CFD as a Design Tool for Pulse Tube Cryocooler

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Abstract : NASA planned few Mars missions in between 2012 to 2018. This mission requires very compact, maintenance free, long life cryocooler for production and storage of cryogenic fluid on Mars. Nowadays, pulse tube cryocoolers are preferred over Stirling cryocoolers due to its advantages. Also to design pulse tube cryocooler, there is no reliable design tool to get the dimensions of pulse tube and regenerator. So an attempt is made to develop a reliable axisymmetric model of Pulse Tube Cryocooler (PTC) for simulation using CFD and this simulation model is validated with available results in literature. One can change the dimensions of pulse tube and regenerator and check whether required cooling effect is obtained at cold tip or not.

***Index Terms* - Pulse Tube Cryocooler (PTC), Axisymmetric model, CFD, Phase shift angle**

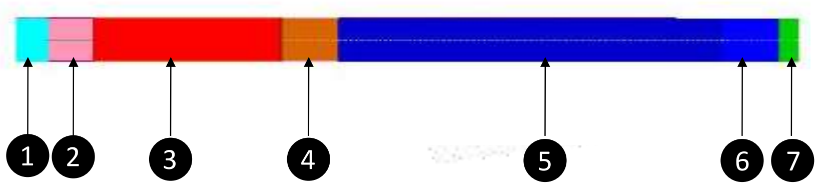
I. INTRODUCTION

Cryocoolers are made up of Linear compressors [1], [2] and cold heads and are used in space related applications like space surveillance, thermal imaging cameras, X-ray astronomy and satellite cooling system etc. Also nowadays pulse tube cryocoolers are beneficial [3] than Stirling cryocoolers as they have no moving parts in cold region and high reliability and stability of temperature at cold end.

A Computational Fluid Dynamics (CFD) software package is used to design pulse tube and regenerator of cryocooler and by using same, heat fluxes are found at cold and hot heat exchangers. The boundary condition for compressor piston is moving surface and for cold and hot heat exchanger as constant temperature wall.

II. CFD MODEL OF PULSE TUBE CRYOCOOLER

In CFD code, continuity, momentum, and energy equations are solved to get convergence. Inputs to CFD model are PTC geometry and boundary conditions. Temperature, pressure, velocity are the typical boundary conditions at fluid inlet and outlet and temperature and heat fluxes at solid boundaries. Standard solid and fluid properties are used to set the model. The various parts of PTC which are modeled in CFD are shown in Fig. 1.



1. Compressor 2. Aftercooler 3. Regenerator 4. Cold end
5. Pulse Tube, 6. Hot end 7. Orifice block

Fig. 1: Mesh generated for PTC

The work input to the piston provides oscillating pressure in the system. Aftercooler is placed between compressor and regenerator. Cold end heat exchanger and hot end heat exchanger are at the both ends of the pulse tube and orifice / inertance is connected to reservoir after hot exchanger.

Compressor walls are modeled as solid wall kept isothermally at 300 K and piston is moving in and out along z-axis sinusoidally. Aftercooler, cold end and hot end are considered as porous regions with copper mesh having porosity of 0.6 and regenerator with stainless steel mesh having porosity of 0.67. In porous regions, inertial and viscous resistance coefficients are used. In basic PTC, negligible flow resistance in axial direction and very high flow resistance in radial direction is provided for all porous regions, so that they will act as a flow straighteners. Helium is considered as working medium as an ideal gas with constant viscosity, heat capacity and thermal conductivity.

III. CASE STUDIES WITH CFD

PTC model is prepared as shown in Fig 1 for the data obtained from our pulse tube code and given in following Table 1 and actual unit is shown in Fig.2 and mesh is generated in preprocessor. Simulation is run with Fluent code [4] for different boundary conditions and compared the results as shown in following Table 2.

Table 1 Summary of cold head design

Component/ parameter	Units	Values
Pulse tube diameter	mm	10
Compressor swept volume	cm^3	08
Operating frequency	Hz	50
Regenerator OD	mm	16
Regenerator length	mm	40
Regenerator mesh (49 gauge)	Mesh / in.	400
Pulse tube length	cm	50
Reservoir volume	cm^3	500
Average pressure	bar	16
Heat rejection temperature	K	300
Refrigeration temperature	K	80
Gross Refrigerating effect	W	12.27
Loss due to regenerator Inefficiency	W	2.2
Temperature swing loss	W	1.72
Conduction loss	W	0.921
PV loss	W	2.81
Shuttle loss	W	0.865
Pumping loss	W	0.40
Conduction loss through gas piston	W	0.921
Compressor power (Ideal)	W	47.8
Regenerator pressure drop	W	8.56
Heat exchanger pressure drop	W	22.83
Net refrigerating effect	W	3.27
PV power	W	98.98
Net power input (87 % motor efficiency)	W	113.7

Fig. 2: Actual PT unit

Table 2 CFD predicted phase shift between pressure and mass flow and heat flux at cold end

Case no.	Cold heat ex. Wall flux W/cm^2	Cold heat ex. Wall temp. K	Phase shift at Cold end	Orifice boundary condition
1	0.11	300K	71^0	Blocked
2	0.45	300K	19.5^0	K=7560

Case 1 is basic pulse tube with cold and hot heat exchanger walls at 300K. But normally cold end wall is not at 300K and is done for comparison purpose here. The basic pulse tube with no heat storage in wall resulted in small heat flux lift of 0.11W/cm^2. The phase shift between peak pressure and mass flow rate is 71^0 as seen in following Fig. 3 and Heat flux vs Crank angle in Fig 4

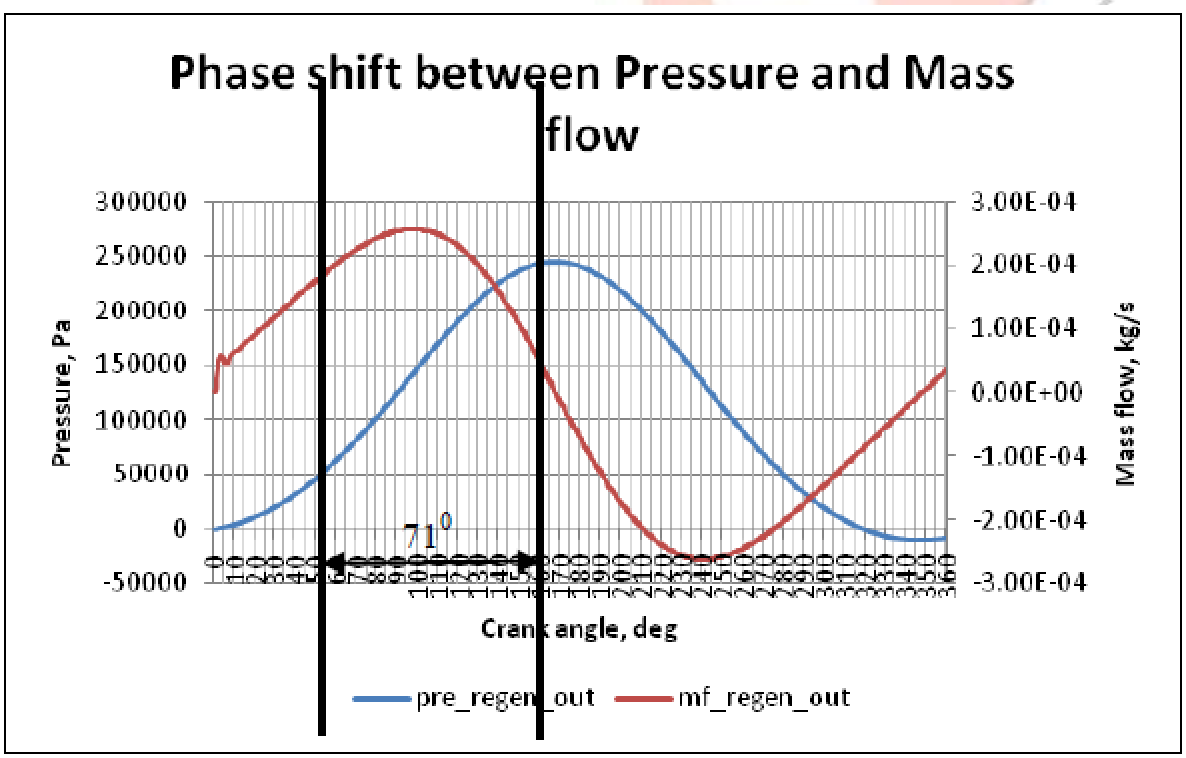


Fig. 3 Phase shift between peak pressure and mass flow at cold end for basic PTC

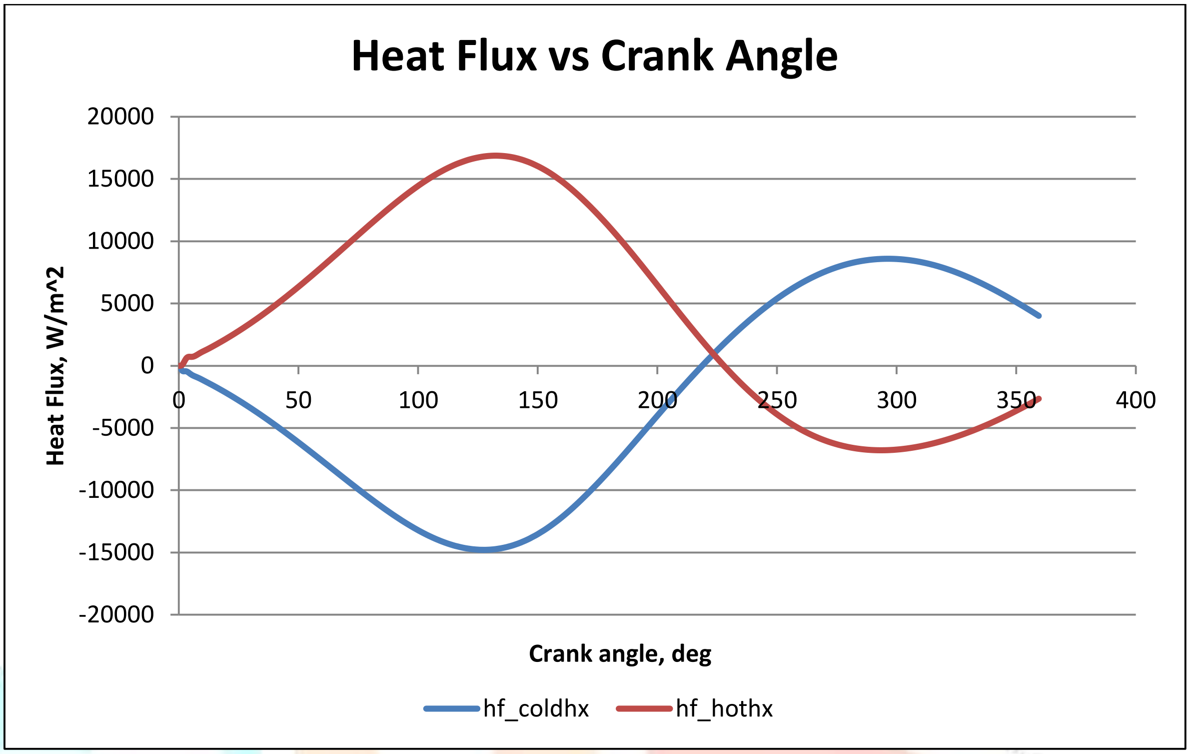


Fig. 4: Heat flux vs Crank angle at cold end for basic PTC

Case 2 is with orifice and reservoir added at the end of pulse tube. Orifice is modeled as flow restriction where pressure drop across it is proportional to the square of mean velocity. The orifice has a K factor of 7560 and compared with first case. Heat flux increased up to 0.45 W/cm^2 and phase shift decreases from 71^0 to 19.5^0 .

Fig 5 below shows phase shift between peak pressure and mass flow rate and Heat flux vs Crank angle in Fig 6 for orifice PTC.

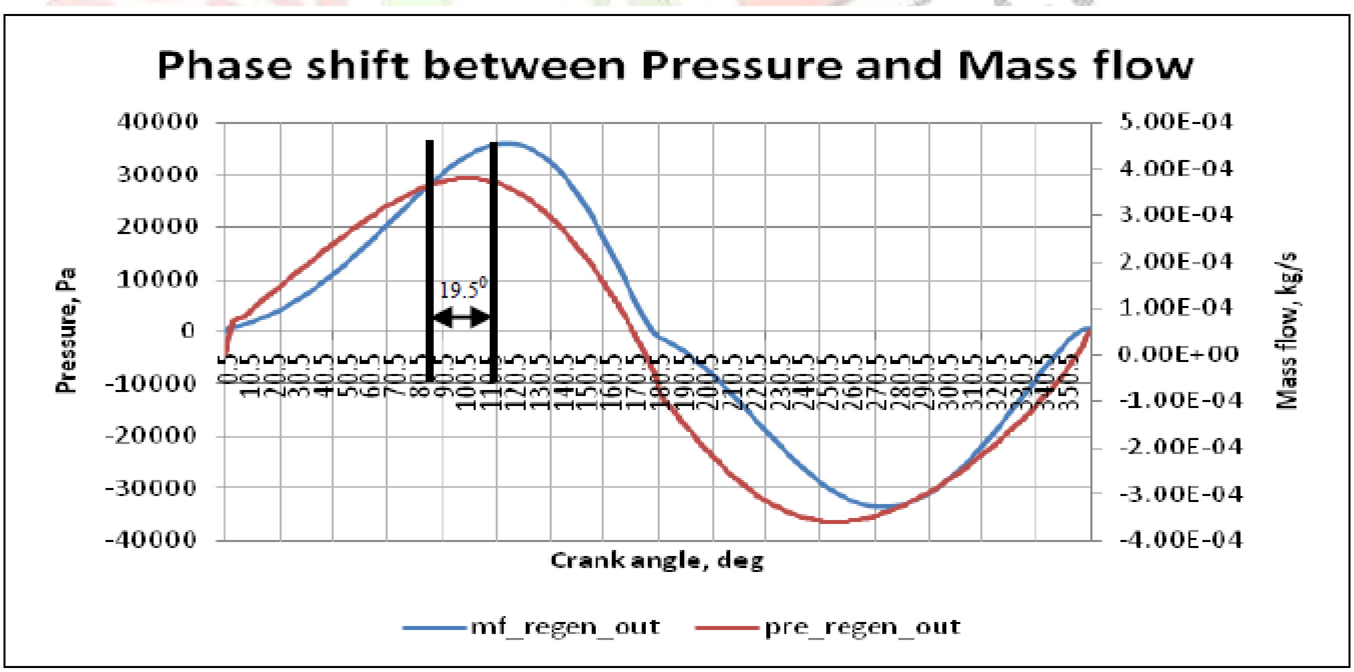


Fig. 5 Phase shift between peak pressure and mass flow at cold end for Orifice PTC

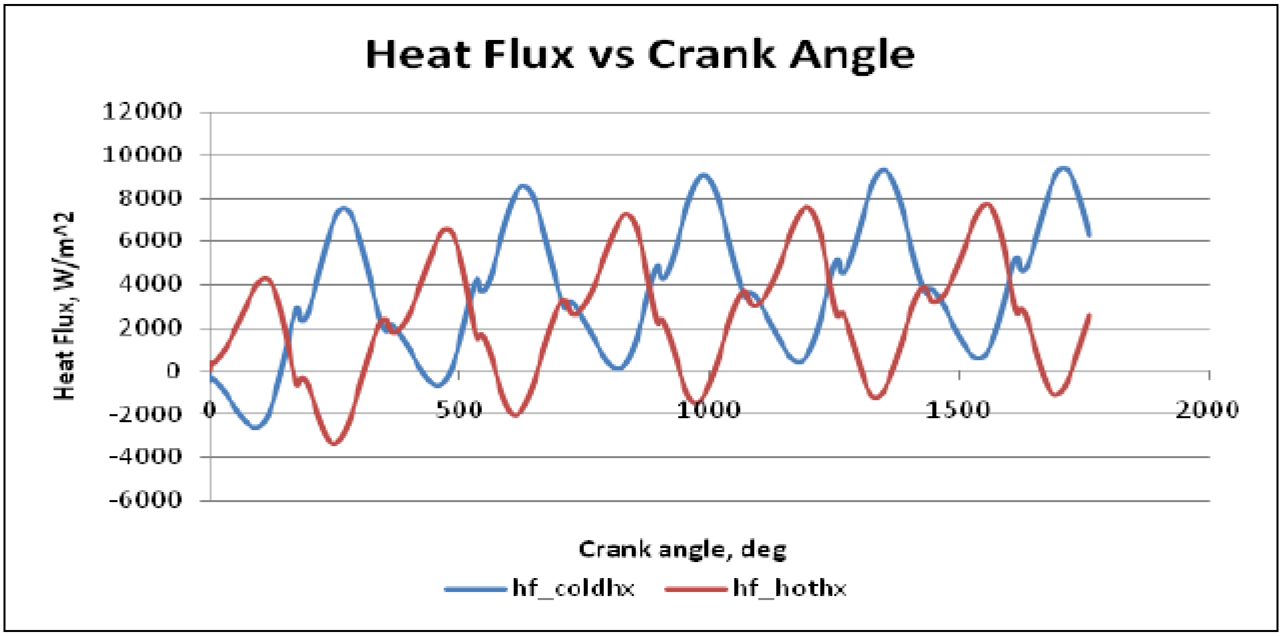


Fig. 6 Heat flux vs Crank angle at cold end for Orifice PTC

IV. Conclusion

An axisymmetric model is developed using commercial CFD package and analysis is carried out by using moving mesh with sinusoidal motion of piston and isothermal walls at cold and hot end. The simulation is run with different conditions by solving Navier-stokes equations which predicts flow dynamics within pulse tube.

Case studies demonstrate basic pulse tube with small heat lift and 710 phase shift and the same Is increased for orifice pulse tube configuration. The results obtained are validated with available literature [5]. Thus the modeling in CFD is utilized in predicting the approximate performance of PTC.

V. Future Enhancement

One can design more precise model using more accurate boundary conditions and find out the required capacity of cryocooler numerically by using CFD code. And then fabricate the actual model of cryocooler and thus saving of time and cost.

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