Experimental Investigation on Travelling-wave Thermoacoustic Heat Pump System Using in Cold Regions

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Abstract:

Compared with the electric heating device, heat pump system could save energy and recover waste heat or low grade heat. However, the traditional vapor compression heat pump encounters abrupt deteriotation in perrformance while used in the cold region.To address it, a novel TWTAHP (travelling-wave thermoacoustic heat pump) is proposed to meet the requirement of even ultra-low temperature. A TWTAHP system mainly includes three linear pressure wave generators coupled with three heat pump sections into one closed loop, which is able to realize the thermoacoustic conversion efficiently. Base on the theoretical simulation and further optimization, we have built a test rig for preliminary validation, which is only one single unit of a whole TWTAHP system. The results show that the simulations and the experimental results are in good agreement as expected. The consistency of the system performance is good enough at the designed working condition. In the appropriate frequency band, this system can obtain the no-load lowest environment working temperature at -30 ℃ easily when the heating temperature coming up to 50 ℃. In the heat pump section, no more than 50% of the acoustic power is used for providing heating capacity, and then the rest of the acoustic power can be recovered in the next stage. With the mean pressure of 5.5 MPa, the system can operate stably at the pressure ratio of 1.12. We believe that the TWTAHP is a powerful technology and has good potential in the ultra-low temperature environment, which could contribute a lot to energy saving as well as greenhouse gas emission reduction.

Keywords:

Alternating flow, Travelling-wave double-action, Thermoacoustic machine, Ultra-low temperature heat pump.

1. Introduction

Focused on higher efficiency and environmentally-friendliness, the interest in heat pump system as a means to recover and recycle energy resources has grown rapidly. With the improvement of living standards and requirements, taking China as an example, energy consumption in building has accounted for about 30% of the total social energy consumption typically, while the heating energy consumption of building in northern China has held 24.63% of the total energy consumption of building as evidenced in 2008 [1]. Therefore, how we can reduce energy consumption of heating in northern regions during the winter has become the very point we must concentrate on. The heat pump system, which has been considered as an environmentally-friendly, low-consumption and high-efficiency air conditioning system, has played an important role in this field. K.J Chua et al. [2] published a review on the development of heat pump systems, which cleared that the thermal energy recycling would become a key technology and more innovative technologies would also be a wide range of needs.

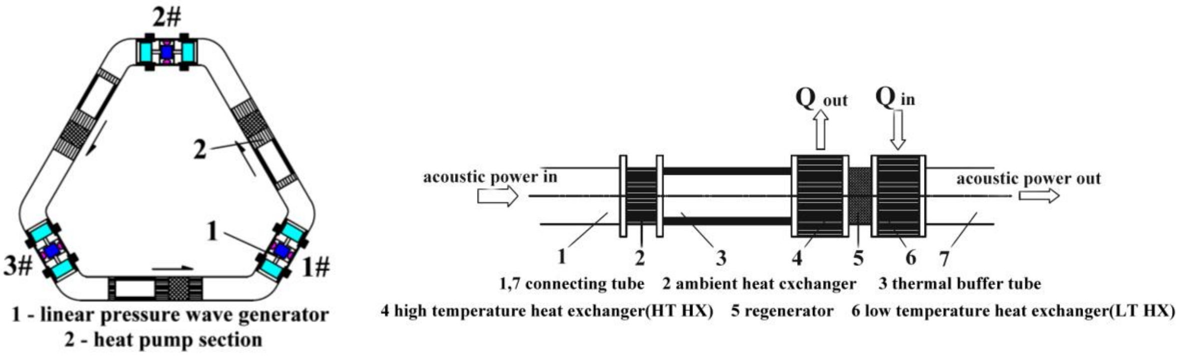
However, such systems have not been applied as widely as they should or could be. In traditional vapour compression heat pumps, system design and optimization remain challenging problems. With the rise of heating temperature or decrease of environment temperature, problems such as higher discharge temperatures, higher pressure ratios, and lower performance efficiencies would occur, which present as big obstacles. Ho-Saeng Lee et al. [3] built a water source heat pump test-bed with a mixture refrigerant of R32/R152a and compared with the R22 system at the same working conditions with -7/41 ℃ in winter. The experimental results showed that using this mixed refrigerant could reduce power consumption by 13.7% in compressor while the COP_h (Coefficient of Performance in Heat Pump) that reached above 3.0 improved by 15.8%. Based on prophase simulation and optimization calculation, Dong Ho Kim et al. [4] set up a two-stage air-water source heat pump using R134a and R410a as refrigerants. The experimental results showed that at the operating condition of ambient temperature at -7 ℃, a downward trend in COP_h could be obtained with the increased demand for hot water temperature. When the hot water temperature increased to 55 ℃, the COP_h dropped to 2.0 or below, while reducing the ambient temperature also caused the same problem. Wei Yang et al. [5] designed a direct-expansion ground source heat pump in Xiangtan, China, for comparing with the traditional ground source heat pump. At the operating condition of ambient temperature at 4.8 ℃, 13.5 ℃ and heating temperature at 50 ℃, the new system could obtain the COP_h of 4.73 on average.

Thermoacoustic refrigerator is a novel kind of cooling system, capable of converting acoustic power to cooling or heating. It can be categorized as standing-wave ones and travelling-wave ones. The travelling-wave thermoacoustic refrigerators are based on the Stirling cycle which has the Carnot efficiency in ideal. The pulse tube cryocooler system is a well known example as the thermoacoustic cooling system working in low frequency. S. Jafari et al. [6] have modelled and optimized a stirling-type pulse tube refrigerator using a genetic algorithm optimization method. The results show that the COP is more sensitive than the temperature of cold end and the frequency is the most sensitive factor in affecting the system performance. Q. Zhou, Y. Zhou et al. [7] have designed and tested a high-frequency coaxial multi-bypass pulse tube refrigerator, which can reach a no-load temperature of 13.9 K with 250 W electric input power. E. C. Luo et al. [8] have introduced an efficient pulse tube cryocooler for boil off gas reliquefaction in liquid natural gas tanks, which can produce 1.2 kW of cooling at 120 K. Therefore, thermoacoustic refrigerator has represented a good potential to face the challenges in both high-efficiency and environmentally-friendliness cooling or heat pump system development.

In this paper, a novel TWTAHP (travelling-wave thermoacoustic heat pump) system is presented to meet the requirements and solve the problems occurring in conventional vapour compression heat pump, especially in ultra-low temperature working condition.

2. Theoretical Model

The TWTAHP (see the schematic in Fig. 1(a)) is composed of three linear pressure wave generators coupled with three heat pump sections in one closed loop. Each heat pump section (see Fig. 1(b)) has an ambient heat exchanger, a thermal buffer tube, a high temperature heat exchanger (HT HX), a regenerator, a low temperature heat exchanger (LT HX), and connecting tubes. The pressure wave generator is of a dual-opposed piston design to realize the double acting function. As indicated in Fig. 1(b), by adding certain amount of the electrical power, the acoustic power will be produced and transferred using the helium as the medium in every heat pump section. Most thermoacoustic machine use plain-weave metal screens as regenerators. Taking one small parcel of gas in regenerator as an explanation, it could oscillate left and right while experiencing oscillating pressure. The phase between pressure and motion is predominantly travelling wave: The gas moves to the right while the pressure is high and moves to the left while the pressure is low, so the acoustic power flows from left to right. The gas expands while it moves to the left, because its temperature rises; it contracts while it moves to the right, because its temperature falls. When this axial temperature gradient exceeds a critical value, the acoustic power would be consumed when it passes through the regenerator from HT HX to LT HX. With this structural arrangement, when the acoustic power transfers to the next heat pump section, the phase angle of the volume flow rate and dynamic pressure decreases by 120°.



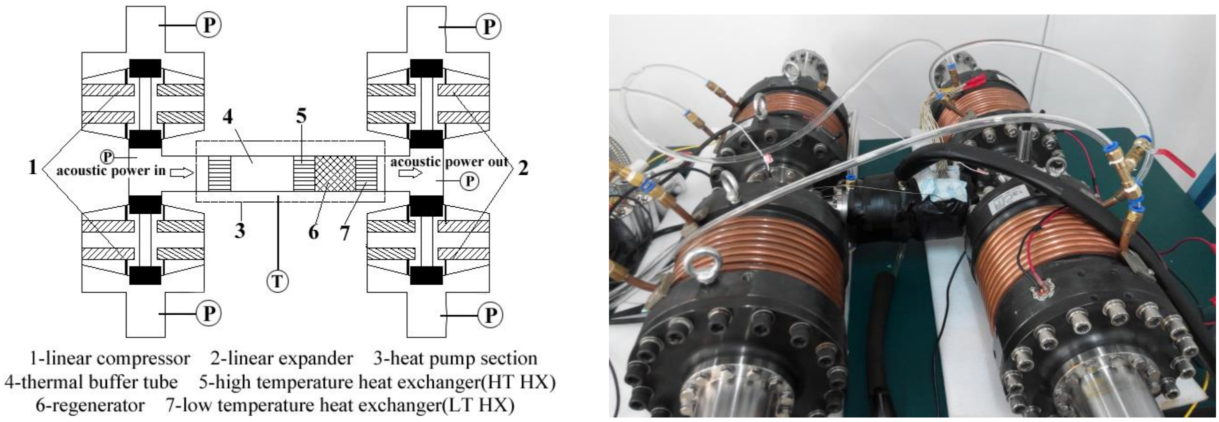
(a) *(b)*

Fig. 1. Schematic of the travelling-wave thermoacoustic heat pump: a) Whole system; b) Detail of one heat pump section

Thermoacoustic theory is a useful tool to understand the working mechanism of a TWTAHP. The model that we employed in designing our heat pump is based on this theory which was first developed by Rott [9]. In this paper, the numerical calculation was conducted by using DeltaEC software developed by Los Alamos National Laboratory [10]. Then an experimental apparatus for preliminary test was built based on the optimization and the experimental results will be shown and discussed in this paper.

3. Experimental Setup

Fig. 2(a) and (b) show the schematic diagram and the photograph of one single unit of the whole TWTAHP system. It mainly consists of two parts, a linear-compressor/expander and a heat pump section. The layout of the apparatus is as follows: Left most hand is the linear-compressor, connected in sequence is the ambient heat exchanger, the thermal buffer tube, the high temperature heat exchanger, the regenerator, the low temperature heat exchanger and the linear-expander on the right most hand. By changing the operating parameters of the linear-compressor and the expander, the single unit system can model the working condition of the TWTAHP loop system. A detailed description of the main parts will be given in the following.



(a) *(b)*

Fig. 2. Experimental apparatus: a) Schematic of the single unit TWTAHP system; b) Photograph

3.1. Linear-compressor/expander

Our research group has developed a series of linear-compressors/expanders for experiments. The parameters of the linear-compressor/expander for this paper are given in Table1. The working frequency is among the range of 50 to 60 Hz and the average pressure is 5.5 MPa. The maximum displacement of the piston is 10 mm for each linear-compressor/expander.

Table1. The parameters of linear-compressor/expander

	Piston D *mm*	Rm *N·s/m*	Stiffness *N/m*	Moving Mass *kg*	BL	L *mH*
Linear-compressor	100	78	7.3×10^5	9.6	176	14
Linear-expander	70	64	4.7×10^5	8.7	260	128

**All the data are the parameters of double compressor/expander.*

3.2. Heat pump section

As addressed above, each heat pump section includes anambient heat exchanger, a thermal buffer tube, a high temperature heat exchanger, a regenerator and a low temperature heat exchanger. The detailed structure parameters are given in Table 2.

Table2. The structure parameters of the heat pump section in TWTAHP system

Components	L *mm*	Parameters
Ambient heat exchanger	40	copper shell-tube heat exchanger, *d*=1 *mm*, Φ=0.20
Thermal buffer tube	65	wall thickness is 4 *mm*
High temperature heat exchanger	40	copper shell-tube heat exchanger, *d*=1 *mm*, Φ=0.20
Regenerator	36	stainless steel wire mesh fills, *d*=0.066 *mm*, Φ=0.71
Low temperature heat exchanger	55	copper fin-type heat exchanger, *d*=0.5 *mm*, Φ=0.27
Connecting tube	114	——

** The inter diameter of all the components is 50 mm.*

3.3. Measurement method

During the experiments, the low temperature heat exchanger has six bores that can hold six cartridge heaters with which a maximum 200 W heating power for each cartridge can be supplied to keep a stable ambient temperature. A low/high temperature water circulating system is used to control the heating temperature. By changing the water flow rate, this circulating system can also adjust the temperature difference between the inlet and outlet of the high temperature heat exchanger. An external sliding electric resistance is connected to the circuit of the expander for the purpose of changing the phase difference of volume flow rate between the inlet and outlet of the heat pump section. On the other hand, the rest of the acoustic power can be converted to electric power through this electric resistance. The local dynamic pressures concerned are measured by the PCB pressure sensors as depicted in Fig. 1(a). The heating exchangers' temperatures are measured by several T-type sheathed thermocouples which have the accuracy of 0.1 K after careful calibration.

4. Experimental Results and Discussions

4.1. Starting experiment

In all the experiments, the mean pressure is controlled at 5.5 MPa at the frequency band from 50 to 60 Hz. The heating temperature is kept at 50 ℃ by the low/high temperature water circulating system. When certain amount of electric power is added into this system, it would be converted to acoustic power which is consumed by the heat pump section subsequently. Fig. 3 shows a complete operating progress in one designed working condition, in which the working frequency is 52 Hz and the ambient temperature is -20 ℃. In the temperature decreasing curve, it only takes no more than 12 minutes to obtain the designed ambient temperature.

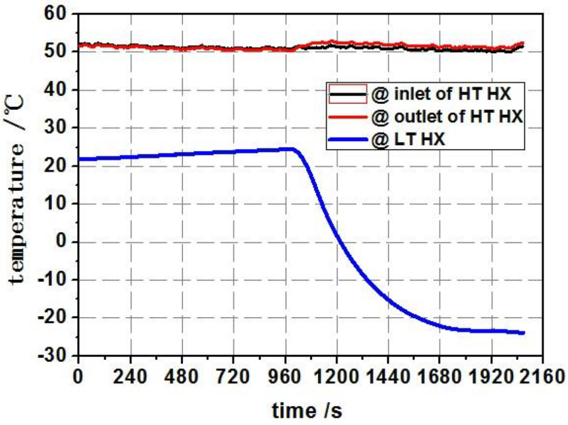


Fig. 3. Temperature decreasing in LT HX in one complete operating progress.

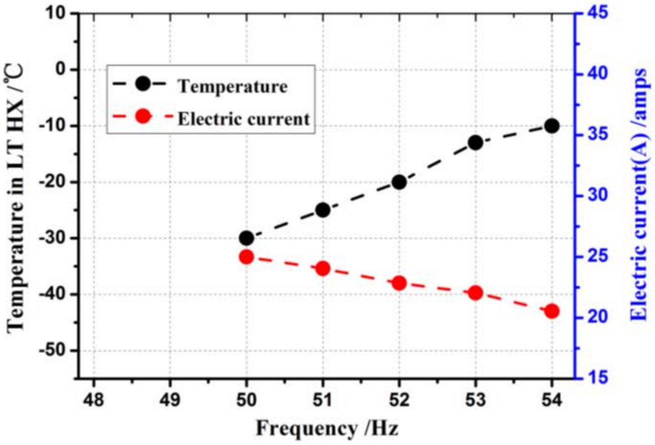


Fig. 4. Temperature and corresponding electric current in different working frequency

It should be noted that the originally designed frequency of the TWTAHP unit is 50 Hz. However, due to the coupling between the TWTAHP unit and the linear compressors, a compromise has to be made between the lowest available temperature at the LT HX and the current of the compressors. As shown in Fig. 4, though lower frequency leads to lower temperature at the LT HX, an opposite trend occurs to the current. For the frequency of 50 Hz, the current has reached the limit of 25 A. Therefore, for a safety operation, the frequency of 52 Hz is chosen for this work.

4.2. Comparative experiment

Firstly, experiments were carried out for three times at one same operating condition, which can investigate the consistency of the system. As shown in the above part, Fig. 5 also gives the curves of temperature decreasing in the low temperature heat exchanger with three totally same experiments.

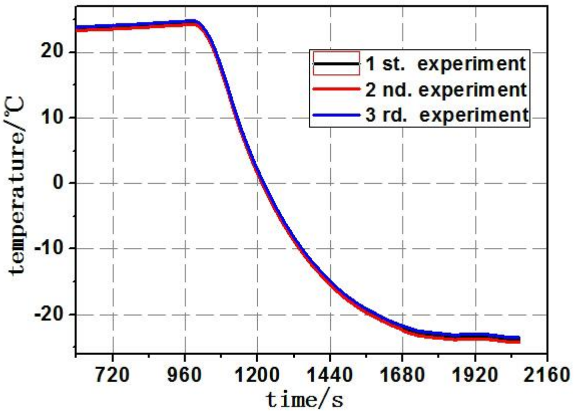


Fig. 5. Curves of temperature decreasing in low temperature heat exchanger in the same experiments

For only one unit, the consistency is quite good because there is only one group of linear-compressor/expander and heat pump section. On the other hand, if this system is assembled into the whole TWTAHP, the inconsistency will appear and become complicated.

Secondly, the experiments have been compared with the simulations. In both experiments and simulations, we use the same parameters, and the input electric power is set to be 2.5 kW. Table 3 shows the comparing results, in which the simulation and the experiment are in reasonable agreement as expected.

Table 3. The experimental results comparing with the DeltaEC simulation

	Wa_in (*W*)	X_com (*mm*)	|U| (m^3/s)	Q_h (*W*)	Q_c (*W*)	Wa_out (*W*)	X_exp (*mm*)	We_out (*W*)	COP_h	Pr
Experiment	1690	5.1	1.31×10^{-2}	1127	368	845	3.8	624	1.33	1.12
Simulation	1781	4.7	1.45×10^{-2}	1317	390	894	3.7	808	1.49	1.12

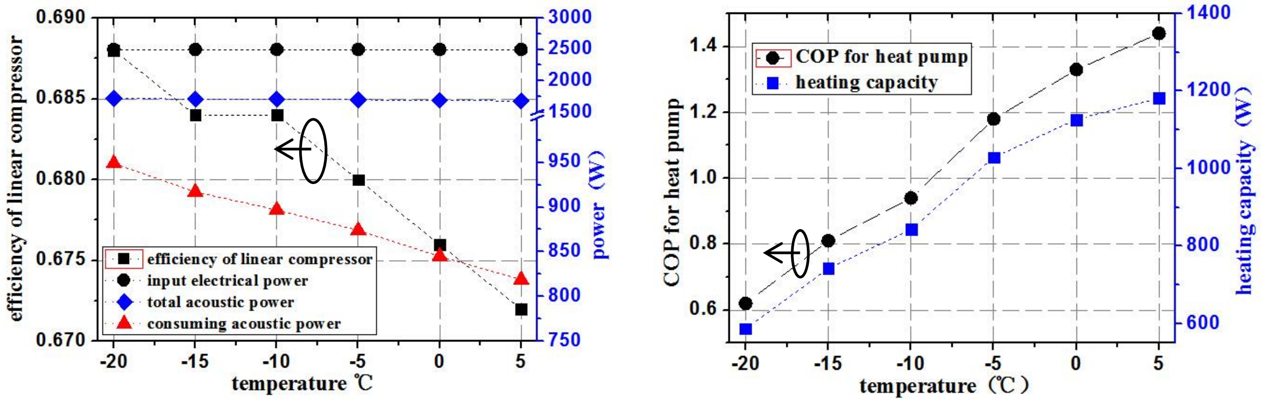
**Wa_in: input acoustic power; X_com: amplitude of the piston in compressor; |U|: volume flow rate; Q_h: pump heating capacity; Q_c: absorb heating capacity; Wa_out: output acoustic power; X_exp: amplitude of the piston in expander; We_out: output electric power; Pr: pressure ratio*

**$COP_h=Q_h/(Wa\_in-Wa\_out)$*

4.3. Influence of ambient temperature

To obtain the operational results in different ambient temperatures, we changed the temperature at the low temperature heat exchanger to -20 ℃, -15 ℃, -10 ℃, -5 ℃, 0 ℃ and 5 ℃. The mean pressure was 5.5 MPa, the frequency was 52 Hz and the heating temperature was kept at 50 ℃.

Fig. 6(a) shows the curves of power flow from compressor to expander. When this system works in the same field of acoustics and is supplied with the same amount of electric power, the quantity of acoustic power produced by the compressor and the efficiency of the compressor doesn't change much. It is clear that the curve of consumed acoustic power in the heat pump section changes obviously at different ambient temperature conditions. With the ambient temperature decreases, the heat pump must consume more acoustic power in order to keep the stable operation. This feature in TWTAHP system is consistent with the traditional heat pump system.



(a) *(b)*

Fig. 6. System performance in different ambient temperatures: a) Power flow; b) Performance of heat pump section

Fig. 6(b) shows the curves of heating capacity and COP_h with the different ambient temperature. By increasing the ambient temperature, the heating capacity and the COP_h both increase. At the ambient temperature of -20 ℃, the system can obtain the heating capacity of 587 W with the COP_h of 0.62. If the ambient temperature increases to 0 ℃, the system performance is able to be greatly improved. The COP_h can climb up to 1.33 with the heating capacity of nearly 1130 W.

5. Conclusions

In this paper, to solve the problems of traditional vapour compression heat pump, a novel TWTAHP is presented to meet the requirement of working in ultra-low temperature. Base on the theoretical simulation and structure optimization, we have built an experimental apparatus for preliminary test.

1. The experimental results show that the consistency of the system performance is good at the designed working condition. The calculated results and the experimental results are in reasonable agreements as expected.

2. On the appropriate frequency, this system can obtain the lowest ambient temperature near -30 ℃ easily by no more than 12 minutes. At the mean pressure of 5.5 MPa, this system can work stably at the pressure ratio of 1.12.

3. Furthermore, the heating capacity of 1130 W with the COP_h of 1.33 can be achieved when the ambient temperature increases to 0 ℃.

However, there is still much to be improved in the future, we believe that the TWTAHP is a powerful technology and has good potential in the ultra-low temperature environment.

Acknowledgments

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