Renewable and Sustainable Energy Reviews 68 (2017) 168–184

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Thermal models for analysis of performance of Stirling engine: A review

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ARTICLE INFO

Keywords:
Stirling engine
Isothermal model
Finite Time Thermodynamic
PSVL thermal model
Finite speed thermodynamics

ABSTRACT

This paper demonstrates a detailed review of the performance of Stirling engine based on the thermodynamic methods like Finite Time Thermodynamic analysis, Finite speed thermodynamic analysis, Isothermal model, Non-ideal adiabatic method, CAFS: The Combined Adiabatic- Finite Speed Thermal Model and Polytropic analysis of Stirling engine with Various Loss mechanisms (PSVL) model are reported. The aim of the paper is to summarize overall research work being carried out worldwide on the thermodynamic performance evaluation of Stirling engine using different thermodynamic methods. In this paper, the conventional thermodynamic methods for GPU3 Stirling engine were compared. The outcome of this comparison revealed that PSVL was better than the other methods.

1. Introduction

The electricity consumption in the world is increasing fast, due to population growth, lifestyle standards evolution, and expansion of industries and economics [1]. Widespread use of fossil fuels has caused carbon dioxide pollution and global warming as a result [2].

There have been many studies in order to find alternative sources of energy and new energy conversion systems. Stirling engine is known as a high thermal efficient engine in comparison with other types of engines. Robert Stirling [3] has created the Stirling engine in 1816. The first period of the Stirling engine was finished by the rapid progress of internal-combustion engines and electric motors. The next period has been begun in 1930 s [4].

Stirling engine is capable to operate in a wide range of temperatures and with different fuels such as solar, bio-mass, waste heat *etc.* Compression and expansion of working fluids such as air, hydrogen, and helium in two chambers is the basis of Stirling engine. Two pistons with phase angle are utilized to transfer the working fluid among the spaces [5,6]. The robustness of the Stirling engines could be changed by different factors such as physical and thermal properties of the working fluid, heat transfer coefficient, and cold and hot sides' temperature difference, efficiency of regenerator, mechanical connections, charge pressure and ratio of impermeability [7]. At the present time, researchers try theoretically and experimentally to enhance the performance of the Stirling engines. Various sizes of Stirling engines up to 336 kW were manufactured by Philips company since 1937 [8].

The materials used in the engine, limit the operational temperature of the engine. Generally, the engines work between a 923 K heater and a 338 K cooler temperature [9]. The Engine efficiency of 30–40% would be achievable in a temperature range of 923–1073 K, in a speed range of 2000–4000 rpm [10].

In general three levels of modeling of Stirling engines can be found. The ideal analysis estimates the ideal theoretical performances of an engine with a zero or limitless convective heat transfer coefficient. The uncoupled analysis takes the outcomes of the ideal analysis and improves them, considering a specific number of losses and finite coefficients in the engine. The coupled analysis is based on a fine discretization of the engine in different control volumes, considering all the main losses.

This paper tries to go through the available thermal approaches for analyzing Stirling heat engines and compare the thermal efficiency and power of each models with experimental ones. Moreover, this paper discusses the error between model outputs and experimental ones and then selects the better thermal approach for analyzing thermal efficiency and power of the Stirling heat engine.

2. Stirling cycle engine

Closed cycle regenerative engine and the regenerative heat exchanger were invented by Robert Stirling. He built an engine which operated on the closed thermodynamic cycle. TS and PV graph illustrated in Fig. 1(a) is the Robert Stirling's engine cycle. Four processes of isothermal expansion and compression and isentropic heat rejection and addition consist the engine cycle..

A simple engine consists of a cylinder encompassing two opposite pistons with a regenerator between the pistons as illustrated in Fig. 1(b

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http://dx.doi.org/10.1016/j.rser.2016.09.033
Received 8 July 2015; Received in revised form 18 February 2016; Accepted 9 September 2016
1364-0321/

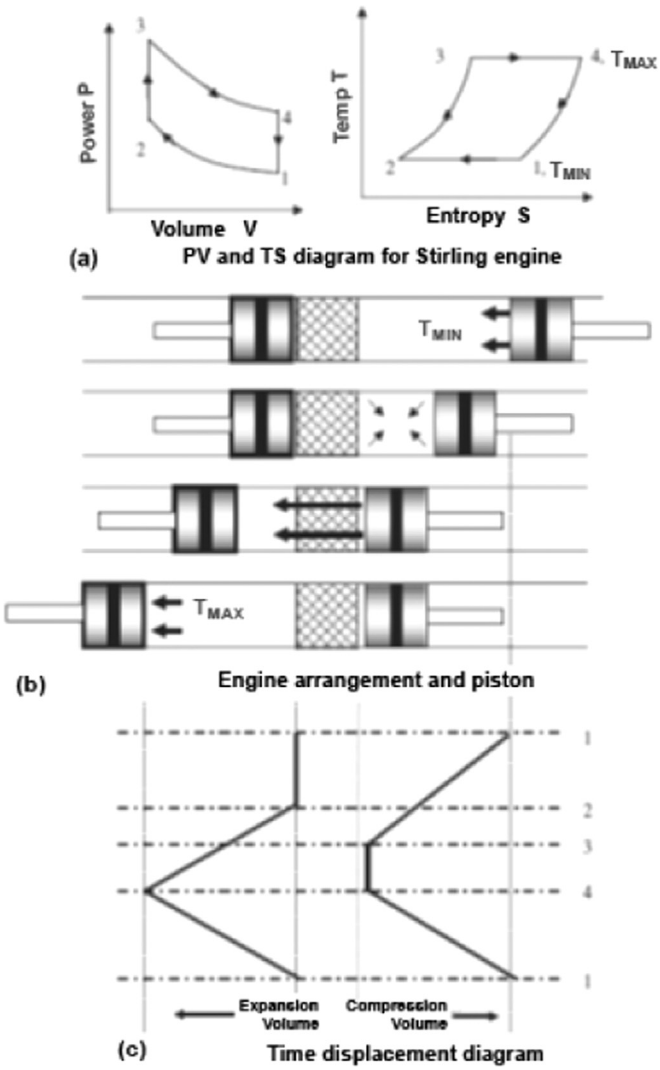

Fig. 1. The Stirling cycle [6].

and c). The regenerator releasing heat and acts as a thermal sponge absorbing. High temperature expansion volume is between regenerator and the right side piston is and low temperature compression volume is between regenerator and left side piston. The temperature gradient of (T_{max}-T_{min}) between two ends of the regenerator would be kept constant.

3. Engine configuration

The Stirling engine consists of two connected volumes with various temperatures via an auxiliary heat exchangers and regenerative heat exchanger. These volumes need to be changed periodically in order to carry out the heat transfer requirements, gas dynamic and thermodynamic of the engine. In order to change the volume exactly, a sufficient drive mechanism is needed. A complete record of promising engine arrangement is presented by Walker [11]. Each engine configuration would be compatible with specific drive mechanism, as all mechanisms are not suitable with every engine array.

The engine variables such as engine speed, pressure and displacement comprises the Beale number [12]. Some considerable parameters, during selection of suitable engine arrangement are listed by Gary Wood [13] (Sun-Power Corp). Senft [14] also revealed that the optimal engine structure should be designed based on the below engine variables:

Table 1
The classification levels of the engines.

(A) Mode of operation	
1. Double acting	
2. Single acting	
3. Multiphase	
4. Single phase	
5. Non-resonant	
6. Resonant	
(B) Forms of cylinder coupling	
1.Gamma coupling	
2.Beta coupling	
3.Alfa coupling	
(C) Forms of piston coupling	
(I) Rigid coupling	1.Rhombic drive
	2.Slider crank
	3.Crank rocker
	4.Swash plate
	5.Ross rocker
(II) Gas coupling	1.Free displacer
	2.Free piston
	3.Free cylinder
(III) Liquid coupling	1.Rocking beam
	2.Jet stream
	3.Pressure feedback

1. Type and size of regenerator
2. Burner/heater type
3. Engine mechanism
4. Displacer and piston construction
5. Engine cylinder layout/arrangement
6. Crankcase construction

Several the classification levels of the engines are reported through Table 1.

3.1. Mode of working

The Stirling engines are generally sorted in to two classes of double acting and single acting. In a single acting engine the working fluid contacts only with one side of the piston. The working fluid is circulated between the two cylinders. The single acting engine could be derived as single cylinder engines in a number of units set with a shared crankshaft and crankcase. Robert Stirling in 1815 was firstly introduced the single acting engine.

Babcock in 1885 was introduced the double acting Stirling engine [6]. Two sides of the piston are employed in the double acting engine for moving the fluid from one side to opposite. The necessity of connection of ducting to working spaces with regenerator has made double acting engines difficult to be arranged. Double acting engines are generally multi-cylinder engines, while at least three pistons are needed to differ the compression and expansion processes. The most advanced double acting Stirling engines are P series of United Stirling which firstly presented by Bratt [15]. A 40 kW four-cylinder double acting Stirling engine tested and designed with various working fluids and heater head temperatures by United Stirling. Finkelstein was studied several new sets for multi-cylinder process.

3.2. Forms of cylinder coupling

3.2.1. Alpha coupling

Alpha engine has two pistons in distinct cylinders, which are joined in series by a cooler, heater and regenerator which is depicted in Fig. 2. The Alpha engine is the modest Stirling engine arrangement; though, both pistons must to be sealed to hold the working fluid. Ross [16] investigated small air engines with novel Alpha designs, such as a balanced “Rocker-V” mechanism and the classical Ross–Yoke drive. The Alpha engine may also be combined with a packed multiple