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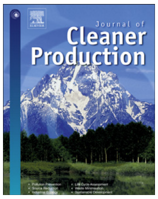

Thermal modeling of a trigeneration system based on beta-type Stirling engine for reductions of fuel consumption and pollutant emission

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A B S T R A C T

Energy recovery is one of the most important ways to clean production and reduce of carbon dioxide emission. Therefore, in this paper, a trigeneration system (combined cooling, heating and power or CCHP) is suggested to reduce fuel consumption and pollutant emission for building applications. The system consists of two beta-type Stirling engines as prime movers, a heat recovery system, an absorption chiller, and a power generator. The Stirling engine has been modeled based on a non-ideal adiabatic analysis in which the frictional and thermal losses of the engine have been considered using a developed numerical code. For model validation, the specifications of the GPU-3 Stirling engine have been used and the results have been compared with the experimental data and previous models. Moreover, the energy modeling of the absorption chiller has been performed using Stirling engine waste heat. Then, the effects of engine rotational speed, wall temperature of heater, and regenerator length on efficiency, fuel consumption, and carbon dioxide emissions reduction have been studied and the appropriate values have been presented. The results show that in these conditions, the appropriate values for the electrical efficiency and trigeneration efficiency are 27.31% and 74%, respectively. Furthermore, the fuel consumption and carbon dioxide emission of this system have been encountered with reduction of 31.83% and 38.44% in comparison with conventional energy systems for buildings of the same conditions.

1. Introduction

The thermal efficiency of the most power plants with fossil fuels which have only one prime mover is less than 40 percent. This means that more than 60 percent of the heating value of input fuel is lost in power plants (Ahmadi et al., 2012). This leads to higher fuel consumption and consequently a rise in carbon dioxide emission. One solution for increasing the efficiency, reducing the fuel consumption, and decreasing the carbon dioxide emissions, is the use of trigeneration (combined cooling, heating and power or CCHP) systems (Yousefi et al., 2017).

Currently, one of the most common type of prime movers is internal combustion engine because of the low installation and maintenance costs. But, these engines have disadvantages of low thermal efficiency, limited fuel types, and high amount of emission (Harrod and Mago, 2010). Stirling engines are external combustion engines that use a heat source to generate power. Theoretically, their thermal efficiencies are close to the Carnot cycle, and therefore they have higher values of thermal efficiency than other heat engines (Batmaz and Ustun, 2008). Also, these engines have some advantages such as low noise and can use different energy sources such as fossil fuels, biomass, solar and nuclear energies (Costa et al., 2013). In addition, the Stirling engines dissipate a significant amount of heat in the power generation process and this heat loss can be recovered. Therefore, using the Stirling engine as a high efficiency heat engine can play an important role toward the sustainable development goals. In order to evaluate of the operating characteristics and estimate the proper conditions for better performance of the trigeneration systems, the modeling and simulation of the Stirling engines are very important. There are different studies carried out about modeling and analysis of the Stirling engines.

West (1986) proposed Beale number as a new dimensionless parameter for predicting the power of Stirling engine. This dimensionless number was defined by mean pressure, power output, rotational speed, and swept volume. The Beale number was

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presented from the Eq. (A.1) (Kongtragool and Wongwises, 2005).

$$P = N_B\, p_m\, V_p\, f \tag{A.1}$$

where P is the power output, and N_B is the Beale number. Also, p_m, V_p and f are mean pressure, power piston swept volume and engine frequency, respectively. The Beal number was presented by West equal to 0.014288 for different sizes and types of Stirling engines (West, 1986; Kongtragool and Wongwises, 2005).

Kongtragool and Wongwises (2005) presented experimental study for analyzing the Stirling engine thermal efficiency. At high temperature ratios, they illustrated that to estimate the Stirling engine power output, the Beale number could not be considered as constant value, which was mentioned. Therefore, they modified this number using a correction factor according to the Eq (A.2) (Kongtragool and Wongwises, 2005).

$$N_B = F\frac{1-\tau}{1+\tau} \tag{A.2}$$

$$\tau = \frac{T_k}{T_h} \tag{A.3}$$

Where F is a correction factor in range of 0.25–0.35, and τ, T_k, and T_h are temperature ratio, wall temperature of cooler and heater, respectively.

In another estimation, the Malmo relation was utilized to calculate the Stirling engine power output (Kongtragool and Wongwises, 2005). This relation needs only the heat input values of heat source plus empirical factors and can be determined from Eq (A.4).

$$P = \eta_H\, \eta_{mech}\, \eta_{thermo}\, E_c\, Q_{in} \tag{A.4}$$

$$\eta_{thermo} = \frac{(1-\tau)}{1+(1-\varepsilon)\cdot(1-\tau)/(\gamma-1)\cdot ln\frac{V_1}{V_2}} \tag{A.5}$$

where η_H, η_{mech}, and η_{thermo}, are the heat source, the mechanical, and the thermodynamic efficiencies of the Stirling engine, respectively. In addition, E_c is the Stirling engine coefficient in the range of 0.55–0.88 (Kongtragool and Wongwises, 2005) and, Q_{in}, ε, V_1 and V_2 are the heat input, the regenerator effectiveness, and the engine volumes in expanded and compressed conditions, respectively.

Schmidt presented one of the prior thermodynamic models for the Stirling engines (Schmidt, 1871). In this model, the temperatures of the compression and expansion spaces were supposed to be constant and equal with the temperatures of cooler and heater, respectively. In a real cycle, especially at high frequencies, the expansion and compression spaces at adiabatic mode are similar to each other (Luo et al., 2016). In Finkelstein's study (Finkelstein, 1975), the compression and expansion spaces were considered to be at adiabatic condition and gas temperature changed during compression and expansion processes. In addition, the heater and cooler were considered at isothermal condition. The adiabatic theory (Finkelstein, 1975) was improved by Urieli and Berchowitz (1984) and the effects of non-ideal recovery of the regenerator, gas pressure drop, and the corrected temperatures of gas inside the heaters and coolers were considered. This improved model was called Simple analysis (Urieli and Berchowitz, 1984). Ahmadi et al. (2016) optimized the GPU-3 Stirling engine to rise the power output and thermal efficiency with five important decisive variables including engine rotational speed, regenerating effectiveness, piston stroke, heat source temperature and volumetric ratio. Timoumi et al. (2008) developed an adiabatic quasi-steady flow model which includes the effects of thermal and frictional losses in different parts of the Stirling engine. Hosseinzadeh and Sayyadi (Hosseinzade and Sayyadi, 2015) offered the CAFS model (Combined Adiabatic-Finite Speed) and expressed that the power output and efficiency of the CAFS model had good agreement with the empirical results of the GPU-3 engine. Babaelahi and Sayyaadi (2014) developed the Simple analysis (Urieli and Berchowitz's work (Urieli and Berchowitz, 1984)) and for the first time added the effects of thermal losses of shuttle and gas leakages to the adiabatic equations. Therefore, the adiabatic differential equations of Urieli and Berchowitz (1984) were modified and the model of Simple II was presented. In another study, a new adiabatic model called ISAM (improved simple analytical model), was presented by Ni et al. (2016) to simulate the thermodynamic performance of the Stirling engine. The ISAM model was developed based on the Simple model (Urieli and Berchowitz, 1984) considering the thermal and power losses including regenerator heat transfer loss, heat conduction loss of regenerator, shuttle heat loss for displacer, pressure drop of heat exchangers, spring hysteresis loss of gas in the expansion and compression chambers, and the effect of gas leakage in the engine.

Also, Chahartaghi and Sheykhi (2018) developed the Simple analysis (Urieli and Berchowitz, 1984) and presented non-ideal adiabatic model for Stirling engine. In their work the thermal and frictional losses of engine such as heat conduction loss between the cooler and heater, the shuttle effect, the finite speed thermodynamics of piston, the mechanical friction between the cylinder wall and piston were added into the Simple analysis. In addition, the effects of rotational speed, mean engine operating pressure and regenerator length on exergy efficiencies and exergy destruction were investigated in their work.

Related to modeling and optimization of cogeneration and trigeneration systems driven by Stirling engines, the following investigations were conducted.

Jahani kaldehi et al. (Jahani Kaldehi et al., 2017) presented a micro CCHP system with an alpha type Stirling engine and estimated the overall efficiency of the system in different climate regions of Iran. Entchev et al. (2004) presented an experimental research for a CHP (combined heat and power) system based on Stirling engine for building applications and the system performance was analyzed during different operating periods. The test results showed that the system efficiency could be 88% and the system satisfied the heating demands of the building. Mehrpooya et al. (Mehrpooya et al., 2017) presented a CCHP system with a molten carbonate fuel cell as the main prime mover which a gas turbine and a Stirling engine were the other power suppliers. The Stirling engine was modeled based on the Malmo relation (Kongtragool and Wongwises, 2005) and impact of some effective parameters such as burner air flow rate and outlet temperature, and fuel utilization factor on system efficiencies were investigated. Entezari et al. (2018) presented a power generation system with hybrid arrangement that includes a Stirling engine and a gas turbine. The engine modeling was performed based on the Malmo relation. The model results showed that the thermal efficiency was close to the Simple analysis. Valenti et al. (2015) proposed a numerical and experimental research for a micro-cogeneration unit with a Stirling engine at different operating pressures. The Stirling engine was modeled with modified Simple analysis. In this analysis, the thermal conduction losses between the cooling and heating chambers and mechanical friction losses between the engine moving parts were considered. Their model results illustrated that the efficiency of the system were strongly influenced by initial pressure of the engine. Karami and Sayyadi (Karami and Sayyaadi, 2015) optimized a trigeneration system driven by Stirling engine in four climate conditions of Iran, in which the CAFS analysis