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# Characteristics study on the oscillation onset and damping of a traveling-wave thermoacoustic prime mover*

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**Abstract:** This paper focuses on the temperature and pressure characteristics of a Swift-Backhaus type traveling-wave thermoacoustic prime mover during its onset and damping processes, in order to understand the intrinsic mechanism of thermoacoustic oscillation onset and the feasibility of using low-grade thermal energy based on a low onset temperature. The influences of heat input and filling pressure on hysteretic loop, due to the noncoincidence between onset and damping processes, are measured and analyzed. The condition for the occurrence of hysteresis is also briefly discussed.

**Key words:** Thermoacoustics, Onset and damping, Hysteretic loop

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## INTRODUCTION

Thermoacoustic engine attracts more and more attention due to its inborn advantages like moving part free, potential environment benignity, and also so many exciting progresses in related researches in the past 40 years (Garrett, 2004). A traveling-wave thermoacoustic engine, which was firstly proposed by Ceperley (1979), has additional advantages of lower onset temperature and higher efficiency, compared with a standing wave thermoacoustic engine. Many successes, including the invention of Swift-Backhaus structure, have been achieved on traveling-wave thermoacoustic engines (Yazaki *et al.*, 1998; Backhaus and Swift, 1999).

Hysteresis phenomena were ever found in thermoacoustic systems. A disagreement of onset and damping temperatures in a standing-wave thermoacoustic prime mover was observed by Zhou and Matsubara (1998). Based on non-steady thermodynamics, a hysteretic loop was firstly proposed and experimentally verified by Chen and Jin (1999). A thermoacoustic prime mover may sustain oscillating at a much lower temperature than the onset temperature after an oscillation is excited. Since then, more efforts have been contributed to this topic by this group (Jin *et al.*, 2007) and other researchers. Besides verifying the hysteretic loop, Liu *et al.*(2007) observed a "secondary onset", i.e., the pressure ratio has two abrupt increasing stages during the whole onset process, in a standing wave thermoacoustic prime mover with helium-argon mixtures. Penelet *et al.*(2002; 2005; 2006) studied the steady state and nonlinear characteristics of the oscillation in an annular thermoacoustic prime mover. The hysteretic loop also means the feasibility and space for lowering the onset temperature. Sun (2005) decreased the onset temperature of their traveling-wave thermoacoustic prime mover from 219 °C to 193 °C by applying a pressure disturbance.

For more comprehensive understanding of the thermoacoustic onset/damping and occurrence of thermoacoustic hysteretic loop, the present work focuses on pressure and temperature profile during the onset and damping processes of a traveling-wave thermoacoustic prime mover. The influences of heat

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input and filling pressure on onset/damping temperature and pressure ratio are observed for further discussion.

## EXPERIMENTAL SETUP AND EXPERIMENTS

The traveling-wave thermoacoustic prime mover is composed of a torus-shaped loop and a resonant tube, as shown in Fig.1. The loop section consists of main and secondary water coolers, regenerator, heater, thermal buffer tube (TBT), feedback tube, compliance tube and membrane. The thermoacoustic core is composed of main water cooler, regenerator and heater. The silica gel membrane is used for eliminating acoustic streaming in the loop system. Main parameters of the components are listed in Table 1. The measuring system includes 16 temperature sensors (labeled as T1~T16 from top to bottom in Fig.1) and 6 pressure sensors (located at P1, P2, …, P6 in Fig.1). The temperature sensors are thermocouples for measuring the temperatures at main water cooler, regenerator, heater and TBT. The signals from temperature and pressure sensors are sent to a LabVIEW-based data acquisition system. The heating temperature (including onset and damping ones) in the following analysis refers to the temperature measured by the thermocouple T7 (located inside the solid of the heater block as shown in Fig.1), which is different from those along the regenerator measured at the external wall of the pipe.

The working fluid in the following study is nitrogen. During the experiments, the onset temperatures are measured under a relatively low heat input except the cases in which the influence of heating input power needs to be investigated, while the damping temperatures are measured under complete heating switch-off. The "relative low heat input", generally ranging from 50 W to 150 W in our experiments, means a heat power for which the thermoacoustic system undergoes a very slow temperature rising process before it is excited to spontaneously oscillate from non-oscillating state. A slow temperature rising process can assure a quasi-steady state and a relatively accurate onset temperature measurement. The "complete heating switch-off" for the damping process means that the heating power is completely cut off during the cooling down process of

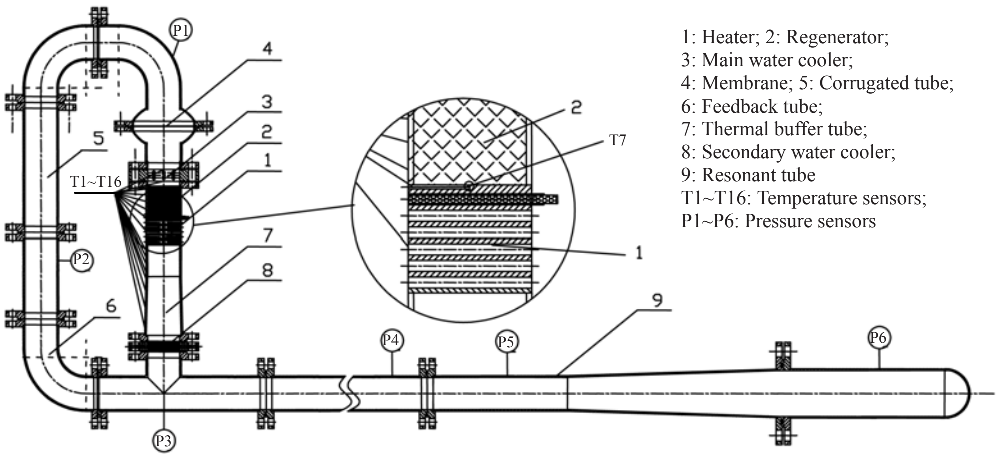


**Fig.1 Schematic of traveling-wave thermoacoustic prime mover**

**Table 1 Main parameters of the components in the thermoacoustic prime mover**

| Component | Length $L$ (mm) | Inner diameter $ID$ (mm) | Other parameter | Material |
|---|---|---|---|---|
| Heater | $L$=75 | $ID$=83 | $W_{max}$=3.6 kW | S.S.*+Cu |
| Regenerator | $L$=78 | $ID$=83 | 120 meshes | S.S. |
| Water cooler | $L_{main}$=26, $L_{2nd}$=20 | $ID_{main}$=83, $ID_{2nd}$=90 | | Al+Cu |
| TBT** | $L$=90+150 (taper) | $ID$=83, $ID_{Taper}$=83→90 | Taper=1.35° | S.S. |
| Resonant tube | $L$=2300+1500 (taper) +500 | $ID_1$=83, $ID_{Taper}$=83→240, $ID_2$=240 | Taper=3° | S.S. |

* Stainless steel; ** Thermal buffer tube

the system. To adopt the complete switch-off strategy, instead of gradual heat input decrease, is based on the following reason: the measurement was ever made with both methods, while the difference between the two results of damping temperature is negligible. The pressure measured by 6 sensors show that a maximal pressure ratio is generally at P1, which is above and near to the membrane. The pressure ratio analyzed hereafter (the ratio of maximum pressure over minimum pressure of an oscillation) is that measured at P1.

## RESULTS AND DISCUSSION

Fig.2 presents the relationship between the onset, damping temperatures and the filling pressures in the range of 0.3 MPa~1.7 MPa. The onset temperature, under the condition of a relatively low heat input, drops with the increase of filling pressure until the pressure reaches 0.5 MPa, corresponding a minimum onset temperature of 133 °C, and then rises with the pressure. Similar tendency for the damping temperature can be found in Fig.2. The onset temperature at the pressure of 1.0 MPa is 164 °C, which demonstrates the ease of exciting this present system to oscillate. The onset curve in Fig.2 is similar to Yazaki *et al.*(1998)'s results. A difference between onset and damping temperatures can be observed when the filling pressure is higher than 1.0 MPa, and their discrepancies get larger as the filling pressure increases.

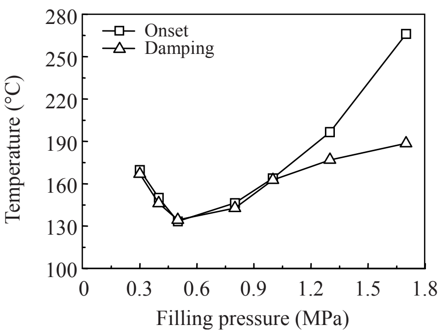


**Fig.2 Onset and damping temperatures vs filling pressure**

The pressure ratios during the onset and damping processes are shown in Fig.3. When the filling pressure is relatively high, as in Fig.3a, both onset and damping are abrupt processes, i.e., the pressure ratio changes suddenly at these moments. Besides, the trace of damping processes does not coincide with the onset one. Therefore, hysteretic loops, firstly proposed and verified in a standing-wave thermoacoustic prime mover (Chen and Jin, 1999), are also found in the present traveling-wave system. As to the above-mentioned temperature difference between onset and damping processes, the hysteretic loop has similar behavior, i.e., it is not so apparent when filling pressure is lower than 1.0 MPa, as shown in Fig.3b.

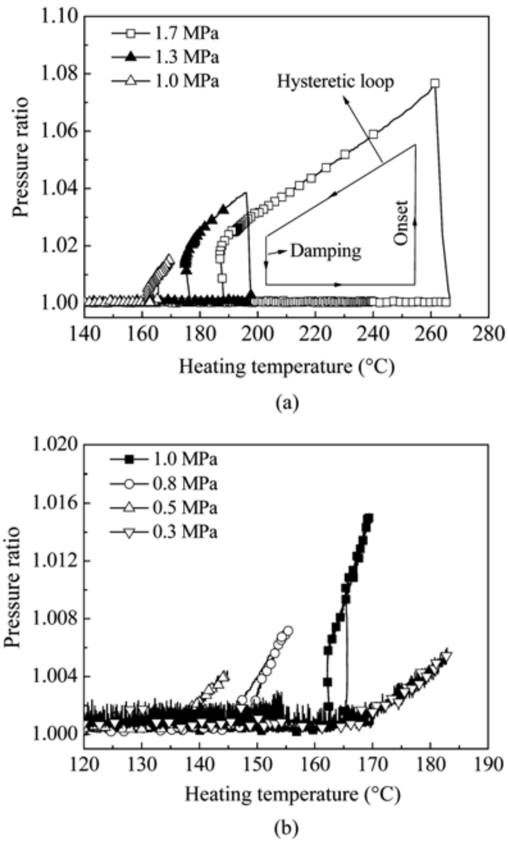


**Fig.3 Hysteretic loop of pressure ratio-temperature profile. Filling pressure is (a) 1.0~1.7 MPa; (b) 0.3~1.0 MPa**

Figs.4 and 5 present onset temperatures and damping temperatures, respectively, at different heating powers and filling pressures. Fig.4 shows the level of the heating power employed, which, however, will be completely switched off when the damping behavior is being observed. The onset temperatures rise with the increase of the heating power, while the pressure dependence of onset and damping temperatures is similar to that given in Fig.2. Figs.4 and 5 show that both heating power and pressure have influence on onset temperature, while damping temperature mainly depends on filling pressure.

Fig.6 presents the heating temperature before and after onset under the above-mentioned relatively low heat input. For the filling pressures between 1.3 MPa and 1.7 MPa, the temperature gradually rises to a peak value till the system starts to oscillate, then the temperature drops down to a certain value, and finally resumes to gradually rise to a steady temperature, depending on the heating input power. The temperature drop after onset indicates a surplus energy input before onset, and the spontaneous oscillation helps to transfer this excess heat energy out of regenerator's hot end, leading to a temporary "cooling". The necessity of surplus energy for exciting the oscillation means the existence of dynamic damping in the system, which is also related to the above-mentioned hysteresis. A greater temperature drop also means a larger area of hysteretic loop. For the filling pressures of 0.5 MPa and 0.8 MPa, the heating temperature continuously rises till a steady value, no apparent influence from onset process. The pressure of 1.0 MPa appears to be (near) the dividing point, since the temperature becomes steady immediately after the onset. The variation of heating temperature under divers heating power inputs is also measured and presented in Fig.7. It is shown that the heating temperature always has a "rise-drop-rise" process for the filling pressure of 1.3 MPa, while for the case of 0.5 MPa the heating temperature always continuously rises to a steady value even though the heat input varies. The variation trends are dependent on filling pressure, but independent on heating input power.

The temperature profiles along regenerator and TBT during onset and damping are also measured and shown in Figs.8 and 9 for the filling pressures of 0.5 MPa and 1.3 MPa, where 0~78 mm and 78~300 mm represents regenerator and TBT, respectively. From Fig.8, we can find that the temperature profiles during onset and damping along regenerator coincide well, when inputting a relatively low heating power (50 W at 0.5 MPa, 100 W at 1.3 MPa). However, with a much higher heat input 500 W at 0.5 MPa, 800 W at 1.3 MPa, the profiles for both regenerator and

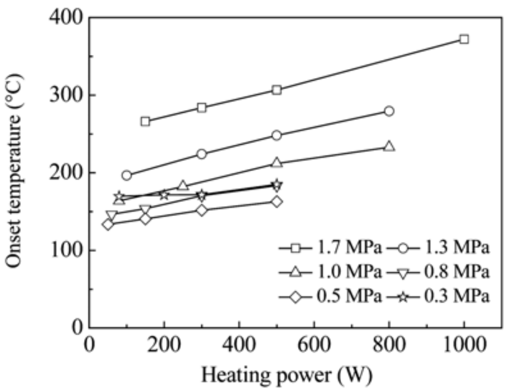


**Fig.4 Onset temperature vs heating power at different filling pressures**

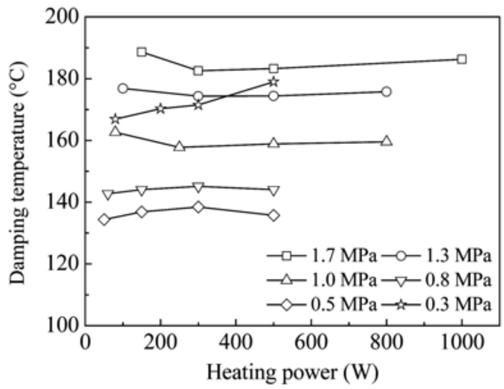


**Fig.5 Damping temperature vs heating power at different filling pressures**

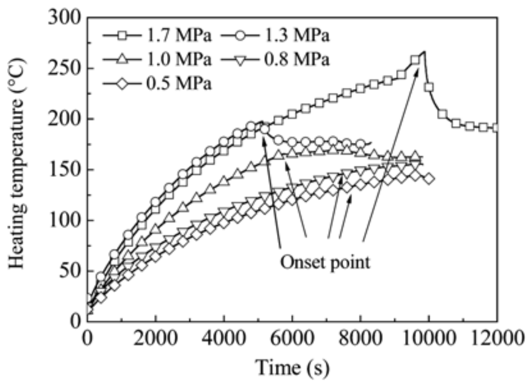


**Fig.6 Heating-up process during onset**

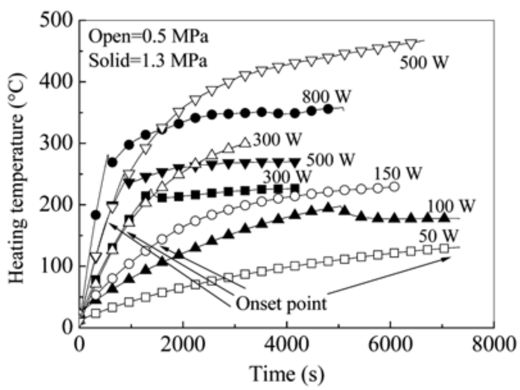


**Fig.7 Heating-up process at different heat inputs**

TBT have greater curvatures and worse coincidence between onset and damping, as shown in Fig.9. There is more reasonability to recommend the onset temperature measured at a low heat input as system's onset temperature, because heat transfer along regenerator can be sufficient and then the temperature rise is gradual. In this case, a minimum temperature difference between the onset and damping can be expected.

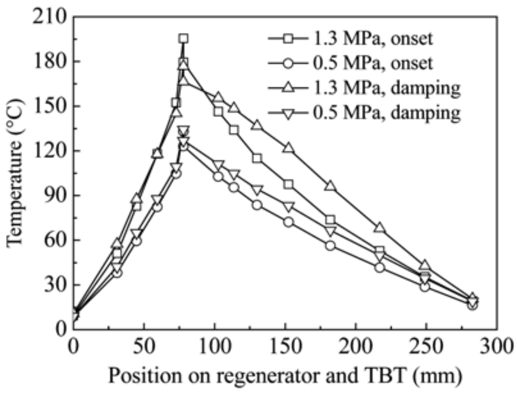


**Fig.8 Temperature distribution along regenerator and TBT for onset and damping process at relatively low heat input (50 W at 0.5 MPa, 100 W at 1.3 MPa)**

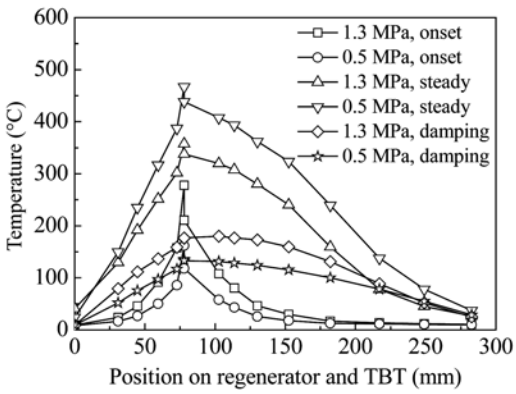


**Fig.9 Temperature distribution along regenerator and TBT during onset, steady state and damping at relatively high heat input (500 W at 0.5 MPa, 800 W at 1.3 MPa)**

## CONCLUSION

Systematic observation of oscillation onset and damping behavior has been conducted on a traveling-wave thermoacoustic prime mover. The following conclusions can be drawn from the present study:

(1) There exists a certain filling pressure, under which the system can be excited to oscillate with a lowest onset temperature, which is 133 ºC for the present system at 0.5 MPa of filling pressure with nitrogen as working fluid.

(2) A hysteretic loop is found in the present traveling-wave thermoacoustic system. However, its occurrence depends on the filling pressure of working fluid. When the filling pressure is above 1.0 MPa, the hysteresis is apparent, but the loop disappears when it is below 1.0 MPa.

(3) The behavior of onset is correlated with hysteresis, i.e., the increase of pressure ratio during onset process is abrupt when an apparent hysteretic loop occurs, while is in a gradual transition if the hysteretic loop disappears. Meanwhile, the temperature variation during onset process also depends on hysteretic loop. For the case of hysteresis occurrence, the heating temperature rises to a peak value before the onset, then drops to a certain lower level, and finally rises again gradually to a steady state depending on the heating input power. If hysteresis phenomenon is not apparent, the heating temperature rises monotonically to a steady value.

(4) Under a fixed charging pressure, heating input power has influence on onset temperature. A higher heating input power may result in a higher onset temperature. In order to have a unified consideration, the onset temperature measured at the condition of a relatively low heat input is recommended, which is generally 50 W~150 W in our experiments.

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