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Mathematical modeling, simulation and optimization of solar thermal powered Encontech engine for desalination

Gorakshnath D. Takalkar, Rahul R. Bhosale*

Department of Chemical Engineering, College of Engineering, Qatar University, P.O. Box – 2713, Doha, Qatar

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ABSTRACT

This paper investigates a solar driven external combustion and regenerative engine, which can be used for desalination of seawater by using gaseous working fluids. The effect of operating and design parameters on engine performance for different suction (P_c) and discharge (P_h) pumping pressures, hot (T_h) and cold (T_c) space temperatures, regenerator effectiveness (ε_R), displacer full stroke length (X_0) and dead volume of hot (X_{ho}) and cold (X_{c0}) spaces is studied in detail. Optimization of pumping discharge pressure based on energy and exergy performance for six different working fluids is simulated. The energetic and exergetic analysis is performed at steady state conditions for the proposed thermodynamic cycle. Predominantly, mass and energy balance equations are applied to optimize the effect of different operating (T_h, T_c, P_c, P_h) and design (ε_R, X_{h0}, X_{c0}, X_0) parameters on the output work and efficiencies. An open source SCILAB code is utilized to solve the derived equations for pressure, volume, temperature, mass, and heat loads. The simulation results provide profiles for energy efficiency, exergy efficiency, and optimization based on selected design and operating parameters. Obtained results show that for each charging pressure and hot space temperature, there is a different optimum discharge pressure and optimum hot temperature based on exergetic and energetic efficiency values. Besides, the net hydraulic work-output rises with the increase in the charged mass and displacer full stroke length. Simulation and thermodynamic analysis of proposed engine can be useful to design and select the optimum pumping heads for an accessible heat source and sink temperatures used for desalination to reduce the electricity consumption.

1. Introduction

Due to the significant energy potential, utilization of solar energy towards various thermal applications draw an enthusiastic support globally (Lewis, 2016). Few of these applications are in the areas of pumping, refrigeration, and electricity production. The current research efforts are directed towards the conversion of low-grade heat acquired from solar into useful high-grade form. Various solar powered thermodynamic cycles such as absorption and adsorption refrigeration (Flannery et al., 2017), organic Rankine cycle (Markides, 2015), and Stirling engine cycle (Chow, 2010; Flannery et al., 2017; Freeman et al., 2015; Jokar and Tavakolpour-Saleh, 2015; Kerdchang et al., 2005; Glushenkov et al., 2016; Siva Reddy et al., 2013; Thombare and Verma, 2008; Wang et al., 2016) have been extensively studied for the conversion of low-grade heat into refrigeration, pumping (Stammers, 1979), and power generation (Mendoza Castellanos et al., 2017). High theoretical heat conversion efficiency, noiseless operation, lower maintenance cost, and fuel flexibility of Stirling engine drives the researchers for further innovation to fulfill the energy security and utilize the abundantly available solar energy.

The Stirling engine is invented by Robert Stirling in 1816. It is an externally heated engine operated on closed regenerative thermodynamic cycle. The proper regeneration of heat into Stirling cycle improves the theoretical performance as high as the efficiency of reversible Carnot cycle. Ultimately, efficient use of solar radiations as a source of heat for Stirling engine will preserve the fossil fuels by reducing the dependency and by decreasing the air pollution. Presently, such engines are employed commercially for air liquefaction and cryogenic cooling. The main drawback of Stirling engine in comparison to the internal combustion engine is its high cost, lower specific power generation, high weight, and limitation of heat transfer rates (Abdollahpour et al., 2014; Ahmadi et al., 2016; Asnaghi et al., 2012; Bianchi and De Pascale, 2011; Boutammachte and Knorr, 2012; Chen et al., 2010; Chmielewski et al., 2015; Delgado-Torres, 2009; Ferreira et al., 2016; Formosa and Despesse, 2010; Glushenkov et al., 2012; Hafez et al., 2016; Karabulut et al., 2009; Kongtragool and Wongwises,

* Corresponding author.
E-mail address: rahul.bhosale@qu.edu.qa (R.R. Bhosale).

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Nomenclature

P	pressure (kPa)
Q	heat load (kJ s^{-1})
R	ideal gas constant (kJ/kmol K)
T	temperature (°C)
V	volume (m^3)
S	cross-sectional area of engine (m^2)
W	Work-done per cycle (J)
D	internal diameter of engine cylinder (m)
X	vertical location of displacer (m)
M	molecular weight of working fluid
m	mass of the working fluid (kg)
C	heat capacity (kJ/kg K)

Greek symbol

υ	swept volume ratio
ρ	density of gas (kg/m^3)
η	efficiency
ε	heat exchanger effectiveness factor
γ	compression factor
β	ratio of rod diameter to engine cylinder diameter

Subscripts

1, 2, 3, 4	state points
c	cooler
h	heater
t	transition
th	thermal
ex	exergy

2007, 2006, 2003; Kwankaomeng et al., 2014; Parlak et al., 2009; Paul and Engeda, 2015; Slavin et al., 2009; Sripakagorn and Srikam, 2011; Tavakolpour et al., 2008; Thombare and Verma, 2008; Timoumi et al., 2008; Tlili et al., 2008; Wang et al., 2016).

Thombare and Verma (2008) reviewed Stirling engine technologies with the use of abundant and free heat sources from solar radiation, waste heat from industry, heat produced from agricultural waste, and so many other low-temperature bases. Tlili et al. (2008) has designed and optimized a solar powered Stirling engine with power generation capacity of 250 W and optimal swept volume of 75 cm^3 with a low temperature difference (LTD) of 300 °C, sink temperature of 20 °C, operating frequency of 75 Hz and total dead volume of 370 cm^3. The effect of geometrical and physical parameters on the optimal performance and comparison of thermodynamic model results with experimental data is presented for General Motor GPU-3 Stirling engine prototype by Timoumi et al. (2008). Hafez et al. (2016) examined the effect of different design and operating parameters via modeling and simulation for parabolic dish Stirling engine with the power output capacity of 10 kW. According to these authors, the performance and the power output of the engine can be improved by refining the physical and chemical characteristics of the collectors, reflectors, receivers, and working fluids. Various researchers probed the dish type Stirling engine integrated with the concentrated solar collector for power generation with the target of improving the overall performance (Chen et al., 2010; Freeman et al., 2015; Kongtragool and Wongwises, 2003; Thombare and Verma, 2008).

Sripakagorn and Srikam (2011) developed a solar powered Beta-type Stirling engine working at the moderate temperature range of 350–500 °C which consumes air as a working fluid. The analysis performed by this team indicates 9.35% thermal performance for swept volume of 165 cm^3 with the power output of 100 W. Ferreira et al. (2016) optimized the Stirling engine models based on thermodynamic and economic inputs with concentrated solar radiation as the heat input. Their simulation examination shows annual economic feasibility with payback period of approximately 10 years. Kongtragool and Wongwises (2007) experimentally tested the performance of a twin power piston, low-temperature differential Stirling engine using a non-pressurized air as the working fluid. They scrutinized the effect of various LTD heat inputs on the power output, engine speed, and engine performance. In another study, the same research group examined the effect of dead volume of cold and hot spaces, and the regeneration temperatures on the performance and net work done by the Stirling engine via conducting a thermodynamic analysis Kongtragool and Wongwises (2006). Recently, Ahmadi et al. (2016) theoretically analyzed and optimized the performance of the Stirling engine using a finite speed thermodynamic analysis. Application of solar energy towards various water pumping techniques at low temperatures has been reviewed by Wong and Sumathy (1999).

Jokar and Tavakolpour-Saleh (2015) have experimentally studied the feasibility of solar-powered active Gamma type Stirling water pump system. These authors theoretically investigated and optimized the effect of various parameters such as regenerator efficiency, dead volumes, and pumping head on the power output of the pump. Slavin et al. (2009) proposed the Stirling engine pump for generation of electricity by conducting the basic modeling of the engine cycle. Wang et al. (2016) reviewed the LTD Stirling engines in terms of performance, specific power output, and cost. They have classified the Stirling engines based on liquid pistons for pumping, kinematic drive mechanisms, free piston and thermoacoustic. They have concluded that, liquid piston Stirling engines require lower cost due to the simple construction but such engines possess lower specific power output, low frequency, and inadequate performance which results into limitations towards large-scale applications.

Two phase reciprocating engine is analyzed in detail by applying the constraints in the form of heat transfer process and associated resistances, nonlinear dynamics, heat loss, power output, pumping performance and working fluid (Kirmse et al., 2015; Markides et al., 2014; Oyewunmi et al., 2017). Recently, Knoke et al. (2017) studied the novel heat conversion engine called “Encontech engine” for dense working fluids with high thermal expansion at high process temperatures and with low compressibility at low temperatures. They have investigated the importance of efficient regeneration and the challenges for working fluids that undergo phase change during the cycle. The Encontech engine comprises of four processes i.e., isobaric expansion, isochoric cooling, isobaric compression and isochoric heating in which the working fluid expands during heating and compress during cooling process. The net work done is obtained by expansion and compression of working fluids at isobaric conditions.

Encontech engine has been proposed as the pump for reverse osmosis desalination with hydraulic power output (Glushenkov et al., 2016; Maxim and Alexander, 2014). The displacer is utilized to move the working gas cyclically through internal regenerator in between hot and cold sections. Such cyclic process induces variation in the working fluid volume through the movement of the power pistons and net power output in the form of hydraulic energy. Encontech engine promises high power density and energy efficiency at lower cost. Therefore, such engine is particularly attractive for conversion of low-temperature heat into power. Based on the advantages, in this paper, the thermodynamic model for Encontech engine has been developed and applied to analyze the potential strengths of a single phase gas based working fluid. The