Experimental investigation on a room-temperature traveling-wave thermoacoustic refrigerator

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Thermoacoustic refrigerators are considered to be an alternative for food refrigeration, air conditioner and other commercial usages. The design and the performance test of a room-temperature traveling-wave thermoacoustic refrigerator were conducted. The lowest temperature of about -28℃ and a cooling power of 108W at 0℃ were achieved with helium when driven by a standing wave thermoacoustic engine at a pressure ratio of 1.05. Gedeon streaming was detected in the experiment. The performance was highly improved by suppressing this streaming with a membrane. The measured performances agreed well with our model results.

INTRODUCTION

Thermoacoustic refrigeration is achieved through utilization of energy in acoustic wave forms. They have been considered for civil, military and other industrial applications. This technology could be alternative for conventional technologies, offering the promise of competitive performance combined with an environmentally friendly system with few or no moving parts, and no need for lubrication or sliding seals. Many efforts have been focused on this new technology and some thermoacoustic refrigerator prototypes have been built [1]. Early efforts were focused on standing-wave prototypes. Recent development of "traveling wave" shows a prospect of higher efficiencies and made this technology more viable. However, relatively fewer literatures on traveling-wave thermoacoustic refrigerators can be found.

Thermoacoustic refrigerators are usually driven by two kinds of drivers, electro-dynamic loudspeakers and thermoacoustic engines. The former type of refrigerator usually operates at high frequency and has small size [2]. The latter one needs a good thermoacoustic engine. It has an aspect to use solar energy and other heat of low level, which makes it especially valuable to where electricity is not available.

The object of this study was to develop a thermoacoustic refrigerator in room-temperature range. The investigation was involved with the design, construction, and measurement of a prototype. The operation variables such as the working gas, the frequency and the mean pressure are specially considered.

EXPERIMENTAL PROTOTYPE

The schematic of the prototype is shown in Figure 1. It is made of two subsystems, the refrigerator unit and the standing-wave thermoacoustic driver section. The driver and the refrigerator were designed separately [3]. Here only the refrigerator will be studied. The refrigerator consists of two heat exchangers, a regenerator, a thermal buffer tube (TBT), a compliance reservoir and an inertance tube. Key dimensions of the segments are listed in Table 1. The whole system was entirely constructed from stainless steel, except for the heat exchangers which were made of copper. Several access ports were made for pressure transducers and valves. The hot end of the drive is heated by electrical heaters. The cooling load is measured by four electrical heaters in the cold heat exchanger of the refrigerator.

When the actual temperature gradient of the stack goes beyond the critical temperature gradient of the stack, the driver begins to work. It absorbs heat from the hot heat exchanger, converting it to acoustic power, which is sent to the refrigerator via the resonator. The directions of the acoustic power flows are illustrated by the arrows in the Figure 1. The regenerator of the refrigerator pumps heat from the cold end, while rejecting heat to the water-cooled heat exchanger. The pressure of the inlet of the refrigerator and water-cold heat exchanger were measured. The temperature of several points along the regenerator, the cold heat exchanger and the thermal buffer tube were measured.

The refrigerator is designed according to linear thermoacoustic theory [4]. The predicted performance of the initial design is a cooling power of 80W at -20℃ and a COP of 2.86. It was designed to operate with 2.0MPa helium at a pressure ratio of 1.10, and it was designed to work under a frequency of 50Hz. In practice these working conditions were not realized yet. Thus it led to a difference between the design goals and the experiment.

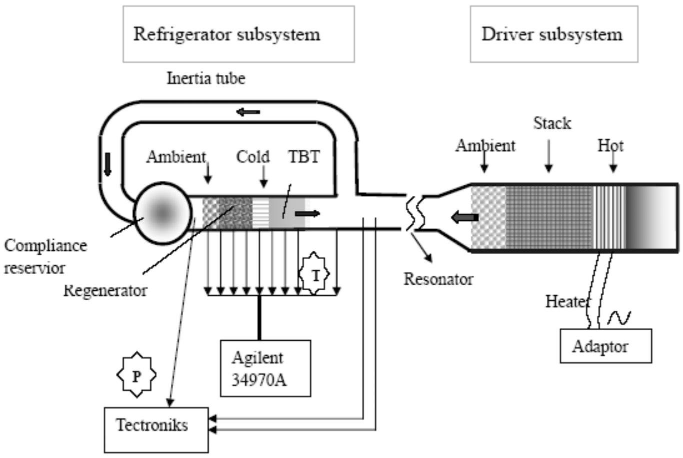

Figure 1: Experimental System

Table 1. Structure Parameters

Section	Inner diameter (mm)	Length (mm)
Regenerator	50	35
Ambient heat exchanger	50	35
Cold heat exchanger	50	30
Thermal buffer tube	50	50
Inertia tube	32	700
Compliance reservoir	0.5 Liter	

EXPERIMENT RESULTS

At the beginning of the experiment, the refrigerator did not work well. Only a small temperature drop was achieved. The cold end temperature of the refrigerator (Tc) went down slowly. In some cases, it worked quite unstably. The cold end temperature came up again after going down for a while. We considered it was caused by the Gedeon Streaming which is a common loss in traveling-wave thermoacoustic systems [5]. In fact we have reserved spaces to take action against possible losses, when the refrigerator was designed. We put a membrane in the refrigerator. Experimental results showed that this membrane worked quite well. It can prevent dc flow while transferring acoustic power. The performance of the refrigerator is greatly improved as illustrated in Figure 2. For 2.1MPa helium under the frequency of 100Hz, the no-load Tc dropped by 24℃ or more.

A series of experiments have been done to study the performance of the system. Different working gases, helium, argon, nitrogen and the mixture of them were used. The mean pressure and the frequency were also changed. Helium achieved the best performance. The most encouraging result is that it got the cooling capacity of about 108W at 0℃ which confirms the viability of this technology for house hold refrigerators. The measured heat pumping capacity (Qc) is shown as a function of the cold end temperature in Figure 3. The data are grouped according to the absolute mean pressure (P_m). The oscillating frequency was 85Hz with a 4.5m long resonator. The no-load Tc decreased and the cooling capacity increased as the mean pressure increased. There are two possible reasons for this trend. Firstly, Figure 4 showed that the drive ratio increased with Pm. This leads to higher amplitude of the pressure wave and, secondly, the property of the different sections, such as the inertance of the inertia tube, the compliance of the reservoir and the resistance of the regenerator, changed with Pm, too. They will change the phase between the pressure and the velocity of the cross sections of the refrigerator. This may also account for the difference.

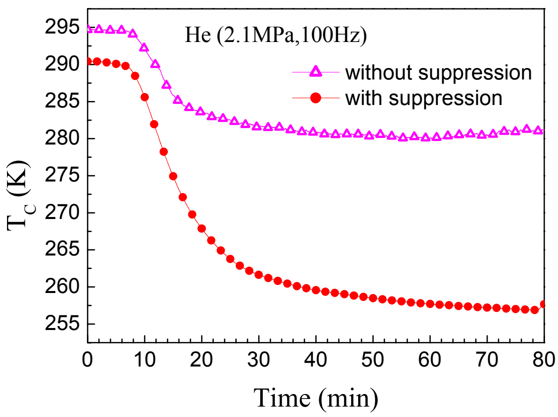

Figure 2 Comparison between with and without the suppression of Gedeon Streaming.

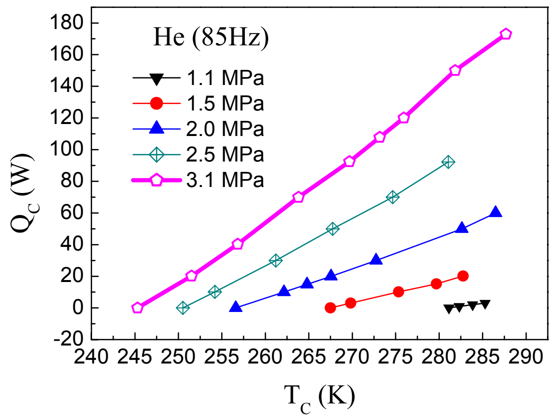

Figure 3 Cooling capacities vs. cold end temperature.

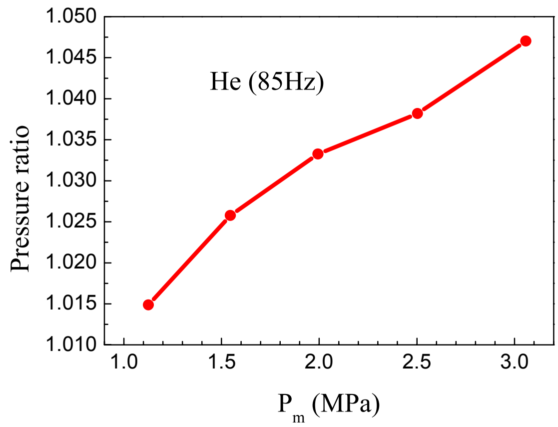

Figure 4 Pressure ratios vs. mean pressure.

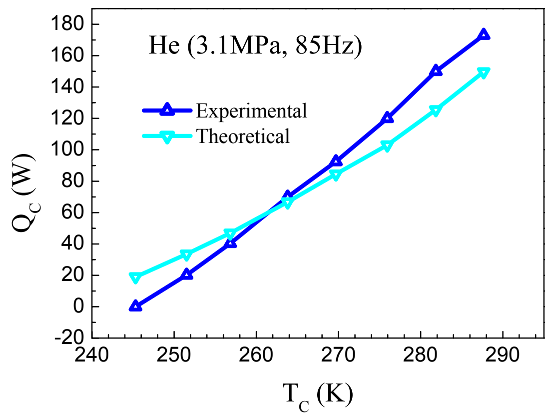

Figure 5 Comparison between the experiment results and the calculation.

To check the numeric model, we first did the experiment, measuring the temperatures and pressures of the refrigerator. Then we did the theoretical calculation. With those given parameters, the cooling power and the acoustic power needed to do it are given out by the model. Figure 5 shows a comparison of the measured and calculated Qc. We found that the experimental result is always smaller than the model result when the Tc below a certain temperature, and larger when Tc goes beyond the temperature. However, the model and the experiment agreed with each other reasonably in general. For the work condition (helium, Tc 0℃, P_m 3.1MPa, pressure ratio 1.05, frequency 85Hz, measured Qc 108W), the calculated Qc is 95.9W and the calculated consumed acoustic power is 46.7W. If the calculation is good enough, then we have the approximate COP of the refrigerator 2.06 (95.9/46.7) at this working condition. In the future we will measure the real work flow to get more precise COP.

CONCLUSIONS

A traveling-wave thermoacoustic refrigerator is designed and tested. Gedeon streaming exists in the traveling-wave thermoacoustic refrigerator and it deteriorated the performance of the refrigerator. Suppression of this streaming greatly improved the performance of the refrigerator. The refrigerator has achieved the no-load Tc of -28℃ and the cooling power of 108W at 0℃, driven by a standing-wave thermoacoustic engine, with helium at a pressure ratio of 1.05. The design target is not achieved due to the operation frequency and the amplitude of the pressure. But the measured performances agreed reasonably with our model results. Further work will be done to measure the acoustic power in the system directly, to study the pressure and velocity field, and to obtain a better driver.

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