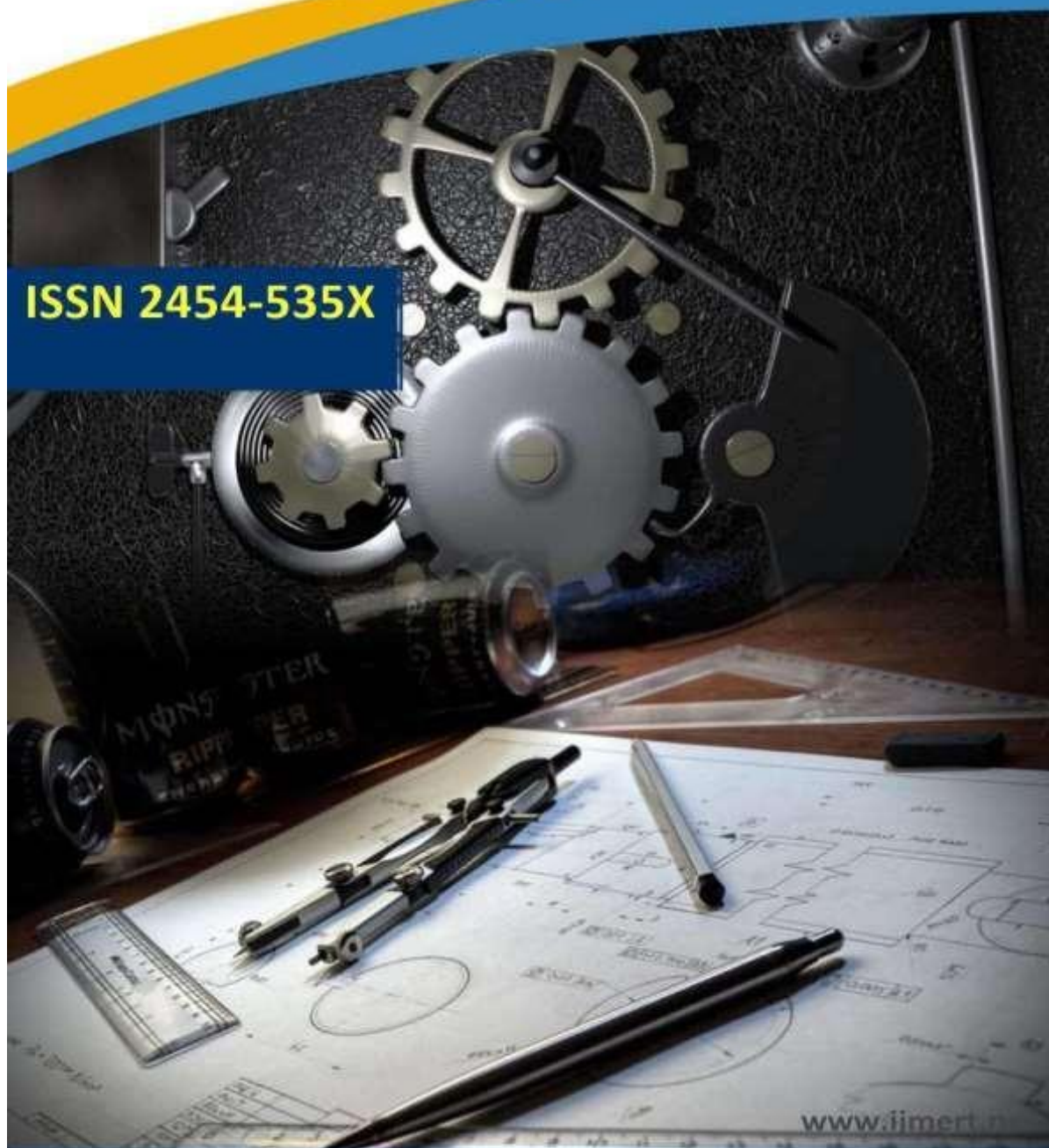




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Using a Heat Phase Adjuster to Modify the Heat Flow in a Loop-Tube Type Thermoacoustic System

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ABSTRACT:

It is suggested a technique to increase the thermoacoustic system's loop-tube type energy conversion efficiency. A heat phase adjuster's (HPA) local thermal input introduces acoustic boundary conditions. The sound intensity was raised in the prior investigation by using HPA to adjust the sound field. This work focuses on the modification of heat flow in the stack utilizing HPA to clarify the process for increasing efficiency. While varying the thermal input to HPA, the experiment measures the sound pressure inside the tube and the stack's temperature. Using the transfer matrix approach based on the Rott equation and taking the temperature gradient into consideration, the sound fields inside the tube are assessed. The rising levels of HPA in a variety of circumstances

INTRODUCTION

A phenomenon known as the thermoacoustic phenomena allows heat and sound to exchange energy with one another [1-3]. In this type of thermoacoustic phenomenon, if a stack-like device with several tiny flow pathways is inserted in an acoustic tube, sound waves are produced by creating a sharp temperature difference between the stack's two ends using hot and cold thermal exchangers. The sound wave produced can be used

for cooling [4-6]. The thermoacoustic system is one that makes use of the thermoacoustic phenomenon in this way. The change in the sound field in the loop-tube type thermoacoustic system along with the operating environment is meant to lessen the instability of the resonance mode and provide a challenge to the practical realization of the thermoacoustic system.⁹¹

PRINCIPLE

Numerical analysis In order to calculate the sound field 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:

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

where $C \equiv \begin{pmatrix} 0 & -i\omega\rho_m \\ -\frac{i\omega}{\gamma P} \{ 1 + (\gamma-1)\chi_a \} & \begin{pmatrix} 1-\chi_v \\ (\chi_a - \chi_v) \end{pmatrix} \frac{dT}{dx} \end{pmatrix}$



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, ω , T_m , ρ_m , γ , 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 $dT_m/dx=0$ for simplicity, that is no temperature gradient along the tube axis. In this paper, the sound field is newly analyzed where the value of dT_m/dx 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]

$$Q = Q_p + Q_s + Q_D, \quad (2)$$

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.

$$Q_p = -\frac{1}{2} \text{Re}\{PU\} \text{Re}\left[\frac{(1-\chi_v)(\chi_\alpha - \chi_v)}{(1+P)1-\chi}\right], \quad (3) \quad Q_s = -\frac{1}{2} \omega \text{Re}\{P\zeta\} \text{Im}\left[\frac{(1-\chi_v)(\chi_\alpha - \chi_v)}{(1+P)1-\chi}\right], \quad (4) \quad Q_D = \frac{\rho_m C U^2 dT}{2\omega(1-P_r^2)|1-\chi_v|^2} \text{Im}\{\chi + P\chi\} d\chi, \quad (5)$$

where P , U and ϕ are the sound pressure, the particle velocity and the particle displacement. Further C_p is the isobaric specific heat and A is the complex conjugate of A . ϕ_a and ϕ_v are used for homologizing three dimensional phenomenon to one dimensional analysis. ⁽¹⁸⁾

Acoustic intensity

The acoustic intensity I [W/m²] 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]. $I = \frac{1}{2} p u \cos \phi$, (6)

where p , u and ϕ 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 $\phi=0^\circ$, 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 ΔI of the intensity between the cold end and the hot end of the prime mover (PM).

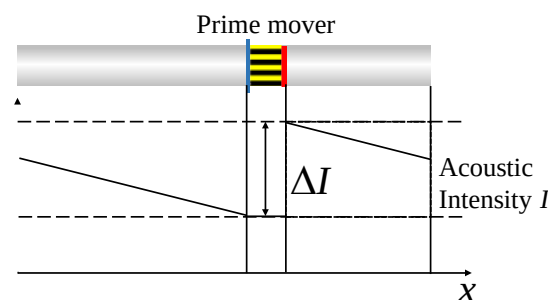


Figure 1. Acoustic intensity flow.

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/inch² 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

defined as $x=0$ mm.

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

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

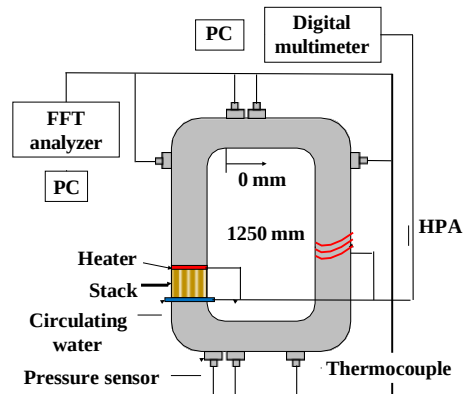


Figure 2. Experimental setup.

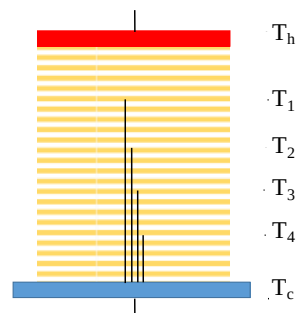


Figure 3. Position of temperature measurement in the stack.

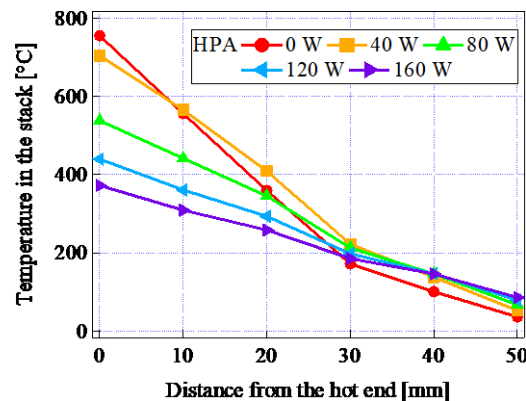
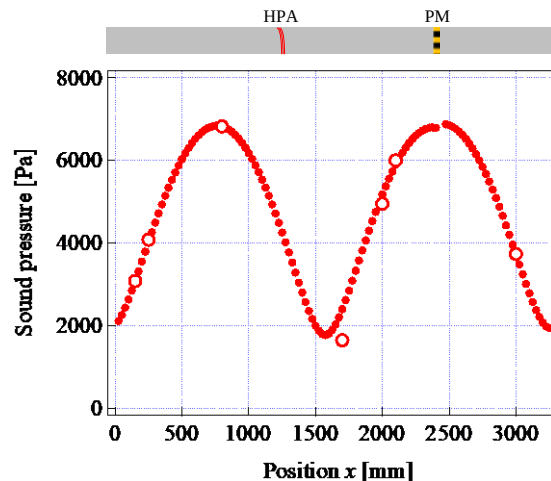


Figure 4. Temperature distribution in the stack.

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. $\square I$ 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 it is suggested the heat flow in the stack can be

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,

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]. $H = I + Q$, (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 $\square I$. Thus, it is considered that HPA can control the heat flow in the PM stack with its thermal input, and $\square I$ 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

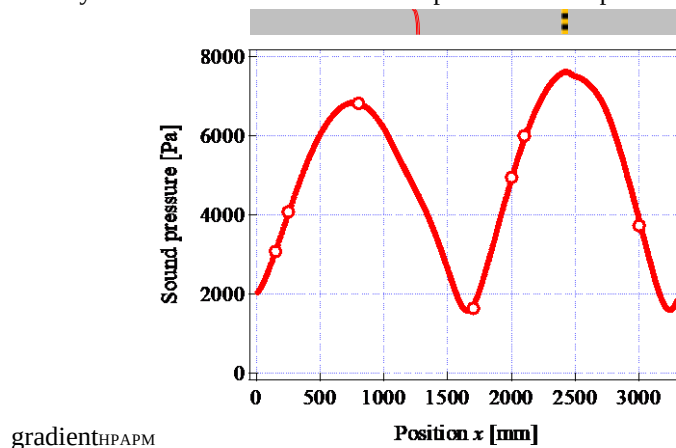


Figure 6. Sound pressure by new analysis ($Q_{\text{HPA}}=160$ W).

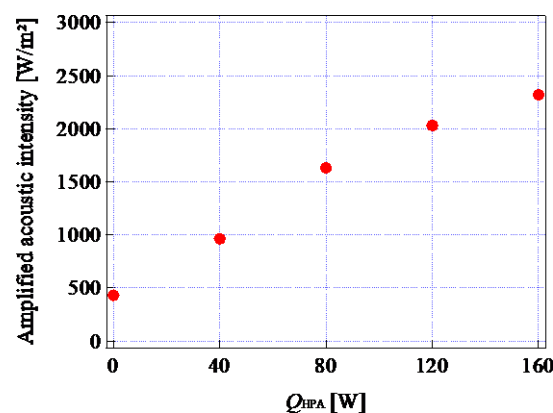


Figure 7. Amplified acoustic intensity as a function of Q_{HPA} .

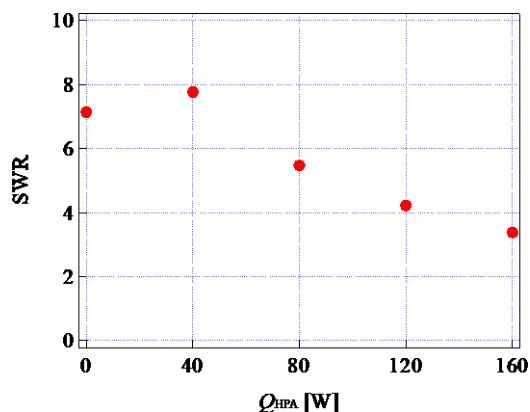


Figure 8. Standing wave ratio as a function of Q_{HPA} .

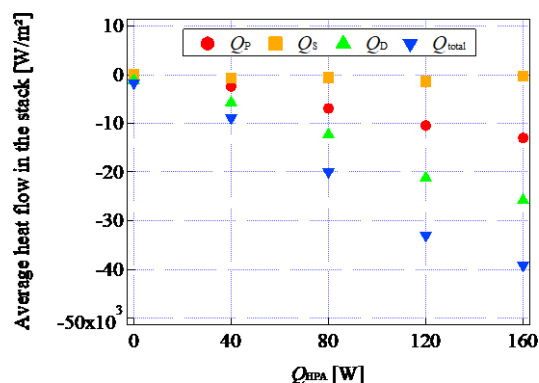


Figure 9. Average heat flow in the stack as a function of Q_{HPA} .

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 $\square I$ was caused by the increase of the heat flow from the hot end to the cold end of the PM stack.

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