Thermoacoustically driven pulse tube refrigeration below 90K

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As a part of our consecutive research efforts on thermoacoustically driven pulse tube refrigeration, recent modification has been made to improve its refrigeration performance, and a refrigeration temperature as low as 88.6K, with helium filling of 2.1MPa as the working fluids, was achieved. The onset temperature was reduced about 200 (from 550 to 340) by the simple operation of the double inlet valve which would broaden the utilization of low-grade heat energy.

INTRODUCTION

Swift and Radebaugh et al.(1990) invented a thermoacoustically driven pulse tube refrigerator (TADPTR), in which a thermoacoustic engine is used instead of the conventional mechanical compressor [1]. Since it has no moving component in the whole system, this new cryocooler occupies advantages. The achievement of TADPTR attracted wide interest from industry immediately. In 1994, Cryenco started a project of developing thermoacoustic natural gas liquefier, powered by heat energy through burning part of natural gas [2]. A practical thermoacoustic natural gas liquefier prototype has been built up in 1998 [3]. The prototype burns 60% of natural gas to liquefy the rest 40% gas, which is regarded as a milestone for the practical application of TADPTR. Recent development of a higher-efficiency traveling wave thermo-acoustic prime mover [4] provides a possibility of burning 30% natural gas to liquefy the rest 70%.

Our consecutive efforts have been contributed to both experimental and theoretical studies on TADPTR since 1996 [5, 6, 7]. The work reported here will focus on the matching between thermo-acoustic prime mover and pulse tube refrigerator, especially the frequency matching. Recent modification has made an important progress that a refrigeration temperature as low as 88.6K was obtained.

EXPERIMENTAL APPARATUS

The framework of our present experimental apparatus is a symmetrically heated standing wave thermoacoustic engine originally built in 1996 [5]. However, a number of modifications have been realized to improve its performance, such as stack material and its packing density, heater, water cooler and also measuring system. As a result, the output pressure ratio has risen from 1.06 to 1.128 with helium as working fluid. The experimental system includes an orifice type pulse tube refrigerator, as shown in Figure 1. The stack of the prime mover is composed of the brass matrix of 6 mesh and 10 mesh alterna-tively with the ratio of 1:2, while the matrix inside the water cooler is 30 pieces of brass matrix of 6 mesh.

The measuring system is a PC-based digital acquisition system developed with LabVIEW, consisting of temperature, pressure and refrigeration capacity measuring modules, as show in Figure 2. FFT function is also included to analyze frequency spectrum of the pressure wave, and then nonlinear character of the thermoacoustic effect at finite amplitudes.

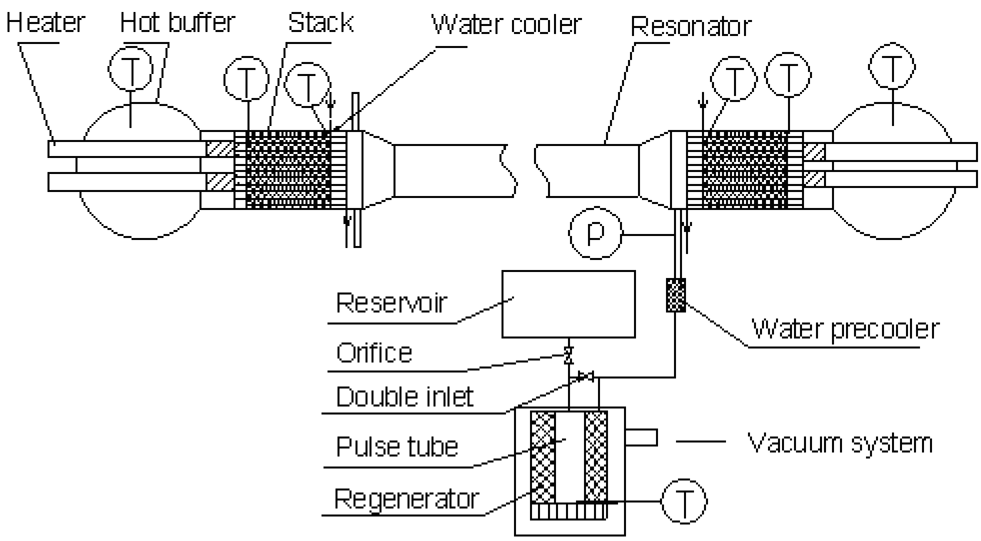

Figure 1　Outline of the thermoacoustically driven pulse tube refrigerator

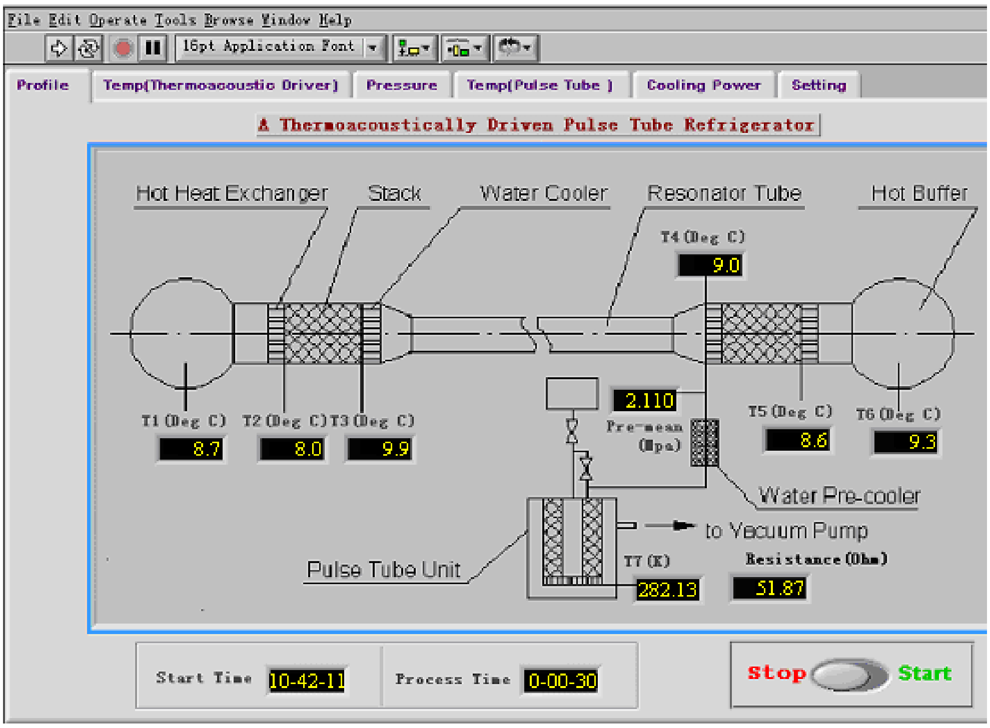

Figure 2　Interface of PC-based measuring system

EXPERIMENTS

In our previous experiments with 4m resonant tube, the operation frequency of the thermoacoustic prime mover is about 70 Hz with helium as working fluid, which brings difficulty for the matching to a pulse tube refrigerator. In order to obtain a better performance of thermoacoustically driven pulse tube refrigeration, the operation frequency was reduced via changing the length of the resonant tube.

With helium (filling pressure of 2.1MPa) as the working fluid and input heating power of 2000 Watts, the operation frequency and refrigeration temperature with different resonant tube lengths are both shown below. From Figure 3, we can see that the operation frequency falls from 70 Hz to 41 Hz, when the resonant tube was extended from 4 m to 9 m, respectively, and the refrigeration temperature drops from 112.8 K to 93.2 K (see Figure 4). Then we made further adjustment on the opening of the orifice and the

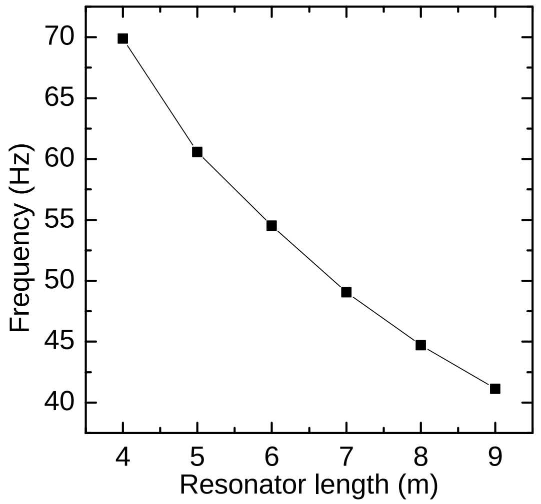

Figure 3 Operating frequency with different length

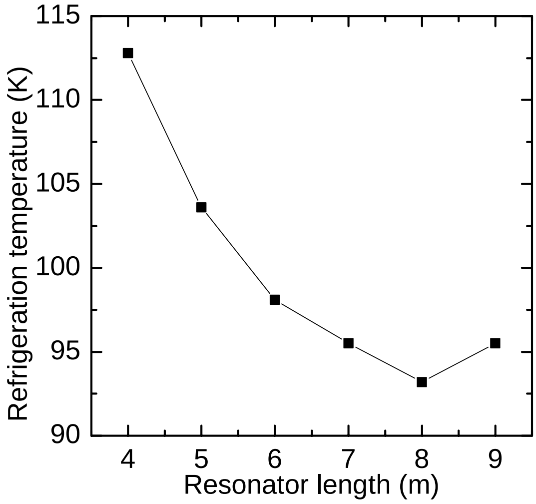

Figure 4 Refrigeration temperature with different length

double inlet, and the input power was increased from 2000W to 2200W, we obtained a lowest refrigeration temperature of 88.6K with 8 m resonant tube (see Figure 5).

Figure 5 shows the typical cooling-down curve of the pulse tube refrigerator. The cooling temperature reaches at 120K half an hour later, and we obtained a lowest refrigeration temperature of 88.6K in 2 hours. The mean operating pressure and the corresponding pressure ratio at this point are 2.64MPa and 1.128, respectively.

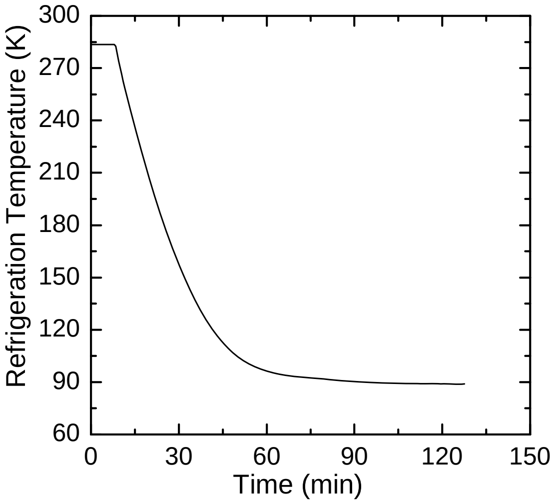

Figure 5 Typical cooling-down curve of the pulse tube

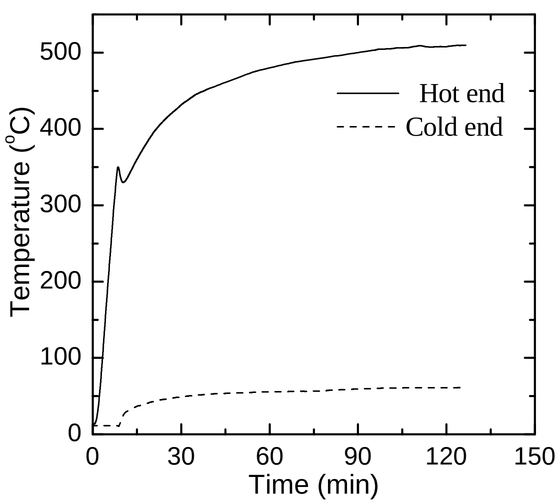

Figure 6 Temperatures vs. time at the hot end and the cold end of the stack

From Figure 6, the temperature profile at the hot end and the cold end of the stack, we can find that 8 minutes after turning on the input power, the temperature at the hot end of the stack reached 340 , and the system starts to oscillate. Meanwhile, the pulse tube refrigerator begins to work and cools down quickly. When the refrigeration temperature is stable at 88.6K, the temperature of the hot end and the cold end of the stack are 497 and 64 , respectively, and the temperature gradient of the stack is 1045.9K/m.

It is worth being mentioned that at the beginning of the experiment, the double inlet valve of the pulse tube refrigerator was closed, and then turned it to the optimal opening value right after the onset of acoustic oscillation. We benefit from this simple operation on the double inlet valve, i.e., the onset temperature of the thermoacoustic system decreases from 550 to 340 . The reduction of the onset temperature of the system benefits doubtlessly to the adoption of low grade heat source in thermoacoustic machines.

DISCUSSION

Although a refrigeration temperature as low as 88.6K has been obtained on the self-made thermoacoustically driven pulse tube refrigerator system, there are still many things to do on our system. The refrigeration power is a problem to be solved. The limitation of present heater structure makes it very difficult for us to input more heat and to reach a high heating temperature, which has been one of the bottlenecks to achieve a lower temperature and a higher refrigeration capacity. On the other hand, a new pulse tube should be designed and fabricated to match the relatively high oscillation frequency thermoacoustic prime mover to improve the overall refrigeration performance. These leave us an interesting thing to investigation in the future.

CONCLUSION

1) With helium as working fluid (filling pressure of 2.1MPa), an 8 m resonant tube results in a resonance frequency of 44 Hz (the input power is 2200 Watts), and a refrigeration temperature of 88.6K was obtained in our self-made thermoacoustically driven pulse tube refrigerator system while the mean pressure and the pressure ratio are 2.64MPa and 1.128, respectively.
2) The simple operation on the double inlet valve, which was closed before the onset of acoustic oscillation and turned to the optimal value as soon as the oscillation started, could decrease the onset temperature of the system greatly. It would broaden the access of utilizing the low-grade heat energy.

ACKNOWLEDGEMENTS

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REFERENCES

1. Radebaugh, R., McDermott K.M., Swift G.W. et al., Development of a thermoacoustically driven orifice pulse tube refrigerator, Proceedings of 4th Interagency Meeting on Cryocoolers, Plymouth, MA, David Taylor Research Center, (1990) Navy Report DTRC91/003 205-220
2. Swift, G.W., Thermoacoustic Natural Gas Liquefier, Proc. of DOE Natural Gas Conference, Houston (1997) 1-5
3. Arman B., Wollan J. J., Swift G. W., et al., Thermoacoustic natural gas liquefiers and recent developments. Cryogenics and Refrigeration-Proceedings of ICCR'2003, International Academic Publishers, (2003) 123-127
4. Backhaus S., Swift G. W., A thermoacoustic-Stirling heat engine, Nature (1999) 399 335-338
5. Jin T, Chen G B and Shen Y. A thermoacoustically driven pulse tube refrigerator capable of working below 120K, Cryogenics (2001) 41 595-601
6. Tang K., Chen G. B., Kong B., A 115K thermoacoustically driven pulse tube refrigerator with low onset temperature, Cryogenics (2004) 44 287-291
7. Chen G. B., Jin T., Experimental investigation on the onset and damping behavior in the thermoacoustic oscillation, Cryogenics (1999) 39 843-846