Energy Conversion and Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Study on a basic unit of a double-acting thermoacoustic heat engine used for dish solar power

S. Zhang [a,b], Z.H. Wu [a], R.D. Zhao [a,b], G.Y. Yu [a], W. Dai [a], E.C. Luo [a,*]

[a] Key Laboratory of Cryogenics, Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

*Article history:*
Available online xxxx

*Keywords:*
Dish-solar power
Double-acting
Thermoacoustic heat engine

ABSTRACT

A double-acting thermoacoustic heat engine was invented recently by our group. It generally consists of several sequentially connected identical units. In order to apply such a system to dish-solar power generation and for better absorbing concentrated solar heat, a special-shaped heater composed of a bundle of tubes was designed. To understand the internal operating mechanism and thermodynamic performance of such a solar-driven thermoacoustic generator, a test rig having only one basic unit was designed, built and tested. Firstly, thermoacoustic conversion performance of this test rig was theoretically predicted based on linear thermoacoustic model. By adjusting the external resistance and moving mass of the expansion motor, the acoustic filed in the THE can be regulated to fulfil better energy conversion. In the simulation, a highest thermal efficiency of 51.37% and a net acoustic power of 1.6 kW under a heating temperature of 650 °C can be obtained. Then, the experiments were conducted and compared with the simulation results. A discrepancy between the theoretical and experimental results was observed and discussed, and guidance was given to improve the experimental system.



## 1. Introduction

Solar energy is the most abundant clean energy on earth. A great portion of solar energy impinging on earth is thermal radiation. However, the efficient and reliable way to use this part of solar energy is very limited. Thermoacoustic heat engines (THE) can effectively convert solar energy to acoustic power, i.e. mechanical energy, based on the thermoacoustic effect, such as the Rijke and Sondhauss effect. THEs also have some other great advantages. First, a THE generally consists of several heat exchangers, regenerator or stack and tubes, which means there are no moving components in high temperature parts, so THEs are more reliable and with a long life-time. Second, THEs are generally charged with inert gases such as helium and nitrogen, hence they are environmentally friendly. Third, in addition to solar energy, THEs can also use other low-grade energy such as waste heat. A comprehensive review of THEs was presented by Swift in 1988 [1]. The mechanism of THE can be understood based on the interaction between solid and gas particles. When heat is supplied through the hot end heat exchanger and the ambient heat exchanger is cooled, the temperature gradient along the regenerator or stack is established. The gas particle interacts with solid materials (stack or regenerator) and when the temperature gradient is large enough the oscillation occurs, realizing the enlarging or generation of acoustic power, i.e. mechanical energy. With the increasing concern of high efficient energy conversion and the utilization of low-grade energy, the researches of thermoacoustic heat engines (THE) are booming in recent decades.

There are two typical kinds of THEs — the standing wave ones and the travelling wave ones. The latter operates based on the Stirling Cycle which has the potential of high efficiency [2]. The first concept of travelling wave THE was proposed by Ceperley in 1979 [3], and later in 1998 Yazaki et al. built a modified THE based on Ceperley's work [4]. But their THEs had a serious problem of large viscous loss in the regenerator or stack. A breakthrough of travelling wave THE was made in 1999 when Backhaus and Swift [5] developed a travelling wave THE with a thermal efficiency of 30%. In 2005, Luo et al. [6] proposed an energy-focused travelling wave THE which contained a tapered resonance tube to reduce the nonlinear dissipation in the resonance tube and the pressure ratio reached 1.4. In 2010, Kees de Blok proposed a novel 4-stage travelling wave THE [7]. The multi-stage configuration is beneficial for even higher energy density and larger power capacity. There are also some real applications for THEs. Since 1994, a project focusing on the application to natural gas liquefier driven by THE has been conducted [8]. A thermoacoustic generator for

* Corresponding author. Tel./fax: +86 10 82543750.
*E-mail address:* ecluo@mail.ipc.ac.cn (E.C. Luo).

http://dx.doi.org/10.1016/j.enconman.2014.02.065
0196-8904/

**Nomenclature**

*Abbreviation*

| | |
|---|---|
| THE | thermoacoustic heat engine |
| 1-D | one dimension |

*Symbols*

| | |
|---|---|
| $a$ | speed of sound, m/s |
| $A$ | area, $m^2$ |
| $B$ | magnetic field, T |
| $c$ | heat capacity per unit mass, J/kg K |
| $D$ | diameter, m |
| $E$ | acoustic power, W |
| $f$ | frequency, Hz |
| $f$ | spatially averaged diffusion function |
| $\dot{H}$ | total energy power, W |
| $i$ | $\sqrt{-1}$, imaginary unit |
| $I$ | input current, A |
| $k$ | thermal conductivity, W/m K |
| $K$ | spring constant, N/m |
| $l$ | length, m |
| $L$ | electrical inductance, H |
| $M$ | mass of piston, kg |
| $p$ | pressure amplitude, MPa |
| $P$ | working pressure, MPa |
| $\dot{q}$ | heat input per unit length, W/m |
| $Q$ | heat transferred, W |
| $R$ | electrical resistance, Ω |
| $R$ | mechanical resistance, N s/m |
| $T$ | temperature, K |
| $U$ | volume flow rate, $m^3/s$ |
| $V$ | input voltage, V |
| $Z$ | impedance, Pa s/$m^3$ |

*Greek symbols*

| | |
|---|---|
| $\gamma$ | specific heat ratio |
| $\delta$ | penetration depth, m |
| $\theta$ | phase delay, ° |
| $\xi$ | correction factor of channel solid thermal parameters |
| $\rho$ | gas density, kg/$m^3$ |
| $\sigma$ | Prandtl number |
| $\tau$ | transduction coefficient |
| $\omega$ | angular frequency, $s^{-1}$ |
| Re [] | real part of |
| Im [] | imaginary part of |
| ∼ | conjugation of a complex quantity |
| \| \| | amplitude of a complex quantity |

*Subscript*

| | |
|---|---|
| 1 | first order |
| 2 | second order |
| *e* | electrical |
| *m* | mean |
| *m* | mechanical |
| *p* | isobaric |
| *s* | solid |
| $\kappa$ | thermal |
| $\nu$ | viscous |
| *com* | compressor |
| *gen* | expansion motor |
| *in* | input |
| *in* | inlet |
| *net* | net |
| *out* | outlet |

applications such as LED lightening or charging battery driven by waste heat from stove has been constructed recently [9]. However, the above-mentioned THEs have a common problem of having a long resonant tube, which has limited the further application of THEs. Thus, in recent time our research group has presented a concept of double-acting multi-cylinder travelling wave THE [10] to solve the problem. It is schematically shown in Fig. 1. This engine mainly consists of several sequentially connected basic units in a closed loop. Each basic unit is composed of main components of a THE sandwiched by the compression and expansion pistons. "Double-acting" means one piston works as compression piston to the previous THE unit and simultaneously as expansion piston to the last unit. This novel configuration not only has the traditional advantages of THEs but also some other advantages as stated below. This double-acting THE is capable of producing larger power because of its multi-cylinder configuration. In addition, several symmetric units cascading in one loop is equivalent to several THEs working together, hence the configuration is relatively compact. Taking advantages of high inertia of the pistons this configuration also eliminates the long resonant tube. Recently, we are considering constructing a double-acting THE for dish-solar power generation, aiming at a 5 kW acoustic power output which is for used to drive electric expansion motors. In order to effectively absorb the concentrated solar heat, a special-shaped heater composed of a bundle of tubes was designed. Different from the generally-used shell-and-tube and plate-fin heat exchangers, this heater has much longer and less tubes and the shape is irregular which will result in problems of jet-flow and turbulence. The whole system is complicated, but it consists of several symmetric units which mean each basic unit should have the same performance. Hence in order to study the advantages as well as drawbacks, and find ways to improve it, a test rig having only one basic unit which is representative to the system was designed, built and tested. Firstly, a numerical analysis was carried out to study the thermal conversion performance. Then experiments

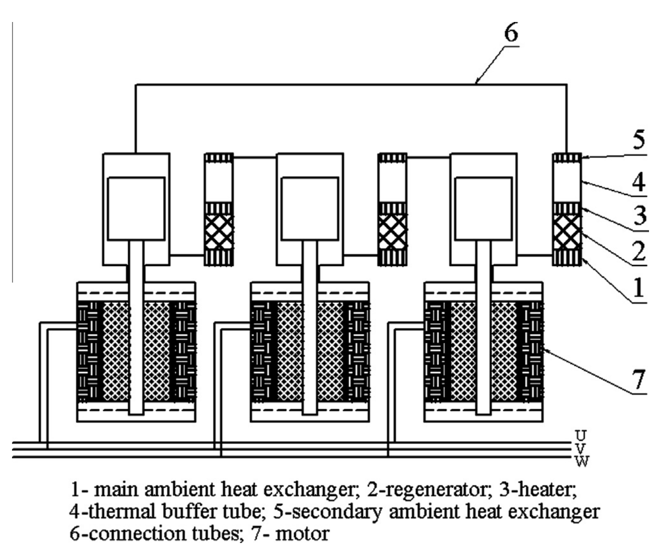


**Fig. 1.** Schematic of double-acting THE.

Please cite this article in press as: Zhang S et al. Study on a basic unit of a double-acting thermoacoustic heat engine used for dish solar power. Energy Convers Manage (2014), http://dx.doi.org/10.1016/j.enconman.2014.02.065