SELF-TUNING MECHANISM IN A LOOPED TUBE THERMOACOUSTIC ENGINE

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Abstract

We constructed a looped tube thermoacoustic engine equipped with a stack made of ceramics having many square pores and two heat exchangers. We employed three stacks with different pore sizes and studied the effect of changing the pore size on the acoustic field excited in the present engine through the pressure and velocity measurements. By analysing the experimental data, we are led to conclude that the present thermoacoustic engine automatically tunes the acoustic field in such way that the energy conversion is executed in the most efficient way under the given condition.

Introduction

When a steep temperature gradient set up along the stack exceeds some critical value, a gas column in the tube begins to oscillate. This phenomenon is caused by the thermoacoustic energy conversion from heat flow Q into work flow I in the stack.[1]

The thermoacoustic energy conversion between Q and I can be controlled by two parameters. One is $\omega\tau$ [1], where ω is an angular frequency of an acoustic wave and τ is the thermal relaxation time required for thermal equilibrium to develop in the cross-sectional area of the flow channel and given as $\tau = r^2/2\alpha$ by the radius r of the flow channel and the thermal diffusivity[2] α. The parameter $\omega\tau$ characterizes the degree of the thermal interaction between an oscillating gas and a solid wall in the stack. If $\omega\tau << \pi$, the gas parcel in the channel moves reversibly, equilibrating at the local wall temperature, whereas if $\omega\tau >> \pi$, the gas motion becomes isentropic. In the flow channel having $\omega\tau \sim \pi$, the gas parcel has irreversible thermal contacts with wall due to incomplete heat transfer.

As another parameter, we refer to the phase lead Φ of cross-sectional mean velocity

$$U = ue^{i(\omega t+\Phi)}$$

relative to pressure

$$P = pe^{i\omega t}$$

in the stack. We call $u\cos\Phi$ the *traveling wave component* (TWC) of U, which is in phase with P, and $u\sin\Phi$ the *standing wave component* (SWC) of U, which is out of phase with P by $\pi/2$.[3] TWC contributes to the energy conversion through the isothermal heat exchange process, while SWC through the irreversible one.[4]

When a resonator is used as a waveguide of a thermoacoustic engine, a spontaneous gas oscillation always forms a standing wave acoustic field.[3,4,6-8] As a result, the energy conversion in the stack inevitably relies only on SWC, instead of TWC. Therefore, we have to carefully choose r of the stack in order to achieve the relation $\omega\tau \sim \pi$ in standing wave engines. On the other hand, if a looped tube was used as a waveguide, an excitation of any modes would be possible, as long as they satisfy the periodic boundary condition imposed on a given loop.

Recently, thermoacoustic engines using the looped tube as a waveguide have been developed. The two different results are reported on the energy conversion: both TWC and SWC existed in one stack[9], whereas only TWC in the other[10]. A question has been addressed as to how Φ in a looped tube thermoacoustic engine is turned without the possession of any external tuning devices.

In this work, we have constructed a looped tube thermoacoustic engine and studied the acoustic fields generated by stacks with different $\omega\tau$. We demonstrate that the thermoacoustic engine tunes the phase lead Φ by itself so as to maximize the energy conversion under a given condition specified by $\omega\tau$ of the stack.

Experimental setup

The experimental setup is schematically illustrated in Fig. 1 (a). The present thermoacoustic engine is composed of a looped tube, a stack, and two heat exchangers. The looped tube is made of a Pyrex glass of 40 mm in inner diameter and is filled with atmospheric air as a working gas. The average length of the looped tube is 2.7 m.

Figure 1 (b) shows the schematic illustration of a honeycomb ceramics used as the stack. It has many square pores with cross-sectional area 2r x 2r. By adopting the stacks with different r, we can change the thermal relaxation time τ to be 2.1, 5.3, and 26.3 ms in the present experiment. The frequency of the gas oscillation turned out to be 125 Hz regardless of r of the stack. Therefore, $\omega\tau$ are deduced to be 1.7, 4.2, and 21, respectively. The stack of 35 mm in length is located in the looped tube and is sandwiched between two heat exchangers: one is water-cooled and kept at room temperature T_C, and the other heated to T_H.

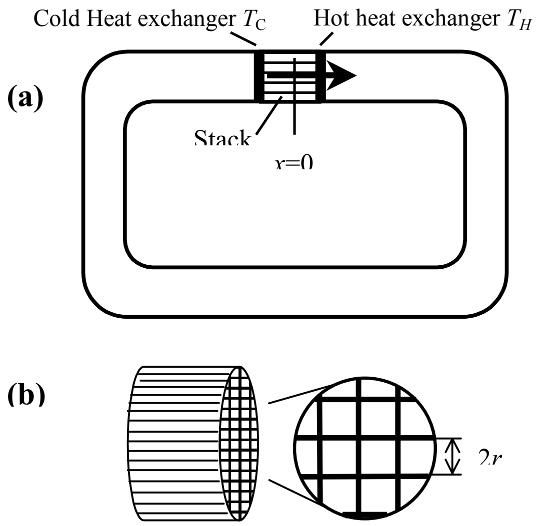

Figure1: a) Schematic illustration of the thermoacoustic engine. A stack sandwiched by two heat exchangers is located in a looped tube. One of heat exchangers is water-cooled and kept at room temperature T_C and the other is heated by an electrical resistance heater up to T_H. The looped tube is 2.7 m in length and 40 mm in diameter. (b) Schematic illustration of the stack. The drawing in the circle is the overhead view of the stack.

Experimental procedure

We measured both pressure $P=pe^{i\omega t}$ and velocity $U=ue^{i(\omega t+\Phi)}$ of the gas in the present engine in order to determine the induced acoustic field. The pressure P was measured by a series of pressure transducers mounted on the wall of the looped tube. The pressure is independent of a radial direction of the tube, because the radius of the tube (=20 mm) is much smaller than the wavelength λ of an acoustic wave induced in it (λ =2.7 m).

The axial velocity was measured by laser Doppler velocimeter (LDV) along a central axis of the tube. In the LDV, two beams generated from a single laser source are crossed at the center of the tube. The tracer particles running together with an oscillating gas scatter light at the cross-point of the beams. The light is detected with a photomultiplier as a burst signal. A frequency of the signal is converted into the voltage proportional to the velocity of the oscillating gas by a tracker-type processor. The velocity changes in a radial direction in the tube because of the presence of viscosity. Hence, the cross-sectional mean velocity $U=ue^{i(\omega t+\Phi)}$ was determined from the measured velocity at the center of the tube by applying a laminar flow theory.[3,11] We performed pressure and velocity measurements while keeping the average pressure amplitude p_a around the looped to be 0.68 kPa.

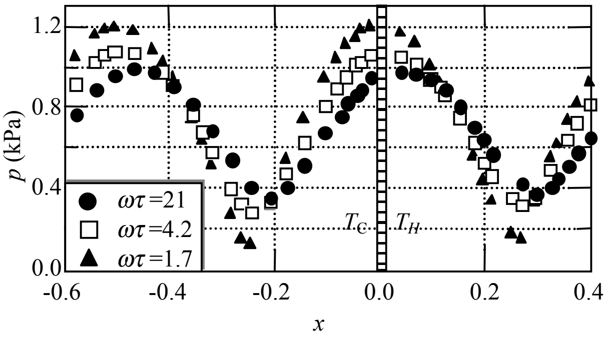

Figure 2: Distribution of the pressure amplitude p. The position of the stack is represented by a hatched area.

Experiments

We measured pressure $P=pe^{i\omega t}$ along the looped tube, when the stack having $\omega\tau$=21 was employed. The measured pressure amplitude p marked with closed circles is plotted in Fig. 2 as a function of the position x normalized with respect to the looped tube length L(=2.7 m). As shown in Fig. 1(a), the center of the stack is an origin of the coordinate x, and the positive direction in x is taken clockwise in the looped tube.

As can be seen in Fig. 2, p takes the maximum value of 1.0 kPa at x =-0.46 and 0.04, while takes the minimum of 0.38 kPa at x =-0.24 and 0.29. This clearly indicates that an acoustic wave having a wavelength equal to the length of the looped tube is generated in it, corresponding the excitation of the fundamental mode. Measured values of p are also plotted in Fig. 2 when the stacks with $\omega\tau$=4.2 and 1.7 were employed. They marked by open squares and closed triangles, respectively. The distributions of p with both $\omega\tau$ =4.2 and 1.7 also show two nodes and two antinodes. However, we realize that, with decreasing $\omega\tau$, the values of p at the nodes decrease while these at the antinodes increase. Furthermore, the positions of the nodes and antinodes are shifted to the negative direction in x. These experimental results show that the spontaneously induced acoustic field automatically changes, when the parameter $\omega\tau$ is varied.

We simultaneously measured velocity U and pressure P so as to determine the phase lead Φ at stack, where the thermoacoustic energy conversion takes place. The measured Φ is shown in Fig. 3 as a function of x for three different values of $\omega\tau$. As can be seen in Fig. 3, the absolute value of Φ outside the stack is increased by decreasing $\omega\tau$. On the contrary, the phase lead Φ at the hot end of the stack is

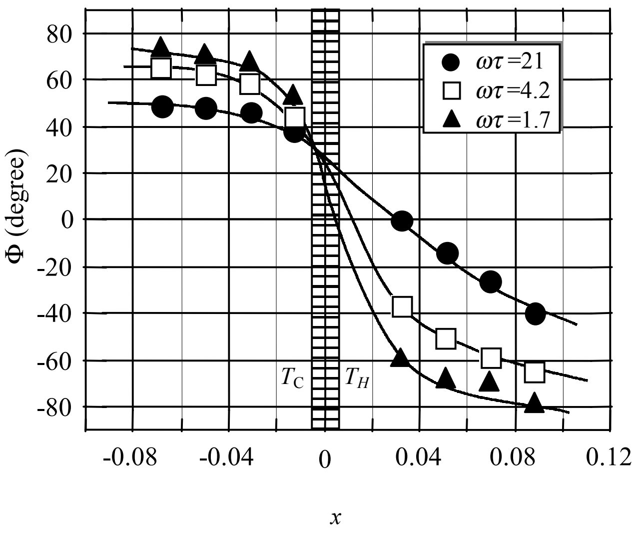

Figure 3: Distribution of the phase lead Φ of U relative to P. The hatched area represents the position of the stack.

decreased and approaches zero with decreasing $\omega\tau$, while it takes a value of about 35° at the cold end, regardless of the value of $\omega\tau$ chosen. This means that TWC becomes more and more dominant in the stack as $\omega\tau$ is decreased. This arises from the fact that the position, where Φ=0, is shifted to a negative direction of x with decreasing $\omega\tau$. Since Φ becomes zero at the velocity node,[9,12] this also shows that the velocity minimum approaches the stack. This contributes to the reduction of viscous losses in the stack.

These experimental results can be taken as a demonstration that, when $\omega\tau$ of the stack is decreased, TWC automatically becomes dominant in it, whereas, when $\omega\tau$ is increased, SWC increases. TWC and SWC perform the thermoacoustic energy conversions through the isothermal and irreversible thermal contacts between an oscillating gas and wall of the stack, respectively.[4,5] Therefore, we conclude that the present thermoacoustic engine tunes the phase lead Φ so as to execute the thermoacoustic energy conversion in the most efficient way under a given $\omega\tau$ of the stack.

Summary

We constructed the looped tube thermoacoustic engine, and observed the acoustic field induced in it through measurements of the pressure P and velocity U while changing $\omega\tau$ of the stack. It was found that the induced acoustic field automatically changes when $\omega\tau$ of the stack is varied. We focus on the phase lead Φ in the stack, where the thermoacoustic energy conversion takes place. It is concluded that the present looped tube thermoacoustic engine has a self-tuning mechanism for the phase lead Φ, which is demonstrated by intentionally varying the parameter $\omega\tau$ of the stack.

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