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Investigation of Solar Collector Design Parameters Effect onto Solar Stirling Engine Efficiency

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Abstract

The performance of a solar-powered heat engine, operating in a Stirling cycle is studied in this work. Also the influence of design parameters on both the optimum solar receiver temperature and overall efficiency is considered. The analysis has also clearly brought out the effect of solar collector design parameters such as concentration ratio, overall heat-loss coefficient, and heat engine parameter on the overall efficiency of solar Stirling power systems.

Keywords: Solar collector; Solar Stirling engine; Concentration ratio; Radiation; Efficiency

Introduction

Thermodynamic cycles have been widely used in conversion of solar radiation energy into the electrical power. Use of solar collector systems in Stirling engine has been investigated in recent literatures [1-5]. Most applications of solar collector systems in Stirling engines are in space power and terrestrial power plant systems in which entirely directed at the electrical power generation. Less attention has been accomplished in small scale terrestrial applications such as in domestic application [6-12]. In recent studies [13,14] it has been identified that the Stirling engine has good potential for meeting continuous power requirements in the 5 to 20 kW range for electrical power generation and water pumping requirements in third world countries.

The dish-Stirling system, comprises of a parabolic dish collector (which is made up a dish concentrator and a thermal absorber) and a Stirling heat engine located at the focus of the dish, tracks the sun and focuses solar energy into a cavity absorber where solar energy is absorbed and transferred to the Stirling engine to heat its displacer hot-end, thereby creating a solar powered Stirling heat engine, as shown in Figure 1.

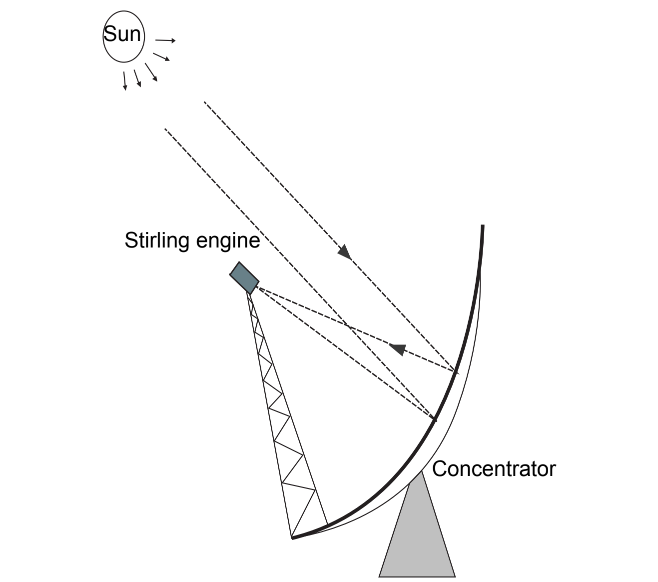

Figure 1: Schematic of a solar stirling engine.

Operation of a solar Stirling engine depends not only on the design parameters of the Stirling engine but also on the design parameters of the heat source, i.e. the solar collector. In the following, a thermodynamic analysis of a solar Stirling engine has been conducted to see the impact of solar collector design parameters on the operation of a solar Stirling engine. A theoretical approach to the determination of optimum working temperature has been described by Sootha et al. [14]. This subject has also been approached by other authors within a different scope and theoretical framework [15-24]. A study on the optimum operation of a solar converter in combination with a Stirling of Ericsson heat engine has also been conducted by Badescu [18,25].

Analysis

Solar energy is incident on a solar collector which is coupled to a Stirling engine as the heat source. The incident energy on the collector includes the direct solar radiation incident on the collector as well as the radiation absorbed from the atmosphere. The collector loses some of its energy to the surroundings by convection and radiation. The rest of the thermal energy is delivered to the Stirling engine. Therefore, the energy balance on the collector is given by [25-28].

$$Q_D + Q_O = Q_R + Q_C + Q_T \tag{1}$$

Where Q_D and Q_O are the energy fluxes absorbed from the sun (short wave) and from the atmosphere (long wave), respectively. Also, Q_R is the flux or radiant energy emitted by the converter, Q_C is the rate of thermal convective losses and Q_T is the rate of thermal energy delivered to the Stirling engine.

The energy flux absorbed from the sun is

$$Q_D = (\tau\alpha)_d I_d + (\tau\alpha)_b I_b C \tag{2}$$

$(\tau\alpha)_d$ and $(\tau\alpha)_b$ are the receiver effective absorptance-transmittance for diffuse and direct(beam) radiation, respectively, while C is

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the concentration ratio of the direct solar radiation; I_d and I_b are irradiances of the solar diffuse and direct(beam) radiation, respectively.

We assume that the energy flux absorbed from the atmosphere is

$$Q_O = (\tau\alpha)_O \sigma T_S^4 \tag{3}$$

Where $(\tau\alpha)_O$ is the effective receiver absorptance-transmittance product for atmospheric radiation; σ is the Stefan-Boltzmann constant and T_{Sky} is the equivalent black-body temperature of the sky [16-18, 25, 26,29].

$$T_{Sky} = 0.0552 T_O^{1.5}$$

Where T_O is the ambient absolute temperature. The rate of radiative energy loss from the collector is given by

$$Q_R = \varepsilon\sigma T_{SB}^4 \tag{4}$$

Where ε and T are solar collector emissivity and temperature of the solar collector, respectively.

The rate of thermal convective losses is given by [16-18,25,27,28]

$$Q_C = U(T - T_O) \tag{5}$$

Where U is the overall converter convective heat loss coefficient of the collector.

The thermodynamic efficiency of a Stirling cycle is given by [25]

$$\eta_C = \frac{1 - \frac{T_O}{T}}{1 + D(1 - \frac{T_O}{T})} \tag{6}$$

Where

$$D = \frac{xC_v}{RLn\frac{v_1}{v_2}}$$

And x is the fractional deviation from ideal regeneration (i.e. x = 1 for no regeneration and x = 0 for ideal regeneration), R is the gas constant, C_v the heat capacity at constant volume of the working fluid and v_1 and v_2 are the specific volumes of the constant volume regeneration process.

Substituting values of Q_D, Q_O, Q_R and Q_C from equation (2)-(5) in equation (1), we have the rate of the thermal energy delivered to the Stirling engine:

$$Q_T = (\tau\alpha)_d I_d + (\tau\alpha)_b I_b C + (\tau\alpha)_O \sigma T_S^4 - \varepsilon\sigma T^4 - U(T - T_O) \tag{7}$$

We define the following non dimensional ratio

$$\theta = \frac{T}{T_O} \tag{8}$$

If Q_T is the rate of thermal energy delivered to the Stirling engine, then the power produced by the Stirling engine is

$$P = Q_T \times \eta_C$$

For the maximum power production

$$\frac{dP}{d\theta} = \frac{d}{d\theta}(Q_T \times \eta_C) = 0 \tag{9}$$

Substituting equation (8) into (7) and then applying equation (9), we have [25]

$$\theta^5 - \left(\frac{3+8D}{D+1}\right)\theta^4 + \left(\frac{D}{D+1}\right)\theta^3 + \frac{b}{4a}\theta^2 - \frac{b}{2a}\left(\frac{D}{D+1}\right)\theta - \frac{1+L-b(D-1)}{4a(D+1)} = 0 \tag{10}$$

Where

$$a = \frac{\varepsilon\sigma T_0^4}{(\alpha\tau)_d I_d + (\alpha\tau)_b I_b C}$$

$$b = \frac{UT_0}{(\alpha\tau)_d I_d + (\alpha\tau)_b I_b C}$$

$$L = \frac{(\alpha\tau)_d \sigma T_S^4}{(\alpha\tau)_d I_d + (\alpha\tau)_b I_b C}$$

The optimum collector temperature

$$T_{opt} = T_O \times \theta_{opt}$$

The maximum efficiency of the solar Stirling engine is

$$\eta_{\max} = \frac{P_{\max}}{Q_D}$$

Result and Discussion

A selectively coated collector system with typical values of emissivity ε = 0.1, overall heat loss coefficient (U = 4Wm^{-2} K^{-1}), $(\alpha\tau)_b$ = 0.8, $(\alpha\tau)_d$ = 0.5, $(\alpha\tau)_O$ = 0.5 has been considered. Figure 2 shows the dependence of the overall efficiency of a solar Stirling system on the Stirling engine parameter and the concentration ratio of the collector system. It is evident from the figure 2 that the overall efficiency of the system is less dependent on increasing values of the engine parameter and increases with the increasing concentration ratio.

Figure 3 shows the variation of the ratio of optimum operating temperature with concentration ratio for various values of engine parameters. By fixed concentration ratio and decreasing engine parameters, caused optimum operating temperature ratio increased. Also in fixed engine parameters by increasing concentration result, optimum temperature ratio increased.

Figure 4 and 5 show the influence of overall heat loss coefficient on the overall maximum efficiency of the solar Stirling power system. As is evident from figure 4, the overall maximum efficiency of a solar Stirling power system based on a flat plate collector is strongly dependent on U

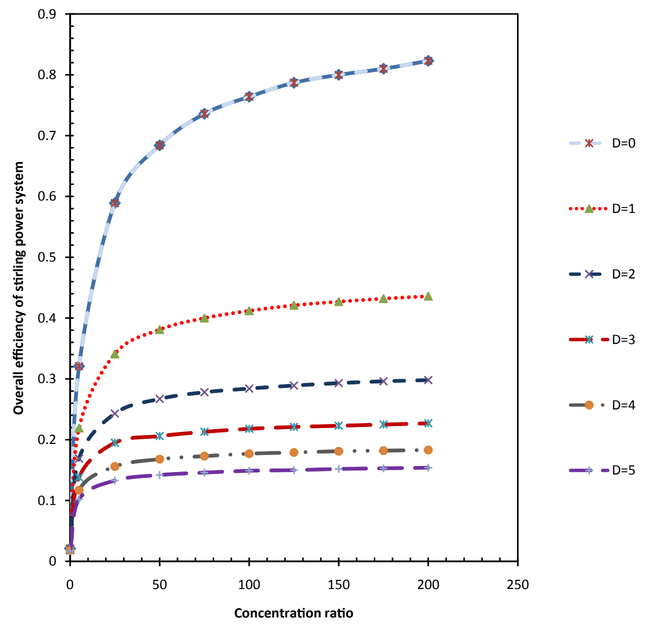

Figure 2: Dependence of the overall efficiency of the solar Stirling system on the engine parameters and the concentration ratio of the solar collector.

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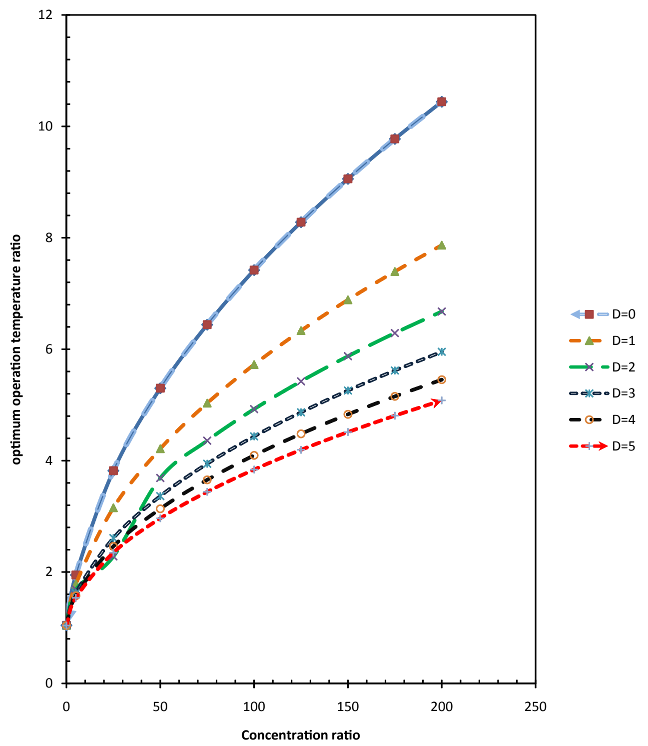

Figure 3: Dependence of the optimum operating temperature ratio on the engine parameters and the concentration ratio of the solar collector.

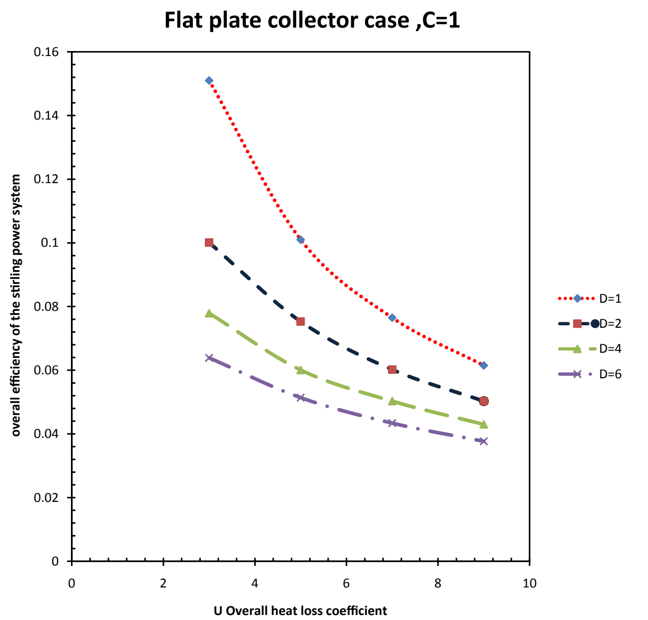

Figure 4: Dependence of the overall efficiency of the Stirling engine system on the overall heat loss coefficient (U).

values in comparison to the system based on a concentrating collector of moderate concentration(C=200)(Figure 5). It is because radiative losses are of a predominant nature for concentrating collectors. Figure 4 and 5 shown that with increased overall heat loss coefficient

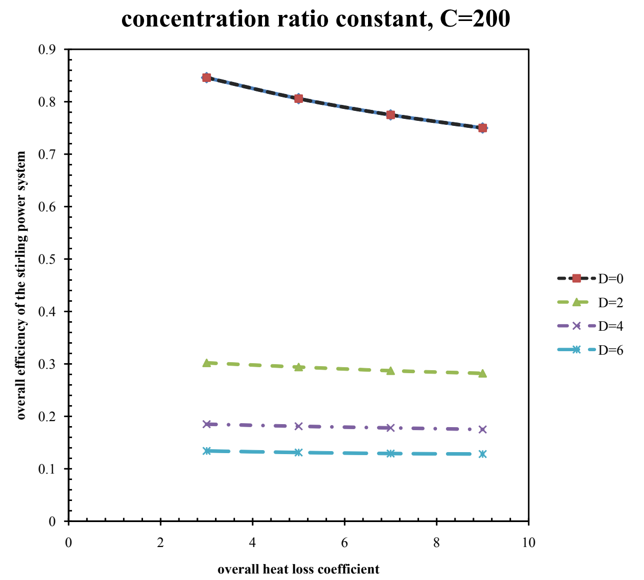

Figure 5: Dependence of the overall efficiency of the Stirling power system on the overall heat loss coefficient (U).

in constant concentration ratio, overall efficiency of Stirling power system decreased which this reduction for flat plate solar collector is more rapidly than concentrating collector. The result shows that concentrating collector-based Stirling power systems are considerably more efficient in comparison to those based on flat plate collectors.

Conclusions

Overall efficiency of Stirling power system has strong dependence on the concentration ratio. As seen maximum system efficiency obtained on optimum operating temperature ratio which optimum operating temperature ratio dependence to concentration ratio and engine parameters. Therefore, performance of Stirling power system is very sensitive to changing in concentration ratio. As show in Figure 2 in the constant engine parameters by increasing concentration ratio, efficiency is increased. Also in constant concentration ratio by increasing overall heat loss coefficient slop of efficiency reduction of system is decreased by this reason we don't recommend using of flat plate solar collector.

Nomenclature

Q Rate of energy, W m^{-2}

U Overall convective heat loss coefficient of the collector, W m^{-2} K^{-1}

ε Emissivity factor

I Irradiance

x The fractional deviation from ideal regeneration

v Specific volume, m3 Kg^{-1}

C_v Specific heat capacity, J mol^{-1}K^{-1}

p Power, W

η Thermal efficiency

T Temperature, K

$(\tau\alpha)$ Effective product transmittance-absorptance

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Subscripts

s Black-body

o Atmospheric

c Stirling engine

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