Research Paper Engineering

CFD Simulation of Inline Pulse Tube Refrigerator and Frequency Test

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ABSTRACT

The most compact and convenient pulse tube refrigerator (PTR) for practical applications is the Inline type. A Computational Fluid Dynamics (CFD) analysis of inline Inertance Pulse Tube Refrigerator (IPTR) is done to predict lowest possible temperature in the cold heat exchanger for no refrigerating load condition. 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 are discussed.

Keywords : CFD analysis; Inertance tube Pulse tube refrigerator; Inline Pulse tube

INTRODUCTION

A pulse tube refrigerator (PTR) has no moving parts in its cold section, and, when driven by a linear compressor, has the potential of achieving higher reliability and lower vibration than other small refrigerators. The most compact and convenient pulse tube cryocooler for practical applications is the inline type. It can often replace Stirling cryocoolers without any change to the dewar or to the connection to the cooled device.

The introduction of the orifice pulse tube by Mikulin, E.I[1]et al. and the double inlet pulse tube by Zhu et al.[2], have allowed pulse tubes configurations to approach, and in some cases exceed the actual performance of a Stirling Cryocooler[3].

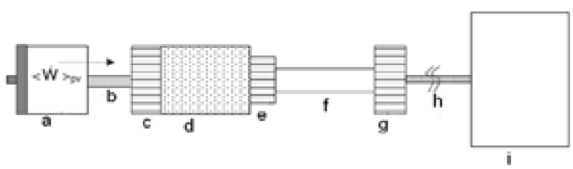
A limitation of the orifice pulse tube is that the mass flow rate must always lead the pressure; in the limiting case, the mass flow rate and pressure may be in phase with each other. This limitation does not allow the optimal phase to be achieved in which the pressure would lead the mass flow rate at the inlet to the expansion space.

Though the introduction of the secondary orifice usually led to increased efficiencies compared to the OPTR, but the performance of DIOPTR was not always reproducible [4].

An alternative means of adjusting the phase between the pressure and mass flow rate is with an Inertance tube, as reported by Kanao, K et al.. The Inertance tube does not suffer from the same limitation as the orifice; through proper selection of the Inertance tube geometry it is possible to force the mass flow rate to either lead or lag the pressure. Inertance is the dynamic characteristic associated with the inertia of a rapidly moving fluid. The Inertance, together with the tube's resistance and compliance as well as the compliance of the terminating reservoir, provides complex impedance at the warm end of the pulse tube. A schematic diagram for Inertance Pulse Tube Refrigerator is as shown in figure 2.7. [5]

IN-LINE PULSE TUBE REFRIGERATOR

In-line PTR arrangement was used first of all by Gifford and Longsworth[6] during the ever since definition of refrigeration obtained by a pulse tube refrigerator. Often such arrangement is used for illustrative purposes and experiments at laboratory. Although placing the pulse tube and regenerator in series produces a slender assembly, the configuration is not readily available to use since the cold junction is in the middle between pulse tube and regenerator and hence required alterations in design of Dewar.



Schematic Diagram of an Inertance Pulse Tube Refrigerator

(a. Compressor, b. Transfer Line, c. Warm Heat Exchanger 1 (WHX1), d. Regenerator, e. Cold Heat Exchanger (CHX), f. Pulse Tube, g. Warm Heat Exchanger 2 (WHX2) h. Inertance tube, i. Surge Volume)

CFD AND MODEL

To understand the principal factors governing performance of Inline Pulse Tube Refrigerator, the commercially available CFD code, such as Fluent® is a powerful tool to numerically solve the Navier–Stokes equations with the finite-volume discretization scheme.

The thermo-fluidic processes in PTRs are complicated, however, and the details of the mechanisms underlying their performance are not well understood. In this study, the commercial computational fluid dynamic (CFD) package Fluent® was utilized for modeling the entire inline inertance pulse tube refrigerator (IPTR) system. The simulations represent a fully-coupled system operating in steady-periodic mode, without any arbitrary assumptions. The objective was to examine the extent of two-dimensional flow effects in an inline tube pulse tube cryocoolers, and their impact on the performance of these cryocoolers. Computer simulation performed for no load refrigerating condition to achieve lowest temperature and also phase lag required between mass flow rate and cold end temperature are to be studied.

A schematic diagram of the In line Inertance Pulse Tube Refrigerator (IPTR) system is shown in Figure 1. For Dimensions of the IPTR components, the inline model of J Cha is taken as reference (J Cha et al. 2004). Dimensions are modified such that, volume of each component remains same. Dimensions are as in figure 1 and table 1.

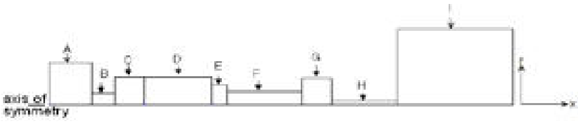


Figure 1: Schematic Diagram of Inline Pulse Tube Refrigerator

Table 1: Component Dimensions

Component	Length[m]	Radius, R_o [m]
A) Compressor	7.5 E-03	9.54 E-03
B) Transfer line	101 E-03	1.55 E-03
C) WHX 1	20 E-03	4.717 E-03
D) Regenerator	58 E-03	4.717 E-03
E) CHX	5.7 E-03	3.717 E-03
F) Pulse tube	60 E-03	2.50E-03
G) WHX 2	1E-02	4.717 E-03
H) Inertance tube	684.1 E-03	4.25 E-04
I) Surge volume	130 E-03	0.013

CFD SIMULATION PROCEDURE

Fluent is a state-of-the-art computer program for modeling fluid flow and heat transfer process in complex engineering problems. Fluent offers the flexibility of meshing any complex geometry and solving complicated 2-Dimensional and 3-Dimensional problems. Transient flow and transport phenomena in porous media, two-phase flow, and volumetrically-generating sources can all be modeled by Fluent. Fluent numerically solves the entire continuum fluid and energy equations with no arbitrary assumptions.

The IPTR mesh model is developed in the ANSYS® Workbench® Modeler®. Boundary as mass flow rate inlet, pressure outlet, axis-symmetry and wall of the all the component are applied to the mesh model as shown in figure 2.

The mesh model exported in ANSYS® Workbench® CFD Fluent®. The CIPTR is simulated by cylindrical and linear alignment, axis-symmetric, two-dimensional flow, laminar model in terms of the physical velocity with working fluid helium as ideal gas. Copper is used in Warm Heat exchanger 1(WHX1), Warm Heat exchanger 2 (WHX2), and Cold Heat exchanger (CHX). Stainless steel 304 is used in all other components including regenerator. The thermal conductivity, specific heat and viscosity are applied as temperature dependant properties. The appropriate boundary condition for the simulated model is given in Table 2. Boundary conditions are from reference of J Cha et al. 2004

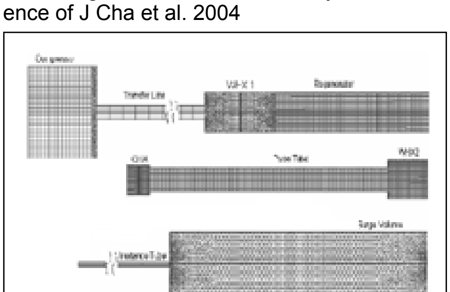


Figure 2:Two Dimensional Axis Symmetry Mesh Model of IPTR
(Mirror View of Axisymmetric Geometry)

Table 2: Boundary condition for different component

Sr. no.	Component	Boundary condition
1	Compressor wall	Adiabatic
2	Transfer line wall	Adiabatic
3	WHX1 wall	293K
4	Regenerator wall	Adiabatic
5	CHX wall	Adiabatic
6	Pulse tube wall	Adiabatic
7	WHX2 wall	293K
8	Inertance tube wall	Adiabatic
9	Surge volume wall	Adiabatic
10	Permeability of porous component β (m^2)	1.06e-10
11	Inertial resistance C(m^{-1})	76090
12	Initial condition	300K
13	CHX load	0W

GOVERNING EQUATION

The mass, momentum and energy equations solved by fluent are as follows:

Continuity equation:

$$\frac{\partial\rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho V_r\right) + \frac{\partial}{\partial x}\left(\rho V_x\right) = 0 \quad (1)$$

Momentum Equation :

$$\frac{\partial}{\partial t}\left(\rho v_x\right) + \frac{1}{r}\frac{\partial}{\partial x}\left(r\rho v_x v_x\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_r v_x\right) = -\frac{\partial p}{\partial x} \quad (2)$$

where,

r = radial coordinate
x = axial coordinate
Vr= Radial velocity
Vx= Axial velocity

The body forces (gravity forces) and any other external forces have been neglected in the above equations.

Energy equation:

$$\frac{\partial}{\partial t}\left(\rho E\right) + \nabla \bullet \left(\vec{V}\left(\rho E + p\right)\right) = \nabla \bullet \left(K\nabla T + \left(\tau \bullet \vec{V}\right)\right) \quad (3)$$

Where

$$E = h - \frac{P}{\rho} + \frac{v^2}{2} \quad (4)$$

All properties represent the properties of the working fluid helium. The above equations apply to all components, except for WHX1, CHX, and WHX2 and to the regenerator. The latter four components are modeled as porous zone, assuming that there is local thermodynamic equilibrium between the fluid and solid structure in these components. The mass momentum and energy equations in the latter four components are:

$$\frac{\partial(\phi\rho)}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(\phi r\rho V_r\right) + \frac{\partial}{\partial x}\left(\phi\rho V_x\right) = 0 \quad (5)$$

$$\frac{\partial}{\partial t}\left(\phi\rho_f\vec{v}\right) + \nabla\left(\phi\rho_f\vec{v}\vec{v}\right) = -\phi\nabla p + \nabla\bullet\left[\phi\bar{\bar{\tau}}\right] - \left(\mu\overline{\overline{\beta^{-1}}}\bullet\vec{j} + \frac{1}{2}\bar{\bar{C}}\rho\left|\vec{j}\right|\vec{j}\right) \quad (6)$$

$$\frac{\partial}{\partial t}\left(\phi\rho_f E_f + (1-\phi)\rho_s E_s\right) + \nabla\bullet\left[\vec{\upsilon}\left(\rho_f E_f + p\right)\right] = \nabla\bullet\left[\phi k_f + (1-\phi)\nabla T + \left(\bar{\bar{\tau}}\bullet\vec{v}\right)\right] \quad (7)$$

Where φ = 0.69, β = 1.06×10−10 [m2] and C = 76090 [m-1] were assumed. These parameters are based on experiments of Harvey [7] for axial flow through a randomly packed stack of 325 mesh stainless steel screens.

Initially we try to obtain the result of PTR simulated in available literature. With the help of dimensions and boundary condition available in recent literature. First we generated the mesh model of PTR and imported in fluent. For prepare the simulated model, we provide, the solid materials and fluid with its real time properties as temperature dependent, boundary condition on the walls and fluid zones are applied as per literature, all the initial condition, mass flux as input, pressure as output is assigned. Simulation is carried out for two-dimensional, axis-symmetric and unsteady state condition.

Desired results are obtained by simulation and qualitative performance prediction can be done with CFD Analysis. The results are discussed below.

RESULTS AND DISCUSSIONS

In order to study thermo-fluidic behavior and to evaluate optimum range of parameter, different cases for IPTR simulation were set. The simulation process set-up is same as discussed above expect some relevant parameters were changes are illustrated in table 3

Table 3: change parameters in PTR.

Sr. no.	CHX Wall Boundary condition	Frequency input at compressor (Hz)
1	Adiabatic (0 watt)	34
2	Heat load (1Watt)	34
3	Heat load (1Watt)	40
4	Heat load (1Watt)	50

Case 1 utilized an adiabatic wall boundary condition at the CHX, equivalent to no refrigeration load applied to the overall system. Prediction of minimum temperature recorded by a cryorefrigerator is always a subject of concern for researchers. A multi-dimensional model of an IPTR is simulated using CFD with 5081 nodes. All the boundary conditions are provided close as possible to a real system shown in table 2 and results are obtained and comparison with cha et al where cha, J [8] and validated present work as shown in figure 3

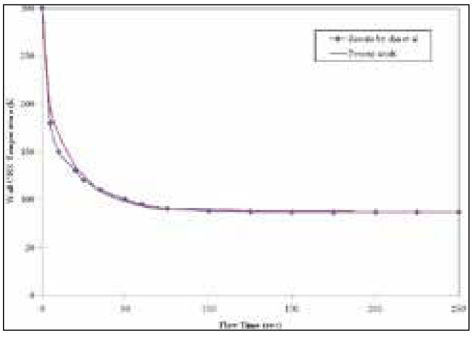


Figure 3:Comparison of Cool-Down Characteristics with That of Cha et al [8]

COMPARISON

The CHX wall cool down curve are compared in figure 4 for IPTR 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 IPTR system.

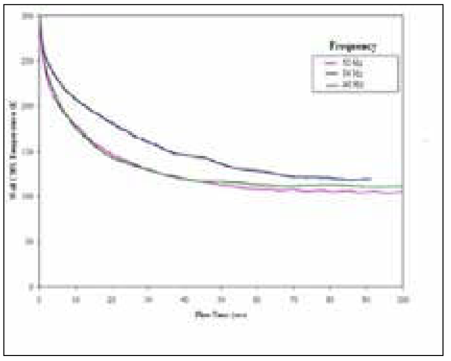


Figure 4:Temperature Cool Down Curves for Different IPTR Models

CONCLUSIONS

Qualitative performance prediction can be possible with the CFD analysis. The complex behaviour of thermo-fluidic process in PTR models and detail mechanisms and their performance can be easily understand with fluent. Piece-wise Polynomial form curve fit property gives accurate result

There is always existence of optimum value of frequency in PTR system for the same boundary condition can be justified Results show the lower drop in temperature with increase in frequency. But for that simulation on more models will give optimum value for system. as compare to that of polynomial curve fit form property equation. Desired results were obtained for the different boundary condition with minimum assumption.

There is always existence of optimum value of frequency in PTR 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.

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