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Thermoacoustic effect of traveling–standing wave

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ABSTRACT

In order to improve thermoacoustic efficiency, the thermoacoustic devices have been developed from standing wave devices to traveling wave devices. Actually, the acoustic field in practical thermoacoustic devices is neither a pure traveling wave nor a pure standing wave. The thermoacoustic effect is the hybrid effect of traveling wave component and standing wave component. Therefore, the thermoacoustic effect of traveling–standing wave will be study in this paper. Firstly, the thermoacoustic conversion performance of the traveling–standing wave are analyzes qualitatively by combining the thermoacoustic conversion performance of the traveling wave with those of the standing wave. Then, based on the basic thermoacoustic formulas, the influence of the parameters of the acoustic field and the regenerator's structure on the thermoacoustic conversion is analyzed, and the optimum condition for the thermoacoustic conversion is discussed. The results are consistent with the qualitative analysis. Additionally, our theoretical results also show a good agreement with the experimental data [Biwa et al. Phys Rev E 2004;69(6):066304(6)], which indicates the validity of the analysis in this paper. Furthermore, the analysis in this paper further provides a more intensive understanding of these experimental results. The conclusions obtained in this paper are significant to guide for the design of new thermoacoustic devices.

1. Introduction

Thermoacoustic researches have made great progress over decades, and benefited greatly from the publication of thermoacoustic conversion theory. In the early time, various standing wave devices [1,2] were built based on thermoacoustic theory. In the standing wave device, gas parcels with $\varphi_z = (2n+1) \times 90^\circ$ realize the conversion between heat and acoustic energy through irreversible thermal contact between the working gas and the stuff in the regenerator, where φ_z is the leading phase of oscillating pressure p_1 to oscillating velocity u_1. However, the purposely imperfect thermal contact on which the standing wave thermoacoustic conversion relies limits its efficiency. With the development of thermoacoustic study, the traveling wave thermoacoustic device was proposed by Ceperley [3] in 1979. In such engine, gas parcels work at the leading phase $\varphi_z = 2n \times 90^\circ$ to realize the reversible thermoacoustic conversion in theory. However, the reversible thermoacoustic conversion realized by reversible thermal contact requires infinitesimal hydraulic radius of the regenerator. This will lead to infinite viscous dissipation which will weaken the thermoacoustic gain and efficiency strongly. So the finite hydraulic radius is adopted in the real traveling wave device, which makes the oscillating temperature of gas parcels lag the oscillating displacement of gas parcels. It indicates that the phase difference between the oscillating temperature and the oscillating pressure deviates from $(2n+1) \times 90^\circ$ because of the thermo-relaxation. Under such condition, for improving thermoacoustic gain and efficiency, the traveling–standing wave phase is necessary to match the phase deviation due to the thermo-relaxation. Biwa et al. [4] demonstrated thermoacoustic energy conversions by making full use of the acoustic field induced in the resonator. He claimed that, in order to achieve high gain and efficiency, one has to choose an optimum φ_z which can make both the traveling wave component and the standing wave component contribute to the amplification of acoustic intensity. However, the leading phase φ_z can be chosen in the region of $-180^\circ \leqslant \varphi_z \leqslant 180^\circ$ for the traveling–standing wave, then how to choose the optimum φ_z for the regenerator becomes a new problem. So far, most researchers still focus their particular attentions on the traveling wave [5,6] or the standing wave [7–10], and few published literatures have studied on the traveling–standing wave field.

Actually, the acoustic field in practical thermoacoustic devices is neither a pure traveling wave nor a pure standing wave. The thermoacoustic effect is the hybrid effect of the traveling wave component (TWC) and the standing wave component (SWC). The functions of the SWC are energy storage and energy conversion, while the functions of the TWC are energy transfer and energy conversion. In the thermoacoustic engine (TAE), the acoustic energy produced by the SWC can be transferred by the TWC, and the acoustic energy produced by the TWC also can be deposited with the SWC state. In the thermoacoustic cooler (TAC), the acoustic

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energy consumed by the SWC can be supplied by the TWC, and the acoustic energy consumed by the TWC can also be compensated from the stored acoustic energy in the SWC.

So, the thermoacoustic effect of traveling–standing wave will be discussed in this paper. The thermoacoustic conversion performance of the traveling–standing wave will be analyzed by combining the thermoacoustic conversion performance of the traveling wave with those of the standing wave. Then, based on the basic thermoacoustic formulas, the influence of the parameters of the acoustic field and the regenerator's structure on the thermoacoustic conversion is analyzed, and the optimum condition for the thermoacoustic conversion is discussed. Additionally, some numerical results comparing with the experimental data [4] will be provided, which will validate the analysis of this paper.

2. Qualitative analysis

The thermoacoustic effect is the hybrid effect of the TWC and SWC in the practical thermoacoustic system. So the conversion capabilities of the traveling wave and the standing wave will be analyzed firstly. And then, the thermoacoustic conversion performance of the traveling–standing wave by combining the thermoacoustic conversion performance of the TWC with those of the SWC will be discussed.

2.1. Standing wave mode

As shown in Fig. 1, the regenerator is located on the left side of the pressure antinode (PAN). Taking the rightward direction as the positive direction of *x*, the leading phase φ_z of the acoustic pressure p_1 relative to the velocity u_1 equals to -90° in the regenerator. In *x* direction, the heat power $\dot{Q}_2$ transferred by the regenerator can be expressed as [1]

$$\dot{Q}_2 = -\frac{1}{4}\Pi\delta_k T_m \beta p_1 u_1 (\Gamma - 1), \quad (1)$$

and the produced acoustic power $\dot{W}_2$ is expressed as [1]

$$\dot{W}_2 = \frac{1}{4}\Pi\delta_k \Delta x \frac{T_m \beta^2 \omega}{\rho_m c_p}(p_1)^2(\Gamma - 1), \quad (2)$$

where Π is the perimeter, Δx is the length of the regenerator, ω is the angular frequency, β is the thermal expansion coefficient, δ_k and δ_v are the thermal penetration depth and the viscous penetration depth respectively, c_p is the isobaric specific heat, ρ_m is the mean density of the working gas, T_m is the cross-section averaged temperature of the fluid, and $\Gamma = \nabla T_m / T_{crit}$ is the ratio of actual temperature gradient ∇T_m to the standing wave critical gradient $T_{crit} = T_m \beta p_1 / \rho_m c_p u_1$.

As shown in Eqs. (1) and (2), the heat power and the produced acoustic power are proportional to the temperature gradient factor $(\Gamma - 1)$. When $\nabla T_m = \nabla T_{crit}$ (i.e. $(\Gamma - 1) = 0$), there is neither heat power transferred nor acoustic power produced. For $\nabla T_m > \nabla T_{crit}$ (i.e. $(\Gamma - 1) > 0$), the heat power is transferred away from the PAN, and the acoustic power is produced in the regenerator. For $\nabla T_m < \nabla T_{crit}$ (i.e. $(\Gamma - 1) < 0$), the heat power is transferred toward the PAN, and the acoustic power is consumed in the regenerator. There are two cases for $\nabla T_m < \nabla T_{crit}$. In the case of $0 < \nabla T_m < \nabla T_{crit}$, the regenerator consumes acoustic power to pump heat from the cold end to the hot end. In the other case of $\nabla T_m \leq 0$, the regenerator dissipates acoustic power, and the heat power is transferred from the hot end to the cold end. In that case, the regenerator will not realize the conversion from heat to acoustic energy, and there is also no heat pumping from the cold end to the hot end. The regenerator located on the right side of the PAN can be analyzed in the same way.

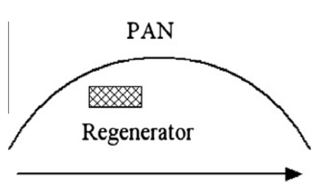

Fig. 1. In the standing wave, the regenerator is located on the left side of the PAN. The positive direction of *x* is taken the rightward direction.

Therefore, some conclusions can be obtained as shown in Fig. 2. The required working conditions for the standing wave engine are: (1) the hot end of the regenerator is close to the PAN; (2) $\nabla T_m > \nabla T_{crit}$ on the left side of the PAN, or $\nabla T_m < -\nabla T_{crit}$ on the right side of the PAN. The required working conditions for the standing wave cooler are: (1) the ambient end of the regenerator should be close to the PAN; (2) $0 < \nabla T_m < \nabla T_{crit}$ on the left side of the PAN, or $-\nabla T_{crit} < \nabla T_m < 0$ on the right side of the PAN.

2.2. Traveling wave mode

The traveling wave thermoacoustic device was originally proposed by Ceperley in 1979 [3]. In the traveling wave heat engine, the heat flow direction is opposite to the direction of wave propagation: the wave propagates from the cold end to the hot end, while the heat transfers from the hot end to the cold end. The regenerator converts heat to acoustic energy when the wave propagates from the cold end to the hot end. In a traveling wave heat pump, the wave pumps heat in the opposite direction to its propagation: the wave propagates from the hot end to the cold end, while the heat is pumped from the cold end to the hot end. The regenerator consumes the acoustic energy to pump heat from the cold end when the wave propagates from the hot end to the cold end. Thus, the regenerators of the TAE and the TAC in the traveling wave should be arranged according to Fig. 3.

2.3. Traveling–standing wave mode

We can analyze the thermoacoustic effect of the regenerator arranged as the four cases in Fig. 4 by combining the thermoacoustic conversion performance of traveling wave and standing wave.

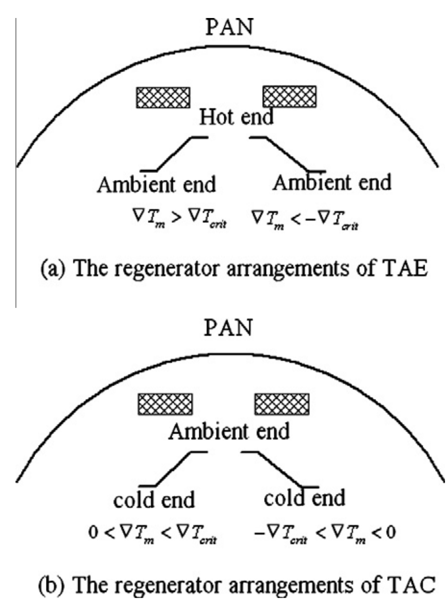

Fig. 2. In the standing wave, the better arrangements of regenerators.