AMPLIFICATION OF THE ACOUSTIC POWER USING THERMOACOUSTIC ENERGY CONVERSION

Y.Tashiro[+], Y.Ueda[+], M. Kozuka[#], T.Biwa[+], T.Yazaki[*] and U. Mizutani[+]
+Department of Crystalline Materials Science, Nagoya University, Furo-cho, Chikusa-ku, 4648603, Nagoya, Japan
Department of Applied Physics, Nagoya University, Furo-cho, Chikusa-ku, 4648603, Nagoya, Japan
[*] Department of Physics, Aichi University of Education, Hirosawa, Igaya-cho, 448-8542, Kariya, Japan
tashiro@mizu.xtal.nagoya-u.ac.jp.

Abstract

We demonstrate the amplification and attenuate of acoustic intensity excited in a resonator through thermoacoustic energy conversion in the regenerator, along which a temperature gradient is created in two opposite directions. We revealed experimentally that there is a unique position corresponding to the velocity node in the resonator, where a pure traveling wave phase is formed and at the same time high acoustic impedance is achieved. By locating the center of a regenerator having a positive temperature gradient near the velocity node, we could amplify the acoustic intensity in the regenerator with the gain I_{out}/I_{in} equal to 1.6. Instead, when a negative temperature gradient is provided across the regenerator, we observed the attenuation of the acoustic intensity much larger than that due to viscous losses obtained in the absence of a temperature gradient in the regenerator.

1.Introduction

When an acoustic wave propagates through a regenerator, oscillating gas with an angular frequency w exchange heat with the regenerator, which has been now well recognized as the thermoacoustic phenomena [1-3]. Recently, new acoustic devices working as heat engines without involving any moving parts have been developed by making use of the thermoacoustic phenomena.

Thermoacoustic phenomena can be understood by taking into account mutual energy conversion between acoustic wave and heat flow. The acoustic intensity I in the tube is defined by using the acoustic pressure $P = pe^{iwt}$ and the cross sectional mean velocity $U = ue^{i(wt+f)}$ as

$$I = \langle P \cdot U \rangle_t = \frac{1}{2} pu \cos f \,, \qquad 1)$$

where f is the phase between P and U, and angular brackets represent time average over a given cycle.

In 1979, Ceperley proposed a pistonless Stirling engine where a traveling wave is employed in place of the mechanical piston in a Stirling engine [4]. In a traveling wave, U oscillates in phase with P (f =0) in the same way as that in a regenerator of a Stirling engine. Thus, Ceperley considered that a gas parcel subjected to the traveling wave mode in the regenerator should perform the Stirling cycle and attempted to excite a traveling wave through a differentially heated regenerator. When a finite temperature gradient is formed across the regenerator, heat flow Q is generated and driven from its hot to cold ends. The energy conversion between Q and I in the regenerator takes place and certainly obeys the energy conservation law as

$$\Delta(Q + I) = 0 \,, \qquad 2)$$

where Δ represents a difference in the respective quantities between both ends of regenerator. The resulting output power ΔI becomes positive, when ΔQ is negative. Moreover, he theoretically showed that the gain I_{out}/I_{in} should reach the temperature ratio of both ends of the regenerator. However, unfortunately, the acoustic intensity could not be amplified because of the presence of strong viscous losses in the regenerator. He attributed it to low acoustic impedance inherent in a traveling wave. Here, the acoustic impedance Z is given by the ratio of P over U or

$$Z = \frac{P}{U} \,, \qquad 3)$$

The impedance becomes equal to $Z_0 = r_0 c$ for the plane traveling wave that Ceperley used, where r_0 and c represent the mean density of gas and sound speed, respectively. As a mater of fact, it is not possible to achieve an acoustic impedance much larger than Z_0 while maintaining the phase difference f =0 through the system.

In this experiment, we have excited acoustic wave having components due to both traveling and standing waves in a resonator and installed a regenerator at the velocity node in it. This allows us to achieve high acoustic impedance reaching 17 Z_0. Furthermore, we could successfully not only amplify but also attenuate the acoustic intensity entering the regenerator, depending on the direction of a temperature gradient applied to the regenerator. We believe that the present results will lead to the development of the new acoustic devices for amplification or attenuation of acoustic waves without any moving parts.

2.Experimental set-up and generation of acoustic field in resonator

The present experimental set-up is shown figure.1a).

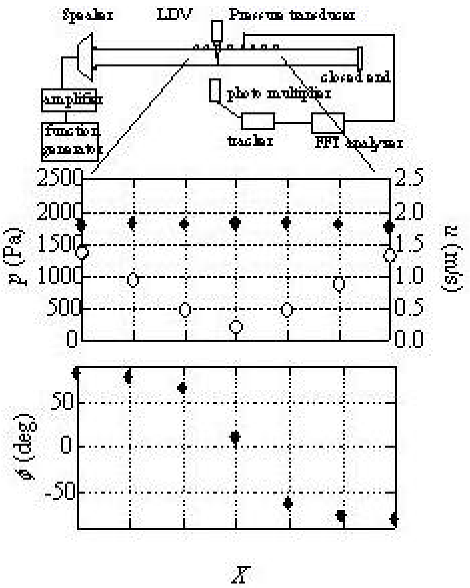

Figure1 a) : Schematic illustration of the present experimental apparatus. b) : Axial distribution of the pressure amplitude p and velocity amplitude u around the middle of resonance tube. c) : Phase lead f of U relative to P.

The acoustic resonator is 3 m in length and 21 mm in inner diameter. One end of the resonance tube and is connected to a woofer speaker while the other is closed by a metal disc. The speaker is driven at the frequency of 103Hz which can excite the second resonance mode in the present resonance tube. We simultaneously measured P and U with pressure transducers and LDV (Laser Doppler Velocimeter), respectively [5-6].

Figure.1b) and c) show the distributions of p, u and phase lead f near the center of the resonator in the absence of the regenerator. Since the second resonance mode is excited, a pressure antinode and velocity node are formed exactly at the center of resonance tube. The acoustic impedance calculated by using measured p and u at the node turned out to be 17 times larger than Z_0. Moreover, we see that the phase f becomes 0 at the velocity node. Therefore, it is this position where a traveling wave component becomes 100% while the acoustic impedance becomes large. Thanks to this finding, we could install a regenerator near this critical position and studied the effect of amplification and attenuation by producing a temperature gradient across it in two different directions.

3. Regenerator

In this experiment, we used stainless screen meshes stacked by 20 mm in length as a regenerator. Each screen mesh has square holes with their sides of r_0=0.05mm. The heat exchange process is known to

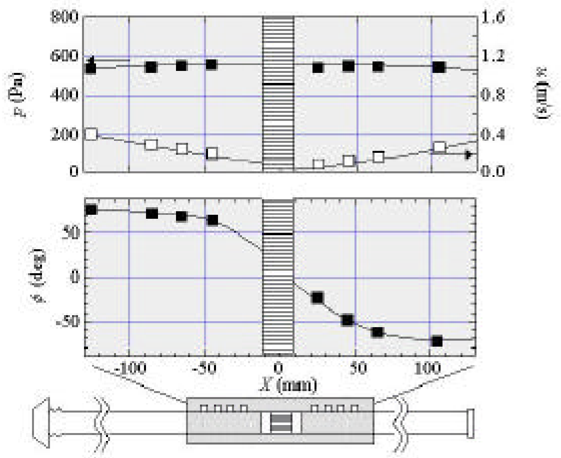

Figure2: Axial distributions of p, u and f around the regenerator in the absence of temperature gradient. The hatched area represents the regenerator.

be well discribed by a nondimensional parameter wt ,where w is an angular frequency and t represents the thermal relaxation time given as $t = \sqrt{r_0^2 / 2a}$, where a is the thermal diffusivity [2]. If $wt \ll \pi$, oscillating gas can move reversibly while keeping local equilibrium with contacting wall. When $wt \sim \pi$, oscillating gas begins to move irreversibly due to the non-negligible time delay for the heat exchange. This results in an incomplete heat transfer to the wall. The wt in the present experiment is estimated to be 0.13 and thus a good thermal contact is assured between acoustic waves and the regenerator. A temperature gradient along the regenerator is created by controlling adjacent two heat exchangers. One is cooled by running water and kept at 300K, the other is heated by a heater and kept at 560K.

4.Experimental Results

Figure 2 shows the distributions of p, u and f near the regenerator in the absence of temperature gradient. The center of the regenerator was located near the velocity node. We found that the phase difference f at the center of the regenerator was 20°, being close to a pure traveling wave phase. Figure 3 shows the distribution of acoustic intensity I calculated by inserting experimental date of p, u and f into Eq.(1). It is clearly seen that a sign of I is always positive in the resonator. This means that the acoustic wave is running from the woofer speaker to the closed end. A negative slope of I indicates the presence of energy dissipation along the resonator. A change in the acoustic intensity after passing the regenerator may be denoted as $I_{out}- I_{in}$ where I_{in} and I_{out} are acoustic intensities at anlet and outlet, respectively. The value $I_{out}- I_{in}$ of representing the energy loss in the regenerator is found to be -5W/m^2. This is safely attributed to the viscosity loss of gas against wall of stainless steel mashes rather than to thermal conduction, since *wt* is very low (=0.13) in the present regenerator.

As our newt experiment, we fed heat power to the regenerator and produced both positive and negative temperature gradients along it. Regardless of the condition for the regenerator, the acoustic intensity of the woofer speaker was adjusted so as to keep I_{in} equal to 25W/m^2 throughout the present experiments. When a positive temperature gradient was created along the regenerator (∇T_m>0), the slope of I in the regenerator became steeply positive, and the positive output power $\Delta I = I_{out} - I_{in}$ of 15W/m^2 was achieved. This is the thermoacousric amplification of I in the regenerator that Ceperley tried but failed to observe. We consider the high acoustic impedance of 17 Z_0 to play a crucial role in the generation of a net amplification of I. The gain given by I_{out} /I_{in} is found to be 1.6. In an ideal Stirling engine, the gain I_{out} /I_{in} should reach the temperature ratio (=560/300=1.87 in the present case). A gain of the present thermoacoustic Stirling engine, which is smaller than the temperature ratio, is ascribed to the viscous loss in the regenerator. If the viscous loss of -5W/m^2 is corrected for, the gain I_{out} /I_{in} reaches 45/25=1.8, exceeding the temperature ratio of 1.87.

When a negative temperature gradient is created along the regenerator (∇T_m<0), the acoustic intensity I is attenuated more strongly than that in the absence of the temperature gradient (∇T_m=0). The gas parcels with a traveling wave phase now undergoes the Stirling cycle under the negative temperature gradient, resulting in reversing the out power *DI* into a negative value. In consequence, the input energy I is found to be strongly attenuated through the thermoacoustic energy conversions. In the other words, we could establish that thermoacoustic energy conversion, when coupled with an enhancement in the acoustic impedance and tuning to the position of the regenerator near *f*=0, can be performed very effectively in either amplifying or damping *I*.

We also performed similar experiments by using a ceramic honeycomb catalyst (r_0=0.77mm, *wt*~3.5) in place of a stacked screen meshes as the regenerator. We found that the output power *DI* obtained when a positive temperature gradient exists, became smaller than that obtained by the mesh regenerator, when *f* in the regenerator is close to a traveling wave phase. However, when the regenerator was displaced away from the velocity node and located at the position where *f* is 80°, the gain I_{out} /I_{in} reached 2.3, far exceeding the temperature ratio. The gas motion with *f* close to a standing wave phase (=90°) is responsible for this gain, since the standing wave also contributes to the energy conversion when *wt*~π.

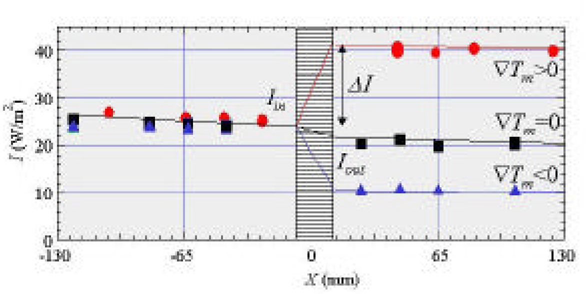

Figure3: The axial distributions of acoustic intensity with (circles: positive, triangles; negative) and without(squares) temperature gradients.

5. Summary

In this experiment, we showed that both a traveling wave phase and the acoustic impedance much larger than Z_0 are formed at the velocity node in the resonator. By locating the regenerator near the velocity node, we could succeed in both the amplification and attenuation of the acoustic intensity by applying heat power along the regenerator in two opposite directions. The present work will contribute to developing the new acoustic devices producing a large acoustic intensity without any moving parts.

References

[1] G.W.Swift, *Thermoacoustics: Aunifying Perspective for Some Engines and Refrigerators* (Acoustical Society of America, Publications, Sewickley, PA, 2002).

[2] A.Tominaga, Cryogenics **35**, 427, (1995); *Fundamental Thermoacoustics* (Uchida Roukaku Publishing, Tokyo, Japan 1998)

[3] J. Wheatley, T. Hofler, G.W.Swift, and A. Migliori, Phys. Rev. Lett. **50**, 499 (1983); J.Acoust. Soc. Am. **74**, 153 (1983); Am. J. Phys. **53**, 147, (1985)

[4] P.H. Ceperley, J. Acoust. Soc. Am. **66**,1508, (1979)

[5] T. Yazaki, A. Tominaga, Proc.R.Soc. Lond.A **454**, 2113, (1998)

[6] T. Biwa, Y. Ueda, T. Yazaki and U. Mizutani, Cryogenics **41**, 305, (2001)