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Numerical model-based prediction of performance of single stage traveling wave thermo-acoustic engines

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Abstract

In the recent past, attraction towards the new power generation technologies and thermal energy recovery have become exponentially increasing due to the environmental and economic concerns. Thermo-acoustic generation has been identified as an attractive novel technology for low-grade energy recovery and power generation. Only moving component of the thermo-acoustic generation system is the linear alternator, which is used to convert acoustic energy into electrical energy, and hence, it leads to increase the reliability of thermo-acoustic systems with comparative to the other power generation technologies. Traveling wave thermo-acoustic generators have higher efficiencies with respective to its counterpart, standing-wave thermo-acoustic generators. Traveling wave thermo-acoustic generators are much economical and less complex as it can be operated with ambient air at atmospheric pressure conditions as the working fluid. During this study, a single stage traveling-wave thermo-acoustic engine was modeled and validated using available test results in the literature. The validated model was used to predict the optimum working conditions for a traveling wave thermo-acoustic engine to obtain the maximum efficiency from the engine. Results show that the increment of temperature in hot heat exchanger tends to increase the efficiency of the system.

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Keywords: Thermoacoustic; Alternative energy; Waste heat recovery; Traveling wave acoustics

1. Introduction

Investigation on reliable, efficient and non-conventional power generation systems has become very popular over the decades due to the scarce of fossil fuel supply and the associated GHG (Green House Gas) emission from the combustion of the fossil fuels. When considering the conventional power generation techniques, they are mostly thermal to mechanical/electricity power conversion-based technologies [1]. But with the absence of moving parts, thermo-acoustic devices provide a great advantage over the other technologies in-terms of the reliability. Only

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Nomenclature

p_1	Pressure amplitude
ρ_m	Mean density
U_1	Volumetric velocity amplitude
A_{gas}	Cross sectional area of the gas channel
f_v	Spatially averaged viscous function
a	Sound speed
γ	Specific heat ratio
f_k	Spatially averaged thermal function
Pr	Prandtl Number
ε_s	Correction factor for finite solid capacity
H	Energy flow
c_p	Specific heat and constant pressure
A_{solid}	Solid cross-sectional area
k_{gas}	Thermal conductivity of gas
k_{solid}	Thermal conductivity of solid
T_m	Mean temperature

moving part of a thermo-acoustic generator is the linear alternator, which converts acoustic energy to electricity. As this technology is still in its infancy, it is difficult to differentiate their efficiency with comparative to the other well-established technologies [2]. There are two types of thermo-acoustic generators and are standing wave and traveling wave. In standing wave engines, the acoustic and pressure oscillations have a 90° phase difference while traveling wave engines do not have a phase difference. The efficiency of traveling wave systems is higher than standing wave systems and hence, this study focuses on the performance characteristics of the traveling wave thermo-acoustic generators [3].

There are various types of traveling wave thermo-acoustic engines and are, looped-tube traveling wave engine [4], multi-stage lopped-tube engines [5], Backhaus and Swift's torus type engine [6] and looped-tube engine with a bypass pipe [7,8]. Main components of a traveling-wave thermo-acoustic generator are hot heat exchanger, primary cold heat exchanger, regenerator, secondary cold heat exchanger, stub and the feedback loop (Fig. 1).

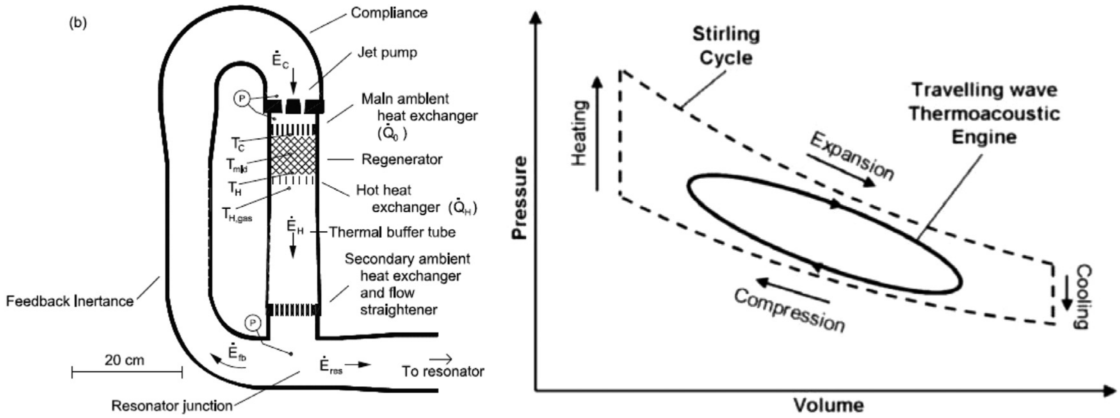

Fig. 1. Components of a thermo-acoustic engine [1] and schematic of the thermodynamic cycle on PV diagram [9].

Thermal energy to acoustic energy conversion of the thermo-acoustic generator takes place in the regenerator. Across the regenerator, a steep temperature gradient is maintained by the hot heat exchanger and the primary cold heat exchanger. In traveling wave thermo-acoustic devices, a good thermal contact (minimum temperature difference between fluid and the surface) has to be maintained among the fluid and the regenerator. The temperature of the regenerator surface and the gas layer near the regenerator surface have to be nearly equal to achieve this good thermal contact. It is obtained by ensuring that the channel size in the regenerator smaller than the thermal penetration depth for the fluid [8]. When designing the regenerator thermal penetration depth (thermal boundary layer thickness) and viscous penetration depth (viscous boundary layer thickness) of the fluid are important parameters which affect the performance. In thermo-acoustic generators temperatures of the heat exchanger and the pressure level inside the loop have been identified as the most significant parameters. Also Fig. 1 shows the P–v diagram of a thermo-acoustic engine.

Thermo-acoustic engines can be operated on various working fluids such as Helium, Nitrogen, Carbon dioxide (CO2) and ambient air [10]. The modeling work of this study is mainly focused on ambient air as the working fluid under the normal atmospheric pressure conditions. A numerical model has been developed using Design Environment for Low-amplitude Thermo-acoustic Energy Conversion (DeltaEC) platform and validated using the results published by McGaughy [11]. During the modeling work, the temperatures of the cold heat exchanger and the pressure levels inside the system has been varied and observed the variations in the acoustic pressure, acoustic volume flowrate and thermal to acoustic efficiency.

2. Modeling

Thermo-acoustic phenomenon was proposed by Kramers (1949) and Rott (1969–1980) by combining the theory of acoustic oscillations and thermodynamics. Later they proposed the theory of linear thermo-acoustic [12]. This concept was based on three basic equations continuity, momentum, and energy and, linearization of them with the following three main assumptions are: Radial acoustic power gradient across the tube is negligible; Average temperature and viscosity changes in radial direction is negligible and; Heat conduction in the axial direction and friction occurred by axial gradient are negligible. Based on the above theories following one dimensional equations can be obtained for continuity, momentum and energy [13]. Equations are given below.

$$\frac{dp_1}{dx} = -\frac{i\omega\rho_m}{(1-f_v)\,A_{gas}} \tag{1}$$

$$\frac{dU_1}{dx} = -\frac{i\omega A_{gas}}{\rho_m a^2}\left(1+\frac{(\gamma-1)\,f_k}{1+\varepsilon_s}\right)p_1 + \frac{f_k-f_v}{(1-\mathrm{Pr})(1-f_v)(1+\varepsilon_s)}\frac{U_1}{T_m}\frac{dT_m}{dx} \tag{2}$$

$$H = \frac{1}{2}Re\left[p_1\overline{U_1}\left(1-\frac{f_k-f_v}{(1-\mathrm{Pr})(1-f_v)(1+\varepsilon_s)}\right)\right] + \frac{p_m C_{p,m}|U_1|^2}{2A_{gas}\omega(1-\mathrm{Pr}\,|1-f_v|^2)}\frac{dT_m}{dx}$$
$$\times\, Im\left[f_k+\frac{(f_k-\widetilde{f_v})}{(1+\varepsilon_s)(1+\mathrm{Pr})}\right] - (A_{gas}k_{gas}+A_{solid}k_{solid})\frac{dT_m}{dx} \tag{3}$$

These equations must be integrated along x direction to obtain solutions for pressure, volume velocity and temperature values of system. For this study DeltaEC has been selected and numerical integration was conducted.

3. Methodology

DeltaEC provides a working environment where the components in the system can be individually added and each of them is connected with the sequence [14]. The loop length of the thermo-acoustic engine considered and modeled during this study is 5.4 m. The focus of this work is to obtain the performance variations which can be obtained using a single thermo-acoustic and identifying its sensitivity for various working conditions.

The considered system had a length of 5.4 m with 72 mm diameter pipes and the designed frequency was 54 Hz. The regenerator was from stacked stainless steel and spacing was 50 µm. Regenerator length was of 22.6 mm. the other parameters is shown in Table 1.

Model was validated with published works in literature and that was the basis of doing the sensitive parameter variation to obtain the performance characteristics [11]. As shown in Fig. 2, the error between the numerical and experimental results was calculated as around 8% for the pressure amplitude values. The same setup was used throughout the process and geometries were kept constant.

Table 1. Parameters of the thermo-acoustic engine.

Parameters	Hot heat exchanger	Ambient heat exchanger 1	Ambient heat exchanger 2
Porosity (%)	79.27	36.62	54
Length (mm)	14.5	22.2	29

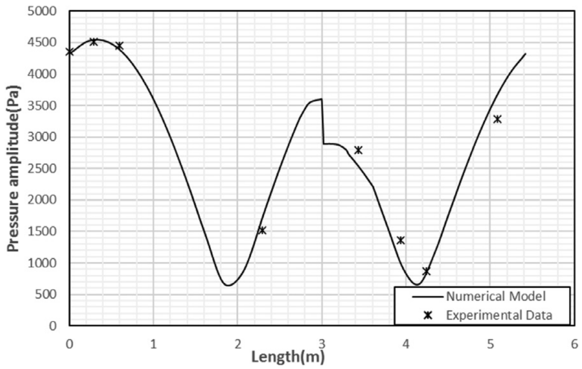

Fig. 2. The results comparison of numerical model and experimental data from McGaughy [11].

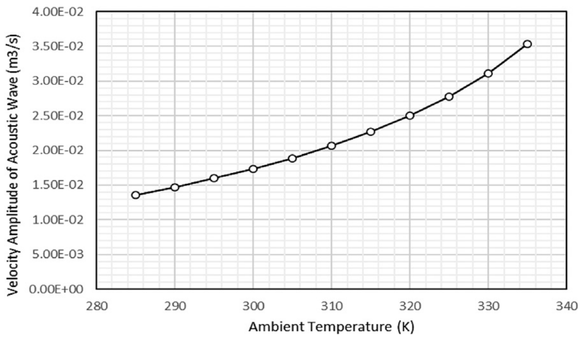

Fig. 3. Volumetric velocity amplitude variation with ambient temperature.

4. Results

Using the numerical model, pressure amplitude, mass, acoustic wave volumetric amplitude and efficiency variation were obtained for considered ambient (cold heat exchanger) temperature levels and pressure levels. The effect of variation in ambient temperature for volumetric flowrate, pressure amplitude, and efficiency (Figs. 3–5) is shown and, the variation in Acoustic (E_{dot}) and Total (H_{dot}) power under considered temperature conditions is shown in Fig. 6.

The performance of the thermo-acoustic generator for different internal pressures were considered during this study. The internal pressures were varied from 101.325 kPa to 201.325 kPa. In this scenario the ambient pressure inside the loop has been varied while maintaining constant temperatures at cold (295 K) and hot (1110 K) heat exchangers.

5. Discussion

As shown in Figs. 3 and 4, the main characteristics of the traveling acoustic generator are pressure amplitude and the volumetric flowrate. From the results it is clear that the pressure and volumetric flowrate are increased with the increment of the ambient air heat exchanger temperature. In Fig. 6 power variations with the position in the thermo-acoustic engine can be observed and the places where the power increments and decrements occur can be identified. 1–2 shows the ambient heat exchanger 1 and 2–3 is the regenerator part. 3–4 is the hot heat exchanger.

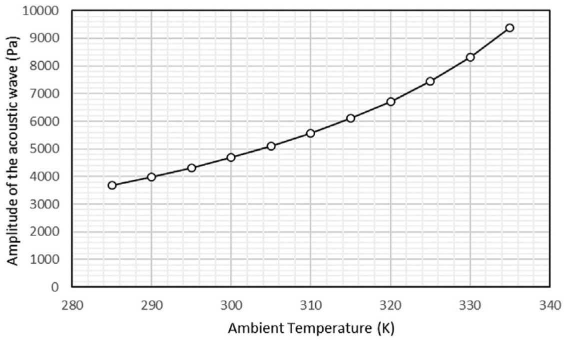

Fig. 4. Pressure amplitude variation with ambient temperature.

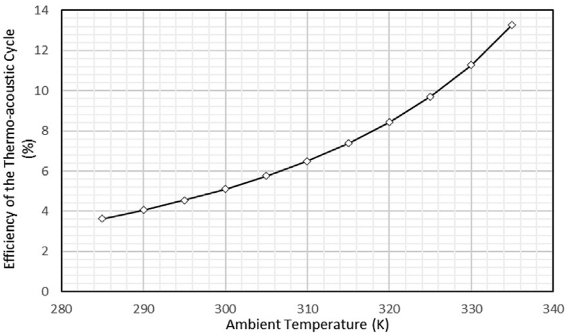

Fig. 5. Efficiency variation with ambient temperature.

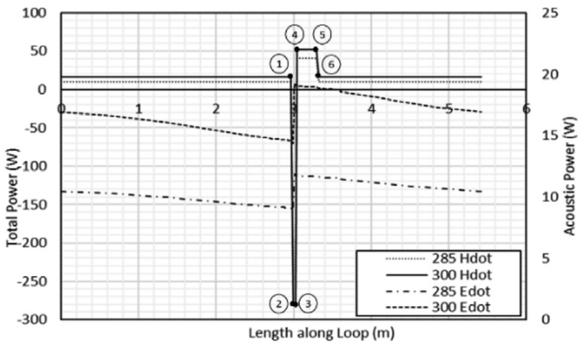

Fig. 6. Power along the loop for different temperature conditions.

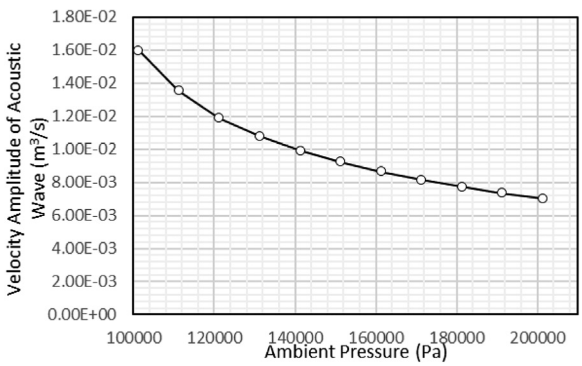

Fig. 7. Velocity amplitude variation with ambient pressure.

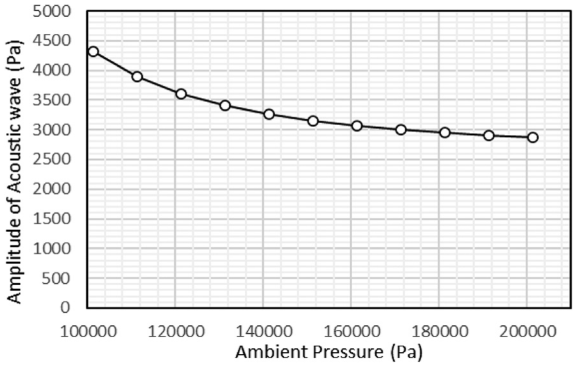

Fig. 8. Pressure amplitude variation with ambient pressure.

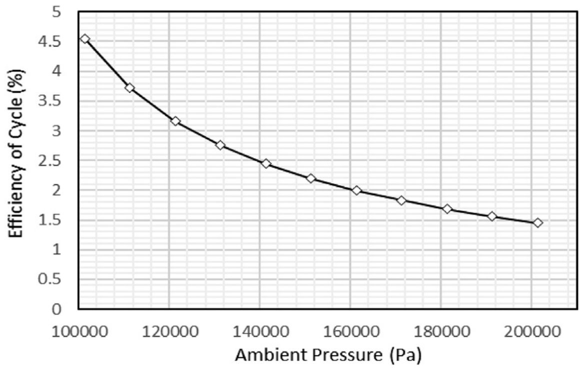

Fig. 9. Efficiency variation with ambient pressure.

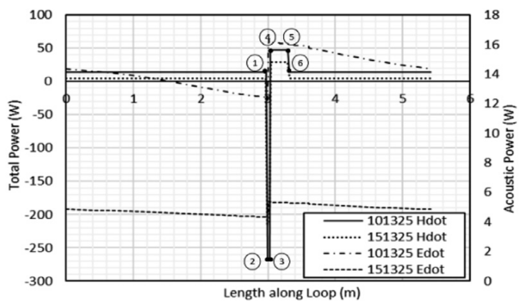

Fig. 10. Power along the loop for different pressure conditions.

And the 5–6 part is the ambient heat exchanger part. This information would be used in designing and analyzing thermo-acoustic engines.

The energy transfer in the thermo-acoustic generator shows a steep drop in ambient heat exchanger 1(cold heat exchanger). After the regenerator, the total power is increased while converting a portion of total energy into acoustic energy. Secondary cold heat exchanger acts as the condenser of the heat engine and removes a certain amount of energy from the cycle. When considering the acoustic power, it can be clearly understood that the increment of acoustic power is caused by the regenerator due to the induced temperature gradient. When the ambient temperature is the amount of total power in the loop is increased while converting certain amount into the acoustic power.

Ambient pressure inside the loop is varied and Figs. 7 to 10 show the variation of the same properties discussed. Main observation shows an exponential decay of pressure amplitude and volumetric flow velocity. This leads in lowering the efficiency of the cycle. Moreover, the total and acoustic power given by the regenerator has been decreased when the ambient pressure is increased. Also, it has been observed that the frequency of the system linearly increases when the ambient temperature in the range considered for the study (285 K–335 K). Moreover, it was noted that the frequency does not show any significant changes when the pressure is varied in the considered range.

6. Conclusion

The study aims to obtain the performance variations of thermo-acoustic generators when the operational parameters (ambient pressure and ambient temperature) are varied. The model was first validated using the results in the literature and the validated model was used to predict the performance under different operational conditions. It was found that the efficiency of the thermo-acoustic cycle increases (3.6%–13.2%) increasing the temperature of the ambient heat exchanger (285 K–335 K) and decreases (4.54%–1.45%) when increasing the internal air pressure of the thermo-acoustic generator (101.235 kPa to 201.325 kPa).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Wu Z, Dai W, Man M, Luo E. A solar-powered traveling-wave thermoacoustic electricity generator. Sol Energy 2012;86(9):2376–82. http://dx.doi.org/10.1016/j.solener.2012.05.010.
[2] Iniesta C, Olazagoitia JL, Vinolas J, Aranceta J. Review of travelling-wave thermoacoustic electric-generator technology. Proc Inst Mech Eng A 2018;232(7):940–57. http://dx.doi.org/10.1177/0957650918760627.
[3] Backhaus S, Tward E, Petach M. Traveling-wave thermoacoustic electric generator. Appl Phys Lett 2004;85(6):1085–7. http://dx.doi.org/10.1063/1.1781739.
[4] Yazaki T, Iwata A, Maekawa T, Tominaga A. Traveling wave thermoacoustic engine in a looped tube. Phys Rev Lett 1998;81(15):3128–31. http://dx.doi.org/10.1103/PhysRevLett.81.3128.
[5] De Blok K. Novel 4-stage traveling wave thermoacoustic power generator. In: Am. soc. mech. eng. fluids eng. div. FEDSM, Vol. 2. 2010, p. 73–9. http://dx.doi.org/10.1115/FEDSM-ICNMM2010-30527.
[6] Backhaus S, Swift GW. A thermoacoustic-stirling heat engine: Detailed study. J Acoust Soc Am 2000;107(6):3148–66. http://dx.doi.org/10.1121/1.429343.
[7] De Blok K. Low operating temperature integral thermo acoustic devices for solar cooling and waste heat recovery. In: Proc. - Eur. conf. noise control, no. December. 2008, p. 3545–50. http://dx.doi.org/10.1121/1.2934526.
[8] Swift GW. Thermoacoustics: A unifying perspective for some engines and refrigerators: Second edition. 2017.
[9] Yu Z, Jaworski AJ, Backhaus S. Travelling-wave thermoacoustic electricity generator using an ultra-compliant alternator for utilization of low-grade thermal energy. Appl Energy 2012;99:135–45. http://dx.doi.org/10.1016/j.apenergy.2012.04.046.
[10] Li DH, Chen YY, Luo EC, Wu ZH. Study of a liquid-piston traveling-wave thermoacoustic heat engine with different working gases. Energy 2014;74(C):158–63. http://dx.doi.org/10.1016/j.energy.2014.05.034.
[11] Mcgaughy M. Design and analysis of a single stage, traveling wave, thermoacoustic engine for bi-directional turbine generator integration. 2018.
[12] Rott N. Thermoacoustics 1980;20(C).
[13] Yang R, Wang Y, Tan J, Luo J, Jin T. Numerical and experimental study of a looped travelling-wave thermoacoustic electric generator for low-grade heat recovery. Int J Energy Res 2019;43(11):5735–46. http://dx.doi.org/10.1002/er.4670.
[14] Clark JP, Ward WC, Swift GW. Design environment for low-amplitude thermoacoustic energy conversion (DeltaEC). J Acoust Soc Am 2007;122(5):3014. http://dx.doi.org/10.1121/1.2942768.