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# A 1 kW-class multi-stage heat-driven thermoacoustic cryocooler system operating at liquefied natural gas temperature range

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This article introduces a multi-stage heat-driven thermoacoustic cryocooler capable of reaching cooling capacity about 1 kW at liquefied natural gas temperature range without any moving mechanical parts. The cooling system consists of an acoustically resonant double-acing traveling wave thermoacoustic heat engine and three identical pulse tube coolers. Unlike other traditional traveling wave thermoacoustic heat engines, the acoustically resonant double-acting thermoacoustic heat engine is a closed-loop configuration consists of three identical thermoacoustic conversion units. Each pulse tube cooler is bypass driven by one thermoacoustic heat engine unit. The device is acoustically completely symmetric and therefore "self-matching" for efficient traveling-wave thermoacoustic conversion. In the experiments, with 7 MPa helium gas as working gas, when the heating temperature reaches 918 K, total cooling capacity of 0.88 kW at 110 K is obtained with a resonant frequency of about 55 Hz. When the heating temperature is 903 K, a maximum total cooling capacity at 130 K of 1.20 kW is achieved, with a thermal-to-cold exergy efficiency of 8%. Compared to previously developed heat-driven thermoacoustic cryocoolers, this device has higher thermal efficiency and higher power density. It shows a good prospect of application in the field of natural gas liquefaction and recondensation. 
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The thermoacoustic heat engine (TAHE) utilizes sound waves instead of mechanical pistons to convert heat energy to acoustic work, i.e., mechanical energy. It has advantages of inherent mechanical simplicity, long lifetime, and high reliability due to no moving mechanical parts. Besides, it is environmentally friendly by using inert gas as working gas. Moreover, it is an external combustion engine and can be driven by various heat sources such as waste heat and solar energy. Utilizing a TAHE to drive a thermoacoustic cooler gives a birth of a cooling system with no moving mechanical parts completely. A thermoacoustic cooler driven by a TAHE is so called the heat-driven thermoacoustic cooler (HDTC). In 1990, Radebaugh *et al.* built the first HDTC system capable of achieving a lowest temperature of 90 K.[1] In recent two decades, many research groups around the world have joined to investigate the HDTCs. The HDTCs capable of reaching liquid nitrogen temperature[2] and liquid hydrogen temperature[3] have been achieved by Luo's group. From 1997 to 2005, Swift *et al.* had built a series of large systems with cooling capacity of several kilowatts at 120 K to liquefy natural gas.[4] They developed a HDTC, which consists of three orifice pulse tube coolers and a traveling wave TAHEs with a large-diameter standing-wave resonant tube. It was designed to obtain a cooling capacity of 7 kW at 120 K. The test data showed that total cooling power of 3.8 kW at 150 K was obtained. The energy density (defined as the ratio of acoustic power to the cross-sectional area) of the resonator is only 860 kW/m$^2$. The thermal-to-cold exergy efficiency of the system is below 5%. The main problems of the previously developed HDTCs are low thermal-to-cold efficiency and low power density due to the large-diameter standing-wave resonator. Some compact HDTCs were studied. In 2002, Yazaki *et al.* studied a system with two stacks in one loop tube to realize the functions of HDTC.[5] One stack generates acoustic work, which is consumed by the other cool regenerator to pump heat from the cold end heat exchanger. In their experiments, the obtained lowest temperature is 246 K. In 2010, de Block proposed a 4-stage traveling wave TAHE with a closed-loop configuration, in which all regenerator units (consists of a high temperature heat exchanger, a regenerator, and a low temperature heat exchanger) and connecting tube sections are identical.[6] Then, they replaced one of the four engine stages of the TAHE by a regenerator unit of the refrigerator and built an integral cooling system.[7] However, the cooling capacity of the system is only 95.4 W at 227.5 K. It seems that the HDTCs, with refrigerator units and TAHE units in series in one loop, are hard to achieve low temperature below liquid natural gas temperature range due to unmatched acoustic impendence.

The object of this article is to build a HDTC system with high efficiency and high power density operating at liquefied natural gas temperature range. In the HDTC, unlike the ones mentioned above, the refrigerator units are bypass connected to the looped THAE. The looped THAE is named acoustically resonant double-acting TAHE proposed by Luo in 2013.[8] In the system, there are multiple thermoacoustic conversion units in one wavelength loop tube, leading to

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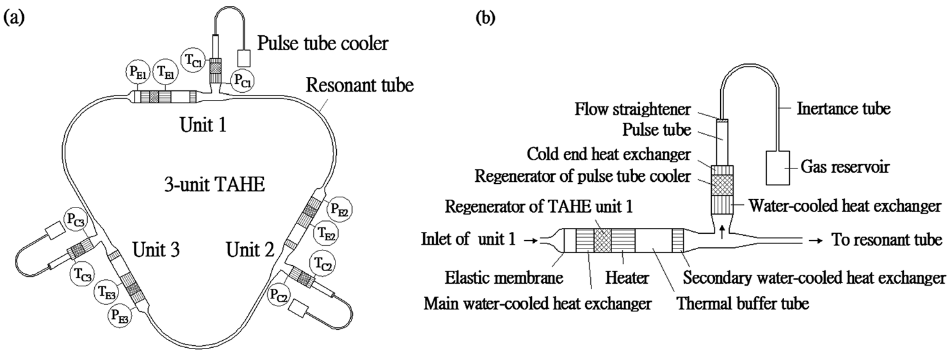



FIG. 1. (a) Overview: the 3-unit heat-driven thermoacoustic cooler. (b) Unit 1 of the system.

higher power density than the traditional TAHEs. By carefully designing the components, the regenerator of each unit could operate on efficient thermoacoustic-Stirling cycle (i.e., traveling-wave thermoacoustic conversion). In this article, a 3-unit HDTC system is designed, built, and tested.

Figure 1 shows the schematic of the 3-unit system. It consists of a 3-unit TAHE and three identical pulse tube coolers. The three pulse tube coolers are bypass driven by the three TAHE units, respectively. As shown in Fig. 1(b), each TAHE unit consists of a main water-cooled heat exchanger, a regenerator, a heater, a thermal buffer tube, a secondary water-cooled heat exchanger, and a resonant tube. Each pulse tube cooler consists of a water-cooled heat exchanger, a regenerator, a cold end heat exchanger, a pulse tube, a flow straightener, an inertance tube, and a gas reservoir. The device is acoustically completely symmetric and therefore "self-matching." By carefully designing those thermodynamic components, the regenerators in the system could operate on efficient thermoacoustic-Stirling cycle. The main dimensions of the TAHE are listed in Table I. The regenerator of each TAHE unit is packed with 150-mesh stainless steel screens. The main dimensions of the pulse tube cooler are listed in Table II. The regenerator of the pulse tube cooler is packed with 300-mesh stainless steel screens. The flow straightener is packed with 40-mesh copper screens. The volume of the gas reservoir is 1 liter.

Based on one-dimensional thermoacoustic simulation model,[9] the calculated results for the typical operating condition (with mean pressure of 7 MPa, ambient temperature of 293 K, heating temperature of 918 K, and cooling temperature of 110 K) are shown in Fig. 2. Theoretically, the three units of the system operate the same. Figures 2(a) and 2(b) show the distributions of the acoustic power flow and phase relationship between pressure and velocity waves in one TAHE unit and a pulse tube cooler, respectively. During the experiments, after the heating power added into the heaters, the gas in the system starts to oscillate when the axial temperature gradient of the regenerators of the TAHE exceeds a critical value. According to Fig. 2(a), an acoustic power of 2.50 kW enters the inlet of the TAHE unit and is amplified along the regenerator with a positive temperature established by inputting heat into the heater and extracting heat from the main water-cooled heat exchanger. The 6.07 kW amplified acoustic power, after small dissipation in the heater, the thermal buffer tube, and the secondary water-cooled heat exchanger, is divided into two branches at the tee joint: one branch of 2.12 kW goes into the acoustic load (i.e., the pulse tube cooler); the other branch of 3.74 kW flows through the resonant tube, after some dissipation, the rest of 2.50 kW enters into the next TAHE unit to be amplified. The calculated result shows that one TAHE unit can deliver a net acoustic power of 2.12 kW with 7.31 kW heating power added to the heater, corresponding to a thermoacoustic efficiency of 29%. According to Fig. 2(b), an acoustic power of 2.12 kW enters the pulse tube cooler and is mainly consumed in the regenerator for pumping heat from the cold end heat exchanger. The acoustic power of 0.65 kW comes out of the cold end heat exchanger, after small dissipation in the pulse tube and the straightener, and mostly dissipates in the inertance tube. The cooling capacity of the pulse tube cooler is 0.39 kW at 110 K. That is to say, under the heating temperature of 918 K, the total cooling capacity of the 3-unit HDTC is 1.17 kW at 110 K with the thermal-to-cold exergy efficiency of 13%. The thermal-to-cold exergy efficiency is given by $Q_c(T_0/T_c-1)/(Q_h(1-T_0/T_h))$, where $Q_c$ and $Q_h$ are the cooling capacity and heating power, and $T_0$, $T_c$, and $T_h$ are the ambient temperature, cooling temperature, and heating temperature.

The key for obtaining high efficiency of the HDTC is to establish traveling wave acoustic field in the regenerators both in the TAHE units and the pulse tube coolers. As shown in Fig. 2(a), in the TAHE unit, the phase angle difference between pressure and velocity wave is about $-30°$ in the middle of the regenerator. That means, the acoustic field in the regenerator is near the traveling wave field but not the optimum. So, there is still room for improvement. According to Fig. 2(b), the phase angle differences through zero point inside the regenerator of the pulse tube. This means that, under the specified operating condition, the pulse tube cooler was well designed.

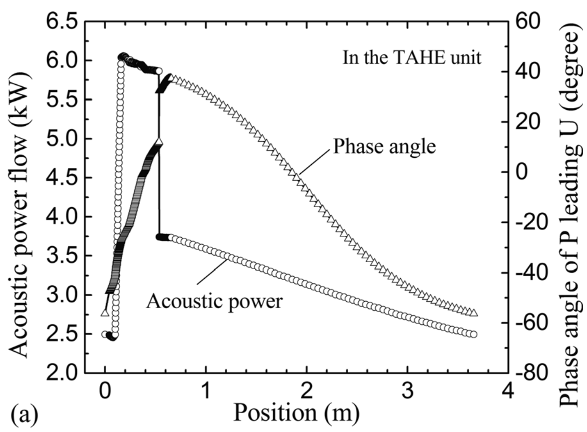
TABLE I. Main dimensions of the TAHE (unit: mm).

| Parameters | Main water-cooled heat exchanger | Regenerator of TAHE | Heater | Thermal buffer tube | Secondary water-cooled heat exchanger | Resonant tube |
|---|---|---|---|---|---|---|
| Diameter | 80 | 80 | 80 | 80 | 80 | 19 |
| Length | 60 | 60 | 80 | 125 | 40 | 3000 |

TABLE II. Main dimensions of the pulse tube cooler (unit: mm).

| Parameters | Water-cooled heat exchanger | Regenerator of pulse tube cooler | Cold end heat exchanger | Pulse tube | Flow straightener | Inertance tube |
|---|---|---|---|---|---|---|
| Diameter | 75 | 75 | 75 | 37 | 37 | 9 |
| Length | 64 | 70 | 30 | 150 | 9 | 1500 |

After the whole system was built, the experiments of the 3-unit HDTC were carried out to test practical cooling performance. The pressure and temperature measuring points are shown in Fig. 1(a). In the experiments, the temperature of the heaters is measured by three K-type thermocouples, respectively. Three calibrated platinum (PT100) resistance thermometers are located at the cold end heat exchangers to measure the cold temperature. In order to measure the added heat energy and carry out the experiment conveniently in the laboratory, the heaters are simulated with electric power. Three electrical power meters are used to measure the heating power input for each heater. Three constantan wires heated by three direct voltage sources are mounted on the three cold end heat exchangers to simulate the cooled loads. The ambient heat exchangers are cooled by 293 K circulating water. The operating pressure of helium gas in the system is 7 MPa. In the experiments, it was found that the Gedon flow[10] exists in the loop structure of the TAHE and has a serious negative impact on the performance of the system. Therefore, an elastic membrane is used at the inlet of unit 1 to suppress the Gedon flow.



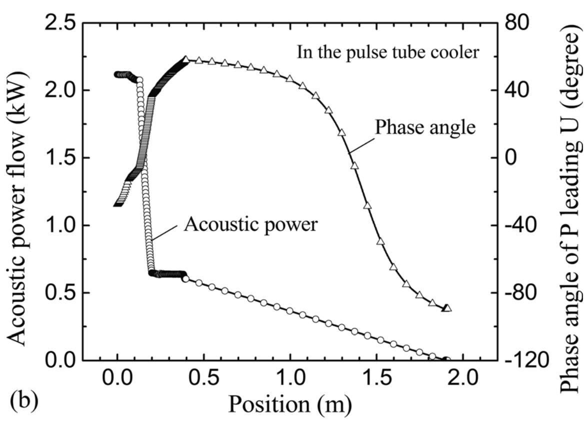




FIG. 2. Calculated results, distributions of the acoustic power flows, and the phase difference between pressure and velocity (a) in the TAHE unit and (b) in the pulse tube cooler; P means the pressure and U means the velocity.

In the experiments, the heating temperature of the three units remained the same by adjusting their added heating power. When heat is input through the heaters, helium gas inside the system begins to self-oscillate as soon as the heating temperature is above 393 K. The pressure wave amplitude increases continually with the increasing heating temperature. Then, the cooling temperature begins to decrease. After the cooling temperature decreases below 110 K, the cooling power was added to the cold end heat exchangers for measurement. The cooling temperature of the three units remained the same by adjusting their cooling power. At last, the system reached energy balance. Figure 3 presents the cooling performance of the whole system under different heating temperature. It shows the influence of the total cooling capacity and the thermal-to-cold exergy efficiency on the heating temperature. With the increase of the heating temperature, the total cooling capacity increases linearly, while the exergy efficiency increases first and then decreases. When the heating temperature is 918 K, the total cooling capacity at 110 K is 0.88 kW, with the exergy efficiency of 7.8%. The operating frequency is about 55 Hz. Under the heating temperature of 903 K, the total cooling capacity of 1.20 kW at 130 K is achieved, with the exergy efficiency of 8%. The energy density of the resonant tube is about 7054 kW/m$^2$, which is much higher than that of the large-diameter standing-wave resonator in the traditional TAHE built by Swift *et al.*

In addition, the comparison between experimental and calculated results with the cooling temperature of 110 K is given in Figs. 4 and 5. Theoretically, the identical three units of the system operate the same. However, there are some differences among the three units in the experiments. Figure 4 shows the cooling capacity at 110 K of each unit and the calculated value of one unit. Figure 5 shows the heating power of each unit and the calculated value of one unit. It can be seen that the diffidence of the three units is less than 9% in the experiments. For the cooling capacity, the experimental

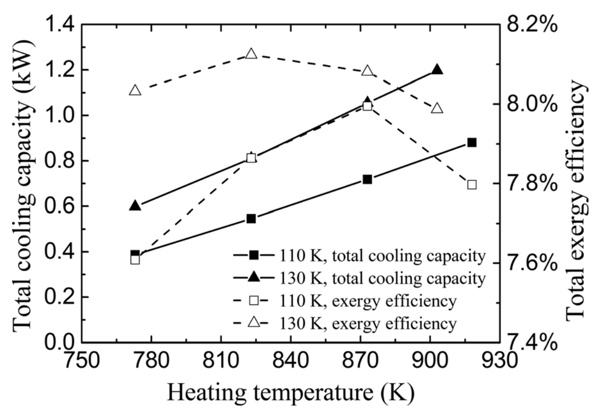



FIG. 3. Experimental results, total cooling capacity at 110 K or 130 K, and the exergy efficiency vs. heating temperature.

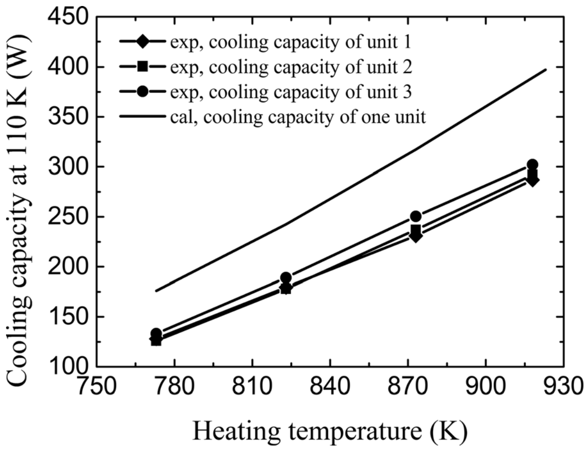



FIG. 4. Experimental and calculated results, cooling capacity of one unit at 110 K.

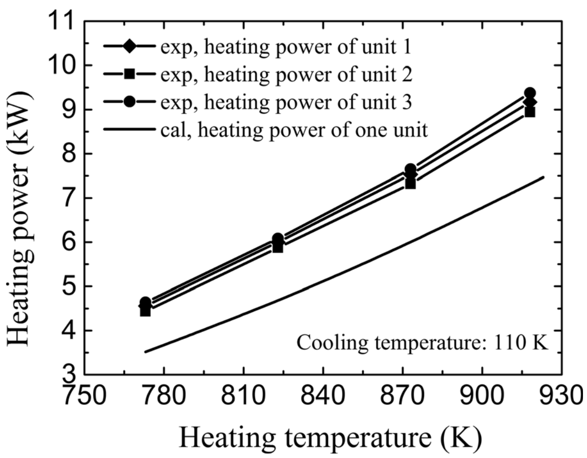



FIG. 5. Experimental and calculated results, heating power of one unit.

value is smaller than the calculated value. For the heating power, the experimental value is larger than the calculated value. The reason might be that the numerical simulation is based on one-dimensional thermoacoustic model, which ignores some losses such as: mixing gas-flowing losses from nonuniform temperature in the regenerators, thermal buffer tubes, and pulse tubes; flow losses due to multidimensional effects especially at the junctions between the components; heat transfer losses due to inefficient heat exchange in the regenerators, heaters, and heat exchangers; and heat losses due to unsatisfactory insulation of the haters. Multidimensional simulations with more realistic model and related experiments are needed to identify the loss mechanisms, which will be carried out in the near future.

In summary, a three-stage heat-driven thermoacoustic cryocooler capable of reaching cooling capacity about 1 kW at liquefied natural gas temperature was reported in the paper. The traveling-wave resonant tubes of the TAHE are much smaller than those of the traditional ones, leading to higher power density. In the verified experiment, with a total heating power of 27.5 kW, the system reached a cooling capacity of 1.2 kW at 130 K and an exergy efficiency of 8%. The total exergy efficiency of this device exceeds that of any previously reported HDTC operating at liquefied natural gas temperature range, showing a good prospect for natural gas liquefaction industry.

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