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A basic study for silencer by using thermoacoustic phenomena
– Experimental discussion for heat exchange and viscous dissipation –

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ABSTRACT

We propose an automobile muffler by using thermoacoustic phenomena. There are two mechanisms when the sound energy is converted to the heat energy. One is the heat exchange between the stack wall and fluid particle. The other is the viscous dissipation in the stack. Results of previous studies have shown that the silence effect achieves a better effect using both of energy conversion mechanisms. This study measures the silence characteristics of frequency and the temperature difference to assess the effectiveness of the multistage stack method. The multistage stack method is that of separating the sources into two stacks. Results show that we succeed in efficiency improvement of the silencing effect by low input driving of the system.

INTRODUCTION

Thermoacoustis systems[1–6] are driven by thermoacoustic phenomena[7–8] is energy conversion between heat energy and sound energy. There systems have various advantages (i.e. to derive driving energy from various waste heat and maintenance free with no moving part). Therefore there systems have attracted attention as a global warming countermeasure technology, various researches are advanced. Especially, in this research, we focous on silence system by using waste heat from the automobile.

Thermoacoustic silence system[6] provide various advantages for automobile mufflers. For example, this system can derive driving energy from engine waste heat and can reduced weight of mufflers. Because the silencing effect is caused by using thermoacoustic phenomena occur in a stack of small devise. The stack consists of many narrow channels less than 1 mm. In the stack, the sound energy is converted to the heat energy. This silence system is realized by this energy conversion. Recently, conventional mufflers have come to weigh more than 5 kg to attenuate low-frequency waves[9]. An acoustic automobile muffler will have greatly reduced weight and increased fuel economy by the system is used practically.

Conversion from sound to the heat results from two mechanisms in thermoacoustic silence systems. One is heat exchange between the stack wall and fluid particle, the other is the viscous dissipation in the stack. In the loop tube, viscous dissipation is treated as a loss. However, in the silence system, viscous dissipation contributes to the silence effect. Therefore, in the silence system, both heat exchange and viscous dissipation are necessary. It is necessary to increase the input heat energy to take the effect of the heat exchange. At the same time, The infulence by the viscous dissipation becomes effective by the multistage stack method. This study measures the silence characteristics of frequency and the temperature difference to assess the effectiveness of the multistage stack method.

THEORY

Thermoacoustic phenomena

In general, when a sound waves passes through free space, fluid particles of the sound wave propagation medium undergo an adiabatic change. However, when sound waves pass through a narrow channel, fluid particles undergo an isothermal change. This isothermal change results from the relation between the period of the sound wave and the thermal relaxation time. When the thermal relaxation time τ is faster than the sound wave period, heat exchange occurs between stack wall and fluid particles. This condition of isothermal change is shown as the nondimensional parameter $\omega\tau$[8,10–12], which is the ratio of the cycle time to the thermal relaxation time. The time necessary for heat exchange to take place between fluid particles and the stack wall varies considerably according to $\omega\tau$.

$$\omega\tau = 2\pi\frac{\tau}{T} = \omega\frac{r^2}{2\alpha} \qquad \text{Eq. 1}$$

Therein, ω represents the angular frequency of the sound wave, α denotes the coefficient of thermal diffusivity, and r stands for the stack's channel radius. When thermal relaxation time τ is much shorter than the oscillation cycle of the fluid particle ($\omega\tau \ll 1$), thermal relaxation occurs almost as soon as the sound pressure changes. Therefore, heat exchange between the fluid particle and stack wall happens instantaneously. From equation 1, realizing good heat exchange necessitates narrowing the channel radius or increasing the coefficient of thermal diffusivity by increasing the temperature.

Thermoacoustic system

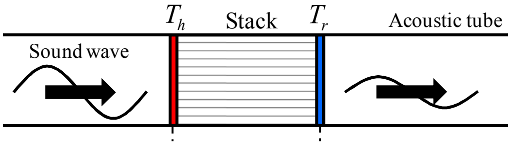
Figure 1 presents a diagram of a thermoacoustic silence system (a) and energy flow in acoustic tube (b). As shown in

Fig. 1, T_r is kept at room temperature by circulating water, T_h is kept at high temperature by a heat exchanger. There, ΔI signifies the work flow and ΔQ stands for the heat flux. New energy is not produced in the stack if there is no heat movement other than the heat exchanger. Therefore, work flow and heat flux have equality[8,10]. In this regard, no propagation loss of the sound wave exists.

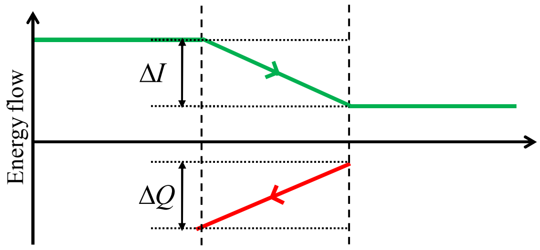
$$\Delta I = \Delta Q \qquad \text{Eq. 2}$$

In other words, conversion between work flow and heat flux is a thermoacoustic phenomenon. Attenuation and amplification of sound power results from this conversion. When the sound wave is inputted to the stack of the high-temperature side, the sound energy is attenuated. When the sound wave is inputted the stack of low temperature side, the sound energy is amplified.

In fact, there is propagation loss and viscous dissipation in the stack. Therefore, the attenuation effect is stronger than the amplification effect. Under the amplification effect, the sound energy is amplified by the heat exchange even though it is attenuated by viscous dissipation. However, under the attenuation effect, sound energy is attenuated by both effects (Fig. 2).

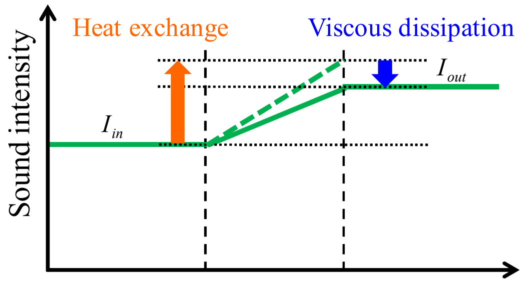


(a) Diagram of thermoacoustic silence system

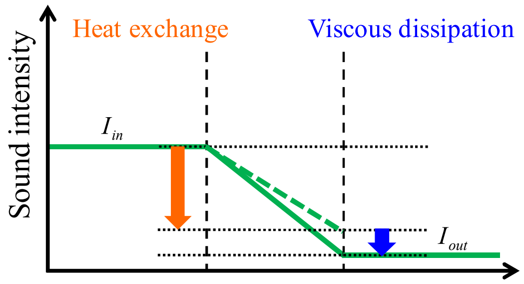


(b) Energy flow in acoustic tube

Fig. 1 Silence theory with thermoacoustic silence system.



(a) Energy flow (Amplification)



(a) Energy flow (Attenuation)

Fig. 2 Influence on sound intensity by viscous dissipation.

Sound intensity in the travelling wave field

Sound intensity is the sound energy per unit time and per unit area. It is represented by equation 3.

$$I = pu\cos\phi \qquad \text{Eq. 3}$$

In that equation, I stands for sound intensity, p represents amplitude of sound pressure, u signifies the amplitude of the particle velocity, and ϕ denotes the phase difference between the sound pressure and particle velocity. For a travelling wave field ($\cos\phi$=1), the sound intensity is represented as the product of sound pressure and particle velocity. Furthermore, for acoustic impedance with Z_0, the sound intensity is represented by equation 4.

$$I = \frac{p^2}{Z_0} \qquad \text{Eq. 4}$$

Therefore, in a travelling wave field, the ratio of sound intensity is a duplicate ratio of two sound-pressure values.

$$G = \frac{P_{out}{}^2}{P_{in}{}^2} \qquad \text{Eq. 5}$$

In this equation, G signifies the change of sound intensity, P_{out} is the sound pressure of the stack passage after, and P_{in} represents the sound pressure of the stack passage before.

Ideal attenuation ratio

First, discussion of the ideal amplification ratio is necessary before discussion of attenuation. When the room temperature side of the stack is held at T_r K and the high-temperature side is held at T_h K, then the ideal amplification ratio G is represented as equation 6[7,10–11].

$$G = \frac{I_{out}}{I_{in}} = \frac{T_r}{T_h} \qquad \text{Eq. 6}$$

From equation 6, without viscous dissipation, the ideal amplification ratio is determined with both ends temperature ratio on the stack.

In contrast, the input and output trade places in the case of attenuation. Then, the ideal attenuation ratio will be represented by both ends' temperature ratio. However, it is predicted that attenuation ratio will exceed the temperature ratio by the viscous dissipation effect.

EXPERIMENTAL METHOD (single stack)

Figure 3 presents the experimental setup. An 8-m-long stainless tube with 42 mm inner diameter was used. An electrodynamic full-range speaker is connected at one end of the tube. A stack is placed in the tube 1 m distant from the speaker. The 10-mm-long stack has many tightly piled up stainless-steel screen meshes (mesh size and channel radius of #40: 0.45 mm). At the speaker-side of the stack, an electric heater is placed as a hot heat exchanger. The temperature of a cold heat exchanger at the counter-speaker-end of the stack is maintained using circulating water. These heat exchangers create a temperature difference in the stack.

A single sine wave is transmitted from the speaker; the sound pressure after passing through the stack is measured using a probe microphone (4182; Bruel & Kjaer) set 2.0 m distant from the speaker.

The temperature difference created in the stack is set to 0 K, 200 K, and 400 K by varying the heat energy supplied to the heater. The low temperature is 300 K; high temperatures are 500 K and 700 K. The sound pressure before passing through the stack is defined as the reference sound pressure.

The rate of sound pressure change of the sound pressure after passing through the stack with a temperature difference is calculated based on the reference sound pressure amplitude. The frequencies of the sound transmitted from the speaker are from 50 Hz to 1000 Hz. The rate of sound pressure change and the rate of sound intensity change are calculated for each frequency.

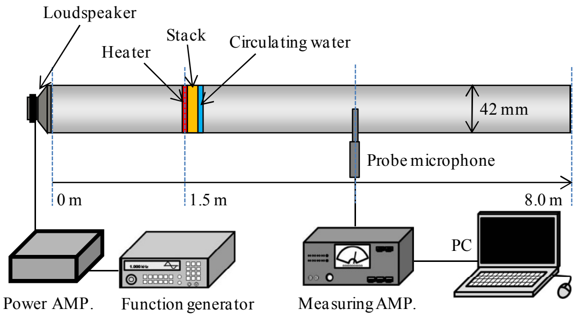


Fig. 3 Schematic of the experimental system with single stack.

RESULTS and DISCUSSION (single stack)

Figure 4 presents frequency characteristics of the thermoacoustic silencer. At the maximum, the sound intensity was attenuated to 42%. Figure 4 shows that this silencer easily attenuates low-frequency waves. The result shows that good heat exchange is achieved at low sound frequencies. This result indicates that good heat exchange occurred when $\omega\tau$ is smaller with low frequency. Regarding the silencer that used general sound absorption material, a high frequency shows a good effect. On the other hand, an important characteristic of this system has a high effect to low frequency. The discharge sound of the automobile is a low spectrum. Therefore, the utility of this system is indicated. However, it is said that the frequency of discharge sound is 50–500 Hz. Expansion of the silence frequency is necessary.

To silence a high-frequency wave, a stack with a smaller channel radius is necessary or the amount of heat energy input into stack must increase.

From equation 6, an ideal attenuation ratio is assumed. When the temperature ratio is 3:5 (i.e. the temperature difference is 200 K), then G is about 0.6. When the ratio is 3:7 (i.e. the temperature difference is 400 K), then G is about 0.43. Silence action has realized a nearly ideal attenuation ratio in this experimental system. However, as described in an ideal attenuation ratio, the attenuation action will exceed the temperature ratio by a viscous dissipation effect. Additionally, it is expected that the attenuation ratio will be 0.36 to set up two stacks of input heat energy 40 W. We designate a method of separating the sources into two stacks using a multistage stack method. The silencing efficiency of the thermoacoustic silence system is improved if the multistage stack method is adopted.

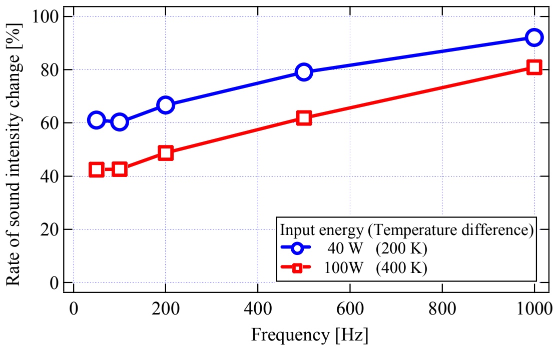


Fig. 4 Relation between temperature difference and the rate of sound intensity change (single stack).

EXPERIMENTAL METHOD (double stack)

Figure 5 presents the experimental setup. A stack is placed in the tube 1 m and 1.5 m distant from the speaker. Other experimental conditions follow the description in a previous chapter.

A single sine wave is transmitted from the speaker; the sound pressure after passing through the stack is measured using a probe microphone (4182; Bruel & Kjaer) set 2.0 m distant from the speaker.

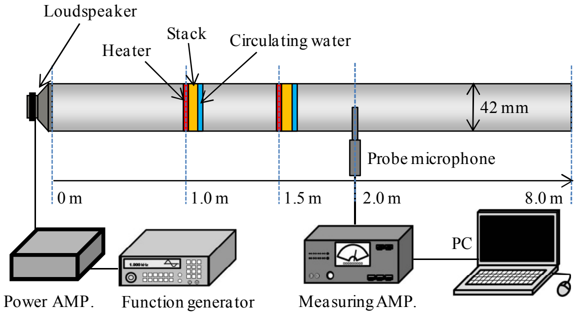


Fig. 5 Schematic of the experimental system with a double stack.

RESULTS and DISCUSSION (double stack)

Figure 6 presents frequency characteristics of a single stack and double stack. We specifically examine data of a single stack with 100 W and a double stack with 40 W. Despite the low input energy, the double stack more effective than single stack. These results indicate that the thermoacoustic silencer has high efficiency with a low driving temperature. The maximum effect is achieved in response to the input heat energy altering the number of stacks.

Using equation 6, the attenuation ratio is calculated. When the temperature ratio is 3:5 in cases with a double stack, G is about 0.36. However, by the experiment result, the silence effect reaches 0.25 at the maximum. Similarly, when the ratio is 3:7, G is about 0.18. In response, the experiment result reaches 0.11. Table 1 shows the calculated temperature ratio. The experimental results are shown for a frequency of 50 Hz. These results show that the silence effect is given both exchange and viscous dissipation. Additionally, the stack of causing viscous dissipation is set up: two stacks might make the double-stack method more effective than the single-stack method.

In this experiment, we were silenced to 0.11 at the maximum with 200 W. However, further improvement of the silence effect is necessary for practical use of this silencer.

In this experiment, no sound field change takes place. However, multistage setup stacks are expected to influence the sound field in an acoustic tube. Therefore, examination of the control of the sound field is thought to be necessary if a multistage stack method is adopted because the energy conversion efficiency of thermoacoustic phenomena is strongly affected by the sound field in the acoustic tube[8,10,14–15].

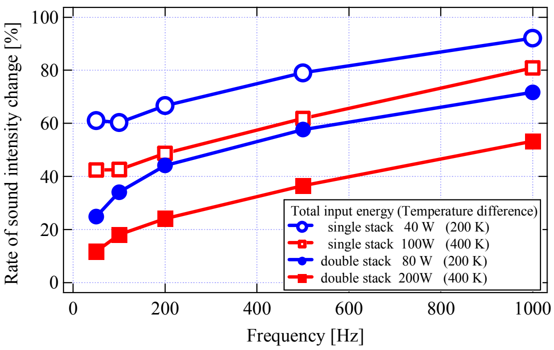


Fig. 6 Relation between temperature difference and the rate of sound intensity change (double stack).

Table 1 Comparation with assumed temperature ratio and experimental results.

Frequency 50Hz	Tr/Th (ΔT=200K)	experimental result	Tr/Th (ΔT=400K)	experimental result
single stack	0.60	0.61	0.43	0.42
double stack	0.36	0.25	0.18	0.11

CONCLUSION

This paper describes an experiment to improve the silencing efficiency of a thermoacoustic silencer. First, the frequency characteristic is measured and the silence effect is evaluated. Results showed that the utility of this system is indicated by the silence effect of low frequency and a multistage stack method is applied. The silence effect improvement was confirmed using a multistage stack method. This improvement is thought to be benefited by silence effects caused by heat exchange and viscous dissipation. However, improvement of the silence effect is imperative for the practical use of this system. Further examination will be necessary.

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