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Experimental Investigation on a Linear-compressor Driven Travelling-wave Thermoacoustic Heat Pump

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Abstract

Heat pump system, offering economical alternatives in recovering waste heat from different sources for using in various industrial, commercial and residential applications, is considered to be a very environmentally-friendly heat and power transfer system. In this paper, to solve the problems of traditional vapour compression heat pump working in unconventional conditions, a novel TWTAHP (travelling-wave thermoacoustic heat pump) is presented to meet the requirement of working in ultra-low temperature. Base on the theoretical simulation and structure optimization, an experimental apparatus for preliminary test has been built, which is only one single independent unit from the whole loop of the TWTAHP system. The results show that the simulation and the testing results were agreeable as expected. Under the -20℃ environment temperature and the 50℃ heating temperature, we could obtain a maximal COP_h (heating COP) of 2.1 and 260W heating capacity for one unit by consuming acoustic power less than 200W. Furthermore, a COP_h above 3.0 could be achieved when the ambient temperature was raised to 0℃。

Keywords: Ultra-low temperature heat pump; Travelling-wave double-action; Thermoacoustic machine; Alternating flow

1. Introduction

Focus on higher efficiency and environmentally-friendly, the interest in heat pump system as a means to recover energy has grown rapidly. As the improvement of living standards and requirements, energy consumption in building has been accounted for about 30% in the total social energy consumption typically, while the heating energy consumption of building in northern China has held 24.63% in the total energy consumption of building in 2008 [1]. Therefore, how we can reduce energy consumption for 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 taken an important role in this field. K. J Chua et al.[2] published

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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. As rising heating temperature or reducing environment temperature, the system will face higher discharge temperatures, higher pressure ratios, and lower performance efficiencies. Ruixiang Wang et al. [3] developed an advanced air source heat pump with a portion of capillary adding to the circulation, which can increase the density of refrigerant at the inlet of the hermetic compressor. Compared with a traditional system using a non-azeotropic mixture R407c as refrigerant, the advanced system could provide three times heating capacity and more than 35% of efficiency at the working condition of -10℃. Xianting Li et al.[4] built an air source absorption heat pump using $H_2O/LiBr$ and $NH_3/LiNO_3$ as working fluid. Based on the simulated performance results, the proposed system could provide energy saving rates of 18%, 28.5%, 37% and 42% in Shenyang, Beijing, Shanghai and Guangzhou respectively (four climatic typically cities in China) with the ambient temperature at -10℃. Ho-Saeng Lee et al. [5] 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 reaching above 3.0 improved 15.8%. Dong Ho Kim et al. [6] set up a two-stage air-water source heat pump, using R134a and R410a as refrigerants based on prophase simulation and optimization calculation. 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 less, while reducing the ambient temperature also caused the same problem. Wei Yang et al. [7] 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 in average.

Recently, ultra-low temperature heat pump technology continues to innovate. Shi Wenxing [8] summarized the new optimization methods for heat pump system, including liquid/vapour injection technology, outdoor heat exchanger optimization and heat accumulation for defrosting. In this paper, a novel TWTAHP (travelling-wave thermoacoustic heat pump) is presented to meet the requirements and to possibly solve the problems occurring in conventional vapour compression heat pump, especially in ultra-low temperature working condition.

2. Theoretical model

The TWTAHP (see 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 a secondary ambient heat exchanger, thermal buffer tube, high temperature heat exchanger, regenerator, main ambient heat exchanger, and connecting tubes. The generator is based on a dual-opposed piston design that minimizes vibrations. By adding a little amount of the electrical power, the acoustic power will be produced and transfer from left to right through the helium as the medium in every heat pump section, as depicted in Fig. 1 (a). The oscillation of sound in the gas medium can make the change of temperature inside the molecules of gas, which mainly happens in the regenerator. Then the ambient heat exchanger absorbs heat from the surroundings at ambient temperature, high-temperature heat exchanger delivers heat to the surrounding for user. With this structural arrangement, when the acoustic power transfers to the next heat pump section, the phase angle for the volume flow rate decreases 120°. In this way, the system is able to use low grade heat sources to obtain heat energy at much higher temperatures.

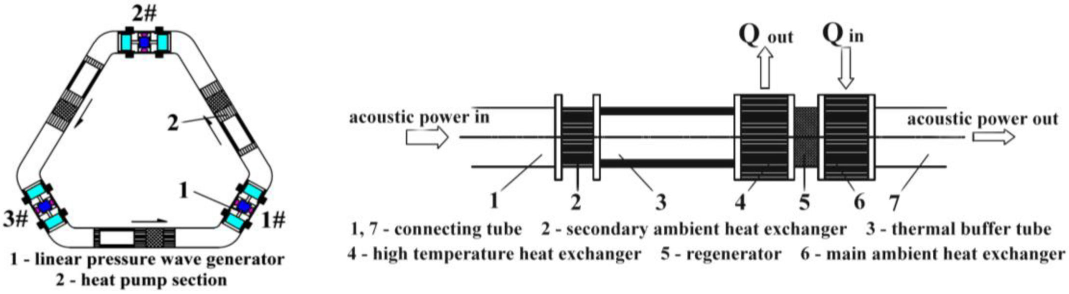

Fig. 1 (a) Schematic of the travelling-wave thermoacoustic heat pump; (b) Detail of one heat pump section.

Thermoacoustic theory is a means 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 developed by Rott based on the laminar flow hypothesis [9]. For this paper, the numerical model was implemented 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 photo of the one single unit of the whole TWTAHP system. It mainly consists of two parts, a linear-compressor/expander and a heat pump section. Following the linear-compressor, there are the secondary ambient heat exchanger, the thermal buffer tube, the high temperature heat exchanger, the regenerator, the main ambient heat exchanger and the linear-expander as the end. By changing the operating parameters in the linear-compressor and the expander, the single unit system can model the working of TWTAHP system. A detailed description of the main parts will be given in the following.

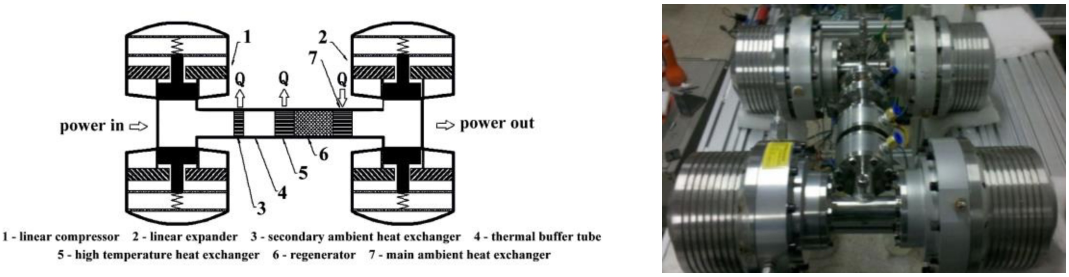

Fig. 2 (a) Schematic of the single unit of the TWTAHP system; (b) The photograph of testing experimental apparatus.

Table.1 Linear pressure wave generator parameters

	Piston diameter mm	Re Ω	BL N·A	Moving mass kg	Stiffness N/m	Rm N·s/m
linear compressor	60	7.44	195.4	4.16	3.6×10^5	32.68
linear expander	50	7.00	190.0	2.63	3.3×10^5	40.00

3.1 Linear-compressor/expander

Our research group has developed a type of linear compressor/expander for experiment using helium as the working fluid. The parameters of the linear compressor/expander for this paper are given in Table. 1. The working frequency is during the range of 80 to 85Hz and the maximum working pressure is 4MPa. The amplitude of the piston in linear compressor is 6.5mm.

3.2 Heat pump section

Every heat pump section includes the secondary ambient heat exchanger, thermal buffer tube, high temperature heat exchanger, regenerator and main ambient heat exchanger. The structure parameters of every part are given in Table. 2.

Table.2 The structure parameters of the heat pump section in TWTAHP system

Components	D	L	Parameters
	mm	*mm*	
secondary ambient heat exchanger	50	30	copper shell-tube exchanger, d=1mm, ϕ=0.25
thermal buffer tube	50	70	wall thickness is 2.5mm
high temperature heat exchanger	50	40	copper shell-tube exchanger, d=1mm, ϕ=0.25
regenerator	50	28.5	stainless steel wire mesh fills, D_{wire}=0.066mm, mesh number is 150
main ambient heat exchanger	50	30	copper fin-type exchanger, d=0.5mm, ϕ=0.25

3.3 Measurement method

During the experiments, the main ambient heat exchanger has four holes that can hold four cartridge heaters from which maximum 200W heating power for each can be supplied to keep a stale ambient temperature. A simple water circulating system is used to control the heating temperature by changing the water flow rate or the water quantity. An outside radiating resistance is connected to the expander for changing the phase difference of volume flow rate between the inlet and the outlet of the heat pump section by adjusting the resistance value. The dynamic pressure is measured by PCB and Kunlun pressure sensors which are placed at both the compressor and expander. The heating exchangers' temperatures are measured by Pt sensors which have the accuracy of 0.1K after calibration.

4. Experimental results and discussions

4.1 Consistency experiment

In this experiment, the working pressure is 4.0 MPa with helium gas operating at the frequency of 84.6Hz. The heating temperature is 50℃ and the ambient temperature is -20℃.

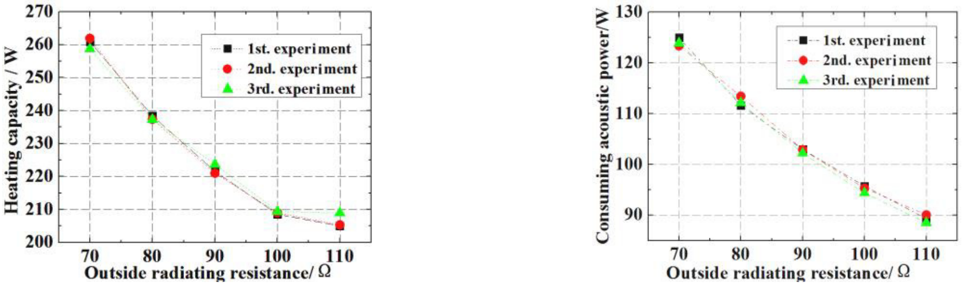

Fig. 3 (a) Curves of heating capacity in the same experiments; (b) Curves of consuming acoustic power in the same experiments.

At the same operating condition, the experiment was set up for three times to obtain the consistency with the system. By focusing on the most concerned targets, including the heating capacity and the consuming acoustic power, Fig. 3 (a) and (b) can give the curves respectively. For only one unit, the consistency is well agreeable because there is only one group of generator. On the other hand, if this system is put back into the whole TWTAHP, the inconsistency with the three groups of generator will appear and become complicated.

4.2 Changing operating temperature experiment

To obtain the operational results in different ambient temperatures, we changed the provided heating temperature at the main ambient heat exchanger with -20℃, -10℃ and 0℃. The working pressure was 4.0MPa with the frequency of 84.6Hz and the heating temperature was 50℃.

Fig.4 (a) shows the curves of consuming acoustic power changing with the outside radiating resistance in the expander at three different ambient temperature conditions. With the ambient temperature decreases, the heat pump must consumes more acoustic power in order to achieve the desired efficiency in the case of increasing the temperature difference between the ambient and high temperature heat exchangers. This behaviour in TWTAHP system is consistent with the traditional heat pump system.

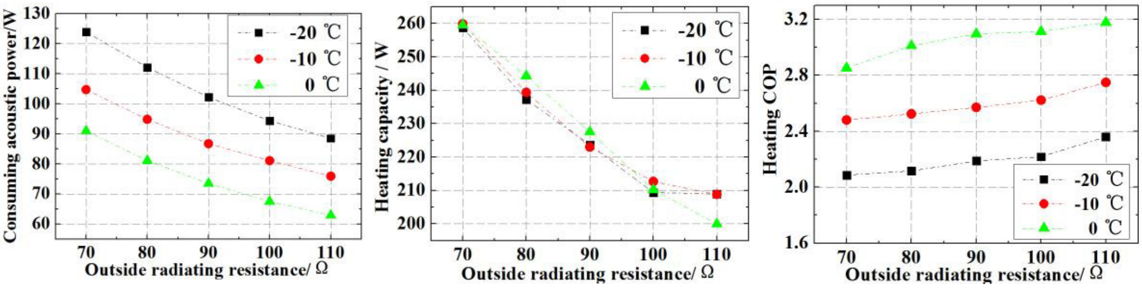

Fig. 4 System performance in different ambient temperatures:

(a) consuming acoustic power (b) heating capacity (c) heating COP

Fig. 4 (b) shows the curves of heating capacity changing with the outside radiating resistance in the expander at three different ambient temperature conditions. With the ambient temperature changes, the heating capacity does not change much at the same value of the outside radiating resistance. One reason might be the amount of input acoustic power is still small, but the influence in heating capacity is much lighter than that in consuming acoustic power which shows in Fig. 4 (a).

Therefore, the COP_h in different temperature conditions was calculated after the experiments. The variation of the COP_h is also very obvious which has been shown in Fig. 4 (c). At the ambient temperature of -20℃ and the heating temperature of 50℃, the system can obtain a maximum heating capacity of 260W with the COP_h of 2.1. By adjusting the outside radiating resistance in the expander to change the property of acoustic field, the system can obtain a maximum COP_h of nearly 2.4 in the above temperature condition. Meanwhile, if the ambient temperature increases to 0℃, the system performance is able to be greatly improved. The COP_h can climb up to more than 3.0 with the heating capacity of nearly 250W.

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 experiment results show that the consistency of the system performance is good enough at designed working condition.
2. Under the -20℃ environment temperature and the 50℃ heating temperature, we can obtain a maximal COP_h of 2.1.
3. Furthermore, a COP_h above 3.0 with the equal heating capacity during all the experiments can be achieved when the ambient temperature increases to 0℃。

In a word, we believe that the TWTAHP is an enabling technology and has good potential in the efficient working at Ultra-low temperature environment.

Acknowledgements

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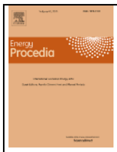

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