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Research Article

"Investigation Variable Parameters In Cryocooler Design CFD Simulation Of Inline And Coaxial Pulse Tube Cryocoolers"

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ABSTRACT

Inline Pulse tube cryocoolers (PTC) is very compact and achieved cryogenics temperature without moving part. In view of design, a cold heat exchanger where is provide surface cooling is placed between regenerator and pule tube. Due to that it become necessary to use secondary heat exchange. Coaxial pulse tube cryocoolers (CPTC)is design remove secondary heat exchanger. Helium is taken as working fluid. The required phase lag between mass flow rate and temperature, temperature and density contour are observed. Some Frequency results for different size of regenerator and pule tube are discussed.

Keywords: Coaxial Pulse tube, Inline Pulse tube ,cryocoolers, Frequency test, different size of regenerator and pulse tube

Introduction

Independently, Richardson, (Oxford University Engineering Laboratory) proposed the design enunciated as Coaxial Pulse Tube Cryocooler. Base on that we design Coaxial pulse tube Cryocooler such that inner cylinder is working as pulse tube and outer cylinder contain regenerator. By this design secondary heat exchanger can be removed. [1]

The objective of this study is to analyze the performance of a Pulse Tube Refrigerator (PTR) and conduct a detailed examination of the complex oscillating flow phenomena inherent to PTR systems. Additionally, the study aims to compare the performance of an inline pulse tube refrigerator (IPTR) with that of a coaxial pulse tube refrigerator (CPTR). Investigations were conducted to assess the influence of operating frequency on the system's performance.

In the Inline Pulse Tube Refrigerator (IPTR), all components except Warm Heat Exchangers 1 and 2 (WHX1 and WHX2) are assigned adiabatic boundary conditions, while WHX1 and WHX2 have isothermal boundary conditions. The regenerator and other heat exchangers are modeled using a porous medium approach in the commercial CFD software Fluent. The working fluid, helium-4 gas, is defined within the fluid domain, with properties considered to be temperature-dependent. The compressor is modeled using dynamic meshing techniques to capture the motion of the piston. The simulations utilize the PISO solution algorithm and an appropriate numerical scheme suitable for time-dependent processes to achieve a steady-periodic state. The simulations represent a fully-coupled system operating without arbitrary assumptions.

The process within a Pulse Tube Refrigerator (PTR) is inherently complex, posing challenges for experimental study of thermo-hydrodynamic flow phenomena. While some experimental setups have been devised using commercial design codes like "SAGE" for PTR and "REGEN" for regenerator selection, literature reporting experimental results often lacks detailed descriptions of basic design and analysis for selected PTR dimensions. Additionally, experimentation is time-consuming, costly, and limited in scope, providing only a selected set of observations. Currently, worldwide research seldom reveals the exact mechanisms underlying PTR performance. Moreover, the intricate periodic flows within PTRs further obscure system analysis. Given these challenges, numerical modeling and performance investigation using advanced computational facilities are recommended for studying thermo-hydrodynamic flow phenomena within PTRs [2,3].

Simulation Tool

CFD (computational Fluid Dynamics) techniques are strongly capable for precisely modeling for complex geometries. multidimensional fluid and heat flow processes provides a clear and accurate study of pulse tube

cryocoolers (PTC). The performance of PTC can be predicted by using multidimensional higher order numerical analysis using CFD techniques, if the model is defined with appropriate boundary conditions. Numerically solving the continuum governing equations based on fundamental principles, without arbitrary simplifications, offers a pathway to comprehending intricate thermos-fluidic processes. This feasibility is facilitated by Computational Fluid Dynamics(CFD) techniques.
Ansys® Workbench 12.0 CFD Fluent® is such a tool. It provides excellent facilities for simulation of fluid flow parameters under different conditions using Computational Fluid Dynamics. We have used this tool in our experiment.

Design Data for Inline and Coaxial Cryocoolers Modelling

The numerical and computational aspects serve as the primary focus of this study. The design data and operating parameters utilized mirror those of the experimental test apparatus housed at the cryogenic Research Laboratory, Georgia Institute of Technology, GA, Atlanta, as extensively documented in the literature and depicted in Figure 1. Specifics regarding dimensions and material compositions of the components can be found in Table 1. [4-7]
Each component comprising the Inline Pulse Tube Cryocoolers (IPTC) exhibits a cylindrical configuration, with all elements arranged in series to from an axis-symmetric system. Consequently, the IPTC is represented in a 2-dimensional, axis-symmetrical coordinate framework. The potential asymmetry stemming from gravity is disregarded under this modeling approach. However, the gravity term would become significant if its magnitude were comparable to that of other terms (e.g., temporal acceleration, convective acceleration) in the momentum equation.

Figure 1: Schematic Diagram (Inline Pulse Tube Cryocooler)

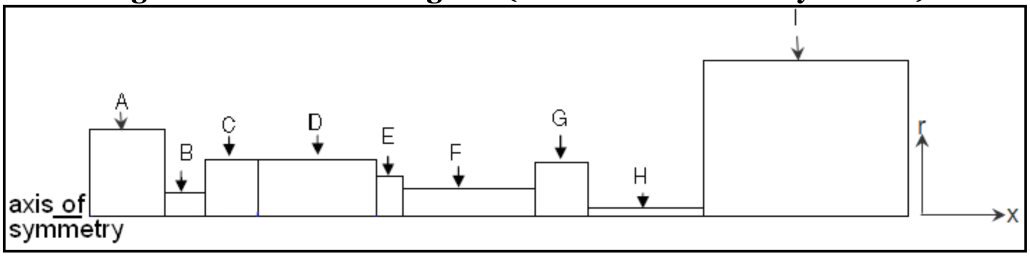

Figure 2: Schematic Diagram (Coaxial Pulse Tube Cryocooler)

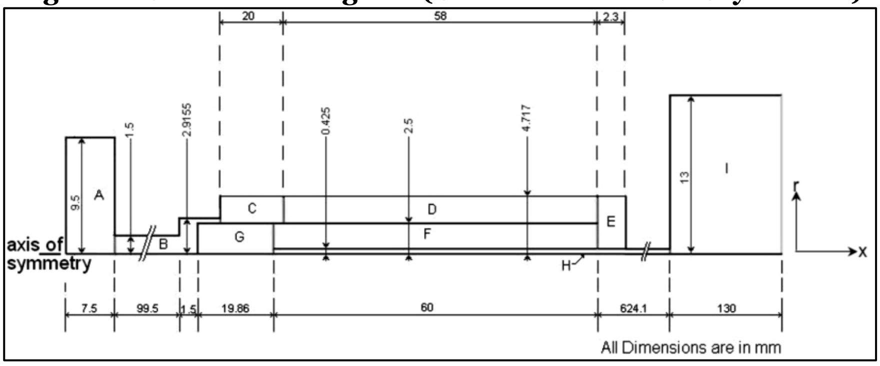

Table 1: Component Detail of IPTC

Sr. No.	Component	Radius(mm)	Length(mm)	Material
A	Compressor	0.954	0.75	S.S (304)
B	Transfer Line	0.155	10.1	S.S (304)
C	WHX 1	0.4	2	OFHC-Copper
D	Regenerator	0.4	5.8	S.S (304)
E	CHX	0.3	0.57	OFHC-Copper
F	Pulse tube	0.25	6	S.S (304)
G	WHX 2	0.4	1	OFHC-Copper
H	Inertance tube	0.0425	68.41	S.S (304)
I	Surge Volume	1.3	13	S.S (304)

From the reference of Ashwin T.R [8], for the design data of CPTC and for comparing the performance of coaxial and inline configuration, the volume of each component is kept the same. The details of dimensions and material of the components is given in Figure 2 and table 2.

Table 2: Component Detail of CPTC

Sr. No	Component	Radius(mm)	Length(mm)	Material
A	Compressor	0.954	0.75	S.S (304)
B	Transfer Line	0.155	10.1	S.S (304)
C	WHX 1	0.4717 – 0.25	2	OFHC-Copper
D	Regenerator	0.4717 – 0.25	5.8	S.S (304)
E	CHX	0.4717 – 0.0425	2.3E-03	OFHC-Copper
F	Pulse tube	0.4717 – 0.0425	6	S.S (304)
G	WHX 2	0.4	1.986	OFHC-Copper
H	Inertance tube	0.0425	68.41	S.S (304)
I	Surge Volume	1.3	13	S.S (304)

The boundary conditions for the modelling of both IPTC and CPTC are summarized in Table 3
Now the model is ready for conducting the simulation exercise. The next chapter is devoted to modelling the IPTC and comparing the simulation results to the experimental results reported by Cha [7].

Table 3: Summary of Boundary Conditions for Components of Both IPTC System and CPTC System

Sr. No.	Components	Boundary conditions
1	Compressor wall	Adiabatic
2	Transfer Line Wall	Adiabatic
3	WHX1 wall	293K
4	Regenerator wall	Adiabatic
5	Pulse Tube wall	Adiabatic
6	WHX2 wall	293K
7	Inertance Tube wall	Adiabatic
8	Surge Volume wall	Adiabatic
9	Permeability of porous component β (m2) for regenerator	1.06E-10
10	Inertial resistance C (m-1) for regenerator	76090
11	Permeability of porous component β (m2) for WHX1, CHX & WHX2	1.345E-9
12	Inertial resistance C (m-1) for WHX1, CHX & WHX2	8147
13	Porosity for regenerator	0.692
14	Porosity for WHX1, CHX & WHX2	0.68
15	Initial Condition	300K, 3.1MPa

Simulated Cases for PTC System Performance Study

In order to study thermo-fluidic behavior and to evaluate optimum range of parameter, different cases for CPTC simulation were set. The simulation process set-up is same as discussed above expect some relevant parameters were changes are illustrated in table 4.

Table 4: Simulated Cases Pressure 3.1 Mpa

Sr. No.	Model	CHX Wall Boundary Condition	Length Of Regenerator	Length Of Pulse Tube	Frequency Input At Compressor (Hz)
Case 1[5]	IPTC	Adiabatic (0 watt)	-	-	34
Case 2[5]	IPTC	Heat load (1Watt)	-	-	34
Case 3[5]	IPTC	Heat load (1Watt)	-	-	40
Case 4[5]	IPTC	Heat load (1Watt)	-	-	50
Case 5	CPTC	Adiabatic (0 watt)	58	60	34
Case 6	CPTC	Heat load (1Watt)	58	60	34
Case 7	CPTC	Heat load (1Watt)	60	60	34
Case 8	CPTC	Heat load (1Watt)	60	60	50
Case 9	CPTC	Heat load (1Watt)	70	70	34
Case 10	CPTC	Heat load (1Watt)	70	70	50
Case 11	CPTC	Heat load (1Watt)	50	50	34
Case 12	CPTC	Heat load (1Watt)	50	50	50

CFD Simulation Procedure (IPTR and CPTR)

The simulation procedure for the no-load test conducted using FLUENT® is detailed as follows:

1. After successful meshing, the mesh model is imported into FLUENT®. Both the Inline Pulse Tube Refrigerator (IPTR) and Coaxial Pulse Tube Refrigerator (CPTR) are simulated with linear alignment, axis-symmetric, two-dimensional flow, and laminar flow settings.
2. The grid is thoroughly checked to ensure its validity.
3. Utilizing the Pressure-based Segregated Solver with First Order Implicit Formulation, as discussed in section 3.3.
4. Solid materials such as 304 stainless steel and OFHC Copper are used for different components of both IPTR and CPTR, as detailed in tables 3.1 and 3.2. Helium-4 gas is designated as the working fluid within the fluid domain of system components. Properties for both solid and gas are assigned in a piece-wise manner, as discussed earlier.
5. To define the compressor, the dynamic meshing option in FLUENT® is employed. The piston is set as a rigid body, with its motion governed by a User-Defined Function (UDF) compiled and integrated with FLUENT®.
6. Defining appropriate boundary conditions with minimal assumptions is crucial for accurate results. For the no-load test, the Cold Heat Exchanger (CHX) wall is assigned an adiabatic boundary condition. The regenerator and other heat exchangers are defined as porous media. The porous zone is defined with specific values for porosity, inertial, and viscous parameters, as shown in Table 3.8.
7. Given the complex fluid flow and heat transfer phenomena occurring at low temperatures in IPTR and CPTR, the PISO solution algorithm is employed to handle the time-dependent, steady-periodic process. Convergence criteria are set for continuity and momentum at 1E-5, and for energy at 1E-7.
8. To plot the results, various monitors are set up for parameters such as mass flow rate, temperature, pressure, and refrigeration load at different locations within the IPTR and CPTR systems.
9. The time step size is calculated based on the frequency value, with 40 steps in one cycle. The maximum number of iterations per time step is set at 5.
10. The solution is initiated with a charge pressure of 3.1 MPa and a temperature of 300 K. The simulation is carried out until a steady-periodic state is achieved.

Result and disruption

From the Figure 3 and Table 5, better cooling is given by IPTC models compare to CPTC models with 34 Hz frequency and same volume of each component. It can be due to huge flow reversal at Cold Heat Exchanger and at WHX2, causes mixing of gas and larger pressure drop and dead volume in CPTC compare to IPTC.

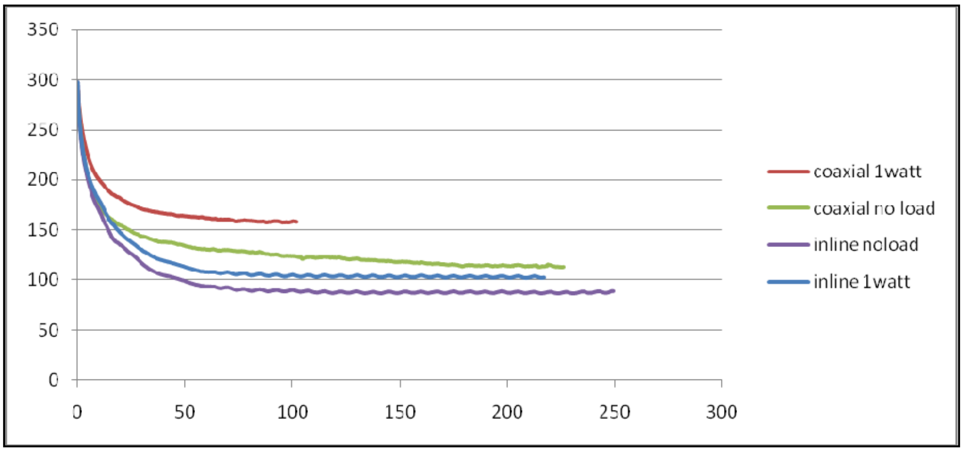

Figure 3: Temperature Cool Down Curves for IPTC and CPTC Models

Table 5: Temperature Comparison for IPTC and CPTC Models

Time	0 Watt(CPTC)	1 watt (CPTC)	0 Watt(IPTC)	1 Watt(IPTC)
0.00	300	300	300	300
50.01	130.57602	169.2356	99.30619	112.61766
100.01	127.82072	148.61313	88.992302	104.98738
149.99	121.36613	-	86.304359	102.96947
200.00	114.70199	-	87.814247	102.22773
250.01	111.56026	-	87.443787	-

The presence of an optimal frequency value in both Inline and Coaxial Pulse tube Cryocooler systems, operating under identical boundary conditions can be substantiated. Similarly, for observation of effect of the length of

pulse tube and length of the regenerator we take more cases-6, 7, 8, 9, 10, 11, and 12. There are three models simulated 34 Hz frequency (case 7, 9, and 11) and three at 50 Hz frequency (case 8, 10, 12). In which we had aspect ratio is one, aspect ratio is calculating by dividing length of pulse tube with regenerator length i.e. one model is having 60mm length of Pulse tube and Regenerator (case 7, 8). Second one is having 70 mm length of Pulse tube and Regenerator (case 9, 10) and one is having 50 mm length of Pulse tube and Regenerator (case11 & 12).
The CHX wall cool down curve are compared in Figure 4 and temperature value in Table 6 for CPTC system. With the two set of frequencies, the models with 50 Hz frequency are achieving lower cooling curves compare to 34 Hz frequency. Still we cannot predict the optimum frequency valve for CPTC system.

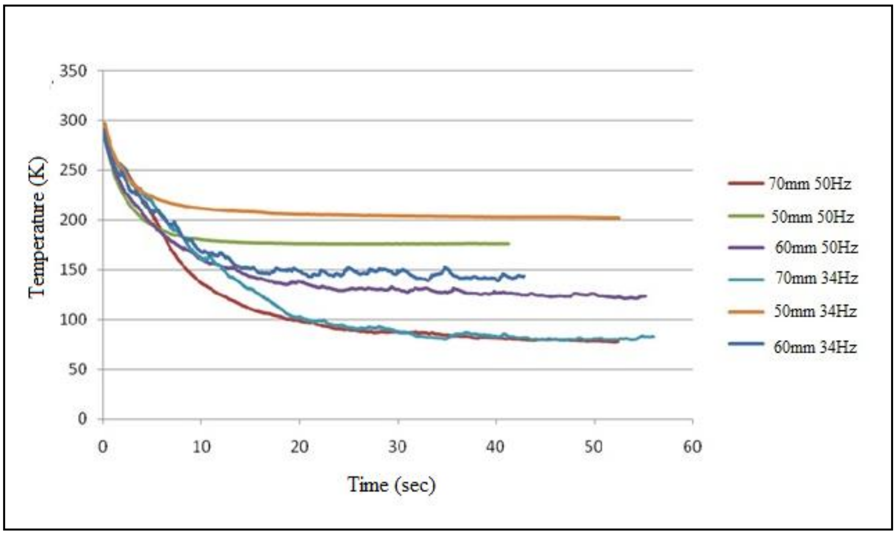

Figure 4: Temperature Cool-down Curves for Different CPTC Models

Table 6: Temperature Comparison for Different CPTC Models

Time	34 Hz			50 Hz		
	60 (mm) long	50 (mm) long	70 (mm) long	60 (mm) long	50 (mm) long	70 (mm) long
0.00	290.55688	297.55609	291.18808	287.94772	291.76831	291.30142
10.00	168.08095	211.47047	159.88597	134.95865	179.42319	158.93114
20.00	148.67845	205.52783	102.16066	97.456497	175.69458	136.63243
29.99	148.56404	203.98669	86.735115	87.597473	175.66574	128.52321
40.00	139.63007	202.82869	82.556625	81.045433	175.69966	127.13794
50.01	148.80106	202.36859	80.18441	78.356186		123.39855

And with the three set of aspect ratio of pulse tube and regenerator length, results shows the higher drop in temperature with increase in length of pulse tube and regenerator. But axial conduction losses are not taken into account which may reduce the drop in temperature. And also it does not predict which one is having a better coefficient of performance.

Conclusions

There is always existence of optimum value of frequency in PTC system for the same boundary condition can be justified Results show the higher drop in temperature with increase in frequency. But for that simulation on more models will give optimum value for system.
Similarly, there is also existence of aspect ratio which gives optimum performance for same boundary condition and operating condition Results shows the higher drop in temperature with increase in length of pulse tube and regenerator. But axial conduction losses are not taken into account which may reduce the drop in temperature.

Recommendation for Future Work

The Fluent simulation results outlined and analyzed in this thesis yielded reasonable predictions that aligned with anticipated trends across the board. These Computational Fluid Dynamics (CFD) simulation offer invaluable insights into local instantaneous processes, enriching our understanding of the system dynamics. To obtain wide range of set of frequency and aspect ratio parameters, more CPTC performance are recommended using more set of frequency. For higher accuracy and prediction 3D model simulation and consideration thermal mass axial conduction and solid conduction should be taken.

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