THE EFFECT OF THE REGENERATOR AND TUBE VOLUME ON THE PERFORMANCE OF HIGH FREQUENCY MINIATURE PULSE TUBE REFRIGERATORS

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ABSTRACT

In this paper, the ratios of the volume of the pulse tube and the void volume of the regenerator to the compressor's swept volume are considered as the two most important parameters for a high frequency miniature PTR design. Firstly, knowing the compressor's swept volume, a 1-D numerical simulation is adapted to investigate the effect of the above two ratios on the performance of the miniature PTR. Under the condition of charge pressure of 2.1MPa, 2.5MPa and 2.9MPa, and the operating frequency of 50Hz, it is found that the optimum ratios of the volume of the pulse tube and the void volume of the regenerator to the compressor's swept volume are in the range of 0.8-1.0 and 1.1-1.3, respectively. To verify this conclusion, 25 PTRs using a 1.66cm^3 compressor are composed of five different size of regenerators and pulse tubes, and all the PTRs are tested under different charge pressure with operating frequency of 50Hz. The experimental results indicate that the optimum ratios of the volume of the pulse tube and the void volume of the regenerator to the compressor's swept volume are in the range of 0.7-1.0 and 1.0-1.2, respectively. The experimental results agree with the simulated results qualitatively.

INTRODUCTION

The high frequency miniature pulse tube refrigerator (PTR) is a variation of the Stirling refrigerator with the moving displacer at the cold end replaced by the pulse tube. Such a configuration results in less vibration at the cold end, simplicity, and a potential for high reliability and long life [1]. But the introduction of the pulse tube brings about low efficiency because of the large void volume of the tube and the passive phase shift method. In order to improve the efficiency of the PTR, most efforts are focused on the phase shift mechanisms at the warm end of the PTR. The first improvement was the introduction by Mukulin et al. of an orifice connected to a reservoir at the warm end of the pulse tube [2].

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Another improvement was the bypass configuration introduced by Zhu et al. [3]. Unfortunately, the bypass configuration is believed to cause DC flows. Recently, the inertance tube was introduced to replace the single orifice. Besides improving performance, the inertance tube can eliminate the circulatory DC gas flows. It has been reported that both the bypass and the inertance tube have successfully improved the efficiency of the PTR [1, 4].

The largest losses in the PTR originate from the regenerator and pulse tube. In other words, optimizing the volume of regenerator and pulse tube for a given compressor is key for high PTR efficiency, and any phase shift configuration must be combined with the appropriate size regenerator and pulse tube to achieve good performance. Several efforts have been made to decide the optimum volume of the regenerator and the pulse tube. On the basis of the enthalpy flow theory, Radebaugh et al. [5, 6] gave the optimum pulse tube volume for a large compressor (with swept volume of 25cm^3):

$$V_t / V_{co} = (3/\sqrt{2})(T_c / T_{co}), \tag{1}$$

where V_t is the volume of the pulse tube, V_{co} is the swept volume of the compressor, T_c is the cold end temperature and T_{co} is the average temperature of the gas in the compressor. The optimum ratio of regenerator volume to compressor's swept volume ($V_{rg} / V_{co} = 0.41$) was given by the experiment. Lewis et al. [7] studied the effects of regenerator geometry on a small compressor (with swept volume of 4cm^3) driven PTR, and the optimum volume of the regenerator and the pulse tube were different from the previous result. Xiao [8] suggested an optimum design method by applying the thermoacoustic theory. This method was time consuming, and provided no clear relationship between the PTR performance and the PTR geometry parameters. With the data from NIST's high efficiency PTRs, Radebaugh [1] gave the design criterion for the small and large PTR. For the regenerator, the ratio of inside cross-sectional area to net refrigeration power at 80K is Ar_q=0.32cm^2/W for the 15W system and 0.28cm^2/W for the 2.5W system. For the pulse tube, the ratios are Ap_q=0.084cm^2/W for the large system and 0.057cm^2/W for the small system, respectively. However, the dimensions of the regenerator and pulse tube for the high frequency miniature PTR in Cryogenic Laboratory, CAS [9], which has 0.5W refrigeration power at 80K, are different from that of Radebaugh's conclusion.

This paper addresses the effect of the volume of the regenerator and pulse tube on the performance of the high frequency miniature PTR. The ratios of the void regenerator volume and the pulse tube volume to the swept volume of the compressor are considered as the key parameters for the performance of a PTR. The one-dimensional numerical method is adopted to find the range of the optimum void regenerator and pulse tube dimensionless volume, and experiments are conducted to verify the simulation results. Here the dimensionless regenerator void volume and dimensionless pulse tube volume are defined as the ratio of the void regenerator volume and the pulse tube volume to the compressor's swept volume, respectively.

NUMERICAL SIMULATION

One-dimensional Numerical Model

The PTR is simple from a mechanical standpoint. However, the thermodynamics and hydrodynamics of the oscillating processes in it are extremely complex. A good understanding of the mechanisms associated with the PTR requires the solution of the three-dimensional Navier-Stokes equations. Because the axial dimension of the pulse tube and regenerator are much longer than their transverse dimension, the transverse velocity is typically an order of magnitude less than the axial velocity. Thereby the three-dimensional Navier-Stokes equations can be simplified to one-dimensional equations, and the calculation can be carried out effectively with reasonable accuracy. A detailed description of the numerical model and the algorithm has been given in reference [10]. However, the one-dimensional model neglects the heat transfer between the gas and the pulse tube wall [11], which means neglecting the shuttle heat transfer from the warm end to the cold end. This is one of the main refrigeration losses of the PTR. According to thermoacoustic theory, the shuttle loss is given by [12]:

$$\langle\dot{Q}\rangle_{shuttle}=\frac{1}{2}\rho c_p\frac{|U|^2}{A\omega}\frac{dT}{dx}g_{qx}. \tag{2}$$

where $\frac{|U|}{A\omega}$ is the amplitude of a gas element; $\frac{dT}{dx}$ is the temperature gradient; g_{qx} is the material and size dependent constant; ρ is the density of gas; c_p is the specific heat at constant pressure.

Numerical simulation results

According to enthalpy flow theory [6], the gross refrigeration power of a PTR is a function of the amplitude of the pressure oscillation and mass flow rate, as well as the phase angle between them at the cold end of the PTR. For a given compressor, the amplitude of the pressure oscillation and the mass flow rate are mainly determined by the void volume of the regenerator and the volume of pulse tube. The numerical simulation is firstly carried out to investigate the effect of the void volume of the regenerator and the volume of the pulse tube on the performance of a high frequency miniature PTR.

An efficient regenerator must provide adequate thermal contact between the helium gas and the solid matrix, and cause small pressure drops across the regenerator. For high frequency PTRs, the 400-mesh matrix material is generally used.

The studies presented by Kirkconnell et al. [13] showed that the performance of small PTRs was independent of pulse tube aspect ratio over the range of 10-16.5, where the aspect ratio is the ratio of length to diameter. For the regenerator, dimensional data of high efficiency PTRs published showed that the aspect ratio lay in the range of 3 to 8 [4, 5, 7, 9].

To investigate the effect of the pulse tube and regenerator aspect ratio on the performance, we take the high frequency miniature PTR developed in Cryogenic Laboratory, CAS [9] as the simulative subject. Figure 1 shows the simulated results. It shows that the optimum pulse tube aspect ratio has a wide range from 8 to 16, and the optimum regenerator aspect ratio is relatively narrow, which is from 4 to 8. The practical PTR has the regenerator and the pulse tube aspect ratio of 7 and 12.5, respectively. To reduce the calculation time, all the simulations given below take 6 and 12 as the regenerator and the pulse tube aspect ratio, respectively.

The main known operating parameters for the simulations are the following:

Compressor:	Swept volume	1.66cm^3,
	Operating frequency	50Hz,
Regenerator:	Matrix material	400 mesh stainless steel screen,

TABLE 1. A selection of typical data for the regenerator and the pulse tube in the simulation.

	1#	2#	3#	4#	5#	6#
V_{rvoid}/V_{co}	0.8	1.0	1.1	1.2	1.3	1.5
V_{pt}/V_{co}	0.4	0.6	0.8	1.0	1.2	

Here V_{rvoid}/V_{co} and V_{pt}/V_{co} are the dimensionless void regenerator volume and dimensionless pulse tube volume, respectively.

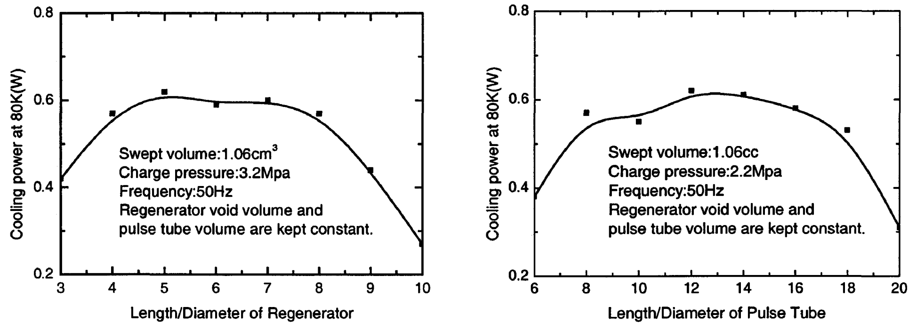
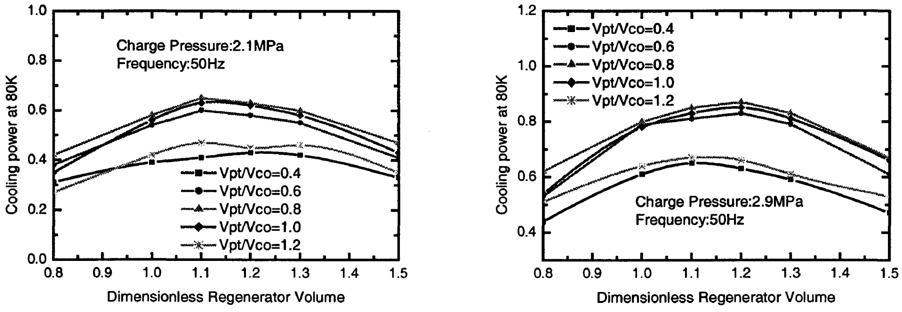


FIGURE 1. The effect of the regenerator (left) and pulse tube (right) aspect ratio on the PTR performance.

	Porosity	0.67,
Reservoir:	Volume	$80cm^3$.

Table 1 is a selection of typical dimensionless void volumes of the regenerators and the pulse tubes for the simulations. Each of the six regenerators is coupled with all the five pulse tubes to form bypass PTRs. The simulations for all the PTRs are performed under the optimum orifice and bypass setting.

Figure 2 shows the simulated results. For a charge pressure of 2.1MPa, the optimum dimensionless void volume of the regenerator and the dimensionless volume of the pulse tube are 1.1 and 0.8, respectively. For the charge pressure of 2.9MPa, the optimum void volume of regenerator increases slightly, the dimensionless void volume shifts to 1.2, and the optimum dimensionless volume of the pulse tube is almost unchanged. The reason may be that gas with higher pressure in the PTR needs a larger regenerator for heat transfer between the gas and the solid matrix. The simulated results also show that the cooling performances of PTRs are almost unchanged with the dimensionless pulse tube volume of 0.6, 0.8 and 1.0; a similar conclusion is found for the PTRs with dimensionless regenerator void volume of 1.0, 1.1, 1.2 and 1.3.



(a) (b)

FIGURE 2. The effect of dimensionless void regenerator volume and pulse tube volume on the PTR performance. (a) Simulative result with charge pressure of 2.1MPa. (b) Simulative result with charge pressure of 2.9MPa.

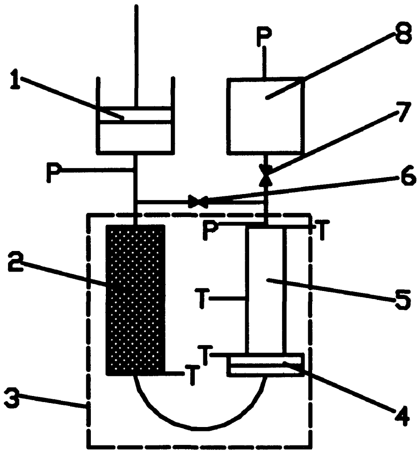


FIGURE 3. Schematic diagram of the experimental set up. 1. Compressor, 2. Regenerator, 3. Vacuum chamber, 4. Connect flange(cold end of the pulse tube), 5. Pulse tube, 6. Bypass, 7. Orifice, 8. Reservoir. T. Type-T thermocouples, P. Pressure transducers.

The one-dimensional PTR model involves several assumptions. It can not fully explain the mechanism of the PTR operation. Thus the simulated optimum volume of the regenerator and the pulse tube may not be the optimum in practice. It is reasonable to say that the simulations give a range for the optimum regenerator and pulse tube volume. For the compressor with 1.66cm^3 swept volume, the optimum range of dimensionless void regenerator volume and dimensionless pulse tube volume are 1.0-1.3 and of 0.6-1.0, respectively.

EXPERIMENTAL SETUP

To verify the simulations, a set of miniature PTRs with various dimensionless void regenerator volume and pulse tube volume have been constructed and tested. Figure 3 is the schematic of the experimental setup. The PTR is arranged in the "U" shape. The cold end of the pulse tube is welded in a male copper flange. This flange is also a flow straightener. The cold end of the regenerator is connected to the cold end of the pulse tube by a narrow copper tube with a female flange at the end. The flanges are sealed by indium, and connected by bolts and nuts. The pulse tube of the PTR with such construction is easy to to be replaced with another during the experiments. Two identical fine needle valves are used as the orifice and bypass. They are placed outside of the vacuum chamber for convenience. The vacuum environment is maintained by a vacuum pump. The lowest vacuum of 1.0Pa can be reached. The temperature is measured at the cold end of the pulse tube with a copper-constantan thermocouple. The dynamic pressures are measured by small quartz pressure transducers in the hot end of the regenerator, in the hot end of the pulse tube and in the reservoir. The compressor is of a rotary type, and is estimated to be only about 50% efficient. It has a constant swept volume of 1.66cm^3. This compressor has been used for more than 10 years and has been severely worn out. After each experimental running, the matrices of the regenerator at the hot end were covered by some tiny brown powder, which deteriorated the performances of the PTRs. Thus the performances of PTRs were not impressive. The experimental results did give us the information about the effect of the regenerator and the pulse tube volume on the performances of PTR, since all the experiments were carried out under the same conditions.

TABLE 2 Dimensions of the regenerators and pulse tubes for the experiments.

No.	Regenerator length	Regenerator inner diameter	Regenerator dimensionless void volume	Pulse tube length	Pulse tube inner diameter	Pulse tube dimensionless volume
1	40.2mm	8mm	0.8	51.8mm	5mm	0.61
2	50.6mm	8mm	1.01	62mm	5mm	0.73
3	56.5mm	8mm	1.13	72mm	5mm	0.85
4	61.5mm	8mm	1.23	84mm	5mm	0.99
5	65.5mm	8mm	1.31	93mm	5mm	1.1

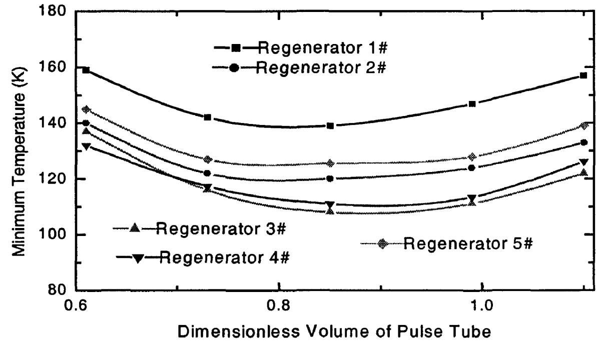


FIGURE 4. Experimental result with charge pressure of 2.1MPa.

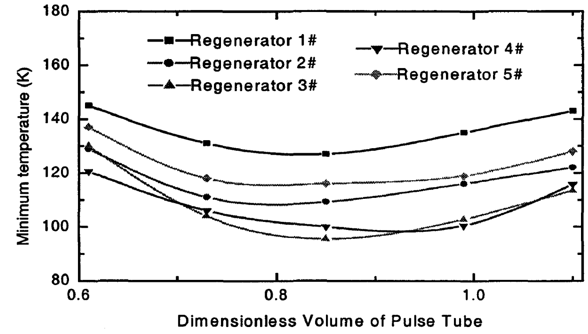


FIGURE 5. Experimental result with charge pressure of 2.5MPa.

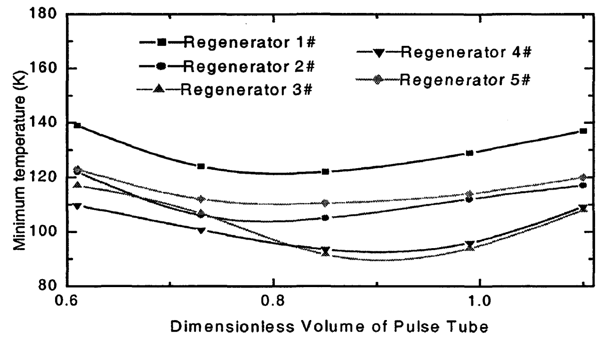


FIGURE 6. Experimental result with charge pressure of 2.9MPa.

The dimensions of the regenerator and the pulse tube are shown in Table 2. There are five regenerators and five pulse tubes with which were composed 25 PTRs. During experiments, each regenerator was coupled in turn with all the pulse tubes. Since the aspect ratio of the regenerator and pulse tube within the range described in the last section was less influence on the performance of PTR, all the regenerators and pulse tubes selected in table 2 had the same inner diameter of 8mm and 5mm, respectively, with only the length of the regenerator and the pulse tube changing. The operating conditions are as follows:

Frequency: 50Hz,
Compressor: air cooled,
Environment temperature: 300K,
Phase shifter: orifice and bypass.

EXPERIMENTAL RESULT AND DISCUSSION

Figure 4, 5, 6 are the lowest temperatures achieved by all the PTRs with charge pressures of 2.1MPa, 2.5MPa and 2.9MPa, respectively. The experimental data of all the PTRs with different charge pressure show a common tendency. The optimum regenerator and pulse tube are both the No.3. The PTR with No.3 regenerator and No.3 pulse tube achieved the lowest temperature of 91.6K under the charge pressure of 2.9MPa. From the experiments we found that PTRs with the regenerator No.3 and No.4 have similar performance. The performance differences among the PTRs with the pulse tube No.2, 3 and 4 are very slight. For the compressor with swept volume of 1.66cm^3, it is reasonable to conclude that the optimum dimensionless void regenerator volume and dimensionless pulse tube volume are within the range of 1.0-1.2 and 0.7-1.0, respectively. The range of optimum regenerator and pulse tube volume from the experimental data is a little narrower than that from the simulations.

Performance of the PTR is a trade off between the theoretical refrigeration and various losses in the refrigerator. The theoretical refrigeration of the PTR is mainly determined by the amplitude of the gas mass flow and the oscillating pressure and the phase angle between them at the cold end of the pulse tube. The losses are mainly caused by the regenerator's inefficiency and the pressure drop across it.

It can be reasonably assumed that the phase angle between pressure and mass flow rate at the cold end of all the PTRs in our experiments are nearly the same, because the geometry differences between all the PTRs are not large enough to cause a obvious change in phase shift, and the orifice and bypass can be adjusted. For PTRs with smaller regenerators, the amplitudes of mass flow rate and the pressure oscillation are larger, which make the theoretical refrigeration larger, but the loss due to the regenerator inefficiency suppresses the increase on cooling power, thus the net refrigeration is smaller. With the void regenerator volume increasing, the amplitudes of the mass flow rate and the pressure oscillation decrease, which means that the theoretical refrigeration decreases. At the same time, the loss due to the regenerator inefficiency decreases, and the net refrigeration may increase until the theoretical refrigeration decreases too much. So there exists regenerator volume range for optimum PTR performance. As for the PTRs with different pulse tube volume, a similar conclusion can be obtained. It seems that the performance of PTRs is less sensitive to the effects of pulse tube volume.

CONCLUSION

Numerical simulations and experiments have been performed to investigate the effect of the regenerator and the pulse tube volume on the performance of high frequency miniature pulse tube refrigerators. The ratios of the volume of the pulse tube and the void volume of the regenerator to the compressor's swept volume are considered as the key parameters for a high frequency miniature PTR design. For the compressor's swept volume of 1.66cm^3, operating frequency of 50Hz and the regenerator matrix of 400-mesh, the simulations show that the optimum ratios of the volume of the pulse tube and the void volume of the regenerator to the compressor's swept volume are in the range of 0.6-1.0 and 1.0-1.3, respectively. The experimental results indicate a narrower optimum range which is 0.7-1.0 and 1.0-1.2 respectively, the experimental results agree with the simulations qualitatively.

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