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Research Paper

Traveling-wave thermoacoustic refrigerator driven by a multistage traveling-wave thermoacoustic engine

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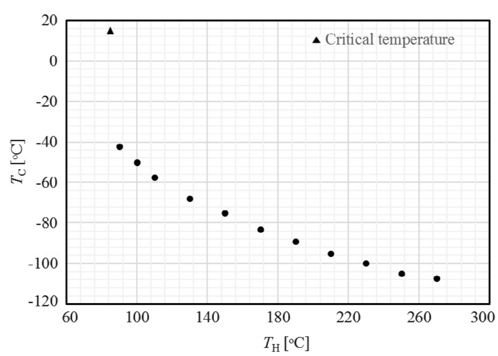
HIGHLIGHTS

- A double-loop-type TWT refrigerator driven by a multistage TWE was constructed.
- Etched stainless steel mesh regenerators were installed close to the sweet spot.
- At T_H = 270 °C the minimum temperature of −107.4 °C was achieved.
- Gas oscillations occurred when the T_H exceeded 85 °C.
- Refrigeration (−42.3 °C) was observed when T_H reached 90 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

A double-loop-type traveling-wave thermoacoustic refrigerator driven by a multistage traveling-wave engine was constructed. To reduce the onset temperature for thermoacoustic oscillations and achieve a refrigerator temperature of −100 °C, three etched stainless steel mesh regenerators were installed close to the sweet spot within the prime mover loop and one regenerator was fixed in the refrigerator loop. The maximum measured COP of the whole system at −50 °C, was 0.029. Gas oscillations occurred when the hot temperature of the regenerator in the prime mover loop exceeded 85 °C. On the other hand, refrigeration (−42.3 °C) was observed when the hot heat exchanger temperature reached 90 °C, which is lower than the boiling point of water. Furthermore, the refrigerator achieved a minimum cold temperature of −107.4 °C when the hot temperature was 270 °C.

1. Introduction

In 1979, Ceperley [1] proposed a traveling-wave thermoacoustic engine (TWTE) in which the acoustic power was amplified by traveling-wave propagation through a differentially heated regenerator. In a TWTE, when the phase difference Φ between the pressure and the cross-sectional mean velocity is zero and viscous losses are negligible, the gas parcels experience thermodynamically reversible processes. Hence, the efficiency of the engine ideally reaches the Carnot efficiency. The concept of Ceperley was practically realized by Yazaki et al. in 1998 [2]. They were the first to build a looped tube TWTE and observed that the energy conversion between heat flow and work flow was executed through the Stirling cycle.

In 1999, Backhaus and Swift [3] built a prototype thermoacoustic engine based on traveling-wave energy conversion and introduced a resonator in a looped tube. They created the traveling-wave phasing with high acoustic impedance in the regenerator area, which is called the sweet spot. Accordingly, their

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engine efficiency reached above 30% thermal efficiency. The sweet spot is a location where the volume velocity is minimum and the phase difference between the pressure and velocity is zero [4]. The sweet spot is dominant when an acoustic wave has high acoustic impedance, in particular when the dimensionless specific acoustic impedance z is greater than or equal to 10 times the specific heat ratio γ (i.e., $z \geqslant 10\gamma$). In the same year, Swift et al. [5] studied a pulse tube refrigerator with acoustic power recovery of lost power in orifice-type pulse tube cryocoolers, which is now called a traveling-wave thermoacoustic refrigerator (TWTR).

Ceperley [1] demonstrated the idea of a thermally driven heat pump operating as a piston-less thermoacoustic refrigerator, which consisted of a pair of TWTEs. Based on the idea of Ceperley, Yazaki et al. [6] constructed a looped-tube thermoacoustic refrigerator driven by a TWTE. Their engine could not achieve high efficiency because of the relatively small value of z with respect to γ ($z = 3\gamma$). This problem was solved by Ueda and Yazaki [7] using a resonator in a looped tube and adjusting the position of the regenerator close to the sweet spot. In their study, z reached a value 10 times greater than γ ($z = 10\gamma$). They achieved a cold temperature of around −25 °C with a cooling power of 11 W. Yazaki et al. [6] used two regenerators in one loop to realize the functions of both a TWTE and TWTR, so the efficiency was still low because one loop does not have two sweet spots to simultaneously keep the pressure and velocity waves in phase. In 2006, Luo et al. [8] built a thermoacoustic refrigerator with two separate traveling-wave loops, and obtained a lowest temperature of −64.4 °C. Furthermore, Yu et al. [9] introduced and tested new configurations of TWTRs driven by a TWTE in 2011. They found that a TWTR with an assembly of lumped inertial mass and flexible membrane as the phase shifter improved the cooling performance.

The temperature of most industrial waste heat ranges from 400 to 600 K, while the critical onset temperature of a thermoacoustic engine is generally in the range 600–1000 K [3]. To overcome this problem, Gardner and Swift [4] proposed a multistage thermoacoustic engine that can lower the critical onset temperature and thereafter the multi-stage thermoacoustic systems were reported by many researchers [10–17]. In 2010, Biwa revealed that the installation of multiple regenerators at suitable positions can markedly enhance acoustic power production, and they obtained a critical onset temperature ratio of 1.19 [18]. Although success has been reported in lowering the critical temperature using multiple regenerators, the appropriate positions of the regenerators and the tube radius to produce low-temperature oscillations with high efficiency have not been established [19]. Therefore, further development of such engines is extremely important for many practical applications.

In 2013, Hasegawa et al. [19] (one of the authors of this paper) numerically optimized a multistage-type thermoacoustic engine to produce thermoacoustic oscillations equivalent to a typical industrial waste heat temperature. They considered three regenerators at optimized positions close to the sweet spot within the prime mover loop, and consequently determined the configuration that enables a low temperature oscillation with high efficiency. Furthermore, they obtained the dependency on the temperature ratio of the prime mover for the temperature ratio of the refrigerator, and concluded that a low temperature drive with high efficiency can be achieved within a multistage thermoacoustic engine. The concept of Hasegawa et al. was practically realized in this study. Accordingly, a double-loop-type TWTR driven by a multistage TWTE was constructed. Three etched stainless steel mesh regenerators were installed close to the sweet spot within the prime mover loop and one regenerator was fixed in the refrigerator loop. The onset temperature, the gas oscillations, the refrigeration, and the total COP were measured. The objective was to reduce the onset temperature for thermoacoustic oscillations and achieve a refrigerator temperature of −100 °C by placing multiple regenerators close to the sweet spot.

2. Experimental setup

Figs. 1 and 2 show the experimental apparatus and its schematic diagram. The apparatus is composed of a prime mover loop, a refrigerator loop, and a branched tube composed of cylindrical stainless steel tubes with an inner diameter of 40 mm. The regenerators used in the apparatus are labeled Regenerator1, Regenerator2, Regenerator3, and Regenerator4, as shown in Fig. 2. All of the regenerators were constructed based on the numerical optimized values. The optimized values of the diameters of regenerators 1, 2, 3, and 4 were 0.2, 0.2, 0.3, and 0.2 mm, respectively. Regenerator1, Regenerator2, and Regenerator3 have the same axial length of 30 mm and were installed at optimized positions close to the sweet spot near the T-junction within the prime mover loop. An ambient heat exchanger and a hot heat exchanger were placed on either side of each regenerator. In the refrigerator loop, Regenerator4 (120 mm in length) was sandwiched between the cold and ambient heat exchangers. Here, we use T_H, T_R, and T_C to denote the temperatures of the hot heat exchanger, ambient heat exchanger, and refrigerator, respectively.

Etched stainless steel mesh regenerators were used and to reduce the axial thermal conductivity, plate sheets with a 0.1 mm gap were used along the axial direction, as shown in Fig. 3.

The heat exchangers consisted of pairs of copper plates aligned in parallel with a 2.0-mm gap between each plate. Each plate was 1.0 mm thick and 27.0 mm in axial length, as shown in Fig. 4.

To control the temperature, an electrical heater (2 M-1-300) was wound around each hot heat exchanger, whereas water chillers (LTC-1200A) whose uncertainty was ±2.0 °C, were used to keep the temperature of the ambient heat exchangers at room temperature (10 °C). The three hot heat exchangers were always kept at identical temperature during the test. K-type thermocouples with uncertainty range of ±2.5 °C, were used to monitor the temperature of the heat exchangers. The output signals from the thermocouples were recorded by a data logger (GL7000). The pressure transducers were connected to the FFT analyzer (DS-3204) for measuring frequency and to monitor the pressure signals, subsequently the two sensor method [20,21] was used to measure the pressure amplitude, the velocity amplitude, and the acoustic power. To reduce thermal losses, the hot and cold heat exchangers were insulated with glass wool insulation. A flexible membrane was used in both T-junctions to suppress Gedoen streaming. The models and the companies for the components are listed in Table 1.

3. Results

Thermoacoustic energy conversion is essentially controlled by two parameters: the ratio between the radius of the flow channel r_0 and the thermal penetration depth δ_κ (r_0/δ_κ), and the phase difference Φ between the pressure and the cross-sectional mean velocity. When Φ is close to zero and $r_0 \ll \delta_\kappa$, the gas can operate with reversible processes. When the value of z is sufficiently large, viscous losses can be reduced [1,2,22]. For the present apparatus, the calculated parameter r_0/δ_κ of Regenerator1, Regenerator2, Regenerator3, and Regenerator4 were 0.19, 0.19, 0.29, and 0.51 respectively. The obtained δ_κ values were much bigger than radius of the flow channel r_0 and the gap of the regenerators. Furthermore, around the sweet spot, Φ was close to zero and the z value was sufficiently large to reduce viscous losses in the regenerators. Thus, the present apparatus could operate as a TWTR where the working gas passing through the regenerators relies on reversible processes with a low level of viscous losses.