

NUMERICAL ANALYSIS of PULSE TUBE CRYOCOOLER

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Abstract: A commercial computational fluid dynamics (CFD) package is used for numerical analysis of the oscillating fluid flow in a pulse tube cryocooler. This model uses helium as a working medium to achieve temperatures in cryogenic range by employing two pulse tubes with 180° phase difference in the mass flow rate and the pressure at the cold end heat exchanger. The cryocooler comprises of compressor, after cooler, regenerator, pulse tube with cold and hot heat exchanger and the inertance tube. A two-dimensional axis symmetric model was used for simulation. This simulation demonstrates the variation in temperature and pressure with respect to time at the cold heat exchanger.

Keywords: pulse tube, cryocooler, CFD, phase difference.

NOMENCLATURE:

D_p	Mean diameter of particles [m].	α & c_2	Resistance coefficients
T	Temperature [K].		
h	Enthalpy [$J.kg^{-1}$]	ε	Porosity [dimensionless].
k	Thermal Conductivity [$W.m^{-1}.K^{-1}$].	$\bar{\tau}$	Stress tensor [$N.m^{-2}$].
p	Pressure [$N.m^{-2}$].	t	Time [s].

SUBSCRIPTS:

f	Fluid		
v	Velocity [ms^{-1}].	r	Radial direction.
μ	Molecular Viscosity [$kg.m^{-1}s^{-1}$].	s	Solid.
ρ	Fluid Density [$kg.m^{-3}$].	x	Axial coordinate.

I.INTRODUCTION

Cryogenics is the branch of physics that deals with the production and study of effects at very low temperatures. Cryogenic Engineering is concerned with temperatures in the range of 0 to 123 K.

The refrigerating machines which are able to achieve and to maintain cryogenic temperature i.e. temperature below 123K are known as cryocoolers. These cryocoolers find applications in space, military and low temperature research as well as in agriculture, transportation and security.

An increased need of cryogenic temperatures in research and huge technological growth during last decade caused a rapid development of cryocoolers. All these applications mostly require efficiency and reliability of the refrigerators along with low cost and long life time. Stirling refrigerators which are primarily used for these cryogenic applications satisfy the above requirements. But the basic problem of these refrigerators is that they have a mean failure time of 4000 hours. This is the reason why they can't be used in satellites and most of the commercial applications. That is why most of the developments in Stirling refrigerators are concentrated towards the techniques that can improve their reliability. This reliability problem can be overcome by research and development of "Pulse Tube Refrigerators" which are having potential for improved reliability, simplicity and low cost.

II. SIMULATED SYSTEM

The proposed model is the modification of Gawali et.al model in which the orifice is replaced with an inertance tube, as shown in figure. It is called as "Inertance Pulse Tube Refrigerator (IPTR)". This enables us to eliminate the orifice required in basic Orifice pulse tube refrigerator (OPTR).

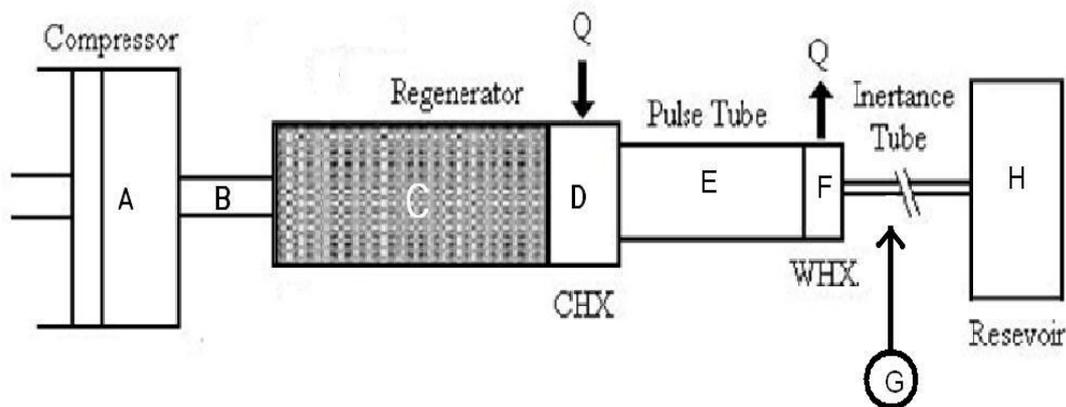


Fig. 1 Simulated Inertance Pulse Tube Refrigerator (IPTR)

In each refrigerator, the volume of gas in pulse tube can be divided into three parts:

1. Cold part: This is the leftmost part of the pulse tube. Here the gas flows from regenerator and expands to give out work.
2. Hot part: This is the rightmost part of the pulse tube. Here the gas flows from the inertance tube and absorbs work.
3. Middle part: The gas at the centre of the pulse tube never flows out of the pulse tube and is similar to a displacer in a Stirling refrigerator.

The solid displacer of the Stirling cycle is replaced by gas displacer. Each refrigerator consists of two heat exchangers namely CHX i.e. cold heat exchanger through which cooling effect is utilized, and HHX i.e. hot heat exchanger for rejection of heat to cooling media.

A. DIMENSIONS OF THE SIMULATED SYSTEM

TABLE I

Component	Radius(mm)	Length(mm)
A (Compressor)	34	72
B (Transfer line)	20	35
C (Regenerator)	24	40
D (Cold heat	24-9,5(varying)	10
E (Pulse tube)	9.5	100
F (Hot heat	9.5	10
G (Inertance Tube)	3	3000
H (Reservoir)	1000	1000

TABLE III

Parameter	Unit	Value
Compressor swept volume	cm ³	254.22
Operating frequency	Hz	12
Transfer line length	mm	35
Regenerator ID	mm	48
Regenerator length	mm	40
Cold heat exchanger	mm	10
Pulse tube ID	mm	19
Pulse tube length	mm	100
Hot heat exchanger (WHX)	cm ³	2.835
Inertance tube ID	mm	3
Inertance tube length	mm	1500
Reservoir volume	m ³	0.8

B. BOUNDARY CONDITIONS

The components are subjected to various boundary conditions as listed in the following table.

TABLE IVVVI

Models	Condition
Compressor wall	Adiabatic
Transfer-line wall	300 K
Regenerator wall	Adiabatic
CHX wall	Adiabatic
Pulse tube wall	Adiabatic
WHX wall	300 K
Reservoir	Adiabatic
Dynamic wall velocity (m/s)	1.728
WHX thickness(m)	Not considered
Regenerator thickness (m)	Not considered
CHX thickness (m)	Not considered
Pulse tube thickness (m)	Not considered
Initial temperature(K)	300 K
Working fluid	Helium
Initial system pressure	8 bar
CHX load (W)	0 W
CHX temperature	142 K
Steady state reached	No

C. MATERIALS OF COMPONENTS

We have used FLUENT 6.3.26 as a solver for the analysis in which we have specified the following materials for the corresponding parts.

TABLE IV

Parts	Material
Compressor wall	Steel
Transfer-line wall	Copper
Regenerator wall	Steel
CHX wall	Copper
Pulse tube wall	Steel
WHX wall	Copper
Reservoir wall	Steel
Inertance tube	Copper
Regenerator porous medium	Steel
CHX porous medium	Copper
WHX porous medium	Copper

III. CFD ANALYSIS

A. MESHING IN GAMBIT

The accuracy of analysis of thermo-fluidic problem or system in CFD is strongly depending on the computational mesh structure applied. Meshing is one of the most time consuming processes in pre-processing. Gambit has different features of meshing. The meshing involves discretization of domain into sub domains or cells. These divided domains are used in the numerical solutions of the differential conservation equations of the mathematical model. For meshing different elements and structures quadrilateral and triangular mesh structure is used.

B. CFD MODELLING

The CFD code FLUENT (6.3.26) is used for simulation. The IPTR system is simulated by assuming cylindrical and linear alignment, axis-symmetric, two-dimensional flow, with working media helium as ideal gas. The transient analysis is done because the process is time dependant. Different algorithms, namely SIMPLE, SIMPLEC, PISO and COUPLED are incorporated in commercial CFD Software, and these algorithms are having their own advantages and disadvantages.

PISO algorithm has been used in this analysis of the pulse tube refrigerator. PISO algorithm is recommended for unsteady calculations and may sometimes be preferred for steady-state ones.

Compressor is modelled by using dynamic mesh feature of the FLUENT. The frequency of the compressor is 12 Hz. The dynamic mesh model in fluent is used to model flows where the shape of the domain is changing with time due to motion of the domain boundaries. The motion is prescribed motion by specifying the linear and angular velocities about the centre of gravity of solid body with time. In order to model compressor, a user defined function with necessary modification was developed in C programming to simulate the piston cylinder effect.

Regenerator, Warm Heat Exchanger (WHX), and Cold Heat Exchanger (CHX) were modelled as porous media. Stainless steel wire mesh screens (mesh size 250) were selected as the regenerator packing material, since they offer high heat transfer surface areas, high heat capacity, and low thermal conductivity. Copper mesh (mesh size 150) is used for WHX and CHX.

Quadrilateral and triangular mesh structure is used for meshing the IPTR system with different features of Gambit [19]. Total numbers of cells for the model with zero thickness are 32744.

Continuum based conservation equation is applied in the system. The mass, momentum and energy equations solved by FLUENT are as follows:

$$\frac{\partial \rho_f}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} [r \rho_f v_r] + \frac{\partial}{\partial x} [\rho_f v_x] = 0 \quad (1)$$

$$\frac{\partial}{\partial t} [\rho_f \vec{v}] + \nabla \cdot [\rho_f \vec{v} \vec{v}] = -\nabla \cdot p + \nabla \cdot [\vec{\tau}] \quad (2)$$

$$\frac{\partial}{\partial t} [\rho_f E] + \nabla \cdot [\vec{v} (\rho_f E + p)] = \nabla \cdot [k_f \Delta T + (\vec{\tau} \cdot \vec{v})] \quad (3)$$

$$\text{Where } E = h - \frac{p}{\rho} + \frac{v^2}{2}$$

All properties represent the properties of the working fluid helium. The above equations apply to all components, except for CHX, WHX and the regenerator. The latter three components are modelled as porous media, assuming that within the volume containing the distributed resistance, there exists everywhere local balance between pressure and resistance forces [18].

$$\frac{\partial (\phi \rho_f)}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} [\phi r \rho_f v_r] + \frac{\partial}{\partial x} (\phi \rho_f v_x) = 0 \quad (4)$$

$$\frac{\partial}{\partial t}(\phi \rho_f \vec{v}) + \nabla(\phi \rho_f \vec{v} \vec{v}) = -\phi \nabla P + \nabla[\phi \vec{\tau}] - [\mu \beta^{-1} j + \frac{1}{2} c \rho_f |j| j] \quad (5)$$

$$\frac{\partial}{\partial t}[\phi \rho_f E_f + (1-\phi) \rho_f E_s] + \nabla[\vec{v}(\rho_f E_f + P)] = \nabla[\phi K_f + (1-\phi) \nabla T + (\phi \vec{\tau} \cdot \vec{v})] \quad (6)$$

All the simulations are carried out as transient processes, starting with an initial system temperature of 300 K. Simulations can be continued until steady-periodic state is obtained. The criterion for steady periodic condition is that the cycle-average temperature of the cold end heat exchanger (CHX) would reach a steady state.

C. ASSUMPTION MADE FOR THE ANALYSIS

1. All components have circular cross-section and have linear alignment.
2. Axis-symmetric geometry is considered for the analysis.
3. Flow is two dimensional and compressible.
4. Helium gas obeys the ideal gas equation.

On the basis of assumption made, the geometry is simplified from three- dimensional to two-dimensional axis symmetric. The property variation in the third direction is strongly dependant on the geometry for the present model and thus is negligible. This simplification will lead to minimum number of cells for meshing and reduce computer time for calculation.

IV. RESULTS AND DISCUSSION

Temperature variation along axial direction is shown in Figure2. Temperature contour along axial direction is shown in Figure3. Significant temperature gradients are predicted in the regenerator and pulse tube.

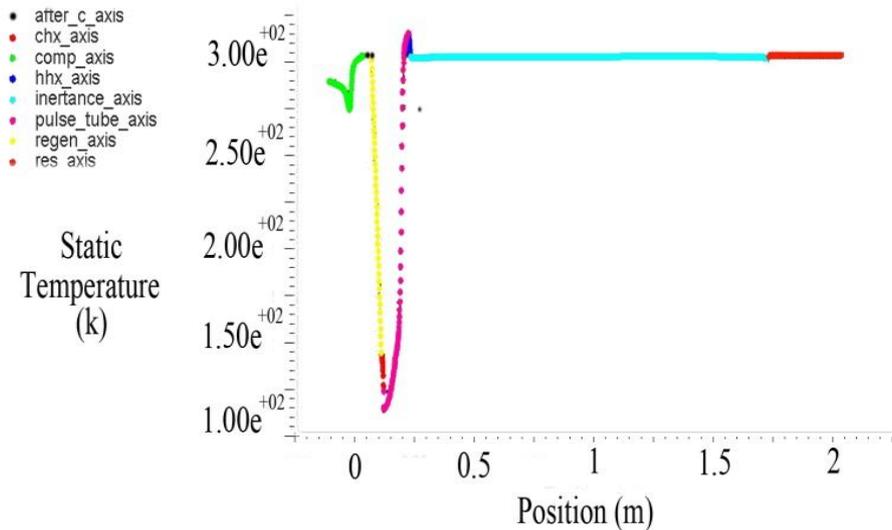


Fig. 2 Temperature variation in axial direction

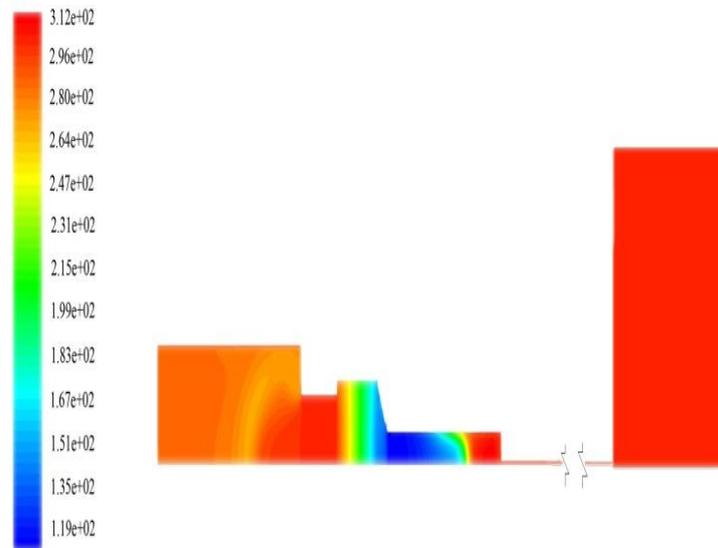


Fig. 3 Temperature (K) contour along axial direction

A. COOL DOWN CHARACTERISTICS

The variation in cycle average temperature at CHX with time is shown in Figure 4. Temperature (cycle average) of 131.994 K is attained after 172.53 sec.

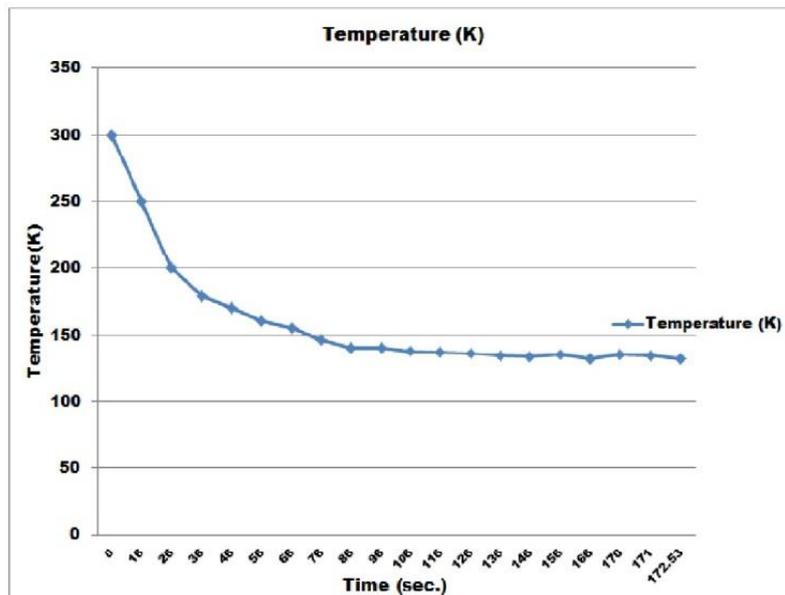


Fig. 4 Cool down characteristics

B. PHASE SHIFT

The variation in pressure and mass flow rate with crank angle at CHX is shown Figure 5. The phase difference in pressure and mass flow rate of 40° is observed. The mass flow rate is lagging the pressure wave.

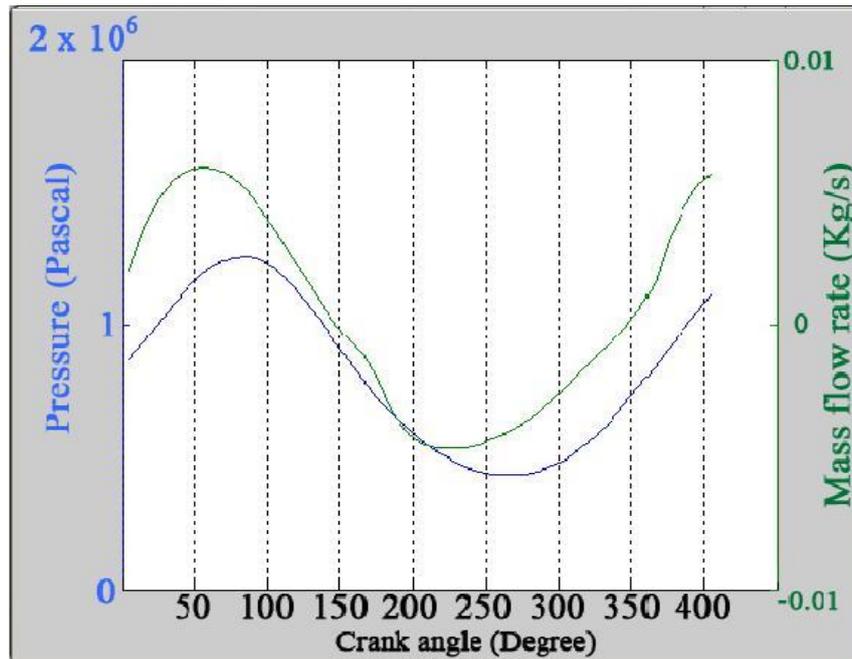


Fig. 5 Phase shift at CHX

C. CYCLIC PROPERTY VARIATION

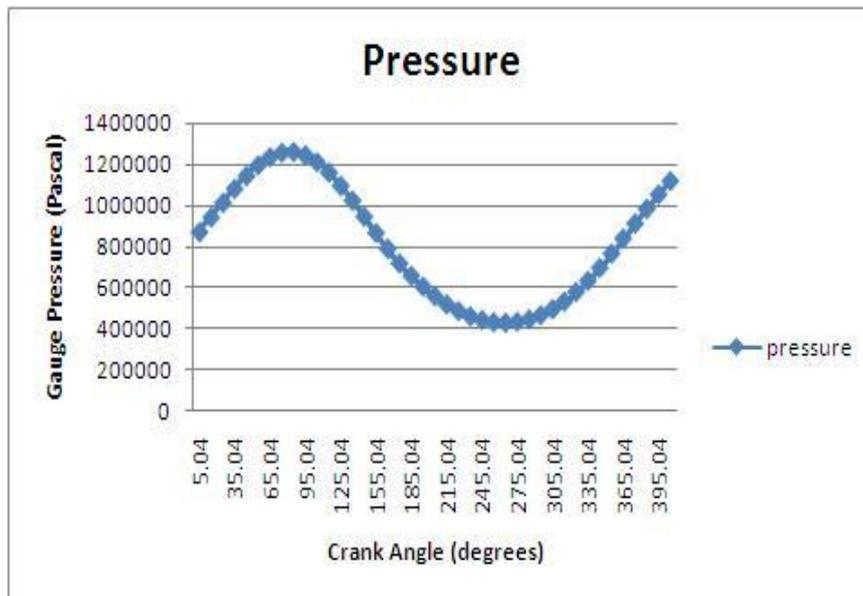


Fig. 6 Cyclic pressure variations with crank angle at CHX

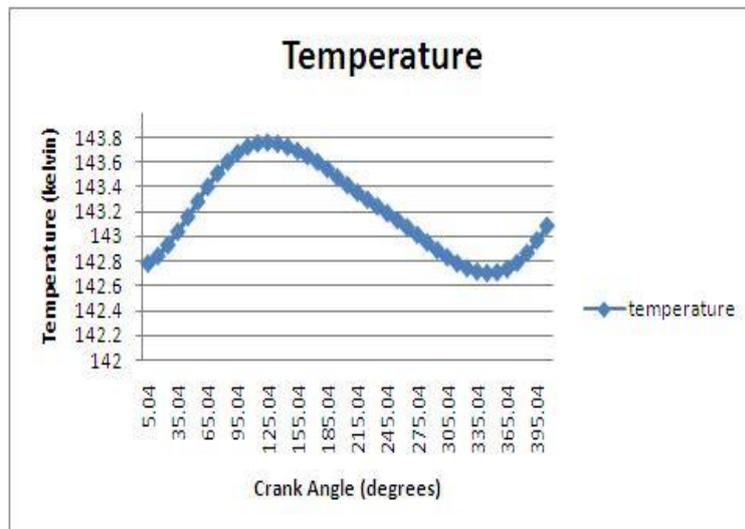


Fig. 7 Cyclic temperature variations with crank angle at CHX

The trends are predicted with the help of CFD tool fluent i.e. figure 2, 3, 4, 5, 6, 7.

V.CONCLUSION

The entire IPTR system operating in periodic state under the given boundary conditions is numerically simulated using CFD code. From present analysis, the lowest temperature at the cold heat exchanger obtained is 132 K in 172 seconds by using helium as the working fluid. The phase shift between the mass flow rate and pressure variation at the cold heat exchanger is observed to be 40° . This indicates the feasibility of the use of commercial CFD software packages for analysing the complex fluid flow and heat transfer phenomena that occur in a pulse tube cryocooler.

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