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Research paper

Thermal performance of a Stirling engine powered by a solar simulator

Fatih Aksoy [a], Halit Karabulut [b], Can Çınar [b], Hamit Solmaz [b, *], Yasar Önder Özgören [a], Ahmet Uyumaz [c]

[a] Department of Automotive Engineering, Faculty of Technology, Afyon Kocatepe University, 03200 Afyonkarahisar, Turkey
[b] Department of Automotive Engineering, Faculty of Technology, Gazi University, 06500 Teknikokullar, Ankara, Turkey
[c] Automotive Technologies, Vocational High School of Technical Sciences, Mehmet Akif Ersoy University, 15100 Burdur, Turkey

HIGHLIGHTS

- The performance of a beta type Stirling engine was investigated.
- 400 and 1000 W halogen lamps were used as a solar simulator in the experiments.
- Cavity temperature was measured 623 and 873 K for 400 and 1000 W lamps.
- 1000 W halogen lamp provided better engine performance and thermal efficiency.
- Experimental results of efficiency were compared with nodal analysis results.

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ABSTRACT

In this study, the performance of a beta type Stirling engine which works at relatively lower temperatures was investigated using 400 W and 1000 W halogen lamps as a heat source and helium as the working fluid. The working fluid was charged into the engine block and the pressure of the working fluid was ranged from 1 to 5 bars with 1 bar increments. The halogen lamps were placed into a cavity adjacent to the hot end of the displacer cylinder, which is made of aluminum alloy. In the experiments conducted with 400 W halogen lamp, the temperature of the cavity was 623 ± 10 K. The power, torque and thermal efficiency of the engine were determined to be 37.08 W, 1.68 Nm and 9.27%, at 5 bar charge pressure. For the 1000 W halogen lamp, the temperature of the cavity was determined to be 873 ± 10 K. The power, torque and thermal efficiency of the engine were determined to be 127.17 W, 3.4 Nm and 12.85%, at the same charge pressure. The experimental thermal efficiencies of the engine were also compared with thermodynamic nodal analysis.

1. Introduction

The demand for energy around the world is escalating day by day. However, existing energy sources and energy diversification is still not sufficient to satisfy energy demand [1]. In addition, the cost of the existing energy sources is increasing steadily [2]. A large proportion of the world's energy requirements are currently generated by fossil-based fuels. Focusing on new energy sources is mandatory because of the risk of petroleum depletion and the negative effects of fossil fuels on the environment and human health [3]. Many researchers exert a great effort in order to develop different renewable energy sources [4].

Solar energy is one of the most attractive alternative renewable energy sources. In addition, solar energy is the most abundant and inexhaustible energy source [5]. The reduction of air pollutant and greenhouse gases, the promotion of national energy independency and the protection of water resources are the main advantages of solar energy [6]. Today solar energy is mainly used for the production of electricity. There are several ways to convert solar energy into electricity, such as with photovoltaic cells [7], parabolic trough collectors [8], solar towers [9] and parabolic dish collectors [10].

* Corresponding author. Tel.: +903122028653; fax: +903122028649.
E-mail addresses: faksoy@aku.edu.tr (F. Aksoy), halitk@gazi.edu.tr (H. Karabulut), cancinar@gazi.edu.tr (C. Çınar), hsolmaz@gazi.edu.tr (H. Solmaz), yasarozgoren@aku.edu.tr (Y.Ö. Özgören), auyumaz@mehmetakif.edu.tr (A. Uyumaz).

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Nomenclature

A_i	nodal values of heat transfer surface (m^2)
C_p	specific heat at constant pressure (J/kg K)
C_V	specific heat at constant volume (J/kg K)
E_i	enthalpy flow in and out the nodal volumes (J)
ℓ_c	length of cold volume (m)
ℓ_h	length of hot volume (m)
$h_p/2$	distance between piston top and piston pin (m)
h_d	displacer length (m)
h_i	nodal values of convective heat transfer coefficient (W/m^2K)
ℓ_d	length of displacer rod (m)
ℓ_m	distance between fixing pin and crank pin (m)
ℓ_r	length of displacer rod (m)
ℓ_p	length of piston rod (m)
m_t	total mass of working fluid (kg)
m_i	nodal values of working fluid mass (kg)
Δm_i	variation of nodal mass within a time frame (kg)
R_g	gas constant (J/kg K)
R	radius of crankshaft (m)
S_L	length of lever arm connected to displacer rod (m)
h_c	length from cylinder top to the center of the fixing pin (m)
T_i	nodal values of working fluid temperature (K)
T_c	cold end temperature of displacer cylinder (K)
T_h	hot end temperature of displacer cylinder (K)
$T_{w,i}$	nodal values of heat transfer surface temperature (K)
t	time (s)
Δt	change in time (s)
V_i	nodal values of volume (m^3)
φ	angle between the lever arms (rad)
β_p	angle made by piston rod with vertical (rad)
β_d	angle made by displacer rod with vertical (rad)
γ	angle made by slotted arm of lever with vertical (rad)
θ	crankshaft rotation (rad)

Generally, in most solar energy applications, solar radiation is converted to heat in order to obtain superheated steam. While the superheated steam expands in a turbine, an electricity generator working with the turbine simultaneously produces electricity. On the other hand, solar radiation can be used to run a heat engine, such as a Stirling engine. The parabolic dish collector focuses the solar radiation on a receiver mounted on the heat engine. The receiver converts the solar radiation to heat and transfers this heat to a working fluid that runs the heat engine. Thus mechanical energy produced by the heat engine is converted to electricity via an electricity generator [11]. The efficiencies of the parabolic trough collectors, the solar energy towers and the dish/heat engines are approximately 21%, 23% and 29% [12]. The photovoltaic cells convert the solar radiation into electricity with peak efficiencies in the range of 5–24% [13]. Xing et al. reported a 5% experimental efficiency for thermoelectric elements [14]. It is seen that dish/heat engine solar energy systems are capable of providing high conversion efficiency.

Stirling engines have a wide range of research and application fields. The Stirling engines are attractive because they can be operated with any heat sources including solar radiation, geothermal energy, fossil fuels, coal, wood and radioisotope [15]. The first idea of solar energy conversion using Stirling engine was investigated by Malik and Parker in 1962 [16]. Many of the dish/Stirling solar energy conversion systems were built with a free piston Stirling engine (FPS). However, kinematic Stirling engines were also used in solar energy applications [17].

Fujita et al. performed a study to compare performance characteristics of three different solar energy systems. In their study, a dish/Stirling engine, a gas turbine operated with a Brayton cycle and a gas turbine operated with a Brayton–Rankine cycle solar energy conversion systems were investigated. It was determined that the gas turbine systems using Brayton and Brayton–Rankine combined cycles had advantages at high temperatures. However, the performance of the dish/Stirling engine solar energy system was higher than the gas turbine applications at temperatures below 950 °C. Therefore, for small-scale solar energy conversion, it was determined that the dish/Stirling engine solar energy conversion system is more appropriate [18].

Advanco Corparation developed a 25 kW dish/Stirling engine solar energy system called the Vanguard System as a result of a three-year study conducted between 1982 and 1985. In the Vanguard System, the United Stirling 4-95 Mark II kinematic Stirling engine and a glass-faceted dish with a 10.5 m diameter were used. Although the lubrication, vibration, noise and hydrogen leakage problems, 29.5% net solar to electricity conversion efficiency was obtained which was the world record [19]. In 1984, two 50 kW dish/Stirling systems were built in Riyadh, Saudi Arabia, by Schlaich-Bergerimann und Partner (SBP) of Stutgart, Germany. United Stirling 4-275 kinematic Stirling engines with direct insolation receivers and 17 m diameter dishes that stretched-membrane concentrators were used in the system [20]. In 1985, a dish-Stirling solar energy system was built in the Jet Propulsion Laboratory of the California Institute of Technology (JPL) on the behalf of US Department of Energy. The Stirling engine used in the solar energy system was United Stirling 4-95 Mark II, the same engine that was used in Vanguard System. The power output of the system reached 25 kW with a conversion efficiency of 35% [21]. In 1991, Cummins Power Generation started to develop two dish/Stirling solar energy systems with 7 kW and 25 kW power [29]. Cummins used advanced technologies in its dish/Stirling solar systems [22]. However, in 1996, the Cummins Engine Company decided to refocus on diesel engine development which was its core research field. As a result, the solar operations of Cummins Power Generation were sold to Kombassan Company in Turkey [20]. Under the Eurodish project, a 10 kW dish/Stirling solar energy system was developed by Deutsches Zentrum für Luft und Raumfahrt (DLR) and SBP. In this system, an alpha type Stirling engine was used. The conversion efficiency and power output of the system were 21.6% and 11.1 kW [23].

Kongtragol and Wongwises performed two investigations on a solar energy system using Stirling engine. In the first study, a gamma type double piston LTD Stirling engine was tested at 399, 409, 419 and 436 K heater temperatures. They used a 1000 W halogen lamp as the heat source in the experiments. While maximum engine torque was obtained as 0.352 Nm at the engine speed of 23.2 rpm, the maximum engine power and thermal efficiency were 1.69 W and 0.645%, at the engine speed of 52.1 rpm [24]. In their other study, the performance of a gamma type LTD Stirling engine with four power pistons was investigated under atmospheric conditions at four different hot source temperatures using four halogen lamps as the solar simulator. The maximum engine power and thermal efficiency were 6.1 W and 0.44% at 20 rpm engine speed and 439 K hot source temperature [25].