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Influence of the gas volume in the void tube connecting compressor and inertance tube on the oscillating flow in an inertance tube phase shifting system

Qingjun Tang[a,b], Jinghui Cai[a], Houlei Chen[a*]

[a]Technical Institute of Physics and Chemistry, CAS, Haidian District,Beijing 100190, China
[b]University of Chinese Academy of Sciences, CAS, Haidian District, Beijing 100190, China

Abstract

Influences of the gas volume in the void tube (connecting tube), connecting compressor and inertance tube, on the oscillating flow characteristics are experimentally investigated. Four void tubes, whose volumes are different from each other, are chosen to connect the compressor and the inertance tube respectively. Piston displacement of the compressor and dynamic pressure at the outlet of the compressor are measured by a laser displacement sensor and a quartz pressure sensor respectively. This investigation focuses on the piston displacement and mass flows at three special positions of the experimental system. The change of the amplitudes and phase angles of the piston displacement and the three mass flows caused by varying the void tubes with different dynamic pressures and frequencies are studied. This investigation is helpful to study the influence of the gas volume in the connecting parts of an inertance tube pulse tube cryocooler, such as transfer tube, cold finger and pulse tube, on oscillating characteristics of the cooler.

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Keywords: gas volume in connecting tube, piston displacement, mass flow, amplitude, phase angle

1. Introduction

Pulse tube cryocooler (PTC) has many advantages over conventional refrigerators, such as low mechanical

* Houlei Chen. Tel.: +86-15201192519; fax: +86-010-82543668.
E-mail address: tangqingsen.2006@163.com

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vibration and high reliability. These advantages own to that phase shift devices at room temperature take place of the cold end phase shift piston. Inertance tube is widely used in a pulse tube cryocooler for phase shifting [1]. In many references, inertance tube model was analogous to a simple a.c. electrical circuit and the performances of IPTC were investigated [2].

However, few investigations focus on the issues that whether phase shifting characteristics of inertance tube is independent of or dependent on the other parts in the cryocooler have been done. The purpose of this paper is to investigate the effect of the gas volume between the compressor and inertance tube on the phase shifting characteristic of inertance tube, piston displacement of the compressor and mass flows at some special positions.

Nomenclature

m	mass	p	pressure
R	gas constant	T	temperature
f	frequency	t	time
V	gas volume	γ	adiabatic index
$\dot{m}$	mass flow	P_d	dynamic pressure

Subscript

1	the position, outlet of compressor	2	position, inlet of inertance tube
i	number of time intervals		

2. Design of experiments

2.1. Experimental apparatus

As is shown in Fig.1, the experimental apparatus consists of a linear compressor, an inertance tube (including a buffer), four connecting tubes (V1, V2, V3 and V4), a laser displacement sensor (LK-G5000) and a quartz pressure sensor (KISTLER 601A) as well as a charge amplifier (KISTELER 5015A). Table 1 lists the dimensions of the compressor and inertance tube and Table 2 lists the dimensions of the void tubes.

The displacement of the compressor piston is measured by the laser displacement sensor and a window is designed on one of the compressor's shell in order to let the laser pass through the shell. The quartz pressure sensor is used to measure the dynamic pressure at the outlet of the compressor. In fact, the pressure here is consistent with that in compression cavity and connecting tube.

2.2. Experimental principle

The experimental principles are based on the following assumptions. The gas that leaks from the gap between pistons and cylinders is negligible. Working gas is ideal and the thermodynamic process of the gas in compressor and connecting tube is adiabatic. The dynamic pressure in connecting tube that connects the compressor and inertance tube is consistent with that in the compression chamber of the compressor. The flow is one-dimensional.

Table 1. Dimensions of the compressor and inertance tube

name	Compression chamber	Inertance tube			
		First length	Second length	Third length	buffer
Volume（mm^3）	2920	628	3140	14130	6750
Diameter(mm)	/	1	2	3	/
Length(mm)	/	800	1000	2000	/

Table 2. Dimensions of the connecting tubes

name	V1	V2	V3	V4
Volume（$mm^3 \times 10^3$）	2390	3820	5310	6075
Diameter(mm)	7.8	7.8	7.8	7.8
Length(mm)	50	80	110	127

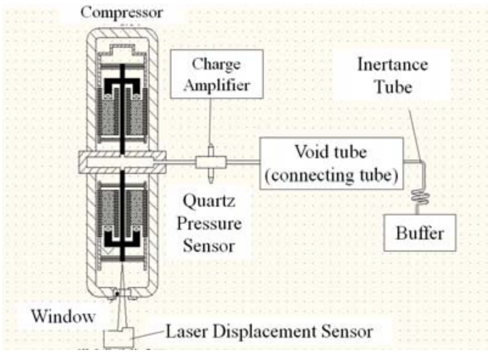

Fig. 1 Schematic of experimental system

Select the volume surrounded by the interface of the piston, walls and the imaginary face (shown in Fig. 2 a) as a control volume. Based on assumption 1, there is only one opening in a control volume.

The ratio of mass change in a control volume can be expressed as

$$\frac{dm}{dt} = \frac{V}{\gamma RT}\frac{dp}{dt} + \frac{p}{RT}\frac{dV}{dt} \tag{2}$$

Since there is only one opening, the imaginary face, for a control volume, mass flow at imaginary face is equal to the ratio of mass change in the control volume. Namely

$$\dot{\boldsymbol{m}} = -\frac{dm}{dt} \tag{3}$$

The mass flows at three different positions are investigated. They are $\dot{\boldsymbol{m}}_{\boldsymbol{1}}$ at the outlet of the compressor, $\dot{\boldsymbol{m}}_{\boldsymbol{2}}$ at the inlet of the inertance tube and $\dot{\boldsymbol{m}}$ at the position between which to the inlet of inertance tube, the volume is constant, as is shown in Fig. 2b. All the data about the parameters, the piston displacement, the mass flows and the dynamic pressure, are filtered by FFT Filter and fitted by Sinusoidal Curve Fitter of OriginLab 8.0.

3. Results and discussion

3.1. Experimental results

The experimental apparatus is cooled by air at room temperature and their wall temperature is kept at 305K. The charging pressure is 3.6 MPa. All parameters in the following paragraphs have been dealt by OriginLab8.0. The phase angles of the dynamic pressures are considered as zero. The phase angles of the piston displacement and the mass flows are the phase differences between their phase angles and phase angle of dynamic pressures.

The dynamic pressure and mass flows as a function of time with different connecting tubes is displayed in Fig. 4. Because of the gas volume in the connecting tube, the phase angle of $\dot{\boldsymbol{m}}_{\boldsymbol{1}}$ is ahead of $\dot{\boldsymbol{m}}$ and the phase angle of $\dot{\boldsymbol{m}}_{\boldsymbol{2}}$ is behind that of $\dot{\boldsymbol{m}}$.

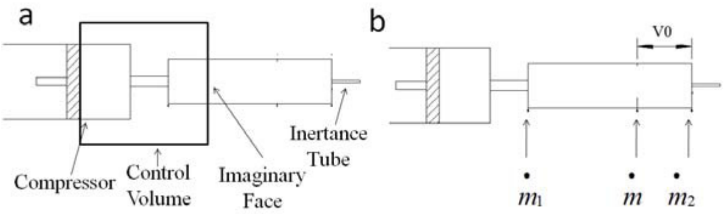

Fig. 2 (a) Sketch of control volume; (b) positions where mass flows are calculated

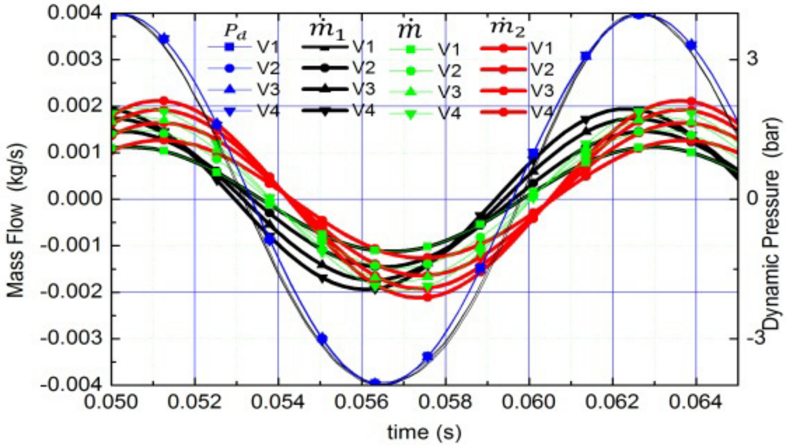

Fig. 3 Piston displacement, dynamic pressure and mass flows as a function of time, P_d=4bar, f=80Hz

For further investigation, amplitude and phase angle analysis is introduced to study the piston displacement and the mass flows, $\dot{\boldsymbol{m}}_1$, $\dot{\boldsymbol{m}}$, and $\dot{\boldsymbol{m}}_2$. Fig. 4 shows the amplitudes and phase angles of the mass flows and piston displacement versus the gas volume in connecting tube. One can see that with the increase of the connecting tube volume that connects to the compressor, amplitudes of the mass flows and piston displacement increases. In contrast, with increasing of the gas volume in the connecting tube, the phase angles of $\dot{\boldsymbol{m}}_1$ and the piston displacement increase, phase of $\dot{\boldsymbol{m}}$ decreases and phase of $\dot{\boldsymbol{m}}_2$ increase slightly.

A series of tests have been performed by varying connecting tube, dynamic pressure and frequency. The results are shown in Fig. 5~ Fig. 8. Fig. 5 shows the amplitudes of the parameters as a function of the gas volume in connecting tube with different dynamic pressures. It can be seen that the amplitudes in high dynamic pressure is larger than those in low dynamic pressure.

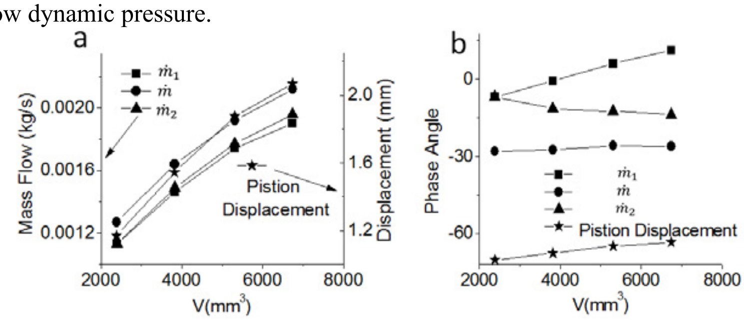

Fig. 4 (a) Displacement and mass flows as a function of the gas volume in connecting tube, P_d=4bar, f=80Hz. (a) amplitudes; (b) phase angles

As is shown in Fig. 6a and Fig. 6b, the phase angles of the piston displacement and $\dot{m}_1$ are also change when the volume connected to the compressor changes. This may be caused by the reason that the gas volume of compression chamber is too small when compared with the gas volume of connecting tube. Fig. 6c and Fig. 6d show that the increase of the gas volume in connecting tube causes the decrease of the phase angle of $\dot{m}$ and the increase of the phase angle of $\dot{m}_2$. One can see from Fig. 6 that dynamic pressure has little influence on the phase angles of the piston and mass flows; especially the gas volume in the connecting to is large enough. What's more, with increasing the gas volume in connecting tube, the phase angles of $\dot{m}$ and $\dot{m}_2$ in different dynamic pressure become much closer to each other respectively.

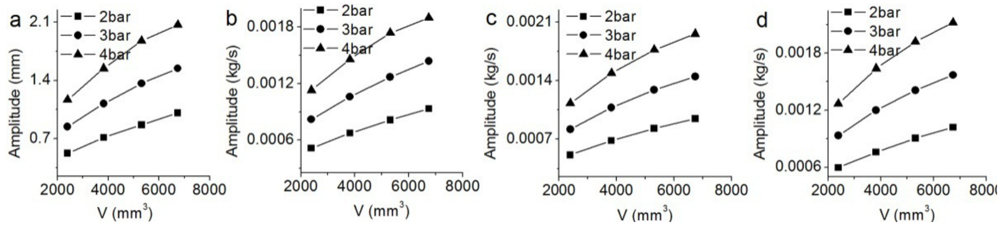

Fig. 5 Amplitudes of the piston displacement and mass flows as a function of the gas volume in connecting tube with different dynamic pressure, f=80Hz. (a) piston displacement; (b) $\dot{m}_1$; (c) $\dot{m}$ (d) $\dot{m}_2$

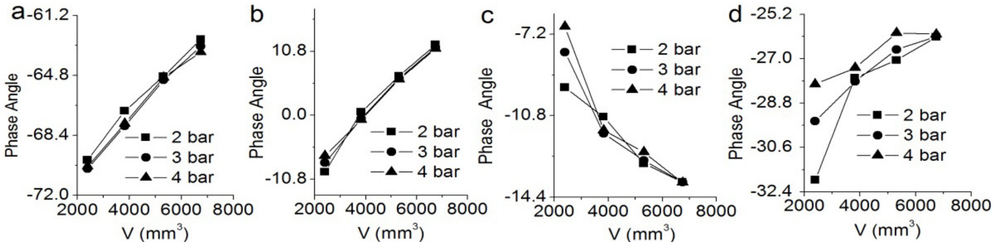

Fig. 6 Phase angles of the piston displacement and mass flows as a function of the gas volume in connecting tube with different dynamic pressure, f=80Hz (a) piston displacement; (b) $\dot{m}_1$; (c) $\dot{m}$; (d) $\dot{m}_2$

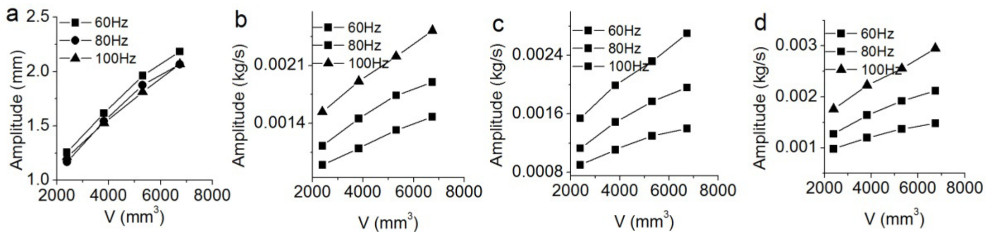

Fig. 7 Amplitudes of the piston displacement and mass flows as a function of the gas volume in connecting tube with different frequencies, P_d=4bar. (a) piston displacement; (b) $\dot{m}_1$; (c) $\dot{m}$; (d) $\dot{m}_2$

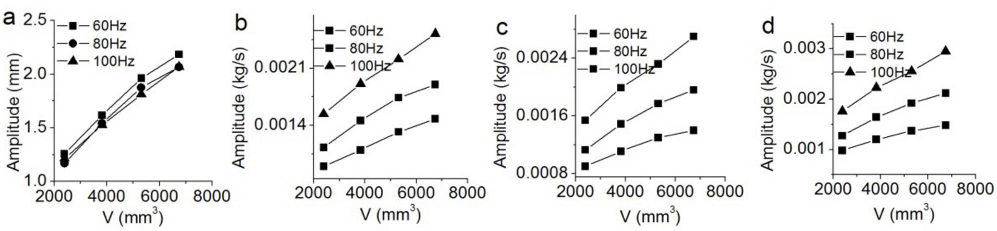

Fig. 8 Phase angles of the piston displacement and mass flows as a function of the gas volume in connecting tube with different frequencies, P_d=4bar, (a) piston displacement; (b) $\dot{m}_1$; (c) $\dot{m}$; (d) $\dot{m}_2$

Fig. 7 shows the amplitudes of the mass flows and piston displacement versus the gas volume in connecting tube. As mentioned above, the amplitudes of the piston displacement and mass flows increase as the gas volume in connecting tube increases. The amplitudes of mass flows are larger in high frequency than those in low frequency. However, as shown in Fig. 7a, frequency has little influence on the amplitude of piston displacement.

The phase angles of the mass flows and piston displacement versus the gas volume in connecting tube is shown in Fig. 8. When the volume kept constant, the phase angles of mass flows is more lagging in high frequency than those in low frequency. It may be caused the phase shifting characteristics of this inertance tube.

3.2. Discussion

This paper aims to study the oscillating flow of pulse tube cryocooler. In this paper, the gas volumes in connecting tube can be regarded as the gas volume of the parts that connects the inertance tube and compressor, such as pulse tube cold finger, transfer tube, and pulse tube. For example, if V0, shown in Fig. 1b is regarded as the gas volume in pulse tube, investigation in this paper can be considered as study of the influence of the gas volume in transfer tube on the oscillating flow characteristics in a pulse tube cryocooler. Though this investigation is not sufficient enough to illustrate the interaction among the inertance tube, compressor and other part of an IPTC quantitatively, it is still full of guidance for the qualitative analysis of the interactions. Many more conclusions can be achieved if regard some special volumes as the gas volume in some parts in pulse tube cryocooler.

4. Conclusion

An oscillating flow system has been investigated for mass flows at three positions and piston displacement as a function of the gas volume in connecting tube, connecting compressor and inertance tube, with different dynamic pressures and frequencies. The mass flow $\dot{\boldsymbol{m}}_1$ is at the outlet of the compressor, $\dot{m}_2$ is at the inlet of the inertance tube and $\dot{\boldsymbol{m}}$ at the position between which to the inlet of inertance tube, the volume is constant.

Amplitudes of the four parameters increase with the increasing of the gas volume of connecting tube. With the same gas volume in connecting tube, the amplitudes of the mass flows in high dynamic pressure in greater than those in low dynamic pressure; the amplitudes of the mass flows in high frequency is greater than those in low frequency, and the piston displacement amplitudes in high dynamic pressure is greater than that in low dynamic pressure. But the piston displacement amplitudes are almost the same when frequency changes.

The phase angles of the piston displacement and the mass flow $\dot{\boldsymbol{m}}_1$became ahead as the gas volume in connecting tube increases. The two phase angles in low frequency are ahead of those in high frequency. Compared with frequency, dynamic pressure has little influence on the phase angles of the two parameters. As the gas volume in connecting tube increases, phase angles of $\dot{\boldsymbol{m}}_1$ fall behind and phase angle of $\dot{\boldsymbol{m}}_2$ becomes ahead. When the gas volume of connecting tube is large enough, the influence of dynamic pressure on the phase angles of the two parameters becomes weak. Thus, with the same connecting tube, the phase angle of $\dot{\boldsymbol{m}}_2$ in different dynamic pressure is almost the same. So is the phase angle of $\dot{\boldsymbol{m}}$. However, in the case of small volume of connecting tube, dynamic pressure still has influence on the phase angles of $\dot{\boldsymbol{m}}$ and $\dot{\boldsymbol{m}}_2$.

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