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Short Communication

A looped heat-driven thermoacoustic refrigeration system with direct-coupling configuration for room temperature cooling

Huizhi Wang [a,b], Limin Zhang [a,*], Guoyao Yu [a], Jianying Hu [a], Ercang Luo [a,*], Ying Ma [a], Chao Jiang [a,c], Xianxian Liu [a,c]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China
[c] School of Future Technology, University of Chinese Academy of Sciences, Beijing 100190, China

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Heat-driven thermoacoustic refrigeration has drawn extensive concern in the past decades due to its advantages of high reliability and external heat-driven mechanism. In such a system, heat can be firstly converted into acoustic power and then the acoustical power drives a refrigerator to generate cooling effect without any moving mechanical components. So far, most of researches on heat-driven thermoacoustic refrigeration have focused on cryogenic application, such as natural gas liquefaction [1,2]. In addition, heat-driven thermoacoustic refrigeration also plays important roles in recovering waste heat and provides an environment-friendly alternative to the current absorption chiller especially in the small-scale power range [3–7]. However, two main obstacles to use the thermoacoustic technology in practice are its relatively low cooling capacity and low cooling efficiency. Either the two-loop configuration proposed by Luo et al. [5] or the configuration of a one-unit refrigerator driven by a three-unit engine brought forward by Kees [6], they both suffer from phase-shifting tube and mismatch between the thermoacoustic engine (TAE) and thermoacoustic refrigerator (TAR). Later, Jin et al. [7] analyzed the acoustic field of the multiple units in a traveling-wave loop and verified that adjusting an area ratio of the regenerator and resonant tube could greatly increase its dimensionless acoustic impedance inside the regenerators and decrease the viscous loss in both regenerator and resonant tube. Another critical issue is acoustic power mismatch between the TAE and TAR in de Blok's configuration. In an ideal regenerator sandwiched by two heat exchangers, the acoustic power flow ratio (defined as the acoustic power flow in the hot end (or cold end) divided by the acoustic power flow in the ambient end) equals to the temperature ratio (defined as heating temperature (cooling temperature) divided by ambient temperature) when the acoustic wave propagates through it. With the cooling temperature of 10 °C and the ambient temperature of 50 °C, the acoustic power flow ratio along a TAR is 12.4% (consumption), and ideally requiring acoustic power flow ratio along three TAEs should be 1.14 times (amplification) to achieve equivalence of the recycling acoustic power flow and starting acoustic power flow in the loop. However, according to the temperature ratio with the heating temperature of 300 °C and the ambient temperature of 50 °C, the acoustic power flow ratio is about 5.58 times in three TAEs. Even considering the acoustic power flow losses in the resonant tubes, the acoustic power generated in three TAEs is much greater than the acoustic power required for the TAR. Thus, the configuration proposed by Kees [6] is much more suitable for lower temperature refrigeration.

According to the phase relationship study on regenerator sandwiched by cold heat exchanger and ambient heat exchanger, the *p*-*U* phase difference (defined as the phase angle of dynamic pressure *p* leading volume flow rate *U*) in the ambient end is negative for cryogenic temperature cooling whereas it is positive for room temperature cooling [8]. Generally, the *p*-*U* phase difference in the outlet of the TAE is positive. Thus, it indicates that the phase-shifting resonant tube between the TAE and TAR is not needed for the heat-driven thermoacoustic refrigerator (HD-TAR) operating in room temperature cooling range. In view of the above viewpoint along with better acoustic power match between the TAE and TAR, a new direct-coupling mode suitable for room temperature refrigeration is firstly proposed in this letter, aiming to obtain a high cooling efficiency and a large cooling capacity. As shown in Fig. 1, a TAE unit and a TAR unit are connected in sequence with no phase shifting components to form a conversion unit, and three identical conversion units are evenly incorporated by resonant tubes in a loop. This coupling features in compactness and simplicity.

* Corresponding authors.
E-mail addresses: liminzhang@mail.ipc.ac.cn (L. Zhang), ecluo@mail.ipc.ac.cn (E. Luo).

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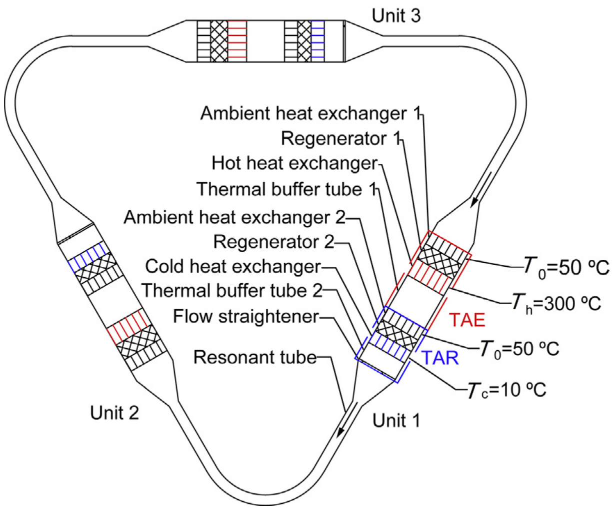

Fig. 1. The three-unit direct-coupling HD-TAR.

With these considerations and the optimization with the aid of commercial software SAGE [9], a three-unit direct-coupling HD-TAR operating in room temperature cooling range was designed, built and tested. The main component dimensions are listed in Table 1. The regenerator 1 and 2 are packed with 120-mesh stainless steel screens. The flow straightener is packed with 20-mesh copper screens. The working gas is helium with a mean pressure of 10 MPa. On account of cyclic symmetry, only one unit needs to be simulated. Fig. 2 illustrates the axial distribution of the *p-U* phase difference and acoustic power flow in one unit. According to Fig. 2, the *p-U* phase difference varies from −32° to −18° inside the regenerator 1 (Reg 1) of the TAE and it varies from 7° to 17° inside the regenerator 2 (Reg 2) of the TAR. There is no doubt that traveling wave dominates the regenerators of the TAE and TAR. The acoustic power is amplified from 2.55 to 3.90 kW in the regenerator 1 of the TAE, corresponding to a thermoacoustic conversion efficiency of 27% with the input heating power of 5.07 kW. The acoustic power is then consumed by the regenerator 2 to pump 2.18 kW heat from 10 to 50 °C. Finally, the rest acoustic power of 2.58 kW enters the next unit to be amplified, consumed and recycled. Finally, a cooling capacity of 2.18 kW and a coefficient of performance (COP, defined as cooling capacity divided by heating power) of 0.43 are obtained at the cooling temperature of 10 °C in one unit.

To validate the calculation, an experimental setup was built, which consists of a three-unit direct-coupling HD-TAR subsystem, a thermal oil heater subsystem, three propylene glycol heater subsystems and a water-circulating subsystem. The hot heat exchangers are heated by the electrical heating thermal oil and the total heating power is measured by a power meter. Similarly, the cold heat exchangers are heated by the electrical heating propylene glycol and the ambient heat exchangers are cooled by 50 °C circulating water. The operating pressure of helium gas is confined to 10 MPa in the experiments, to be consistent with the above calculations. Additionally, an elastic membrane is used to suppress the global DC flow [10] in the loop. When the heating temperature exceeds 80 °C, the direct-coupling HD-TAR begins to self-oscillate with a resonant frequency of about 56 Hz. Fig. 3 gives the experimental results of the overall cooling capacity and COP at the cooling temperature of 10 °C. When the thermal oil temperature is 300 °C, a total cooling capacity of 3.4 kW and a COP of 0.19 are obtained with a refrigeration temperature drop of 40 °C. As respect to the thermal oil temperature of 340 °C, a maximum total cooling capacity of 4.5 kW is achieved with a COP of 0.19. Compared with the previously reported HD-TARs (namely, COP is below 0.1 and cooling capacity is below 0.5 kW under the same temperature drop operating condition), the experimental results exhibit advantages in both COP and cooling capacity. However, a large deviation of approximately 50% could be readily observed between the calculated results and experimental results. For the discrepancy, one reason might consist in the unaccounted heat loss between the heat transfer fluid and solid wall in the heat exchangers. Another reason might lie in the numerical model which underestimates the loss induced by the complicated flow and heat transfer in the thermal buffer tubes and the loss by the local streaming in the regenerators due to the large aspect ratio. In the near future, multidimensional simulations by computational fluid

Table 1
Main dimensions of the direct-coupling HD-TAR (unit: mm).

	Component	Inner diameter	Length
TAE	Ambient heat exchanger 1	102	35
	Regenerator 1	107	45
	Hot heat exchanger	102	50
	Thermal buffer tube 1	110	100
TAR	Ambient heat exchanger 2	102	35
	Regenerator 2	107	35
	Cold heat exchanger	102	35
	Thermal buffer tube 2	110	50
	Flow straightener	110	5
	Resonant tube	28	3,000

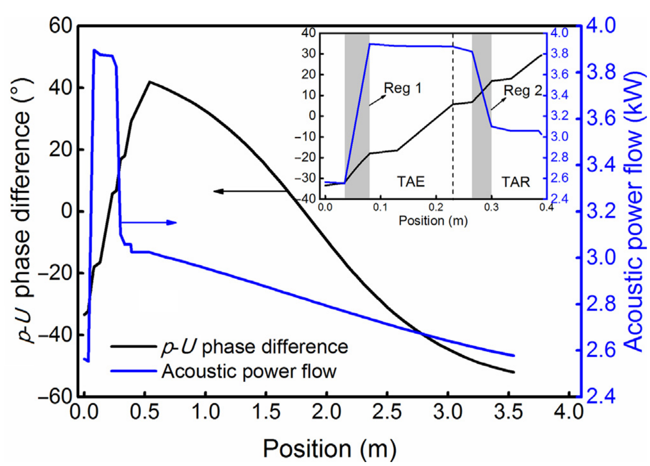

Fig. 2. The axial distributions of the *p-U* phase difference and the acoustic power flow in one unit.

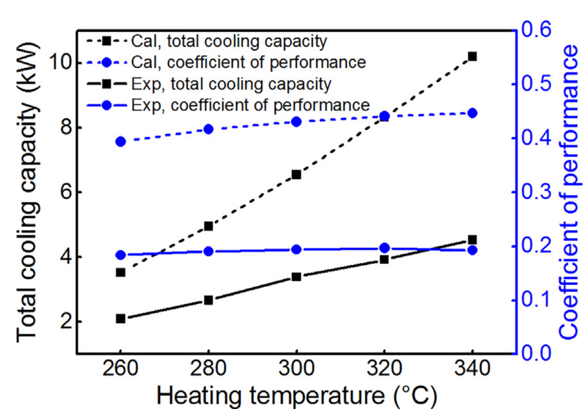

Fig. 3. Experimental and calculated results, total cooling capacity and coefficient of performance at 10 °C.

dynamics will be carried out to identify the quantity of the losses and improvements will be made accordingly.

In summary, a three-unit direct-coupling HD-TAR operating in room temperature cooling range is reported for the first time in the letter. The cooling capacity of 3.4 and 4.5 kW are obtained when the hot heat exchanger temperature is 300 and 340 °C respectively, corresponding to a COP of 0.19 for both cases, showing a good prospect for air-conditioning and refrigeration for recovering waste heat of trucks, cars and fishing vehicles in future.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

L. Z., J. H., E. L., and H. W. conceived the plan. H. W., Y. M., C. J. and X. L. performed the experiments. H. W., G. Y. and L. Z. wrote the paper.

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Huizhi Wang obtained his Bachelor Degree from the Central South University in 2015. Afterwards, he was recruited as an exam-exempted Ph.D. candidate at the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. His current research interest focuses on the heat-driven thermoacoustic refrigerator in room temperature range.

Limin Zhang obtained her Ph.D. degree in Refrigeration and Cryogenic Engineering from the University of Chinese Academy of Sciences in 2013. Since then, she has worked in the Technical Institute of Physics and Chemistry of the Chinese and Academy of Sciences. Her research focuses on thermoacoustic heat engines and refrigerators. Her most recent effort is experimental and numerical analysis of heat-driven thermoacoustic cooling systems.

Ercang Luo obtained his Bachelor Degree from Tsinghua University in 1990 and his Ph.D. degree from the Cryogenic Laboratory of Chinese Academy of Sciences in 1997. Now, he is a full professor in the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. His current research interest mainly focuses on the pulse tube cryocooler, thermoacoustically-driven refrigerator and thermoacoustic electrical generator by using solar energy and industrial waste heat.