Experimental investigation on the dynamic character of thermoacoustic engine and parameters of regenerator

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As a result of temperature difference and self-organization of regenerator, some oscillatory fluid is filtered whose oscillatory frequency is far from thermoacoustic engine intrinsic frequency in regenerator. And someone is maintained which is close to the engine intrinsic frequency, thus part energy is concentrated on the band of close to the engine intrinsic frequency. Effect of heat conduction and fluid viscosity between the oscillatory fluid and solid interface of regenerator, magnification and attenuation of amplitude of oscillatory fluid simultaneously take place. The dynamic character is achieved with the actions of heat conduction, viscosity and oscillation between the oscillatory fluid and the solid interface, so it is significance to find out the transforming rules of the three objects.

FOREWORD

We used four thermoelectric couples which were even distributed along the regenerator's axis to measure the interior temperature of regenerator. Then, we calculated the parameters of regenerator. Furthermore, we analyzed the variation rules, validated the evolving process of thermoacoustic engine.

EXPERIMENT RESULTS INTRODUCTION

In our experiment, inner diameter and length of the regenerator packed with stainless screens are 25.4 mm and 32 mm respectively. The charge pressure of regenerator is 1.6Mpa. Experiment results can be seen from table 1 below：

Table 1 Experiment results

power(W)	mesh	start oscillation frequency (Hz)	extinguish frequency (Hz)	ultra oscillatory state
223	60	523	maitain	steady high frequency
179	200	528	73	intermittent oscillation of high and low frequency
223	200	528	73	steady low frequency oscillation
223	300	75	maitain	steady low frequency oscillation

From the rows 1, 3, 4, we can see that the temperature of regenerator under high frequency steady state is higher than that of under low frequency. It's well known that the energy to overcome fluid viscosity under low frequency mode is more than that of under high frequency. Therefore, the temperature under low frequency mode would descend firstly then turns to steady, but the temperature under high frequency mode would slowly increase before steady. Row 2 shows that when the system is under transition state the temperature of starting oscillation is higher than that of forming reliable low frequency oscillation mode. It means that after system starting oscillation, part of heat energy converted into acoustic energy. Therefore, the temperature would decrease. And the sound wave must consume energy to get over the resistance of fluid during transferring process. If this part of energy can not be gotten, the temperature of regenerator would decrease continuously until the system can not oscillate.

We can see the movement of thermoacoustic engine is closely related to the temperature of regenerator for it reflects the effect of heat contact and viscosity contact between fluid and solid interface of regenerator. Therefore, we can utilize the extrinsic phenomena of the system to study the dynamic character of thermoacoustic self-excitation oscillation.

VISCOSITY DISSIPATION OF SOUND WAVE

As sound wave transfers in viscous fluid, the viscosity of fluid increase the energy dissipation. This part energy is transferred with diffusion. Now, we discuss the dissipation of sound wave in viscous fluid.
Wave equation, diffusion equation, linearized Navier-Stokes equation:

$$\frac{\partial \rho'}{\partial t} = \frac{1}{c_0^2}\frac{\partial p'}{\partial t} \tag{1}$$

$$\frac{\partial p'}{\partial t} + \rho_0 c_0^2 \frac{\partial u}{\partial x} = 0 \tag{2}$$

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p'}{\partial x} = \frac{4}{3}\mu'_0 \frac{\partial^2 u}{\partial x^2} \tag{3}$$

Where $c_0^2 = c_p(k-1)/\beta_0^2 T_0$ for the velocity of sound, β_0 for coefficient of heat expansion, $\mu'_0 = \mu_0(1+3/4\cdot\mu_{v0}/\mu_0)$, μ_{v0} for coefficient of viscosity expansion. From formula (1), (2), (3) we can get

$$\frac{\partial^2 p'}{\partial t^2} = c_0^2\left(1+\frac{4}{3}\frac{v_0}{c_0^2}\frac{\partial}{\partial t}\right)\frac{\partial^2 p'}{\partial x^2} \tag{4}$$

The solution of (4) can be expressed in vector form:

$$p' = \mathrm{Re}\left[\tilde{p}(x)e^{-j\omega l}\right] \tag{5}$$

Then get

$$p''(x) + K^2 \dot{p}(x) = 0 \tag{6}$$

Where $K^2 = (\omega/c_0)^2/[1-j(4\omega v_0/3c_0^2)]$, it can be written as $K = k_1 + jk_2$, thus we get

$$p(x,t) = A\cdot e^{-k_2 x}\cos(k_1 x - \omega t + \theta) \tag{7}$$

Where, K^2 must satisfy $(c_0/\omega)^2(k_1^2 - k_2^2 + 2jk_1k_2) = [1-j(4\omega v'_0/3c_0^2)]^{-1}$, it can be expressed as

$$\overline{\beta}^2 - \overline{a}^2 = (1+\omega^2\tau_v^2)^{-1}, \overline{a} = k_2 c_0/\omega \tag{8}$$

$$2\overline{a}\overline{\beta} = \omega\tau_v/(1+\omega^2\tau_v^2), \overline{\beta} = k_1 c_0/\omega \tag{9}$$

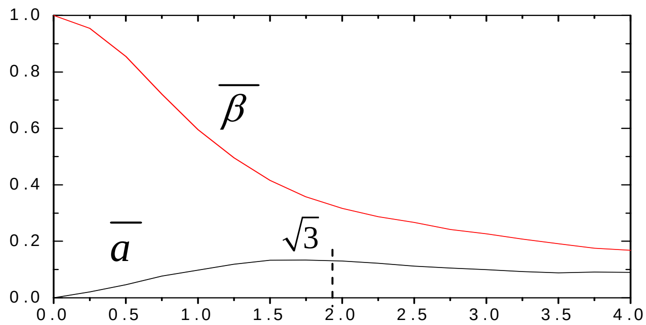

Figure 1 relation of $\overline{a}, \overline{\beta} \sim \omega\tau_v$

Where, $\tau_v = 4v'_0/3c_0^2$, $\overline{a}$ for coefficient of oscillatory attenuation, $\overline{\beta}$ for coefficient of phase shift, ω/k_1 for wave velocity with dissipation, so $\overline{\beta}$ represent the ratio of velocity and describe the infection of dissipation to the velocity of transfer.

We can know from above dissipation makes oscillatory attenuation, which is reflected from the imaginary part of complex wave number K. And variety of wave velocity makes phase shift. Oscillatory attenuation and phase shift rest with $\omega\tau_v$. τ_v depends on the dissipation of sound wave. And ω is the frequency of oscillatory fluid. The product $\omega\tau_v$ reflects the diffusion wave transferring depends not only wave but also diffusion.

Figure 1 shows the relation of $\overline{a}$, $\overline{\beta}$ and $\omega\tau_v$. $\overline{\beta}$ is always less than 1, this means the velocity of sound wave with dissipation is higher than that of without dissipation. The momentum diffusion velocity that results from dissipation is append to c_0.

ANALYSIS OF THE PARAMETERS

The parameters below are close to the temperature of oscillatory fluid in regenerator: depth of heat penetration and viscosity penetration δ_k, δ_v, distribution function of viscosity and heat conduction f_v, f_k, relaxation time of viscosity and heat τ_v, τ_k, coefficient of flow magnify e. From the expression of e, we can get the real part of coefficient of flow magnifying Re[e] and the imaginary part of Im[e]:

$$\mathrm{Re}[e]=\frac{\left(\mathrm{Re}\left[\beta\left(f_\kappa-f_\nu\right)\right]\mathrm{Re}\left[1-f_\nu\right]+\mathrm{Im}\left[\beta\left(f_\kappa-f_\nu\right)\right]\mathrm{Im}\left[-f_\nu\right]\right)}{\left|1-f_\nu\right|^2\left(1-\sigma\right)}\frac{dT_m}{dx} \tag{10}$$

$$\mathrm{Im}[e]=\frac{\left(\mathrm{Re}\left[\beta\left(f_\kappa-f_\nu\right)\right]\mathrm{Im}\left[f_\nu\right]+\mathrm{Im}\left[\beta\left(f_\kappa-f_\nu\right)\right]\mathrm{Re}\left[1-f_\nu\right]\right)}{\left|1-f_\nu\right|^2\left(1-\sigma\right)}\frac{dT_m}{dx} \tag{11}$$

From the experimental data, we calculated these parameters shown in Figures 2,3,4,5.

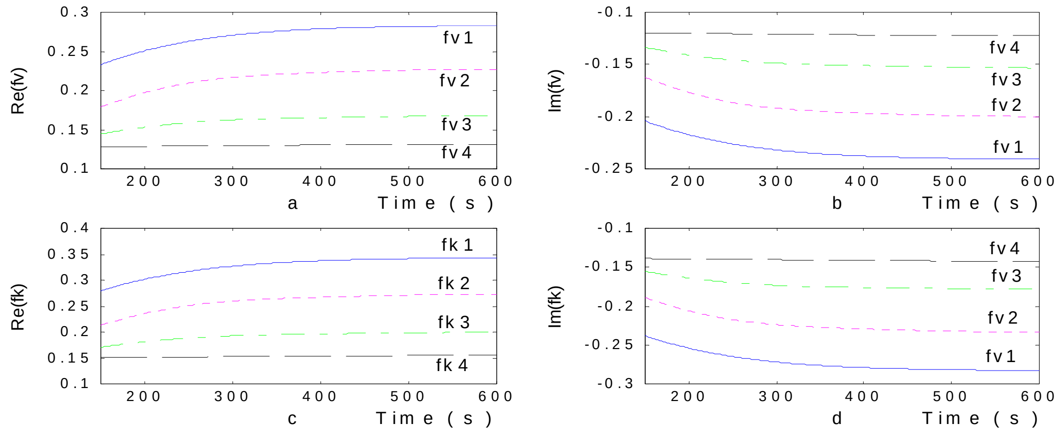

Figure 2 distribution function under high frequency mode

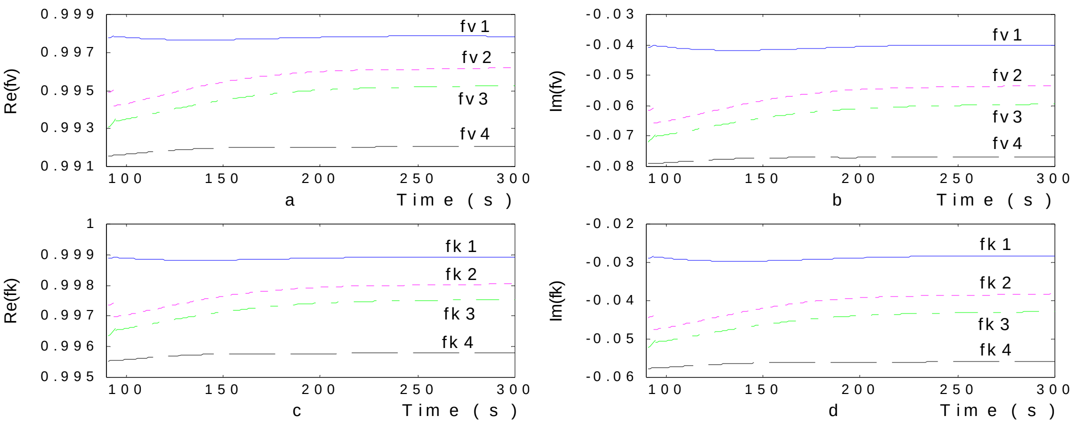

Figure 3 distribution function under low frequency

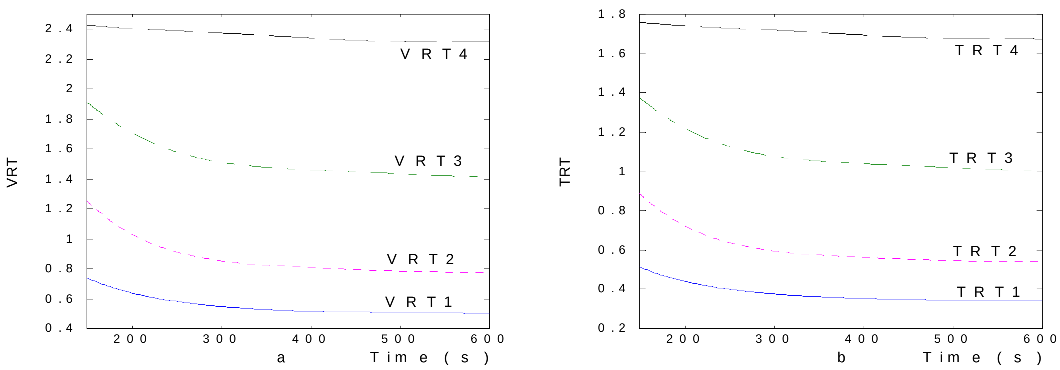

Figure 4 variation of $\omega\tau_v$ under constant high frequency

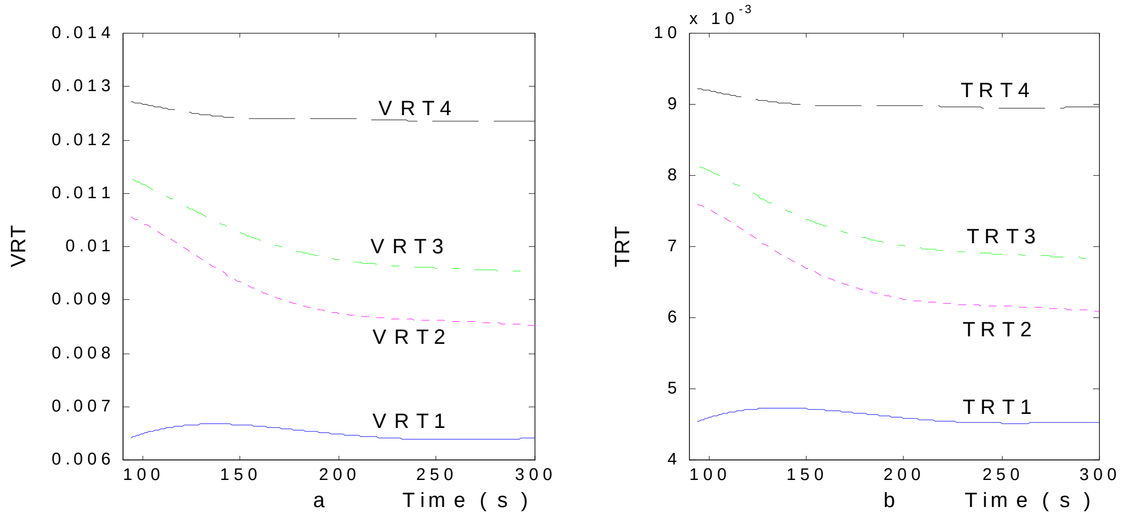

Figure 5 variation of $\omega\tau_v$ under constant low frequency

Where1, 2, 3, 4 for the four temperature sensors, VRT for period of viscosity diffusion, TRT for the period of heat diffusion. From the above we can get some conclusions:

(1) Absolute values of the real part and imaginary part of f_k are larger than those of f_v under high frequency. According to formula (10,11), we can easily get that the real part of coefficient of flow increasing under high frequency mode is less than that under low frequency, but the imaginary part is reverse. Figure 2 shows that sound pressure is thoroughly different under different modes.

(2) The velocity of sound wave is more rapidly in viscous fluid. This relates to microcosmic property of material. And the value of coefficient of phase shift changes small, the phase angle of sound wave varies sharply. For traveling wave, f_v is small, and the phase shift will be small, so the variation of phase angle must small. Therefore, sound wave can maintain a constant speed. Furthermore, the phase angle of sound pressure is different on different position at the same time. But for standing wave, viscosity dissipation may lead to phase angle identical.

(3) $\omega\tau_v$ is correspond to $\bar{a}$ and $\bar{\beta}$. While $\omega\tau_v$ is in the range of $0\sim\sqrt{3}$, $\bar{a}$ increase with it. So, we can understand that the temperature difference of regenerator under high frequency is larger than that under low frequency. This means relaxation time of viscosity determines dissipation of sound wave .The numerical value of $\bar{\beta}$ decrease while $\omega\tau_v$ increasing. Therefore, $\bar{\beta}$ is larger under low frequency. It means that phase shift becomes larger. So, it is possible to keep phase angle stable at the same time.

CONCLUSION

We analyzed and quantified the parameters of regenerator with temperature temporal series of oscillatory fluid in the regenerator. The dynamic character of thermoacoustic engine is performed with these parameters. Mechanism of oscillatory mode transferring is described with no dimension time scale $\omega\tau_v$.

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