Effect of induced pressure fluctuation in reservoir of a pulse tube cryocooler

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Abstract. Pulse Tube Cryocoolers are used extensively in aerospace applications, environmental studies, and medical applications. It has several advantages of which some are very low vibration and long life. The performance of Pulse tube cryocooler can be enhanced by using a combination of inertance tube and reservoir. For practical applications the pulse tube cryocooler should be compact in size. This could be achieved by reducing the volume of the reservoir. This paper analyses the feasibility of introducing a reverse fluctuation inside the reservoir to minimize reservoir volume. Reverse fluctuation could be introduced by using the back volume of hermetically sealed linear compressor. To ascertain the same a numerical model was developed and simulated using Ansys Fluent. The effect of pressure variation in the reservoir and its equivalent performance was also simulated. The results suggest that the use of bounce space has a better results at lower volume and equivalent performance on increasing volume when compared to the cryocooler with reservoir.

1. Introduction

The application of cryogenic temperature in advanced technology in medicine, metallurgy, military and space missions require high performance Cryocoolers or Cryogens. Momentous advantages of cryocooler make them suitable for Superconducting Quantum Interference Devices(SQUIDs), cooling of infrared sensors, low noise electronic amplifiers, superconducting magnets, liquefaction of gases, etc. Stirling type Cryocoolers are used in infrared detectors, which works at temperature environment as low as 60K. These sensors are used widely in remote sensing satellites and astronomical detection. Cryocooler research on space compatible, focus on the development of Stirling Pulse Tube Cryocooler. The advantages of these regenerative type Cryocoolers includes closed cycle operation (Stirling), reliable working, low vibration etc. makes them suitable for space applications [1].

The research on space compatible mini-cryocoolers focuses on the development of Pulse Tube Cryocooler(PTC). The latest of its kind, inertance type Pulse tube Cryocoolers are on focus due to reliable working and low noise. Boer [2] confirm the fact that the inertance kind of cooler is very efficient compared to the orifice or double inlet type coolers The major drawback of pulse tube cryocooler are its geometric structure and the performance. Works like tandem type, mass and spring feedback system for the work recovery, adjustable inertance tube and active phase shifting are suitable examples for modifications inorder to improve the performance and compatibility [3] [4].
This work aims to suggest a method to make a pulse tube cryocooler compatible by the use of bounce space (i.e. back volume) of the linear compressor as the reservoir. The function of the inertance tube and reservoir is to compensate for the undesired pressure and mass flow variation at the warm end of the Pulse tube so to get an improved phase shift at acceptor. The bounce space of linear compressor is supposed to have an phase shift of 180 deg compared to the compressor space, so with proper design of inertance tube connected to bounce space could act as an active reservoir. To analyze the influence of Bounce space pressure fluctuation on the performance of pulse tube cryocooler an inertance pulse tube cryocooler whose power input not higher than 100W is designed for different cases as in Table 1. Table 2 gives the working parameters of the proposed cryocooler.

**Table 1: Simulation Cases considered**

| Case | Type                |
|------|---------------------|
| 1    | 300 cc Reservoir space |
| 2    | 300 cc Bounce space  |
| 3    | 600 cc Reservoir space |
| 4    | 600 cc Bounce space  |

**Table 2: Working Parameters**

| Parameter       | Values    |
|-----------------|-----------|
| Working fluid   | Helium    |
| Charge Pressure | 3MPa      |
| Frequency       | 50Hz      |
| Ambient temperature | 310K    |

2. CFD Simulation

Computational Fluid Dynamics (CFD) is the analysis of fluid flows using numerical solution methods. Using CFD, analysis of complex problems involving fluid-fluid or fluid-solid interaction is made possible. The analysis of thermodynamic cycles analysis in a pulse tube refrigerator was done by Chen et al. [5], and states that the two dimensional axial symmetric CFD model results are comparable with the theoretical analysis, which predicts the same type of thermal cycles at same locations.

![Figure 1: Part model for CFD analysis](image)

Fluent in Ansys workbench is used to model the fluid flow and heat transfer interactions in Coaxial Inertance Pulse tube Cryocooler. The analysis of the Cases 1-4 a part geometry as shown in Fig.1 is considered. To ease computation and to analyze the dependence of pressure ratio, linear compressor and bounce space were replaced by two Pressure inlets using user defined functions. For Cases 1 and 3 pressure inlet-1 at aftercooler is used, and for cases 2 and 4 pressure inlets-1 and 2 are used. Axisymmetric, two-dimensional flow was analyzed for coaxial inertance PTC. The geometry, working parameters, material selection, heat load at acceptor and amplitude of pressure at two inlets and was based on Sage simulation. The part model and mesh generation were done with the help of Ansys workbench. The regenerator and Heat Exchangers
materials were SS304 and Copper respectively. Thermophysical properties of Helium, Copper and Stainless Steel were incorporated in the simulation. Detailed parameters of components and the boundary conditions are illustrated in table 3.

### Table 3: Boundary conditions and material.

| Components          | Boundary Conditions | Material | Mesh | Porosity |
|---------------------|---------------------|----------|------|----------|
| After Cooler        | Wall Temperature 300K | Copper   | 100  | .65      |
| Regenerator         | Adiabatic wall      | SS304    | 400  | .78      |
| Acceptor            | Wall with heat load | Copper   | 100  | .65      |
| Pulse Tube          | Wall Temperature 300K | SS304    | -    | -        |
| Warm heat Exchanger | Wall Temperature 300K | Copper   | 100  | .65      |
| Inertance Tube      | Wall Temperature 300K | Copper   | -    | -        |
| Reservoir           | Wall Temperature 300K | Copper   | -    | -        |
| Bounce space        | With Pressure inlet 2 | Copper   | -    | -        |

#### 2.1. Method of Solution

The finite volume method of CFD is used for the analysis of Inertance Pulse Tube Cryocooler, validation of model scheme is done with experimental results from journals. Pressure based solver with the Coupled scheme is used for analysis. For density and momentum, second-order upwind scheme is used. For pressure, spatial discretization Presto scheme is used. The convergence criteria for continuity and momentum is $10^{-03}$ similarly for energy is $10^{-06}$. The time step is $1 \times 10^{-04}$ with 20 iterations per step, the simulation was done until the acceptor temperature reaches 70K. The energy conservation equation based on the thermal equilibrium modes are given by [6]:

$$\frac{\partial}{\partial t}(\rho_f e_f) + \nabla[\vec{v}(\rho_f e_f + P)] = \nabla[k_f \nabla T + (\overline{\tau}.\vec{v})]$$

(1)

Here $\rho_f, \vec{v},$ and $P$ denotes density, velocity, and pressure of working fluid. Similarly $T, e_f$ and $k_f$ are the temperature, energy and thermal conductivity of the working fluid. $\overline{\tau}$ indicates stress tensor.

#### 3. Results and Discussion

The Coefficient of Performance (COP) of a PTC equals to the ratio of acceptor to the hot end temperature as reported by Radebaugh [7], this value is less than the actual Carnot COP since no work is recovered at low-temperature side. The same ideal COP is obtained by De Waele [8] by analyzing an ideal regenerator without entropy generation. Boer [2] concludes that parameters that influence the performance of Pulse Tube Cryocoolers are the charge pressure, regenerator effectiveness, Pulse Tube volume, Inertance tube dimensions and frequency of operation. The results based on variation of reservoir volume and the performance is discussed in detail.

#### 3.1. Effect of reservoir volume on performance

The variation of pressure and mass flow amplitude at acceptor for different cases 1-4 are given in Fig 2 and 3. The obtained phase shift for cases 1 and 2 were 44 and 48 at acceptor. The phase shift obtained with 300 cc bounce space is better compared to 300 cc reservoir and so the Coefficient of Performance (COP), this is evident from the phase shift at acceptor and from table 4 which compares the performance of all the four cases. In case of 600 cc reservoir and bounce space
The phase shift obtained is same this could be inferred from Fig 2. The increase of bounce space volume did not affect the performance of the system. This is because of increasing the bounce space volume the pressure fluctuation inside ceases to act like a normal reservoir. Evidently, it is unwise to use bounce space without considering its volume if an increased performance is expected.

The simulation shows the variation of pressure and mass flow at identical points of acceptor for all the cases considered. The only varying parameter is the bounce space volume, characteristics of systems are entirely different. The amplitude of pressure for Case 1 and 3 were 0.02MPa and 0.01MPa inside the reservoir. The magnitude of pressure fluctuation inside bounce space for Case 2 was 0.045MPa whereas for case 4 it was 0.01MPa, it indicates the net power input is less for the latter.

The Phase difference between pressure and mass flow for cases 1, 2, 3, and 4 are 44, 48, 40, and 44 respectively, which indicate that all the coolers have good characteristics. Amplitude of Mass flow at the acceptor for Case 1, 2, 3, and 4 are is 3.6g/s, 4.8g/s, 3.12g/s, and 4.7g/s. The characteristics of mass flow indicates there is an effective difference on the functioning of compressor ie the power input varies according to mass flow and so the effective performance, this could be ascertained from table 4.

3.2. Performance comparison

Temperature contour for case 2 of the axisymmetric model of the acceptor including after cooler, regenerator, warm heat exchanger, and acceptor are shown in Fig. 4. The figure describes temperature variation inside a cryocooler at an instant when the temperature reaching 70K at Acceptor. The temperature contours were found in good agreement to the reported related works [9].

To analyze the performance of cryocooler the CFD simulation were done as each cooler has different performance. The heat load on the cold heat exchanger was based on Sage analysis and substituted for the boundary condition for Acceptor. The cooling curves of Cases 3 and 4 were almost similar indicates that as the bounce space volume increases the effect of pressure fluctuation is negligible and so the difference in performance. Performance comparison of the cases considered are given in table 4, the load indicates thermal load at the acceptor and input indicates the power input to the compressor as simulated using Sage.
Figure 4: Temperature contour at 70K.

The following inference could be made from plots, the performance of the case 4 is expected to be better than Case 2. The pressure amplitude inside the compressor the Case 2 is higher, which indicates higher power consumption compared to Case 4. Considering the mass flow and pressure amplitude Case 4 has better performance.

4. Conclusion
This paper investigates the feasibility of using bounce space of the linear compressor as the reservoir and its performance. When bounce space is used as a reservoir, it is subjected to pressure fluctuation, which is at an opposite phase of the compressor space pressure fluctuation so that the bounce space more or less acts as an active reservoir when designed for the appropriate phase shift. Analysis was based on a single stage inertance tube coaxial Pulse Tube Cryocooler, which gives a cooling power of at least 2W at 77K. The simulation results showed the feasibility of the work, for detailed analysis Sage V11 model and a two-dimensional Axis symmetric CFD model with thermal equilibrium model is developed to simulate the internal process for detailed analysis. The performance of the cooler was analyzed for various combinations of reservoir capacity of 300 cc and 600 cc using the reservoir and using bounce space is reservoir volume. The effect of the 300 cc with bounce space makes a more significant contribution to the enhancement of the cooling performance than that of the 600 cc bounce space. The modeling also indicates that better the control of reservoir fluctuation more efficient the cryocooler. For every simulation conducted the results were mutually agreeable. The cooling powers were calculated at 70K, and the CFD simulation was done until the acceptor showed 70K. A cooling power of 2.37W at 70K with an input power of 74.2 W with 300 cc static reservoir whereas for 300 cc induced pressure it was 2.80W with an input power of 78.1W. The Coefficient of performance improved 12.4 percent with the use of bounce space of the compressor as a reservoir. However, as for the case of 600 cc with reservoir and bounce space, the performance difference was marginal.

5. References
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| Case | Load(W) | Power(W) | COP |
|------|---------|----------|-----|
| 1    | 2.37    | 74.2     | .0319 |
| 2    | 2.80    | 78.1     | .0358 |
| 3    | 2.32    | 58.2     | .0398 |
| 4    | 2.97    | 75.0     | .0396 |