Investigation on A Thermoacoustically Driven Pulse Tube Cooler Working at 82.5 K

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It is an efficient way to increase the performance of the thermoacoustic refrigeration system by improving the frequency matching between thermoacoustic engines and pulse tube coolers (PTCs). Investigation on the performance of the refrigeration system under different operating frequency was carried out by changing the length of the resonance straight tube of a thermoacoustic Stirling engine. With working pressure and heating power of 2.8 MPa and 2500 W respectively, the single stage double-inlet PTC reaches the refrigeration temperature of 82.5K at 45 Hz.

INTRODUCTION

A thermoacoustic engine converts thermal energy into acoustic power, which can be used to drive a pulse tube cooler (PTC) or other kinds of thermoacoustic refrigerator. Research and development of thermoacoustic field is booming in recent years. Thermoacoustic heat engine develops from the standing wave to the traveling wave mode, and its efficiency has increased substantially. To commercialize thermoacoustic heat engines, their output powers need to be increased as well as the efficiencies, which is of importance for large scale applications. Recently, some researchers proposed cascade thermoacoustic heat engine [1], two-end driving traveling wave thermoacoustic heat engine [2] to increase the output power. Concerning thermoacoustic refrigeration, orifice PTC, coaxial single-stage PTC, thermoacosutic refrigerator directly coupled into the torus of a thermoacoustic Stirling engine, and acoustic recovery PTC were developed one after the other. Up to now, there are two main development directions for thermoacoutic refrigeration. One aims to obtain lower refrigeration temperature below 120K, in which common PTCs, such as orifice and double-inlet PTCs, are adopted as refrigeration unit. The other is to obtain large refrigerating capacity above 120K, in which orifice and traveling-wave PTCs are adopted. This is promising for natural gas liquefaction and even for daily life refrigeration.

This paper follows up our former study [3-4], and focuses on the frequency matching between a thermoacoustic heat engine and a single stage double-inlet PTC. The operating frequency was adjusted by lengthening the resonance tube of the thermoacoutic engine. Experimental results show that the operating frequency can greatly influence the performance of the PTC. With working pressure and heating power of 2.8 MPa and 2500 W, respectively, the PTC obtained the minimum refrigeration temperature of 82.5K, which is a new record for the PTC driven by a thermoacoustic engine.

THEORETICAL ANALYSIS

In the thermoacoustic engine there is plane wave acoustic field, where the energy of gas micelle consists of two parts: one is kinetic energy due to motion of gas micelle, the other is potential energy associated with compression and expansion of gas micelle. And the total energy of acoustic field is thus the sum of these two kinds of energy of all gas micelles in acoustic field. The total acoustic energy can be qualitatively written as:

$$E = \eta Q \propto \bar{p}_a^{\,2} \times L \times S$$

Where, η is thermoacoustic conversion efficiency, Q is net heating power, and $\bar{p}_a$ denotes average pressure amplitude in the whole sound wave duct. L and S are the total length and cross-sectional area of the sound propagation pipe, respectively. L influences the performance of thermoacoustic engine in two aspects. One is to determine the operating frequency of the thermoacoustic engine. The other is to change the volume of acoustic field. So there is a tradeoff between the pressure oscillation intensity and the operating frequency by varying L.

EXPERIMENTAL CONFIGURATION

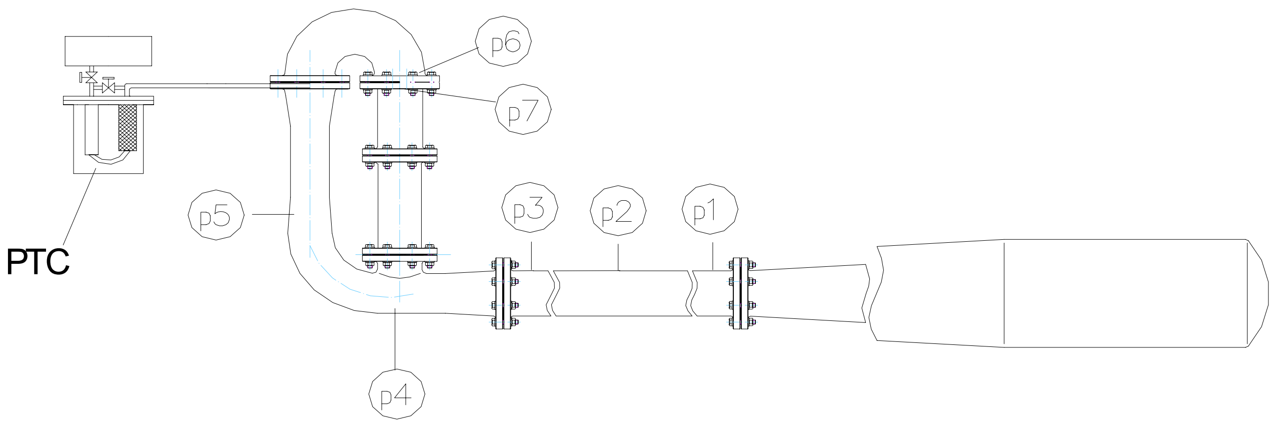

Figure1. Schematic of the thermoacoustically driven PTC system

The experimental apparatus includes a thermoacoustic Stirling engine, a single-stage double-inlet pulse tube cooler, vacuum system, and measurement system. Fig.1 shows the thermoacoustically driven PTC system and the pressure measurement locations. The configuration of each part of the system was introduced in details in reference [3-4].

EXPERIMENTAL RESULTS

Effect of total resonance tube length on working frequency

According to boundary conditions of acoustic field and analysis of pressure amplitude along the length of the engine, the pressure amplitude in acoustic field distributes along the direction shown in Fig.2 as 1/4 standing wave. The total length of the resonance tubes is a sum of the resonance straight tube and tapered tube. The start point (pressure antinode) of the 1/4 standing wave distribution of pressure amplitude is at P7, and terminal point is between P1 and P2, about 100 mm from the entrance of the tapered tube (see Fig.1).We regulated the frequency of the heat engine by lengthening the resonance straight tube. To predict the matching between the PTC and thermoacoustic engine, we calculate the working frequency of the heat engine with different resonance tube lengths as shown in Fig.3. The tendency of predicted frequencies is in good agreement with experimental results.

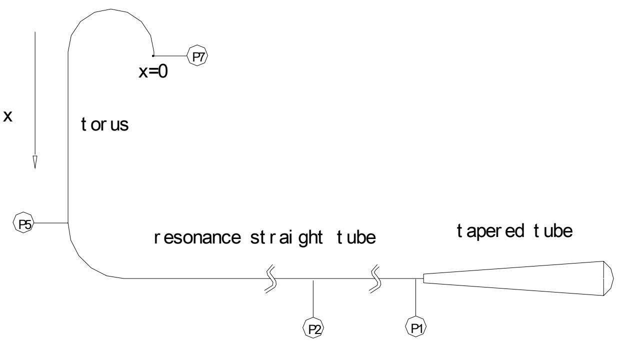

Figure 2 Distribution of pressure amplitude along the heat engine

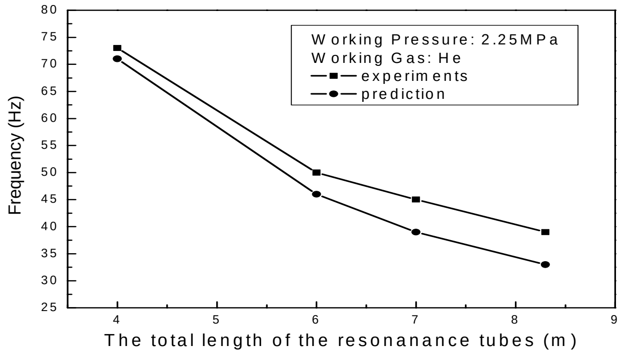

Figure 3 comparison between the predicted and experiments frequency of the engine

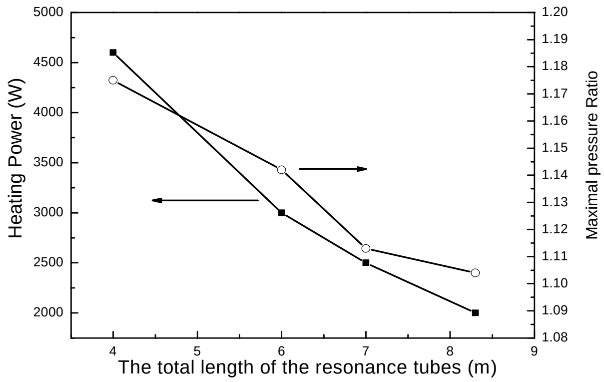

Figure 4 Effect of total resonance tube lengths on heating power, maximal pressure ratio

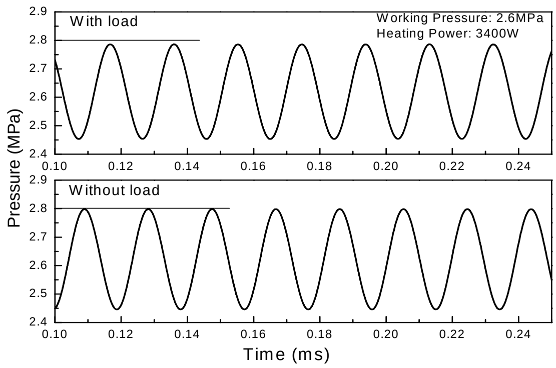

Figure 5 Variations of pressure wave with and without PTC connected (the resonance tubes length, 6 m)

Heating power and maximum pressure ratio

Fig. 4 shows the effect of resonance tube length on the heating power and maximal pressure ratio. The maximum heating temperature is fixed at 675±5℃. With the length of the resonance straight tube increasing, the heating power absorbed by the thermoacoustic engine decreases, theoretically so does the acoustic power. Consequently, the pressure amplitude declines to some extent. It is consistent with our former theoretical prediction. Therefore, there is a coupling problem among the net heat absorbed, pressure oscillation intensity and operating frequency.

Variations of pressure wave with and without PTC connected

In order to study the effect of the load (PTC) on the thermoacoustic engine, pressure wave with and without load was acquired and analyzed under the same heating power. During the experiment, when the PTC came to a stable state, i.e. when the refrigeration temperature of PTC and the pressure oscillation of the engine were stable, we closed the connection between the engine and the pulse tube cooler. Fig. 5 shows variations of pressure wave with and without PTC at the joint point. We can find that with the PTC connected the pressure ratio falls about 7%. The operating frequencies with and without PTC connected are the same, which means that there is no effect of the PTC on the operating frequency.

Cool-down of pulse tube cooler

Fig. 6 shows the cool-down process of PTC driven by the thermoacoutic Stirling engine with total resonance tube length of 4 m. The refrigeration process of PTC starts once the engine onsets. After about 3 hours, the refrigeration temperature reaches 120 K, and finally reaches a steady state at 110.5 K. The heating power is increased gradually from 3000 to 4900 W. The operating frequency of thermoacoustic engine is 72.5 Hz. Obviously, the operating frequency is too high to get lower temperature although the pressure ratio is big enough. As a tradeoff between the operating frequency and the pressure ratio (see Fig. 4), we selected the engine with the resonance tubes of 7 m to drive the same PTC. Fig.7 shows the cool-down process. The ambient temperature is 12 ^{o}C higher than that of Fig. 6. With heating power and working pressure of 2500 W and 2.8 MPa, respectively, the refrigeration temperature reaches a stable state at 83 K after 2 hours. By further valve setting optimization, the lowest refrigeration temperature obtained is 82.5 K, which is the new record of PTC driven by a thermoacoutic engine. It indicates proper frequency matching between the engine and the PTC greatly benefits the refrigeration temperature of the PTC.

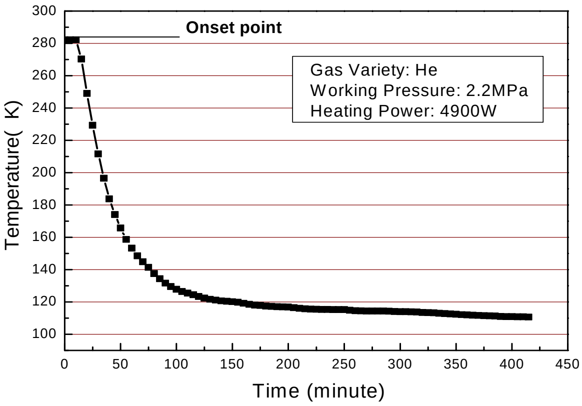

Figure 6 Cool-down process with resonance tubes of 4 m

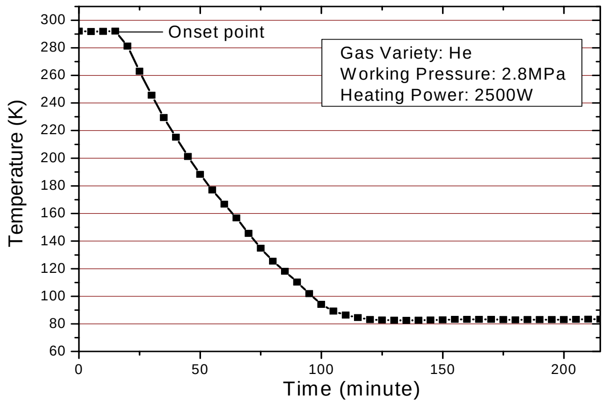

Figure 7 Cool-down process with resonance tubes of 7 m

CONCLUSIONS

The frequency matching between thermoacoustic engine and pulse tube cooler is of greatest importance to obtain better cooling performance for a pulse tube cooler. It is efficient to adjust the operating frequency by changing the length of the resonance straight tube. A pulse tube cooler driven by a thermoacoustic Stirling engine with the resonance tubes of 7 m obtains a minimum temperature of 82.5 K at 45 Hz.

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REFERENCE

1. Gardner. D. L. and Swift. G. W., A cascade thermoacoustic engine, J. Acoust. Soc. Am.(2003) Vol. 114 1905-1919
2. L.M Qiu, D.M Sun, et al, Tow-end driving traveling wave thermoacoustic heat engine, China patent, Application number: 200420020570.9
3. L.M Qiu, D.M Sun, W Zhang, et al, Experimental study of a large-scale multifunction thermoacoustic engine, Cryogenics and Refrigeration-Proceedings of ICCR'2003 157-160
4. D.M Sun, L.M Qiu, W Zhang, et al, Investigation on A Traveling-wave Thermoacoustic Heat Engine with High Pressure Amplitude, Accepted by Energy conversion and management (2004-2)