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Explanations on the onset and damping behaviors in a standing-wave thermoacoustic engine

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HIGHLIGHTS

- A thermodynamics analysis is carried out to understand the onset process.
- A new explanation is proposed to understand the onset and damping behaviors.
- The experimental results at different tilted angles confirms the explanations.

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ABSTRACT

In order to understand the onset and damping behaviors of the thermoacoustic engine, a series of experiments and a simplified thermodynamics analysis are carried out. It is found that both the efficiency and the acoustic power of the gas increase with the increase of the gas-stack heat transfer coefficient, the gas displacement amplitude and the heating difference. Before onset, since the gas-stack heat transfer coefficient of natural convection and the amplitude of the gas are very low, a higher temperature difference is required to produce enough acoustic power to overcome the thermal and viscous dissipation and to excite oscillation. In the damping process, the gas-stack heat transfer coefficient and the amplitude of the gas are much higher because of the thermoacoustic oscillation. So a lower temperature difference is required to maintain the oscillation. In order to further verify this analysis, the experimental investigations are carried out at different tilted angles ranging from 90° to −90°. As the tilted angle decreases, the gas-stack heat transfer coefficient of the natural convection increases. The experimental results show that both the onset and damping temperature differences decrease with the decreasing of the tilted angle, which further confirms the above explanations.

1. Introduction

Thermoacoustic engine is novel thermodynamic machinery which converts thermal energy to acoustic power based on the thermoacoustic effect. Compared with traditional engines, thermoacoustic engine has three most important advantages: (1) it has no moving parts except for the working gas undergoing the acoustic motion, which makes the structure simple and highly reliable; (2) the working gas is usually noble gases, such as He, Ar, Xe, N_2, CO_2, etc, which are environmentally friendly; and (3) it can be driven by low-grade heat source, including solar energy, industrial waste heat, geothermal energy, etc. These advantages attracted both academic and industrial interests in the last three decades [1–4]. Thermoacoustic technology (including thermoacoustic heat engine [5], thermoacoustic refrigerator [6], thermoacoustic separation [7], and thermoacoustic electric generator [8]) has made rapid development and will receive more and more attentions in the future. The most powerful thermoacoustic Stirling heat engine has achieved an efficiency of 30%, which is comparable to that of the common internal combustion engines and piston-driven Stirling engines [9].

It is one of the most potential applications for thermoacoustic engine to utilize low-grade heat source to drive a refrigerator [10–13] or electrodynamic linear alternator [8]. Solar energy, which is abundant, pollution-free and inexhaustible, is considered to be the most convenient heat source and has attracted more and more research interests [14,15]. As a result, solar powered thermoacoustic engine, having both the advantages of solar energy and thermoacoustic engine, is expected to have a wide application in the future. The first solar-driven thermoacoustic engine was

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designed and constructed by Chen and Garrett in 1998 [16]. The measured sound pressure level can reach 120 dB easily on a clear day. After that, they built a large solar powered thermoacoustic cooler [17]. Its acoustic power was generated by solar radiation in the thermoacoustic engine and subsequently used to pump heat from external loads in the thermoacoustic refrigerator. The device achieved cooling although compromised by gas leakage and thermal losses. In 2000, Adeff and Hofler [18] built a solar driven thermoacoustic refrigerator. When the heating temperature was 450 °C, 2.5 W of cooling power was produced at a cold temperature of 5 °C. In order to explore solar thermal electric power generation and solar powered refrigerator, our research group designed a two-axis tracking solar powered thermoacoustic engine in 2009 [19]. However, the self-excited oscillation was impeded and the onset temperature of the thermoacoustic engine was elevated to more than 500 °C for gas leakage and thermal losses. Therefore, it is imperative to investigate the self-excited oscillation process and the onset and damping behaviors of thermoacoustic engine powered by solar energy.

In fact, the onset mechanism of thermoacoustic oscillation is always a hot research topic, because a lower onset temperature means that we can utilize lower-graded heat source. The mechanism of thermoacoustic oscillation has been recognized gradually since the discovery of thermoacoustic effect. In 1887, Rayleigh [20] pointed out that “if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged.” This explanation is referred to as “Rayleigh criterion” and is considered to be a rational explanation of thermoacoustic effect by now. Rayleigh criterion gives a qualitative understanding on how to maintain oscillation in a thermoacoustic engine. Then Rott [21] and Swift [22] gave a quantitative study on the building of thermoacoustic oscillation and proposed “critical temperature gradient” [22], which was the boundary between the heat pump and prime mover functions of thermoacoustic engines.

Since 1992, Atchley et al. [23–25] had conducted series of studies on the onset behavior and a quality factor was proposed to measure the transition to onset in a thermoacoustic prime mover. Arnott et al. [26] showed that the instability occurs when $\overline{W_s} + \overline{W_{\mathrm{ext}}} \geq 0$, where $\overline{W_s}$ is the acoustic power produced in the stack, $\overline{W_{\mathrm{ext}}}$ is the work loss by thermal and viscous dissipation in the system and found the normalized onset temperature gradient.

However, the above researches were based on the assumption that the damping point coincided with the onset point. In 1998, Zhou and Marsubara [27] carried out an experimental study on the onset process of thermoacoustic prime mover and found that the onset and damping temperatures were different from each other. Then Chen and Jin [28] conducted detailed study on the onset and damping behavior in a thermoacoustic prime mover and found that the damping temperature lagged the onset temperature. Based on this, a hysteretic loop, due to the temperature difference between the onset point and the damping one, was recognized for the first time. This hysteresis phenomenon was discussed by analogy to other phenomena widely found in nature, such as light induced reaction, boiling heat transfer and the magnetization effect. However, no reasonable interpretation had been given on the fundamental cause of the discrepancy between the onset and damping temperatures and the hysteretic loop in thermoacoustic oscillation. In 2003, Yu et al. [29] observed a low frequency mode and a high frequency mode in the onset process of a thermoacoustic Stirling engine. In 2006, Qiu et al. [30] proposed a new method to decrease the onset temperature of thermoacoustic engine by introducing a pressure disturbance. Based on plenty of experimental results, they predicted that the onset temperature should approach the damping temperature under the disturbed condition. Most recently, Wang et al. [31,32] used infrared imaging as a visualization method for the first time to characterize the onset mechanism and found that Gedeon streaming had significant influence on the axial temperature distribution in the onset and damping processes. Numerical simulation method was also used to investigate the onset characteristics in standing wave thermoacoustic engines [33–35].

All of the existing results have greatly promoted the research of the onset and damping mechanisms of thermoacoustic oscillation. However, further explanations are still needed on the fundamental cause of the difference between the onset and damping temperatures, the hysteretic loop in thermoacoustic oscillation, and the decreasing of onset temperature by a pressure disturbance. In order to decrease the onset temperature and improve the thermoacoustic conversion efficiency and apply our solar powered thermoacoustic engine to a thermoacoustic refrigerator, experiments have been performed in a standing-wave thermoacoustic engine in this paper. Firstly, three fundamental questions about the onset and damping phenomena are raised and discussed in detail. Then a simplified thermodynamics analysis is performed and an integrated explanation on the onset and damping behaviors is proposed. Finally, a series of experiments are carried out at different tilted angles ranging from −90° to 90° to further verify the above explanations.

2. Experimental apparatus

The experiments presented in this paper are based on a standing-wave thermoacoustic engine as shown in Fig. 1. The apparatus includes six main parts: hot buffer, hot heat exchanger, parallel-plate stack, cooling heat exchanger, resonance tube, and resonance cavity. Seven temperature sensors are used to measure

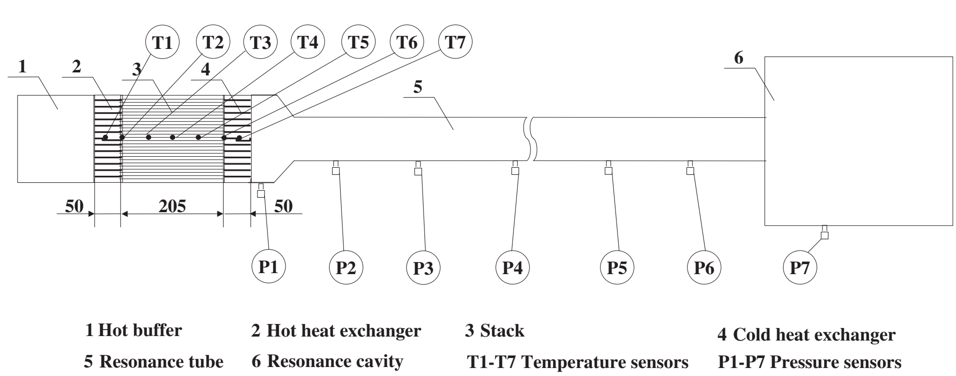

Fig. 1. Schematic of the standing-wave thermoacosutic engine.