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Relationship between a prime mover positioning and a thickness of viscous boundary layer in narrow channel
－Study of a coaxial thermoacoustic system－
PM 設置位置と細管流路内の粘性境界層の厚み
－同軸型熱音響システムにおける検討－

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1. Introduction

Thermoacoustic phenomenon means the mutual energy conversion between heat and sound. The device called a stack, consisting of many narrow tubes, is used in its conversion part installed in the thermoacoustic system. The stack to convert the heat energy into the sound energy is called a prime mover (PM) and another stack to oppositely convert them is called a heat pump (HP). The cooling system without moving parts can be constructed by setting these stacks in the tube[1].

To effectively cool, the looped-tube thermoacoustic system where a traveling wave is generated has been proposed[1]. However, since the application of the loop-tube system conventionally studied is limited because of its large size, the downsizing is a task for the practical realization. The present group is then studying the coaxial type thermoacoustic system. Because of its capability of creating the traveling-wave sound field and its linear shape, this system is expected to be more compact than the looped-tube and to have wider applications[2].

Since the sound field in the tube of coaxial system depends on the PM position, the cooling capability may also depend on the PM position even in the case where HP is installed. To improve the cooling capability, the influence of the PM position on the energy conversion is investigated.

2. Thickness of viscous boundary layer and acoustic streaming in resonance tube

The thickness of viscous boundary layer[3] δ_ν is represented as follows (1).

$$\delta_\nu = \frac{1}{\kappa} = \sqrt{\frac{2\nu}{\omega}} \qquad (1)$$

where ω and ν denote the angular frequency and the dynamic viscous coefficient. It has been demonstrated in the previous studies that the resonance frequency of the self-oscillation is spontaneously determined by the thickness of the viscous boundary layer[3]. Hence the thickness of the viscous boundary layer formed in the channel at the high-temperature end of PM installed in the coaxial system is focused in this paper.

The driving force of Rayleigh acoustic streaming[4] is represented as follows (2).

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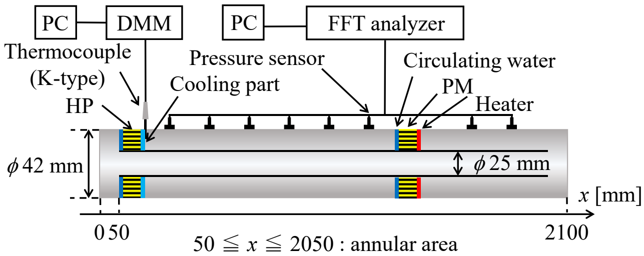

Fig. 1 Experimental setup.

$$F_x = F_{x1} + F_{x2} \qquad (2)$$

$$\begin{cases} F_{x1} = \rho k u_0^2 \sin 2kx \\ F_{x2} = \dfrac{1}{4}\rho k u_0^2 \{e^{-2\kappa y} - 3e^{-\kappa y}\cos\kappa y + e^{-\kappa y}\sin\kappa y\}\sin 2kx \end{cases}$$

The input heat energy which must have entered into the high-temperature end of PM is carried from the high-temperature. This effect significantly degrades the efficiency of the thermoacoustic system[4].

3. Experimental method

The experimental system is shown in **Fig. 1**. The working fluid is air at atmospheric pressure. A stainless tube closed at both ends whose inner diameter and total length are 42 and 2100 mm, respectively, is used for the outer tube. The axial coordinate with the origin x = 0 mm at the left end of the outer tube is defined. A stainless tube with 2000 mm total length and 27 mm outer diameter opened at both ends is set coaxially with the outer tube in the range of 50≤x≤2050 mm. A honeycomb ceramics with 50 mm length and 0.65 mm channel radius is used for HP by setting so that the low-temperature end is located at x = 50 mm. Another honeycomb ceramics with 50 mm length and 0.65 mm channel radius is employed for PM by setting so that the location of the low-temperature end is varies between x = 1500 and 1850 mm by 50 mm step. Installing an electric heater at PM high-temperature end, the heat quantity of 330 W are supplied. By circulating 20 degrees C water at the low-temperature ends of PM and HP. The pressure is measured with the pressure sensor (product of PCB Co.) fixed at outer tube wall. Furthermore, when the PM position is set at x = 1700 mm, this system is driven and stopped at 950 s later. Then the temperature variation is observed at 200 mm from the high-temperature end of PM.

4. Experimental results and discussion

The temperature decrease from the reference temperature of the HP cooling end is shown in **Fig. 2** for each condition. In order to obtain high cooling capacity, it is desirable that the acoustic impedance P/U is large and P and U are in-phase, where P and U denote the sound pressure and the particle velocity, respectively, in the annular flow path. It is presumed that the cooling capability is improved by expanding the distance between PM and HP so that the HP position approaches the ideal setting condition. The shift of PM position in the positive direction along the x axis means the expansion of the distance between PM and HP. For the PM position of x = 1500-1700 mm, the cooling capability is improved. However, for the PM position over 1700 mm, the improvement of cooling capability is not found anymore. In order to consider the contributory factor for this, the sound field generated in the annular path is examined. The sound pressure at the HP cooling part is also shown in **Fig.2** for each condition. Since the cooling temperature and the sound pressure at the HP cooling part show the same trend, the contributory factor not for enhancing the cooling capability is assumed to be the decreased sound pressure at the HP cooling part.

The frequency spectrum at x = 220 mm is obtained under each condition. The second harmonic sound levels is confirmed to increase with the expansion of the distance between PM and HP. The contributory factor is supposed to lie in the process of the shift from the 1 wavelength resonance to 2 wavelength resonances. In the previous study, it has been found that the resonant frequency is spontaneously selected so that the thickness of the viscous boundary layer becomes smaller than the channel radius of the stack[3]. Hence, the thickness of the viscous boundary layer is calculated with Eq. (1). As a result, it is confirmed that the thickness of viscous boundary layer increases and approaches the channel radius, for x of the PM setting position over 1700 mm. Therefore, in order to make the thickness of viscous boundary layer smaller than the stack channel radius, this system is assumed to shift to the 2 wavelength resonance. From Eq. (2), the wavenumber k depends on ω because $k = \omega/c$. Consequently it is suggested that the driving force increases as the 1 wavelength resonance shifts to the 2 wavelength resonance. The acoustic streaming generated by this driving force lets out the thermal energy that has once entered into the high-temperature end of PM[4]. By virtue of this, the sound pressure is assumed to be decreased. As the appearance of the thermal leakage due to the acoustic streaming, the temperature change at 200 mm distant from the high-temperature end of PM is shown in **Fig. 3**. This figure demonstrates the rapid increase of the temperature at 950 s after stopping the system. When the system is stopped, the conversion from the thermal energy to the acoustic energy also stops. However, since the acoustic streaming is kept for awhile even after stopping the system, the thermal energy which became inconvertible is carried by the streaming. As a result, it is supposed that the temperature rapidly increases because the thermal

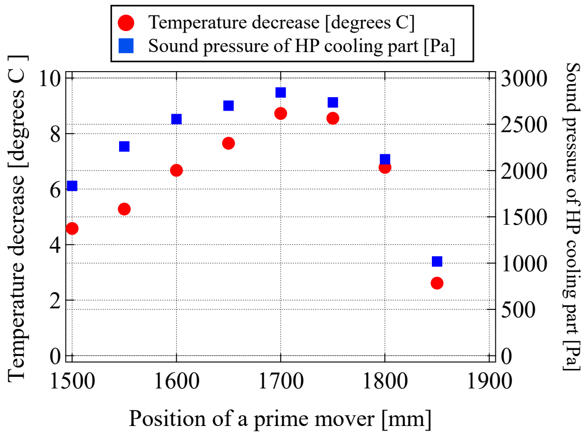

Fig. 2 Relationship between position of PM and temperature decrease, sound pressure of HP cooling part.

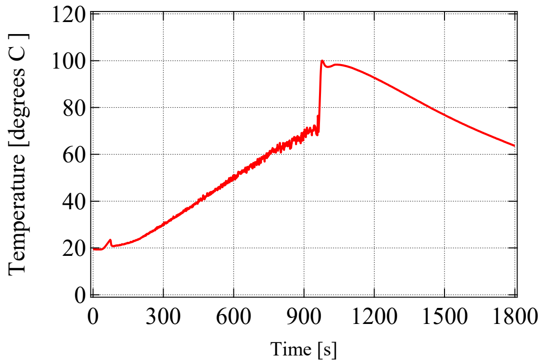

Fig. 3 Temperature variation at position 200 mm from PM high-temperature end.

energy greater than the amount during the system works is carried. From this result, it is confirmed that the acoustic streaming occurs the thermal leakage.

5. Conclusion

In this report, the influence of the distance between PM and HP on the cooling capability was investigated. The capability was assumed to be enhanced as the distance was expanded. However, in the range over 1700 mm, it was suggested that the enhamcement of the cooling capability is disturbed by the thermal leakage due to the acoustic streaming.

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