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Numerical simulation on onset characteristics of traveling-wave thermoacoustic engines based on a time-domain network model

K. Wang, D.M. Sun*, J. Zhang, J. Zou, K. Wu, L.M. Qiu, Z.Y. Huang

Faculty of Engineering, Zhejiang University, Hangzhou 310027, PR China

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ABSTRACT

Onset characteristics of thermoacoustic engines are of great importance for understanding the internal working mechanisms of thermoacoustic conversion. A one-dimensional time-domain network model for predicting the onset characteristics of traveling-wave thermoacoustic engines with helium as working gas is built. The acoustic resistance, inertance, compliance, and thermal-relaxation effects of all the acoustic components are included. The viscous and heat transfer terms in the time-domain governing equations of the acoustic tubes and the heat exchangers are deduced from the frequency-domain linear thermoacoustic theory. Combining the time-domain governing equations of the regenerator, numerical simulations of the whole onset process are then conducted in a wide operating condition range. The complete dynamic pressure wave evolution processes are simulated successfully. It is shown that a steady standing-wave acoustic field forms in almost all parts of the traveling-wave thermoacoustic engine except for the regenerator area. Onset temperature, operating frequency, and quality factor are calculated with a relatively high accuracy. The thermal relaxation effects in the regenerator are found to have a remarkable impact on the onset characteristics, especially at high mean pressures. It is also shown that the experimental damping temperature is closer to the calculated onset temperature than the experimental onset temperature. Furthermore, the reasonable distributions of the pressure and volume flow rate and the phase relationship between them in the whole system are obtained and analyzed.

1. Introduction

Thermoacoustic engines are capable of converting thermal energy into acoustic power with comparable efficiencies as that of conventional heat engines [1]. Due to the unique feature of no moving mechanical components, thermoacoustic engines have great advantages of simple structure, high reliability, and low costs. Thermoacoustic engines can be classified into standing-wave [2–10] and traveling-wave types [11–14] based on the differences in configuration and working mechanism. Standing-wave thermoacoustic engines have simpler structures but lower efficiencies due to the intrinsically imperfect heat transfer in the stacks. The energy conversion process in a traveling-wave thermoacoustic engine takes place reversibly based on a good thermal contact between gas and porous solids in the regenerator. As a result, traveling-wave thermoacoustic engines work more efficiently and are more promising in the practical applications compared to their standing-wave counterparts [12,15].

During the past decades, great efforts have been made to reveal the working mechanisms and improve the performance of thermoacoustic engines. Linear thermoacoustic theory [16] is now widely adopted to design thermoacoustic engines and predict the performances of them operating at steady states. However, as the control equations are linearized in the frequency-domain, transient processes in thermoacoustic systems can not be simulated by linear thermoacoustic theory, which obscures important time-domain information of thermoacoustic effect.

Onset process indicates the spontaneous transition of the working gas in a thermoacoustic engine from the stationary to a periodic oscillating state when a sufficient temperature gradient is established along the stack or regenerator. The pressure amplitude in the system then grows until it gets saturated when an energy balance between acoustic generation and dissipation is reached. The nonlinear behaviors of thermoacoustic engines in onset process are of great importance for better understanding thermoacoustic phenomenon. Besides, onset temperature, i.e. the lowest heating temperature required to excite the oscillations, is also an

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* Corresponding author. Tel./fax: +86 571 87952769.
E-mail addresses: wangkai7089@gmail.com (K. Wang), sundaming@zju.edu.cn (D.M. Sun).

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important parameter because it determines the lowest grade of heat that a thermoacoustic engine can harvest.

Previous numerical calculations mainly focused on the onset characteristics of standing-wave thermoacoustic engines [17–26] due to the much simpler configuration and earlier invention of them. However, much less numerical work has been done to characterize the onset process of traveling-wave thermoacoustic engines. Lycklama et al. [27] and Yu et al. [28] performed axisymmetric 2D simulations of traveling-wave thermoacoustic engines by using commercial computational fluid dynamics (CFD) softwares in 2005 and 2007, respectively. Onset temperature and nonlinear pressure amplification were obtained. However, a special topological transformation should be made to turn the original configuration into an axisymmetric 2D model, which introduces the extra difficulties for the modeling and adds uncertainty for the prediction of onset parameters. The long computational time and huge resources required by CFD methods are also big problems. In 2009, de Waele [29] proposed a simplified thermodynamic model for the simulation of onset condition and transient effects in traveling-wave thermoacoustic engines. All components were treated by lumped parameter method and losses in the pipes were represented by an arbitrarily given resistance load, which diverges much from the real system. Up to now, it still lacks an efficient and accurate time-domain model for the simulation of the onset and transient characteristics of traveling-wave thermoacoustic engines.

In this paper, a one-dimensional time-domain thermoacoustic network model capable of calculating the onset temperature and the simulation of dynamic onset process is proposed. Nearly all the thermoacoustic effects, including resistance, inertance, compliance, and thermal-relaxation, are considered in the acoustic tubes and the heat exchangers. Effects of the thermal relaxation effects in the regenerator on the onset characteristics are studied with two different treatments of the continuity equations for the regenerator. The complete time-domain differential equations for an entire traveling-wave thermoacoustic engine are first given, and the discretization method as well as the algorithm are further presented in detail. The overall evolutionary onset process, the onset temperature, the operating frequency and the quality factor are then obtained, which are then verified by experimental results.

2. Mathematical model

2.1. Geometry parameters

Fig. 1 shows the schematic diagram of the traveling-wave thermoacoustic engine used in the model and the experiments [12]. The engine is composed of a hot heat exchanger (HHX), a stacked-screen regenerator, a main ambient heat exchanger (AHX), a secondary ambient heat exchanger (2nd AHX) and a few tube components. As the oscillating flow generates a second order mean flow around the loop, i.e. Gedeon streaming, which is harmful to the performance, an elastic membrane is placed above the main AHX to totally suppress it. The main AHX is of shell-and-tube type with working gas flowing inside the thin tubes. The total number and inner diameter of the tubes are 301 and 2 mm, respectively. The regenerator is filled with stainless steel screens with a porosity of 0.777 and a hydraulic radius of 52.4 μm. The HHX is of fin type with a porosity of 0.361 and the fin spacing is 1 mm. The 2nd AHX is also of shell-and-tube type; the inner diameter of gas tubes is 3 mm; the total porosity is 0.179. The main geometric parameters of the components are given in Table 1.

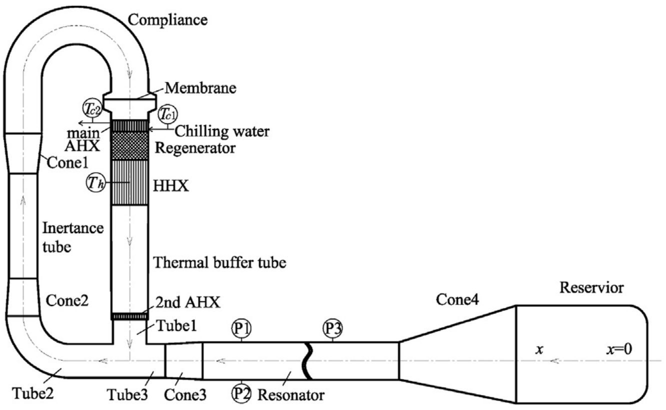

Fig. 1. Schematic diagram of traveling-wave thermoacoustic engine.

2.2. Governing equations

The model in this study is based on the following assumptions and simplifications:

1) The period of pressure wave is much shorter than the growth time of the onset instability, which can be commonly met in practice.
2) Time dependent oscillation variables except for velocity, such as the fluctuation pressure, temperature, etc., are much smaller than their average values. The time dependent oscillating velocity is much smaller than the speed of sound.
3) Linear temperature profile is assumed along the regenerator and thermal buffer tube. Axial thermal conductions through the regenerator matrix and the walls are ignored.
4) The source term arising from the temperature gradient of the thermal buffer tube is considered to be small enough to be ignored in the continuity equation.
5) The elastic membrane is not included in the model. The cavities above and below the membrane are all treated as ducts with the same diameter as that of the compliance.
6) Laminar flow is assumed during the whole onset process.
7) No acoustic streaming occurs in the system.

2.2.1. Ducts and heat exchangers

The duct components include the compliance tube, inertance tube, resonator, reservoir, and the connecting tubes, etc. As the hydraulic radius is much larger than the thermal penetration depth

Table 1
Geometric parameters of traveling-wave thermoacoustic engine and the grid number used in computation.

Component	Inner diameter/m	Length/m	Grids
Tube1	0.09	0.126	3
2rd AHX	0.09	0.02	1
Thermal buffer	0.1	0.291	7
HHX	/	0.12	2
Regenerator	0.09	0.074	10
AHX	/	0.056	2
Compliance	0.1	0.6767	10
Cone1	/	0.1	2
Inertance tube	0.076	0.28	6
Cone2	/	0.095	2
Tube2	0.09	0.295	5
Tube3	0.09	0.095	2
Cone3	/	0.1	2
Resonator	0.1	2.3	20
Cone4	/	1.31	11
Reservoir	0.261	0.52	5