Energy Conversion and Management 110 (2016) 135–141

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A novel method for improving the performance of thermoacoustic electric generator without resonator

Yufang Wang [a], Zhengyu Li [b,*], Qing Li [b]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

[b] State Key Laboratory of Technologies in Space Cryogenic Propellants, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 22 July 2015
Accepted 28 November 2015
Available online 24 December 2015

Keywords:
Thermoacoustic heat engine
Electric generator
Linear alternator
Without resonator
Impedance modulation

ABSTRACT

A thermoacoustic electric generator without resonator designed for aerospace application is discussed in this study, which is developed by a traveling-wave looped-tube thermoacoustic heat engine coupling with two linear alternators directly. A novel method of filling phase modulation object in the acoustic power output port is proposed to improve the performance of the thermoacoustic electric generator. The experimental results show that the ellipsoid makes the most significant influence among sphere, cylinder and ellipsoid serving as phase modulation object. Varying the major axis of the ellipsoid only, the influence of it increases first and then decreases. The ellipsoid fixed in different positions makes different effects. The maximum output electric power of 73.31 W and the maximum system efficiency of 14.12% are obtained in the upper and middle positions respectively.

1. Introduction

Thermoacoustic technology serving as a new type of energy conversion is one of the most active research fronts in the present world. Thermoacoustic electric generation acting as an important application of thermoacoustic technology has made rapid development in recent years. Backhaus et al. [1] firstly carried out the research of traveling-wave thermoacoustic electric generator. This opened up a new direction for electricity generation aboard spacecraft. Wu et al. [2,3] designed a 200 W solar-powered thermoacoustic electric generator and a 3 kW three-cylinder double-acting thermoacoustic Stirling electric generator respectively. Zhao [4] designed a convection-driven Rijke–Zhao thermoacoustic-piezo system involving no heat exchangers and stacks, and the output electric power and energy conversion efficiency were increased by 60% and 105% respectively. Gonen et al. [5] developed a measurement method for precise determination of variable mechanical resistance on electro dynamic alternator efficiency. Kang et al. [6] designed a two-stage traveling-wave thermoacoustic electric generator with loudspeakers as alternators and a maximum electric power of 204 W was obtained. Hail et al. [7] validated the integration of the linearly-acting variable-reluctance generator into a thermoacoustic power converter for its high output power of 84 W and generator efficiency of 78%. Thermoacoustic electric generator (TAEG) mainly consists of a thermoacoustic heat engine (TAHE) and a linear alternator (LA). The acoustic power flowing out from the TAHE pushes the LA to do a reciprocating motion, and then electric power would be generated based on Faraday's law of electromagnetic induction. The TAHE converts high-temperature heat into acoustic power with a high efficiency based on thermoacoustic effect, which is resulted from the interaction between the oscillating compressible fluid and the solid material. In the traveling-wave TAHE, the gas parcel executes a Stirling-like thermodynamic cycle [8,9], so the thermal efficiency has been greatly improved. The thermoacoustic Stirling heat engine proposed by Backhaus et al. [10] attained a thermal efficiency of 30%, corresponding to 41% of the Carnot efficiency. In 2011, Tijani et al. [11] studied the same type of heat engine and obtained the highest thermal efficiency of 32%, corresponding to 49% of the Carnot efficiency. Using air or noble gas as working medium, absence of mechanical moving parts and utilizing low quality heat sources make it attracting a lot of attention for the advantages of environmentally friendly, high reliability, low cost and great potential. Swift [12] studied a 13-cm-diam thermoacoustic engine and obtained 630 W of acoustic power using 13.8 bar helium as working medium. Backhaus et al. [10] designed a thermoacoustic Stirling heat engine that could deliver 710 W of acoustic power. Yu and Jaworski [13], Liu et al. [14], Bo et al. [15] and Tourkov and Schaefer [16] discussed the effect of the regenerator on the efficiency of the TAHE from the acoustic impedance and volumetric velocity, the coincident effect characteristic in a

* Corresponding author. Tel./fax: +86 10 82543662.
E-mail address: lizhengyu@mail.ipc.ac.cn (Z. Li).

http://dx.doi.org/10.1016/j.enconman.2015.11.065
0196-8904/

Nomenclature

Abbreviations

LA	linear alternator
TAEG	thermoacoustic electric generator
TAHE	thermoacoustic heat engine

Symbols

A	cross-sectional area, m^2
Bl	transduction coefficient, N/A
E	acoustic power, W
I	electrical current, A
K	stiffness, N/m
L	inductance, H
M	moving mass, kg
p	pressure, N/m^2
P	electric power, W
Q	heating power, W
R	electrical/mechanical resistance, Ω/N s/m
t	time
u	velocity, m/s
U	volumetric flow rate, m^3/s
V	voltage, V
Z	impedance, N s/m^5
η	efficiency
ϕ	phase angle, °
ξ	displacement, m
ω	angular frequency, rad/s

Subscripts

ALT	alternator
b	behind
e	electric
f	front
h.net	net heat input
L	load
m	mean/mechanical
1	first order
2	second order

Supplementary notations

Re[]	real part of
$\sim$	complex conjugate
$\|\|$	magnitude of complex number
Δ	difference
i	square root of −1

thermoacoustic generator, a novel thermoacoustic regenerator using multi-temperature heat sources and the appropriate position of the regenerator respectively. Chaitou et al. [17] used the Particle Swarm Optimization method for the first time to research the exergetic optimization of a thermoacoustic engine. Blok [18] and Zhang and Chang [19] researched a four-stage thermoacoustic engine by experimental study and simulation respectively, and the simulation results showed great agreement with the published experimental data. Zhang et al. [20] studied and simulated a double-acting thermoacoustic heat engine used for dish solar power, and then they presented a new method of using displacer to suppress the jet-flow [21]. The LA is adopted to convert acoustic power into electricity for its high efficiency and reliability. Non-contacting clearance seal, with a clearance of 15 μm, between the piston and its cylinder wall requiring no lubrication is adopted by the LA, which can eliminate the contact wear and the pollution accompanying with it. The blade springs, formed by monolithic spring steel, could provide a powerful axial force for the reciprocating motion of the piston as well as a sufficient radial force to ensure the piston on neutral.

The impedance matching between the TAHE and the LA plays a significant role in the system performance from the viewpoint of acoustics. A perfect impedance matching could make the LA to be an optimal acoustic load of the TAHE, and then more acoustic power would flow into the LA and the system performance would be improved. This makes the impedance modulation becoming more meaningful and many researchers have been concentrating on it. Luo et al. [22] verified that the system did not work when the LA was directly connected to the TAHE without resonance tube, so the resonance tube was still used to perform the match between the LA and TAHE. Yu et al. [23] designed a low-cost electricity generator composed by an alternator in series with a traveling-wave looped-tube thermoacoustic engine in 2010. They connected a 37 cm long 'stub' tube to the resonator to improve the impedance matching. Next, they made the length of the 'stub' can be varied by moving a piston to obtain the fine tuning effect, and the electric power increases about ten-fold as the 'stub' length varies from 0 to 0.68 m [24]. Wu et al. [25], in 2011, studied the relationship between the output acoustic power characteristics of the engine and the load impedance to find the appropriate matching impedance for the engine, and then designed a LA to realize this impedance. In 2014, they charged 4.5% mole fraction argon gas into the system charged with helium to decrease the system operating frequency from 74 Hz to 64 Hz, so the impedance of the LA was matching with the proper output impedance of the engine [26]. In 2013, Sun et al. [27] studied the performance of a traveling-wave TAEG with a variable electric R–C load to optimize the load impedance. By adding an appropriate capacitance in the external circuit, the inductance caused by the LA winding could be basically counteracted. So the LA could roughly achieve an electrical resonant state. In 2015, Wang et al. [28] modified a pair of LAs with appropriate acoustic impedance and volume flow rate to couple with the thermoacoustic torus directly in numerical study.

In the ordinary TAEG, the TAHE is formed by a traveling-wave looped-tube linked with a long resonator. The onset and working frequency are mainly determined by the length of the resonator, and the LA makes a very little contribution to them. The impedance of the LA is only determined by its parameters. The TAEG discussed in this study is designed for aerospace application, so the mass and volume of the whole system should be minimized while obtaining the maximum output electric power. In this system, the traveling-wave looped-tube couples with the LAs directly, so it is called TAEG without resonator. The main differences between it and the thermoacoustic electric generator in Ref. [1] are that it uses rubber diaphragm and moving-magnet alternator replacing the jet pump and moving-coil alternator in Ref. [1]. Another, the working frequency of 90 Hz is different from that of Ref. [1], 120 Hz, because the size of the components and charging pressure are different. Its maximum size is about 0.45 m at an operating frequency of 90 Hz, while that of the TAEG with a long resonator would reach to about 4 m at the same operating frequency. The LAs replace the resonator not only decreasing the mass and volume of the system but also reducing the great nonlinear acoustic power dissipation caused by the resonator [27–30]. This makes the system becoming a resonant device. So its onset and operating frequency are determined by the TAHE and the LAs together, but the LAs play a decisive role.