Experimental study of an acoustic resonant cooling system

Tong Huan\textsuperscript{a,b}, Hu Jianying\textsuperscript{a}, Zhang Limin\textsuperscript{a}, Luo Ercang\textsuperscript{a,*}

\textsuperscript{a} Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Science, Beijing 100190, China
\textsuperscript{b} University of Chinese Academy of Science, Beijing 100049, China

Abstract

Using a thermo-acoustic engine to drive a pulse tube cryocooler achieves the goal of having a cooling system without any moving parts. Moreover, to generate larger cooling capacity, a multi-stage acoustically resonant cooling system is presented. A three stage experimental prototype is built. In experiments with charge pressure of 3.5 MPa and heating temperature of 923 K, the cold fingers reach a minimum temperature of 76 K, and obtain a total cooling capacity of 100 W at a liquefied natural gas temperature of 130 K; the overall relative Carnot heat driven efficiency reached 3.5%. In different working conditions, system performance improves as charging pressure and heating temperature rise. Preliminary experimental results suggest that this is a great breakthrough in heat-driven cooling systems. As the matching mechanism is further improved and dimensions and stages further enlarged, this acoustically resonant cooling system will produce greater cooling capacity and much higher efficiency.

Keywords: thermo-acoustic engine; pulse tube cryocooler; acoustically resonant; closed loop; multi-stage.

1. Introduction

For reliability and long service life, as well as potentially high efficiency, the traveling-wave thermo-acoustic engine (TE) and pulse tube cryocooler (PTC) have drawn extensive interest. Using a TE to drive a PTC would produce a device with no moving parts. In 1979, Ceperley was first in proposing the concept of traveling-wave TE [Ceperley P. H. (1979)]. However, because of a limited understanding of the mechanism underlying the thermo-
acoustic conversion and the lack of effective means to decrease the resistance loss in the regenerator, no workable TE had been invented. In 1998, Yazaki and Iwata proposed a looped traveling-wave TE [Yazaki T. et al. (1998)], but incurred great energy losses at the stack because of viscous resistance and rapid rate of gas flow. No feasible solution was presented. Later on, Backhaus and Swift invented a thermo-acoustic Stirling engine [S. Backhaus et al. (1999)] that incorporated a feedback-inertance structure and closed resonator, which, although making a great improvement in performance, dissipated a lot of acoustic energy because much of the acoustic field in the resonator remained mainly as standing waves. In 2010, de Blok developed a 4-stage traveling TE [De Block K (2010)], which increased the cross-section ratio between regenerators and resonant tubes so as to solve the problems of viscous loss by effectively lowering the gas flow rate. Nevertheless, the system still did not function well because the thermal buffer tube and the membrane used to restrain the DC flow were not included in his system. In 2012, Luo Ercang from China proposed a double-acting process assembling TEs and double-acting linear motors to form a loop [Hu Jianying et al. (2013)] that recycled the acoustic energy as the piston expanded and increased the efficiency considerably. Nevertheless, importing double-acting linear motors increased problems with consistency significantly and there remains no good way of avoiding these problems.

Based on this background, we present a traveling wave acoustically resonant system that not only solves the problems of viscous loss in the regenerator, but also eliminates the DC flow that is inevitable in a loop structure. Moreover, it avoids the troublesome inconsistency caused by the double-acting linear motors.

2. Experimental system

A three-stage resonant cooling system is described (Fig. 1) consisting of three traveling-wave thermo-acoustic heat engines forming a loop connected by resonant tubes, each of which drives a PTC. The TE, resonant tube, and PTC constitute a single unit (Fig. 2). The TE is formed from a primary water cooler, a regenerator, a hot end, a thermal buffer tube, and a secondary water cooler whereas the PTC is composed of a primary water cooler, a regenerator, a cold tip, a pulse tube, a secondary water cooler, an inertance tube, and a reservoir. The acoustic field inside the heat engine is adjusted by the resonance tube and that inside the PTC is regulated by the inertance tube and reservoir. The optimized dimensions of the system are listed in Table 1.

The operating principle of the system is as follows: as the temperature of the TE’s hot end rises when heated by heating rods, a temperature gradient is established at both ends of the regenerator and thermo-acoustic conversion occurs. Part of the acoustic energy generated in the regenerator is transferred to the PTCs, and the rest is recycled in the next unit through resonant tubes. Instead of complete dissipation, recycling promotes greater efficiency compared with traditional traveling-wave TEs while using all acoustic energy in the resonant tubes.

During the experiment, the temperature of the TE’s hot end is measured by a calibrated thermocouple thermometer whereas the cold tip is measured by a calibrated platinum resistance thermometer. Constantan wire heated by direct current is entwined around the cold tip to simulate thermal load. The PCB pressure sensors are equipped at the entrance of each PTC to measure the pressure fluctuation and one of the TEs is fitted with a Kunlun pressure sensor measuring the mean pressure. Circulating cooling water of 293 K is used to cool down the primary
Table 1. The optimized dimensions of the system.

<table>
<thead>
<tr>
<th>Components</th>
<th>Thermo-acoustic engine</th>
<th>Pulse tube cryocooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerator</td>
<td>Ф50 mm × L75 mm, 300 mesh stainless screen</td>
<td>Ф50 mm × L65 mm, 300 mesh stainless screen</td>
</tr>
<tr>
<td>Thermal buffer tube</td>
<td>Ф50 mm × L75 mm</td>
<td>Ф32 mm × L105 mm</td>
</tr>
<tr>
<td>Resonant tube</td>
<td>Ф13 mm × L3 m</td>
<td>--</td>
</tr>
<tr>
<td>Inertance tube</td>
<td>--</td>
<td>Ф3.5 mm × L2.3 m</td>
</tr>
<tr>
<td>Air reservoir</td>
<td>--</td>
<td>1L</td>
</tr>
</tbody>
</table>

and secondary water coolers.

Because of discrepancies in processing technical and fabricating methods, there inevitably exists some differences among the three units in the system; hence, the three TEs and three PTCs are tested separately before the loop-system experiment. Testing the TEs involves attaching a linear compressor and a linear expansion motor at both ends. The temperature of the hot end is fixed at 650°C and the acoustic power flowing into the engines is stabilized and the acoustic energy generated is measured when the external electrical resistance of the expansion motor changes. Testing of the PTCs involves using a linear compressor to drive them and measuring the cooling capacity at 77 K while stabilizing the input acoustic power. The results are shown in Figs. 3 and 4, from which we can see non-uniformity in the three engines but slight (<10%) differences in the PTCs.

3. Experimental results

A DC flow that greatly influences the pressure ratio and heat exchange is unavoidable when all three units are enclosed in a loop. The system without load is tested first with a charging pressure of 4 MPa to verify the impact of this mass flow. Figs. 5 and 6 depict the variation in the pressure ratio at the entrance of TE #1 and the hot-end temperature before and after a membrane is added. This demonstrates that both the pressure ratio and the hot-end temperature increase rapidly after eliminating the DC flow with the added membrane. Moreover, with smaller dimensions, this system can obtain a comparatively high pressure ratio in contrast to the traditional traveling-wave TE. This illustrates the enormous potential of the acoustic resonance loop system.

Afterwards, we conducted an experiment with the same looped acoustic resonant system driving a single PTC, connected only at the exit of TE #2 and an initial charging pressure of 3 MPa. The system starts to vibrate at a temperature of 105 °C and a working frequency of 64.4 Hz, which would rise slightly when the temperature of the TE’s hot end increases and that of the PTC’s cold tip decreases. The temperature curves of the TE’s hot end and PTC’s cold tip (Fig. 7) show that the temperature of the TE under load from the PTC increases much slower than for the other two engines. This is because much more acoustic power is dissipated with a load whereas the acoustic power produced by the other two engines is just dissipated through the resonant tubes. Using the voltage regulator,
the temperature of the hot end of the three TEs is maintained at 650 °C when the cold tip reaches the lowest temperature and measurements of cooling capacity are taken. The lowest temperature the PTC achieves is 64.3 K, thus yielding a cooling capacity of 52.3 W at 130 K.

The pressure fluctuation ranges at the exits of the three TEs when the cold-end temperature is at 130 K are shown in Fig. 8. The fluctuation range of engine #2 under load from the PTC is the smallest. Because of differences in loads, these pressure fluctuation ranges vary considerably. Nevertheless, because of the loop structure, the phase difference between each unit generally matches 120 °.

In the next experiment, the looped acoustic resonant system drove three PTCs, each connected to the exit of one of three TEs. As before, the original charging pressure is 3 MPa and the system starts to vibrate at a temperature of 140 °C with a working frequency of around 60 Hz. The temperature variation curves of the hot ends and cold tips are presented in Fig. 9. When the heating capacity of the three TEs is similar, the temperature variations among the three PTCs and engines are reliably consistent. Hence, the system attains stability even when there exist small discrepancies among the three units.

The lowest temperatures that the three PTCs can reach are 81, 84, and 83 K following their order in the loop. When the heating capacity of these three engines reaches 1620, 1630, and 1650 W, the total cooling capacity generated by the three PTCs is 82 W when the temperature is maintained at 130 K and the relative Carnot efficiency of total system is 3.32%. Fig. 10 exhibits the pressure fluctuation range at the exits of the three TEs, from which it can be found that the fluctuation is relatively consistent among the three TEs and the phase difference between two successive TEs stabilizes at 120 °.
Figs. 11 through 14 present the performance of the system under different working conditions. Figs. 11 and 12 show the obtainable lowest temperature, the cooling capacity, and relative Carnot efficiency achieved under different cold-tip temperatures with different charging pressure when the hot-end temperature is maintained at 650 °C. Similarly, Figs. 13 and 14 exhibit the obtainable lowest temperature, the cooling capacity, and Carnot efficiency achieved under different cold-end temperatures with different hot-end temperatures with charging pressure kept at 3 MPa. According to these figures, if the hot-end temperature is maintained constant, the obtainable lowest temperature decreases as charging pressure increases and the total cooling capacity would also increase.
Keeping charging pressure constant, the obtainable lowest temperature would decrease as the temperature of the TE’s hot-end increases; the cooling capacity rises as well. The relative Carnot efficiency display similar trends. Hence, by increasing the charging pressure to 3.5 MPa while maintaining the hot-end temperature at 650 °C, the best experimental result is achieved if the lowest temperature of the PTCs reached is 76 K. A cooling capacity of 100 W is obtained when the cold-end temperature is 130 K giving a total relative Carnot efficiency of 3.5%. Although there is room for further improvement in performance, a good breakthrough in the field of heat-driven cooling system has already been achieved.

4. Conclusion

Based on previous research on traveling wave thermo-acoustic engines, this paper proposed a heat-driven system, the multi-stage acoustically resonant cooling system, which has no moving parts. The feasibility of this system was demonstrated through a sequence of experiments. The three units presented good consistency despite slight discrepancies in components of the units. The loop structure self-regulates the phase difference in pressure fluctuations at 120 ° even when the system drives only one PTC.

The experimental results showed that as charging pressure and hot-end temperature are increased, a larger cooling capacity is obtained along with a higher total relative Carnot efficiency. Finally, with charging pressure set at 3.5 MPa and a hot-end temperature of 650 °C, the PTCs attain the minimum temperature of 76 K yielding a 100 W cooling capacity at 130 K with total relative Carnot efficiency of 3.5%. This represents a breakthrough for heat-driven cooling systems, and lays a solid foundation for future developments of resonant cooling systems.

While this system was initially successful, performance remains to be further improved. Increasing the ratio of cross-sectional area between the core components and resonant tube not only decreases the gas velocity in the regenerator, but also enhances the velocity in the resonant tube, thereby augmenting energy losses. Moreover, energy losses are also present in the junctions of the engines and resonant tubes and in the T-joints between the resonant tubes and PTCs. Reducing these losses to increase system efficiency is the focus in future work.

Acknowledgements

This work is supported by the Natural Sciences Foundation of China (Grant No. 51276187), Joint Funds of NSFC-Yunnan (Grant No. U1137606) and the National Basic Research Program (No. 2010CB227303).

References