1aEA5. Study on thermoacoustic system to drive by low temperature -Effects of loop-tube thermoacoustic system connected with parallel double stacks on the onset temperature ratio

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In a thermoacoustic system, as the temperature ratio of both ends of a stack increases gradually and reaches a critical value, sound waves begin to oscillate. This temperature ratio is called the onset temperature ratio. It is necessary to decrease the onset temperature ratio for practical application of a thermoacoustic system using factory exhaust heat or solar heat. A previous study examined a thermoacoustic system with a number of prime movers connected in series. This system can be driven by a lower onset temperature ratio than a thermoacoustic system with a prime mover. However, it is considered that the heat loss increases when the heat is carried to a number of high heat exchangers. Therefore, a parallel loop-tube thermoacoustic system was proposed. This system can drive two prime movers by a heat input part because it is connected in parallel to prime movers. This study compared the onset temperature ratio of this system with that of a normal loop-tube system with a prime mover. Results show that the parallel loop-tube system can be driven by a lower onset temperature ratio than the normal loop-tube system.

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INTRODUCTION

Earth’s environmental deterioration from global warming and depletion of energy resources is increasingly viewed with anxiety. Thermoacoustic systems\textsuperscript{1-9}, important future energy systems, have been attracting attention because energy resource depletion problems have surfaced. These systems, which can convert from heat to sound, have various styles: straight-tube type, loop-tube type, and various combinations thereof. Their energy conversion device comprises a low-heat exchanger, a high-heat exchanger, and the stack, which is a porous device. When the temperature ratio of both ends increases through the use of two heat exchangers, the working gas in the system oscillates spontaneously. These systems are useful especially when driven by unused energy sources such as waste heat and solar heat, because they are external combustion engines. Moreover, they are applicable as electrical generation and cooling systems. If low-temperature driving of the system can be achieved, then the systems can be put to practical use. We investigated the onset temperature ratio of both ends of the stack to achieve low-temperature driving of the systems. The onset temperature ratio is the minimum temperature ratio for sound wave generation. To drive the system at low temperatures, it is necessary to assess the design because the onset temperature ratio is determined by the geometry and the working gas in the systems. An earlier report described that the onset temperature ratio decreases when using the thermoacoustic engine with multiple stacks\textsuperscript{10}. However, two problems arise because multiple stacks are connected serially. First, the propagation loss of heat toward the high heat exchangers increases because multiple high heat exchangers are used. Second, one high-heat exchanger heats up another low heat exchanger between two stacks. Therefore, a parallel loop-tube system was proposed. This system can drive two prime movers from one heat input because the prime movers are connected in parallel. In this report, the onset temperature ratios of the parallel loop-tube system and the normal loop system are compared.

PRINCIPLE

Distribution of sound pressure fluctuation is closely related to the stack position in the thermoacoustic system. The sound pressure fluctuation in the high heat exchanger is higher than that in the low heat exchanger. Half-wavelength and one-wavelength resonance modes in a straight tube thermoacoustic system are shown in FIGURE 1 and FIGURE 2. The resonance mode changes because of the stack position. The sound pressure fluctuations of both ends are the most valuable because both ends are closed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Half wavelength resonance mode in a straight tube thermoacoustic system. (A stack is placed at the position of $4/5L$ [m] from the left end. The high heat exchanger is placed to the right of the stack. The low heat exchanger is placed to the left of the stack.)}
\end{figure}
FIGURE 2. One wavelength resonance mode in a straight tube thermoacoustic system. (A stack is placed at the position of $3/8L$ [m] from the left end. The high heat exchanger is placed to the right of the stack. The low heat exchanger is placed to the left of the stack.)

The resonance mode in loop tube thermoacoustic system is shown in FIGURE 3. The distribution of sound pressure fluctuation is formed in relation to the stack position because no boundary condition of closed ends exists.

FIGURE 3. One wavelength resonance mode in a loop tube thermoacoustic system. (The position of $L$[m] is equal to the position of 0 m. The high heat exchanger is placed to the right of the stack. The low heat exchanger is placed to the left of the stack.)

When multiple stacks are used, it is necessary to choose the stack positions considering the relation between the system geometry and the distribution of sound pressure fluctuation.
EXPERIMENT AND DISCUSSION

The experimental system of the parallel loop-tube system is presented in FIGURE 4. The lengths of the lower tube is 2.5 m. The lengths of the upper connecting tube are half those of the lower tube: 1.25 m, and two stacks are put into connecting tube. The lengths of three tubes between two connecting tubes are equal. By the resonance mode in loop tube thermoacoustic system, sound pressure antinodes are formed in two connecting tubes. The stack thickness is 50 mm, the channel radius of the stack is 0.55 mm, and the material is ceramic.

FIGURE 4. Experimental system of loop-tube thermoacoustic system connected with parallel double stacks. The stack in the lower tube is defined as stack 1, and the upper connecting tube is defined as stack 2.

The experimental system of the normal loop system is shown in FIGURE 5. The loop tube length is the same as the lower tube of the parallel loop-tube system: 2.5 m. The stack conditions are the same as those shown in FIGURE 4.

FIGURE 5. Experimental system of normal loop-tube thermoacoustic system (total length is 2.5 m).

Each high heat exchanger is heated gradually using the electric heater. The temperatures of both ends of the stacks are measured when sound waves begin to oscillate. However, the same amount of heat is input in two stacks of the parallel loop-tube system. The measurement time is 500 s.

The results of the stack temperature ratio in the parallel loop-tube system (2.5 m length of the lower tube) and a normal loop tube (2.5 m total length) are shown in FIGURE 6. The onset temperature ratio of the parallel loop-tube system is confirmed as lower than the normal loop tube’s temperature. The temperatures of high heat exchangers in the parallel loop-tube system and the normal loop tube are 290°C and 420°C: the temperature difference is 140 K. The input quantities of heat are 43.2 W (parallel loop-tube system) and 61.6 W (normal loop-tube system).
FIGURE 6. Onset temperature ratio results of parallel loop tube (2.5 m length under the loop tube) and a normal loop tube (2.5 m total length).

Sound intensity flow in the parallel loop-tube system (2.5 m total length) is shown in FIGURE 7. The sound intensity flow is calculated using numerical analysis\textsuperscript{11-13}. The divided parallel loop-tube system is presented in FIGURE 4. The upper tube is the upper connecting tube in FIGURE 4. The starting point of the abscissa axis is the end face of the high heat exchangers. The sound intensity of the cavity tube (parallel loop-without) is higher than the sound intensity of the tubes connected the stack (parallel loop-stack 1 and stack 2). The sound intensity in the cavity tube attenuates and the sound intensity in the stack amplifies. In this study, the sound intensity in the stack is not calculated. The attenuated sound intensity $\Delta I$ in the cavity tube of the parallel loop-tube system is 13.8 W/m\textsuperscript{2}, and $\Delta I$ in the stacks of the normal loop tube is 9.4 W/m\textsuperscript{2}. Therefore, the attenuated sound intensity is amplified in each stack of the system. The parallel loop-tube system has two stacks. Therefore, $\Delta I$ that one stack generated is half (6.9 W/m\textsuperscript{2}). Compared with the amplified sound intensity by one stack in the parallel loop-tube system and the normal loop tube, the onset temperature ratio of the parallel loop-tube system is lower than that of the normal loop tube because the oscillation condition is satisfied by the lower generated energy (amplified sound intensity). If a thermoacoustic system can be driven by a lower generated energy, the onset temperature ratio is further reduced.

FIGURE 7. Sound intensity flow of each part in loop-tube thermoacoustic system connected with parallel double stacks. (The parallel loop-without is shown to the right of the lower tube in FIGURE 4. The parallel loop-stack 1 is shown to the left of the lower tube. The parallel loop-stack 2 is shown to the upper connecting tube.)
SUMMARY

For development of a low-temperature driven thermoacoustic system, a parallel loop-tube thermoacoustic system was proposed. This system can drive two prime movers from one heat input because the prime movers are connected in parallel. Comparing the onset temperature ratio of the parallel loop-tube system and the normal loop-tube system, we confirmed that the parallel loop-tube system can be driven by a lower temperature ratio. The amplitude sound intensity in one stack of the parallel loop-tube system is lower than the normal loop-tube system. Therefore, if a thermoacoustic system can be driven by a lower generated energy, the onset temperature ratio is further reduced.

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