CFD Analysis of a Pulse Tube Cryocooler

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Certificate of approval

This is to certify that the project with title of **"CFD Analysis of a Pulse Tube Cryocooler"** which is submitted by ***Mr. BIJAYA KUMAR MEHER*** has been done under my supervision to partially fulfill 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: 6th may 2015

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ACKNOWLEDGEMENT

I express my humble gratitude sincerely to my guide Prof. R. K. Sahoo for his priceless guidance and never ending support during the course of this project work. Productive and innovative discussions with him have made this project fruitful. It is a matter of honor for me to work under his supervision. I am also thankful to Mr. Sachindra Rout, PhD for his selfless support and motivation in my 7th semester and I am also indebted to Mr. Pankaj Singh, PhD for guiding and supporting me in my 8th semester. I am grateful to all the faculty staff and lab superintendent of Department of Mechanical Engineering for their kind help and suport. I acknowledge all my friends' selfless help moral support on this work. Last but not the least, I express my earnest gratitude to my beloved parents for their constant motivation and believe in me.

DATE: /05/2015

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ABSTRACT

Pulse tube refrigerators are latest technical instrument in the field of refrigeration engineering. So they are preferred over other types of cryocooler like Stirling and Gifford-McMahon coolers because of no moving parts in the cooler making the cooler widely useful for various purposes. Other ordinary refrigerators use vapor compression cycle but pulse tube utilizes oscillatory expansion and compression of gas present inside it. Pulse tube cryocooler has long life compared to other refrigerators, high reliability and low vibration because of no solid piston moving. These coolers have vast applications like semiconductor manufacture and its endless use in military for the cooling of the infrared sensors. They are also used for the cooling of astronomical detectors. They are also used for pre coolers of dilution refrigerators. They are used in space application also.

In this work study of Stirling type OPT cryocooler is considered for CFD analysis using fluent present in ANSYS15 workbench. 2D axis-symmetric geometry is created and used for CFD analysis. The simulations represent a fully-coupled system operating in steady periodic mode, with a trapezoidal pressure profile. Nothing is assumed rather than ideal gas and no gravity effect. The boundary conditions applied on this model are a oscillating pressure of trapezoid profile created using user defined function (UDF), thermal boundary conditions like adiabatic and known heat flux at the cold end heat exchanger. The purpose is to study the Orifice Pulse tube cryocooler(OPTR) using CFD fluent analysis. Where dimensions of components of OPTR are taken from YP Banjare thesis[1] for values of optimum result. In order to observe refrigeration pressure wave of same specification like frequency and amplitude are applied for both cases as described. For each condition two separate analyses are done. One analysis assumes no load or adiabatic cold-end heat exchanger (CHX); other assumes isothermal or known cooling heat load. Each analysis was started with initial conditions, and carried on until steady periodic conditions are attained. The unsteady CFD model successfully predicts OPTR performance through solving an ideal gas equation and heat transfer. The result is discussed in Result and Discussion section.

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CHAPTER 1

INTRODUCTION

In science, cryogenics is portrayed as an application which works in the absolute zero to around 123K(-150°C) of temperature range. A person who studies conditions and elements subjected to very low temperature is called cryogenicist. Cryogenicist uses Kelvin temperature scales.

Accord to Walker (1983) there are 2 sorts of cryocoolers. Those are recuperative and regenerative type. The previous incorporates the Joules Thomson and the Brayton cryocooler. The last incorporates the Stirling cryocooler and the Gifford McMahon cryocooler

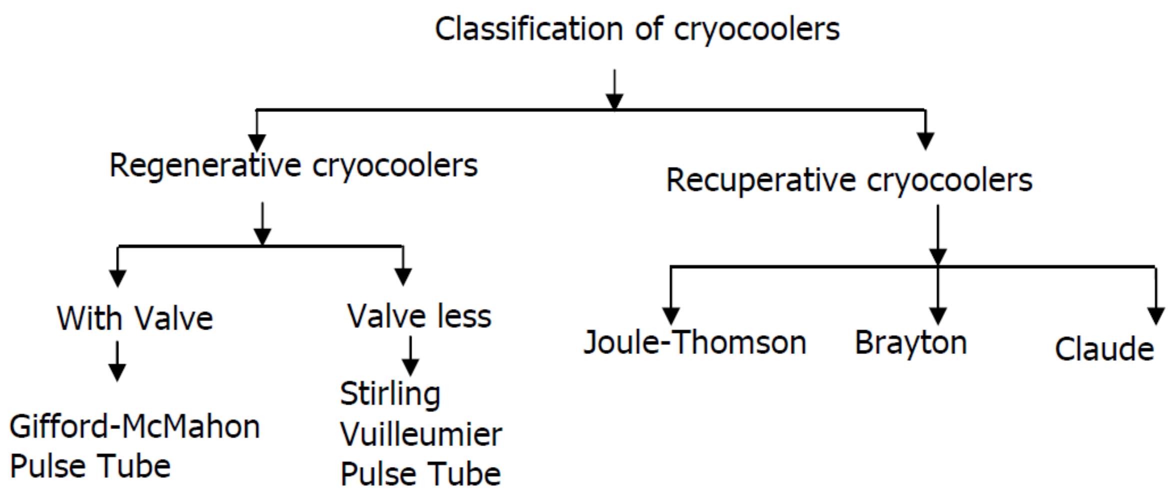


Figure1 classification of Cryocoler

Regenerative refrigerator has higher productivity because it loses less heat, Stirling cryocoolers and Gifford-McMahon kind coolers have been generally utilized as a part of distinctive application fields. In both the Stirling and Gifford-McMahon refrigerator there are moving parts fitted at the chilled end. The pulse tube cooler has the preferences over other kind of cryocoolers because of easiness in the development, because they don't have any moving part at the chilled end, and hence is more worthy of being depended on in operation. Hence more consideration has been paid to the research of pulse tube cooler as of late.

1.1 APPLICATION OF CRYOCOOLERS

- Cooling of infrared sensors for night vision, missile guidance, surveillance or astronomy
- To cool thermal radiation shields.
- To cool microwave filter for cell phone towers.
- To cool electronics for superconductivity and low noise.
- Used in cryo pumps to create high vacuum (about 15k).
- To cool superconducting magnets which are used in MRI scanning.
- To liquefy industrial gases.
- For cryogenic cathering and cryosurgery.
- Biological cells and specimens can be stored.

Cryocoolers are of two types: recuperative type and regenerative type

Recuperative type includes the joule Thomson cryocooler and Brayton cryocooler.

Regenerative type includes the Stirling type and Gifford- McMahon type cryocooler.

I. Recuperative Cryocoolers

Expander and Compressor have distinct outlet and inlet valves so that flow way can be maintained. Valves become important when the systems have any turbine or rotary components. During rotary motion of turbine or other component there are maximum chances for back flow of the working fluid, so in order to avoid that valves are necessary. The main advantage of recuperative cryocooler is that they can be made available for any size of specific output.

II. Regenerative cryocooler

Oscillatory motion of the working fluid inside these type of cryocoolers occur, it oscillates in cycles and when the fluid moves through the regenerator part of the cryocooler, working fluid exchanges heat with the mesh present inside the regenerator.

The structure of wire mesh is, it is filled with has very high heat capacity wire cloth which stores the heat during one half of the cycle and in the other half it gives it back to the working fluid. They are very effective because very low heat is lost but these cannot be scaled up to large size output. Regenerator can be considered as the heat exchanger in regenerative cycles. The coming hot and compressed gas transfer some energy to the wire mesh of the regenerator, heat energy is stored in the mesh for 1st half of the cycle and then in the 2nd half of the cycle during the returning of the chilled gas, which flows in the opposite direction through the channel and it takes heat from the wired mesh and returns to the matrix at its earlier 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.

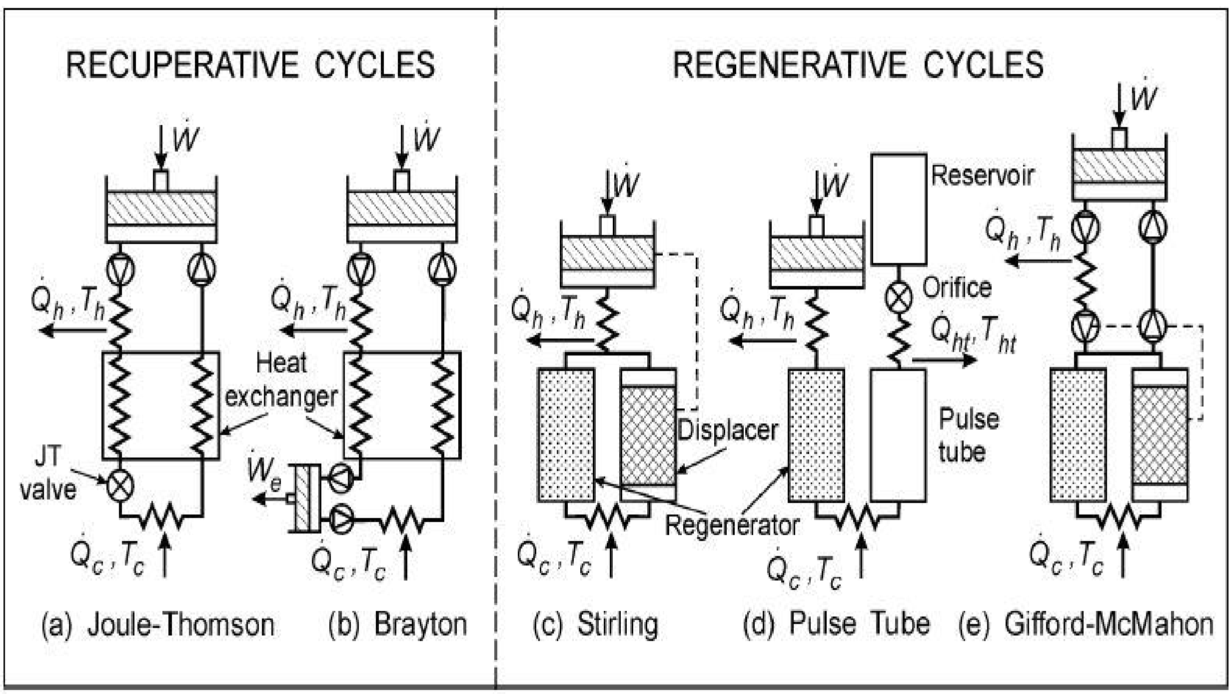


Figure2. Recuperative and Regenerative cycle

Different types of Regenerative and Recuperative Cryocoolers

Comparisons between G- M type Cryocoolers and Stirling type

Stirling type cryocooler	G-M type cryocooler

Operates at very high frequency (20-120Hz)	Operates at very Low frequency (1-5Hz)
Expander is directly connected to Compressor	Through a valve Compressor is connected to expander
Dry compressor is used	Oil lubricated compressor is used
Coefficient of Performance is high	Coefficient of Performance is low
Low Pressure ratios	high Pressure ratios
Reaches 20K using two stages of cooler	Reaches 2K using two stages of cooler
Compressors are comparatively smaller (capacity range is in few hundred Watts)	Compressors are comparatively bulky(capacity range is in Kw)

Pulse Tube Refrigerators

World's 1st pulse tube refrigerator was designed by Longsworth and Gifford in the sixties. It doesn't have any moving part in the cold end area and this make it simple in construction and during use and makes it highly efficient because friction is absent here.

- How does pulse tube refrigerators work

  Ordinary cryocooler works on the principle of vapor compression cycle, on the other hand pulse tube refrigerator works on the theory of oscillatory expansion and compression of the gas inside the closed volume to reach wanted temperature.

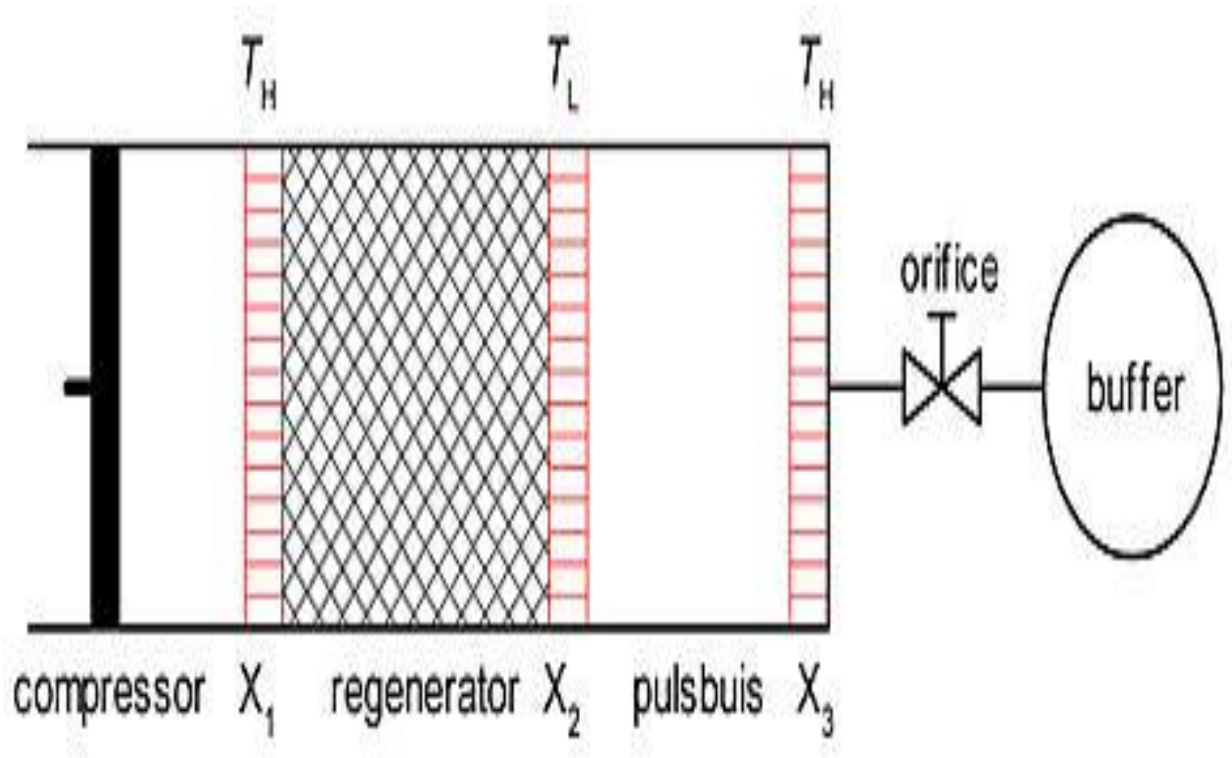


Figure3. Schematic diagram of stirling type Pulse Tube Cryocooler

This is a Stirling type orifice type pulse tube cryocooler

X^1- Heat Exchanger

X^2- CHX

X^3- HHX

T_{H}- Temperature of HHX

T_L- Temperature of CHX

The temperature of gas near X2, which moves to and fro in the system, changes when it passes the heat exchanger. In the regenerator and in the HHX the heat contact between the gas and its surrounding is there which is not isolated. Practically the temperature is ambient here . However, in the pulse tube section the gas is thermally isolated (adiabatic), so, in the pulse tube, the temperature of the gas changes according to the pressure.

The molecule at HHX (hot end heat exchanger) (x_3) flow into the tube when there is low pressure and same gas molecule leaves the tube when there is high pressure in the tube hence temperature will be higher here than T_H and the cold end gas goes to the tube via CHX (x_2) when the pressure is higher with temperature T_L and return when the pressure inside the tube is low having a temperature below T_L. When gas returns it takes away heat fromX_2 giving desired cooling effect.

CLASSIFICATION OF PULSE TUBE REFRIGERATORS

- Depending upon type of pressure wave generated
  1. Stirling type orifice Pulse Tube cryocooler (valve less)
  2. GM type PTR(with valve)

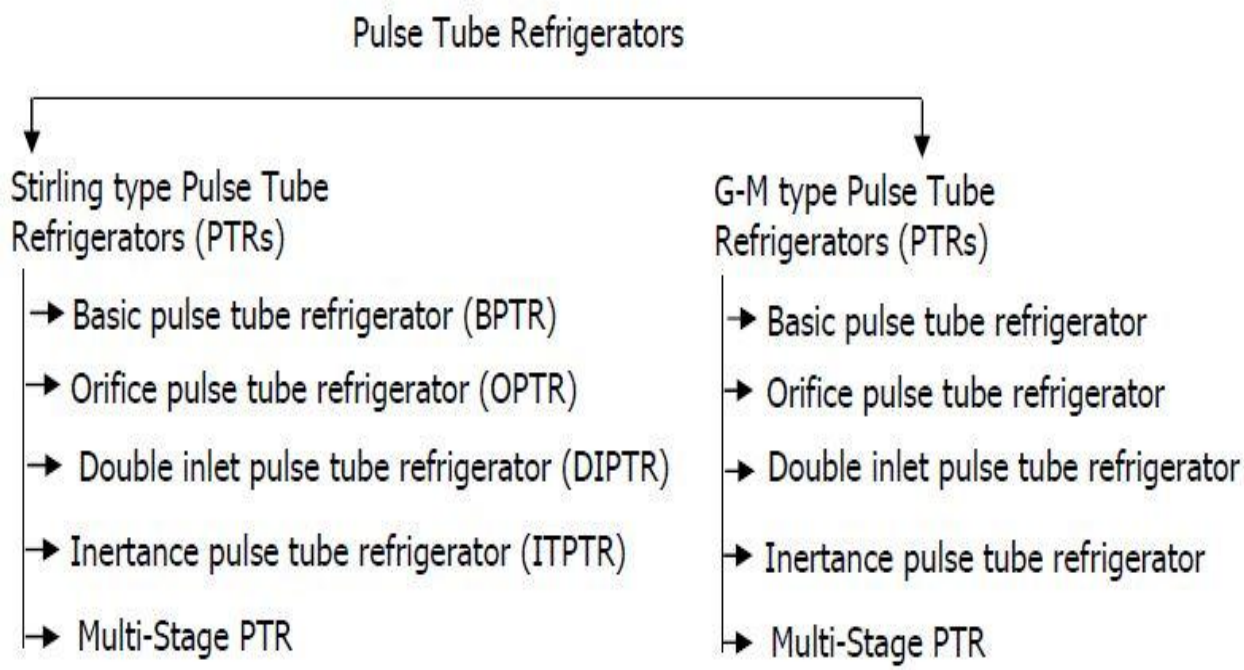


Figure4. Classification of Pulse Tube Cryocooler

- Depending upon type of geometry it can be classified as:

(viii) In-line type PTR

(ii) U type PTR

(iii) Coaxial type PTR

- According to Phasor Analysis:

(i) BPTR

(ii) OPTR

(iii) DIPTR

(iv)Pulse tube refrigerator with multiple inlet

(v)Inertance tube PTR

- Developed in the course of time

(i)Single stage PTR

(ii)Multi stage PTR

(iii)Thermoaccoustic PTR

Parts of Pulse Tube cryocooler

Compressor

It is a vital component of cryocooler. Its function is to pressurize and depressurize gas in the closed chamber. It works on Electrical power. This electrical energy is converted into the mechanical work to give desired pressure waves like trapezoidal, so the gas motion occurs. Inside the ideal compressor, the electrical power becomes equal to $\int$ PdV. Here P is the pressure of the compressor, and f is called frequency of compressor. But in an real system, power mentioned (the PdV power) is always less than the theoretically calculated electrical power because of irreversibility.

After cooler

After cooler is used to grave the heat which is generated inside the compressor at the time of the compression of the gas and take it out into the environment. This lowers the temperature of the warm end this makes the regenerator to work more and gives low temperature gas to the desired space. Copper wire mesh which are directly in contact with the housing wall are used for these types of heat exchangers.

Regenerator

The function of the regenerator is to take out the heat from the entering gas at the time of forward stroke, and gives that heat back to the gas at the time of the return stroke. Pulse tube refrigerator regenerators with no pressure drop and a heat exchanger effectiveness of high amount is desired, to get the enthalpy flow inside the pulse tube. The efficiency of the real regenerator is very less if compared to

ideal regenerators. Most often, Stainless steel wire mesh are used to pack the regenerator material, because they gives higher heat transfer areas, less drop in pressure, large heat capacity, and low thermal conductivity

Figure5. Figure of Regenerator

- Cold Heat Exchanger (CHX)

Here refrigeration load is kept in the system. This is situated between pulse tube and regenerator. Generally copper wire cloth are used which absorb heat of the load when gas is compressed and it releases heat when gas expands.

- Pulse Tube

This is the most vital part of the pulse tube cooling system. The function of the pulse tube is to transfer heat from CHX (Cold end heat exchanger) to HHX (Hot end heat exchanger). It is just a hollow cylinder type generally made from stainless steel material.

Figure6. figure of Pulse tube

- Hot End Heat Exchanger

Here Gas rejects heat to the environment .It receives heat from adjacent part, pulse tube then the heat load at higher temperature is rejected to environment. It is necessary to cool the heat exchanger, so, either water cooling or air cooling is done. For most of the cases water cooling is done though it is more effective.

- Orifice Valve, Inertance Tube

Both of these are used to change the phase difference between pressure and mass flow rate. By adjusting the orifice diameter or inertance tube diameter the desired phase difference can be obtained. Generally orifice valve is a needle valve and the inertance tube is an open cylinder tube.

Surge Volume

It is a closed buffer reservoir to adjust the small pressure variations due to oscillating mass flow.

AIM OF THE PRESENT PROJECT WORK

All PTR operate as closed systems where exchange of mass between the cryocooler and its environment doesn't occur.

Piston or Rotary valve is the only moving component which moves to and fro to generate oscillating pressures for the refrigerant. Frequently helium is preferred as working fluid because it has the lowest critical temperature as compared to other available gases. Its thermal conductivity is also high. Accurate modelling of the PTR is key to anticipate its execution furthermore, and predict it's performance

CHAPTER II

LITERATURE REVIEW

Here in this chapter literature review is discussed. It is classified under two categories. The first part deals with theoretical advancement in the field of pulse tube cryocooler namely BPTR and OPTR, and the second part deals with CFD analysis of the orifice pulse tube refrigerators.

Gifford and Longsworth of Syracuse University introduced pulse tube refrigerator in 1963. The innovation of pulse tube models for research purpose actually started in 1963, but in 1964 the first paper was published. In that paper the concept of "the depressurization and pressurization of any kind closed volume from a point on its periphery sets up temperature gradients in the volume" was discussed.

The first design was made up of a hollow cylindrical tube. It has one end open but the other end is kept closed. The closed end is kept in contact with an heat exchanger of ambient temperature, while the other end which was open was connected with cold end. Because of the oscillatory flow done by piston, the open end was forced to an oscillatory pressure from the regenerator, resulting the open end to chill. In their second paper, Gifford and Longsworth showed useful cooling in a pulse tube working below critical pressure ratio.

Mikulin et al introduced OPTR in 1984. This invention is considered as the milestone of the developments of pulse tube cooler. An analytical model of OPTR was first done by Starch and Radebaugh and they made a simple expression for a gross refrigeration power. Wu et al. did a numerical analysis with a valve less compressor. They also described the process occurring and working principle of the pulse tube.

Richardson stated that valved pulse tube/OPTR have potential to reach much less temperatures. Lee et al. showed the influence of gas speed on surface heat displacing for the OPTR. Kasuya et al. has showed in their work optimum phase angle between pressure and gas displacement in PTR. Jiao et al. have done an innovative and improved numerical modeling technique to predict the total performances and characteristics of an OPTR. Storch et al. have done an analytical model of OPTR with the help of phasor analysis. Zhu et al. did isothermal modeling for an OPTR that is way too simple than nodal analysis. By using characteristics method Wu et al. did a numerical model of OPTR and did comparison with experiment.

Barrett et al. has used CFD or fluent software to model oscillating flow for a PTR. Banjare et al. have analyzed CFD simulations for OPTR and ITPTR . They have taken different frequency, and have used dual opposed piston compressor. They stated that at higher frequency turbulence and recirculation of fluid can be observed, which harms the overall performance of the system. From CFD simulation results they reach to the conclusion that for an optimum frequency for each PTR model, it can deliver maximum refrigeration.

CHAPTER III

COMPUTATIONAL FLUID DYNAMIC

Computational fluid dynamics or CFD is a powerful tool to analysis of systems which involves processes like fluid flow, heat transfer and many other thermal phenomenon by solving numerical simulations or iteration. The technique is very herculean and it is utilized in vast area of industrial and nonindustrial section. The availability of fast computers equipped with very large memories allow for remarkably precise numerical simulations. The main CFD tools are PHONICS, FLUENT, FLOW3D and STAR-CD etc. Fluent is a state-of-the-art computer program for modeling heat transfer and fluid flow process in complex engineering problems. With the help of this one can generate code and set boundary condition by User Defined Functions (UDF). Fluent has also a dynamic meshing function. This function allows the user to create deforming mesh volumes such that applications involving volume compression and expansion can be modeled. Thus in view of Fluent's versality, its capability for solving the compression and expansion volume, allowing UDF boundary conditions and modeling capability for porous media, it is selected for the simulation of the Stirling type OPTR.

This chapter presents the details of geometry and boundary conditions for CFD simulations of Stirling type OPTR by using commercial software, Fluent6.1. For CFD simulation of any model the basic required parameters are their dimensions and boundary conditions. Therefore the geometrical dimensions of each part of PTR model is created in ANSYS15 software and complete meshing of the geometry and also the boundary conditions for the model is presented in this chapter. Simulation is done for OPTR in ANSYS FLUENT.

MODELING THE GEOMETRY

The geometry of OPTR is same as BPTR except a short tube with orifice valve is kept in between HHX and Surge Volume. The three dimensional view of the OPTR system is demonstrated in Fig.5.5. The system consists of a dual opposed piston compressor, , an after cooler, a transfer line, regenerator, CHX, pulse tube, HHX, a needle valve connecting tube, and a reservoir. Figure5.6 illustrates the two-dimensional physical geometry of the OPTR. Figure 5.5 shows that every component of the OPTR system is in fact cylindrical in shape and all the components are aligned in series and form an axis-symmetric system. The OPTR is therefore modeled in a 2-dimensional axis-symmetric co-ordinate system. The potential asymmetry caused by gravity is thus neglected. This gravity term however will be important if the order of magnitude of the acceleration become comparable with the other terms (such as temporal acceleration, convective acceleration etc.) in the momentum equation. Figure5.7 shows the two-dimensional geometry of the OPTR which is created in ANSYS software. The 2D mode option ANSYS is used to create the geometry.

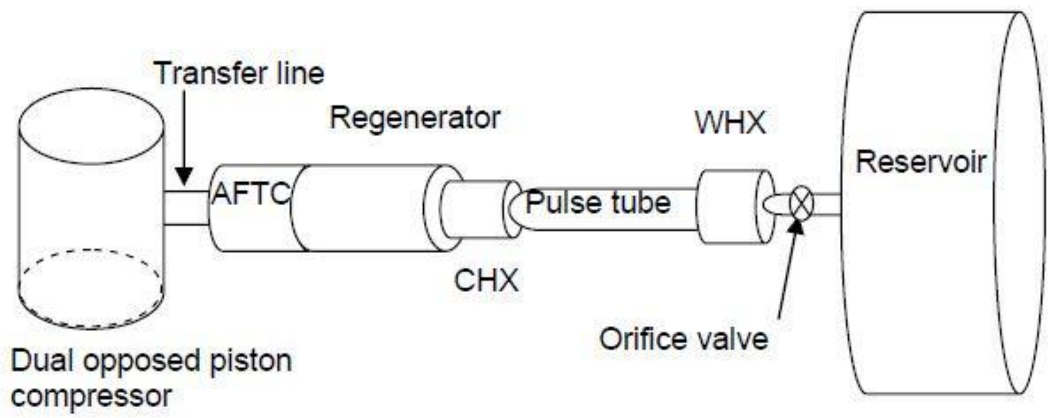


Figure7. Three Dimensional view of Stirling type Orifice Pulse Tube Cryocooler

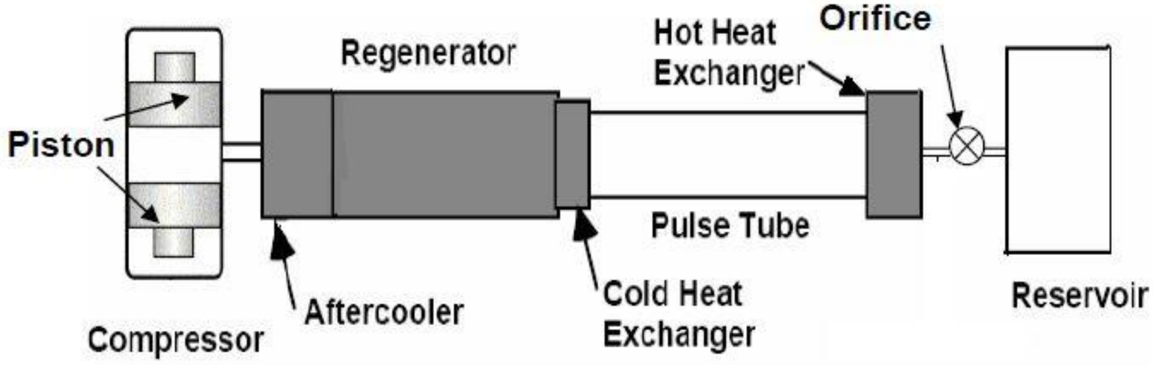


Figure.8. Two-Dimensional view of orifice pulse tube refrigerator.

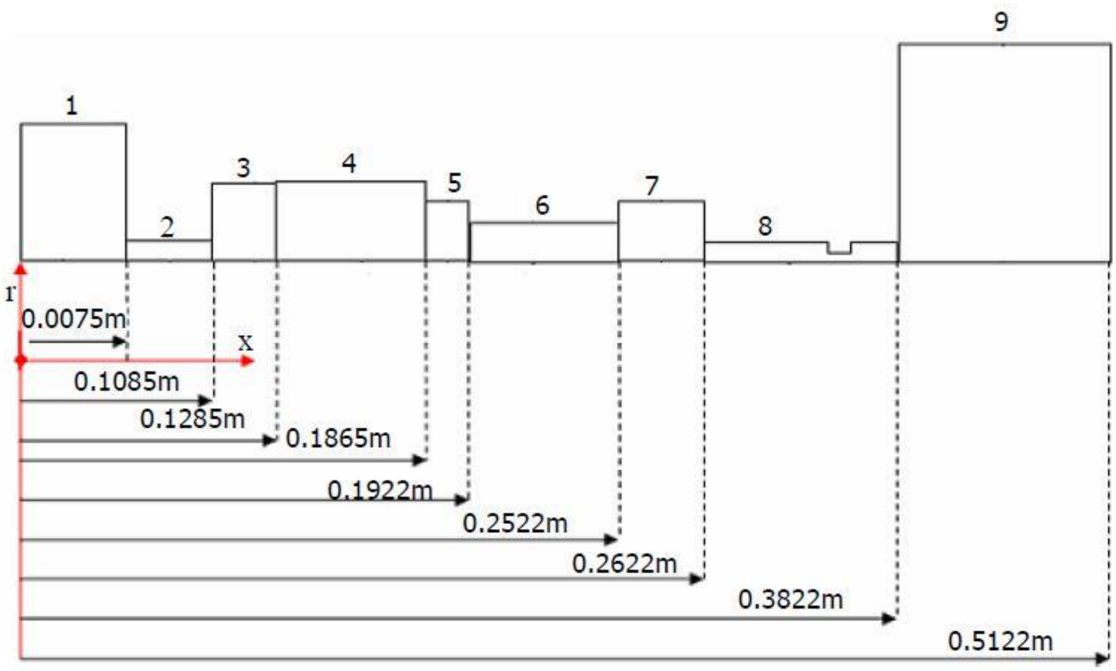
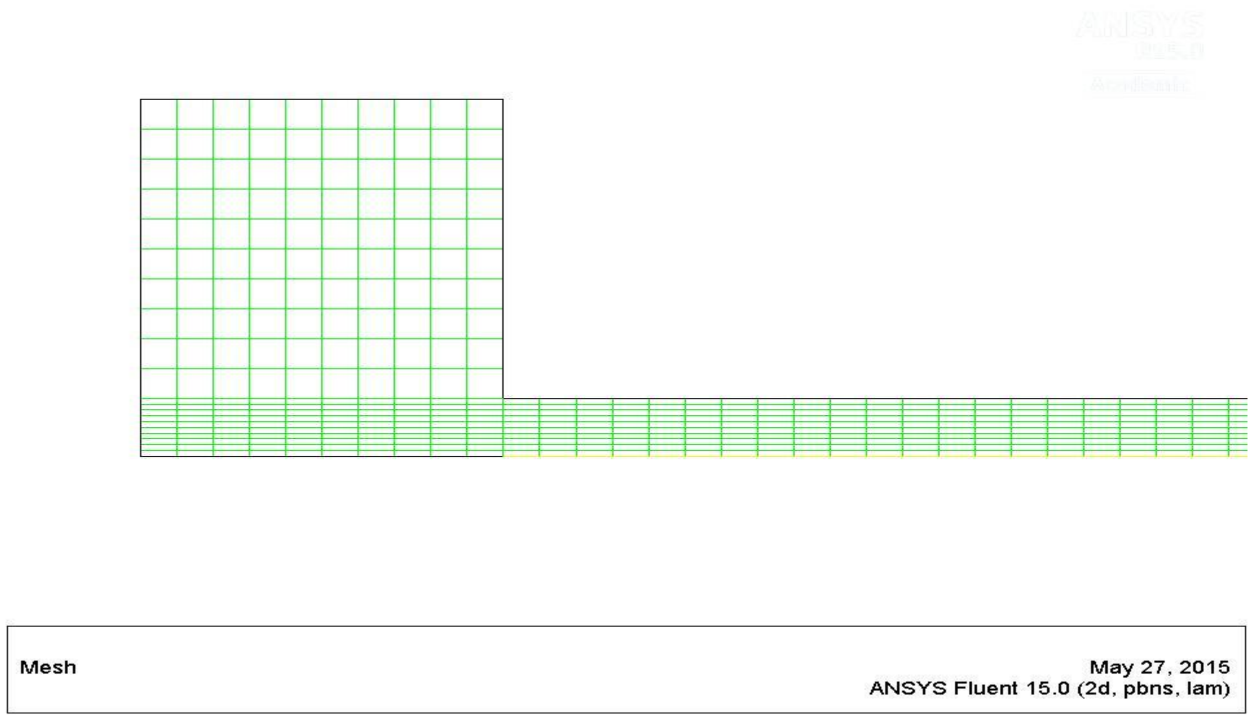
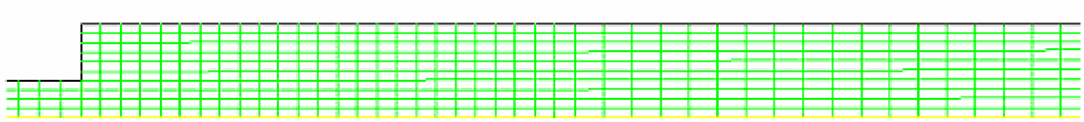


Figure9. Two-dimensional axis-symmetric geometry of OPTR.

Compressor Transfer line



After Cooler Regenerator



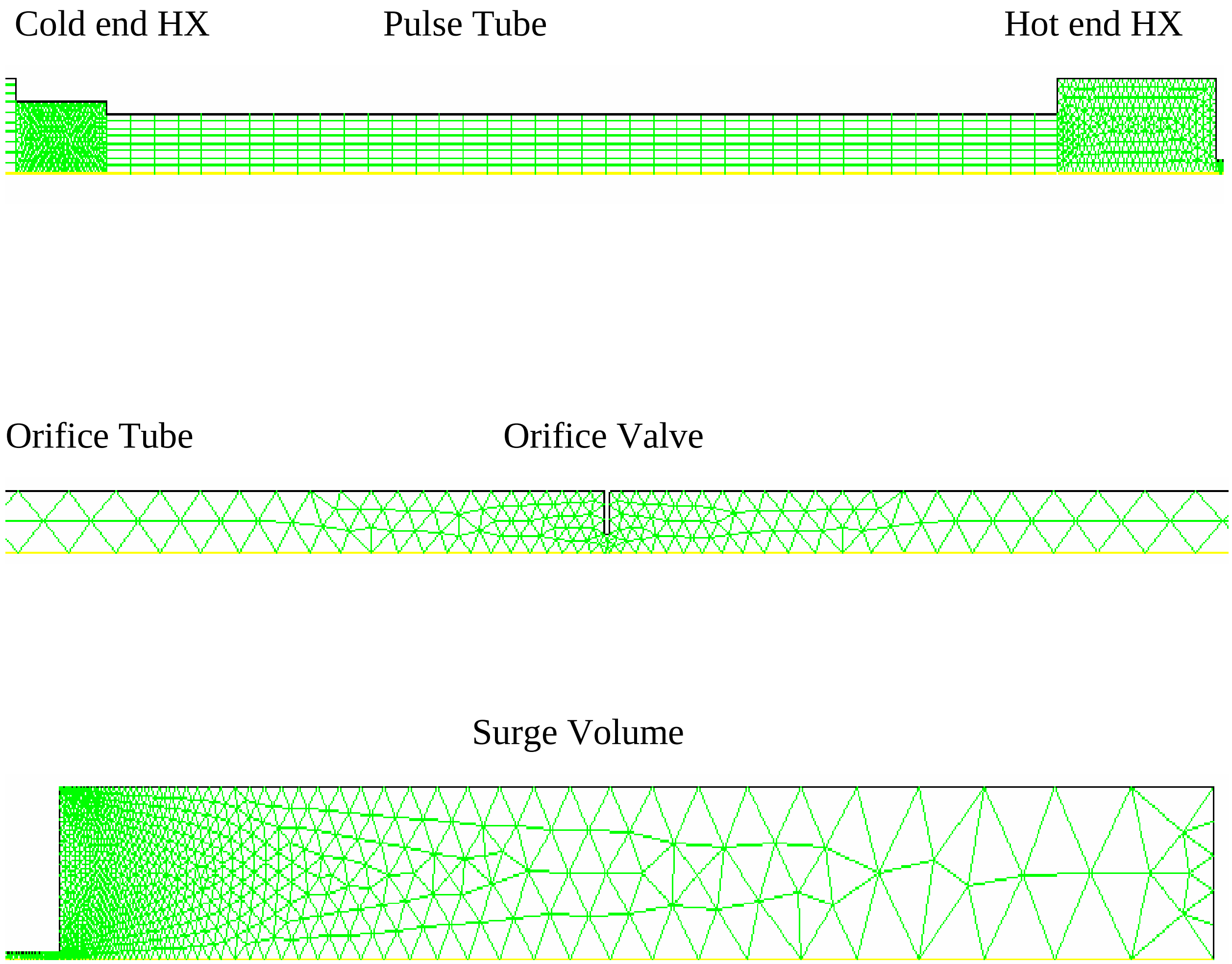


Figure10. Two-dimensional axis-symmetric mesh of OPTR.

Table 1 Component dimensions of OPTR

Serial Number	COMPONENTS	RADIUS (M)	LENGTH (M)
1	COMPRESSOR	9.54E-03	7.05E-03
2	TRANSFER LINE	1.55E-03	1.01E-01
3	AFTER COOLER	4.00E-03	2.00E-02
4	REGENERATOR	4.00E-03	5.80E-02
5	CHX	3.00E-03	5.70E-03
6	PULSE TUBE	2.50E-03	6.00E-02
7	HHX	4.00E-03	1.00E-02
8	ORIFICE VALVE	1.00E-03	1.20E-01
9	SURGE VOLUME	1.30E-02	1.30E-01

Table 2 Boundary and initial conditions for OPTR

STUDY CASE	CASE 1	CASE 2
Compressor Wall	Adiabatic	Adiabatic
Transfer Line Wall	Adiabatic	Adiabatic
After Cooler Wall	293K	293K
Regenerator Wall	Adiabatic	Adiabatic
Cold Wall	Adiabatic	Heat Flux 5W
Pulse Tube wall	Adiabatic	Adiabatic
Hot end Wall	293K	293K
Surge Volume Wall	Adiabatic	Adiabatic
Viscous Resistance(m^{-2})	9.44E+09	9.44E+09
Inertia Resistance(m^{-1})	76090	76090
Initial Conditions	300K	300K
Cold end Load	0	5W
Cold end Temperature	109K	181K

Dynamic Meshing Function

Fluent15 has a featured called dynamic meshing function. This feature model in Fluent can be used to model geometry where the shape is not steady means it keeps on changing with time due to motion on the domain boundaries like in reciprocating compressor. For this type of model such feature are provided in ansys so that these problem could be handled in fluent by using it. The motion can be anything a prescribed motion can be an unprescribed motion where motion is calculated based on the solution for real time. The update is handled itself by fluent at each time step based on the new positions of the boundaries. To use the dynamic mesh model, it is needed to provide a starting volume mesh initially and the description for motion of moving zones present in the model. Fluent describes the motion using either user-defined functions (UDFs) or boundary profiles. Thus in view of Fluent's versatility, its capability for solving the compression and expansion of volumes, compressor has been modeled using dynamic meshing in Stirling type pulse tube refrigerators. In Fluent different method are available for mesh update like smoothing, layering and remeshing for dynamic meshing. The compressor is modeled as a solid wall (piston) that can be oscillated in and out by different oscillation motion along a fixed stroke length. The piston and cylinder walls are nominally specified as adiabatic boundaries. Work input at the piston in cylinder of a compressor provides the oscillating pressure that drives the cycle.

To do the modeling of the piston and cylinder, Fluent dynamic meshing function must be used. In C programming language user defined function (UDF) can be developed to simulate the piston cylinder effect. The compressor that is used in this simulation is a reciprocating dual opposed-piston design. The equation for trapezoidal pressure profile for a mean pressure of 35 bar and frequency of 20 Hz is calculated.

The fluid is research grade He, considered as an ideal gas and having constant viscosity, heat capacitance and thermal conductivity. Nodalization of pulse tube refrigerator is done by the Gambit software. First, an actual physical drawing of the problem is created in the 2-dimensional axis-symmetric co-ordinate system using ANSYS15. Table 5.3 shows the model boundary conditions. The momentum transport resent in porous regions equations include a source term with inertial and viscous resistance coefficient which has been specified. Boundaries are defined and flow characteristics are detailed in Fluent. Segregated solvers are used for all models. These solver solve the energy equation and the flow implicitly and separately

USER DEFINE FUNCTIONS (UDF)

To model the compressor the dynamic mesh feature of the fluent are used. For this the pressure user defined function (UDF) has been written in C language with the help of Fluent UDF manual [177]. This UDF is saved as “pressure_rectangular.c”. This has to be stored in a folder and then mesh files are saved in the same folder. This UDF was first compiled and then linked to piston which is reciprocated according to the command given in UDF. Using Fluent’s user defined function manual [177] the pressureUDF for piston head motion is mentioned below

```
#include "udf.h"
DEFINE_PROFILE(unsteady_pressure, thread, position)
{
face_t f;
real t = CURRENT_TIME;
int i;
real p=0;
begin_f_loop (f, thread)
{
          if (t < (p+0.01))
F_PROFILE(f, thread, position) = 101325*(0.3+5*(t-p));
else if(t<(p+0.020))
F_PROFILE(f, thread, position) = 35463.75;
else if(t<(p+0.030))
F_PROFILE(f, thread, position) = 35463.75-101325*5*(t-0.015-p);
else if(t<(p+0.040))
F_PROFILE(f, thread, position) = 25331.25;
else if(t<(p+0.05))
F_PROFILE(f, thread, position) = 25331.25+101325*5*(t-0.04-p);
```

```
else p=p+0.05;
}
end_f_loop (f, thread)
}
```

Mesh Motion Preview

After compiling UDF and defining dynamic mesh zones it is necessary to check the motion of mesh whether it is moving properly or not. For mesh motion preview one select only the compressor portion of the geometry. Mesh motion preview of Stirling type pulse tube refrigerator after compiling user defined function (UDF) is shown in figure 5.9(a) and (b). At initial condition, piston is at rest. When the piston moves, the compression and expansion of the gas system inside the cylinder takes place.

The mesh motion preview gives an information regarding motion of mesh in either direction from initial position w.r.t. time. This shows compressor's expansion and compression process. From initial condition mesh moves in upward direction reaches TDC and then returns down till BDC. First set of Figure5.9 (a) shows the axisymmetric geometry. If there is not proper matching between grid size spacing and time increment the mesh won't move. In this case fluent will show an error message for negative volume. So before starting the simulation it is necessary to check the motion of the mesh for the selected grid size. If it shows error then the grid size for compressor or time step size is changed and the process is repeated.

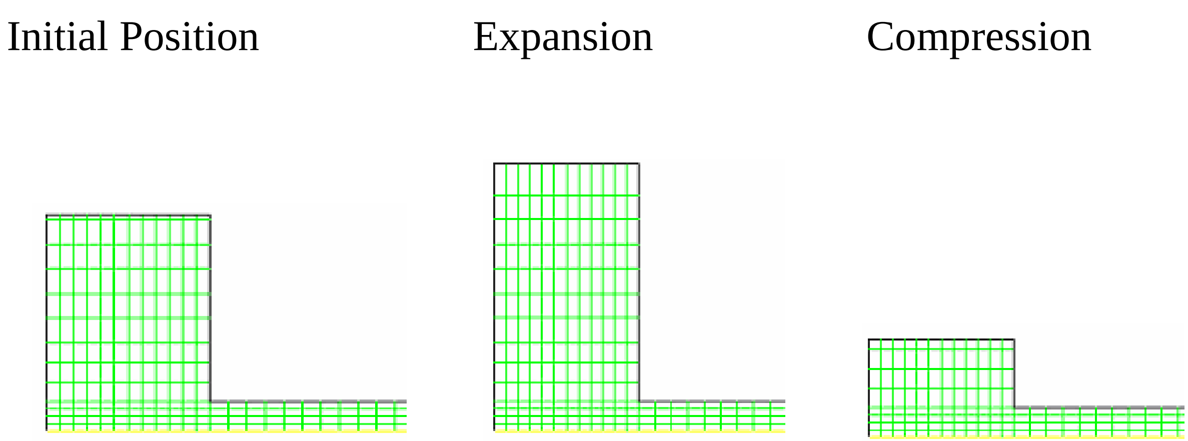


Figure11. mesh preview of compressor for Initial position Expansion and expansion

CHATER IV

RESULT AND DISSCUSION

The OPTR is simulated with the different boundary condition taking trapezoidal pressure curve profile. The pressure curve VS Time Graph is shown in figure 12. For OPTR the dimension of component and its different boundary conditions are given in Table 1 and 2 respectively. For OPTR steady periodic CFD analysis results will be discussed in below section for different boundary conditions at CHX

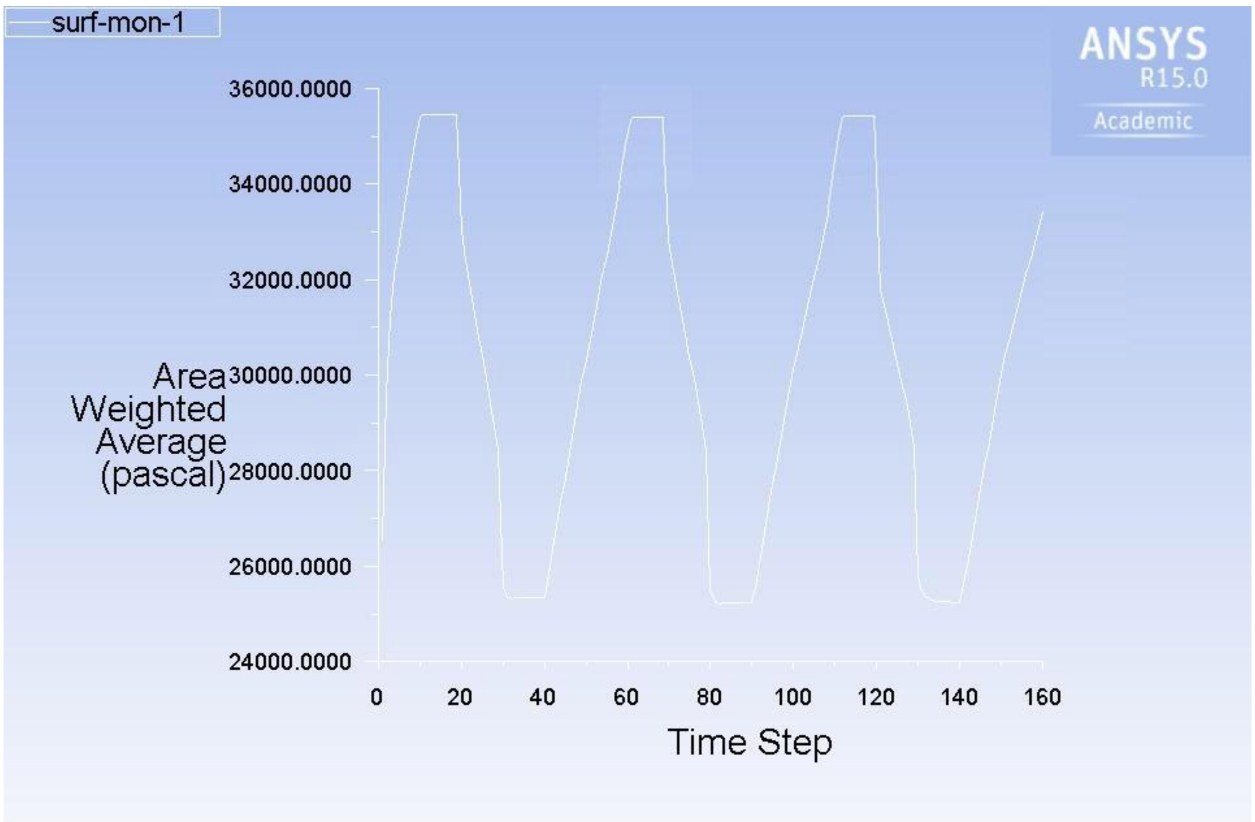


Figure12. Pressure Time graph

Case1: Adiabatic Boundary Condition

For adiabatic boundary condition at cold end heat exchanger of OPTR for trapezoidal pressure curve is discussed. The system has reached a steady periodic condition and the CHX reaches a minimum temperature of 168K for case1 as shown in Figure shows the temperature distribution respectively along the axial position after system reaches a steady periodic condition. Fig.12 and Fig13 show the snapshot of temperature and density contours respectively

Case2: Known Heat flux Boundary Condition

In this case a 5W constant heat load is applied at the CHX side wall and the HHX side wall is held isothermal at 293K. A quasi-steady state has been reached with the CHX approaching a cycle average temperature of 185K as shown in Fig. show the variation of temperature respectively along length of entire simulated system. Fig.5.38 and 5.39 depict the contour of temperature and density respectively.

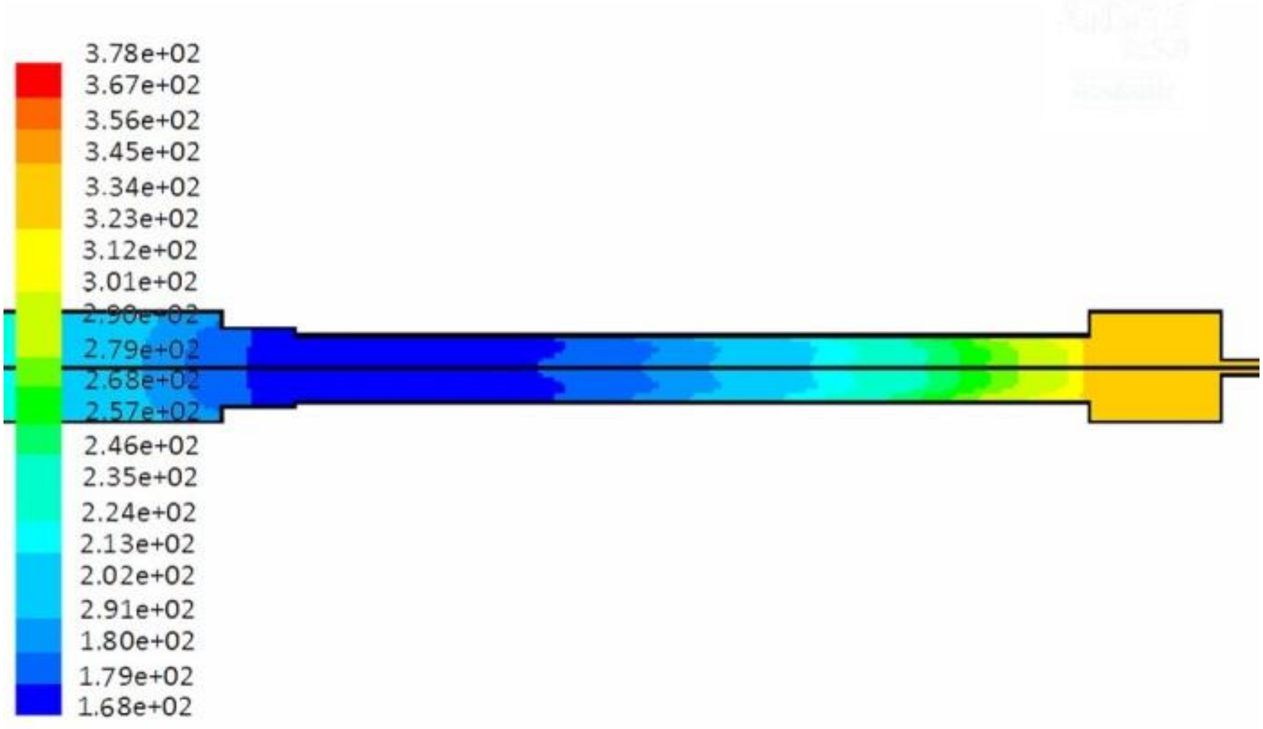
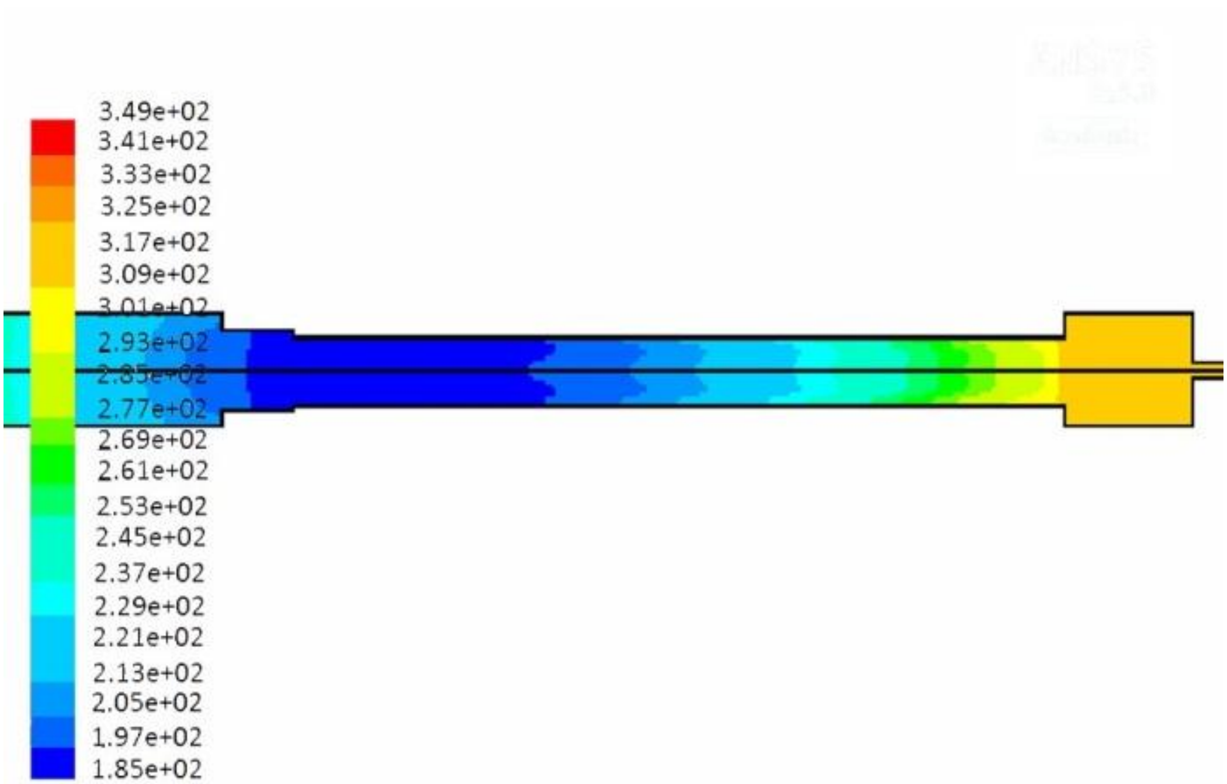


Figure13. Temperature contour for case1 CHX



. figure14. Temperature contour for case2 for CHX

Discussion

The simulation results show that for adiabatic case (case1) CHX the temperature achieved at cold end is 168K in case of OPTR. And for 2nd case, a heat load of 5W is imposed at CHX, the temperature achieved CHX is 185K in case of OPTR.

CHAPTER V

Scope for Future work

Like Trapezoidal Pressure curve different pressure profile can be generated using UDF like triangular rectangular. In this thesis only for Orifice Pulse tube Refrigerator the analysis has been done. For different type of Pulse Tube like Inertance tube Pulse tube, Double inlet pulse tube taking trapezoidal pressure profile analysis can be done for different boundary condition like adiabatic condition to get minimum temperature for no load, Isothermal condition to get refrigeration effect for a specific temperature, analysis for a known load condition to get minimum temperature for a given refrigeration effect.

CHATER VI

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