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Study of a liquid-piston traveling-wave thermoacoustic heat engine with different working gases

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ABSTRACT

Thermoacoustic technology is becoming increasingly attractive because of its high reliability and environmental friendliness. The double-acting traveling-wave thermoacoustic heat engine using liquid pistons, proposed by our group, can improve the thermoacoustic conversion efficiency further and yield a more compact engine. In this study, three different environmentally friendly working gases, helium, nitrogen and carbon dioxide, were studied experimentally, primarily in terms of thermoacoustic conversion parameters, including the onset temperature, the resonant frequency, and the pressure ratio, under different working mean pressures. Results show that the working gas significantly influences thermoacoustic performance. They also suggest a very encouraging application prospect for this novel thermoacoustic heat engine. Finally, we performed theoretical analysis to better understand thermoacoustic conversion with the different working gases.

1. Introduction

Environmental impact and energetic efficiency have become central concerns of energy production in recent years. Modern internal combustion engines consume large amounts of gasoline, coal, and other non-renewable resources. The resulting air pollution is both harmful ecologically and unsustainable in the long term. Thermoacoustic heat engines are a kind of external combustion engine with a highly variable heating temperature, potentially amenable to exploiting low-grade heat sources like industrial waste heat or solar energy. The working gas in such engines (e.g., helium or nitrogen) is also eco-friendly. The engines are relatively more durable, thanks to having no moving parts.

Our novel double-acting traveling-wave thermoacoustic engine with liquid pistons (Fig. 1) can improve the thermoacoustic conversion efficiency further, allowing more compactness and better load matching [1], when compared with traditional thermoacoustic engines. By using gas–liquid coupling vibrations [2], it greatly enhances the pressure amplitude, and effectively reduces the resonant frequency. Each heat engine unit in the looped, double-acting system requires no phase-adjusting device and can operate in an ideal acoustic field [3].

In a thermoacoustic system, the working gas not only serves as a carrier for transferring and storing heat and acoustic energy, but is also the key component of the thermoacoustic conversion process [4]. The heat penetration depth and the viscous penetration depth of the working gas play important roles in the conversion processes: the former for driving the thermoacoustic effect, and the latter for dissipating kinetic energy. Reducing the viscous penetration depth and increasing the heat penetration depth in this manner can improve the overall efficiency. The ratio between these two penetration depths varies as $Pr^{1/2}$, and therefore the gas used in the working medium should have a low Pr [5]. Another way to improve the efficiency is to use a working gas with a small speed of sound. For these reasons, helium, nitrogen and carbon dioxide have been widely used in thermoacoustic systems, and their performance parameters are listed in Table 1.

This study examined these three environmentally friendly working gases experimentally, focusing on a few specific thermoacoustic conversion parameters: the onset temperature, the resonant frequency, and the pressure ratio, under different working mean-pressure conditions. The results show that the working gas has a significant influence on the thermoacoustic performance, and theoretical analysis compared thermoacoustic conversion based on the different working gases. Each of the three working gases has advantages and disadvantages, and the best working gas therefore depends on the particular application considered.

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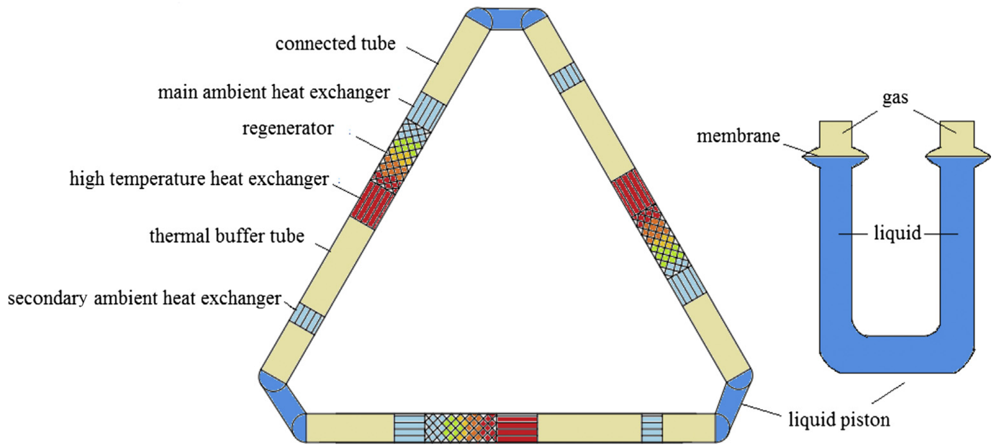

Fig. 1. Schematic diagram of the liquid-piston travelling-wave thermoacoustic heat engine.

2. Experimental device

The experimental device of the double-acting traveling-wave thermoacoustic engine with liquid pistons is shown in Fig. 2. The diameter of each component is 50 mm, and the designed heating power, the designed output acoustic power, and the mass of water in a single engine are 3 kW, 1 kW and 3 kg, respectively. During the experiments, the heating temperature was measured by nickel–chromium/nickel–silicon sheathed thermocouple, the mean pressure by a piezoresistive pressure sensor (Kunlun Coast, Beijing), and the oscillating pressure by another piezoelectric pressure sensor (PCB Piezotronics, Inc.).

To reduce vibrations and for safety reasons, the engine was suspended during the experiments and the new U-type resonator with a membrane, shown in Fig. 3, was used. This resonator design completely isolates the gas and the water and controls the DC in the loop [6]. As the length of the air tube remained constant, the engine was stable. We also increased the membrane cross-sectional area to reduce the displacement amplitude and to make the membrane more durable.

Each gas used in the thermoacoustic process has its optimal relative hydraulic radius [7]. The appropriate regenerator hydraulic radius must be chosen according to the characteristics of the working gas in order to optimize thermoacoustic conversion.

The initial design of the regenerator of this engine being destined for helium, we chose a 120-strand stainless-steel mesh, with a porosity of approximately 73%. Fig. 4 shows the regenerator and the stainless steel mesh. This setup is suboptimal for nitrogen or carbon dioxide, but we can nonetheless use it to analyze the effect of these gases on thermoacoustic performance. Future experimental studies will use regenerators with a structure size optimized for nitrogen, carbon dioxide, or any other working gas.

Table 1
Performance parameters of three working gases.

	Viscous penetration depth (10^{-5} m)	Heat penetration depth (10^{-5} m)	Pr	Speed of sound (m/s)
Helium	22.2	27	0.68	819
Nitrogen	7.98	9.44	0.71	345
CO_2	6.02	7.54	0.64	286

3. Experimental results and analyses

3.1. Helium

Helium is a common working gas used in thermoacoustic systems because its large heat penetration depth and low Pr, together with a low boiling point, makes it the most suitable working

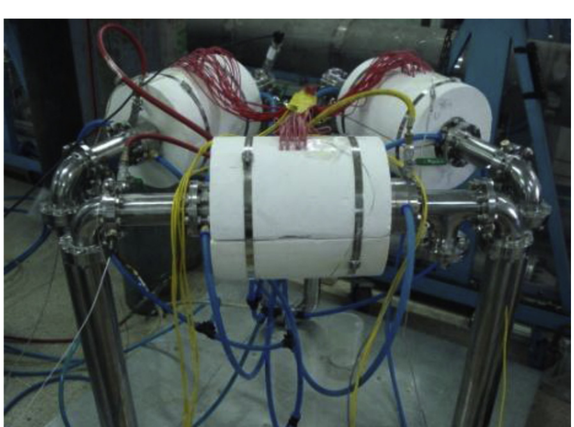

Fig. 2. Experimental system.

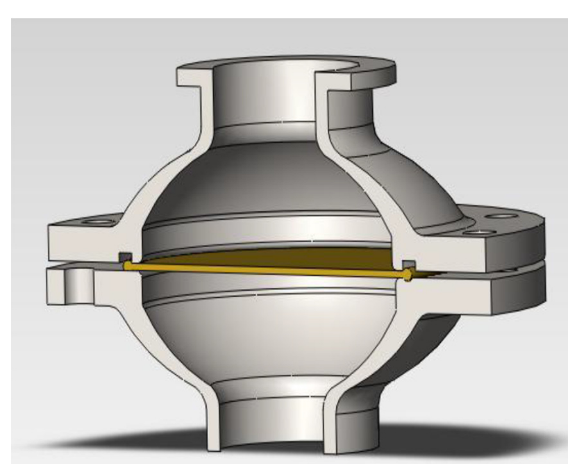

Fig. 3. Membrane configuration.