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Investigation on the thermoacoustic conversion characteristic of regenerator

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HIGHLIGHTS

- A novel experimental setup was developed to investigate the regenerator performance.
- This approach was proved to control the phase angle of the engine efficiently.
- A highest thermal efficiency of 35.6% was achieved with random fiber regenerator.
- Flow resistance and heat transfer area are crucial to design a regenerator.

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ABSTRACT

Regenerator is the core component in the regenerative heat engines, such as thermoacoustic heat engine, and Stirling heat engine. The regenerator has a porous configuration, in which the thermoacoustic effect happens between the working gas and solid wall converting heat into acoustic work. In this paper, a novel experimental setup was developed to investigate the thermoacoustic conversion characteristic of the regenerator. In this system, two linear motors acted as compressors to provide acoustic work for the regenerator and the other two linear motors served as alternators to consume the acoustic work out of the regenerator. By changing the impedance of the alternators, the phase difference between the volume velocities at the two ends of the regenerator could be varied within a large range. In the experiments, the influence of phase difference, heating temperature and different materials on the performance of the regenerator were studied in detail. According to the experimental results, the output acoustic power increased when the phase difference between velocities of the compression and expansion pistons increased within this phase angle range. And the thermoacoustic efficiency had different optimum values with different heating temperatures. Additionally, it also shows that flow resistance and heat transfer area were very important to the performance. In the experiments, a maximum output acoustic power of 715 W and a highest thermoacoustic efficiency of 35.6% were obtained with stack and random fiber type regenerators respectively under 4 MPa pressurized helium and 650 °C heating temperature. This work provides an efficient way to investigate the thermoacoustic conversion characteristic of the regenerator. It also provides some clues to the regenerator design.

1. Introduction

Regenerative heat engines, such as thermoacoustic engines and Stirling engines, are capable of converting external heat to mechanical work with high efficiency. This mechanical work can be further used to produce electricity or realize heat pumping from low temperature to high temperature. Thereby, these engines are quite suitable for solar energy and industrial waste heat application areas. Nowadays, more and more researchers are paying their attentions on these machines.

Regenerator is the core component in the regenerative heat engines, in which high-frequency oscillating flow gas converts heat absorbing from the solid to acoustic work. This phenomenon is called the thermoacoustic effect [1]. Due to a porous structure, the flow and heat exchanging conditions in the regenerators are very complicate. Thermoacoustic theories were founded by Rott [2–4], Swift [5], Backhaus [6] and Xiao [7–9] to reveal the thermoacoustic conversion characteristic of the regenerator and other components. It showed that the thermoacoustic conversion

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Nomenclature

Symbols

A	area (m^2)
A_h	heat transfer area (m^2)
c_p	isobaric heat capacity per unit mass (J/kg/K)
D	diameter (m)
d_{wire}	wire diameter (m)
d_{gap}	flow channel gap of the stack (m)
i	imaginary unit
K	spring constant (N/m)
k	thermal conductivity (W/m/K)
L	electrical inductance (H)
l	length (m)
m	moving mass (kg)
P_0	mean pressure (Pa)
p	pressure amplitude (Pa)
Q	heating power
R_m	mechanical damping factor (kg/s)
R	load resistance (Ω)
r	resistance of the alternator winding (Ω)
T	temperature (K)
U	volume velocity (m^3/s)
V	volume (m^3)
V_b	volume of back space (m^3)
W	acoustic power (W)
x	displacement (m)
β	thermal expansion coefficient (K^{-1})
γ	specific heat ratio
η	thermoacoustic efficiency
θ	phase angle (°)
ρ	density, (kg/m^3)
τ	transduction coefficient (N/A)
Φ	porosity of regenerator
ω	angular frequency (rad/s)

characteristic of the regenerator is mainly determined by the acoustic field, temperature gradient, structure, and so on. The acoustic field means the phase difference between the pressure and the velocity waves. Experimental and numerical works also have been performed to describe the regenerator. In 2002, Ueda et al. studied the acoustic field of the regenerator in a loop configuration engine [10]. In 2004, Biwa et al. investigated the thermoacoustic conversion performance of the regenerator driven by a loudspeaker [11]. They adjusted the position of the regenerator in the experiments trying to obtain different acoustic fields of the regenerator. In 2013, Lawn investigated the acoustic pressure losses in the regenerator [12] and Kato et al. studied the regenerator efficiency of Stirling engine [13]. However, in these experiments, the obtained acoustic fields were very limited and the experiment processes were inconvenient. In recent years, Computational Fluid Dynamics (CFD) technology has been applied to investigate the regenerative systems, including engines [14–16] and cryocoolers [17,18]. However, the numerical results also need further verification by experiments. In this paper, in order to deeply and conveniently investigate the thermoacoustic conversion characteristic of the regenerator with different acoustic field conditions, a novel experimental setup was developed and the performance of the regenerator was evaluated.

In the following sections, the experimental setup is presented first as well as the typical structural parameters. Secondly, the experimental principle is introduced. Then, the experimental investigation is presented in detail. Lastly, some conclusions are made.

2. Experimental apparatus

Fig. 1 shows the schematic and photograph of the experimental apparatus developed in this paper. As demonstrated in Fig. 1(a), the setup consists of a linear compressor, a linear alternator and a thermoacoustic engine sandwiched between them. The engine includes a compression space, a main ambient heat exchanger, a regenerator, a hot-end heat exchanger, a thermal buffer tube, a secondary ambient heat exchanger and an expansion space. The hot-end heat exchanger and main ambient heat exchanger provide a temperature gradient along the regenerator, which is required by the thermoacoustic conversion effect. The thermal buffer tube is used to avoid the alternator piston working within a high temperature environment. The compressor is used to provide acoustic work for the regenerator, the acoustic work will be amplified by the regenerator under the temperature gradient. The alternator converts the acoustic work outputted by the regenerator into electricity, which will be consumed by a load resistance connected with the alternator. The working principle of the system will be introduced in next section.

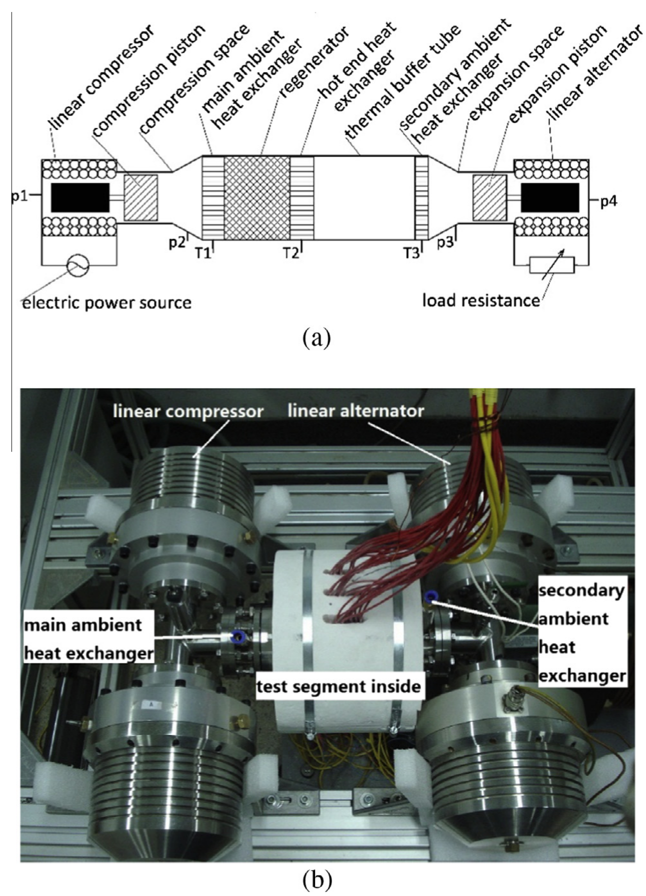

Fig. 1. Experimental setup: (a) schematic, (b) photograph.