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Designing a powered combined Otto and Stirling cycle power plant through multi-objective optimization approach

Mohammad H. Ahmadi [a,*], Mohammad Ali Ahmadi [b], Fathollah Pourfayaz [a,*], Hadi Hosseinzade [c], Emin Acıkkalp [d], Iskander Tlili [e], Michel Feidt [f]

[a] Department of Renewable Energies and Environmental, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran
[b] Department of Petroleum Engineering, Ahwaz Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Ahwaz, Iran
[c] Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, Tehran, Iran
[d] Department of Mechanical and Manufacturing Engineering, Engineering Faculty, Bilecik S.E. University, Bilecik, Turkey
[e] Mechanical Engineering Department, Engineering College, Majmaah University, Almajmaah, Saudi Arabia
[f] Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, ENSEM, 2, avenue de laForêt de Haye, Vandoeuvre, France

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A B S T R A C T

Throughout the recent years, several efforts have been conducted in studying Stirling engine which have yielded various models for analysis of Stirling engine thermal efficiency and output power. In the present study, the applicability of a combined Stirling and Otto cycle power plant where a Stirling cycle engine would serve as a bottoming cycle for a stationary Otto cycle engine is investigated. Output power of Stirling engine and Stirling engine thermal efficiency are optimized and total pressure losses of Stirling engine is optimized executing NSGA approach and finite speed thermodynamic analysis. The outcomes gained are satisfactory verified versus actual recorded data of Stirling engine. Decision making was performed via three well-known methods. Finally, error analysis was performed on the outputs obtained from this optimization.

Contents

* Corresponding authors.
E-mail addresses: mohammadhosein.ahmadi@gmail.com (M.H. Ahmadi), pourfayaz@ut.ac.ir (F. Pourfayaz).

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1. Introduction

A big issue for the near future of the societies is summarized to security of sustainable energy [1]. Huge amounts of investment should be paid to establish primary requirements of the renewable and environmental friendly energy sources and technologies [2–5], which consists of algae based or bio fuels, electricity generated by wind and solar energy and carbon dioxide (CO_2) capture, utilization and sequestration [6–16]. Thanks to this fact, toward better future from energy point of view, scrutinized planning should be performed with respect to the aforementioned prospect.

One of the prime original air cycles with standard for heat engines is Stirling cycle [17,18]. Advantages of Stirling engines are high efficiency and external heat source. Stirling engines can employ available solar energy during the day. The process combustion throughout the Stirling engine is continuous and can burn various kinds of fuel with no quality limitation [18–20].

Recently, some works at the DIT are employed a Stirling cycle engine as a bottoming cycle on a stationary Otto cycle engine to develop the theoretical novel combined cycle power generation system.

These power plants would find usage in small to middle level power generation settings. Recent work is described features of Otto engine systems from a technological point of view [21], and a procedure for analysis of the combined cycle energy system regarding an automotive setting [22] and several primary modeling outcomes for the aforementioned system [23,24].

The suggested model is established under the backgrounds of what are named Finite Speed Thermodynamics (FST) and Finite Time Thermodynamics (FTT). The ideas of FTT propose a hypothetical improvement of Classical Thermodynamics by employing the obligation of a finite time limitation on heat transfer from/to the system.

In general, Beginning of the approach is ascribed to the researches of Novikov and Chambadal [25,26], and a study by Curzon and Ahlborn [27].

The analysis and optimization of thermodynamic cycles for various optimization objectives have made great development applying FTT [28–37].

Studies on optimal performances of Otto cycle contain the three features: (i) the optimal performance when specific heats is constant; (ii) the optimal performance when specific heats is variable; (iii) the optimal performance when specific heat ratio is variable.

The Otto cycle is appropriately explicated throughout the previous works of Finite Dimensional Optimization Thermodynamics.

Angulo-Brown et al. extended in an advanced research to comprise an irreversibility factor within the cycle [39].

Moreover, Calvo Hernandez and colleagues [40] improved this approach for non-instantaneous adiabatic strokes. Ge and colleagues [41] presented thermodynamic simulation of an Otto cycle with considering the heat transfer throughout the system and various specific heats of the fluid of working.

Chen and colleagues provided details of the optimization of the Otto cycle regarding maximum power and maximum efficiency [42] and calculated corresponding relevant parameters.

Curto-Risso and colleagues [43–45] developed a finite time approach which comprises parameters of the engine speed-related irreversibility. The aforementioned approach is certified numerically and is illustrated to propose helpful correlation. Emission of carbon dioxide is a limitation of using fossil fuels in around the industries that stimulates evolvement of maximal electric energy and higher efficiency per 1 kg CO_2 emitted technologies [46,47].

By using Stirling cycles the CO_2 emissions to the atmosphere can be reduced. In this regard, one of the chief principal air cycles with standard for heat engines is Stirling cycle [48,49].

As noted previously, pros of Stirling engines are summarized to high efficiency and external heat source. Moreover, Stirling engines gain available solar energy through the day. Furthermore, the process combustion throughout the Stirling engine is continuous and can burn different kinds of fuel with no quality restrictions [50,51].

A numerical model with the lumped analysis method has been developed by Timoumi et al. In this model, irreversibilities in the Stirling cycle which are essential points in evaluation of Stirling engine's performance are considered in the analysis. This investigation and prior studies [53,54] have illustrated that these irreversibilities have a considerable impact upon the prediction of the performance of the engine. Recently, noticeable researches have been accomplished on these losses [57,58]. Costea et al. developed a precise model by taking into account internal irreversibilities consisted of the finite speed of the friction, throttling and piston in the regenerator of Stirling engines and demonstrated that the model is credible for a widespread range of Stirling engines. This category of irreversible thermodynamics is called "Thermodynamics with Finite Speed and the Direct approach". Ahmadi et al. optimized a powered Stirling engine by implementation of NSGA procedure [59].

Use of the Stirling cycle as a bottoming cycle has been studied also by several different parties, for example [60–64].

The Stirling cycle is usually established problematic to simulate and model, mainly owing to the conventional presence of a regenerator within the cycle and the prerequisite for comparatively complex heat exchangers at the sink and source.

Conventional approaches for modeling Stirling cycle are explained in Ref. [65–67]. In the previous works of Finite Dimensional Optimization Thermodynamics the cycle has possibly not gained from the similar interest as other cycles; though, substantial development is created.

Kaushik and Kumar have studied the endo-reversible Stirling cycle with presence for regenerative losses and for finite heat capacity of the external reservoirs [68]. Also they studied the influence of the robustness of the different heat exchangers, the inlet temperatures of external heat reservoirs on the thermal efficiency and the corresponding power output

Feidt and colleagues optimized heat exchanger stock for fixed heat transfer rate input or fixed power output [69]. Furthermore, Erbay and Yavuz investigated an optimization of the irreversible cycle with presence of polytropic processes [70,71].

Petrescu and colleagues performed a comprehensive study of the cycle using a finite speed [72]. Also, this approach is employed by Costea and colleagues [57] and Petrescu and colleagues [73–75] regarding solar thermal Stirling engines.

Multi-Objective optimization is diversely used in various complex engineering problems [76–78]. In this method, optimization of numerous goals is simultaneously satisfied which are sometimes in conflict with each other. Evolutionary algorithm (EA) inadvertently specifies some points in the possible area and finds a set of logical solutions in which all points satisfy the objective condition without being conquered by any other solution [79,80]. This assortment of feasible outcomes generates a vector of the best points (so-called Pareto frontier) which is a trade-off between objectives. Many researchers conducted a multi-objective optimization on diverse thermodynamic and energy systems [81–103]. Ahamdi et al. [81,82] applied non dominated sorting genetic algorithm for thermodynamic and thermo-economic optimization of Stirling heat pump. Ahmadi and colleagues [83] studied finite time thermodynamic analysis and optimization of performance of Otto cycle. Ahmadi et al. [84,85,87] developed an intelligent approach to figure power of Stirling heat engine by implementation of evolutionary algorithms. Sayyaadi et al. [90] applied non dominated sorting genetic algorithm for optimal design of a Solar-Driven Heat Engine. Sadatsakkak et al. [91] performed a thermodynamic and thermoeconomic analysis on Brayton engine to