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Experimental investigation on a thermoacoustic engine having a looped tube and resonator

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Abstract

The purpose of this paper is to study the impact of regenerator hydraulic radius, resonator length, and mean pressure on the characteristics of the tested thermoacoustic engine, which has a looped tube and resonator. Two different acoustic oscillations are observed in the tested engine [Yu ZB, Li Q, Chen X, Guo FZ, Xie XJ, Wu JH. Investigation on the oscillation modes in a thermoacoustic stirling prime mover: mode stability and mode transition. Cryogenics 2003;43(12):687–91]. In this paper, they are called two acoustic modes, high frequency mode (with a frequency independent of the resonator length) and low frequency mode (with a frequency depending on the resonator length). Experimental results indicate that the relative penetration depth (the ratio of penetration depth over hydraulic radius) plays an important role in the excitation and pressure amplitude of the two acoustic modes. For each tested regenerator hydraulic radius, there is a measured optimal relative penetration depth, which leads to the lowest onset temperature difference. Note that, in the tested engine, the measured optimal relative viscous penetration depths are in the range 3–5 (for low frequency mode). Furthermore, experimental results also show that the resonator length affects the presence of high frequency mode in this engine.

Keywords: Thermoacoustic engine; Relative penetration depth; Acoustic mode

1. Introduction

A thermoacoustic engine (TAE) consisting of a looped tube and resonator, with the thermoacoustic core in the looped tube, was for the first time constructed and studied by Backhaus and Swift [2,3]. It was called thermoacoustic Stirling engine. With Helium as working gas, the engine worked at a frequency of 80 Hz, which was a quarter-wavelength mode. At its most efficient operating point, the efficiency was 0.30. In 2001, Biwa et al. also described a TAE of this type [4–6]. Two modes, traveling wave mode (273 Hz) and standing wave mode (100 Hz), were observed in their system. Furthermore, with increasing heat supplied to the engine they found a transition from standing to traveling wave mode through the quasi-periodic states involving both standing and traveling wave modes [4,5]. In 2002, Ueda et al. [7,8] constructed another TAE of this kind with Pyrex glass tubes. They measured pressure and velocity simultaneously. The experimental results indicated that the phase lead φ of U relative to p in the regenerator was −20, but not a traveling wave phase ($\varphi = 0$) as reported by Backhaus and Swift [2,3]. Moreover, they studied experimentally the optimization of the length ratio of the resonator and the looped tube as well as the position of the connecting point between the resonator and the looped tube.

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We also constructed a TAE having a looped tube and resonator in 2001 [9]. Two different acoustic modes, high frequency mode (HFM, 528 Hz) and low frequency mode (LFM, 76 Hz), were observed in this TAE, when the working gas is nitrogen [1]. The transition from HFM to LFM was investigated in detail for a 150-mesh regenerator. The results indicated that the mean pressure p_m was an important control parameter influencing the mode stability in the TAE. (Note that the "modes" mentioned in this paper are defined only by the different frequencies which distinguish the two kinds of oscillations in the tested TAE. HFM denotes the oscillation with a frequency independent of the resonator length, while LFM denotes the oscillation with a frequency depending on the resonator length.)

In this paper, we concentrate on the effect of the regenerator hydraulic radius r_h, resonator length, and mean pressure on the excitation and performance of the two modes. Note that the role of the relative penetration depth was studied in detail. Furthermore, the presence of the HFM and the means to eliminate it in the tested engine are studied and discussed.

2. Experimental apparatus

The tested TAE is schematically shown in Fig. 1. Its details can be found in previous papers [1,9,10]. The resonator includes a straight stainless-steel pipe and a cavity, which are of 35 and 70 mm inner diameter, respectively. The length of the straight pipe L_2 can be changed. The mean length of the looped tube (L_1) is 0.708 m. The regenerator is a pile of stainless steel gauze, the mesh of which is given by the manufacturer as shown in Table 1. Five piezoelectric pressure sensors for measuring the pressure amplitudes are placed in the looped tube and indicated by P_1–P_5 in Fig. 1. Four thermocouples (T_1–T_4) are equidistantly placed along the length of the regenerator from the hot to the cold end [1].

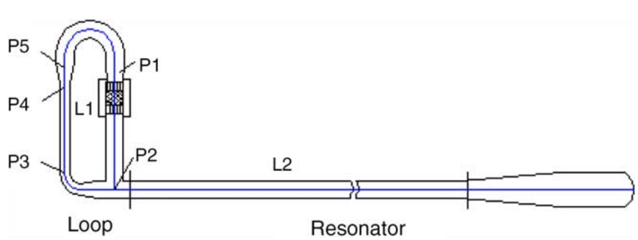

Fig. 1. Schematic illustration of the tested TAE.

3. Experimental results

3.1. Regenerator hydraulic radius

In the following experiments, the working gas was nitrogen. Its mean pressure p_m was varied from 0.1 to 2.6 MPa (absolute pressure), with steps of 0.1 MPa. The resonator length was fixed at 1.138 m. We measured the relationship between onset temperature difference ΔT_{onset} and p_m by varying the hydraulic radius r_h. It was found that the minimum heating power needed to make the tested TAE oscillate varied when either the mean pressure, the working gas, or r_h were changed. We chose a heating power (208 W), which makes the tested TAE oscillate at all test conditions, for obtaining comparable experimental results over the full variation range of these operating conditions.

For a 60-mesh regenerator, two measured curves are shown in Fig. 2(a). The experimental phenomena were similar to those of the 150-mesh regenerator investigated previously [1]. There was a critical mean pressure $p_{m,cri}$ (about 0.24 MPa), above which the HFM (536 Hz) could be observed, and below which the engine began to oscillate in the LFM (76 Hz), and then reached stationary conditions. Oscillation in the HFM could reach stationary conditions only if the temperature difference was strictly controlled in the region between the two intersecting curves. Otherwise, the oscillating mode would change from HFM to LFM through the quasi-periodic state involving both HFM and LFM. On the other hand, there was an optimal mean pressure $p_{m,opt}$,

Table 1
Measured critical mean pressure, optimal mean pressure, lowest onset temperature difference, and optimal relative viscous penetration depth $(\delta_v/r_h)_{opt}$ when the r_h of the regenerator is varied

Mesh	60[a]	80	120	150	200	250	300	350
Hydraulic radius r_h (μm)	97.3	71.1	47.4	37.7	27.2	22.3	18.2	15.6
Critical mean pressure[b] $p_{m,cri}$ (MPa)	0.24	0.45	0.6	1.0	1.3	2.3	–	–
Optimal mean pressure $p_{m,opt}$ (MPa)	–[c]	0.26	0.4	0.6	0.6	0.8	1.6	2.1
ΔT_{low} (K)	–	209	174	226	149	139	105	314
$(\delta_v/r_h)_{opt}$	–	3.0	3.6	3.8	4.6	4.7	4.1	5.4

[a] Meaning 60 wires per inch in each of the two perpendicular directions of the weave.
[b] Absolute pressure.
[c] Not observed.