Three dimensional numerical computation of the flow field in a pulse tube

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A physical and numerical model of the pulse tube in the pulse tube refrigerator has been set up in this paper. Three-dimensional computation of a compressible and oscillating flow field in pulse tube was numerically investigated using a self-developed code. The distributions of the velocity and pressure waves and the velocity vector in the pulse tube were provided in this paper. The velocity wave near the hot end of the pulse tube lags behind that near cold end, and at the some cross section of middle part of the pulse tube the direction of the axial velocity reverses.

INTRODUCTION

Pulse tube refrigerator (PTR) is an attracting device of small cooling capacity widely used in aerospace engineering and for military purpose because of its inherent advantages such as no moving parts in the cold stage, low manufacturing cost, reduced mechanical vibration, etc [1]. The advantages and developments achieved in recent years enable PTR to have brought more and more interest and many laboratories around the world are presently working on the subject.

The internal working process in the PTR is very complex due to the unsteady, oscillating compressible gas flow, the porous media in the regenerator, etc. In recent years, it has been recognized that in the pulse tube of PTR secondary flows exist [2,3]. Such secondary flows are resulted from the combined effect of forced convection of the pulsating streaming and the natural convection caused by the large temperature difference between the hot and cold ends. The secondary flow and the mass streaming in a pulse tube can be a major heat loss mechanism. It carries heat from the hot heat exchanger(i.e. hot end) to the cold heat exchanger(cold end), thereby reducing the cooling power of a PTR. In reference [4], the characteristics of DC-Flow phenomenon in PTR are analyzed theoretically. The analytical results demonstrated that the gas velocity and density fluctuations in phase and amplitudes owing to the pressure fluctuations are the root to produce the DC-Flow in the PTR. Obviously, one-dimensional numerical simulations for PTR can not describe the complex secondary flows and DC-Flow phenomena in the PTR. In order to have a better understanding of the working processes in the PTR, improve their refrigeration performance and eliminate their drawbacks, we must set up a multidimensional numerical model for the PTR.

In recent years the NASA Ames research center declared that they have set up the two-dimensional physical and numerical model of predigestion PTR and whose numerical results agree well with the experimental data. Except America many other countries have started to research the multidimensional physical and numerical model of PTR, such as Japan, South Korea, Germany, etc. A multidimensional model of PTR are being investigated in our research center. Three-dimensional numerical model will be used in the pulse tube, and the heat exchanger will be simulated by a two-dimensional model, while the connection tube will be calculated using one-dimensional mode. In a simplified way, the method of our research is called 3-2-1 model of the PTR.

As he first step for 3-2-1 model, a three-dimensional physical and numerical model of the pulse tube in the PTR has been set up in this paper. The compressible and oscillating flow field in pulse tube was numerically investigated using a self-developed code. The distributions of the velocity and pressure waves in the pulse tube were revealed, and the velocity vector in the longitudinal section of the pulse tube was provided in this paper.

NUMERICAL METHODS AND GOVERNING EQUATIONS

The program for solving viscous flows problem at all Mach numbers was developed based on the SIMPLEC algorithm, using the compressible form [5]. On the basis of the compressible program the influence of the oscillating was considered in this paper. Only the pulse tube was taken as a model for the calculation. The velocity and pressure waves coming from the compressor was directly input to the cold end of the pulse tube as the calculation boundary condition. The calculation model was presented in Figure 1.

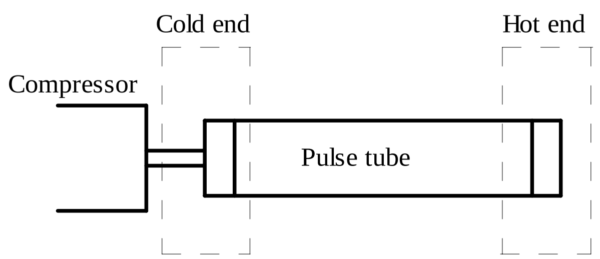


Figure 1 The calculation model

The three dimensional governing equations for compressible and oscillating fluid flow in the pulse tube take following form

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho\phi)+\frac{\partial}{\partial z}(\rho u\phi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v\phi)+\frac{1}{r}\frac{\partial}{\partial \varphi}(\rho w\phi)=\\&\frac{\partial}{\partial z}(\Gamma\frac{\partial\phi}{\partial z})+\frac{1}{r}\frac{\partial}{\partial r}(\Gamma r\frac{\partial\phi}{\partial r})+\frac{1}{r}\frac{\partial}{\partial\varphi}(\frac{\Gamma}{r}\frac{\partial\phi}{\partial\varphi})+S\end{aligned} \tag{1}$$

where ϕ is the general variable, representing u, v and w, Γ is the general diffusion coefficient, and S is the general source term. The calculation frequency is 13.3Hz, the charge pressure is 12bar, the working fluid is helium, the inner diameter of the pulse tube is 27.8mm and its length/diameter ratio is 9.

RESULTS AND DISCUSSION

The distributions of the velocity and the pressure waves in the pulse tube

The distribution of the velocity waves is shown in Figure 2, and Figure 3 shows pressure distribution in the pulse tube. From Figure 2 we can see that the velocity wave near the hot end of the pulse tube lags behind that near cold end, and the value of the velocity is gradually become less and less from the cold end to the hot end of the pulse tube. The lag phenomena of the velocity wave was caused by the compressible character of the working fluid.

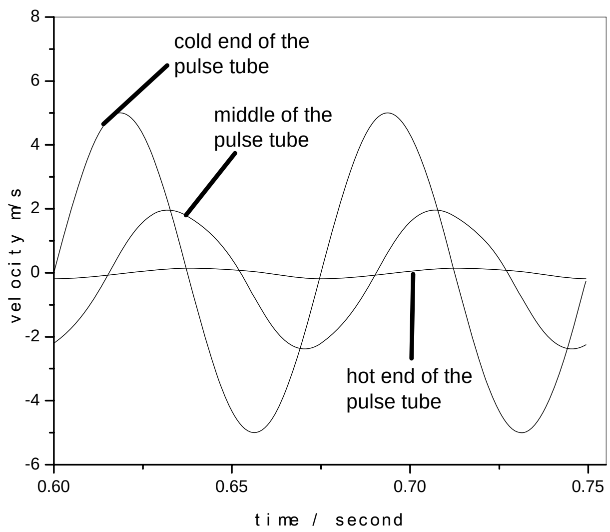


Figure 2 The distributions of velocity waves

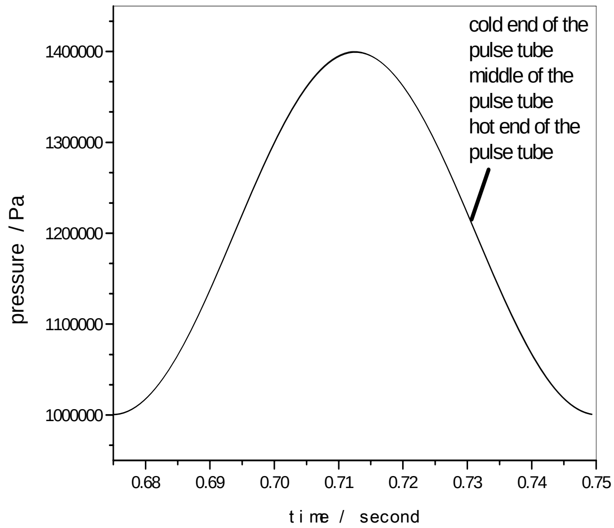


Figure 3 The distributions of pressure waves

<u>Velocity vector in longitudinal section</u>

A general view of the velocity distribution in the longitudinal cross section across the axis of the pulse tube is shown in Figure 4. For the purpose of clarity, the picture is not drawn in scale. To see the flow direction more clearly, the local velocity vectors near the hot and cold ends are magnified and presented in Figure 5. In both Figures 4 and 5, the crank angle is 90 degree.

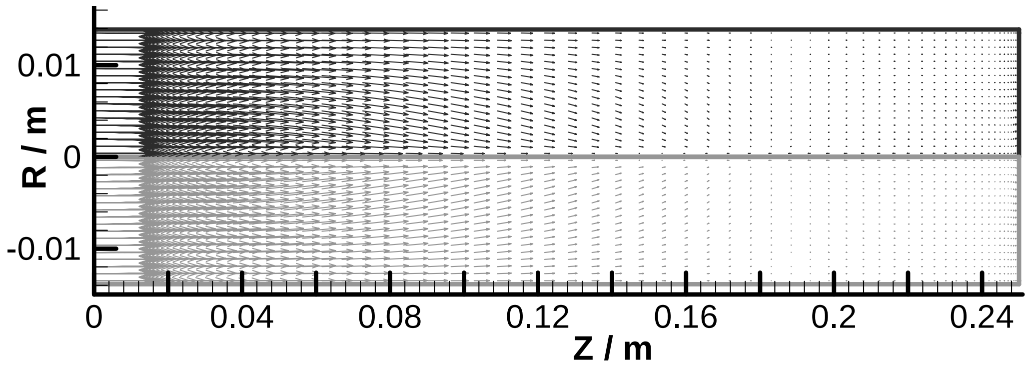
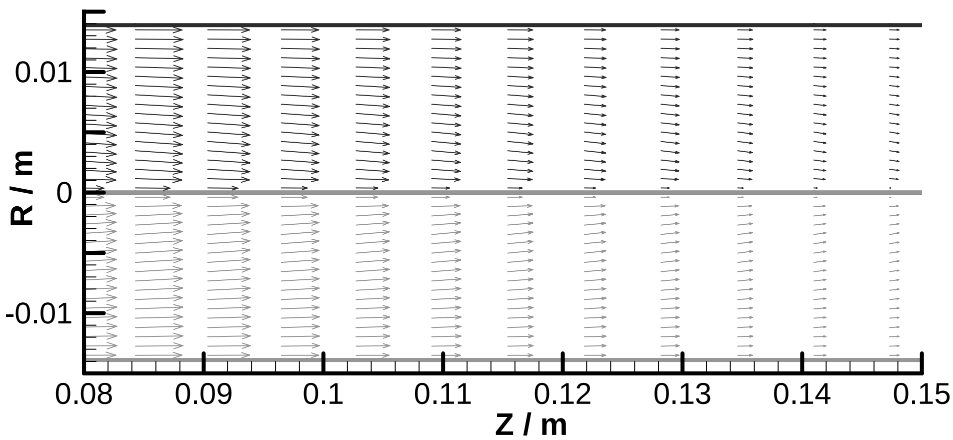
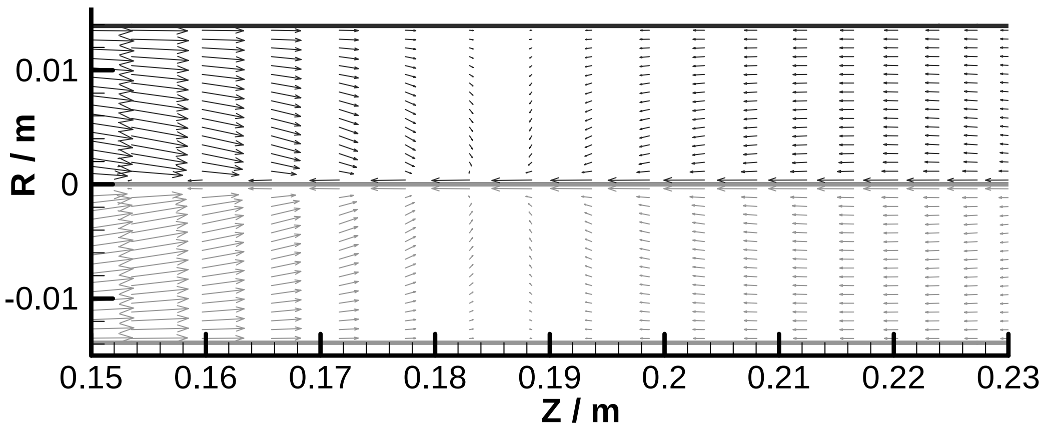


Figure 4 Velocity vector in longitudinal section for the crank angle of 90 degree



(a) Local velocity field near cold end



(b) Local velocity field near hot end

Figure 5 Details of flow pattern in longitudinal section for the crank angle of 90 degree

It can be clearly seen from Figures 4、5 that the direction of the axial velocity reverses at the some cross section of the middle part of the pulse tube. The changing of the axial velocity direction starts from the center part of the pulse tube, that is the direction changing of the axial velocity of the center part of the pulse tube makes the whole cross section to reverse the axial velocity direction. So there is some radial velocity in the cross section where the axial velocity reverses. From Figure5 (a)、(b) following feature may be noted: The axial velocity of the center part of the tube becomes smaller and smaller from the cold end to the hot end of the pulse tube, at the some cross section the axial velocity of the center part of the tube disappears, then there is reverse axial velocity at the center part of the tube, and the axial velocity of the other part of the tube is gradually reverses caused by the working fluid in the center part of the tube.

CONCLUSIONS

The velocity wave near the hot end of the pulse tube lags behind that near cold end. At the some cross section of the middle part of the pulse tube the direction of the axial velocity reverses, the changing of the axial velocity direction starts from the center part of the pulse tube.

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