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PAPER

Experimental study on resonance frequency of loop-tube-type thermoacoustic cooling system

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Abstract: The relationship between the viscosity boundary layer and the resonance frequency of the generated sound in a loop-tube-type thermoacoustic cooling system is investigated. The frequency of the sound has been observed for various loop-tube lengths, inner pressures and working fluids, and the influence of the viscosity boundary layer upon the resonance frequency is discussed. It was generally considered that the sound generated in the loop-tube was usually resonated with the tube length by 1 wavelength. Under certain conditions, however, the resonant wavelength is 2. This results from the influence of the viscosity boundary layer. It is found that the loop-tube determines the resonance frequency so that the thickness of the viscosity boundary layer is smaller than the stack channel radius. As a result, the resonant wavelength is 2 under certain conditions. The frequency is an important parameter for the thermoacoustic cooling system. From obtained results, one of the factors for selecting the frequency is found.

Keywords: Thermoacoustic cooling system, Viscosity boundary layer, Resonance frequency

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1. INTRODUCTION

Recent technological advance has brought about environmental destruction. In particular, global warming is rapidly getting severe. Cooling systems are identified as one of the causes of environmental problems. In existing cooling systems, poisonous cooling media such as chlorofluorocarbon are generally used. It is known that chlorofluorocarbon is one of the green house gases and destroys the ozone layer. In addition, during operation of an existing cooling system, waste heat is exhausted from the cooling system. This waste heat is also one of the causes of global warming. The operation of existing cooling systems brings “Tragedy of the Commons” for the global environment.

Our studies are intended to construct a new practical cooling system based on the thermoacoustic effect [1]. The thermoacoustic effect induces a mutual energy conversion of sound energy and heat energy [2–4]. By applying the thermoacoustic effect, it will be possible to construct a new epoch-making cooling system with many unique advantages: effective use of waste heat, no use of poisonous cooling media and no moving parts.

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From the past experimental results, it is found that the sound pressure of generated sound in our thermoacoustic cooling system is increased with increasing supplied heat energy [5]. The detailed cooling mechanism, however, is not clarified yet. The resonance frequency is an important parameter for selecting other parameters of the thermoacoustic cooling system such as stack channel radius, total loop-tube length and inner pressure. Therefore, in this paper, the frequency of the sound generated in the thermoacoustic cooling system has been observed for various loop-tube lengths, inner pressures and working fluids, and the influence of the viscosity boundary layer upon the resonance frequency is discussed.

2. THERMOACOUSTIC EFFECT

The thermoacoustic cooling system is a new cooling system based on the thermoacoustic effect.

In general, sound propagating through free space does not exchange heat energy with the medium through which the sound propagates. In this case, the sound undergoes an adiabatic compression process. When the sound propagates through narrow channels such as a stack, the medium far from the channel wall undergoes an adiabatic compression change and the medium close to the wall undergoes an isothermal compression change. This is because of the influence of the heat boundary layer. When the medium is in the isothermal compression change, heat energy is exchanged between the channel wall and the medium. This means that energy conversion between sound energy and heat energy is introduced. This mutual energy conversion of sound energy and heat energy is the thermoacoustic effect [6].

In our thermoacoustic cooling system, a temperature gradient is first created in stack 1 of the prime mover. Then heat energy is exchanged between the stack channel wall and the medium, namely, the working fluid, and self-sustained sound is generated. This means the heat energy is converted to sound energy. The sound generated at the prime mover propagates through the loop-tube and, at stack 2 of the heat pump, the sound energy is reconverted to heat energy. As a result, the cooling point at the heat pump is cooled.

When heat energy is exchanged between the stack channel wall and the oscillating working fluid as in a thermoacoustic cooling system, the efficiency of energy conversion depends on the thickness of the viscosity boundary layer formed in the channels. Since viscosity obstructs the energy conversion from heat into sound, the thickness of the viscosity boundary layer has an influence upon energy conversion efficiency.

3. VISCOSITY BOUNDARY LAYER

The thickness of the viscosity boundary layer is represented as follows [7]:

$$\delta_\nu = \sqrt{\frac{2\nu}{\omega}} \tag{1}$$

$$\nu = \frac{\mu}{\rho} \tag{2}$$

where δ_ν is the thickness of the viscosity boundary layer, ν is the dynamic viscosity rate, ω is the angular frequency, μ is the coefficient of viscosity and ρ is the specific gravity.

When δ_ν is much smaller than the channel radius, viscosity does not significantly affect the efficiency of energy conversion. To make δ_ν smaller, ω should be higher or ν should be lower. To make ω higher, the resonance frequency of the sound generated in the loop-tube should be higher. This means that total loop-tube length should be shorter or the sound speed in the working fluid should be higher. To make ν lower, μ should be smaller or ρ should be larger. To make ρ larger, the inner pressure of the loop-tube should be higher.

4. EXPERIMENTAL

A loop-tube is employed as our thermoacoustic cooling system [1]. The loop-tube consists of stainless tubes connected by 90-degree elbows. The total length of the loop is 1,900, 2,600, 3,270 and 3,970 mm. A schematic explanation of the loop-tube is shown in Fig. 1. The diameter of the tube is 40 mm and the thickness of the tube wall is 5 mm. Two stacks, stacks 1 and 2, are placed in the loop-tube. Each stack is sandwiched between heat exchangers. Stack 1 is employed as a prime mover and stack 2 as a heat pump.

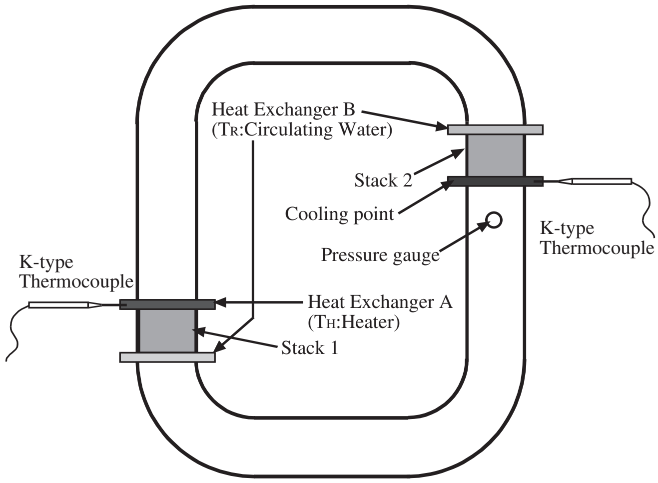

Fig. 1 Schematic explanation of loop-tube.

Each stack is 50-mm-long honeycomb ceramic. For stack 1, a 0.45-mm-channel-radius stack is used and for stack 2 a 0.35-mm-channel-radius stack is used. The cooling effect of the thermoacoustic cooling system is influenced by the channel radii of stacks [8]. In our past experiments, the greatest temperature decrease was observed with a 0.45-mm-channel-radius stack for stack 1 and a 0.35-mm-channel-radius stack for stack 2. The channel radii of both stacks used in this study are determined on the basis of this result. Stacks 1 and 2 are placed so that the distance between the stacks is a half of the total length of the loop-tube. For the heat exchanger A on stack 1, a whorl-shaped electric heater is used. An electric energy of 330 W is supplied to the electric heater. The heat exchangers B are placed under stack 1 and on stack 2. In the heat exchangers B, there are copper fins, which are 5 mm in length and 1 mm in thickness. The fins are maintained at the reference temperature (T_R), 18°C, by circulating water. These heat exchangers create a temperature gradient in the stacks.

As working fluid filling the loop-tube, air at 0.1 MPa or argon gas (hereinafter referred to as Ar) at 0.1, 0.2, 0.3, 0.4, or 0.5 MPa is used. Ar can be easily pressurized, and air and Ar have very similar characteristics in terms of sound speed. Pressurized Ar is directly infused to the loop-tube from a compressed-argon cylinder, after the loop-tube is vacuumed. The pressure of infused Ar is controlled by a gas regulator. Inner pressure and resonance frequency in the loop-tube are measured with a pressure gauge (KISTLER 601A).

The temperature at the cooling point under stack 2 is measured at the center axis of the tube with a K-type thermocouple 1.6 mm in diameter. The measurements of the temperature and the heat supply are simultaneously started. The heat supply is stopped 800 s later, and in the next 400 s the measurements are continued.

The sound generated in the loop-tube is a standing wave that resonates over the total tube length. There are two antinodes of the sound pressure in the loop-tube and the sound pressure is above 160 dB. The two antinodes are at point-symmetrical positions. The prime mover is near one antinode and the heat pump is placed near the other antinode. Since the amplitude of the sound pressure is large at the antinodes, it is regarded that effective energy conversion from sound energy to heat energy can be induced by placing the heat pump near an antinode [4].

5. RESULTS AND DISCUSSION

In this experiment, 40 s after the heat energy is supplied, the self-sustained sound is generated in the loop-tube by the thermoacoustic effect. At the same time, the temperature starts to decrease.

Figure 2 shows the observed resonance frequency of the thermoacoustic self-sustained sound generated in the loop-tube when the working fluid is air. It was generally considered that the sound generated in the thermoacoustic cooling system is resonated with the loop-tube length by 1 wavelength. As shown in Fig. 2, however, when the total length of the loop-tube is over 2,600 mm and the working fluid is air at 0.1 MPa, the resonant wavelength is 2 wavelengths.

It seems that the resonance frequency depends on the thickness of the viscosity boundary layer formed in stack 1 of the prime mover.

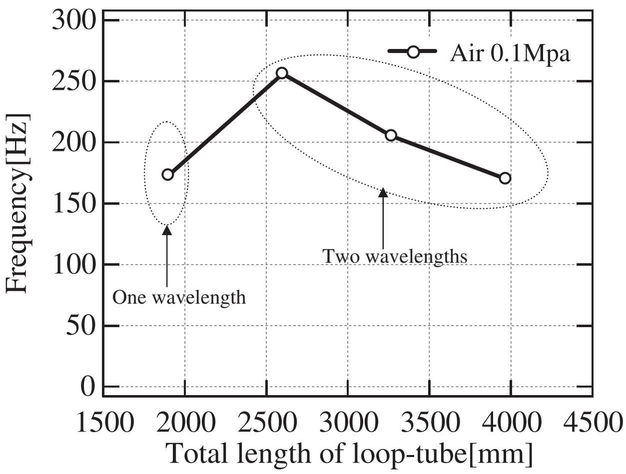

Fig. 2 Observed frequencies of thermoacoustic self-sustained sound as function of total length of tube. Working fluid: air at 0.1 MPa.

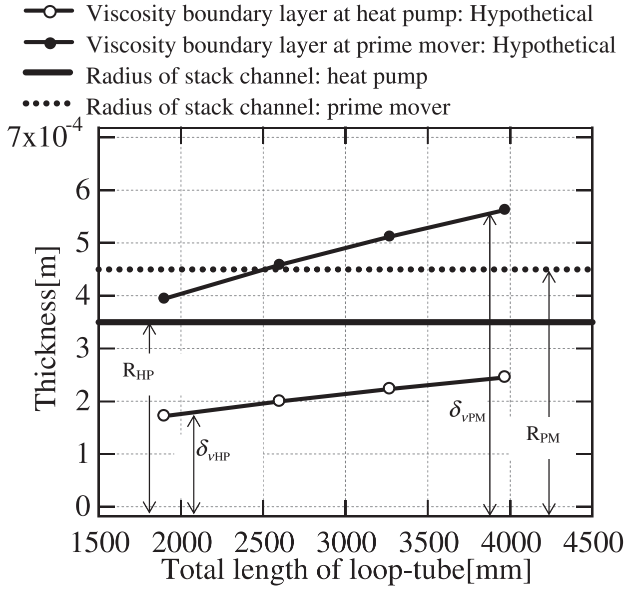

Fig. 3 Relationship between stack channel radius and hypothetical thickness of viscosity boundary layer formed in stacks as function of total length of tube. Resonant wavelength: 1 wavelength (hypothetical), working fluid: air at 0.1 MPa.

Figure 3 shows the hypothetical thickness of the viscosity boundary layer, under the hypothetical conditions that the working fluid is air at 0.1 MPa and the resonant wavelength is 1 wavelength. When the loop-tube length is 1,900 mm, the resonant wavelength is 1 wavelength, so the thickness of the viscosity boundary layer is calculated from the observed resonance frequency. In another case, the resonant wavelength is hypothetical and the thickness of the viscosity boundary layer is calculated from the hypothetical resonance frequency. R_{PM} in the figure is the channel radius of stack 1 of the prime mover and R_{HP} is the channel radius of stack 2 of the heat pump. $\delta_{\nu HP}$ is the hypothetical thickness of the viscosity boundary layer formed in stack 2, and $\delta_{\nu PM}$ is that in stack 1. $\delta_{\nu HP}$ and $\delta_{\nu PM}$ are found from Eqs. (1) and (2). ω is found from $2 \times \pi \times f$ and the hypothetical resonance frequency is assigned to f. ν is found from the literature [9] according to the temperature in the stack. The temperature in the prime mover is about 800 K, and that in the heat pump is about 300 K. Figure 3 indicates that the thickness of the viscosity boundary layer in stack 1 is larger than the stack channel radius of stack 1 when the loop-tube length is over 2,600 mm. Under these conditions, the influence of viscosity is dominant. Viscosity obstructs the energy conversion from heat into sound, and self-sustained sound is not generated. To prevent this, the loop-tube determines the resonance frequency so that the thickness of the viscosity boundary layer is smaller than the stack channel radius.

The actual thickness of the viscosity boundary layer

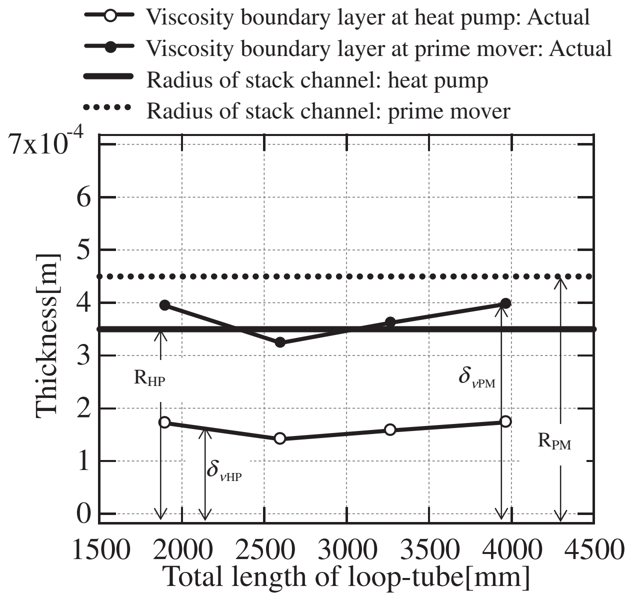

Fig. 4 Relationship between stack channel radius and actual thickness of viscosity boundary layer formed in stacks as function of total length of tube. Resonant wavelength: observed wavelength, working fluid: air at 0.1 MPa.

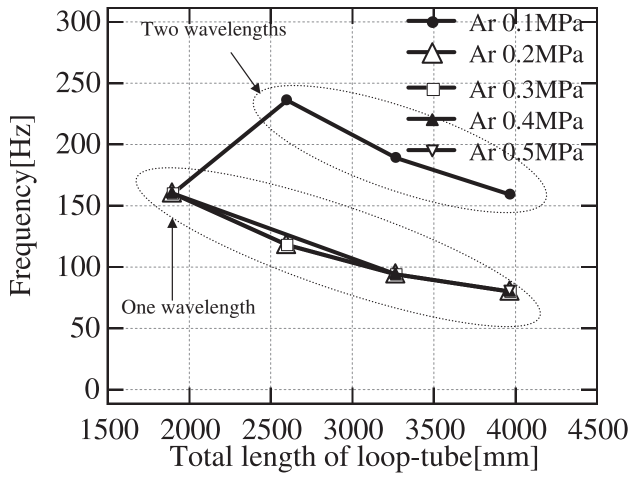

Fig. 5 Frequencies of thermoacoustic self-sustained sound as function of total length of tube. Working fluid: Ar.

calculated from the observed resonance frequency is shown in Fig. 4. $\delta_{\nu HP}$ and $\delta_{\nu PM}$ are found from Eqs. (1) and (2), and the observed resonance frequency is assigned to f. It is shown in Fig. 2 as observed frequencies that the resonant wavelength is 1 wavelength when the total tube length is 1,900 mm, and that the wavelength is 2 when the tube length is over 2,600 mm. In both cases, Fig. 4 indicates that the thickness of the viscosity boundary layer in stack 1 is smaller than the stack channel radius. This is different from Fig. 3. When the thickness of the viscosity boundary layer is smaller than the stack channel radius, the influence of viscosity is not dominant and sound is generated.

From Fig. 4, it is regarded that the influence of the viscosity boundary layer in stack 2 of the heat pump is little because the thickness of the viscosity boundary layer is quite smaller than the channel radius of stack 2.

Figure 5 shows the observed resonance frequency when the working fluid is Ar. As in the case of air, when the inner pressure is 0.1 MPa and the tube length is over 2,600 mm, the resonant wavelength is 2 wavelengths. When the inner pressure is 0.2, 0.3, 0.4 or 0.5 MPa, the sound is resonated by 1 wavelength with any tube length. This is because the thickness of the viscosity boundary layer is smaller at higher pressure. This is found from Eqs. (1) and (2). With increasing inner pressure, ρ increases. As ρ increases, ν and $\delta_{\nu PM}$ decrease. As a result, even when the working fluid is Ar, the thickness of the viscosity boundary layer is always smaller than the stack channel radius of stack 1.

6. CONCLUSION

In this study, the relationship between the viscosity boundary layer and the resonance frequency of the sound generated in a thermoacoustic cooling system is investigated. It was generally considered that the generated sound is resonated with the loop-tube length by 1 wavelength. Under certain conditions, however, the resonant wavelength is 2.

When the thickness of the viscosity boundary layer in a stack is larger than the stack channel radius, the influence of viscosity is dominant. Viscosity obstructs the energy conversion from heat into sound, and self-sustained sound is not generated. To prevent this, the loop-tube determines the resonance frequency so that the thickness of the viscosity boundary layer is smaller than the stack channel radius. As a result, the resonant wavelength is 2 in such a case that the total loop-tube length is longer or the inner pressure is lower.

The resonance frequency is an important parameter for selecting other parameters of the thermoacoustic cooling system such as stack channel radius, total loop-tube length, and inner pressure. From obtained results, one of the factors for selecting the frequency is found, and this will induce effective energy conversion in a thermoacoustic cooling system.

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