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Basic study for practical use of thermoacoustic electric generation system

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ABSTRACT

An electrical generation system using thermoacoustic phenomena is proposed, as a technology to improve global warming and energy resource depletion. A loudspeaker is used as, an electroacoustic converter of the magnetic induction method in this study. A loop-tube-type thermoacoustic system(loop tube) is used as the prototype system. The open-end-type resonance tube, with the length adjusted to 1/4 length of the loop tube, is added on the loop tube system to realize stable sound generation. The possibility of electrical generation was investigated using the presented prototype system. Stable sound generation is observed even if a part of the loop tube is opened. The prototype system consists of the 3300 mm length of the loop tube, and 825 mm length of resonance tube. The inner diameter of each tube is 42 mm. The full-range loudspeaker is located at the end of resonance tube and the energy conversion from heat to electricity is observed in various conditions. The sound pressure level of more than 160 dB is realized using the presented system. Results demonstrate electrical generation capability of 1.1 W active power using the proposed thermoacoustic system.

INTRODUCTION

Recently, efforts to preserve the global environment have been exerted worldwide. Global warming caused by greenhouse-effect gases such as carbon dioxide has presented humanity with the risk of global environmental destruction. The development of new energy sources and technologies to preserve the global environment are therefore urgently required. Focusing on thermoacoustic phenomena—conversion between heat energy and sound energy—the authors are pursuing the establishment of a basic technology that can contribute to global environmental preservation.

Thermoacoustic systems[1-4] have attracted interest as next-generation systems. Thermoacoustic systems are driven by thermoacoustic phenomena[5,6]: mutual conversion between heat energy and sound energy. Heat energy is applied to the prime mover of energy conversion section of a thermoacoustic system. Oscillation of the fluid at the prime mover is amplified. The frequency of the sound wave generated in the system is decided depending on the total length of the system. Consequently, heat energy is converted to sound energy. Sound pressure generated by the presented system is expected to be extremely strong compared with ordinary environmental sounds. Actually, the sound pressure level is higher than 160 dB, so that particle displacement of 3 mm is realized at 100 Hz. Therefore, the thermoacoustic electric generation system can be designed using conversion methods of a piezoelectric element or magnetic induction[8]. This thermoacoustic electric generation system can utilize solar and waste heat energy as an energy source. Moreover, this system is thought to be the technology to solve global environmental problems such as the global warming and the depletion of energy resource because CO_2 is not emitted at all during the process of converting energy from heat to electricity.

This report describes experimental investigations of the possibility of thermoacoustic electric generation. The loop tube is known to have higher energy conversion efficiency from heat to sound than the resonance tube[1-5]. We attempted to the energy conversion from heat to electricity by connecting the loudspeaker with the loop tube. It is necessary to investigate the boundary condition of the loudspeaker when the loudspeaker is connected with the loop tube. Then, experimental investigations of the boundary condition of the loudspeaker were conducted by connecting the loudspeaker with the tube end of the resonance tube type thermoacoustic system. Experimental investigations of the possibility of electric generation were conducted by connecting the loudspeaker with the loop tube based on the result.

PHASE DIFFERENCE

The thermoacoustic phenomenon arises in cases where fluid particles experience a thermodynamic cycle when a sound wave propagates in a narrow channel such as that in a stack. In such cases, heat exchange occurs between a working fluid and the stack wall. The energy conversion from heat to sound occurs by heat exchange between the working fluid and the stack wall. The phase difference between sound pressure and the particle velocity is important for energy conversion in the stack of the prime mover. Here, we show the relation between the sound pressure and the particle velocity. Interconversion between heat energy and sound energy in the stack is generated by heat exchange between the working fluid and the wall surface of flow channel because of compression and expansion of the fluid and movement of the working fluid in the flow channel.

Distribution of the sound pressure, the particle velocity and the phase difference between sound pressure and particle velocity in the loop tube are shown in Fig. 1. A sound field in this system is formed by a traveling wave and a standing wave. The traveling wave is a sound wave for which the sound pressure and the particle velocity change in the same phase. This wave converts energy using a reversible heat exchange of the work fluid and the stack wall. In addition, the standing wave is a sound wave for which the soud pressure and the particle velocity change in shifts of the phase $\pi/2$. This wave converts energy by using irreversible heat exchange. An important ratio is that by which reversible heat exchange in the stack is increased by the phase difference between the sound pressure and the particle velocity. Highly efficient energy conversion from heat to sound is known to increases when that difference is close to 0° overall in the system [1-5].

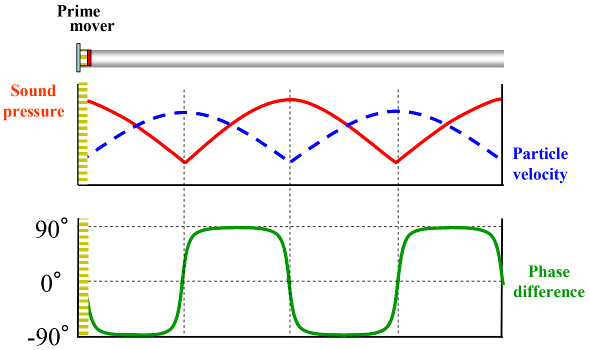

Fig. 1 Distribution of sound pressure, particle velocity, and phase difference between sound pressure and particle velocity in loop tube.

LOUDSPEAKER BOUNDARY CONDITION

EXPERIMENTAL SYSTEM AND METHOD

A loudspeaker diaphragm is vibration by receiving sound wave from the outside. Therefore, the sound field in the system is thought to change by the diaphragm vibration. Moreover, the method of connecting the loudspeaker probably changes by the boundary condition of the loudspeaker when connecting it with the loop tube. Therefore, it is necessary to examine the boundary condition of the loudspeaker and the change of the sound field in the system when connecting it with the loop tube. This report describes experimental investigations of the sound field in the system were conducted by connecting the loudspeaker with the tube edge of the resonance tube type thermoacoustic system.

A block diagram of the measurement system is shown in Fig. 2. The 2000-mm-long system was constructed with a stainless-steel tube of 42 mm inner diameter. We defined the position of the closed end as 0 mm. The tube center is the axis. Rightward was defined as the positive direction. The system was filled with air at 0.1 MPa pressure. The prime mover stack was a 50-mm-long honeycomb ceramic with a channel having a 0.45 mm radius. A spiral-type electrical heater inserted at the left side of the stack served as the heat source. A heat exchanger was placed at the right side of the stack to maintain the system at room temperature. Heating power of 330 W was supplied for 600 s using a heater. The temperature at the left side of the stack was measured using a K-type thermocouple. In addition, pressure sensors (PCB Inc.) were set on the system wall to measure the sound pressure in the resonance tube. The intensity, sound pressure, the particle velocity, and the phase difference between the sound pressure and the particle velocity were calculated using a two-sensor power method with pressure measurement results[7].

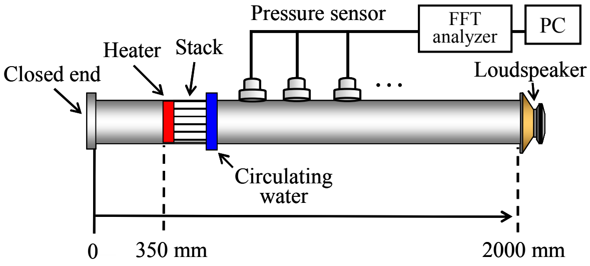

Fig. 2 Diagram of measurement system.

RESULTS

The distribution of the sound pressure and the particle velocity in the resonance tube are shown respectively in Fig. 4 and Fig. 5. The distribution of the open end with the resonance tube is shown in a triangular plot. Results show that a sound wave of the 3/4-wavelength mode resonance was generated in the resonance tube from the triangular plot. Additionally, results confirmed that the open end side of the resonance tube becomes the node of the sound pressure and the antinode of the particle velocity. The distribution of the closed end with the resonance tube is shown in a circle plot. Results show that the sound wave of the half-wavelength mode resonance was generated in the resonance tube from the circle plot. Additionally, the closed end side of the resonance tube becomes the antinode of the sound pressure and the node of the particle velocity. Furthermore, the distribution of connecting the loudspeaker with the resonance tube is shown as a square plot. The sound wave of the 3/4-wavelength mode resonance was shown to be generated in the resonance tube from the square plot. Additionally, the connection side of the resonance tube becomes the node of the sound pressure and the antinode of the particle velocity.

The loudspeaker boundary condition is thought to be similar to that of an open end from these results. It was confirmed that the maximum value of the sound pressure and the particle velocity changed by connecting the loudspeaker with the resonance tube. The sound field changes by connection of the loudspeaker with the resonance tube, although the boundary condition of the loudspeaker is similar to that of the open end.

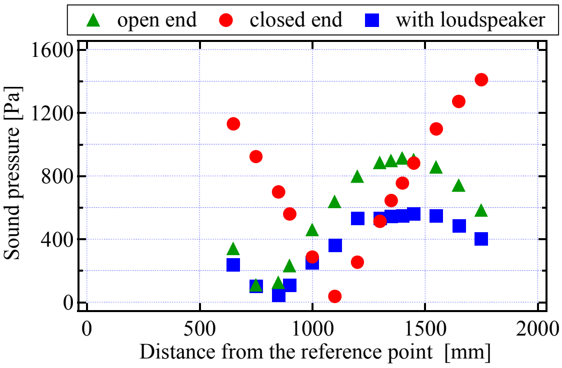

Fig. 3 Distribution of sound pressure in the resonance tube.

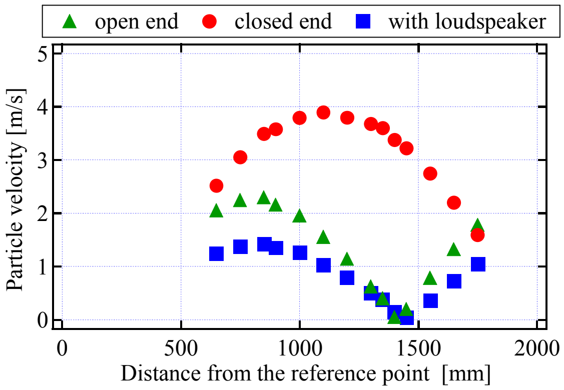

Fig. 4 Distribution of the particle velocity in the resonance tube.

DISCUSSION

The distribution of the sound pressure and the particle velocity in this system show similar tendencies, although the loudspeaker was connected with the resonance tube. However, it was confirmed that the maximum value of the sound pressure and the particle velocity changed by connecting the loudspeaker with the resonance tube. Consequently, the phase difference between sound pressure and particle velocity changed too. The energy conversion efficiency from heat to sound changes when the phase difference between the sound pressure and particle velocity changes. Change of the phase difference between the sound pressure and particle velocity when connecting the loudspeaker with the resonance tube is thought to be smaller than without the loudspeaker. However, the influence of the phase difference between sound pressure and particle velocity when the loudspeaker is connected in the loop tube is thought to be greater than in the case without the loudspeaker. Therefore, it is necessary to consider both the change of the phase difference between the sound pressure and particle velocity and a part of the loop tube must be open end. A part of the loop tube is open ended if the loudspeaker is connected directly with the loop tube; additionally, the oscillation condition becomes unstable. Therefore, the resonance tube is added on the loop tube to realize stable generation of the sound. Moreover, the phase difference between sound pressure and particle velocity changes according to the resonance tube location and total length. The energy conversion efficiency from heat to sound also changes. The connected position of the resonance tube is selected by previous research[9,10] for the position where the efficiency of energy conversion improved.

POWER GENERATION USING A LOOP TUBE

EXPERIMENTAL SYSTEM AND METHOD

A block diagram of the measurement system is shown in Fig. 5. The system includes an 850-mm-long, 500-mm-wide stainless steel tube, with 3300 mm total length. Its inner diameter was 42 mm. We defined the position of the tops of the prime mover stack, heater as 0 mm. The tube center is the axis. Clockwise was defined as the positive direction. The resonance tube of 825 mm total length was connected with the position at 1980 mm from the heater. The system was filled with air at 0.1 MPa pressure. The prime mover stack was a 50-mm-long honeycomb ceramic with a channel having a 0.45 mm radius. A spiral-type electrical heater inserted at the top of the stack served as the heat source. A heat exchanger was placed at the lower part of the stack to maintain the system at room temperature. Heating power of 330 W was supplied for 600 s using a heater. The temperature at the top of the stack was measured by using a K-type thermocouple. Pressure sensors (PCB Inc.) were set on the system wall to measure the sound pressure in the resonance tube. The intensity, the sound pressure, the particle velocity, and the phase difference between the sound pressure and the particle velocity were calculated using a two-sensor power method with pressure measurement results[7].

The full-range loudspeaker was located at the end of resonance tube. Impedance of the loudspeaker is 50 Ω when a resonant frequency of this measurement system is 100 Hz. Resistance was connected with the loudspeaker, and the electric power was measured using a wattmeter.

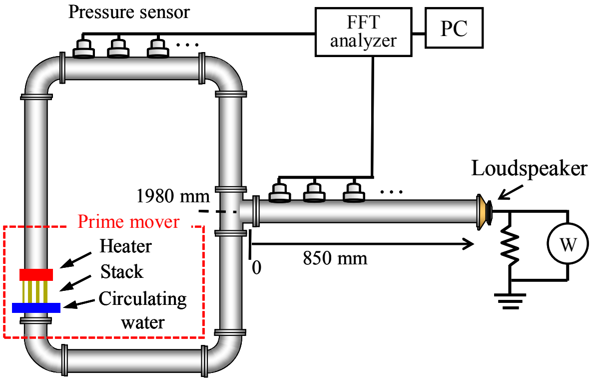

Fig. 5 Diagram of measurement system.

RESULTS

The resonance tube is added to the loop tube; the loudspeaker is added to open end side of the resonance tube. Distribution of the sound pressure in the resonance tube is shown in Fig. 6. The distribution of open end with the resonance tube is shown in the square plot. We understood that the loop tube side is the antinode of the sound pressure and the open end side is node of the sound pressure from the circle plot. The sound wave of the quarter-wavelength mode resonance was generated in the resonance tube. The distribution of connecting the loudspeaker with the resonance tube is shown in the circle plot. The maximum value of the sound pressure decreases about 1000 Pa compared with the value obtained without the loudspeaker from the square plot. Additionally, results confirmed that the sound pressure has finite value in the connection of the loudspeaker. Therefore, it is understood that the boundary condition of the open end side at the resonance tube has changed by connecting the loudspeaker. The change of the boundary condition influences the sound field in this system. Therefore, the energy conversion efficiency from heat to sound in the loop tube changed.

Distribution of the phase difference between the sound pressure and particle velocity in the loop tube is shown in Fig. 7. Distribution of the sound energy in the loop tube is shown in Fig. 8. The maximum value of the phase difference between sound pressure and particle velocity is smaller than that without the speaker, as shown in Fig. 7. In addition, the sound energy increased overall, as shown by comparison of levels with the without the speaker from the Fig. 8. Furthermore, the resistance of 50 Ω was connected with the loudspeaker. The electric power was measured using a wattmeter. Results confirmed electric generation of active power of 1.1 W using the proposed thermoacoustic system.

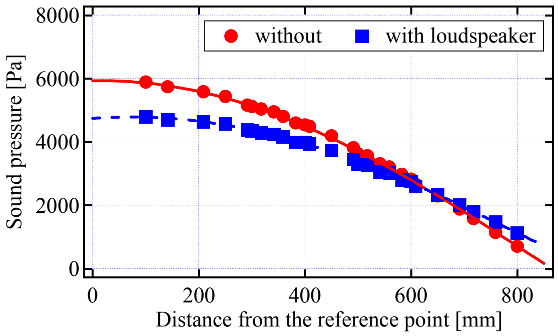

Fig. 6 Distribution of sound pressure in the resonance tube.

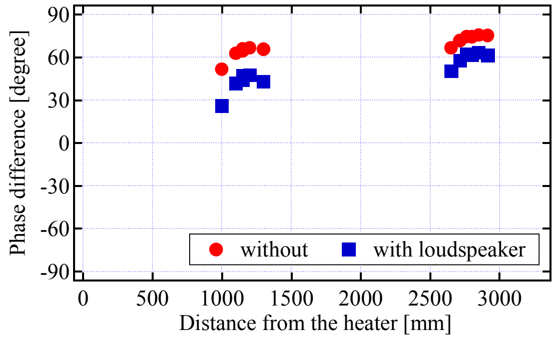

Fig. 7 Distribution of phase difference betwee n the sound pressure and the particle velocity in the loop tube.

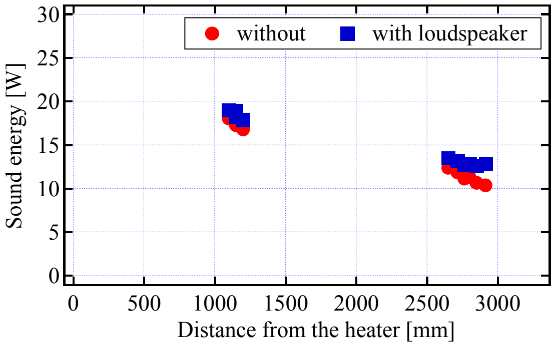

Fig. 8 Distribution of sound energy in the loop tube.

DISCUSSION

Results confirmed that the energy conversion efficiency from theat to sound increased to 20 times by connecting the resonance tube with the loop tube. One factor is that the maximum value of the phase difference between the sound pressure and particle velocity probably became small overall by connecting the resonance tube. The phase difference between the sound pressure and the particle velocity in the prime mover stack changes because its maximum value became small. Therefore, the ration which using a reversible heat exchange in the stack is thought to increase because of the change of the phase difference between the sound pressure and the particle velocity in the stack. Consequently, the energy conversion efficiency improved. The maximum value of the sound pressure in the resonance tube became small, 1000 Pa, by connecting the loudspeaker to the resonance tube. The energy conversion efficiency is thought to be improved through decrease of the sound pressure because the maximum value of the phase becomes small.

We succeeded in connection of the loudspeaker without decreasing the efficiency of energy conversion from heat to sound. Moreover, we succeeded in stable sound generation even if a part of the loop tube is opened. Furthermore, a resistance of 50 Ω was connected with the loudspeaker. The electric power was measured using a wattmeter. Results show electric generation of active power of 1.1 W using the proposed thermoacoustic system. The energy conversion efficiency from heat to electricity is about 0.3 %: the input heat energy in the heater is 330 W. Power generation was accomplished using the thermoacoustic phenomenon, although it must be improved for practical use.

CONCLUSIONS

In this report, experimental investigations were conducted to elucidate the possibility of thermoacoustic electric generation. The loudspeaker is used as, an electroacoustic converter using magnetic induction. Results show that the boundary condition of the loudspeaker resembles that of an open end. Therefore, a part of the loop tube is the open end if the loudspeaker is connected directly with the loop tube and the oscillation condition becomes unstable. The open-end-type resonance tube whose length is adjusted to the 1/4 length of the loop tube is added on the loop tube system to realize stable sound generation. The full-range loudspeaker is located at the end of the resonance tube. The sound pressure level of more than 160 dB is realized by the system presented herein. Furthermore, electric generation of active power of 1.1 W using the proposed thermoacoustic system was confirmed. The energy conversion efficiency from heat to electricity is about 0.3 % because the input heat energy in the heater was 330 W. Useful thermoacoustic electric generation system can be produced by improving the energy conversion efficiency.

ACKNOWLEDGEMENT

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