Experimental analysis of the oscillating flow characteristics for high frequency regenerators

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In this paper, effects of different operating conditions on amplitudes of the dynamic pressure and mass flow rate and phase shift between them at the cold-end of the regenerator under high frequency oscillating flow are studied in details. The instantaneous velocity at the outlet-end of the regenerator is obtained by using a hot wire anemometer. The results show that there are optimal values for orifice settings, operating frequencies, mean pressures, and pressure ratios to improve the refrigeration performance of high frequency pulse tube refrigerators. The reasons of the optimal value existed are discussed.

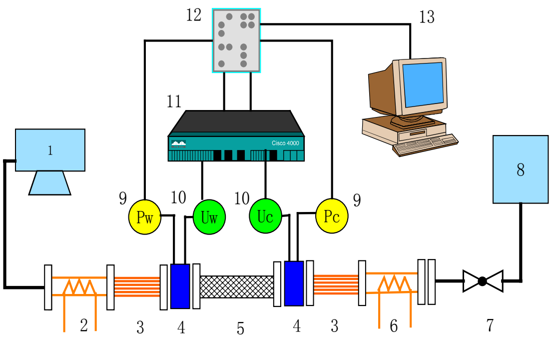
INTRODUCTION

For optimization of the regenerative machines, it is important to predict accurately friction and heat transfer losses of regenerators. Recently, some experimental investigations [1,2,3,4] on flow characteristics of regenerators under reciprocating flow have been made, in which have shown that flow friction factors of regenerators under the oscillating flow are larger than those of under steady flow. These results are useful for the understanding of the mechanisms and the prediction of performance and design of cryogenic regenerators.

In this paper, pressure and velocity performance of the regenerator under oscillating flow are measured in a carefully designed apparatus to simulate actual operation of cryocoolers. The effects of operating frequencies, orifice settings, mean pressures and pressure ratios at the warm-end of regenerators on the amplitude and phase difference of dynamic pressures and velocities are discussed. It is very useful to understand operating mechanisms in a pulse tube refrigerator.

EXPERIMENTAL APPARATUS AND METHODS

Figure 1 shows the schematic diagram of the experimental apparatus in which the dynamic velocities and pressures at both sides of the regenerator are measured. Details of experimental arrangement and measurement approaches can be found in the authors' other research papers [2, 5].



1. compressor;2. cooler;3. velocity straightener;4. connector;
5. regenerator;6. heater;7. orifice valve;8. reservoir;
9. pressure transducer;10. hot-wire probe;
11. hot-wire anemometer;12. A/D coversion board;13. computer

Figure 1 Schematic diagram of experimental apparatus

RESULTS AND DISCUSSIONS

Properties of tested stainless steel regenerators are summarized in Table 1. The wire diameter and pitch are measured using a profile projector. The porosity and hydraulic diameter are determined from the equations in the reference [2].

Table 1 Properties of the tested regenerators

Length (mm)	**Diameter (mm)**	**Number of packed screens**	**Mesh No.**	**Wire diameter (mm)**	**Pitch (mm)**	**Porosity**	**Hydraulic Diameter (mm)**
104	7.9	1380	400	0.03	0.0635	0.63	0.051
74	11	852	400	0.03	0.0635	0.63	0.051

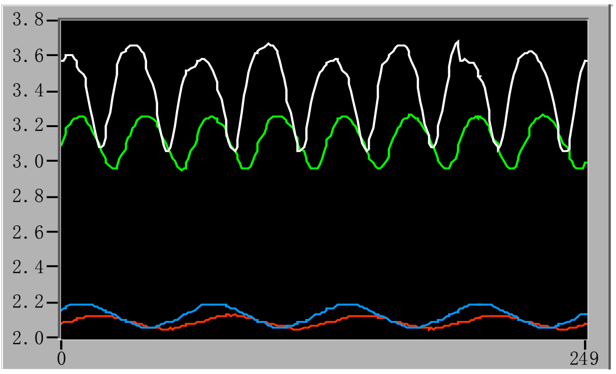


Figure 2 Typical prototype of velocity and pressure wave

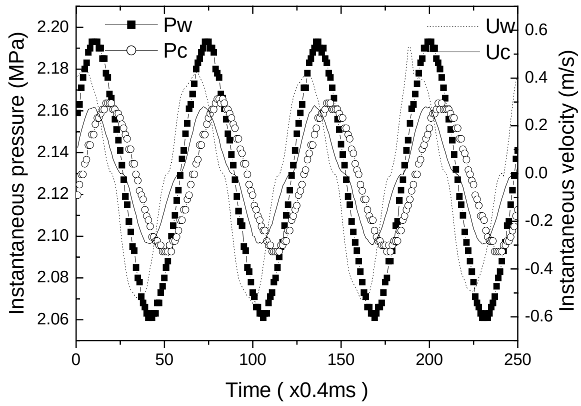


Figure 3 Processed experimental data

The typical raw experimental data of oscillating flow is shown in Figure 2. The raw experimental data measured from the hot wire anemometer and the pressure transducers require data processing which include velocity transformation and correction. Figure 3 shows the real pressure and velocity wave at the inlet (U_w, P_w) and the outlet (U_c, P_c) of the test regenerator. Pressure and velocity for high frequency clearly show phase shift and amplitude attenuation.

According to Redebaugh [6], an enthalpy flow in a pulse tube can be expressed as:

$$(H)=\left\langle P_d\dot{V}\right\rangle=(1/2)P_1\dot{V}_1\cos\theta=(1/2)RT_0\dot{m}_1(P_1/P_0)\cos\theta \tag{1}$$

where P_1 is the amplitude of pressure variation, P_0 is the mean pressure, $\dot{m}_1$ is the amplitude of the sinusoidal mass flow rate, θ is the phase angle between the pressure and the flow. It can be seen from this equation that, P_1 , $\dot{m}_1$, θ are three crucial parameters to improve the refrigeration performance of a pulse tube refrigerator. In this paper, effects of the orifice settings, the mean pressure, the operating frequency and the pressure ratio at the warm-end of the regenerator on three parameters above at the cold-end of the regenerator are studied in details. The experimental results are presented as follows.

<u>Effect of orifice settings</u>

Figure 4 shows the effects of the orifice settings on the phase angle ($\Delta\theta_{mc,Pc}$) and amplitude of dynamic pressure (Pc_{max})and mass flow rate (mc_{max}) at the cold-end of the regenerator. The measurements are made at mean pressure of 2.0 MPa, with the operating frequency of 30 Hz. The orifice opening setting is from the closed position (0) to the 60 grids that it is fully opened. it is clearly found that the phase angle $\Delta\theta_{mc,Pc}$ and the pressure amplitude (Pc_{max}) at the outlet end of the regenerator decreases rapidly, while the amplitude of the mass flow rate (mc_{max}) increases greatly with the opening value of the orifice valve increasing. The optimum position of the orifice is determined from integrating the three factors. This shows that the opening value of the orifice valve is crucially important to the refrigeration performance of a pulse tube refrigerator.

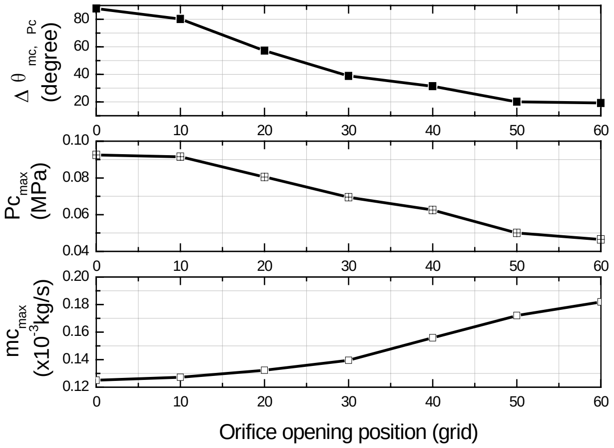


Figure 4 Effect of the orifice setting

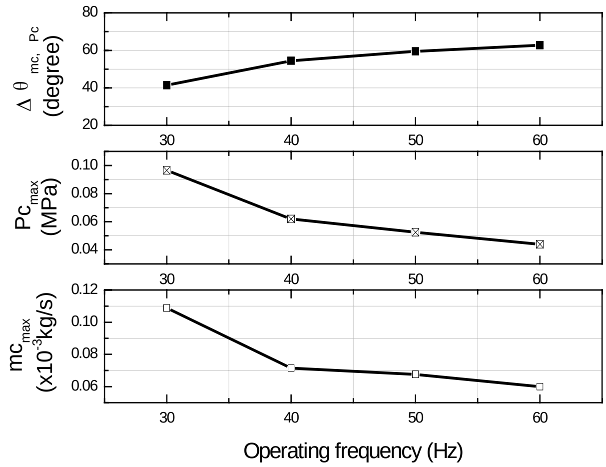


Figure 5 Effect of the operating frequency

Effect of operating frequencies

The experimental data are carefully chosen to be sure that only the frequency is varying and that other parameters are kept constant. The effects of difference operating frequencies on the flow characteristics at the outlet-end of the regenerator are shown in Figure 5. The phase shift $\Delta\theta_{mc,\ Pc}$ goes up, while the amplitude of mass flow rate (mc_{max}) and pressure (Pc_{max}) at the outlet-end of the regenerator goes down when operating frequency varied from 30 Hz to 60 Hz in our experimental conditions. The results show that the theoretical refrigerator power is inverse proportional to the operating frequency under high frequency conditions in a pulse tube refrigerator. However, there is also a limit imposed by the optimum frequency of the compressor. The efficiency of the compressor is advantageous under its optimum frequency. So the optimum frequency in practice is determined from the two factors as mentioned above. Each of them should be considered carefully in our design and experimental work.

Effect of mean pressures

The objective of the third experiment is to verify the dependency of refrigeration performance on mean pressures. The frequency is kept constant at 30 Hz, and the orifice value is set at 20 grids. The measurements are made at mean pressures of 1.0, 1.5, 2.0, 2.5, 3.0 MPa. To show more clearly the effect of mean pressures, the variation of the pressure ratio (Pc_{max}/P_0) of the Pc_{max} to the mean pressure is plotted in Figure 6. we can see from the figure that mc_{max}, Pc_{max}/P_0 increases rapidly, and $\Delta\theta_{mc,\ Pc}$ is reduced with the mean pressure varied from 1.0-2.0 MPa, as a result, the refrigeration capacity is improved. Though $\Delta\theta_{mc,\ Pc}$ is decreased, the pressure ratio is also lessoned rapidly, and mc_{max} has little change when the mean pressure is from 2.0 MPa to 3.0 MPa, So we can predict there is an optimum mean pressure in a pulse tube refrigerator.

Effect of pressure ratios

Figure 7 illustrates the influences of the pressure ratio at the inlet-end of the regenerator on the outlet parameters of the cold end with the frequency of 30 Hz, the mean pressure of 2.0 MPa. The different pressure ratios are achieved by adjusting input electric power of the compressor. mc_{max}, Pc_{max}, $\Delta\theta_{mc,\ P2}$ have a steep increase when the pressure ratio increased. The results show that the refrigerator capability is enhanced rapidly with the elevation of the pressure ratio. On the other hand, the increase of the mass flow rate with the pressure ratio becoming high leads to large regenerator losses. So an optimum pressure ratio is required to improve refrigeration performance in pulse tube refrigerators.

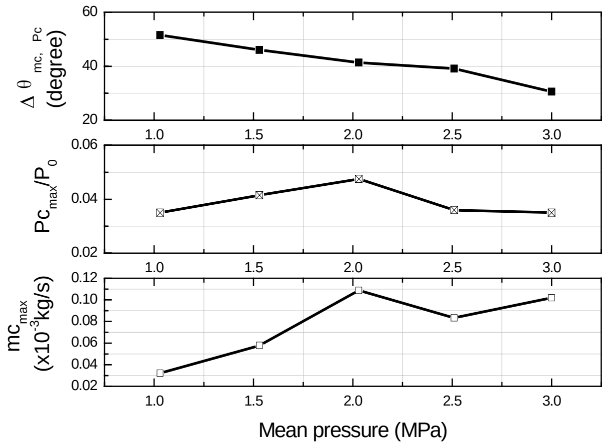


Figure 6　Effect of the mean pressure

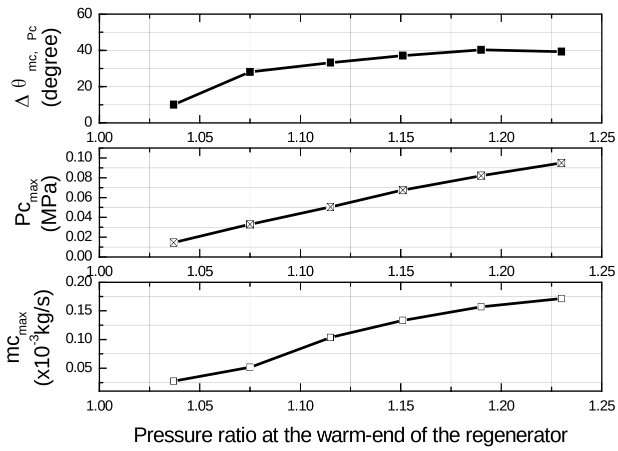


Figure 7　Effect of the pressure ratio

CONCLUSIONS

Detailed experimental data on the oscillating flow characteristics of high frequency regenerators in a pulse tube cryocooler are presented in this paper. The influences of factors, including the orifice setting, operating frequency, system mean pressure, and the pressure ratio at the warm-end of the regenerator on the flow characteristics of the regenerator are achieved. For a given pulse tube refrigerator under high frequency conditions, the orifice position, operating frequencies, the mean pressure, and the pressure ratio have an optimal value existed, and the existent reasons are presented. The results avail the desirable design and experimental studies of pulse tube refrigerators.

ACKNOWLEDGEMENTS

The National Natural Science Foundation of China funds this work. (Grant No. 50206025)

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