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Utilizing the heat rejected from a solar dish Stirling engine in potable water production

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ABSTRACT

In this paper, the potential of utilizing rejected heat from solar Stirling engines for water distillation is discussed. The proposed idea is to use the heat rejected from the cold chamber in the engine to evaporate water, and then condensing it on a cold surface continuously cooled by the ambient. A mathematical model for the proposed system has been put and performance simulation based on real weather data for six different days have been carried out. The weather data were provided by the energy center in Jordan University of Science and Technology in Irbid-Jordan. Finally, an economic analysis for four different scenarios has been carried out. Although the water production rate is variable during the day, yet the analysis shows that the amount of water is feasible and can increase the revenue, which affects the cost dynamics of solar the Stirling engine system.

1. Introduction

In 1816, Robert Stirling invented the Stirling engine. After that, the engine started serving different applications such as marine engines, thermal power plants, and combined heat and power systems (Kongtragool and Wongwises, 2003a,b). Nowadays, Stirling engines are integrated with solar dishes to generate power (Ferreira et al., 2016). However, just like any other heat engine, there is some heat rejected from the engine. Since heat is a low-grade form of energy, waste heat utilization in thermal applications is attractive. Therefore, the potential in using waste heat from Stirling engines is discussed in this article. However, the main limitations of using Stirling engines in general include the low power to weight issue, which makes using Stirling engines economically infeasible in certain applications like automotive (Rajaram et al., 2011). Another issue is the ability to perfectly seal the engine chambers, this issue arises when using hydrogen and helium as working fluids (Sripakagorn and Srikam, 2011). The following is a list of the advantages and disadvantages discussed in literature (Kongtragool and Wongwises, 2003a,b; Ferreira et al., 2016):

- Advantages:
  - o High cycle thermal efficiency.
  - o Can use sources other than fossil fuels like solar heating and biomass, which makes it a cleaner system and more friendly to the environment.
  - o Since it utilizes external continuous heating sources, Stirling engine runs more smoothly than other cycles like Otto, which reduces its noise.
  - o It has fewer moving parts compared to other (similar in size) power generating systems, hence, more reliability is obtained.
  - o A good thermal to electrical power ratio.
- Limitations:
  - o Because of high temperature and pressure conditions, some parts must be manufactured from certain alloys, which increases the production cost.
  - o Sealing and gas leakage issues.
  - o It has a relatively long warm up periods and slow change in engine output.

The interest in Stirling Engine performance characterization and optimization is clear in recent research. Tremendous efforts were put in developing and proofing Stirling engine theoretical models (Tlili, 2012; Thombare and Verma, 2008; Harrod et al., 2012; Zainudina et al., 2015; Timoumi et al., 2008; Kongtragool and Wongwises, 2006; Zarinchang and Yarmahmoudi, 2008). García et al. (2014) presented a study that has characterized the subsystems efficiency and power of the Stirling engine. They have used the similarity method and they have considered the models of

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Nomenclature

A_{cond}	condenser area (m^2)
A_H	receiver area (m^2)
A_o	aperture area (m^2)
b	dimensionless constant
C	concentration factor (dimensionless)
g	gravitational acceleration (m^2/s)
h_c	external convection coefficient (W/m^2 K)
$h_{cond\text{-}C}$	natural convection coefficient (W/m^2 K)
h_{fg}	enthalpy of vaporization (J/kg K)
h^*_{fg}	corrected (sensible) enthalpy of condensation (J/kg K)
I	solar radiation (W/m^2)
K	volume ratio (dimensionless)
k_l	liquid thermal conductivity (W/m K)
k_{air}	air thermal conductivity (W/m K)
L_c	characteristic length (m)
L	vertical plate height (m)
$\dot{m}_{produced}$	water production mass flux (kg/m^2 s)
P_{mean}	mean effective pressure (Pascal)
Pr	Prandtl number (dimensionless)
q''_{cond}	condensation heat flux (W/m^2)
q_{cond}	condensation heat transfer (W)
q''_{reject}	rejected heat flux (W/m^2)
q_{reject}	rejected heat transfer (W)
q_u	useful heat transfer rate (W)
q''_u	useful heat flux (W/m^2)
T_A	ambient temperature (K)
T_c	cold chamber temperature (K)
T_{cond}	condenser temperature (K)
T_f	film temperature (K)
T_H	hot chamber temperature (K)
T_{sky}	sky temperature (K)
T_{sat}	saturation temperature (K)
T_s	surface temperature (K)
V_∞	free wind speed (m/s)
V_{SC}	compression space swept volume (m^3)
V_{SE}	expansion space swept volume (m^3)
W_{comp}	compression work (J)
W_{exp}	expansion work (J)
W_{net}	net work (J)
$W_{net,d}$	dimensionless net work (dimensionless)
α	advance angle (radians)
ε	emissivity (dimensionless)
$\eta_{collector}$	collector efficiency (dimensionless)
$\eta_{optical}$	collector optical efficiency (dimensionless)
$\eta_{receiver}$	receiver efficiency (dimensionless)
$\eta_{stirling}$	Stirling engine efficiency (dimensionless)
$\eta_{stirling,actual}$	actual Stirling engine efficiency (dimensionless)
η_{system}	system efficiency (dimensionless)
θ	dimensionless constant
ρ_l	liquid density (kg/m^3)
ρ_v	vapor density (kg/m^3)
μ_l	dynamic viscosity (Pa s)
ν	air kinematic viscosity (m^2/s)
σ	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)

the working fluid thermodynamically. Babaelahi and Sayyaadi (2015) have predicted the performance of Stirling engine using a model that is based on the polytropic expansion and polytropic compression in the Stirling cycle. Their model predicted the efficiency of the GPU-3 engine (stands for "Ground Power Unit 3", which is a Stirling generator manufactured by General Motors (Walker, 1980)) with a difference of +3.14%. Gheith et al. (2014) studied experimentally the regenerator temperature distribution in a γ-type Stirling engine.

Araoz et al. (2015) developed and validated a numerical model for a γ-type Stirling engine. Their model succeeded in predicting the brake power with an error less than 8%. They also succeeded in calculating the hot-side temperature with an error less than 9%. The errors associated with the regenerator and cold side temperatures prediction are less than 17% and less than 1% respectively. Ahmadi et al. (2015) optimized a Stirling heat pump using the genetic algorithm. Li et al. (2012) developed and tested a waste gases driven Stirling engine and found similarity between the experimental results and Schmidt method. Ahmadi et al. (2014) optimized a Stirling heat pump. They implemented three different methods to find the optimal solution.

Cheng and Yang (2013) presented a mathematical model that is able to predict the thermodynamic efficiency and the indicated work of a thermal-lag Stirling engine. Their model succeeded in predicting the optimum bore size that accounts for maximum efficiency. Paul and Engeda (2014) presented a model for a Stirling engine. Their model is based on the adiabatic and heat exchanger models; and it has the ability to predict the specific fuel consumption and the power of a GPU-3 Stirling engine with an error of 14%. The GPU-3 Stirling model is studied further theoretically. Timoumi et al. (2008) presented a second order model to design and optimize the GPU-3 engine. They studied the effect of the engine geometry on the performance of the engine; and they found optimal values for the engine that increased the efficiency from 39% to 51%.

Utilization of solar power in electricity production and thermal energy storages is well investigated as found in the literature (Zhang et al., 2013; Singh, 2013; Mahian et al., 2013; Al-Nimr and Al-Dafaie, 2014).

Lately, the integration of Stirling engine with a solar energy system is an attractive research topic because of the mentioned advantages (especially the high cycle efficiency) and the fact that manufacturing technologies are continuously being developed, also, they have the ability to use (García et al., 2014) solar energy as its heat source by integrating them with solar concentration (solar dishes), this increases the temperature of the hot chamber significantly. Also, the peak efficiency and annual solar to electricity efficiency for parabolic trough are (14–20%) and (11–16%) respectively, while the corresponding values for the Dish-Stirling engine are 30% and (12–25%) respectively (IRENA, 2012). Thus, the system efficiency, and the range of annual solar to electricity efficiency is higher for dish Stirling engine system.

Ahmadi et al. (2013a,b) optimized a solar dish Stirling engine using the evolutionary algorithm. Shazly et al. (2014) has developed a mathematical model for a low temperature Stirling engine using MATLAB. In their paper, they showed a complete design (the engine's part with their corresponding dimensions) for the proposed Stirling engine. Ahmadi et al. (2013a,b) modeled thermodynamically a solar dish Stirling engine. The engine is optimized for maximum efficiency and output power using three different methods. Tlili (2012) developed a program to optimize the solar Stirling engine, and the results showed good match with the experimental data of the GPU-3.

Reddy et al. (2013) modeled a solar power plant that has 2000 units of solar dish Stirling engines. They have carried out performance and exergetic study for the power plant components. They reported an annual thermal efficiency of 15.57–27.09%. Aksoy et al. (2015) studied experimentally a low temperature β-type Stirling engine under solar simulator. The solar simulator was a 400 W