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A Thermally Non-equlibirium Approch for CFD Simulation of a Pulse Tube Refrigerator

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ABSTRACT

This paper deals with a new type of numerical computational fluid dynamic (CFD) approach of making more realistic to the porous media inside the regenerator of a pulse tube refrigerator. The available commercial software package FLUENT for solving Computational fluid dynamics (CFD) has capable of define a porous media and solve the governing equation for this region. But one problem arises is that inside the porous media region the software consider the fluid medium temperature and solid matrix medium temperature remains same in any spatial location which is impractical in real case. So to avoid this impractical situation we made attempt to make a non-thermally equilibrium medium inside the regenerator by putting a solid inside the regenerator, a size equal with solid matrix and added the source term to the fluid and solid of the regenerator by user define functions (UDF). In this analysis we used inertance tube pulse tube refrigerator (ITPTR) and helium is the working fluid.

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1. INTRODUCTION

Since 1964 it is the vast area of research on pulse tube refrigerator which was discovered by Gifford and Longsworth on that year. Day by day it was improved to produce more colling effect and more capacity by researchers. Mikuluin [2] bring a modification to the introductory type Basic pulse tube Refrigerator. To get better cooling effect he modified in such a way that the phase angle between temperature and velocity changes due to adding a small orifice which causes enthalpy flow increasing near hot end. Such type of pulse type of refrigerator is named as Orifice Pulse Tube Refrigerator (OPTR). There are some other papers which deal with theoretical approaches to study the phase shift, efficiency and flow cycles [3]-[10] inside the pulse tube refrigerator. Cha et al. [11] first time made a CFD model on a single stage iterance pulse tube refrigerator using FLUENT software which gives a better solution to optimise pulse tube refrigerator. This model was based on thermally equilibrium to the regenerator. So the fluid and solid matrix temperature remains same in any spatial axial location. Using the same CFD Solution method by changing the dimension of (ITPTR) Ashwin et al. [12] proceed with a non-thermally equilibrium medium by adding source term using some special type function called User Defined Scalars (UDSs) and general scalar transport equations also added with the different UDSs. Dion et al. [13] used an advanced rarely available software package CFD-ACE+ to solve the governing equation which has capacity to solve thermally non equilibrium equation for porous zone.

2. GEMOTRICAL DESIGN OF PTR FOR CFD ANALYSIS

2.1. Mathematical Formulation

Figure 1 shows the schematic representation of the 2D axi-symmetric model of the inertance pulse tube refrigerator used for the present computational analysis. The detail dimension is given in the Table 1.

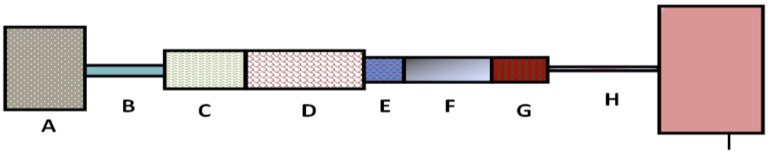

Figure 1. Schematic diagram of computational domain of ITPTR: A - compressor, B – transfer line, C - after cooler, D – regenerator, E – cold heat exchanger, F – pulse tube, G – hot heat exchanger, H - inertance tube, I – reservoir

Table 1. The detail dimension

Constituent part	Diameter (m)	Length (m)	Boundary condition
Compressor (A)	0.01908	0.0075	Adiabatic
Transfer line (B)	0.0031	0.101	Adiabatic
After cooler (C)	0.008	0.02	300 K
Regenerator (D)	0.008	0.058	Adiabatic
Cold heat exchanger (E)	0.006	0.0057	Adiabatic
Pulse tube (F)	0.005	0.06	Adiabatic
Hot heat exchanger(G)	0.008	0.01	300 K
Inertance tube (H)	0.00085	0.684	Adiabatic
Reservoir (I)	0.026	0.13	Adiabatic

1. Governing equations

The governing equations for the above analysis can be written as:

a) Continuity Equation

$$\frac{\partial}{\partial t}[\xi\rho]+\frac{1}{y}\frac{\partial}{\partial y}\left[\xi r\rho_y\right]+\frac{\partial}{\partial x}\left[\xi\rho_f v_x\right]=0 \tag{1}$$

b) Momentum Equation

For axial direction:

$$\begin{gathered}\frac{\partial}{\partial t}[\xi\rho v]+\frac{1}{y}\frac{\partial}{\partial y}\left[\xi r v_x v_y\right]+\frac{1}{y}\frac{\partial}{\partial y}\left[\xi y\rho_f v_x v_y\right]= \\ -\frac{\partial p}{\partial y}+\frac{1}{y}\frac{\partial}{\partial y}\left\{y\mu\left(2\frac{\partial v_x}{\partial x}-\frac{2}{3}\left(\vec{\nabla}.\vec{v}\right)\right)\right\}+\frac{1}{y}\frac{\partial}{\partial y}\left\{y\mu\left[\frac{\partial v_y}{\partial y}+\frac{\partial v_y}{\partial y}\right]\right\}+S_y\end{gathered} \tag{2}$$

For radial direction:

$$\begin{gathered}\frac{\partial}{\partial t}\left[\rho_f v_y\right]+\frac{1}{y}\frac{\partial}{\partial x}\left[r v_x v_y\right]+\frac{1}{y}\frac{\partial}{\partial x}\left[x\rho_f v_y v_y\right]=-\frac{\partial p}{\partial x}+\frac{1}{r}\frac{\partial}{\partial x}\left\{2x\mu\left(\frac{\partial v_x}{\partial x}-\frac{1}{3}\left(\vec{\nabla}.\vec{v}\right)\right)\right\}+\frac{1}{y}\frac{\partial}{\partial y} \\ \left\{2y\mu\left[\frac{\partial v_x}{\partial y}-\frac{1}{3}\left(\vec{\nabla}.\vec{v}\right)\right]\right\}+\frac{2\mu}{y}\left[\frac{\left(\vec{\nabla}.\vec{v}\right)}{3}-\frac{v_y}{y}\left(\vec{\nabla}.\vec{v}\right)\right]+S_x\end{gathered} \tag{3}$$

Where S_x and S_y are the two source term in the axial and radial direction which values is zero for nonporous zone. But for the porous zone the source term which is solved by the solver is given by the following equation.

$$S_x=-\left(\frac{\mu}{\beta}v_x+\frac{1}{2}C\rho_f\left|v\right|v_x\right) \tag{4}$$

$$S_y = -\left(\frac{\mu}{\beta} v_y + \frac{1}{2} C \rho_f |v| v_y\right) \tag{5}$$

In the above equation the first term is called Darcy term and the second term is called the Forchheimer term which are responsible for the pressure drop inside the porous zone.

c) Energy Equation:

$$\frac{\partial}{\partial t}\left(\xi \rho E_f + (1-\xi)\rho_s E_s\right) + \vec{\nabla}.\left(\vec{v}\left(\rho_f E_f + p\right)\right) = \vec{\nabla}.\left(k \vec{\nabla} T_f + \tau.\vec{v}\right) \tag{6}$$

Where,

$$k = \xi k_f + (1-\xi) k_s \tag{7}$$

$$E_f = h - p/\rho_f + v^2/2 \tag{8}$$

2.2. Detail Modeling and Boundary Conditions

All the boundary condition with dimension is shown in Table 1. Similar type of 2-D Axi-symmetric geometry was modelled using the modelling software GAMBIT as shown in Figure 1. The number of mesh for this case is 4400 which is chosen after a grid independency test which shows that after this value there no variation in the result of simulation. To guide the compressor piston a FLUENT User Define Function (UDF) is attached to the piston with a correlation a = a_0* sin*(ωt). The operating frequency is taken z = 34 Hz. Where a is the piston displacement and a_0 = 0.0045m is the amplitude with a time increment of 0.0007s is assumed and the piston head velocity is related with the correlation v = a_0*ω*cos*(ωt). Where v is the piston head velocity. For porous media region the parameter s are taken from [15], inertial resistance 76090 m^{-1} and permeability 1.06 × 10^{-10} m^2. Steel is chosen as the component material. The working gas is chosen is helium and the property (viscosity, thermal conductivity, specific heat) of the gas are taken as temperature dependent from NIST data base.

3. NUMERICAL SOLUTION PROCEDURE

The governing equations as described above are solved by Fluent. Axisymmetric, unsteady, cell based, physical velocity with segregated solver is taken for analysis. PISO algorithm with a PRESTO (Pressure Staggered Option) scheme for the pressure velocity coupling is used for the pressure correction equation.

Suitable Under relaxation factors for pressure, momentum and for energy were used for the better convergence. Quad lateral cells were used for the entire computational domain. For all equation Convergence of the discretized equations are said to have been achieved when the whole field residual was kept at 10^{-6}.

4. RESULT AND DISCUSSION

The Figure 2 shows that the present CFD results match well with the Cha et al. [11] model. It is noticeble from the Figure 3 that the steady state temperature is reached after 50s for both the case after which there no change in temperature with respect to time. The Cha et al. model reporting a temperature of 87 K using 4200 number of cell where in the present case it is found a 86 K using 3900 cell.

To making more realistic we made attempt to make a non-thermally equilibrium to the regenerator. In thermal non-equilibrium approach it considers the heat interaction between gas and solid matrix of porous region. Thus to calculate the heat interaction it requires the solid matrix and gas to be described by two different energy equations. The heat transfer co-efficient between solid and fluid can be calculated using standard correlations. Non-thermal model accounts for thermal losses in porous zone in components like regenerators, where thermal inertia plays a very important role, non-equilibrium model tends to be more accurate. FLUENT solve the extra equation in a region or zone with the help of some functions called User.

Defined Scalars (UDSs). The simulation of the extra equations in the porous zone is accomplished with the help of separate UDSs. The fundamental scalar transport equation defined with the help of the UDSs contains four terms, namely, convection term, the unsteady term, the source term and diffusion term.

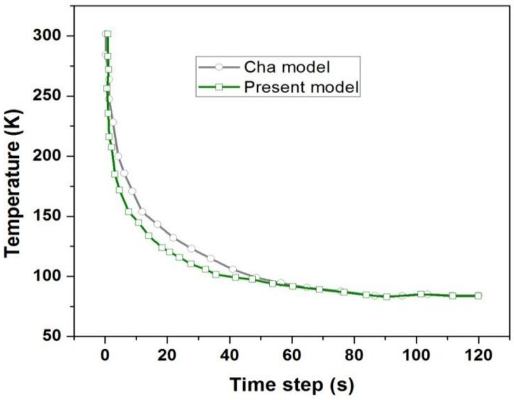

Figure 2. Validation plot between present model and Cha et al. [11] model

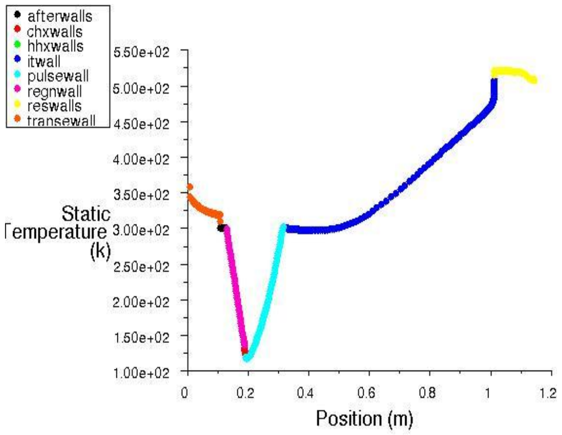

Figure 3. Axial temperature variation for the pulse tube system after steady state of temperature for Non- thermally equilibrium model

The Figure 3 shows the Axial temperature variation for the pulse tube system after steady state of temperature for Non- thermally equilibrium model. It can be found from the simulation that a good temperature gradient is generated axially between the hot heat exchanger, pulse tube and the regenerator, respectively. The plot is taken after a steady state temperature achieved by the pulse tube refrigerator. It shows that the cold heat exchanger end temperature reach a temperature of below 115 K for the present thermally non equilibrium case where the reservoir temperature is maximum about 500 K. Due to the effect of solid matrix inside regenerator the temperature at cold end rises from the ideal thermally equilibrium model. As it is well known that the thermally equilibrium model has the same temperature of fluid with the solid matrix at any spatial location of porous region.

Figure 4 and Figure 5 shows the temperature profile for solid matrix and the gas inside regenerator. At the inlet of regenerator the fluid and solid matrix temperature remains 300 K but at exit the solid matrix temperature is about 20k higher.

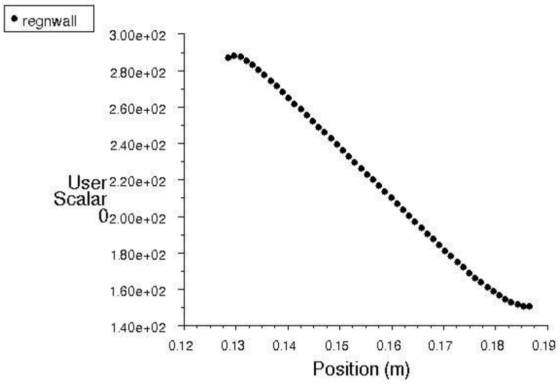

Figure 4. Axial temperature distribution of solid matrix inside regenerator

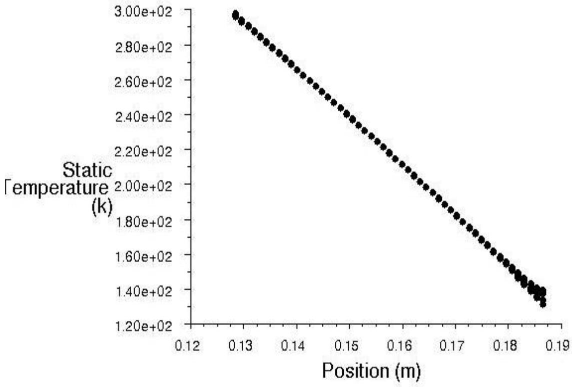

Figure 5. Axial temperature distribution of fluid inside Regenerator Regenerator

5. CONCLUSION

The study focuses on CFD investigation to make more realistic model of the pulse tube refrigerator. So applying proper UDSs to the porous medium through FLUENT it comes as a success model. This model helps to get a proper cooling temperature which closer to real experimental data. From the above investigation it shows that the inlet fluid and solid matrix temperature are same where at exit of the regenerator the fluid temperature is about 130 K where the solid temperature is more than 150 K. This conclude that the regenerator works properly with this non-thermally equilibrium model, which was our main aim of this work.

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