CFD study of the 2D gas piston in pulse tube cryocoolers

Zhimin Guo\textsuperscript{1,3}, Shaowei Zhu\textsuperscript{1,2}, John M Pfotenhauer\textsuperscript{3}

\textsuperscript{1}Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Tongji University, 4800, Cao’an Road, Shanghai 201804, China

\textsuperscript{2}Shanghai Key Lab of Verticle Aerodynamics and Thermal Management Systems, Tongji University, 4800, Cao’an Road, Shanghai 201804, China

\textsuperscript{3}University of Wisconsin-Madison, Madison, WI 53706, USA

swzhu2008@yahoo.com

Abstract. There are three parts of the gas moving through the pulse tube of the pulse tube cryocooler, part I is the gas moving between the cold heat exchanger and the pulse tube, part II is the gas oscillating in the pulse tube all the time, part III is the gas moving between the pulse tube and the warm heat exchanger. The part of the gas that always moves in the pulse tube performs the same function as a solid piston; this part of the gas is called the gas piston. The shape and the position of the gas piston changes with time and the operating conditions rather than remaining fixed. A 1D model cannot capture the change of the gas piston near the wall, but a 2D model capturing changes in the axial and radial directions can. Further, the uniformity of the fluid flow field in the pulse tube can be depicted by the shape of the gas piston which can be simply envisioned as a 2D gas piston in the pulse tube. In this study a CFD method is used to obtain the details of the 2D gas piston. The velocity field in the pulse tube is obtained by the commercial code ANSYS Fluent, and a LaGrange particle tracing method is introduced to process the velocity data in order to obtain the boundary of the 2D gas piston. Additionally, this work investigates the influence of various parameters including pressure ratio, pulse tube aspect ratio and frequency on the shape of the gas piston. It reveals that a larger pressure ratio, larger aspect ratio and lower frequency cause a larger deformation of the gas piston in one cycle. These effects are especially noticeable at the warm end of pulse tube, which displays a larger deformation than other positions in the pulse tube under the influence of changes in those parameters.

1. Introduction

The pulse tube cryocooler has the advantages such as simple structure, no moving parts in the cold stage, long lifetime and minimal mechanical vibration. It has been playing an increasingly important role in the aviation and aerospace fields. The concept of a “gas piston” within the pulse tube represents that portion of the gas that does not exchange heat with either the cold or hot heat exchangers. The mass within the gas piston remains within the pulse tube and produces cooling by transmitting PV power from the cold to warm end rather than by the expansion mechanism utilized in a Stirling cooler. The gas piston expands and contracts with the time. Y. Matsubara \cite{1} suggests that the gas piston in the pulse tube works as a compressible displacer, and the enthalpy is transferred from the cold end of the pulse tube to the warm end \cite{2}. In addition, the Carnot efficiency that is possible in the Stirling cryocooler could also be realized in the pulse tube if an ideal phase shifter was added at the warm end. The nature of the gas piston is still being examined, and there is little research to date on the influence of its physical shape.
The commercial software Fluent is a useful tool to research the flow and heat transfer of a pulse tube refrigerator, and there have been many studies using this method to study the mechanism of pulse tube refrigerators [3-9]. In this work, the physical shape of the 2D gas piston has been studied by numerical simulation through Fluent, and the change of the shape of the gas piston in the process of expansion and compression in one cycle is obtained. It reveals that the parameters including the pressure ratio, the aspect (L/D) ratio and the frequency influence the physical shape of the gas piston. A representation of the 2D gas piston is shown, revealing that the real gas piston is not a regular rectangle due to the effect of the viscous resistance, and that the shape will change under expansion and compression in one cycle.

2. Simulation model

Multiple successful and reliable reports exist describing 2D numerical simulations of the parts of the pulse tube cryocooler and the whole refrigeration system. Although various detailed phenomena can be obtained by 2D numerical simulation, it is difficult to obtain the same rich information through 1D models. The commercial software ANSYS Fluent has been used to conduct a 2D numerical simulation of the pulse tube and the results are presented in this paper.

The geometry associated with the 2D axisymmetric model is shown in figure 1. The following working conditions are constant in all cases: The mass flow at the cold (left side) inlet is given by \( m = m_a \sin(\omega t) \), the cold and warm end temperatures are fixed at 77K and 300K, and the pressure at the warm (right side) outlet is represented by \( p = p_0 + p_a \sin(\omega t + \theta) \). The assumption that both the pressure wave and the mass flow rate are ideal sinusoidal waves is adopted. The wall of the pulse tube is adiabatic. The charge pressure \( p_0 \) is 2 MPa and the working medium is ideal helium gas. The size of the model and working condition parameters are shown in Table 1.

![Figure 1. 2D axisymmetric model.](image)

**Table 1. Geometry, frequency and pressure ratio values used in the parametric study.**

| Case | L(mm) | R(mm) | f(Hz) | Pressure ratio |
|------|-------|-------|-------|----------------|
| Case1 | 75    | 7.5   | 50    | 1.1            |
| Case2 | 75    | 7.5   | 50    | 1.2            |
| Case3 | 75    | 7.5   | 50    | 1.3            |
| Case4 | 75    | 9.375 | 50    | 1.3            |
| Case5 | 75    | 6.25  | 50    | 1.3            |
| Case6 | 75    | 9.375 | 50    | 1.3            |
| Case7 | 75    | 9.375 | 50    | 1.3            |

The Lagrange particle tracing method is used to obtain the position of the particle at each time step, then the boundary of the gas piston is obtained and the changing shape of the 2D gas piston is also captured. To begin, the velocity data in one cycle is obtained from Fluent after the simulation reaches a cyclic...
steady state. Subsequently, the shape of the gas piston is obtained by processing the velocity data using the LaGrange particle tracing method: assuming that the velocity of the gas particles is constant at each time step, the new position (and velocity) for each particle along an initially flat cross-sectional area is tracked through a complete cycle. For any particles that end up between nodes at a given time step, a linear interpolation method is used to determine its velocity for the next time step. The tracking method is used to track each particle along both the radial and axial directions. Then the particles which can move to the boundary of the pulse tube at some time in one cycle could be obtained. The gas piston boundary is formed by those particles that will move to the ends but not out of the pulse tube.

3. Results and discussions

3.1. Boundary layer and velocity field

Figure 2 shows the axial velocity distribution along the radial direction of the pulse tube and reveals that the velocity becomes small near the wall because of the influence of viscous resistance at the pulse tube wall. Additionally, the compression and expansion of the moving gas close to the wall lag that far from the wall under the influence of viscous resistance, so the physical shape of the gas piston is also affected. The axial velocity distributions near the wall of different positions in the pulse tube are represented in figure 2, including the left (cold) boundary of the gas piston shown in figure 2(b), the right (warm)
boundary of the gas piston shown in figure 2(d), and the middle position of the pulse tube in figure 2(c). And figure 2(a) shows the axial velocity distribution from the central to the wall in the middle position of the pulse tube. A maximum value exists near the wall, but because of the effect of the viscous force near wall, the velocity decreases along the radial direction. The thickness of the viscous layer gradually increases from the cold end to the hot end of the pulse tube, growing from about 0.5 mm at the cold end of the pulse tube, to approximately 0.75 mm in the middle of the pulse tube, and 1 mm at the hot end of the pulse tube. The closer to the hot end, the greater the maximum velocity value is, resulting in slightly different boundaries for the gas piston at the cold and hot ends.

3.2. Gas piston characteristic

Figure 3 displays the time dependent temperature distribution in the pulse tube during one cycle. It reveals that a well-distributed layered temperature profile is formed in the pulse tube. However, there are some curved lines near the wall because of the boundary effect, especially at the warm end of the pulse tube. Furthermore, the temperature distribution is similar to the shape of the gas piston. Also, the temperature map at different times shows that the gas piston changes shape as the gas compresses and expands. The two boundaries of the gas piston are defined as the gas boundary that periodically touches the left or the right end of the pulse tube. In order to avoid numerical anomalies at the boundaries of the cold and warm heat exchangers, the axial end locations of the gas piston are chosen at one grid spacing away from the heat exchangers.

![Temperature distribution in pulse tube.](image)

There is no obvious viscous effect near the axis of the pulse tube, so the figures shown below only display values near the wall of the pulse tube. The amount of change in the size of the piston is directly related to the work transmission in the pulse tube. The gas contained within the gas piston compresses and expands adiabatically in one cycle and only produces cooling by transferring energy away from the cold end by the associated piston work.

![Gas piston boundary without porous media (a) and with porous media (b).](image)
3.2.1. Entrance effect. In the above cases, the boundary of the simulation models includes a mass flux oscillation at the inlet and a pressure oscillation at the outlet. Such a choice may have an effect on the velocity field of the pulse tube. So, a model including two porous zones at the two ends of the pulse tube is also investigated. A comparison of the gas piston boundary when including the porous media or not is presented above when the ratio of length to diameter is 5:1, the pressure ratio is 1.1, and the frequency is 50 Hz. As shown in figure 4, the boundary of the gas piston is well-distributed when the porous media is included, but there is no obvious change in the shape of the gas piston.

The boundary of the gas piston at different times within one cycle is shown by the 4 figures in figure 5. It shows that the boundary of the gas piston is a curved shape rather than a regular rectangle due to the viscous effect of the solid boundary.

3.2.2. Pressure ratio effect. Figure 6 shows the changes to the shape of the gas piston under different pressure ratio conditions. The analysis reveals that a larger pressure ratio causes a greater deformation of the gas piston. This feature is shown explicitly in figure 6(d), which is the axial length of the gas piston in the center of the pulse tube throughout one full cycle. In other words, the compression and expansion are more obvious under a bigger pressure ratio. This is because the larger pressure ratio causes a larger amplitude of the pressure wave, and the gas moving in the pulse tube will experience greater compression and expansion. When the volume of the gas piston in the pulse tube experiences a larger change due to the larger pressure ratio, the gas piston will transfer more cooling power.

Figure 5. Gas piston boundary at 4 times in one cycle
**Figure 6.** Gas piston boundary at (a) pressure ratio=1.1, (b) pressure ratio=1.2, (c) pressure ratio=1.3, (d) Central axial length of the gas piston during 1 cycle
3.2.3. The LD ratio effect. As shown in the figure 7, when the LD ratio increases, the shape of the gas piston becomes more deformed near the walls. Figure 7(d) shows the near wall effect under different LD ratio. A new character is defined as r*/r, r* means the distance from the 0.9*L position to the wall tube, L is the amplitude of the right boundary of the gas piston, r is the radius of the tube, and the definition example is shown in figure7(c). This is due to the characteristics of the fluid flow in the pulse tube. The larger LD ratio has a thinner channel with the same length of the pulse tube. As a result, the gas moving in the pulse tube experiences a larger change of inertia at either end of its cycle.

3.2.4. Frequency effect. Figure 8 shows the frequency effect on the deformation of the gas piston. With the decrease of frequency, the change in the axial length of the gas piston in one cycle will be bigger, as shown in figure 8(d). The results are consistent with the expectation that the oscillatory stroke of the gas particles will become larger under low frequency, and from a macro point of view, the boundary of the gas piston will have a bigger elasticity.

It can be seen from the above analysis that the boundary of the gas piston is affected by many variables, including the pressure ratio, the LD ratio and the operating frequency, especially at the warm boundary of the gas piston. Because the viscous force is more significant at the higher temperatures, the deformation of the gas piston is more obvious at the warm end.
Figure 8. Gas piston boundary at (a) Frequency = 50 hz, (b) Frequency = 40 hz, (c) Frequency = 30 hz, (d) Central axial length of the gas piston during 1 cycle

4. Conclusions

A LaGrange particle tracing method, enabled through the use of the CFD code FLUENT, has been used to explore the time dependent shape of the 2D gas piston in a pulse tube refrigerator. The shape of gas piston is affected by many factors. Those studied in this paper include the pressure ratio, operating frequency and the LD ratio. The investigation quantitatively demonstrates the increased variation of the axial length of the gas piston as a result of an increased pressure ratio. When the LD ratio increases, the larger change of inertia at the ends of the cycle results in a more radially deformed shape of the gas piston. Finally, the results quantitatively demonstrate the expected decrease in gas piston length variation over one cycle as frequency is increased.

5. References

[1] Matsubara Y and Gao J L 1994 Cryogenics 34 259-262
[2] Kittel P 2005 Enthalpy, Entropy, and Exergy Flows in Ideal Pulse Tube Cryocoolers Cryocoolers 13 (Springer, Boston, MA) pp333-341
[3] Dai Q, Chen Y Y and Yang L W 2015 International Journal of Heat and Mass Transfer 84 401-408
[4] Chen L and Zhang Y 2010 Cryogenics 50 743-749
[5] Cha J S, Ghiaasiaan S M and Kirkconnell C S 2008 Experimental Thermal and Fluid Science 32 1264-1278
[6] Zhang X B, Qiu L M and Gan Z H 2007 Cryogenics 47 315-321
[7] Ashwin T R, Narasimham G S V L and Subhash. J 2010 Applied Thermal Engineering 30 152-166
[8] Cha J S, Ghiaasiaan S M, Desai P V, Harvey J P and Kirkconnell C S 2006 Cryogenics 46 658–665
[9] Zhi X Q, Qiu L M and Pfotenhauer J M 2016 International Journal of Heat and Mass Transfer 103 382-389

Acknowledgments

This research is supported by the National Natural Science of China (NSFC) under the contract No.51476117.