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Exergetic optimization of a thermoacoustic engine using the particle swarm optimization method

Hussein Chaitou *, Philippe Nika

Institut FEMTO-ST/UMR CNRS 6174, Parc Technologique, 2, Avenue Jean Moulin, 90000 Belfort, France

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ABSTRACT

Thermoacoustic engines convert heat energy into acoustic energy. Then, the acoustic energy can be used to pump heat or to generate electricity. It is well-known that the acoustic energy and therefore the exergetic efficiency depend on parameters such as the stack's hydraulic radius, the stack's position in the resonator and the traveling–standing-wave ratio. In this paper, these three parameters are investigated in order to study and analyze the best value of the produced acoustic energy, the exergetic efficiency and the product of the acoustic energy by the exergetic efficiency of a thermoacoustic engine with a parallel-plate stack. The dimensionless expressions of the thermoacoustic equations are derived and calculated. Then, the Particle Swarm Optimization method (PSO) is introduced and used for the first time in the thermoacoustic research. The use of the PSO method and the optimization of the acoustic energy multiplied by the exergetic efficiency are novel contributions to this domain of research. This paper discusses some significant conclusions which are useful for the design of new thermoacoustic engines.

1. Introduction

The thermoacoustic energy conversion is interpreted as the thermodynamic interaction of a compressible moving oscillating fluid with a solid wall which has a temperature gradient in the direction of the oscillation. During the displacement of the fluid, the variations of the pressure within the fluid generate heat transfers with the wall of the solid, constituting the stack or the regenerator of the thermoacoustic device. According to whether the fluid is heated or cooled during the phases of compression or expansion and according to the direction of its displacement, the fluid carries out a thermodynamic cycle which makes it possible to generate or consume mechanical/acoustic energy. When this energy is generated, the thermoacoustic device is called an engine or a prime mover, and when the energy is consumed, the thermoacoustic device is called a refrigerator or a heat pump. In the case of the thermoacoustic engines, the energy generated can thereafter be used to drive loads such as electrical generators or pulse tube refrigerators.

In fact, the thermoacoustic devices have many advantages. Firstly, these devices can use any external energy sources like solar energy, radio isotope sources, combustion of any fuel oil, biomass, hot gas downstream from cycle, etc. Secondly, these devices do not contain any moving part except the driven loads in the devices coupled to the thermoacoustic systems (for example, the electric production devices or the actuator of pressure used in the cooler devices). Hence, it is obvious that the thermoacoustic systems offer a high level of reliability and low maintenance requirements. Furthermore, as shown in Fig. 1, these devices basically consist of a stack (when using a standing-wave) and/or a regenerator (when using a traveling-wave), a cold and a hot heat exchanger, and a resonator. That is why the realization cost of these thermoacoustic systems is quite low comparing to other conventional systems. And last, but not least, these devices are also friendly environmental because they use a non-toxic working gas (air, helium, nitrogen, etc.).

The interest to thermoacoustic systems has been arisen and expanded since the early 1980s when Swift from Los Alamos National Laboratory and Garrett from PEN State University, whom can be regarded as the precursors in the field [1,2], have successfully worked and made the first practical thermoacoustic devices that produced a useful work.

Based on the works of Rott [3–9], Swift [10–12] has shown that the boundary functioning between thermoacoustic stack-based engines and heat pumps corresponds to a critical mean temperature gradient across the stack. When the value of the wall temperature gradient is higher than the value of the critical mean temperature gradient, the acoustic wave is created and the thermoacoustic device works as an engine (a prime mover). Moreover, when the value of the wall temperature gradient is less than the value of the critical mean temperature gradient, the acoustic work is consumed and the thermoacoustic device functions as a refrigerator (a heat pump).

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* Corresponding author. Tel.: +33 384578220; fax: +33 384570032.
E-mail address: hussein.chaitou@univ-fcomte.fr (H. Chaitou).

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Nomenclature

A	cross-sectional area (m^2)
c	speed of local sound ($m\,s^{-1}$)
c_0	speed of sound ($m\,s^{-1}$)
c_p	isobaric heat capacity ($J\,Kg^{-1}\,K^{-1}$)
f	frequency (Hz)
$\dot{H}_x$	total energy flux in the x direction (W)
k_0	wave number (m^{-1})
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_{eq}	equivalent thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	stack's length (m)
p	pressure (Pa)
Pr	Prandtl number
$\dot{Q}_x$	heat flux in the x direction (W)
r	gas constant ($J\,Kg^{-1}\,K^{-1}$)
r_h	hydraulic radius (m)
$\dot{S}$	entropy flux ($W\,K^{-1}$)
T	temperature (K)
t	time (s)
u	velocity ($m\,s^{-1}$)
$\bar{u}$	volume flow rate ($m^3\,s^{-1}$)
$\dot{W}_x$	work flux in the x direction (W)
$\langle\rangle$	time-averaged
$\Re[]$	real part of
$\Im[]$	imaginary part of

Greek letters

α	thermal expansion coefficient (K^{-1})
γ	ratio, isobaric to isochoric specific heat
δ	penetration depth (m)
ε	porosity
ε_s	plate heat capacity ratio
ρ	density ($kg\,m^{-3}$)
λ_0	wave length (m)
η_{ex}	exergetic efficiency
η_{en}	energetic efficiency
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
τ	traveling–standing-wave ratio
ω	angular frequency ($rad\,s^{-1}$)

Subscripts

0	ambient
a	first order oscillation
g	gas
s	solid
t	thermal
v	viscous

Superscripts

$\bar{f}$	mean, space-averaged perpendicular to x of f
$\dot{f}$	time rate of f
$\tilde{f}$	conjugate part of f
f^*	dimensionless number of f

In addition to the two classes of thermoacoustic devices (engines and refrigerators), we can also classify each thermoacoustic devices as a standing-wave or traveling-wave (Fig. 1a and b respectively). In a standing-wave (stack-based devices), the phase between the oscillating velocity of the gas and the oscillating pressure is close to 90°, and the gas interacts with the stack's wall by a voluntarily imperfect thermal contact. While in a traveling-wave (regenerator-based devices), the phase is close to 0°, and the gas and the regenerator's wall are in very good thermal contact. In 1979, the American engineer Ceperley [13] has discovered that the Stirling machines are not other than traveling-wave thermoacoustic devices. In such a device, energy conversion efficiency can approach the theoretical maximum efficiency, i.e. Carnot efficiency, which depends only on the temperatures of both the hot and the cold thermal reservoirs. The prototypes achieved by Backhaus and Swift [14–18] of "thermoacoustic" Stirling machines have opened the way to the realization of increasingly powerful systems. The mini electric thermoacoustic generator produced by Backhaus et al. [19,20] for NASA offered already an electric output power of 58 W with a total efficiency of 18%, thus approaching the 25% of the efficiency of the gasoline engines with internal combustion (efficiency of the sink to the wheels).

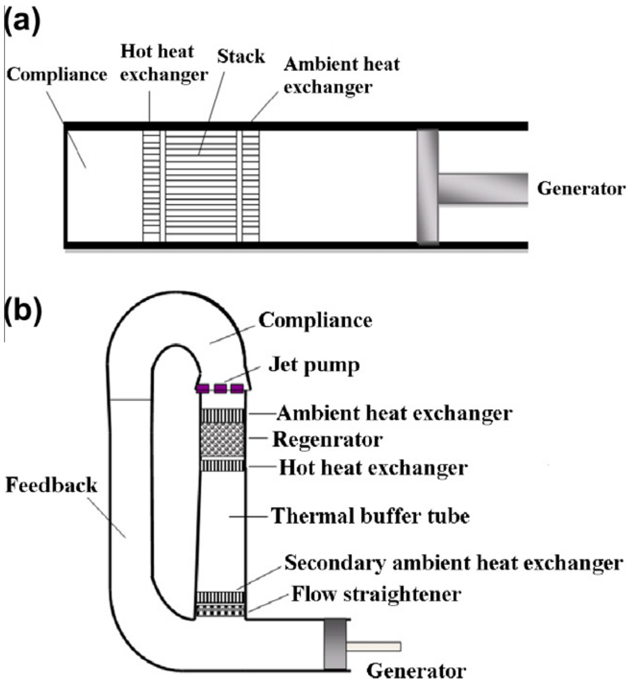

Fig. 1. General structure of a thermoacoustique engines: (a) standing-wave; (b) traveling-wave.

At the present time, thermoacoustic systems, either the engines or the refrigerators, do not reach sufficient exergetic efficiency (the ratio between the system conversion efficiency and the theoretical Carnot efficiency). The most values of output exergetic efficiency usually published are between 10% and 20%, and at best 30%, but an objective of 40% seems however to be realistic if the various sources of energy dissipations or degradations are identified and decreased. For example, in the pulse-tube refrigerators, one can avoid using devises, such as long capillaries, in order to realize the phasing between the pressure and volumetric velocity oscillations, because these are acoustic impedances, which represent a degradation source for the acoustic power. However, one can replace these impedances by adding a feedback acoustical loop to the acoustic network in order to recycle a large part of the acoustic energy carried out from the regenerator back into its entry. But, by doing this, one open the door to other categories of acoustic energy degradations which are named "streaming flows". However, it is