

CFD simulation of the gas flow in a pulse tube cryocooler with two pulse tubes

C L Yin^{1,2}

¹Institute of Cryogenics and Electronics, Hefei, 230043, China

²The Provincial Laboratory of Cryogenics and Refrigeration, Hefei, 230043, China

E-mail: yclabc.good@163.com

Abstract. In this paper, in order to instruct the next optimization work, a two-dimension Computational Fluid Dynamics (CFD) model is developed to simulate temperature distribution and velocity distribution of oscillating fluid in the DPTC by individual phase-shifting. It is found that the axial temperature distribution of regenerator is generally uniform and the temperatures near the center at the same cross section of two pulse tubes are obviously higher than their near wall temperatures. The wall temperature difference about 0-7 K exists between the two pulse tubes. The velocity distribution near the center of the regenerator is uniform and there is obvious injection stream coming at the center of the pulse tubes from the hot end. The formation reason of temperature distribution and velocity distribution is explained.

1. Introduction

The pulse tube cryocooler (PTC) is a unique type of regenerative cryocooler in that it does not have any moving parts in cold end and thus has considerable system advantages over most other types of cryocoolers in terms of reliability, lifetime, vibration and cost. Therefore, the application of pulse tube cryocooler is increasing rapidly in the aerospace field, such as the cooling of infrared detectors and optic devices. According to different arrangements of the regenerator and pulse tube, there are three types of pulse tube cryocooler: coaxial type, U-shape type, and in-line type [1]. The U-shape pulse tube cryocooler allows the regenerator and the pulse tube to unpack and can support large and heavy devices. In order to realize larger and heavier mass supporting without additional supporting components, a new structural pulse tube cryocooler (DPTC) based on traditional U-shape pulse tube cryocooler and with one regenerator and two parallel pulse tubes had been machined and experimented. This new structural pulse tube cryocooler had been also proposed by J.Yuan and J.M.Pfotenhauer in 1997 [2].

In previous works [3], two prototypes of U-shape two-pulse-tube paralleled cryocooler have been designed and tested. The U-DPTC1 was able to gain 120K@6W cooling power with 80W electric input power. Two methods of phase-shifting by inertance tube and reservoir were tested. The experiment results demonstrated the feasibility of individual phase-shifting and DC flow could occur under general phase-shifting, reducing the performance of the cryocooler.

In this paper, in order to optimize the design of the new structural pulse tube cryocooler to improve the performance further, a two-dimension Computational Fluid Dynamics (CFD) model is developed



to simulate temperature distribution and velocity distribution of oscillating fluid in the DPTC by individual phase-shifting to instruct the next work.

2. CFD model of the DPTC

The physical model and the mathematical model applied are reported below.

2.1. Physical model

The prototype of the regenerator and two pulse tubes and the 2D simplified physical model of the DPTC beside the compressor is depicted in figure 1, which include an aftercooler, a regenerator, a re-cold end heat exchanger, a T-shape connecting tube, two pt-cold end exchangers, two same pulse tubes, two same hot end exchangers, two same inertance tube assemblies and two same reservoirs (not shown in figure 1). All heat exchangers at hot end and cold end are made of OFHC with high conductivity and adopt uniform slits using a wire electro-discharge machine (EDM) and the pt-cold end exchangers are filled with several 80 mesh copper screens. The regenerator is filled with 400 mesh stainless steel screens.

The grid models of main components are shown in figure 2, which include regenerator, a T-shape connecting tube, two same pulse tubes. Their specific details about the scale can refer to the TABLE 1 in previous paper [3]. All the components adopt a rectangle grid beside the T-shape connecting tube with a triangle grid because of its abnormality. In order to describe the fluid characteristic more accurately, the grid near the variable cross-section is made denser. The total number of the grid is between 12000-15000.

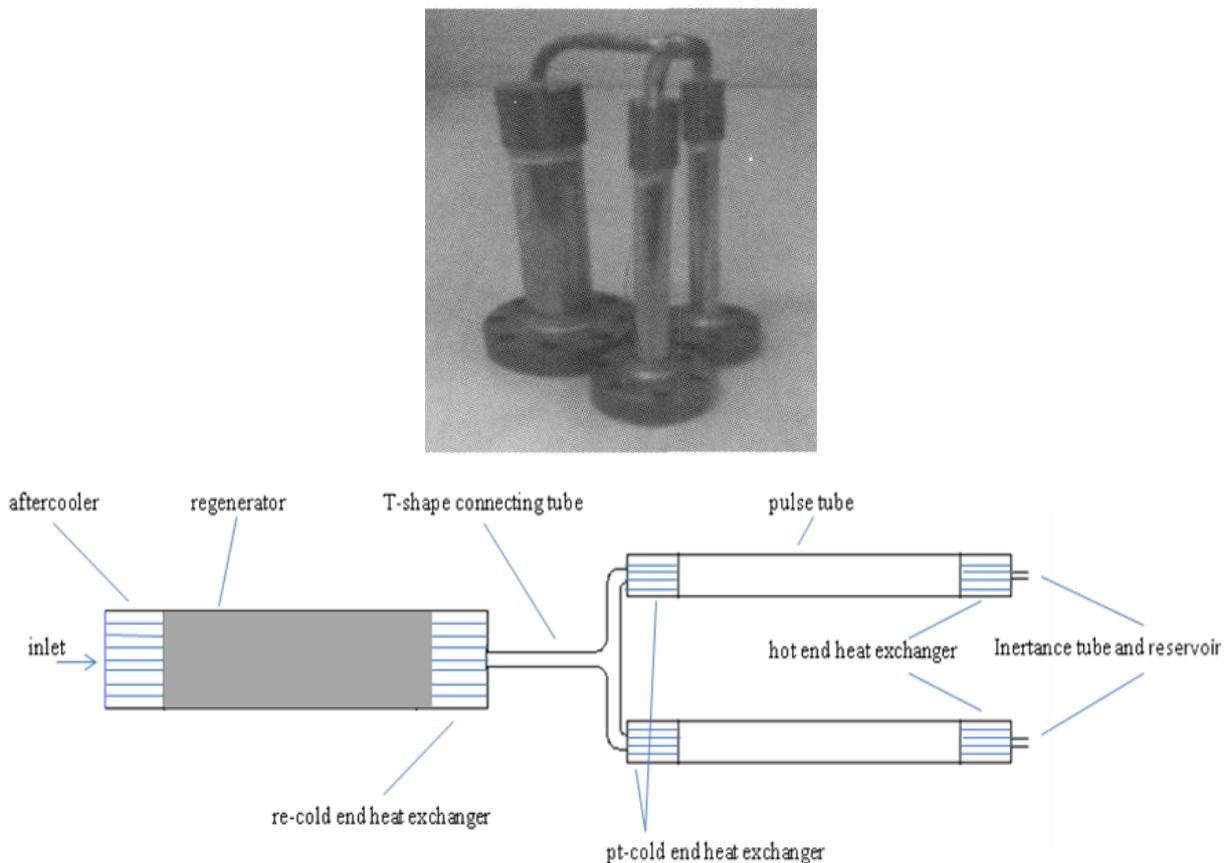


Figure 1. The prototype and 2D physical model simplified of the DPTC beside the compressor.

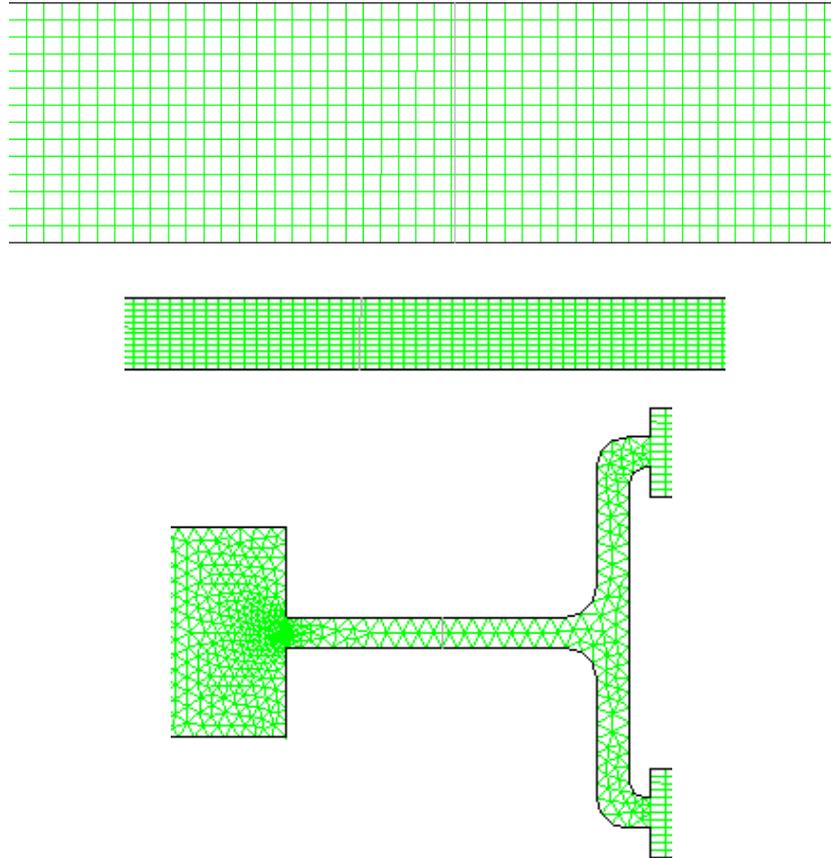


Figure 2. The grid models of regenerator, pulse tube and T-shape connecting tube.

2.2. Mathematical model

The model assumes that all the walls has no thickness. The hot end and the cold end heat exchangers are assumed to be of constant temperature, 300 K and 120 K respectively. The outer walls of the regenerator and the two pulse tubes are an adiabatic boundary and the other walls are set to an isothermal boundary at conatant temperature of 300 K. The various heat exchangers and the regenerator are modeled as porous media with the relevant solid properties of the regenerator and the heat exchanger materials. Working helium is treated as an ideal gas in the 120-300 K temperature region. The charging pressure is 3.8 MPa and operating frequency is 52 Hz. The inlet boundary condition is pressure with a pressure ratio of 1.17 at 300 K. In the CFD model, the inlet boundary condition is defined by userdefined functions written in the C programming language.

The fluid dynamic equations of conservation of mass, momentum and energy are solved in the fluid domain. The mass, momentum and energy conservation equations and the gas phase equations for the porous media regions are solved simultaneously as shown below [4]:

$$\varepsilon \frac{\partial \rho_f}{\partial t} + \nabla \cdot (\varepsilon \rho_f \vec{v}) = 0 \quad (1)$$

$$\frac{\partial (\varepsilon \rho_f \vec{v})}{\partial t} + \nabla \cdot (\varepsilon \rho_f \vec{v} \vec{v}) = -\varepsilon \nabla p + \varepsilon \nabla \cdot (\overline{\tau}) + \overline{f} \quad (2)$$

$$\frac{\partial}{\partial t} (\varepsilon \rho_f E_f + (1-\varepsilon) \rho_s E_s) + \nabla \cdot (\vec{v} (\rho_f E_f + p)) = \nabla \cdot ((\varepsilon k_f + (1-\varepsilon) k_s) \nabla T) + \Phi + S_f^h \quad (3)$$

Where ε is porosity of porous media, ρ_f , ρ_s represents the density of gas and screen respectively, the phasor f represents momentum loss caused by resistance, k_f , k_s represents the thermal conductivity of gas and solid respectively. The formula of resistance source term f is shown as below:

$$\mathbf{f} = -\left(\frac{\mu}{\alpha} \nu + \frac{1}{2} C \rho_f |\nu| \nu\right) \quad (4)$$

Where μ , α represents dynamical coefficient and the penetrability of gas respectively, C represents resistance coefficient of mesh screens.

The commercial code Fluent software that had been proved availability is used for solving the governing equations [5, 6], making use of a 2nd order upwind scheme and implicit formulation to discretize the governing equations, choosing standard k- ε turbulent model to address the turbulence, adopting the piso method in solver for pressure-velocity coupling. There are 100 time steps in one cycle, which is sufficient to accurately simulate the model. By monitoring the periodic temperature at the surface of the regenerator and the pulse tubes to decide whether the calculation is steady or not, and the calculation is steady when the monitored parameters do not change any more.

3. Result and analysis

3.1. temperature distribution characteristic in regenerator and pulse tubes

The temperature contours inside the regenerator and pulse tubes is shown in figure 3. It is seen from the figure 3 that the axial temperature distribution of regenerator is generally uniform, although there is small radial temperature difference. For example, it has been demonstrated that there exists a temperature difference about 3 K between near wall and center at the middle cross-section in figure 4. But, the temperatures near the center at the same cross section of two pulse tubes are obviously higher than their near wall temperatures.

The wall temperatures of regenerator and two pulse tubes are depicted in figure 5 and figure 6. The wall temperature of regenerator distributes linearly. But the wall temperature of pulse tubes presents concave curve distribution. Moreover, the two pulse tubes although have been imposed the same parameters, the temperature difference about 0-7 K exists between the any same positions of two pulse tubes. According to the previous experimental results, there also existed the no-load temperature difference about 2.5 K between the cold ends of two pulse tubes.

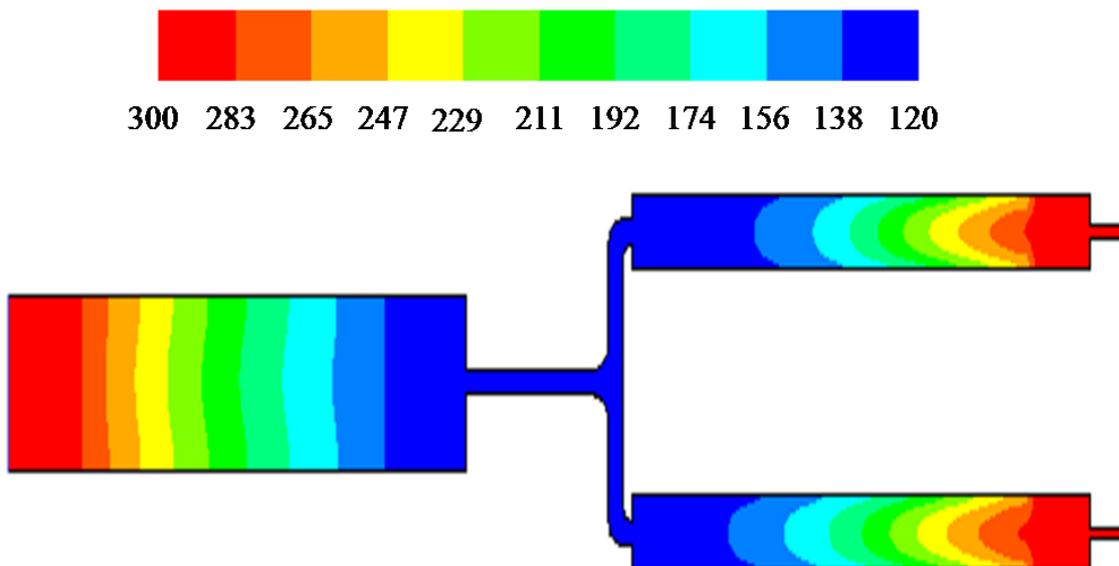


Figure 3. The temperature contours of regenerator and pulse tubes.

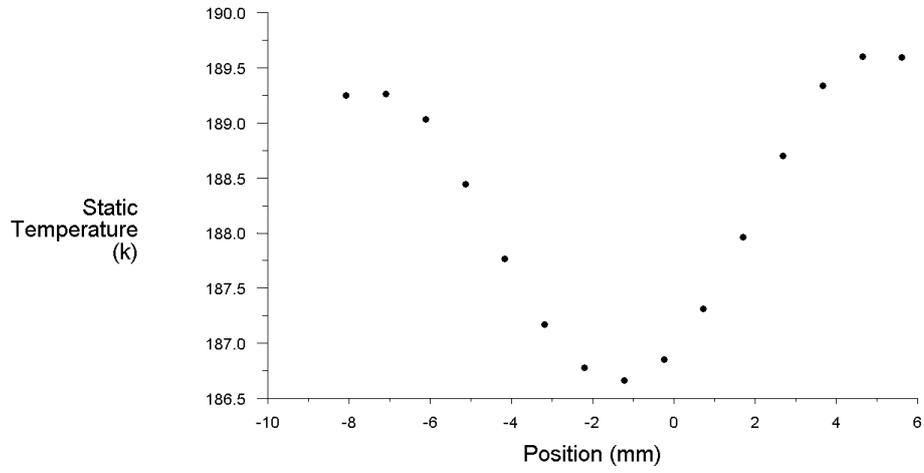


Figure 4. The temperature at the middle cross-section of regenerator.

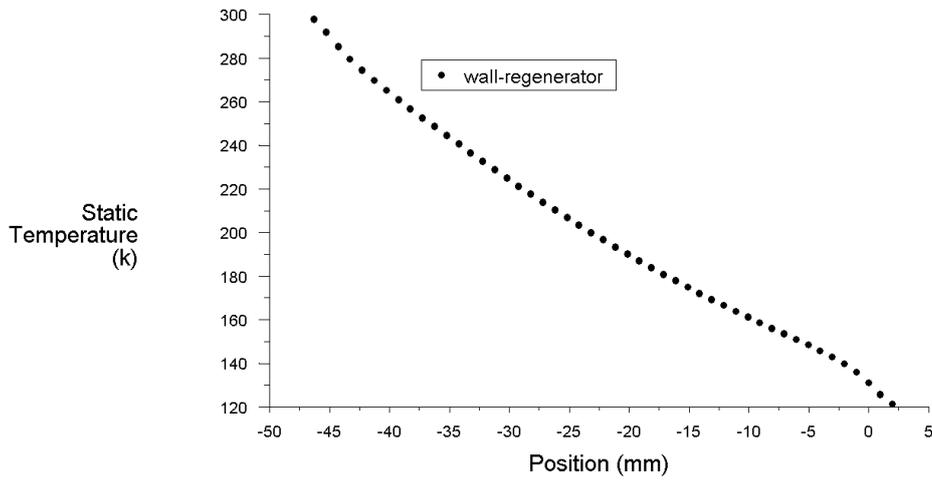


Figure 5. The wall temperature of regenerator.

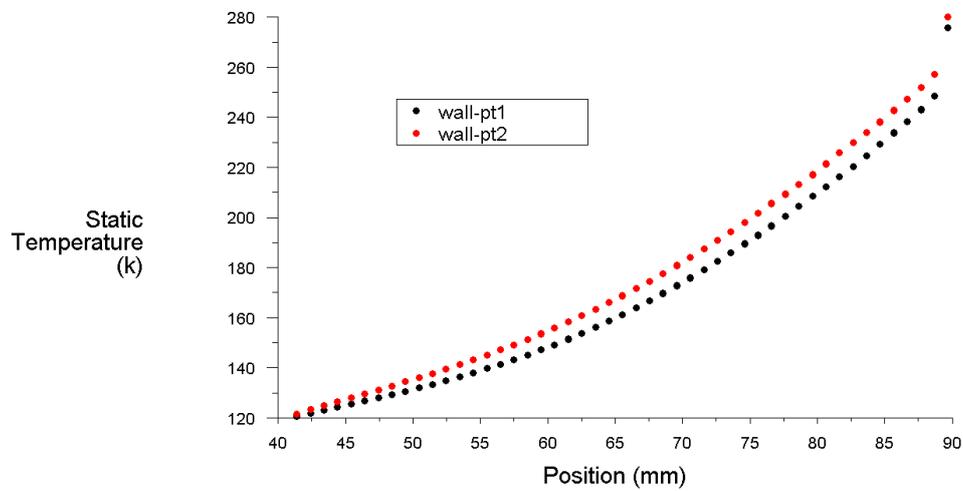


Figure 6. The wall temperature of pulse tubes.

3.2. Velocity distribution characteristic in regenerator and pulse tubes

The velocity distribution inside the regenerator and pulse tubes is shown in figure 7. It is seen from the figure 7 that the velocity distribution near the center of the regenerator is uniform and there is obvious injection stream coming from the hot end at the center of the pulse tubes. It is analyzed that the injection stream is caused by the variable cross-section at the T-shape connecting and re-cold end heat exchanger and at the inertance tubes and hot end heat exchangers, with the area ratio of 46.9 and 8.41 respectively. But, the screen matrix is filled in the regenerator and makes the fluid flowing uniform coming from the re-cold end heat exchanger filled some copper screens with the total equivalent porosity of 0.7. However, there are only hollow tube in the pulse tubes, so the injection stream is forming by the flow coming from the hot end heat exchangers with the high porosity of 0.9.

According to the temperature distribution and velocity distribution in the pulse tubes, it is the injection stream that caused the temperature distribution in two pulse tubes shown in the figure 4. Moreover, it is because of the screen matrix that makes the fluid flowing uniform in the regenerator, so it can be a feasible method that adding a few low mesh copper screens to hot end heat exchangers for solving the the injection stream.

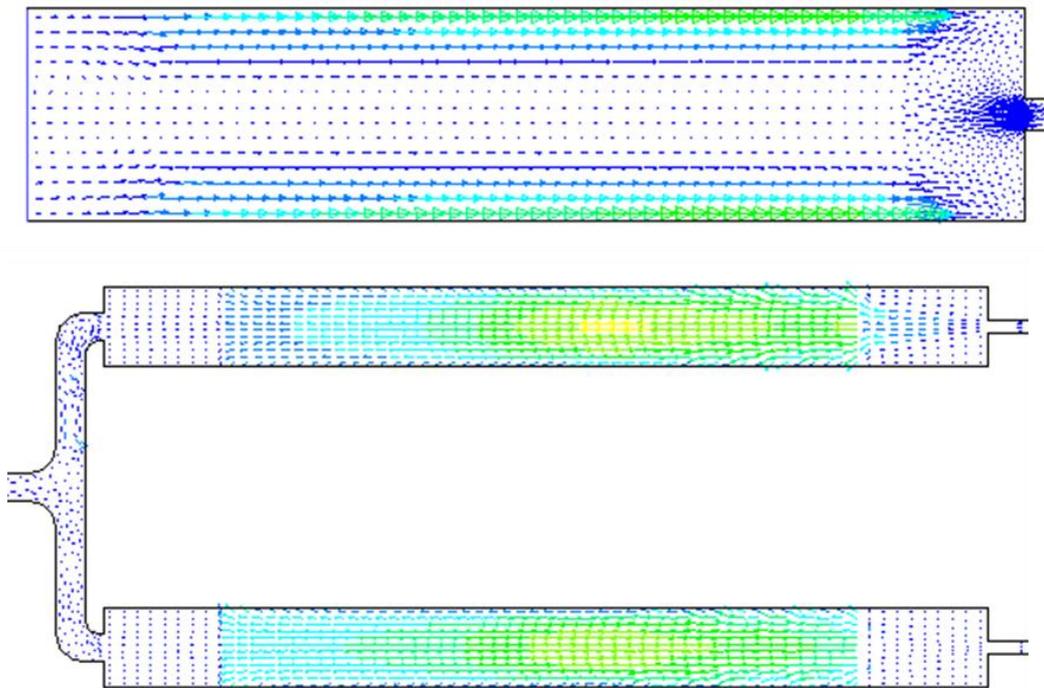


Figure 7. The velocity distribution inside the regenerator and pulse tubes.

4. Conclusion

Based on the two-dimension model, this paper presents the use of the CFD method to simulate the temperature distribution and velocity distribution of oscillating fluid in the DPTC by individual phase-shifting. The results reveal that the axial temperature distribution of regenerator is generally uniform, but there is a temperature difference about 3 K between near wall and center at the middle cross-section of regenerator. The temperature near the center at the same cross section of two pulse tubes is obviously higher than their near wall temperature and the temperature difference about 0-7 K exists between the two pulse tubes. The velocity distribution near the center of the regenerator is uniform and there is obvious injection stream at the center of the pulse tubes coming from the hot end heat exchanger. Adding a few low mesh copper screens to hot end heat exchangers would help to reduce the influence of the injection stream.

5. References

- [1] Radebaugh R, Zimmermann J, Smith D R and Louie B 1986 *Advances in Cryogenic Engineering* **31** 799
- [2] J Yuan, J M Pfotenhauer 1997 *Cryocoolers* **9** 295
- [3] C L Yin, H L Chen, M G Zhao, Q S Fei, J H Cai and Y L Li 2012 *Advances in Cryogenic Engineering A* **57** 547
- [4] L W Yang 2001 *Cryocoolers* **11** 353
- [5] E C Landrum, T J Conrad, S M Ghiaasiaan and C S Kirkconnell 2009 *Cryocoolers* **15** 337
- [6] D Antao and B Farouk 2011 *Cryocoolers* **16** 220