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ABSTRACT
Stacks are among the most important devices for influencing the energy-conversion efficiency of work flow to heat flow during thermoacoustic phenomena. An optimal stack design is indispensable for the practical application of thermoacoustic systems. To this end, it is necessary to estimate the heat flow generated in the stack. This study proposes to estimate this quantity based on the sound generated by a thermoacoustic phenomenon in a stack without any temperature gradient. The heat flow caused by a standing-wave component generated by this thermoacoustic phenomenon is successfully measured.

When a sound wave propagates through a narrow channel, it does not change adiabatically but exchanges heat with the channel wall. This is known as a thermoacoustic phenomenon; heat is exchanged between a fluid and a solid through which energy conversion occurs.

Two energy flows have been reported: heat flow, i.e., the flow of thermal energy, and work flow, i.e., the flow of sound energy in thermoacoustic research. Several studies have reported the methods for measuring the work flow. However, measuring the heat flow is difficult and solutions to address this issue are scarce.

In thermoacoustic phenomena, the heat flow mainly occurs in the stack. The stack has a structure similar to a bundle of narrow channels; it is one of the most important devices influencing energy-conversion efficiency during such phenomena. The optimum design of the stack is indispensable for the practical application of thermoacoustic systems. Moreover, the heat flow generated in the stack affecting its design needs to be estimated.

Heat flow is classified into three types. The heat flow \( q \) is represented by the following equation:

\[
q = Q_p + Q_s + Q_d.
\]  

The first heat-flow component, \( Q_p \), is caused by a traveling wave, and the second heat-flow component, \( Q_s \), is caused by a standing wave. These heat flows depend on the state of the sound. The third heat-flow component, \( Q_d \), is caused by a temperature gradient.

This study proposes a method for estimating the heat flow caused by the thermoacoustic phenomenon in the stack. Thermoacoustic systems operate by generating a temperature gradient in the prime mover stack. However, depending on the operating conditions, the temperature gradient in the stack may change. Thus, \( Q_d \) will change and a heat flow, \( Q_{M} \), is observed from the outside of the system due to the temperature difference inside and outside the system. Therefore, estimating the heat flow arising from thermoacoustic phenomena in the stack is difficult.

This study aims to estimate the sound-based heat flow by generating a thermoacoustic phenomenon without adding a temperature gradient to the stack. In other words, \( Q_p + Q_s \) can be estimated using this method by excluding \( Q_d \). Since \( Q_d \) is the heat flow caused by the temperature gradient, it becomes zero when this gradient disappears, thus allowing \( Q_p + Q_s \) to be estimated.

Figures 1(a) and 1(b) show the measurement concept and the image of the heat flows. A force-driven thermoacoustic heat pump was used in this experiment. Figure 1(a) shows the state in which a sound wave enters the stack in the thermoacoustic system and cooling is performed by the heat pump. The temperature of the \( T_{HX} \) part is defined as \( T_{HX} \), and the temperature of the \( T_c \) part is defined as \( T_c \). The sound energy is propagated from left to right, and the \( T_c \)
part is cooled via thermoacoustic phenomena. \( T_{\text{HX}} \) is fixed to the ambient temperature by circulating water to eliminate the generated heat flow. In the stack, the heat flows \( Q_{\text{p}} + Q_{\text{s}} \) and \( Q_{\text{d}} \) are generated. Under this experimental condition, \( Q_{\text{p}} + Q_{\text{s}} \) and \( Q_{\text{d}} \) flow in opposite directions.\(^{3,12,14}\) \( Q_{\text{p}} + Q_{\text{s}} \) exits the system via a heat exchanger. \( Q_{\text{p}} + Q_{\text{s}} \) and \( Q_{\text{d}} \) make \( T_{\text{c}} \) lower than \( T_{\text{HX}} \). In addition, \( T_{\text{c}} \) is lower than the surrounding temperature, causing \( Q_{\text{M}} \) to flow into the system from the surroundings. In this state, estimating the heat flow \( Q_{\text{p}} + Q_{\text{s}} \) generated by the thermoacoustic phenomenon in the stack is difficult. Therefore, a new system is proposed herein that incorporates an electric heater into the \( T_{\text{c}} \) part, as shown in Fig. 1(b). This heater forcibly creates a heat flow \( Q_{\text{L}} \) and sets \( T_{\text{c}} \) and \( T_{\text{HX}} \) to the same temperature. Thermoacoustic phenomena occur, and only the heat flow \( Q_{\text{p}} + Q_{\text{s}} \) generated by the thermoacoustic phenomenon in the stack is difficult.

Therefore, a new system is proposed herein that incorporates an electric heater into the \( T_{\text{c}} \) part, as shown in Fig. 1(b). This heater forcibly creates a heat flow \( Q_{\text{L}} \) and sets \( T_{\text{c}} \) and \( T_{\text{HX}} \) to the same temperature. Thermoacoustic phenomena occur, and only the heat flow \( Q_{\text{p}} + Q_{\text{s}} \) is generated. Since there is no temperature gradient and \( T_{\text{c}} \) and \( T_{\text{HX}} \) are the same temperature, neither \( Q_{\text{M}} \) nor \( Q_{\text{d}} \) arise.

The experimental system is shown in Fig. 2. The resonance tube was a stainless-steel tube with an inner diameter of 42.6 mm closed with a steel plate and hermetically sealed. One end of the tube was connected to a forced-vibration device by a linear motor via a bellows, and a structure in which the gas inside the tube is forcibly vibrated by moving the closing plate in the tube-axis direction was adopted. The resonance tube was \( \sim 3.3 \) m long, and atmospheric-pressure air was sealed in the tube. A honeycomb-ceramic stack was installed between 0.12 and 0.17 m from the right closed end on the fixed side. The flow-path radius of the stack is \( \sim 0.45 \) mm. On the closed-end side of the stack, a heat exchanger, \( T_{\text{HX}} \) part (parallel-plate fin 1.5-mm thick, 1.5-mm interval, and 2-mm length in the axial direction of the tube), was installed. On the other side, a spiral electric heater, \( T_{\text{C}} \) part (sheath diameter 1 mm and length 300 mm), was installed. Two K-type thermocouples were installed at the center of the tube in the heat exchanger \( T_{\text{HX}} \) and in the center of the electric heater, and the temperatures \( T_{\text{HX}} \) and \( T_{\text{C}} \) were measured. In the heat exchanger \( T_{\text{HX}} \) part, water at room temperature was circulated and kept at a constant temperature. To confirm the thermoacoustic oscillation in the tube and determine the frequency, pressure sensors were mounted on the tube wall and signals were transmitted to a fast Fourier transform analyzer for measuring the sound pressure.

The phase difference, \( \phi \), between sound pressure and particle velocity can be estimated using a two-sensor method\(^{1,10}\) based on pressure measurements.

With the room-temperature cooling water circulated in the heat exchanger, the thermal load was first set to 0 W and then vibration was started with a constant current, waiting until the temperature on either side of the stack became constant (\( \sim 20 \) min). The minimum temperature was obtained. A sinusoidal command current of 51 Hz and an amplitude of 0.7 A were set for the motor amplifier, and vibration was applied constantly at \( \sim 7 \) W. After obtaining the minimum temperature, application of electric power to the load heater began and the thermal load was obtained by waiting until the cooling-part temperature became constant with respect to the input power. The applied electric power was gradually increased stepwise to obtain the characteristics of the temperature with respect to the thermal load (electric power). The measurement result of the minimum attained temperature is shown in Fig. 3. In addition, the result of the measurement of the temperature characteristic against the thermal load is shown in Fig. 4. As can be seen from Fig. 4,
the thermal load under the condition of no temperature difference between the cooling edge and the room is \( \sim 1.2 \) W. Here, \( Q_d \) does not exist because there is no temperature gradient at either end of the stack because the forced heat flow, \( Q_L \), exists at the place where it should be cooled. In addition, there is no temperature gradient at room temperature in the system; therefore, \( Q_M \) does not exist either. Thus, \( Q_p + Q_s \), which is the generated heat flow, can be considered alone during the thermoacoustic phenomenon. Under this experimental condition, \( Q_p + Q_s \) is 1.2 W.

Moreover, the contents of \( Q_p + Q_s \) are discussed herein. The distribution of the phase difference, \( \varphi \), between the sound pressure and the particle velocity obtained using the two-sensor method is shown in Fig. 5. It is apparent that the phase difference of the stack setting is almost 90\(^\circ\). \( Q_p + Q_s \) is related to the phase difference \( \cos \varphi \).\(^1\)\(^2\)\(^3\) In other words, since the phase difference is almost 90\(^\circ\), \( Q_p \) is considered to be almost zero. Therefore, under this experimental condition, \( Q_s \) is 1.2 W.

We succeeded in measuring the standing-wave component of the heat flow generated via a thermoacoustic phenomenon in the stack. We believe that this experimental method will be effective for future use.

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REFERENCES

\begin{enumerate}
\item A. M. Fusco, W. C. Ward, and G. W. Swift, J. Acoust. Soc. Am. \textbf{91}, 2229 (1992).
\item G. W. Swift, J. Acoust. Soc. Am. \textbf{84}, 1145 (1988).
\item A. Tominaga, \textit{Cryogenics} \textbf{35}, 427 (1995).
\item T. Yazaki, A. Iwata, T. Maekawa, and A. Tominaga, \textit{Phys. Rev. Lett.} \textbf{81}, 3128 (1998).
\item S. Backhaus and G. W. Swift, \textit{Nature} \textbf{399}, 335 (1999).
\item T. Yazaki, T. Biwa, and A. Tominaga, \textit{Appl. Phys. Lett.} \textbf{80}, 157 (2002).
\item Y. Ueda, T. Biwa, U. Mizutani, and T. Yazaki, \textit{J. Acoust. Soc. Am.} \textbf{115}, 1134 (2004).
\item S. Sakamoto and Y. Watanabe, \textit{Ultrasounds} \textbf{42}, 53 (2004).
\item Y. Ise, S. Sakamoto, Y. Orino, T. Fujii, S. Hirayama, D. Ito, Y. Inui, and Y. Watanabe, IEICE Technical Report, Vol. 115, No. 423, US2015-98, pp. 83–86, 2016 (in Japanese).
\item T. Wada, S. Sakamoto, Y. Orino, S. Ueno, and Y. Kajiura, Jpn. J. Appl. Phys., Part 2 \textbf{56}, 07JE09 (2017).
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