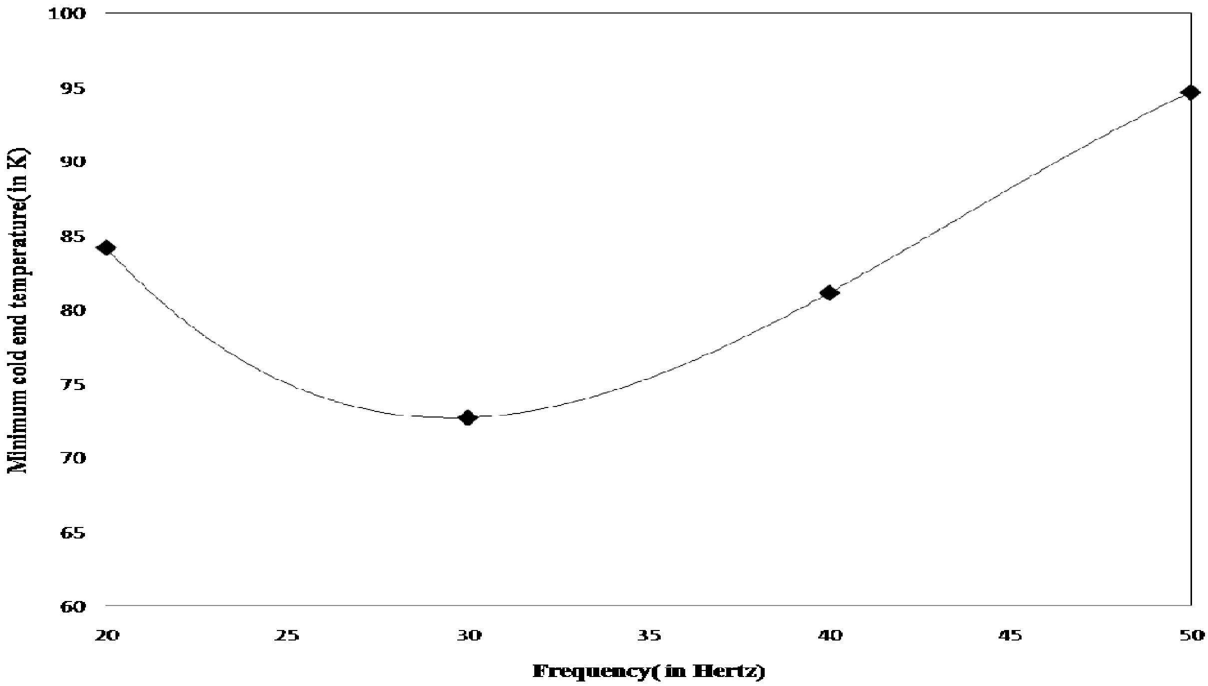


Fig. 18 Comparison of minimum cold end temperature attained with different frequencies of reciprocating motion.

CHAPTER 5

CONCLUSION

A CFD simulation for a Stirling cryocooler was successfully developed. The cryocooler had two moving parts i.e. piston and displacer which were at a certain phase difference but reciprocated at same frequencies. Numerous cases of no load conditions were simulated by varying the frequency of reciprocating motion. This was done in order to determine the optimum frequency which was found to be 30Hz. The minimum temperature reached in this case was about 72K. The effect of cooling load was also studied and a minimum temperature of 91K was achieved with a 0.5W load and 40Hz frequency of reciprocation. A further modification of design could allow the study of various types losses like shuttle loss, pressure drop loss etc.

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