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Experimental investigation of transient nonlinear phenomena in an annular thermoacoustic prime-mover: observation of a double-threshold effect

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Abstract

Thermoacoustic engines have been subjected to numerous studies for the past 10 years. Our current research is focused on the transient regime in an annular thermoacoustic prime-mover. It appears that several nonlinear phenomena can play a role in the amplification and saturation regimes. Indeed, acoustically induced conductivity, forced convection due to acoustic streaming, minor loss phenomenon, and saturation due to harmonic generation can be quoted among the others. The experiments presented here show for the first time a double-threshold phenomenon during the amplification regime. The first threshold, which corresponds to the setting of the thermoacoustic instability, is followed by a saturation regime. Then after a time delay, without any changes in the control parameters, a second threshold corresponding to an additional amplification has been observed.

Keywords: Thermoacoustic prime-mover; Acoustic streaming; Thermoacoustic instability

1. Introduction

The idea of a traveling-wave thermoacoustic engine was put forward more than 20 years ago [1]. However the first annular thermoacoustic prime-mover, which employs for the transformation of the thermal energy into mechanical energy a quasi-adiabatic interaction between an inhomogeneously heated stack of solid plates and resonant gas oscillations, was built only in 1997 [2]. Later a closed-loop thermoacoustic engine employing quasi-isothermal regime of sound propagation through the stack was reported [3,4].

An important part of the research on the prime-movers is devoted to studies of the nonlinear processes leading to saturation of the thermoacoustic instability and limiting the amplitudes of the acoustic waves in these devices. The role of the nonlinear acoustic phenomenon (cascade process of higher harmonics excitation) was studied both experimentally [5,6] and theoretically [7–9] in the case of the standing-wave prime-mover. Possible role of the acoustic turbulence in the waveguide, of the minor losses at the edges of the stack, and of the heat exchangers was discussed and estimated [6,10]. All the above mentioned nonlinear phenomena should be important in the traveling-wave thermoacoustic engines as well. However in the devices containing a closed-loop path for the acoustic wave propagation there is an additional efficient nonlinear mechanism influencing the high-amplitude acoustic waves. This mechanism is due to possible excitation in these devices of directional (closed-loop) acoustic streaming carrying a nonzero mass flow through each cross-section of the device. This streaming provides convective heat transport in the inhomogeneously heated parts of the prime-mover, modifies temperature distribution in the system, and, as a result, influences the thermoacoustic amplification of sound. The first analysis of how a nonzero net time-averaged mass flow can arise in Stirling and pulse-tube cryocoolers whenever a closed-loop path exists for steady flow was proposed in 1997 [11], and the theory of the acoustic streaming in an annular thermoacoustic prime-mover was developed in

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2000 [12]. The experiments [3,4,13] confirmed the existence of these circular (closed-loop) streaming. Moreover, it was demonstrated [4] that suppression of the streaming leads to a significant increase in the efficiency of the device performance. Different methods for streaming suppression were proposed [4,14]. Consequently acoustic streaming is an important nonlinear mechanism influencing the sound level in thermoacoustic engines.

In the stationary regime of a prime-mover operation acoustic streaming acts in parallel with the other nonlinear phenomena. However in the transient regime the development of the different nonlinear phenomena might proceed differently (with different time scale). So the experimental investigation of the transient process of an annular thermoacoustic engine stabilization might provide information on independent (separated in time) influence of different nonlinear phenomena on thermoacoustic instability. It might help to identify the dynamics of acoustic streaming development, the dynamics of temperature field modification by streaming, and the characteristic times for the operation of this mechanism of acoustic wave self-action. This is a draft of a physical idea, which initiated our experiments. However, it should be mentioned as well that, surely, the investigation of transient processes is important not only for fundamental research but also for the applications (as ultimately we are interested in the creation of the thermoacoustic devices with the shortest possible turn-on time).

Though in all the experiments with thermoacoustic prime-movers the researchers inevitably observed transient phenomena, these observations are very poorly documented in the literature [6,10,15]. The "classical"-type observation for the standing-wave devices consists in the initial exponential growth of the acoustic wave amplitude (above the threshold of the thermoacoustic instability) with subsequent smooth (in time) saturation [10,14] (similar to the behavior presented in Fig. 2 later here). However much more sophisticated transient regimes were also reported. In Ref. [6 (p. 1555)] the observation of the acoustic pressure amplitude oscillation with a long period and the possibility of exponential growth of the envelope of this oscillation (followed by the entire stop of the engine) were mentioned. The regime of the periodic turn on and turn off of the engine with a period of hours was also observed [6]. Note that all these observations have been documented for the standing-wave devices only.

In the following we present what is, to the best of our knowledge, the first documentation of the transient processes observation in the annular thermoacoustic device. Our observations confirm the possibility of the regime of smooth stabilization and of the regime of long-time quasi-stable operation followed by a spontaneous turn off of the prime-mover (both were observed earlier in standing-wave devices). The unexpected and interesting observation is the existence of the regime where the exponential growth of oscillations (first threshold) is followed by an intermediate quasi-stabilization (with wave amplitude slowly growing in time), which before the final stabilization of the amplitude is followed by another exponential growth (second threshold). All these processes (including two subsequent instabilities) proceed in time one after another for the fixed control parameter (fixed temperature in the vicinity of the hot heat exchanger). We called the observed effect the double-threshold phenomenon. We have not found in the literature any reports on the earlier observations of this type of transient behavior in thermoacoustic devices.

2. Experimental apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. The torus-shaped stainless steel tube of inner diameter $R = 53$ mm and length $L = 2.24$ m is filled with air at atmospheric pressure. The stack (length $H = 150$ mm) is a ceramic porous material with square channels of cross-section $d \times d$ ($d = 0.9$ mm). Considering that the thermal boundary layer $\delta_\kappa = (2\kappa/\omega)^{1/2}$ (thermal diffusivity $\kappa = 4\ \mathrm{W\,m^{-1}\,K^{-1}}$) at the first harmonic pulsation $\omega_1 = 2\pi c/L$ (sound speed $c = 342$ $\mathrm{m\,s^{-1}}$) is about four times smaller than d, the prime-mover employs a quasi-adiabatic regime. The cold heat exchanger is a copper circular shell set around the tube with flowing cooling water inside at temperature T_c, and a copper wire mesh inside the tube (attached to the stack). The hot heat exchanger is an appropriately coiled stainless steel ribbon (width = 25 mm) at a distance of 2 mm from the stack side, radially heated with electrical heat resistances, which are soldered in a stainless steel block around it. The heating power can be adjusted to the wanted T_h hot temperature, using a controller connected to a thyristor unit and a type K thermocouple fitted between the outer tube and the block.

The instrumentation of the device is schematically shown in Fig. 1. Two piezoresistive microphones allow the amplitude, frequency and relative phase measure-

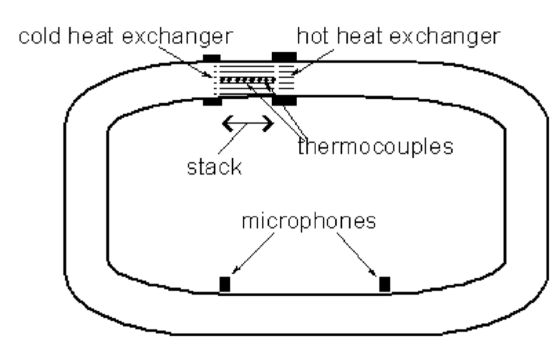

Fig. 1. Schematic presentation of the experimental apparatus.

ments of the acoustic wave generated in the tube. Particular attention has been paid to the temperature distribution measurement along the stack. A total of eight type K thermocouples (70 μm in diameter), sandwiched in thin copper strips (40 μm in diameter), are equally placed along the stack, and glued with a ceramic putty. The highly thermal conducting copper strips ensure an isothermal condition between the thermoelectric junctions and the stack surface with an acceptable response time (less than 5 s). In order to investigate the possible inhomogeneity in the radial temperature distribution, two additional thermocouples are placed in the stack at a distance $x = 4H/7$ away from the cold end of the stack ($x = 0$), and at 10 and 20 mm from the median axis, respectively. All sensors are compensated with ambient temperature and the conditioner is linked to an A/D converter for signal processing.

3. Experiments

For each measurement, the temperature difference $(T_h - T_c)$ is set just below its critical value corresponding to the onset of the thermoacoustic instability. A 1 K increment on T_h is then sufficient for the acoustic wave to be generated in the waveguide. Note that care has been taken before each measurement to wait for the temperature stabilization in the whole device.

Fig. 2 presents what we can call a « classical » onset of the thermoacoustic instability, in linear (top) and logarithmic (bottom) scales. Solid lines in Fig. 2 correspond to pressure amplitude at fundamental resonance frequency $f_1 = 153$ Hz. An exponential growth of the acoustic wave is followed by a stabilization regime. The second harmonic ($f_2 = 306$ Hz, dotted lines) grows in the same way as the first harmonic. The corresponding normalised temperature distribution along the stack is presented in Fig. 3, at two different moments in the transient regime. The influence of the directional nonzero mass flow due to acoustic streaming is observed

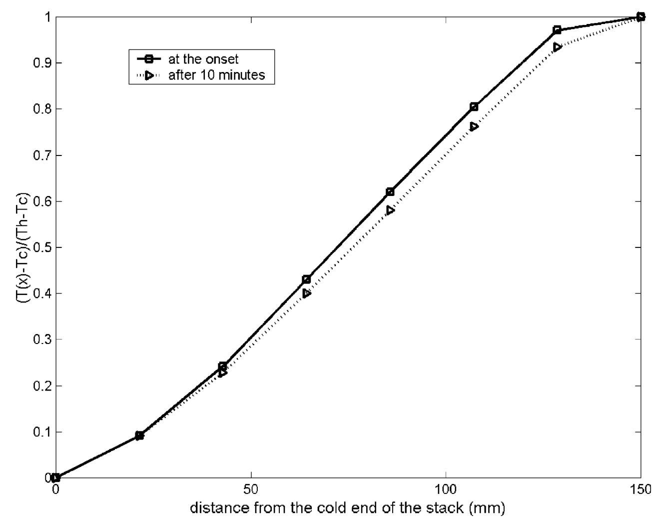

Fig. 3. Normalized temperature profile $(T(x) - T_c)/(T_h - T_c)$ along the stack, at two different moments in the transient regime. The x-axis corresponds to the distance away from the cold end of the stack.

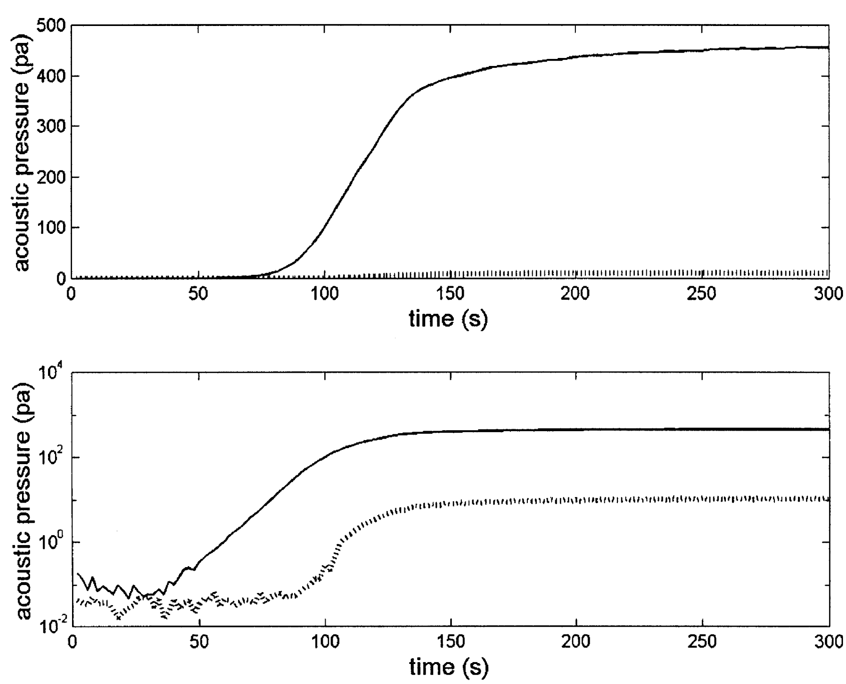

Fig. 2. RMS amplitude of acoustic pressure for the fundamental frequency (solid line) and the second harmonic (dotted line) during the onset and stabilization of the thermoacoustic instability, in linear (top) and logarithmic (bottom) scales. The measurements are documented for the engine instrumented with thermal sensors. The ΔT increment above the threshold is 7 K.

when comparing the temperature distribution before the onset of the thermoacoustic instability (solid line) and after stabilization of the acoustic wave (dotted line). Heat convection due to directional flow of fluid shifts the temperature distribution in the direction of the flow.

A more surprising result, where a double threshold has been observed during the amplification regime, is shown in Fig. 4. A first exponential growth of acoustic oscillations is followed by an intermediate quasi-stabilization regime (with wave amplitude slowly growing in time), which is followed before stabilization by another exponential amplification regime. This double threshold phenomenon occurs only for small ΔT increments (less than 12 K above the threshold), and characteristic times for the first and second amplification thresholds are increasing with diminishing ΔT.

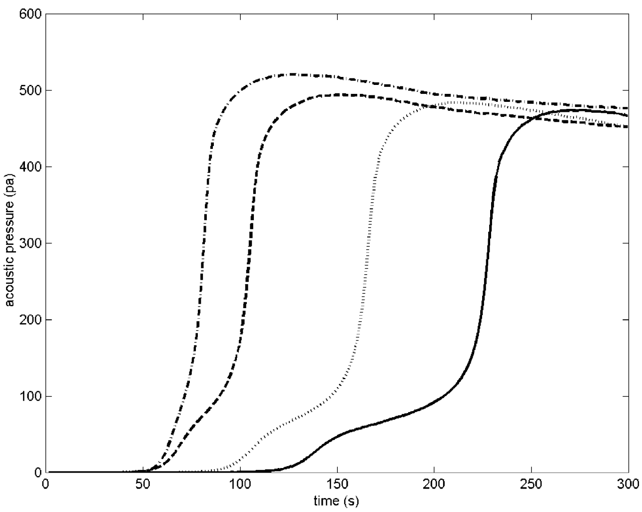

Fig. 4. RMS amplitude of the acoustic pressure at fundamental frequency during a double-threshold amplification regime, for different increments. Solid line: $\Delta T = 7$ K; dotted line: $\Delta T = 9$ K; dashed line: $\Delta T = 12$ K, dash-dotted line: $\Delta T = 14$ K.

The experimental results presented in Fig. 4 were obtained before the instrumentation of the stack with multiple thermocouples. After the installation of the thermocouples, the range of temperature increments ΔT, where the double-threshold effect was observable, shrinked from $\Delta T \leqslant 12$ K to $\Delta T \leqslant 2$ K. The distance between the stack and the heat exchangers was modified, perhaps, in the process of the thermocouples installation. However, at the current stage of the work, we can neither precisely identify nor control the parameters responsible for the change in ΔT. The temperature distribution evolution for a double threshold transient regime measured after the instrumentation of the stack with thermal sensors, and corresponding to a ΔT increment of 1 K, is shown in Fig. 5. The transient regime duration is then up to 40 min. For a better readability, only four temperature signals are presented. The values T1, T3, T6, T8 at the vertical axis represent the measured temperatures at distances $x = 0, 2H/7, 5H/7$ and $x = H$ away from the cold end of the stack, respectively. The acoustically induced directional mass flow results in

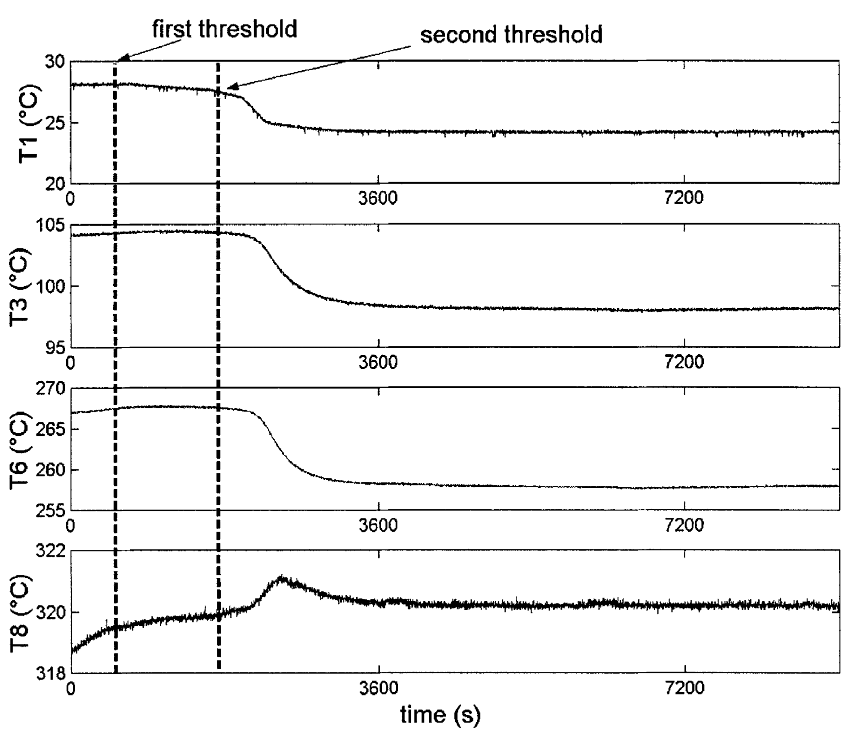

Fig. 5. Temperature evolution versus time during a double-threshold amplification regime. The values T1, T3, T6, T8 at the vertical axis represent the measured temperatures at distances $x = 0, 2H/7, 5H/7$, and $x = H$ away from the cold end of the stack, respectively.

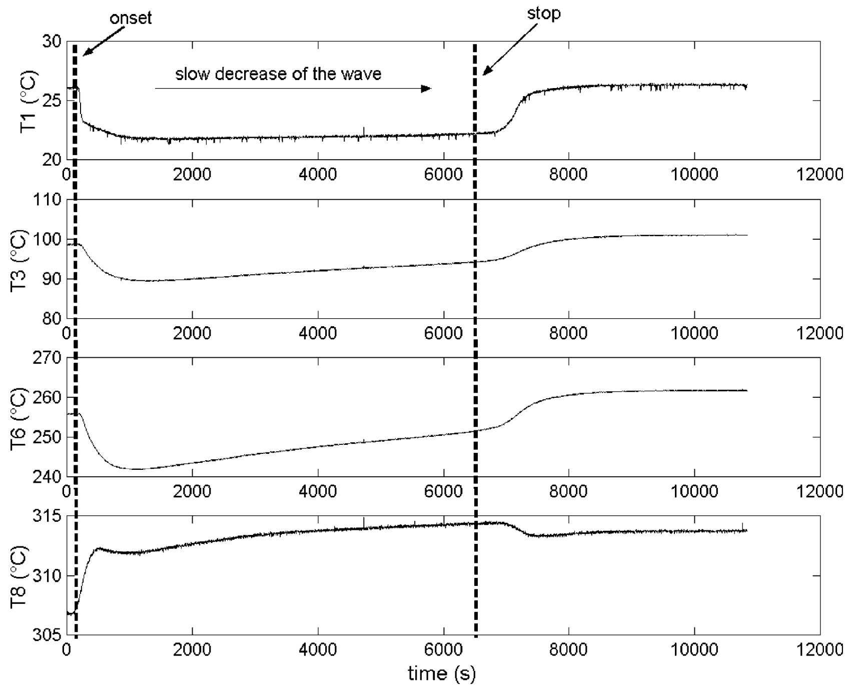

Fig. 6. Temperature evolution versus time during an onset regime followed by a spontaneous turn off of the prime-mover. The values T1, T3, T6, T8 at the vertical axis represent the measured temperatures at distances $x = 0, 2H/7, 5H/7$, and $x = H$ away from the cold end of the stack, respectively.

an important decrease of temperatures along the stack except for the sensor placed on the hot end of the stack. Indeed, this measured temperature increases by about 2 K, whereas the initial ΔT increment (relative to reference thermal sensor) was only 1 K. Concerning the possible inhomogeneity in the radial temperature distribution, measurements show a 1 K difference between the thermocouple placed on the resonator axis (at a distance $x = 4H/7$ away from the cold end of the stack) and the sensor placed at 20 mm from the resonator axis.

Earlier experiments [6] made on standing wave devices report the possibility under some heating conditions to observe a periodic turn on and turn off regime. As shown in Fig. 6, our observations confirm the possibility for the traveling-wave prime-mover to turn off spontaneously. Four temperature signals are presented versus time. For this experiment, the control parameter ($T_h - T_c$) was initially set 10 K below the onset, and a 10 K increment is applied. Fig. 6 demonstrates that the temperature distribution along the stack does not reach stabilization until the turn off of the acoustic wave.

4. Discussion

Preliminary estimates demonstrate that the observed effects cannot be entirely attributed to classical nonlinear acoustic and minor loss phenomena [6–9] even at the highest level of pressure oscillations in our experiments (i.e. above the second threshold). Energy dissipation due to superharmonics excitation (with their subsequent absorption) and due to vorticity generation (in the regions of the resonator cross-section variation) is insufficient to compensate completely net thermoacoustic amplification. Additional mechanisms of the acoustic wave self-action should be taken into account. One of the possibilities is a modification of the temperature distribution in the resonator by the acoustic streaming [3,4,13], which might lead to diminishing of the thermoacoustic amplification and saturation of the instability. Transient changes in temperature distribution were observed in our experiments. The estimates indicate that this mechanism can provide contribution to transient processes near the second threshold and might play the major role near the first threshold, where the acoustic and minor loss nonlinearities are negligible. It should be mentioned as well that temperature distribution can be also modified directly by acoustic energy dissipation both in the boundary layers and in the regions of minor loss localization. This might provide an additional mechanism of the acoustic wave self-action.

Currently we believe that the observed intriguing double-threshold effect has an intrinsic link to the phenomena of bistability (and multistability) theoretically predicted for standing wave acoustic resonators with strong coupling between thermal and acoustic fields [16]. Bistability is a general concept for the description of any system possessing two different steady-state operation regimes for the same value of control parameter. The related to bistability phenomenon of the acoustic intensity self-oscillation was observed experimentally in the system filled with a fluid exhibiting strong dependence of sound velocity on temperature [17], and also in standing-wave thermoacoustic prime-mover [6]. The observation of the related to bistability phenomenon of hysteresis in turn-on and turn-off of the standing-wave thermoacoustic engine was also reported [18]. All these phenomena are finally due to inverse influence of temperature field on sound propagation and sound attenuation/amplification, while the temperature field itself is modified by sound absorption, acoustically induced additional thermal conductivity, and acoustic streaming. Note that in the resonators the temperature distribution and streaming have also influence on acoustic wave backscattering and, consequently, have influence on the coupling between acoustic waves travelling in opposite directions. This modifies the structure of the internal modes of the resonator.

5. Conclusion

The double threshold effect has been observed for the first time in the thermoacoustic engine. It consists in the final stabilization of the thermoacoustic instability through two separated in time successive regimes of the exponential growth of acoustic oscillations. In the thermoacoustic devices the nonlinear phenomena are more complicated in comparison with those in “empty” resonators because of spatial inhomogeneity provided by stack heating. In annular thermoacoustic devices new nonlinear phenomena are stimulated by the existence of the closed loop for the acoustic streaming carrying nonzero mass flow. The development of an adequate theory describing transient interactions between acoustic and temperature fields in moving inhomogeneous medium is challenging.

Acknowledgements

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