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Daisuke Noda and Yuki Ueda

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A thermoacoustic oscillator powered by vaporized water and ethanol

Daisuke Noda and Yuki Ueda[a)]
Graduate school of Bio-Applications and Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan

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We measure the temperature difference required to drive a thermoacoustic oscillator containing air, water vapor, and liquid water as the working fluids. The oscillator is composed of a large tube containing an array of narrow tubes connected at one end to a tank of liquid water. When the water is heated, the temperature difference across the tube array increases until thermoacoustic oscillations occur. The temperature difference at the onset of oscillation is measured to be 56 °C, significantly smaller (by ~200 °C) than the temperature measured when the tank is filled with dry air instead of water. The temperature difference can be further reduced to 47 °C by using ethanol instead of water.
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I. INTRODUCTION

The propagation of an acoustic wave in a narrow tube can lead to a variety of thermoacoustic phenomena. As an example, Fig. 1(a) shows a device that is used to demonstrate thermoacoustic oscillations.[1–3] It is composed of a large tube containing an array of narrow tubes, called a stack. When a heat source (such as a flame) is used to establish a temperature difference across the stack, a critical point is reached when the gas inside the tube spontaneously begins to oscillate, resulting in the emission of an acoustic wave from the tube. The structure of this device is quite simple and it can be used to explain the physical basis[1] of thermoacoustic phenomena to students interested in investigating thermoacoustic engines and heat pumps.[4–6]

The temperature difference across the stack at the onset of thermoacoustic oscillation ΔT_o, depends on various aspects of the oscillator, such as the length and position of the stack, and is typically between 200 °C and 500 °C. To achieve such a high temperature difference, combinations such as liquid nitrogen and ambient air, or ambient air and burning gas are used as the heat sink and heat source, respectively.[1–3] In this study, we demonstrate a method of reducing ΔT_o to below 60 °C, which facilitates the demonstration of thermoacoustic oscillations. The basic idea for this method is taken from a Japanese instrument called "Kibitsunokama."

The Kibitsunokama is an instrument used in historical Japanese shrine rituals. This instrument has a long history; it is mentioned in the diary of a Buddhist monk written in 1568[7] and is described in a story published in 1776.[8] The instrument is composed of an iron bowl and a barrel and is schematically illustrated in Fig. 1(b). The barrel is mounted on the iron bowl and both its ends are open. A mesh screen is located in the barrel and covered with rice grains, and liquid water is placed in the iron bowl. When the water is externally heated, the gas in the Kibitsunokama begins to oscillate spontaneously and emits a sound similar to the lowing of cattle; this sound is used for fortune telling. In Japan, high school and undergraduate students have replicated this spontaneous oscillation.

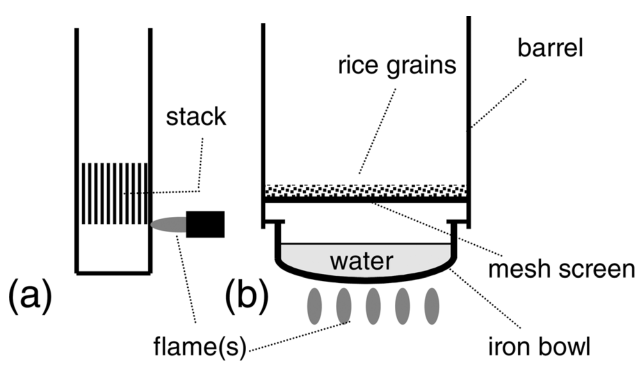

Fig. 1. Schematic illustrations of: (a) a conventional thermoacoustic oscillator and (b) a Kibitsunokama.

The basic components of the Kibitsunokama are similar to those of the thermoacoustic oscillator—each has a large tube containing narrow flow channels—however, the temperature differences required to drive them are quite different. For the Kibitsunokama, the temperature difference necessary to induce oscillations is only around 100 °C, significantly smaller than that required to drive the thermoacoustic oscillator (~200–500 °C). The reason for such a large difference in ΔT_o is not obvious, but the fact that the Kibitsunokama contains water, whereas the thermoacoustic oscillator does not indicates that the addition of water is a key factor in the reduction of ΔT_o.

In this study, we construct a thermoacoustic oscillator and experimentally determine the value of ΔT_o using air, water, and diluted ethanol as working fluids. We find that ΔT_o decreases by more than 200 °C when using water and air compared to using air alone. Moreover, the use of diluted ethanol further reduces ΔT_o by an additional 10 °C.

II. EXPERIMENTAL SETUP

A schematic diagram of our setup is shown in Fig. 2. We construct a Sondhauss-tube-type thermoacoustic oscillator[9–11] composed of a tube of length 100 mm and radius 24 mm connected to a tank of volume 380 cm^3 (a tank is used because it allows for easy storage of liquid water). The stack used for the present experiment is made of ceramic and is composed of many flow channels. The cross section of the channels is a square of side length 0.96 mm; the length of the stack is 20 mm. The stack is located at the end of the tube nearest the tank, and a cold-temperature heat exchanger is attached to its cold side. The water is heated using an electric heater that has a power $\dot{E}_{el}$ supplied to it. Thermocouples are used to measure the temperatures at both ends of the stack (T_C and T_H) and a

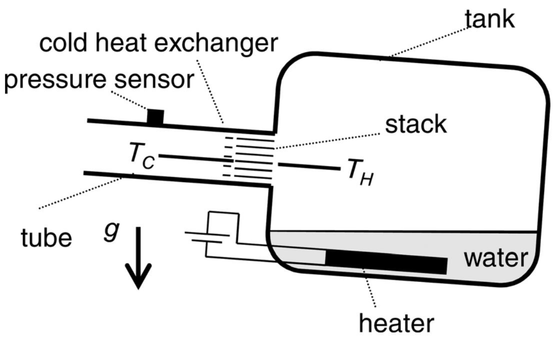

Fig. 2. Schematic illustration of the experimental setup.

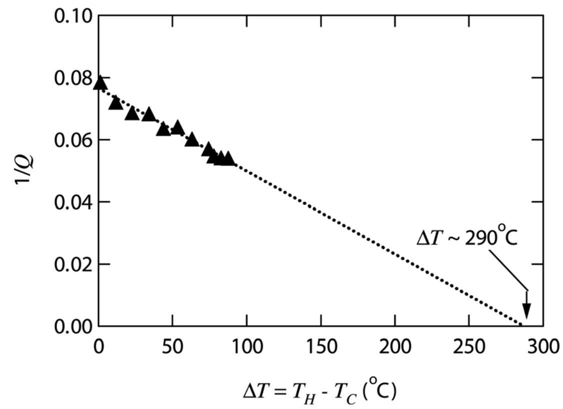

Fig. 3. Inverse of Q-value versus temperature difference $\Delta T = T_H - T_C$ in the thermoacoustic oscillator filled with dry air.

pressure sensor (JTEKT Co. PMS-5M) is mounted to measure the (oscillatory) pressure inside the tube.

III. EXPERIMENT

To begin, we used dry air as a working fluid to obtain the temperature difference ΔT_o for the onset of thermoacoustic oscillation under conventional conditions. Although water is illustrated in Fig. 2, the tank had no water during this experiment. Because our setup has no high-temperature heat exchanger, it is difficult to increase temperature T_H beyond 110 °C and we observed no oscillation with $T_H = 110\,°C$. Therefore, we estimated ΔT_o by focusing on the relation between the Q-factor and $\Delta T = T_H - T_C$.

Atchley *et al.*[12] and Biwa *et al.*[13] have demonstrated that the Q-factor in a thermoacoustic oscillator can be expressed as

$$Q = 2\pi f \frac{E_s}{\dot{E}_d - \dot{E}_g}, \tag{1}$$

where f is the resonant frequency of the gas column in the setup, E_s is its stored acoustical energy, $\dot{E}_d$ is the rate of dissipated acoustic energy in the column, and $\dot{E}_g$ is the rate of acoustic energy generation in the stack due to thermoacoustic energy conversion.[3] Because $\dot{E}_g$ increases with increasing ΔT, there is a critical value of ΔT when $\dot{E}_d = \dot{E}_g$, at which point the value of Q approaches infinity. This critical value can be regarded as ΔT_o.[12,13]

To obtain the Q-factor for our setup, a loudspeaker is placed outside the oscillator and the acoustic waves were fed into our setup. The loudspeaker is driven with a sweep signal and the pressure in the tube is measured with the pressure sensor. Using a fast Fourier transform analyzer (Onosokki Co. Ltd. DS-2000), we obtain a resonance curve from which we can calculate the Q-factor. Repeating this experiment for different ΔT values allows us to extrapolate to find the (approximate) temperature difference when $Q \to \infty$.

Figure 3 shows our experimental results plotted as $1/Q$ versus ΔT. As seen in this figure, the value of $1/Q$ decreases with increasing ΔT. Assuming a linear relation and extrapolating to $1/Q \to 0$, we find $\Delta T_o \approx 290\,°C$ for our thermoacoustic oscillator filled with dry air. We note that the frequency at the peak of the resonance curve when $\Delta T = 88\,°C$ was 166 Hz, indicating that the resonance mode in the oscillator was of the Helmholtz type.[14]

Next, we place 20 cm^3 of liquid water in the tank. We measure the temperatures T_H and T_C and the oscillatory pressure as functions of time t while maintaining the input electrical power at $\dot{E}_{el} = 40$ W. The measured temperatures are shown in Fig. 4(a). Up until $t = 710$ s (dotted line on graph) there is no pressure oscillation; the temperature of T_C is relatively stable at 26 °C, while T_H steadily increases. At $t = 710$ s, when T_H reaches 82 °C, the working fluids inside the setup spontaneously begin oscillating with a frequency of 181 Hz. Thus, when using water in the oscillator we find $\Delta T_o = 56\,°C$, more than 200 °C less than our estimate of ΔT_o when using only air in the oscillator. It is worth noting that the value of T_H at the onset of the oscillation ($T_{H,o}$) is lower than the boiling point of water.

As can be seen in Fig. 4(a), T_H remains relatively stable at approximately 82 °C after $t = 710$ s. Conversely, T_C steadily increases from 26 °C at $t = 710$ s to 44 °C at $t = 1\,200$ s. After $t = 1200$ s, both temperatures remain fairly stable and the amplitude of oscillatory pressure was found to have a constant value. In other words, the smallest temperature difference ΔT^* with which thermoacoustic oscillations are maintained in the present experiment was 42 °C (when water is used as one of the working fluids).

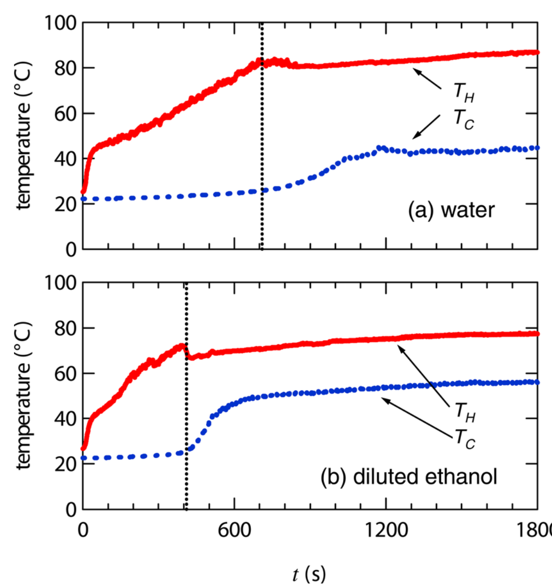

Fig. 4. Temperatures T_H and T_C shown as functions of time t in the thermoacoustic oscillator using working fluids of water (a) and diluted ethanol (b).

As mentioned above, the frequency of oscillation at the onset was 181 Hz. However, this oscillation frequency varied slightly with time, first increasing (up to 185 Hz) and then decreasing and finally stabilizing at 171 Hz. Such a frequency change can be attributed to a change in the speed of sound in the experimental setup, which depends on temperature and molar fraction of vaporized water in the working gas.

The total weight of the setup, including water, remained approximately the same before and after the experiment. However, we noticed that the stack was wet after the experiment, whereas it was dry at the beginning of the experiment. These facts indicate that air with a relative humidity of 100% became the working fluid, and that condensation and evaporation occurred continuously in the stack and tank. In addition, Raspet *et al.*[15] give a theoretical argument that condensation and evaporation contribute to the enhancement of the thermoacoustic effect. Hence, the large reduction of ΔT_o can likely be attributed to the phase change of water. In the future, a quantitative comparison between the experimentally obtained and the theoretically calculated values of ΔT_o may be presented.

As a final experiment, we used $20\,cm^3$ of diluted ethanol instead of water as the working fluid to see if this might further reduce ΔT_o; the diluted ethanol had a density of $0.83\,g/cm^3$ before the start of the experiment. The experiment was repeated while again holding $\dot{E}_{el} = 40\,W$ and the results are shown in Fig. 4(b). Once again we see that initially T_H increases steadily while T_C remains relatively constant at around 25 °C. When $t = 410\,s$ (dotted line on graph), thermoacoustic oscillation is detected at a frequency of 159 Hz. The onset occurs for $\Delta T_o = 47\,°C$, almost 10 °C smaller than the experiment with water as the working fluid. After the onset of oscillation, T_H stabilizes at around 72 °C while T_C begins increasing until about $t = 650\,s$, when both temperatures level off and increase much more slowly. At $t = 1\,500\,s$, the temperatures remain almost constant and the amplitude of the oscillation also takes on a constant value. At $t = 1800\,s$ we have $T_H = 77\,°C$ and $T_C = 56\,°C$, giving a smallest temperature difference of $\Delta T^* = 21\,°C$.

IV. SUMMARY

We estimate and measure the temperature difference ΔT_o for the onset of thermoacoustic oscillation under three different conditions. Under the first condition, dry air is used as the working fluid; under the second condition, air and water are used; and under the third condition, air and diluted ethanol are used. The experimental results show that the values of ΔT_o for these experiments are 290 °C, 56 °C, and 47 °C, respectively. Furthermore, the smallest measured temperature difference while maintaining thermoacoustic oscillations (ΔT^*) was 42 °C and 21°C under the second and third conditions, respectively. Hence, we can conclude that the introduction of water or ethanol into a thermoacoustic oscillator has a large effect on the reduction of the temperature difference required to drive the oscillator.

From a thermodynamic point of view, thermoacoustic oscillators can be regarded as heat engines[1] because they convert thermal energy (heat) into acoustic waves that can in turn do useful work, such as moving a speaker cone to produce electrical energy. Recently, thermoacoustic oscillators have been designed to produce energy from waste heat,[16,17] and hence reductions in ΔT_o and ΔT^* have been pursued by thermoacousticians.[13,16] The present results indicate that using water or ethanol as one of the working fluids can reduce these temperature differences while preserving the simplicity of the thermoacoustic energy converter.

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[a]Electronic mail: uedayuki@cc.tuat.ac.jp

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