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Experimental validation and numeric optimization of a resonance tube-coupled duplex Stirling cooler

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HIGHLIGHTS

- Resonance tube coupled duplex Stirling cooler is proposed.
- It possesses high exergy efficiency, high reliability and simple structure.
- Experimental setup has been built and no-load temperature of 110 K has been achieved.
- Working mechanism of the configuration is revealed based on thermoacoustic theory.
- System with heat-to-cooling-power exergy efficiency of 26.8% at 110 K was designed.

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ABSTRACT

Combining thermoacoustic concepts with free piston Stirling systems, this paper puts forward a resonance tube-coupled duplex Stirling cooler which is thermally driven. The novel configuration consists of a free piston Stirling engine, a free piston Stirling cooler and a resonance tube to couple them. Possessing advantages of high exergy efficiency, high reliability and simple structure, it serves as a promising candidate for small scale natural gas liquefaction by burning a small part of natural gas to liquefy the rest and long lifetime space coolers. Using the off-the-shelf components in our laboratory, an experimental setup has been built and a no-load temperature of 110 K has been achieved. As the feasibility of the concept has been verified experimentally, further calculation was done to explore the potential of the configuration. Based on Sage software, the engine and the cooler subsystem were optimized respectively, then a system level numeric model was established and the performance of the system was studied. Among the numeric results, a heat-to-cooling-power exergy efficiency of 26.8% and a cooling power of 2.4 kW were obtained at 110 K with an inner diameter 60 mm resonance tube, charging pressure of 6 MPa, hot temperature of 923 K, ambient temperature of 303 K, working frequency of 75 Hz.

1. Introduction

Utilization of natural gas is expanding with the growing concerns over environmental protection. The share of liquefied natural gas (LNG) in global gas trade has also grown steadily in recent years due to its high energy density [1,2]. Small scale plants are quite important for natural gas liquefaction as they can be used to collect gas at remote places, re-condense boil-off gas or for peak-shaving purposes, etc. Main liquefaction processes used for the small-scale liquefaction plants include cascade refrigeration, nitrogen expansion and mixture refrigeration. For on-site operation of these systems, electric power source is needed to drive the refrigeration cycle. Normally, an internal combustion engine (or turbine) burns parts of the natural gas and output mechanical power to drive a generator to produce electricity, which powers the refrigerator to liquefy the rest part of the gas [3,4]. These systems are relatively complicated and require regular maintenance.

The regenerative heat-driven cooler, including a duplex Stirling cooler and a heat-driven thermoacoustic cooler, consists of an engine driving a cooler directly. It promises advantages of high reliability and simple structure for eliminating intermediate energy conversion unit, i.e., an electric generator and a compressor. Thus, it serves as a promising candidate for small scale natural gas liquefaction.

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Nomenclature

Abbreviation

$\dot{E}$	acoustic power (W)
p_1	oscillating pressure (Pa)
U_1	volume flow rate (m^3/s)
θ_{pU}	phase difference between p_1 and U_1 (deg)
Z	acoustic impedance (Pa s/m^3)
Re []	taking the real part of a complex number
^	complex variable
*	conjunction of a complex number
||	magnitude of a complex number
η_E	relative Carnot efficiency of the engine
η_T	relative Carnot efficiency of the resonance tube
η_C	relative Carnot efficiency of the cooler
η_{tot}	heat-to-cooling-power exergy efficiency of the total system
$\dot{E}_E$	output acoustic power of the engine (W)
$\dot{E}_C$	power of the cooler (W)
$\dot{Q}_H$	heating power (W)
$\dot{Q}_C$	cooling power
T_H	heating temperature (K)
T_0	ambient temperature (K)
T_C	cooling temperature (K)
p_{comp}	oscillating pressure in the compression space (Pa)
p_{exp}	oscillating pressure in the expansion space (Pa)
U_{exp}	volume flow rate of displacer at side adjacent to compression space (m^3/s)
U_{comp}	volume flow rate of displacer at side adjacent to compression space (m^3/s)
A_{disp}	displacer area (m^2)
A_{rod}	rod of the displacer area (m^2)
Rm	equivalent mechanism damping of the displacer (N s/m)
K	stiffness of the plate spring (N/m)
M	moving mass of the displacer (kg)
ω	angular frequency (rad/s)
u_{disp}	velocity of the displacer (m/s)
R_v	viscous resistance
L	inertance
C	compliance
r_v	viscous resistance per unit length
r_k	thermal-relaxation conductance per unit length
f_k	spatial averaged thermal function
f_v	spatial averaged viscous function
T_m	mean temperature (K)
σ	Prandtl number

A classical duplex Stirling system (DSS), as shown in Fig. 1, consists of a free-piston Stirling engine, a free-piston Stirling cooler and a power piston. The power piston with a large mass is used to transfer the mechanical power from the engine to the cooler and to tune the different impedance interfaces of the engine and the cooler. It was first proposed by Sunpower corporation in the 1980s [5] and there had been several reports [6–9]. In 2009, a project was proposed by the United States National Aeronautics and Space Administration (NASA) to develop a DSS to cool down the electronics which would be launched to Venus or other planets with harsh environment [10,11]. However, in order to tune the different impedance interfaces between the engine and the cooler, the mass of the power piston must be very large, which causes a serious vibration issue and decreases the reliability of the system [12]. More importantly, a recent study by Hu et al. shows that the performance of the system is sensitive to the diameter and mechanical resistance of the power piston, which hinders its technical development [13].

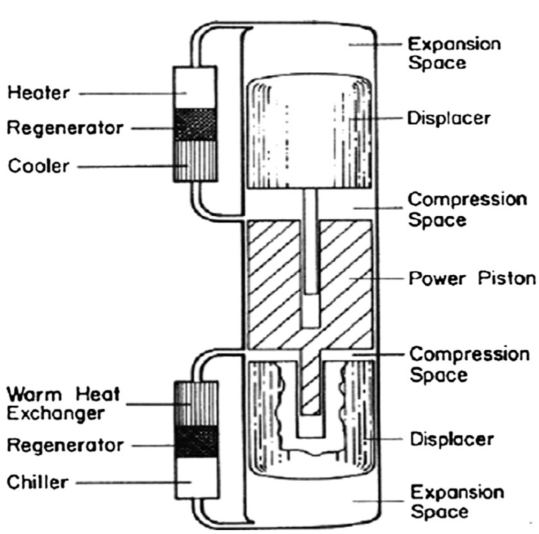

Fig. 1. Schematic of a typical duplex Stirling cooler [5].

The thermoacoustic heat-driven cooler consists of a thermoacoustic engine driving a cooler. With the advantage of no mechanical moving parts, it has been developed rapidly since it was first proposed by Radebaugh [14–16]. Inside most of the systems, the resonance tube is large and long due to dominant standing wave therein, which leads to a low specific power of the system. Most recently, de Blok [17,18] and Luo [19] have put forward a looped multi-stage thermoacoustic engine and cooler. For this configuration, the travelling wave dominated in the system, therefore the specific power was much improved. In 2015, Zhang, et al. built an experimental system that could generate 1.2 kW cooling power with a heat-to-cooling-power exergy efficiency of 8% at 130 K [20], the schematic of which is shown in Fig. 2. Nevertheless, Zhang et al. found that the DC flow existed in the engine loop and had a serious negative impact on the performance of the experiment setup. As for now, there is no reliable way to suppress the DC flow without deteriorating the performance of the system. Furthermore, the pulse tube cooler cannot recover the acoustic power in the pulse tube, so the efficiency of it is limited. Besides, high efficiency impedance match between the engine and the pulse tube cooler is difficult to achieve. Thus the reported highest heat-to-cooling-power exergy efficiency of the system by calculation is only 16.3% [21].

This paper puts forward a resonance tube-coupled duplex Stirling cooler (DSC-R). It mainly consists of an engine, a resonance tube and a cooler, as shown in Fig. 3. Compared with a classical DSS, a DSC-R uses a simple straight tube to couple the engine and the cooler subsystem, thus eliminates the supporting, vibration and sensitivity issues caused by the power piston of a DSS. It has advantages of simple structure, low vibration and high reliability. Compared to the looped multi-stage thermoacoustic heat-driven cooler (shown in Fig. 2), the DSC-R has no DC flow in the system and the efficiency of a free piston Stirling cooler is much higher than that of a pulse tube cooler [22,23]. In the following, the feasibility of the DSC-R is verified through experiments firstly,