4pPAb4. Introduction of conical phase adjuster for thermoacoustic system
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We have proposed a phase adjuster for the thermoacoustic system and succeeded in improving the energy conversion efficiency from heat to the sound. A phase adjuster in a cylindrical shape was used in the past experiments. In this report, a conical phase adjuster is introduced. The inside diameter in one side of the phase adjuster is 20.5mm, and the other is 39.5mm. The length of phase adjuster is 45mm. The phase adjuster is placed in two ways; the larger inner diameter of the phase adjuster is placed in the left side and the smaller is in the right (with PA L39.5 R20.5); the smaller inner diameter is in the left and the larger is in the right (with PA L20.5 R39.5). The total length of the loop is 3.3 m and the phase adjuster is placed 1.125 m away from the upper end of the prime mover stack in the clockwise direction. The measurements are conducted in three conditions: without phase adjuster and with each phase adjusters. Both the sound pressure and sound intensity generated in the thermoacoustic system with phase adjuster are greater than those without phase adjuster. The biggest sound intensity is observed with PA L39.5 R20.5.

Published by the Acoustical Society of America through the American Institute of Physics
1. INTRODUCTION

Recently, efforts to conserve the global environment have been exerted worldwide. Ozone depletion by chlorofluorocarbon refrigerants and global warming related to greenhouse gases such as carbon dioxide have been recognized as causes of global environmental destruction. Consequently, the development of new energy sources and technologies to preserve the global environment are urgently required. Therefore, specifically addressing the thermoacoustic phenomenon, the authors are working to establish a basic technology that can contribute to global environmental preservation. Sound waves propagating in a sufficiently narrow tube compared with their wavelength exchange heat at the tube wall produce the thermoacoustic phenomenon. Thermoacoustic systems using the thermoacoustic phenomenon have practical applications in many fields. These systems are useful especially when driven by underused energy sources such as waste heat and solar heat because they are external combustion engines. They are useful as examples of global environment maintenance technology. Nevertheless, their energy conversion efficiency is lower than that of internal combustion engines. Examples of their practical use are few.

Ceperley expected that the phase difference between sound pressure and particle velocity, which becomes 0 degree or near 0 degree, would make a thermoacoustic system highly efficient. Backhaus and Swift at Los Alamos National Laboratory have constructed thermoacoustic systems and studied their properties to enhance the output power and to improve conversion efficiency. They used helium gas pressurized to over 2.0 MPa, as a working gas. Yazaki at Aichi University of Education and coworkers, Biwa et al. at Tohoku University, and Ueda et al. at the Tokyo University of agriculture and Technology, have studied thermoacoustic phenomenon properties and proposed their measurement method and calculation method.

We have proposed several methods to control the phase difference of the generated sound in the prime mover in a thermoacoustic system. We have considered that the phase difference in the prime mover is important to energy conversion in the thermoacoustic system. We suggested various methods to control the phase difference 0 degree or near 0 degree without dampening the advantage of the loop-tube-type thermoacoustic system. For example, we have successfully reduced the cross section of the loop tube, which we call the phase adjuster (PA) and have developed methods to connect the resonant tube to a loop tube, as well as methods to set up a thin film in a system. A phase adjuster in a cylindrical shape was used in past experiments. By placing the phase adjuster, the cross-sectional area of this part of the thermoacoustic system is narrowed and the particle velocity around the phase adjuster is increased. It has been already confirmed from our past experiment that the phase adjuster adjusts the phase difference between the sound pressure and the particle velocity and improves the energy conversion efficiency of the thermoacoustic system.

In this report, a conical phase adjuster is introduced. We have investigated the effect of the shape of the phase adjuster on the system. The measurements are conducted in three conditions: without a phase adjuster and with conical phase adjusters.

2. CONICAL PHASE ADJUSTER

A schematic illustration of a conical phase adjuster is presented in Fig. 1. A cylindrical phase adjuster was used in past experiments. In this report, a conical phase adjuster is introduced. The inside diameter in one side of the phase adjuster is 20.5 mm. The other is 39.5 mm. The phase adjuster length is 45 mm. The phase adjuster is placed in two ways. The larger inner diameter of the phase adjuster is placed on the left side and the smaller is on the right (with PA L39.5 R20.5). The smaller inner diameter is on the left. The larger is on the right (with PA L20.5 R39.5). A phase adjuster is placed 1.125 m away from the upper end of the prime mover stack in a clockwise direction.

FIGURE 1. A schematic illustration of a conical phase adjuster.
3. EXPERIMENTAL SYSTEMS

A schematic illustration of the experimental setup for our loop-tube-type thermoacoustic system (loop tube) is presented in Fig. 2. To determine the effect of the phase adjuster, a heat pump was not used. The stack top is defined as a distance of 0 m. The tube center is the axis: clockwise is defined as the positive direction. The loop tube consists of stainless tubes connected by 90° elbows. The total loop length is 3.3 m. The tube inner diameter is 42 mm. The stack was a 50-mm-long honeycomb ceramic with a 0.45 mm channel radius. The stack is a honeycomb ceramic with many penetrating holes along the longitudinal direction. 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 the reference temperature. The phase adjuster is placed 1.125 m away from the upper end of the prime mover stack in a clockwise direction. To avoid the influence of humidity, argon, instead of air, is filled in the loop tube at atmospheric pressure as the working fluid. Heating power of 330 W was supplied for 600 s using an electrical heater. Pressure sensors (HM112A21; PCB Piezotronics Inc.) were set on the system wall to measure the sound pressure in the loop tube. The resonant frequencies of these sensors were higher than 250 kHz. Measurements of sound pressure were started and continued for 900 s after heat energy was supplied. The pressure and the sound intensity in the system were calculated using a two-sensor power method\(^6,7\) with pressure measurement results by the pressure sensors.

**FIGURE 2.** Experimental system of loop-tube-type thermoacoustic system with PA.
4. EXPERIMENTAL RESULTS

Figure 3 exhibits sound pressure distributions in a loop tube with and without PAs. Results show that the generated sound pressure is the highest, greater than 5 kPa, when the PA L39.5 R20.5 is placed. The generated sound pressure is 3.1 kPa when a PA is not placed. Therefore, it was increased about 1.6 times by placing PA.

Figure 4 presents sound intensity distributions in loop tubes with and without PAs. The sound pressure at the middle point of two pressure sensors is represented as follows:

\[ p = \frac{P_A + P_B}{2 \cos \left( \frac{\kappa d}{2} \right)} \]  \hspace{1cm} (1)

here, \( P_A \) and \( P_B \) are the observed sound pressures obtained using two pressure sensors; \( \kappa \), the wave number; and \( d \) the distance between two sensors. Particle velocity is represented as follows:

\[ u = \frac{\kappa (P_A - P_B)}{2 \sin \left( \frac{\kappa d}{2} \right)} \]  \hspace{1cm} (2)

Sound intensity is represented as follows:

\[ I = \rho \omega \nabla^2 \]  \hspace{1cm} (3)

The results show that the sound intensity is the highest, about 20 kW/m², at the prime mover top end when the PA L39.5 R20.5 is placed. The acoustic power is multiplied by the cross section of the tube and the sound intensity. Acoustic power under these conditions was about 27 W. For practical use, it is necessary to improve the heat-to-sound energy conversion efficiency. The reasons for the low efficiency based on our previous results are apparently the effect of phase difference and the leakage of heat input. The sound intensity is 3 kW/m² when the PA is not placed. Therefore, it is increased about six-fold by placing PA L39.5 R20.5 comparing without PA.

**FIGURE 3.** Sound pressure distributions in a loop tube with and without PAs.
5. SUMMARY

We have proposed a phase adjuster for the thermoacoustic system and succeeded in improving the efficiency of energy conversion from heat to sound. A cylindrical phase adjuster was used in past experiments. This report explains the use of a conical phase adjuster. The measurements are conducted in three conditions: without a phase adjuster and with phase adjusters. Both the sound pressure and sound intensity generated in the thermoacoustic system with a phase adjuster are greater than those without a phase adjuster. The greatest sound intensity is observed with PA L39.5 R20.5. A conical phase adjuster contributes to improvement of the efficiency of heat to sound energy conversion in a thermoacoustic system.

ACKNOWLEDGMENTS

This research was partially supported by the Japan Society for the Promotion of Science, a Grant-in-Aid for Young Scientists (A), (B) and a Grant-in-Aid for Exploratory Research, the Program for Fostering Regional Innovation, and Adaptable and Seamless Technology transfer Program through target-driven R&D.

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