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Experimental observation on a small-scale thermoacoustic prime mover*

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Abstract: A miniature thermoacoustic prime mover, consuming heat to radiate sound, may be considered as a potential way of heat management in microcircuits because of its simplicity and stability. A prototype with variable resonant tube length of 10 to 25 cm was built, and experiments were carried out to observe its performance, such as onset temperature, oscillation amplitude and operating frequency. The results with atmospheric air showed that proper structures and operating conditions can make the system start an oscillation at a temperature lower than 100 °C, which proves the feasibility of potential usage in electronic units. The influences of stack position, heat input power or tube inclination on the oscillation amplitude, onset temperature and operating frequency are also presented.

Key words: Thermoacoustics, Miniaturization, Onset temperature
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INTRODUCTION

In the past 30 years, much progress has been achieved in thermoacoustic research (Backhaus and Swift, 1999; Garrett *et al.*, 1993; Zhou and Matsubara, 1998). However, most of them were still at laboratory scale. Aiming for industrial applications, recent researches began to pay attention to larger or smaller scale systems. The problem of heat dissipation from miniature high-tech products (say ICs, MEMS) attracts more attention due to the higher heat flux accompanying the rapid function and performance upgrade. Since the late 1990s, several institutions started work on miniaturization of thermoacoustic engines. Early effort included a research project named HERETIC (Heat Removal by Thermo-integrated Circuits) supported by the Defense Advanced Research Projects Agency (DARPA) (USA), which aimed to develop basic technologies and efficient methodology for cooling and thermal management at the chip level. The thermoacoustic refrigeration part in the HERETIC was carried out by Rockwell Science Center and University of Utah (Symko *et al.*, 2004; Tsai *et al.*, 2002). Hofler and Adeff (2001) also reported a thermoacoustic refrigerator for ICs achieving a temperature drop of 12 °C. Jin *et al.*(2004) built a PZT driven miniature thermoacoustic refrigerator operating at a frequency of around 4 kHz, and Liu (2004) also discussed the design and parameter matching of miniature thermoacoustic refrigerators .

As another type of thermoacoustic system, a prime mover can also realize heat dissipation through its hot-end heat exchanger (Bastyr and Keolian, 2003; Symko *et al.*, 2004). Based on miniaturization, the onset temperature is expected to be much lower than that of the usual system, which provides the possibility of using low grade thermal energy. Moreover, the oscillation generated from a thermoacoustic prime mover may be used to drive a refrigerator, which may then be used to cool an object point requiring lower temperature. In this paper, we will introduce a prototype of small-scale thermoacoustic prime mover and some preliminary experiments.

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EXPERIMENTAL SETUP

The experimental prototype shown in Fig.1 is a standing wave thermoacoustic prime mover, including a heater, a stack and a resonant tube. The lack of a heat exchanger at the stack's cold end leads to natural cooling for the stack's cold end, which is composed of honeycomb porous ceramic with square pores (pore dimensions of 1 mm×1 mm, wall thickness of 0.3 mm, stack length of 25 mm) (friendly provided by Prof. S.L. Garrett from Pennsylvania State University). The resonant tube inner diameter is 22 mm. The location of stack inside the resonant tube is variable for relative position optimization during experiments. The heater is an electric resistance embedded at one end of the stack, where a slot has been fluted beforehand. The heating input is controlled by a voltage transformer. Based on Garrett's setup (Garrett and Chen, 2000), the total length of the present prototype is within the range of 10 cm to 25 cm for measurement convenience.

Two thermocouples are set at both ends of stack to measure the hot-end and cold-end temperatures. An electret microphone at the resonant tube open end is used to measure the sound output.

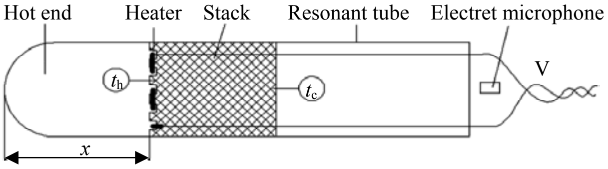
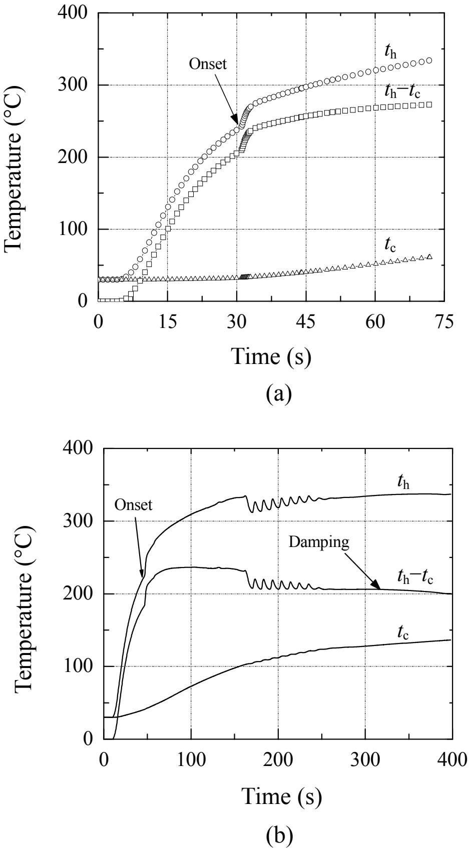


Fig.1 Prototype of a small-scale thermoacoustic prime mover

EXPERIMENTS AND RESULTS

Before an experiment starts, the adjustable stack and the embedded heater should be fixed at a certain position. Then, the electric voltage from a transformer is input to the heater. When the temperature at the stack's hot end reaches a threshold value, an oscillation onsets and the sound output can be measured with an electret microphone at the resonant tube open end. The signal from the microphone is then amplified and input to a digital oscillograph for observing the wave form, oscillation amplitude and frequency. At the same time, the temperatures at both ends of the stack are collected with thermocouples, digital multimeter and computer.

Fig.2a presents typical curves of temperature change, where t_h and t_c are hot-end and cold-end temperatures of stack, respectively. The curve slopes of t_h and temperature difference (t_h-t_c) change after the system starts to oscillate. During a short period of time after the onset, the slope becomes much steeper than that below onset, because the oscillation can promote heat transfer from the heater to its vicinity. And then, the curve becomes gentler due to the thermal energy consumption by the oscillation. If the heat input is near the critical value, the oscillation may disappear after a temperature fluctuation, as shown in Fig.2b.



(a)

(b)

Fig.2 Typical temperature profile at the ends of stack
(a) With a normal heat input; (b) With a critical heat input

The oscillation amplitude read from the digital oscillograph can be used to evaluate the relative intensity of sound output from the resonant tube. From Fig.3, we can see that the amplitude rises with the increase of heat input, while the increasing rate becomes smaller. Since the oscillation is not severe enough to completely attribute the decreasing slope to nonlinear effects, the rise of the cold-end temperature, which leads to a lower increase rate of temperature difference, is considered an important reason. The direct reason is the lack of a cold-end heat exchanger, which should be added in the future. Besides the heat input, the stack's location will also affect the amplitude, since the thermoacoustic conversion efficiency depends greatly on the stack's relative position in a wave form, leading to different pressure and velocity (including their amplitudes and phase angles). Fig.4 shows the influence of stack's location on the amplitude, where the abscissa "*x*" indicates the distance from the hot end of resonant tube (as shown in Fig.1). A better performance can be achieved with an *x* of 4 to 8 cm.

Since the system is open at one end, the resonant frequency f can be predicted with 1/4 wavelength model $f=a/(4L)$ or $1/f=4L/a$, where a is sound velocity of working fluid and L is total length of the resonant tube. Fig.5 shows the relation between measured frequency and resonant tube length, from which good linearity was found for the relation between $1/f$ and length. However, we obtained a different type fitting equation, i.e., $1/f=4(L+L_e)/a$, where L_e is an experimentally determined "end correction", which is 0.1853 cm for the present system. The mean sound velocity a_m=349.65 m/s. The frequency mainly depends on the structural parameters especially the total length of resonant tube when the diameter is not yet comparable with the length. We can see from Fig.6 that the stack's relative location and the heat input has little influence on the measured frequency. The miniaturization of a thermoacoustic engine can be realized by increasing the operating frequency.

Potential application of heat dissipation requires a system to have a low onset temperature, which depends on many factors such as mean pressure, working fluid, operating frequency and stack structure (Chen and Jin, 1999). In the present experiments, the

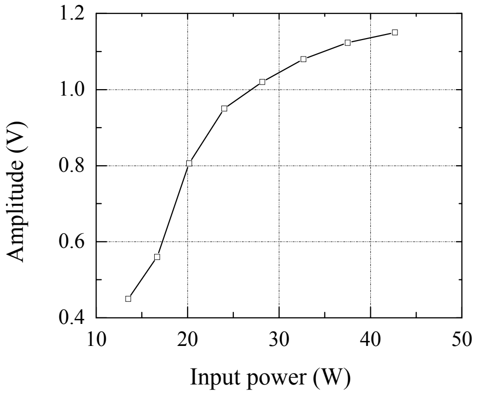


Fig.3 Amplitude vs power input of the heater

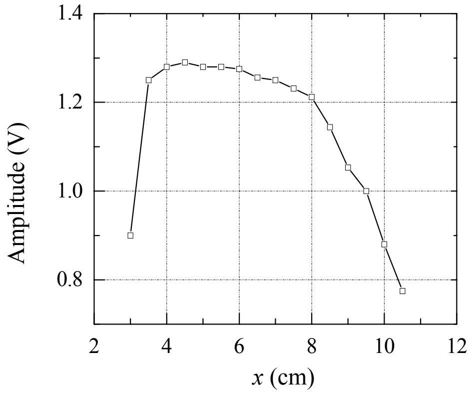


Fig.4 Amplitude vs the stack location in the resonant tube

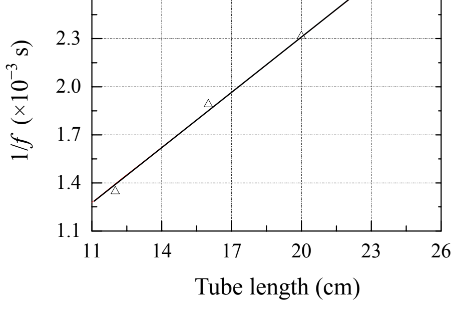


Fig.5 Measured frequency vs resonant tube length

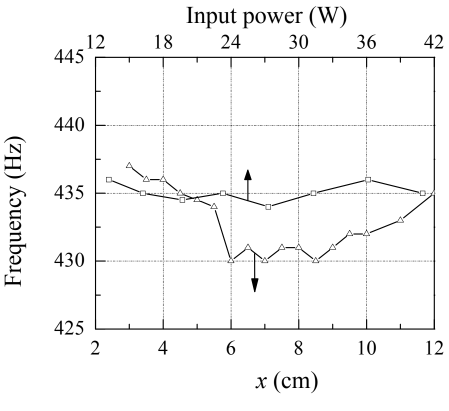


Fig.6 Measured frequency vs stack position and power input

influence of stack position, inclination of resonant tube and also heat input was observed. Fig.7 tells us that a proper location of stack helps to achieve a lower onset temperature, which occurs around x=8 cm when the total length is 20 cm and the heat input is 19.5 W. Since the heat transfer inside a tube depends not only on the temperature difference but also on the tube direction (considering natural convection), the resonant tube inclination may also affect the process of oscillation onset. Experiments were also concluded with variable inclinations and the results are also given in Fig.7, where 0, 90, −90 degree indicate horizontal, vertical (open end upward) and vertical (open end downward) position, respectively. The results showed that the lowest onset temperature was achieved around the horizontal position. Fig.8 shows that the onset temperature in our experiment also depends on the heating input power, i.e., a higher input power will lead to a lower onset temperature. However, based on the viewpoint of critical temperature gradient, the difference should not be so apparent when all other structural and operating parameters are determined. We would like to attribute this result to temperature rise at the stack's cold end, due to the lack of a cold heat exchanger there. When the input power is 50 W, the onset temperature can be lower than 100 °C. This proves the feasibility of a low onset temperature with a higher heat input or an efficient cold heat exchanger.

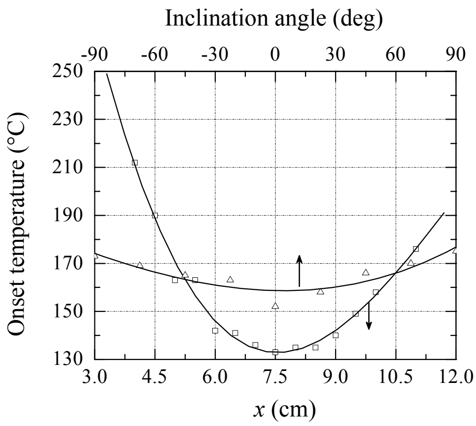


Fig.7 Influence of stack position and inclination angle of resonant tube on onset temperature

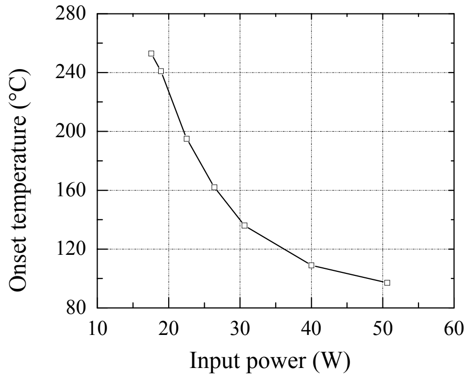


Fig.8 Onset temperature vs heating input power

CONCLUSION

Thermoacoustic prime mover can dissipate heat out of a heat source by converting thermal energy into sound wave. A prototype of thermoacoustic prime mover with a variable resonant tube length of 10 to 25 cm has been built. Experiments were conducted to observe the system's performance, especially focusing on onset temperature, oscillation amplitude and operating frequency.

Experimental results showed that the onset temperature of the present system can be lower than 100 °C. The structural parameters, including stack position and tube inclination, may also affect the onset temperature. The lowest value can be observed at a proper stack position (8 cm) in a horizontal resonant tube. As to operating frequency, the resonant tube length is its crucial factor, while there is little influence from heat input and stack's position. When the resonant tube length is 10 cm, the measured frequency of the output sound is near 1 kHz, and an ultrasonic frequency may be realized if further shortened. If the onset temperature can be further lowered and the heat transfer between the electronics component and the stack's hot-end temperature can be effectively enhanced, the miniature thermoacoustic prime mover has potential use for thermal management of electronics units.

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