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Development of a Prototype Step-shaped-type Thermoacoustic Cooling System by Force Driven

強制駆動による段差形状熱音響冷却システムの試作

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1. Introduction

Thermoacoustic[1)] systems with thermally induced gas oscillation are a kind of external combustion engine. It is expected that these systems will effectively use waste heat from factories and electronic devices to drive systems. On the contrary, heat pump cycles allow thermoacoustic cooling systems.[2,3)] In recent years, electronic components have been integrated and their thermal density has been increased. The downsizing of thermoacoustic cooling systems is necessary for using them to cool electronic components.

A previous study showed that a thermoacoustic prime mover combined with two tubes with different inner diameters can achieve a high acoustic power.[4)] Setting the tube length ratio of different inner diameters to 1:1 led to improvement in the energy conversion efficiency.[5)] However, little attention has been given to applications of this topology to thermoacoustic cooling systems. The purpose of this study is to develop a miniature thermoacoustic cooling system by force driven for electronic devices. In this study, we developed a prototype step-shaped-type thermoacoustic cooling system and evaluated the cooling temperature and sound pressure. We also investigated a sound field by changing the sinusoidal current applied to a loudspeaker.

2. Experimental system and methods

Figure 1 shows a brief schematic of the experimental system. We developed a step-shaped-type thermoacoustic cooling system by connecting two tubes with different inner diameters. The system comprised stainless steel tubes filled with atmospheric air. The total length of the system was 1.004 m. The inner diameters of the tubes were 42.6 mm and 24.6 mm. The length of the larger diameter tube was 0.5 m and that of the smaller diameter tube was 0.504 m. The larger diameter tube had a loudspeaker (TOA Inc., TU-750) connected to one end and the end of smaller tube (x = 1.004) was closed. The smaller diameter tube had a heat pump (HP) stack placed inside and the stack was constructed by randomly stacking stainless steel

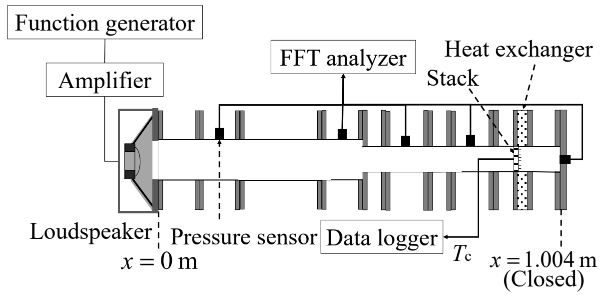

Fig. 1 Schematic of the experimental setup.

wire meshes. The mesh number (the number of openings in one linear inch of screen) of stainless steel wire meshes used in the experiments were 10, 20, and 50, and the corresponding wire diameters of the meshes were 0.4, 0.18, and 0.1 mm, respectively. The meshes were stacked to a thickness of 5 mm. The installation position of the HP was 0.945 m from the loudspeaker. Water at 24°C was circulated through the heat exchanger to maintain the temperature on the constant temperature side of the stack.

We investigated the cooling temperature T_c and sound field in a steady state by generating an acoustic standing wave in the system using the loudspeaker. The temperature of the cooling point and the sound pressures in the system were measured using a K-type sheathed thermocouple and five pressure sensors (PCB Piezotronics, 112A21), respectively. The frequency output from the loudspeaker was 166 Hz, which is the lowest frequency at which the sound pressure measured at the closed end (x = 1.004) becomes maximum for a fixed electrical power. The experiments were carried out with constant amplitudes of the sinusoidal current applied to the loudspeaker, i.e., 0.8, 1.0, and 1.2 $A_{p\text{-}p}$.

From the measured sound pressures, the cross-sectional average particle velocity was calculated using the two-sensor method.[6)] The distribution of the sound field was extrapolated using the equations of sound propagation[7)] by dividing the system into three areas with identical diameters, i.e., $0 \le x \le 0.5$, $0.5 \le x \le 0.945$, and $0.95 \le x \le 1.004$.

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3. Experimental results and Discussion

The temperature decrease ΔT at the cooling point was evaluated for all the stacks. The largest value of ΔT was 5.6 K for the stack with a mesh number of 20 and an applied current amplitude to the loudspeaker of 0.8 $A_{p\text{-}p}$. For amplitudes of 1.0 $A_{p\text{-}p}$ and 1.2 $A_{p\text{-}p}$, the corresponding ΔT values were 5.3 K and 5.4 K, respectively.

Figure 2 shows the distribution of sound pressure for the stack with a mesh number of 20, which gave the largest value of ΔT. The sound pressures (0-peak) at the closed end were 5920, 6930, and 7900 Pa for applied current amplitudes of 0.8, 1.0, and 1.2 $A_{p\text{-}p}$, respectively. From these results, it is shown that the sound pressure is larger near the closed end than near the loudspeaker because of the difference in the diameter of the tubes. **Fig. 3** shows the distribution of particle velocity. The particle velocities (0-peak) at the HP (x = 0.945) were 2.6, 3.1, and 3.5 m/s for applied current amplitudes of 0.8, 1.0, and 1.2 $A_{p\text{-}p}$, respectively. **Fig. 4** shows the distribution of acoustic power, in which positive values indicate power flow in the direction towards the closed end. The results showed that there are acoustic power losses at the step (x = 0.5) and in the stack ($0.945 \leq x \leq 0.95$). The acoustic power loss is given by $S\Delta I$, where S is the cross-section area of the tube and ΔI is the decrement of acoustic intensity at the step or stack. The $S\Delta I_{\mathrm{step}}$ values were about 0.3, 0.5, and 0.7 W for applied current amplitudes of 0.8, 1.0, and 1.2 $A_{p\text{-}p}$, respectively. Moreover, the corresponding $S\Delta I_{\mathrm{stack}}$ values, i.e., the expended and dissipated power at the stack, were about 0.05, 0.07, and 0.1 W, respectively. The $S\Delta I_{\mathrm{stack}}$ increased on increasing the applied current amplitude to the loudspeaker; however, ΔT did not increase. The temperature decrease at the cooling point seemed to be prevented by the heat flow component in the direction opposite to the cooling heat flow, which increases with increasing particle displacement.[1)]

4. Conclusion

We investigated the cooling temperature and sound field for a prototype step-shaped-type thermoacoustic cooling system by force driven. The results confirmed large sound pressure at the heat pump and a certain level of temperature decrease.

Acknowledgments
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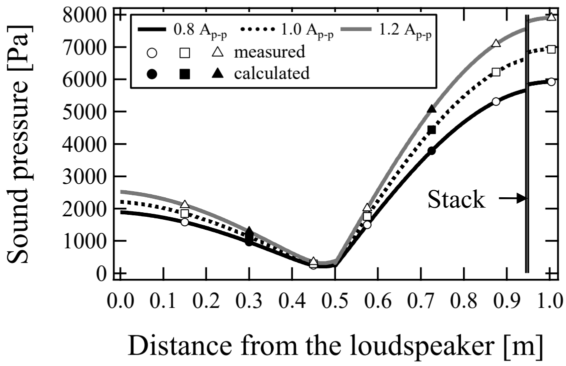

Fig. 2 Distribution of sound pressure for the stack with a mesh number of 20.

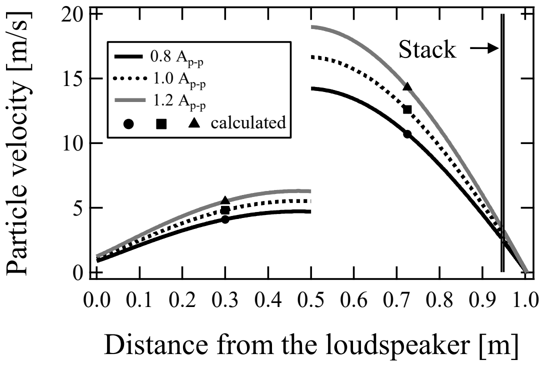

Fig. 3 Distribution of particle velocity for the stack with a mesh number of 20.

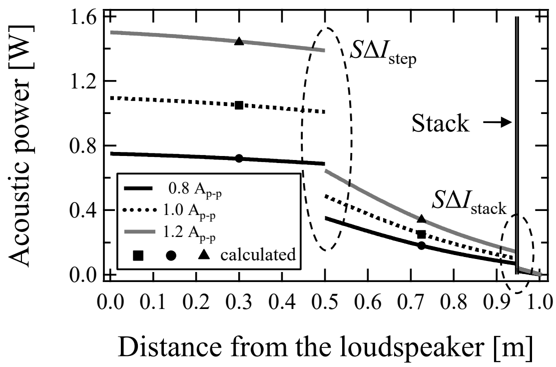

Fig. 4 Distribution of acoustic power for the stack with a mesh number of 20.

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