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Travelling-wave thermoacoustic high-temperature heat pump for industrial waste heat recovery

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ABSTRACT

Many industrial processes need steam at temperatures from 100 to 200 °C, normally produced by directly heating water via coal, natural gas or oil combustion. Nevertheless, large amounts of unused heat below 100 °C are wasted in other industrial processes. In principle, a high-temperature heat pump capable of using the industrial waste heat can provide steam above 100 °C. However, until now, efficient and reliable heat pump technology for the application is not available. In this paper, a novel TWTAHP (travelling-wave thermoacoustic heat pump) is presented to meet this requirement, which can potentially solve the problems occurring in conventional vapour-compression heat pump such as high discharge temperatures, high pressure ratio, and low efficiency. This system comprises three linear pressure wave generators which are coupled with three heat pumps into one single closed loop. Theoretically, this system is able to complete the thermoacoustic conversion with a much higher efficiency. The theoretical simulations were performed at varied waste-heat temperatures (40–70 °C) and different hot-end temperatures (120–150 °C). The computing results show that this new heat pump system has a high relative Carnot efficiency of about 50%–60%. In using a reliable linear compressor and a thermoacoustic heat pump with no-moving parts, this technology has an inherent potential for high reliability. Therefore, it is believed that the travelling-wave thermoacoustic heat pump is an enabling technology with good prospects in efficiently harvesting industrial waste heat.

1. Introduction

As the depletion of Earth's energy resources continues to be a serious problem, saving energy and improving energy using efficiency become imperative. Heat pump systems offer economical alternatives in recovering waste heat from different sources for using in various industrial, commercial and residential applications. With the rising of fuel costs and global warming at the forefront of the world's attention, the interest in heat pumps as a means to recover energy has grown. However, such systems have not been applied as widely as they should or could be. In traditional heat pump systems on the basis of the vapour compression cycle, system design and optimisation remain challenging problems as rising the delivering temperature can result in higher discharge temperature, higher pressure ratio, and lower performance efficiency. On the one hand, there are huge amounts of waste heat below 100 °C from industrial processes that have not to be used yet. On the other hand, many processes need steam at the temperatures higher than 100 °C, which is currently produced by directly heating water with the combustion of coal, natural gas, or oil. It is urgent that an efficacious method should be found to transform the low-grade heat sources into the high-grade heat sources. Wang [1] carried out theoretical and experimental investigations on a moderately high-temperature heat pump using environmentally-friendly refrigerants. The result indicated that on the evaporating and condensing temperatures of 44 °C and 90 °C, this heat pump could achieve an associated COP_h (coefficient of performance with heat pump) for HC600 and HC600a of 3.84 and 3.33 respectively. Using a high-temperature heat pump with the zeotropic mixtures as refrigerants, Zhao [2] studied the nonlinear relationship of various system parameters. The theoretical results showed that the zeotropic mixtures, which have a smaller maximum temperature difference in the condenser and a smaller minimum temperature difference in the evaporator could attain the highest COP.

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Antonijevic [3] studied six different heating systems on the basis of the vapour compression cycle with either two-stage or one-stage compression. The two-stage compression had the best seasonal COP as well as the system exergy parameters, which can attain a COP of nearly 4.0 with the evaporating and condensing temperatures of nearly −10 °C and 65 °C respectively. In the recent research, the traditional vapour compression system has been advanced in many different areas. However, despite some valuable improvements, there would be an increased cost associated with using more complicated and expensive hermetic reciprocating compressors. Dong Ho Kim et al. [4] set up a two-stage air–water source heat pump, using R134a and R410A as refrigerants based on pro-phase simulation and optimization calculation. The experimental results showed that at the operating condition of the ambient temperature at −7 °C and the heating capacity with 15 kW, a downward trend in COP could be obtained with the increased demand for hot water temperature. When the hot water temperature increased to 55 °C, the COP dropped to 2.0 or less, 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. With the operating condition of the ambient temperature at 4.8 °C, 13.5 °C and the heating temperature at 50 °C, the new system could obtain the heating COP of 4.73 in average. M. Noro et al. [6] made a research of a multisource heat pump system, which included evaluation and analysis of the data obtained through real time monitoring of the working system in operation, for a period of approximately two heating seasons. During this time, the behaviour of the system was assessed and the incorrect settings of the plant were identified and subsequently adjusted as required. The energy balance indicated that the integration of different sources not only increased the thermal performance of the system as a whole, but also optimized the usage of each source.

In this paper, a novel TWTAHP (travelling-wave thermoacoustic heat pump) is presented to meet the requirement, which could possibly solve the problems occurring in conventional vapour compression heat pumps. Thermoacoustically driven systems for heating or cooling have received much attention in recent years for their heat-driven mechanism, without moving parts, and structural simplicity. Thermoacoustic machines, which mainly include thermoacoustic heat engines and refrigerators, make use of thermoacoustic effect to realize the conversion between heat and sound energy. Until 1999, Swift et al. [7] studied a pulse tube refrigerator with acoustic power recovery of lost power in the orifice-type pulse tube cryocoolers, which is now called thermoacoustic-Stirling refrigerator or TWTAR (travelling wave thermoacoustic refrigerator). Recently, much effort has been done in developing TWTARs for higher cooling temperature range [8,9], in which the linear compressors are more widely used as the drivers. Taking advantage of thermoacoustic theory, we have designed a TWTAHP system to test its effectiveness. The theoretical model, the optimisation procedure and the results of this new system will be introduced.

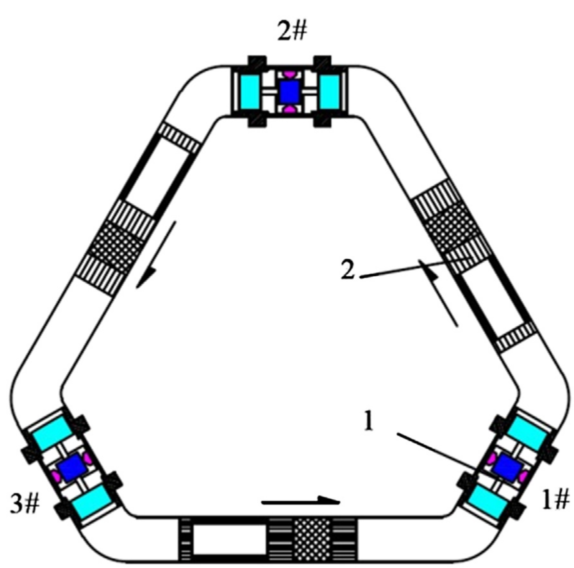

Fig. 1. Schematic of the travelling-wave thermoacoustic heat pump.

2. Theoretical model

The TWTAHP (see schematic in Fig. 1) composes three linear pressure wave generators coupled with three heat pump sections in one closed loop. Each heat pump section (see Fig. 2) includes an ambient heat exchanger, thermal buffer tube, hot-end heat exchanger, regenerator, cold-end heat exchanger, and connecting tubes. All the heat exchangers are made of copper with the rest of the elements are made of stainless steel. The linear pressure wave generator is based on a dual-opposed piston design that minimises vibrations. By adding a little amount of the electrical power into the generator, the acoustic power will be produced by the generator and transfer from left to right through the helium as the medium in every heat pump section, as depicted in Fig. 2. The oscillation of sound in the gas medium can make the change of temperature inside the molecules of gases, which mainly happens in the regenerator. The regenerator is the core of this system, which is filled with pieces of the stainless steel wire mesh. The gas in this porous medium has lower fluidity and higher heat conduction. As a result, the two ends of the regenerator will have the highest temperature and the lowest temperature respectively. Then, with the thermoacoustic conversion in regenerator, the cold-end heat exchangers begins to absorb heat from the waste heat source and the hot-end heat exchangers started to deliver heat to the user area. The thermal buffer tube is used to decrease and control the temperature in ambient heat exchanger. Then the ambient heat exchangers could protect the linear pressure wave generators from over heat. With this structural arrangement, when the acoustic power is transferred to the next heat pump section, the phase angle for the volume flow rate decreases 120°, which is one of the best phase in travelling wave system. At last, the transmission of sound wave will come back to the beginning. In this way, the system is able to use low grade heat sources to obtain heat energy at much higher temperatures.

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

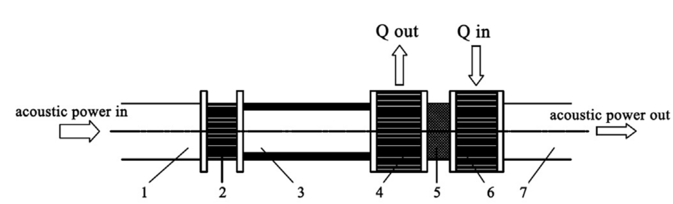

Fig. 2. Detail of one heat pump section.