International Journal of Heat and Mass Transfer 123 (2018) 367–381

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Theoretical and experimental investigation of the dynamic behaviour of a standing-wave thermoacoustic engine with various boundary conditions

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ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 23 January 2018
Accepted 28 February 2018

Keywords:
Thermoacoustic engine
Standing wave
Acoustic radiation
Deformable plate
Onset temperature
Onset frequency
Energy harvesting

ABSTRACT

This paper investigates the dynamic behaviour of a one-dimensional, standing-wave thermoacoustic engine with various boundary conditions. The thermoacoustic engine is composed of an acoustic tube and a ceramic stack with two heat exchangers. The tube has one end open and the other end closed with a deformable plate whose boundaries are constrained. Theoretical models are developed based on the acoustic wave equations and the linear theory of thermoacoutics and validated by experiment. With the validated theoretical models, a parametric study is performed to investigate the influence of the boundary conditions at both ends of the tube. It is found that acoustic radiation at the open end and the presence of the deformable structure at the closed end not only influence the onset temperature and frequency of the system, but also affect the acoustic field along the tube. The developed theoretical models and experimental method in this study provide useful guidelines for the design of thermoacoustic engines for potential energy harvesting systems.

1. Introduction

The thermoacoustic phenomenon concerns the coupling and interaction between thermal and acoustic fields. Devices utilizing thermoacoustic effects can convert heat into sound energy, or, in a reverse way, sound energy is consumed to pump heat. Therefore such devices are called thermoacoustic engines and refrigerators, respectively. Thermoacoustic engines offer many potential benefits such as low manufacturing and maintenance costs, no moving parts, and using inert gases as the working fluid. The first qualitative description of the thermoacoustic effect was given by Rayleigh [1] approximately 130 years ago, when he noted the importance of the phase relationship between fluid motion and temperature in order to maintain acoustic oscillation. Since then, there have been many analytical and numerical studies of the thermoacoustic phenomenon. In 1969, Rott developed an accurate theoretical analysis whose results were presented in a series of papers [2–6] and established the theoretical foundations from which the linear thermoacoustic theory was derived. Based on Rott's analysis, Swift [7–12] extensively advanced the linear theory to predict the power transmission inside various geometry pores and developed the well-known software DeltaEC (Design Environment for Low-amplitude ThermoAcoustic Energy Conversion) [13] that can help the user to design equipment to achieve desired performance.

The technology of thermoacoustics has been widely used in energy harvesting fields in the past decades. By connecting acoustic-to-electric transducers to the thermoacoustic engine, thermal energy, such as solar and waste heat energy, is converted directly into electricity. For example, Yu et al. [14] adopted loudspeakers as low-cost linear alternators for a thermoacoustic energy harvester, to convert acoustic power to electricity. In their work, the alternator was tested at different operating frequencies, cone displacements and load resistance values, and the measurements were discussed and compared in detail with the calculations based on the linear acoustics model. Luo et al. [15] developed a new kind of electricity generator by coupling the travelling wave engine with a linear alternator. It was reported that a maximum electric power of 1043 W with a thermal-to-electrical efficiency of 17.7%, and a maximum thermal-to-electrical efficiency of 19.8% with an electric power of 970 W were obtained in their experimental rig. A piezoelectric transducer was first used by Johnston et al. [16] to convert the acoustic oscillations of a Stirling engine into electric energy. The advantage of this system is efficient operation at high frequencies which in return has the potential of producing high-density power in compact, lightweight systems. Since then, a number of studies have attempted to evaluate various configurations of

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.121
0017-9310/

Nomenclature

C_{eff}	effective damping coefficient (kg/s)
c	speed of sound (m/s)
c_p	specific heat at constant pressure (J/kg K)
E	Young's modulus (kg/s^2 m)
E_k	kinetic energy (W)
f	thermo-viscous function
K_{eff}	effective stiffness (kg/s^2)
k	wave number (m)
k_f	thermal conductivity of fluid (W/m K)
L	length of tube (m)
M_{eff}	effective mass (kg)
p	pressure (Pa)
r_a	tube radius (m)
r_h	hydraulic radio
S	cross-section area (m^2)
T	temperature (K)
t_p	plate thickness (m)
U	volume velocity (m^3/s)
u	x component of velocity (m/s)
w_m	mean deflection (m)
w_r	deflection of plate (m)
x_l	left end of stack (m)
x_r	right end of stack (m)
Z	acoustic impedance (kg/m^{2}s)

Greek symbols

α	loss factor
γ	ratio of isobaric to isochoric specific heat
δ	penetration depth (m)
μ	dynamic viscosity (kg/s m)
ν	Poisson's ratio
ρ	density (kg/m^3)
σ	Prandtl number
ω	angular frequency (rad/s)

Subscripts

A	part A (hot buffer)
B	part B (stack)
C	part C (resonator)
k	thermal effects
s	solid
v	viscous effects

Abbreviations

Re	real part of a complex quantity
Im	imaginary part of a complex quantity

piezoelectric transducers employed in thermoacoustic engines (Symko et al.[17], Matveev et al. [18] and Nouh et al. [19,20]).

To date, there has been a variety of studies investigating the thermal and acoustic characteristics of a typical standing wave thermoacoustic engine closed with a rigid wall at one end and open at the other end. In the literature [21–26], the acoustic impedance at the open end of a standing wave engine was assumed zero for simplicity, that is, no acoustic radiation. In physical implementation, however, sound radiates from the open end of the engine into the surrounding medium [27]. In addition, in the thermoacoustic piezoelectric energy harvester, the boundary at the closed end of the resonator is not a rigid wall, but a flexible substrate bonded with a piezo-element. In [19,20], the flexible piezoelectric plate was modelled as a moving rigid piston. Such an approximation does not account for the practical application where the flexible endplate deforms non-uniformly over the cross-section. For piezoelectric energy harvesting, such deformation is required to deform the piezoelectric diaphragm and hence harvest electrical energy. The coupling between the deformable endplate and the working gas inside the tube remains unclear. Therefore, the objectives of this study are to investigate the impact of acoustic radiation and deformable boundaries on the dynamic behaviour of a standing-wave thermoacoustic engine.

This study focuses on the theoretical modelling and experimental investigation of a standing-wave thermoacoustic engine with different boundary conditions and aims to provide some guidelines on the potential design of energy harvesting systems based on thermoacoustic engines. The rest of this paper is structured as follows: Section 2 presents the theoretical analysis of the standing-wave thermoacoustic engine with various boundary conditions. Section 3 introduces the experimental rig and process. The theoretical performance and experimental results of the thermoacoustic engine are discussed in Section 4. Section 5 provides concluding remarks drawn from this study.

2. Theoretical modelling and analysis

2.1. Model of the standing-wave thermoacoustic engine

A simple standing-wave thermoacoustic engine is composed of an acoustic resonator tube, a hot buffer and a stack with a hot heat exchanger at one side and a cold heat exchanger at the other, as illustrated in Fig. 1. The acoustic resonator is assumed to have a cylindrical cross-section with rigid walls with an internal radius r_a, and terminated at $x = L$ with an open end. The left end of the hot buffer is closed with a circular deformable plate, which is here assumed to be clamped at its edges. This is motivated by the advantage of directly utilizing the acoustic energy from large-amplitude pressure oscillations at this end, as opposed to, for example, a large Helmholtz cavity to the open end of the resonator as was adopted in [19,20]. The stack is made up of parallel ceramic plates and placed near the left end of the tube. A temperature gradient is maintained along the stack plates by the hot and cold heat exchangers (not shown in the figure) at the left and right sides of the stack. When the thermoacoustic instability occurs inside the tube, a high-amplitude acoustic field is established and acoustic radiation occurs at the open end of the resonator. Note that the

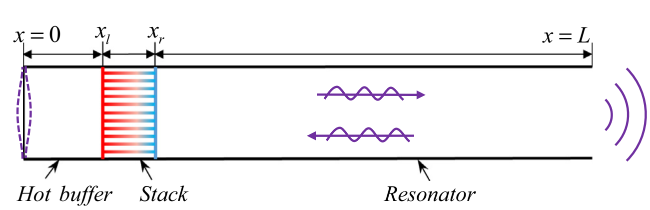

Fig. 1. A simple standing-wave thermoacoustic engine.