Measurement of Acoustically Induced Mass Transfer in Wet Wall Narrow Channels

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Acoustically induced mass transfer was investigated experimentally using a standing-wave thermoacoustic cooler. The cooler comprised three ceramic honeycombs with narrow channels, an acoustic driver, and a tube. The three honeycombs were placed in series within the tube. The central honeycomb was wet, and the others were dry. One end of the tube was closed with a rigid plate, while the other end was connected to the acoustic driver. When an acoustic wave was introduced via the driver, a temperature gradient developed along the honeycombs due to thermoacoustic effects. The weights of the three honeycombs were measured before and after the acoustic wave was applied. This experiment allowed us to determine both the amount and direction of the mass transfer. The results revealed two key findings. First, the value of the mass transfer reached a maximum of 0.39 mg/s. Second, the direction of the mass transfer depended on the temperature gradient along the honeycombs: when the temperature gradient was small, the mass was transferred from the speaker side toward the closed end; when the temperature gradient was large, the direction was reversed. These results were compared with numerical predictions, and the comparison showed good quantitative agreement.

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I. INTRODUCTION

When an acoustic wave propagates in a narrow channel, a rich variety of thermoacoustic phenomena occur through the thermal interaction between the channel wall and the working medium. Thermoacoustic engines use thermoacoustic phenomena to convert thermal power into acoustic power, whereas thermoacoustic coolers convert acoustic power into thermal power. Thermoacoustic engines and coolers have been investigated owing to their simple structure and environmental friendliness.

Thermoacoustic devices are typically composed of an acoustic driver (or electric generator), waveguides, and a stack, which has many narrow channels so that the thermal interaction actively takes place. As working media, gases, such as nitrogen, helium, argon, and air, are used in thermoacoustic devices. A stack is located in one of the waveguides and sandwiched between two heat exchangers. In a thermoacoustic engine, a temperature gradient along the stack is formed using the two heat exchangers. When the temperature gradient exceeds a critical value, an acoustic wave is spontaneously generated, which is then input to the electric generator. In a thermoacoustic cooler, an acoustic wave is input from the speaker, resulting in acoustic wave propagation in the stack. As a result of this, a temperature gradient is formed along the stack.

Recently, the use of a wet stack has been proposed to improve the performance of thermoacoustic devices[1–9]. On the wall of the wet stack, a reactive component, such as water or ethanol, is contained. Noda and Ueda demonstrated that when a wet stack is used in a thermoacoustic engine, the critical temperature gradient required to excite a spontaneous acoustic wave decreases dramatically.[1] Yang et. al. demonstrated that the cooling power of a thermoacoustic cooler and the output power of a thermoacoustic engine are increased by the use of a wet stack and theoretically pointed out that the key to wet-stack thermoacoustic devices is the mass transfer caused by the coupling between acoustic effects and the effects of phase change of the reactive component.[6,8]

As mentioned above, it is predicted that the acoustically induced mass transfer in a wet-wall waveguide plays a key role in wet-stack thermoacoustic devices. A few experimental studies have investigated the acoustically induced mass transfer. Brustin et al. attempted to measure mass transfer in a thermoacoustic engine.[4] They constructed a thermoacoustic engine with a wet stack, activated the engine for approximately 20 minutes, and measured the weight of the wet stack. The difference between the measured weight before and after the measurements shows that the mass transfer is caused by the spontaneously generated acoustic wave, and the mass transfer increases with an increase in the amplitude of the acoustic wave. However, the direction of the mass transfer cannot be determined experimentally.

In this study, a thermoacoustic cooler was constructed. A unique feature of the cooler is that it has

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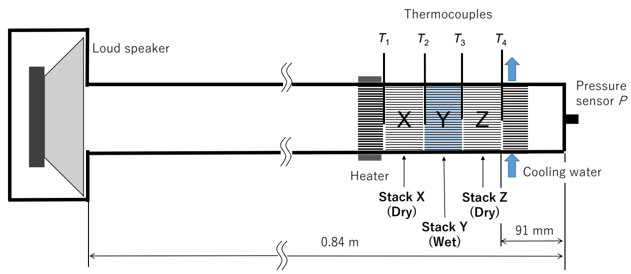

FIG. 1. Schematic illustration of the experimental setup.

three stacks. The three stacks were set in series, and only the center stack was wet. The stack weights were measured before and after each measurement. The temperature gradient formed along the stacks was controlled by using two heat exchangers. The experimental results clearly demonstrate that mass transfer occurred in the stacks, and the direction of the mass transfer depended on the value of the temperature gradient. The results were compared with theoretically[6,10,11] predicted values.

The remainder of this paper is organized as follows: Section II describes the experimental setup and measurement method. Section III presents the experimental results, and Section IV presents a comparison between the experimental and the theoretical results. The results are summarized in Section V.

II. EXPERIMENT SETUP AND METHOD

A. Setup

Figure 1 shows a schematic of the experimental setup. It comprises an acoustic driver (loud speaker), a straight tube, two heat exchangers, and three ceramic honeycomb stacks. The length of the straight tube was 0.84 m and its inner diameter was 40 mm. One end of the tube was closed by a rigid plate, and the other end was connected to the driver. The three stacks were made of cordierite ceramic and were placed in series inside the straight tube. Hereafter, they will be referred to Stack X, Stack Y, Stack Z, as shown in Fig. 1. The length of each stack was 40 mm, and the stacks contain several square channels. One side of the square was 1.07 mm, and the porosity of the stacks was 0.71. The distance from the closed end of the straight tube to one side of Stack Z is 91 mm. Four sheath thermocouples with a diameter of 1 mm were set on each side of the stacks; hence, the spacing between them was approximately 1 mm and the distances from the closed end to the tips of the thermocouples were 0.09 m, 0.13 mm, 0.17 m, and 0.21 m. Both heat exchangers were the parallel-plate type, made of brass, and had a length of 10 mm. The plate thickness was 0.6 mm, and the spacing between the plates was 0.8 mm. One of the heat exchangers, wrapped with a heater, was placed on one side of Stack X, whereas the other, cooled by water, was placed on one side of Stack Z. The experimental setup was filled with atmospheric air. The temperature in the laboratory was controlled to be about 22°C and the humidity was between 20%-60%.

B. Measurement Method

Before starting the measurements, Stack Y was dipped in water to wet the surface of its wall and then shaken.[12] The amount of water contained in the wall of Stack Y was controlled at approximately 4.3 g. Note that we visually verified that the square channels of Stack Y were not closed by water. On the other hand, Stack X and Stack Z were dried using a dryer. The mass (weight) values of Stacks X, Y, and Z were measured using an electronic balance immediately before and after the measurements. We denote the mass of the stacks before and after the measurements as $m_{k,before}$ and $m_{k,after}$ ($k = X, Y, Z$), respectively, and define the mass change as

$$\Delta m_k = m_{k,after} - m_{k,before}. \tag{1}$$

Based on measured Δm_k, the amount and the direction of the mass transfer are obtained.

By using the four thermocouples, the temperature values at each end of the stacks were measured. They are labeled as T_1, T_2, T_3, and T_4, as shown in Fig. 1. The time of the measurements was always kept at 5700 s (=95 minutes), and they were recorded every 60 s. The values of the temperature changed in 5700 s; hence, we define the time-averaged temperature as

$$\overline{T}_i = \frac{1}{95}\sum_{j=1}^{95} T_{i,j} \qquad (i = 1, 2, 3, 4), \tag{2}$$

where j is the data number, and we also focus on the temperature difference:

$$\Delta\overline{T}_{i+1,i} = \overline{T}_{i+1} - \overline{T}_i \tag{3}$$

On the closed-end plate, a pressure sensor (PD-104, Jtect LTD) was installed. The signal from the sensor was input to an FFT analyzer (DS-3000, Onosokki), so that the pressure amplitude at the closed end, P_{end}, was obtained. The heater wound around the heat exchanger was connected to a DC electric supply. The electric power input to the heater is measured and denoted as Q.

III. EXPERIMENTAL RESULTS

A. Effect of Acoustic Wave

Because atmospheric air with a relative humidity (20∼60%,) was used as the working gas, it was possible that Stack Y would dry, although an acoustic wave was not applied. Hence, the measurements were first performed under conditions that P_{end}=0 kPa and $Q = 0$ W. In Fig. 2(a), the measured T_1, T_2, T_3, and T_4 are shown as functions of the experimental time t. Because Stack Y was wetted with liquid water whose temperature was slightly lower than the room temperature, T_2 and T_3 are smaller than T_1 and T_4 near $t = 0$s. After $t \sim 1000$ s, they are almost same, resulting in $\Delta\overline{T}_{32} = -0.2$ K. The measured $m_{k,before}$ and $m_{k,after}$ are shown in Fig. 2(b): the maximum Δm_k is -0.08 g, and hence, this value is the effect of natural drying on Δm_k.

Next, the effect of temperature gradient without acoustic waves is evaluated. To generate the temperature gradient along the stacks, $Q \neq 0$ W was applied to the heater. In this measurement, Q was not constant but was controlled to realize $|\Delta\overline{T}_{32}| \sim 4$ K. This value is approximately the maximum temperature difference owing to the thermoacoustic effects, which will be described later. The time dependences of T_1, T_2, T_3, and T_4 with $Q \neq 0$ W are shown in Fig. 2(c). As can be seen from this figure, the temperature gradient was formed along the stacks, and $\Delta\overline{T}_{32}$ was found to be -3.9 K. With this condition, $m_{k,before}$ and $m_{k,after}$ were measured. Figure 2(d) illustrates that Δm_Y has a negative value (-0.18 g) and Δm_Z has a positive value (0.05 g), whereas Δm_X is almost zero. This indicates that the water contained in Stack Y was delivered to Stack Z due to the effect of the temperature gradient.

Finally, the measurements with an acoustic wave were performed. An AC voltage with a frequency of 108Hz and an amplitude of 16 V was applied to the loud-speaker. Consequently, the pressure amplitude P_{end} at this frequency was 4.93 kPa. Under these conditions, temperatures T_1, T_2, T_3, and T_4 were measured, as shown in Fig. 2(e). Although Q=0 W, T_3 and T_4 increase, whereas T_1 and T_2 decrease. This is caused by the thermoacoustic effects[13]. The time-averaged temperature difference $\Delta\overline{T}_{32}$ is 4.4 K. This value approximately equals the absolute values of $\Delta\overline{T}_{32}$ shown in Fig. 2(c). The values of the mass of the stacks before and after the measurements with Q=0 W and $P_{end} = 4.93$ kPa are shown in Fig. 2(f): Δm_X is a positive value of 2.22 g, and Δm_Y is a negative value of -3.07 g, whereas Δm_Z is almost zero. The value of $\Delta m_X (= 2.22$ g) is much larger than the mass changes shown in Fig. 2(d). Therefore, these results clearly show that the acoustic wave transferred water contained in Stack Y to Stack X. Note that $\Delta m_X + \Delta m_Y + \Delta m_Z$ is not zero. We believe that the reason for this is that the water was transferred to the outside of the stacks. This was because we observed water droplets on the tube wall and the heat exchangers after the measurements, although they did not exist before the measurements.

B. Effect of Temperature Gradient with Acoustic Wave

Salton et al.[14], Weltsch et al.[11] and Offner et al.[10] theoretically investigated acoustic wave propagation under two conditions. One is that a working gas is a mixture of a non-reactive gas and a reactive gas and the other is that the wall of the waveguide acts as a source of the reactive gas. For example, the working gas is a mixture of nitrogen and water vapor, and the wall of the waveguide has a liquid water film. They indicated that the mass streaming of the gas mixture is influenced by the

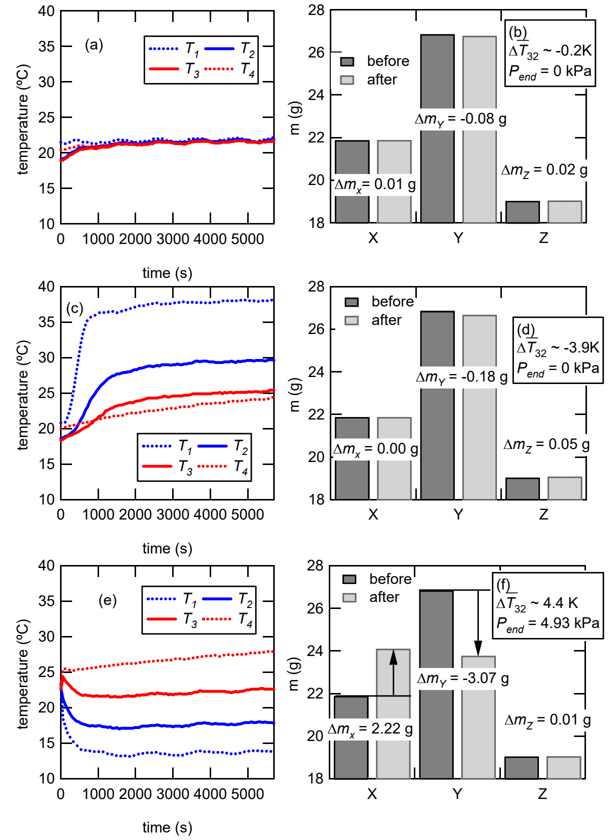

FIG. 2. Experimental results with and without acoustic wave. (a) and (b) are obtained without acoustic wave and without temperature difference: (c) and (d) are obtained without acoustic wave but with temperature difference that is generated by heat input Q: (e) and (f) are obtained with acoustic wave and temperature difference that is generated by the acoustic wave.

amplitudes of the acoustical waves and the temperature gradient. This motivated us to investigate the effects of $\Delta\overline{T}_{21}$, $\Delta\overline{T}_{32}$, and $\Delta\overline{T}_{43}$ on Δm_k.

In our experimental setup, $\Delta\overline{T}_{21}$, $\Delta\overline{T}_{32}$ and $\Delta\overline{T}_{43}$ could be changed by controlling Q, and hence, the effect of Q on Δm_k was experimentally investigated. To avoid rapid temperature change, Q was increased at a rate of approximately 1.1 W/min, and the final value of Q is denoted as Q_{in}. The input voltage to the speaker was kept at 16V, resulting in $P_{end} = 4.89 \pm 0.05$ kPa. The duration of each experiment was kept at 5700 s. In Fig. 3(a), the obtained $\Delta\overline{T}_{i+1,i}$ is shown as a function of Q_{in}. When $Q_{in} = 0$ W, $\Delta\overline{T}_{21}$, $\Delta\overline{T}_{32}$, and $\Delta\overline{T}_{43}$ are 3.8 K, 4.4 K and 4.5 K, respectively, as already shown in Fig. 2(e) . With increasing Q_{in}, they naturally decrease, and then when Q_{in}=5.3 W, they are 0.1 K, 1.3 K and 0.0 K, respectively. It should be noted that when $t > 5040$ s with $Q_{in} = 5.3$ W, T_2 became higher than T_3. The reasons for this will be mentioned below.

In Fig. 3(b), the relation between Δm_k and Q_{in} is plotted. When Q_{in} is small, namely, when the tempera-

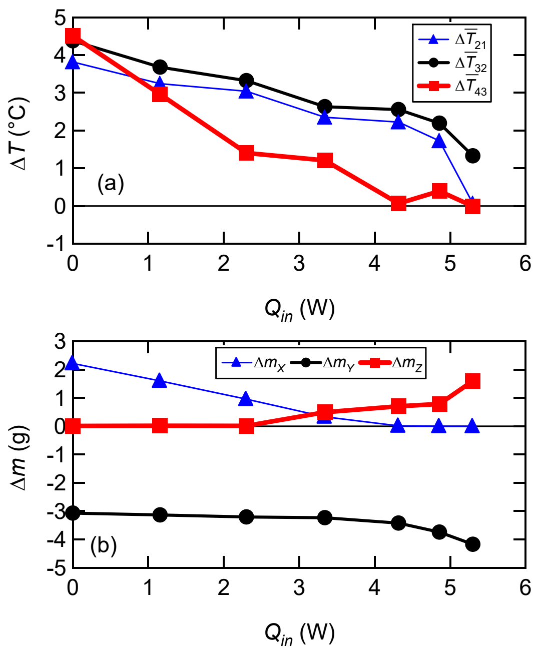

FIG. 3. (a) Relation between heater power Q_{in} and temperature dependence across each of the stacks; (b) relation between Q_{in} and mass change of each of the stacks. Data were obtained with $P_{end} = 4.89 \pm 0.05$ kPa.

ture gradient along the stacks is large, Δm_X is large, and on the contrary, $\Delta m_Z \sim 0$. The value of Δm_X becomes small with increasing Q_{in}. At Q_{in}=3.3 W, both Δm_X and Δm_Z are small but have positive values, whereas Δm_Y is negative. This indicates that water is transported from Stack Y to both Stack X and Stack Z. Above Q_{in}=3.3 W, Δm_Z increased with increasing Q_{in}, whereas $\Delta m_X \sim 0$. These results evidently show that the magnitude of the acoustically caused mass transfer depends on the temperature gradient, and that the direction of the transfer is changed by the value of the temperature gradient. Because the mass transfer from the hot side to the cold side contributes to the performance reduction of thermoacoustic coolers[6], the critical temperature gradient, at which the direction is changed, is very important. The critical temperature gradient in the experiment is approximately 65 K/m.

When $Q_{in} = 5.3$ W, Δm_Y was -4.17 g as can be seen in Fig. 3(b). This value is close to the amount of water added to Stack Y before the measurements, which was 4.3 g. Therefore, it is expected that a significant portion of Stack Y was dried within the measurement time (0 s$< t <$ 5700 s). This causes the above-mentioned result $T_2 > T_3$ in 5040 s$< t <$ 5700 s and is the reason why we did not perform the experiment with $Q_{in} > 5.3$ W.

IV. DISCUSSION

As previously mentioned, Salton et al.[14], Weltsch et al.[11], and Offner et al.[10] investigated acoustically induced mass transfer. Their studies incorporated the effects of phase change and mass diffusion into the framework of linear thermoacoustic theory. In their theoretical model, the wall was assumed to contain a uniformly reactive component (water), which differs from the present experimental setup, where Stacks X, Y, and Z were dry, wet, and dry, respectively. Furthermore, part of the present experiment was conducted under unsteady-state conditions, as shown in Fig. 2(a), (c), and (e), whereas the theory assumes steady-state conditions. Nevertheless, we believe that a qualitative comparison between the theoretical predictions and the experimental results can be conducted and offers valuable insights.

Using the theory[6,11] derived by Weltsch et al., the mass flow can be expressed as:

$$\dot{m} = ARe\left[p_1\widetilde{U}_1F_a\right] - B\frac{|U_1|^2}{\omega}Im[F_b]\frac{dT_m}{dx} - C\frac{dT_m}{dx}, \quad (4)$$

where A, B, and C are the real number coefficients depending on the properties of the working gas, and F_a and F_b are wet-thermoacoustic functions that are complex numbers and depend on the properties and the structure of a waveguide: p_1 and U_1 are acoustic pressure and velocity, respectively, and they are complex numbers: ω is the angular frequency of the acoustic wave: $\frac{dT_m}{dx}$ is the gradient of the time averaged temperature along a waveguide. The details of this equation can be found in the literatures[6,11]. The first term on the right-hand side (RHS) of Eq. (4) can be expressed as

$$ARe[p_1\widetilde{U}_1F_a] = A(Re[p_1\widetilde{U}_1]Re[F_a] - Im[p_1\widetilde{U}_1]Im[F_a]).(5)$$

Since a standing-acoustic wave was used in the present experiment,

$$|Im[p_1\widetilde{U}_1]| >> |Re[p_1\widetilde{U}_1]|,$$

and since the stacks were located near the closed end in the present experiment,

$$Im[p_1\widetilde{U_1}] \sim -|p_1||U_1|.$$

Furthermore, the experimental results shown in Fig. 2(d) indicates that the third term on the RHS can be neglected under the present experimental conditions. Hence, $\dot{m}$ can be approximated as follows:

$$\dot{m} \sim \dot{m}_{stand} = A|p_1||U_1|Im[F_a] - B\frac{|U_1|^2}{\omega}Im[F_b]\frac{dT_m}{dx}.(6)$$

Using linear acoustic theory[15] with dry air, $|p_1|$ and $|U_1|$ with $P_{end} = 4.89$ kPa and $T_m = 295°$C were calculated at two positions. One position was the boundary between Stacks Y and Z, and the other was that between Stacks Y and X. Using the properties of humid air[16] at 295°C, $Im[F_a]$ and $Im[F_b]$ were obtained. With these values, the values of $\dot{m}_{stand}$ at the two positions were evaluated as functions of dT_m/dx. The direction of the axis x is taken from the speaker to the closed end. The two evaluated values of $\dot{m}_{stand}$ are shown in Fig. 4 by lines: the blue lines were calculated at the Stack X -

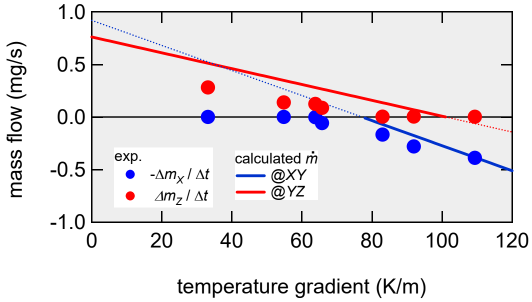

FIG. 4. The experimentally obtained mass transfer rate and the calculated mass streaming. Note that $\Delta m_X/\Delta t$ and $\Delta m_Z/\Delta t$ always had positive values owing to the experimental conditions.

Stack Y boundary and the red lines at the Stack Y - Stack Z boundary. To compare the theoretical value, the experimentally obtained Δm_X and Δm_Z are divided by the experimental time $\Delta t = 5700$ s, and $\Delta\overline{T}_{32}/\Delta L$ is employed as the temperature gradient, where ΔL is the length of Stack Y. By symbols, $-\Delta m_X/\Delta t$ and $\Delta m_Z/\Delta t$ are plotted as functions of $\Delta\overline{T}_{32}/\Delta L$ in Fig. 4: The minus sign is needed to express the direction from Stack Y to Stack X.

Figure 4 shows that the absolute value of $\dot{m}_{stand}$ is different from $-\Delta m_X/\Delta t$ and $\Delta m_Z/\Delta t$. However, similarly to the experimental results, the calculated $\dot{m}_{stand}$ decreases with increasing dT_m/dx, and $\dot{m}_{stand} = 0$ is realized when dT_m/dx is within the experimental condition of $\Delta\overline{T}_{32}/\Delta L$. Furthermore, when 77 K/m$< dT_m/dx <$ 102 K/m, the $\dot{m}_{stand}$ shown by the blue line is negative and the $\dot{m}_{stand}$ shown by the red line is positive. This implies that the mass flowed from Stack Y to both sides, as observed in the experiment. Based on these results, we consider that the calculated $\dot{m}_{stand}$ is qualitatively in agreement with the experimental results.

V. CONCLUSION

In this study, we experimentally investigated mass transfer induced by acoustic waves. An experimental setup comprising three stacks with relatively small flow channels was constructed. The unique feature of the setup is that one of the stacks is wet and the others are dry. It was found that when an acoustic wave was input to the stacks, the water contained in the wall of the wet stack was transferred to the walls of one or both dry stacks. The maximum transfer rate was found to be 0.39 mg/s and the direction of the mass transfer depended on the temperature gradient formed along the stacks. The experimental results were compared with the theoretically predicted mass flows. A comparison of the experimental and theoretical values showed qualitative agreement. Mass transfer can enhance the performance of wet-wall thermoacoustic devices; however, it can also lead the drying of a wet stack, which is the key to wet-thermoacoustic devices,[8,9] and sometimes reduces their performance. Hence, the rate of mass transfer should be known, and the present study supports the idea that the theory[6,11] can be used to estimate it.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data and code that support the findings of this study are available from the corresponding author upon reasonable

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