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Changing the Heat Flow in The Stack of Loop-Tube Type Thermoacoustic System Using a Heat Phase Adjuster

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ABSTRACT: A method to improve the energy conversion efficiency of the loop-tube type thermoacoustic system is proposed. Acoustic boundary conditions are introduced by the local thermal input to a heat phase adjuster (HPA). In the previous study, controlling the sound field by HPA, the sound intensity was increased. In this study, the change of the heat flow in the stack using HPA is focused for clarifying the mechanism to improve the efficiency. In the experiment, the sound pressure in the tube and the temperature of the stack are measured while changing the thermal input to HPA. The sound fields in the tube are evaluated with the transfer matrix method based on the Rott equation considering temperature gradient. In various conditions of HPA, the increasing amounts of the sound intensity and heat flow in the stack are calculated using the sound pressure in the stack. As the result, it is revealed that the heat flow in the stack increases with the thermal input to HPA. It is also demonstrated that HPA has the effects of increasing the heat flow in the stack. Therefore, it is suggested that the factor of improving efficiency due to HPA is increased by the heat flow.

INTRODUCTION

Thermoacoustic phenomenon is a phenomenon that enables the mutual energy conversion between heat and sound [1-3]. In such a thermoacoustic phenomenon, provided a device called stack with numerous narrow flow paths is installed in an acoustic tube, sound wave is generated by producing a steep temperature gradient between both ends of the stack with a hot thermal exchanger and a cold thermal exchanger. The generated sound wave can be applied to refrigeration [4-6]. The system utilizing the thermoacoustic phenomenon in such a manner is called thermoacoustic system. As a problem toward the practical realization of the thermoacoustic system, the change of the sound field in the loop-tube type thermoacoustic system along with the operation environment to reduce the instability of the resonance mode is supposed. To solve such a problem, the techniques to install a phase adjuster (PA) and an expanding phase adjuster (EPA) which adjust the particle velocity and the phase by creating boundary conditions with the locally changed radius of the acoustic tube have been proposed [7-9]. It has been reported that, since these adjusters work as devices to change the phase of the sound field by selecting the setting position, a resonance mode with high efficiency and stability can be realized. However, since these devices are premised to be used by infixing in the acoustic tube, it is hard to flexibly adjust for conserving the high-efficiency conversion along with the operation environment of the system. Then, as a method to control the resonance mode avoiding such a disadvantage, the present research group has presented a heat phase adjuster (HPA) which controls the resonance mode by locally producing a high-temperature region in the acoustic tube [10-14]. HPA has an advantage that the setting position and the thermal input can be much more easily changed externally even after starting the driving of system comparing with PA and EPA, and the resonance mode can be adjusted corresponding to the driving environment. Although HPA is supposed to be a technique to improve the energy conversion efficiency by controlling the sound field utilizing the newly added boundary condition in the tube, the mechanism has not been clarified yet. In the previous study concerning HPA, the present authors have reported that the excessive thermal input power can be a contributing factor to decrease the energy amplifying quantity.(14) Further, Morishita et al. have reported that the temperatures at both ends of the stack change due to HPA. The factor is expected to increase the heat flow from the hot end to the cold end. In order to clarify the contributing factor to improve the energy conversion efficiency, this paper pays attention to the inside of the stack. The sound field in the whole loop tube is calculated by the transfer matrix method considering the temperature gradient in the tube [15-18]. The relationship between heat flow in the stack and the energy amplifying quantity is discussed.

PRINCIPLE

Numerical analysis

In order to calculate the sound filed in the tube, its numerical analysis is performed using the linear theory and the transfer matrix method. For the thermoacoustic numerical computation, the equations of motion and mass-conservation under long-wavelength approximation, linear approximation and ideal-gas approximation are used as the governing equations shown as follows:

$$\frac{d}{dx}\begin{pmatrix} P \\ U \end{pmatrix} = C\begin{pmatrix} P \\ U \end{pmatrix}, \tag{1}$$

$$\text{where } C \equiv \begin{pmatrix} 0 & -\dfrac{i\omega\rho_{\mathrm{m}}}{1-\chi_{\mathrm{v}}} \\ -\dfrac{i\omega}{\gamma P_{\mathrm{m}}}\left\{1+(\gamma-1)\chi_{\mathrm{a}}\right\} & \dfrac{(\chi_{\alpha}-\chi_{\mathrm{v}})}{(1-P_{\mathrm{r}})(1-\chi_{\mathrm{v}})T_{\mathrm{m}}}\dfrac{\mathrm{d}T_{\mathrm{m}}}{\mathrm{d}x} \end{pmatrix}$$

Here P is the fluctuation component of the pressure and U is the average particle velocity across a sectional area. They are simply called the sound pressure and the particle velocity, respectively, hereafter. Further, □, T_{m}, □$_{\mathrm{m}}$, □, P_{m} and P_{r} are the angular frequency of the vibration, the average temperature across the sectional area of working fluid filled in the tube, the average density across the sectional area, the specific heat ratio, the average pressure in the tube and the Prandtl number, respectively. In the previous study analyzing the loop-tube type thermoacoustic system, it has been conventionally assumed $\mathrm{d}T_{\mathrm{m}}/\mathrm{d}x=0$ for simplicity, that is no temperature gradient along the tube axis. In this paper, the sound field is newly analyzed where the value of $\mathrm{d}T_{\mathrm{m}}/\mathrm{d}x$ is assumed from the measured value of the temperature in the tube.

Heat flow

The heat flow Q is the heat amount passing through unit sectional area during unit time in the sound field. Further, it is proportional to the entropy flux and is used for the discussion on the efficiency of thermal engine. A thermal engine with higher temperature ratio of the high temperature and the low temperature has higher efficiency. The heat flow Q in the thermoacoustic phenomenon is defined as [19, 20]

$$Q = Q_{\mathrm{P}} + Q_{\mathrm{S}} + Q_{\mathrm{D}}, \tag{2}$$

where Q_{P} is the heat flow due to the travelling wave component whose direction is opposite to the work flow. Furthermore, Q_{S} is the heat flow due to the standing wave in the direction to increase the pressure and Q_{D} is the heat flow due to the dream pipe effect in the direction toward low temperature from high temperature [21]. As suggested above, the directions of Q_{P} and Q_{S} are determined by the sound field while the direction of Q_{D} is determined by the temperature gradient. On the other hand, since Q_{D} flows toward low temperature from high temperature, its direction is determined depending on the temperature gradient. In the loop-tube type thermoacoustic system used in the present work, Q_{P} is in the directions from high temperature to low temperature while Q_{S} and Q_{D} are in the direction from low temperature to high temperature. Here the above direction of Q_{S} is the direction in the case assuming that the anti-node of the sound pressure locates at the hot end of the stack of the loop-tube type thermoacoustic system. Each heat flow is expressed as follows.

$$Q_{\mathrm{P}} = -\frac{1}{2}\mathrm{Re}\left\{P\tilde{U}\right\}\mathrm{Re}\left\{\frac{(1-\chi_{\mathrm{v}})(\chi_{\alpha}-\tilde{\chi}_{\mathrm{v}})}{(1+P_{\mathrm{r}})\left|1-\chi_{\mathrm{v}}\right|^{2}}\right\}, \tag{3}$$

$$Q_{\mathrm{S}} = -\frac{1}{2}\omega\,\mathrm{Re}\left\{P\tilde{\zeta}\right\}\mathrm{Im}\left\{\frac{(1-\chi_{\mathrm{v}})(\chi_{\alpha}-\tilde{\chi}_{\mathrm{v}})}{(1+P_{\mathrm{r}})\left|1-\chi_{\mathrm{v}}\right|^{2}}\right\}, \tag{4}$$

$$Q_{\mathrm{D}} = \frac{\rho_{\mathrm{m}} C_{\mathrm{p}} |U|^2}{2\omega\left(1-P_{\mathrm{r}}^2\right)\left|1-\chi_{\mathrm{v}}\right|^2} \mathrm{Im}\left\{\chi_{\alpha} + P_{\mathrm{r}}\tilde{\chi}_{\mathrm{v}}\right\} \frac{dT_{\mathrm{m}}}{dx}, \quad (5)$$

where P, U and □ are the sound pressure, the particle velocity and the particle displacement. Further C_p is the isobaric specific heat and $\tilde{A}$ is the complex conjugate of A. □$_\alpha$ and □$_v$ are used for homologizing three dimensional phenomenon to one dimensional analysis. (18)

Acoustic intensity

The acoustic intensity I [W/m^2] is the amount of the sound energy passing through the cross section of unit area in the sound field which is defined as follows [22].

$$I = \frac{1}{2}|p||u|\cos\phi, \quad (6)$$

where p, u and □ are the sound pressure, the particle velocity and the phase difference between the sound pressure and the particle velocity, respectively. In the case of the traveling wave with □=0°, the energy conversion is performed by utilizing a reversible heat exchange between the working fluid and the wall of the flow path. In the travelling-wave type thermoacoustic system like a loop-tube type, the utilizing rate of the reversible heat exchange is increased by making the phase difference between the sound pressure and the particle velocity close to 0°. Then the energy conversion efficiency is enhanced [23]. An example of the distribution of the acoustic intensity in the thermoacoustic system is also shown in Fig. 1. The energy amplifying quantity is defined by the difference □I of the intensity between the cold end and the hot end of the prime mover (PM).

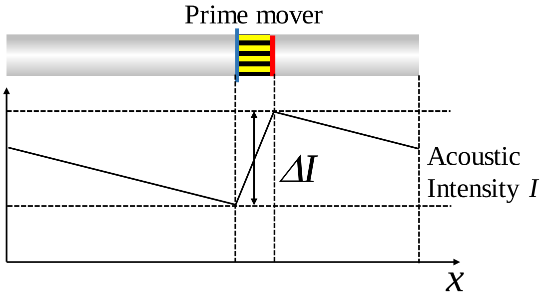

Figure 1. Acoustic intensity flow.

EXPERIMENTAL METHOD

The experimental system is illustrated in Fig. 2. The loop-tube with a 3300 mm total length is built with a stainless-steel tube with a 42 mm inner diameter. A 50 mm thick PM stack consisting of flow paths with a 900 cell/inch^2 density and a 0.45 mm radius for each path is constructed by sandwiching with an electric heater and a circulating water on both ends. The input to the heater is kept at 330 W and the cold end is kept at 20°C by circulating water for creating a temperature gradient. Another electric heater is used for HPA which is set on the external wall at the position of 2100 mm from the hot end that has been reported as the optimum position for inducing one wave-length resonance of the loop tube. The setting width of HPA is kept constant at 30 mm. The input thermal quantity Q_{HPA} into HPA is varied in the range of 0-160 W by the step of 40 W. The temperatures at the PM stack and the HPA setting position are measured with K-type thermocouples. As shown in Fig. 3, the temperature of the PM stack is measured with a thermocouple inserted deeper into the stack by a 10 mm step. The temperatures are named T_{h}, T_1, T_2, T_3, T_4 and T_{c} in order of the distance from the hot end. Furthermore, the pressure fluctuation in the tube is measured with a pressure sensor (product of PCB Co.), and the sound field in the tube is calculated from the measured sound pressure value using the transfer matrix method taking the temperature distribution into account. As shown in Fig. 2, the position at 850 mm from the PM hot end is defined as *x*=0 mm.

RESULTS AND DISCUSSION

The temperature gradient in the stack is shown in Fig. 4. While the measured values are plotted by circles, straight lines are drawn between them to clearly show the gradients. When Q_{HPA}=0 W similar to the usual loop-tube driving, the gradient is steep at 0-30 mm and is gentle at 30-50 mm. As the cause of this, it is supposed that the heater at the hot end is dominant for 0-30 mm while the circulating water is dominant at 30-50 mm. However, comparing the case of Q_{HPA} = 40 W with that of Q_{HPA} = 0 W, the temperature lowers at 0 mm in spite of the elevation at 30 and 50 mm. Thus, it is seen that, when HPA is operated, the determinative factor for the temperature gradient in the stack shifts from the temperature control effect by the heater and the circulating water to the sound field effect accompanied by the sound field control. In addition, by increasing the thermal input to HPA, the sound field effect is increased and the temperature almost linearly changes with the distance over the stack. Thus, the formative factor for the temperature gradient in the stack is considered to be changed from the temperature effect to the sound field effect controlled by HPA. Furthermore, Sugimoto *et al*. has reported, in the previous study, that the energy amplified quantity can be maximized when the temperature is adjusted to change linearly over the stack with an embedded nichrome wire heater [24]. Consequently HPA is supposed to be a technique to be able to improve the energy amplifying quantity by adjusting the temperature to change linearly over the stack. Since the change of the temperature gradient is assumed to be caused by the change of the heat flow, the sound field is calculated for the evaluation of the heat flow applying a new analytical method. Fig. 5 shows the sound field calculated by the conventional analytical method, whereas Fig. 6 shows that by the new analytical method. The hollow circles are the measuring points. Since the transfer matrix method is performed using only the sensors at two positions, the adequacy of the calculation can be judged by checking if the measured values at other unused sensors agree well with the calculated values. It is

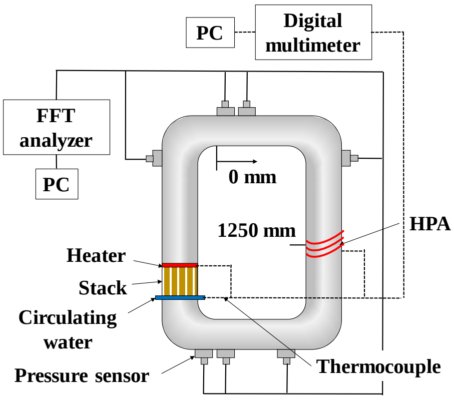

Figure 2. Experimental setup.

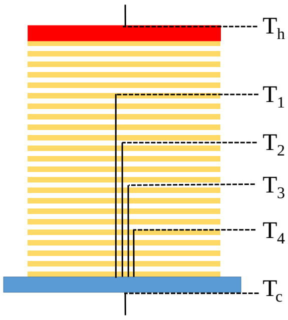

Figure 3. Position of temperature measurement in the stack.

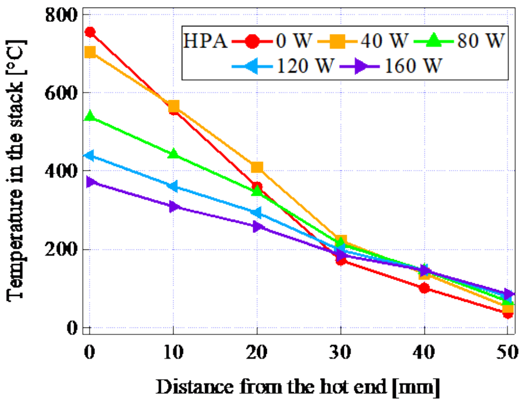

Figure 4. Temperature distribution in the stack.

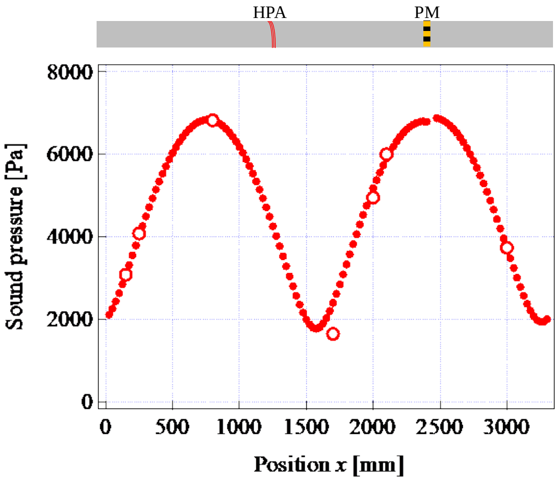

Figure 5. Sound pressure by conventional analysis (Q_{HPA}=160 W).

decided that the sound field can be calculated more accurately with the new analytical method because the calculated value at the point of 1700 mm after passing through HPA agrees well with the measured value in Fig. 6. Furthermore, since the calculated values agree with the measured values at the sensors set above and below the PM stack, it can be decided that the calculation will be successful even in the PM stack. □I and SWR for various conditions are shown in Figs. 7 and 8, respectively. It is confirmed that they both show the trend similar to the previous study. Within the same resonance mode, SWR decreases as Q_{PHA} increases. Since this means the approach to a traveling-wave sound field, the heat flow is assumed to change in the stack. Then, dividing the inside of the stack into 100 parts, the heat flow is calculated with the transfer matrix method. The average heat flow is shown in Fig. 9, where the direction from the cold end to the hot end is defined as the positive direction and Q_{total} is the summation of Q_P, Q_S and Q_D. Although the change of Q_S depending on the condition is relatively small, Q_P and Q_D increase to the negative direction as Q_{HPA} increases. Accordingly Q_{total} also increases in the negative direction. Therefore, it is surmised to be demonstrated that, as Q_{HPA} increases, SWR lowers and the heat flow in the stack from the hot end to the cold end increases. Summarizing the above results, it is suggested the heat flow in the stack can be controlled by the thermal input to HPA. To discuss the relation between the change of the heat flow and the energy amplifying quantity, the enthalpy flow H expressed by the following equation is considered [25].

$$H = I + Q, \tag{7}$$

where *I* is the amount of work (acoustic intensity), and *Q* is the heat flow. When the enthalpy flow is considered to be the supplying energy to the PM stack, the enthalpy flow is supposed to be constant because the thermal input to the PM stack is constant. Defining the direction from the cold end to the hot end of the stack to be positive, the work flow is in the positive direction while the heat flow Q_{total} is in the negative direction. It is assumed that the work flow increases in the positive direction as Q_{total} increases in the negative direction. Namely, it is assumed that the acceleration of the conversion from the thermal energy to the acoustic energy in the PM stack causes the increase of □*I*. Thus, it is considered that HPA can control the heat flow in the PM stack with its thermal input, and □*I* increases as the heat flow changes [26-29].

CONCLUSION

Although the effectiveness of HPA as a control technique for the sound field in a loop-tube type thermoacoustic system had been reported, the principle was scarcely known yet. In this paper, the contributing factor for enhancing the energy amplifying quantity in the PM stack due to the thermal input to HPA was discussed by calculating the heat flow in the stack. As the result, it was confirmed that the temperature could change almost linearly with the distance in the stack provided the input to HPA was adjusted. Furthermore, the temperature gradient

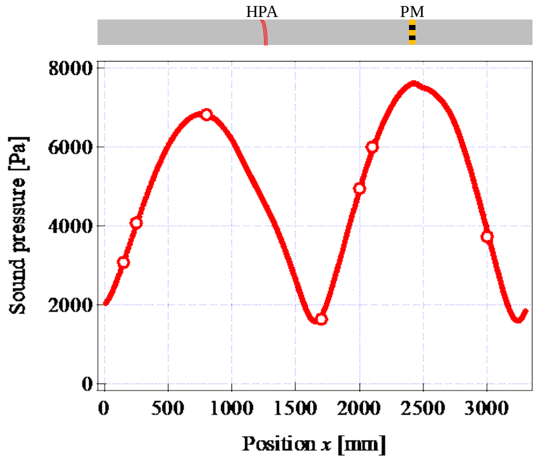

Figure 6. Sound pressure by new analysis (Q_{HPA}=160 W).

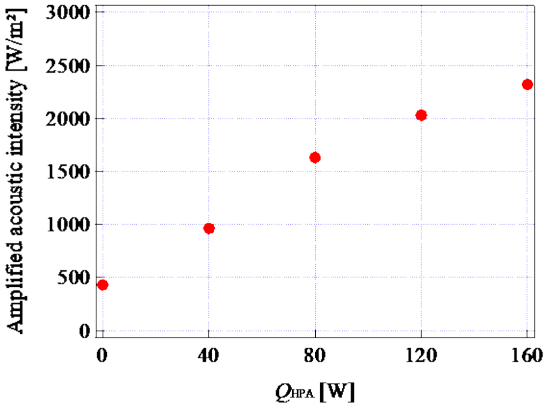

Figure 7. Amplified acoustic intensity as a function of Q_{HPA}.

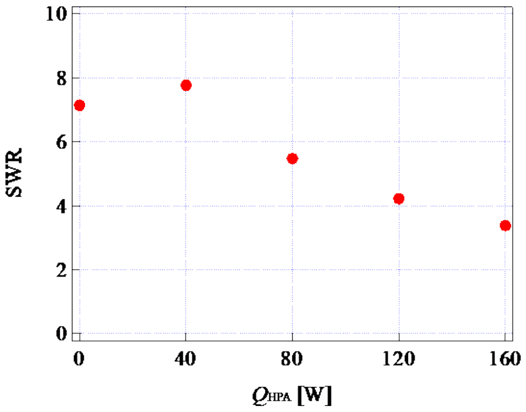

Figure 8. Standing wave ratio as a function of Q_{HPA}.

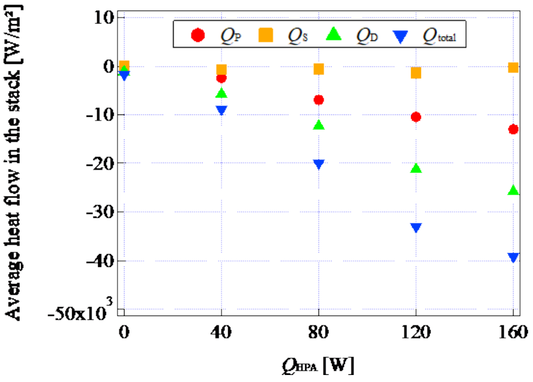

Figure 9. Average heat flow in the stack as a function of Q_{HPA}.

changed primarily caused by the increase of the heat flow from the hot end to the cold end of the PM stack was demonstrated. It was also demonstrated that the energy generation quantity was increased by the increased heat flow. Thus, it was considered that HPA could control the heat flow in the PM stack with its thermal input, and the enhancement of □I was caused by the increase of the heat flow from the hot end to the cold end of the PM stack.

NOMENCLATURE

P sound pressure, Pa
U particle velocity, m/s^2
ζ particle displacement, m/s
□□angular frequency, rad/s
T temperature, K
□ density, Kg/m^3
□□specific heat ratio, J/(Kg·K)
P_r prandtl number, W/(m·K)
Q heat flow, W/m^2
C_p isobaric specific heat, Kg/mol
□$_{\alpha,v}$ degree of heat exchanger
Re{} real number
Im{} imagine number
I acoustic intensity, W/m^2
□□phase difference between sound pressure and particle velocity, rad
H enthalpy flow, W/m^2

Subscripts
m time average
P traveling wave
S standing wave
D dream pipe
c circulating water

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