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Research Paper

Four-stage loop-type cascade traveling-wave thermoacoustic engine

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HIGHLIGHTS

- A loop type cascade traveling wave thermoacoustic engine with four regenerators is demonstrated.
- Enlarged regenerators and incrementally enlarged duct diameters were used.
- The prototype engine has a high acoustic impedance at regenerators, and traveling wave field in ducts.
- This engine enables acoustic power amplification by a factor of the number of regenerators.

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ABSTRACT

We designed and built a prototype of a loop-type cascade traveling-wave thermoacoustic engine with four regenerators. The objective with this prototype engine was to achieve both high acoustic impedance at the regenerator position and a traveling-wave field in ducts, and to amplify the acoustic power by a factor equal to the number of regenerators. To achieve this objective, we enlarged the regenerator cross-sectional area and incremented the duct diameter. We measured and analyzed the acoustic field and verified that its characteristics met the objectives.

1. Introduction

Based on the phase relation between oscillatory pressure p and oscillatory velocity v for a traveling wave being equivalent to the phase relation for a gas in a Stirling engine [1], in 1979 Ceperley proposed a traveling wave engine [2] depicted in Fig. 1. This traveling-wave thermoacoustic engine amplifies acoustic power when a traveling wave passes through the bundle of narrow channels ("regenerator") with axial temperature gradient. Its gain is determined identically by the ratio of the absolute temperatures at the ends of the regenerator (that is, the ratio of the temperature T_H at the high-temperature end to the temperature T_C at the cold-temperature end). This proposal has led researchers to develop various traveling-wave thermoacoustic engines [3–5] and refrigerators [6–8]. Assuming a traveling-wave phase and negligibly small viscous loss, gain G for a thermoacoustic engine of power W is given [2] by

$$G = \frac{T_H}{T_C} = \frac{W_H}{W_C} \tag{1}$$

where W_H and W_C are the acoustic power of the regenerator outlet and inlet, respectively. With A denoting the cross-sectional area, the acoustic power is

$$W = \frac{A}{2}|p||v|\cos\varphi \tag{2}$$

Ceperley also proposed a cascade amplifier connecting n regenerators in series to increase the gain,

$$G = \left(\frac{T_H}{T_C}\right)^n \tag{3}$$

Acoustic power amplification in this cascade traveling-wave thermoacoustic engine was demonstrated by Biwa et al. in 2011 [9]. However, connecting multiple regenerators causes deviations from a traveling wave phase. This occurs because a reflected wave arises in the regenerators. The number of regenerators n_r that can be inserted is then limited for that reason. Furthermore, effects of heat transport [10] from oscillatory velocity were large, and the thermal efficiency was low in the regenerator because the specific acoustic impedance $z = \rho_m c$, (where ρ_m is the mean density and c is the adiabatic sound speed) was low. Here, the specific acoustic impedance z is expressed as the ratio of oscillatory pressure to oscillatory velocity (= p/v). The relationship between the thermal

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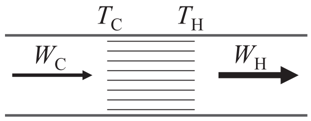

Fig. 1. Traveling-wave thermoacoustic amplifier.

efficiency and specific acoustic impedance z in a regenerator was also calculated by Ceperley in 1985 [11]. His calculation results showed that regenerator thermal efficiency η_{Reg} is limited to around 10% of the Carnot efficiency η_c when z of the regenerator is equivalent to the characteristic acoustic impedance of a traveling wave in free space. Here, assuming a thermal input Q_H into the hot end of the regenerator, η_{Reg} and η_c are given as follows:

$$\eta_{Reg} = \frac{W_H - W_C}{Q_H} \tag{4}$$

$$\eta_c = 1 - \frac{T_C}{T_H} \tag{5}$$

Ceperley furthermore showed that if z can reach $10\rho_m c$, then the thermal efficiency reaches 79% of the Carnot efficiency. According to his calculation, a high z is necessary to increase the thermal efficiency of the regenerator. Backhaus et al. built a $\lambda/4$ (λ: wavelength of the sound wave) mode traveling wave thermoacoustic engine [4] by attaching a branch resonator to a loop so as to reduce viscous loss in the regenerator. This engine achieved $z \gg \rho_m c$ in the regenerator, and its efficiency relative to the Carnot efficiency η_{Loop}/η_c reached 42%. Here, if W flowing out into the branch ducts is denoted by W_B, then the loop efficiency η_{Loop} is

$$\eta_{Loop} = \frac{W_B}{Q_H} \tag{6}$$

The apparatus of Backhaus et al. achieves $z \gg \rho_m c$ in the regenerator, but the attenuation of W caused by viscous loss [12,13] is large because of the standing wave acoustic field in the duct [4]. In 2010, Ueda et al. investigated the relationship between η_{Reg} and dimensionless dissipation Γ in the duct,

$$\Gamma = \frac{(W_H - W_C) - W_B}{W_H - W_C} \tag{7}$$

by numerical calculation [14]. They investigated the relationship between η_{Reg} and Γ by varying the position, length, and flow-channel radius of a regenerator in a refrigerator using the $\lambda/4$ mode. According to this result, η_{Reg} and Γ affect the coefficient of performance (COP) of the refrigerator and establish a trade-off. For this reason, to maximize COP for the entire refrigerator, it is necessary to have optimal values of both η_{Reg} and Γ.

If this trade-off can be resolved and high η_{Reg} and low Γ can coexist, then it is possible to improve the thermal efficiency of the thermoacoustic engine. It is difficult to reduce Γ in the $\lambda/4$ mode thermoacoustic engine proposed by Backhaus et al. because a standing wave is established in the duct. Nonetheless, the thermoacoustic device with λ as the looped tube length proposed by Yazaki et al. [3] can reduce Γ because a traveling wave is in the duct. Accordingly, if $z \gg \rho_m c$ can be satisfied locally at the position of the regenerator in the thermoacoustic device with looped tube length of λ, then it is possible that high η_{Reg} and low Γ coexist. Ceperley proposed enlarging locally the cross-sectional area of the regenerator section in comparison with the cross-sectional area of the duct as a means to satisfy $z \gg \rho_m c$ locally at the regenerator [11,15]. The four-stage traveling-wave thermoacoustic power generator [16] by de Blok is an example of achieving $z \gg \rho_m c$ by changing the cross-sectional area. Through self-matching conditions, he produced a traveling wave with $z \approx \rho_m c$ by symmetrically placing a regenerator and an acoustic load inside a looped tube of length λ at every $\lambda/4$. In this device, the regenerator is placed centrally with respect to the acoustic load. Γ becomes large over half the total duct length relative to locations upstream of the regenerators because $z < \rho_m c$ downstream of the regenerators. Moreover, acoustic power amplification by factor n_r as proposed by Biwa et al. [9] cannot be obtained because an acoustic load is applied to every regenerator. Furthermore, self-matching conditions exist that must be satisfied, such as all regenerator temperatures being equal in principle and the natural frequencies of the electric generators being the same [16].

In this study, we designed and built a prototype engine that enables acoustic power amplification by factor n_r while satisfying self-matching conditions without using multiple generators. To accomplish this, we use the variation of duct cross-sectional area in a traveling-wave thermoacoustic engine with four regenerators in a looped tube. We furthermore evaluated experimentally whether both $z \gg \rho_m c$ in the regenerator and small Γ in the ducts is possible.

2. Apparatus design

2.1. Design concept

In this section, we present the design concepts for an apparatus in which it is possible to connect four regenerators in series in a loop while satisfying both $z \gg \rho_m c$ in the regenerators and small Γ in the ducts. First, we consider the conceptual model shown in Fig. 2. Here, a single unit comprises an upstream duct, a cold heat exchanger CHX (temperature T_C), a regenerator REG, a hot heat exchanger HHX (temperature T_H), and a downstream duct. We assume a traveling wave with specific acoustic impedance $\rho_m c$ enters the regenerator from the upstream duct. To achieve $z \gg \rho_m c$, the cross-sectional area of the regenerator is enlarged as proposed by Ceperley and de Blok [11,16]. Furthermore, the apparatus is designed such that in the duct $z \approx \rho_m c$ to establish a small Γ. When there is no viscous dissipation as stated by Ceperley, oscillatory pressure does not vary at either end of a regenerator that is sufficiently short in comparison with the wavelength, and ideally the oscillatory velocity is amplified by the ratio of the absolute temperatures at each end. To maintain $z \approx \rho_m c$ in the downstream duct after the regenerator, the cross-sectional area ratio A_b (downstream duct cross-sectional area) relative to the upstream duct cross-sectional area A_a (upstream duct cross-sectional area) should be set to the absolute temperature ratio, $A_b/A_a = T_H/T_C$. Fig. 3 shows the model designed based on the design concept, Table 1 shows its various specifications, and Table 2 shows specifications for each heat exchanger and regenerator. The regenerators used were general-purpose honeycomb ceramics. The flow path diameter was determined as shown in Fig. 3.

The loop length of the experimental apparatus in this study was set to 4.76 m. We experimentally verified that the objective $z \gg \rho_m c$ is realized both at the regenerators and for the traveling wave in the ducts in this experimental apparatus (referred to as the "proposed model (Model A)" for which the regenerator area

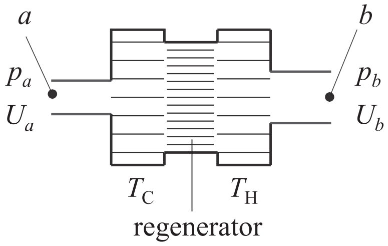

Fig. 2. Conceptual model.