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Energy and Exergy Analysis of a New Small Concentrating Solar Power Plant

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ABSTRACT

A new small concentrating solar power plant which is suitable for urban area is presented, and a theoretical framework for the energy and exergy analysis in the overall power plant is also constructed. The framework can be used to evaluate the energy and exergy losses in each component. Furthermore, the energy and exergy efficiencies have also been computed and compared for the individual components as well as for the overall plant.

Keywords: Exergy Analysis; Concentrating Solar Power; Thermal Energy Storage; Stirling Engine

1. Introduction

In the present world, the daily primary energy source is fossil fuels such as coal, petroleum and natural gas. They are not only limited in the earth but also release gaseous or liquid pollutants during operation. Because solar energy is an inexhaustible, clean and safe source of energy, it has received much attention as one of the most promising candidate to substitute for the conventional fuels for electricity supply. Taiwan is located in subtropical zone, rich in solar energy resources. However, Taiwan is mostly mountainous in the east, with gently sloping plains in the west. Hence, the installation area for solar power plant is limited.

Recently, rapid development occurred worldwide in the basic technology and market strategy for the concentrating solar power (CSP) technologies, including parabolic trough, power tower, and dish/engine. However, the power generation efficiencies of the CSP systems are found to be low, which indirectly increases the capital costs of electricity generation, and great efforts have to be concentrated on the future research and development of CSP systems. Dish–Stirling systems have demonstrated the good efficiency of any solar power generation system by converting nearly 30% of the direct-normal incident solar radiation into electricity after accounting for parasitic power losses. Furthermore, solar-powered Stirling engines can operate at low, medium, and high temperatures. Hence, the feasibility of a solar power system based on the Stirling dish and current status for commercial markets are very attractive compared with other concentrated technology [1-3]. However, the general solar dish Stirling engine systems do not contain thermal energy storage (TES), so their power production is influenced by the weather.

TES involves the temporary storage of high or low temperature thermal energy for later use. It is an excellent candidate to offset the mismatch between thermal energy availability and demand. For example, storage of solar energy is used for overnight heating. TES systems achieve benefits by fulfilling one or more of the following purposes: increase generation capacity, enable better operation of cogeneration plants, shift energy purchases to low cost periods, increase system reliability and integration with other functions [4]. TES options for CSP plants are classified to three categories: sensible, latent, and thermo chemical storage. The only TES that currently operates with multiple hours of storage is the sensible, two-tank, molten salt system. The system has demonstrated reliable operation at commercial scale [5].

Generally, the performance of thermal power plants is evaluated through energetic performance criteria based on first law of thermodynamics, including electrical power and thermal efficiency. In recent decades, the exegetic performance based on the second law of thermodynamics has found as useful method in the design, evaluation, optimization and improvement of thermal power plants. The exegetic performance analysis can not only determine magnitudes, location and causes of irreversibilities in the plants, but also provides more meaningful assessment of plant individual components efficiency. These points of the exegetic performance analysis are the basic differences from energetic performance analysis. Therefore, it can be said that performing exegetic and energetic analyses together can give a complete depiction of system characteristics. Such a comprehensive analysis will be a more convenient approach for the performance evaluation and determination of the steps towards improvement [6].

So far, the energy and exergy analysis of solar power tower plant, which uses parabolic dish, TES tank, and stirling engine, has not been reported till now. In this regard, the objective of this article is to present a new small concentrated solar power plant which use molten salt as storage media and is suitable for urban area. Furthermore, a theoretical framework for the energy and exergy analysis, which can be used to evaluate the energy and exergy losses in each component and in the overall power plant, is constructed. The energy and exergy efficiencies have also been computed and compared for the individual components as well as for the overall plant.

2. System and Analysis

2.1. System Description

Figure 1 depicts the schematics of the proposed small concentrating solar power plant using molten salt as thermal energy storage media. The solar power plant under developing is consisted of a parabolic dish concentrator, receiver, TES tank, and Stirling engine. The sun rays fall on the parabolic dish concentrator which has dual-axis tracking system and are reflected into the aperture area of the receiver. The receiver is a heat pipe with selective absorbing film on the top and able to downward transfer the absorbed thermal energy to TES tank without pump when absorbed thermal energy is enough. Besides, the receiver stops operation when solar irradiation is weak so that reversely heat transferring is avoided, The TES tank uses molten salt as thermal energy storage media and transfers the energy to Stirling engine. The Stirling engine then converts the thermal energy to mechanical power by expanding the gas in a piston cylinder. In this study, two modes of operation are considered: solar and dark modes. Solar mode is happened during the day time and sunny weather, and all the solar energy absorbed by receiver is stored in TES tank and then used to drive Stirling engine. Dark mode is happened during the night time or cloudy weather, and no solar energy is available and the stored energy in TES tank is used to drive Stirling engine.

TES system designed here is to guarantee the supply of energy even in the absence of solar radiation, such as at nights or on cloudy days. Therefore, the energy produced by the CSP is not limited solely to hours of sunshine. Furthermore, the choice of molten salt is motivated by the fact that this type of material provides an efficient heat storage system, it is not toxic, eco-compatible and cheap. Above all, it is able to keep the temperature at a higher level than hot water storage system. To reduce the inventory cost relatively expansive molten salt in TES tank, a low cost filler material compatible with molten salts, such as quartzite rock, is used to fill much of the volume in the TES tank and acts as the primary thermal storage material [7, 8].

2.2. Energy and Exergy Analysis

The analysis of the individual subsystems of the proposed CSP plant in **Figure 1** is carried out at steady state condition by assuming steady state operation, and the energy flow is illustrated in **Figure 2**. The solar input power is transferred through parabolic dish and receiver, and then buffered in TES tank. Finally, the stored energy in TES tank is transferred to Stirling engine for electric power generation. For the first and second law of thermodynamics, the energy balance and exergy balance of a non-flow control volume can be expressed as:

$$W_{c.v.} + E_{c.v.} = \sum_j Q_j \tag{1}$$

$$W_{c.v.} + Ex_{c.v.} = \sum_j Ex_j - I_{des} \tag{2}$$

where $W_{c.v.}$, $E_{c.v.}$, and Q_j are the work, the internal energy accumulation, and transferred thermal energy of control volume, $Ex_{c.v.}$ and Ex_j are the exergy of $E_{c.v.}$ and Q_j, I_{des} is the exergy consumption.

From equation (1) and equation (2), the energy balance and exergy balance of parabolic dish subsystem are given by:

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_{PDloss} \tag{3}$$

$$\dot{Q}_1 = A_{PD} \cdot I_S \tag{4}$$

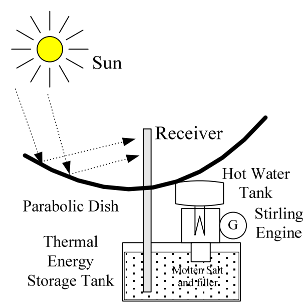

Figure 1. Schematic of a new small concentrating solar power plant.

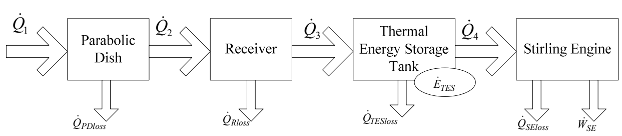

Figure 2. Energy flow diagram of the new small concentrated solar power plant.

$$\dot{E}x_1 = \dot{E}x_2 + \dot{I}_{PDloss} \tag{5}$$

where $\dot{Q}_1$ is the total solar power input to parabolic dish, $\dot{Q}_2$ is the reflected solar power out from parabolic dish, A_{PD} is the reflector area of parabolic dish, I_S is the direct normal irradiation, $\dot{Q}_{XXloss}$ and $\dot{I}_{XXloss}$ are the heat and exergy loss of XX subsystem.

The total exegetic solar power input to parabolic dish subsystem is given by [9]:

$$\dot{E}x_1 = \dot{Q}_1\left(1-\tfrac{4}{3}\left(\tfrac{T_0}{T_1}\right)+\tfrac{1}{3}\left(\tfrac{T_0}{T_1}\right)^4\right) \tag{6}$$

$$\dot{E}x_2 = \dot{Q}_2\left(1-T_0/T_2\right) \tag{7}$$

where T_0 is the atmosphere temperature, T_1 is the sun temperature, and T_2 is the receiver absorber temperature.

The energy efficiency and exergy efficiency of parabolic dish subsystem are defined as:

$$\eta_{I\_PD} = \dot{Q}_2/\dot{Q}_1 \tag{8}$$

$$\eta_{II\_PD} = \dot{E}x_2/\dot{E}x_1 \tag{9}$$

Similarly, the energy balance and exergy balance of receiver subsystem are given by:

$$\dot{Q}_2 = \dot{Q}_3 + \dot{Q}_{Rloss} \tag{10}$$

$$\dot{Q}_3 = A_R\left[C\cdot F_R\cdot I_S - U_R\left(T_2-T_0\right)-\varepsilon_R\sigma_R\left(T_2^4-T_0^4\right)\right] \tag{11}$$

$$\dot{E}x_2 = \dot{E}x_3 + \dot{I}_{Rloss} \tag{12}$$

$$\dot{E}x_3 = \dot{Q}_3\left(1-T_0/T_3\right) \tag{13}$$

where $\dot{Q}_3$ is the thermal power transferred to TES tank, A_R is the absorber area of receiver, C is the concentration ratio, F_R is the intercept factor of receiver, T_3 is the receiver bottom temperature, U_R is the heat convective coefficient of receiver, ε_R is the absorber emissivity of receiver, and σ_R is the Stefan-Boltzmann constant.

The energy efficiency and exergy efficiency of receiver subsystem are defined as:

$$\eta_{I\_HD} = \dot{Q}_3/\dot{Q}_2 \tag{14}$$

$$\eta_{II\_HD} = \dot{E}x_3/\dot{E}x_2 \tag{15}$$

The energy balance balance of TES tank is given by:

$$\dot{E}_{TES} = \dot{Q}_3 - \dot{Q}_4 - \dot{Q}_{TESloss} \tag{16}$$

$$\dot{Q}_{TESloss} = A_{TES}\cdot U_{TES}\cdot\left(T_{TES}-T_0\right) \tag{17}$$

where $\dot{Q}_4$ is the thermal power transferred to Stirling engine, A_{TES} is the surface area of TES tank wall and bottom, T_{TES} is the molten salt temperature of TES tank and U_{TES} is the heat convective coefficient of TES tank, E_{TES} is the net internal energy accumulation of TES and expressed as

$$E_{TES} = V_{TES}\cdot\rho_{TESavg}\cdot Cp_{TESavg}\cdot\Delta T_{TES} \tag{18}$$

where V_{TES}, ρ_{TESavg} and Cp_{TESavg} are the volume, average density and average specific heat of thermal storage material, ΔT_{TES} is the temperature rising of TES. The average property of thermal storage material is expressed as:

$$\rho_{TESavg}\cdot Cp_{TESavg} = \varepsilon_v\cdot\rho_{salt}\cdot Cp_{salt} + \left(1-\varepsilon_v\right)\rho_q\cdot Cp_q \tag{19}$$

where ρ_{salt} and Cp_{salt} are the density and the specific heat of molten salt, ρ_q and Cp_q are the density and the specific heat of quartzite rock, ε_v is the void fraction.

The TES tank is charging and discharging at the same time in solar mode, and discharging only in dark mode, as shown in **Figure 3** the energy balanced diagram.

The exergy balance of TES tank is given by:

$$\dot{E}x_{TES} = \dot{E}x_3 - \dot{E}x_4 - \dot{I}_{TESloss} \tag{20}$$

$$Ex_{TES} = E_{TES}\left[1-T_0\cdot\ln\left(T_{TES2}/T_{TES1}\right)/\left(T_{TES2}-T_{TES1}\right)\right] \tag{21}$$

$$\dot{E}x_4 = \dot{Q}_4\left(1-T_0/T_4\right) \tag{22}$$

where T_{TES} is rising from T_{TES1} to T_{TES2}, and T_4 is the hot space temperature of Stirling engine. The energy efficiency and exergy efficiency of TES tank are defined as:

$$\eta_{I\_TES} = \left(\dot{E}_{TES}+\dot{Q}_4\right)/\dot{Q}_3 \tag{23}$$

$$\eta_{II\_TES} = \left(\dot{E}x_{TES}+\dot{E}x_4\right)/\dot{E}x_3 \tag{24}$$

The energy and exergy balance of Stirling engine is given by:

$$\dot{Q}_4 = \dot{W}_{SE} + \dot{Q}_{SEloss} \tag{25}$$

$$\dot{E}x_4 = \dot{W}_{SE} + \dot{I}_{SEloss} \tag{26}$$

where $\dot{W}_{SE}$ is the output power of Stirling engine.

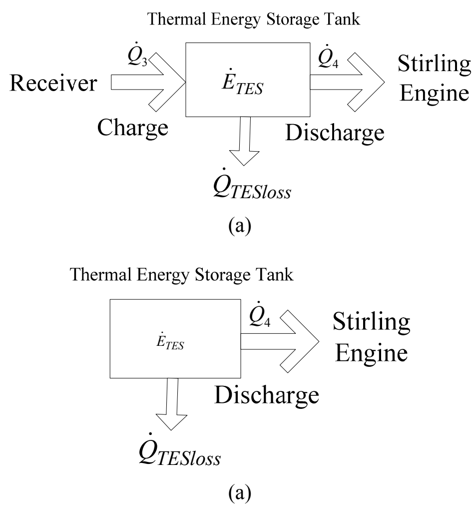

Figure 3. Energy balance diagram of the TES tank: (a) solar mode; (b) dark mode.

The energy efficiency of Stirling engine is given by [10]:

$$\eta_{I\_SE} = \dot{W}_{SE} / \dot{Q}_4 \quad (27)$$

$$\eta_{I\_SE} = F_E \cdot E_S \quad (28)$$

$$F_E = E_H \cdot E_M \cdot K_C \quad (29)$$

$$E_S = (1-\tau) \Big/ \left\{ 1 + (1-e)(1-\tau) \Big/ \left[(k-1)\left(\ln \tfrac{V_1}{V_2}\right) \right] \right\} \quad (30)$$

where F_E is the empirical factor, E_S is the thermodynamic efficiency, k is the air specific heat ratio, and temperature ratio τ is defined as:

$$\tau = T_0 / T_4 \quad (31)$$

The exergy efficiency of Stirling engine is defined as:

$$\eta_{II\_TES} = \dot{W}_{SE} / \dot{E}x_4 \quad (32)$$

3. Results and Discussion

The model built in the preceding section is validation and used for energy and exergy analysis. In this study, the new CSP plant with 25 kW_e Stirling engine is considered. Besides, the storage material is molten salt accompanied with filler material. The molten salt is the mixture of 60 wt% $NaNO_3$ and 40 wt% KNO_3, and the filler material is quartzite rock. The other properties of the new small CSP plant are shown in **Table 1**.

For a typical sunny weather in Taiwan, the variation of direction normal irradiation for length of a day is shown in **Figure 4**. The irradiation rises from zero at 06:00, reaches maximum value 1100 W/m^2 at 12:00, and falls to zero at 18:00. As shown in **Figure 5**, the thermal power to TES is varied according to solar irradiation and the thermal power time is smaller than 12 hours, the Stirling engine output power still keeps 25 kW constantly all 24 hours. Viewing the temperature of TES for length of a sunny day shown in **Figure 6**, the temperature rises in solar mode and falls to initial value in dark mode. This indicates that the internal energy accumulation is enough to supply heat loss and Stirling engine operation all day long.

The results of energy and exergy analysis of the system are shown in **Figures 7-10**. From the energy analysis, it is found that the solar input energy of 445.5 kW can generate net output electricity of 25 kW and thermal storage power of 184.157 kW for the new CSP plant in solar mode. The overall energy efficiency of the whole system

Table 1. Properties of the new small CSP plant.

A_{PD}	445.5 m^2	K_C	0.7
A_R	1.485m^2	T_0	298 K
A_{TES}	15 m^2	T_1	6000 K
C	300	T_2	873 K
E_H	0.9	T_3	773 K
E_M	0.85	T_4	673 K
E_S	0.55	U_R	8 W/(K·m^2)
e	0.99	U_{TES}	2 W/(K·m^2)
F_R	0.75	V_1/V_2	2
I_S	1000 W/m^2	ε_R	0.9
k	1.4	σ_R	5.67·10^{-8} W/(K^4·m^2)

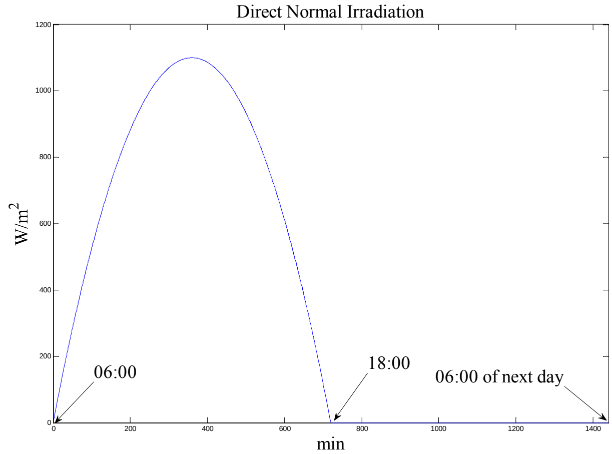

Figure 4. Variation of direct normal irradiation for length of a sunny day.

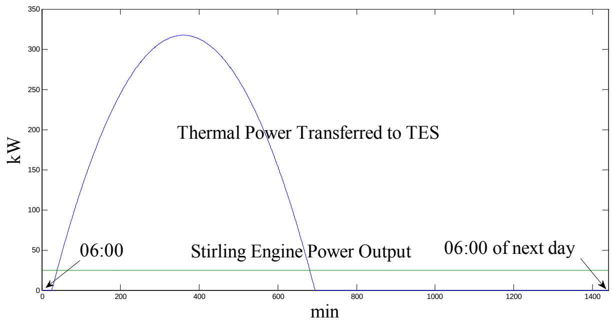

Figure 5. Thermal power transferred to TES and Stirling engine output power for length of a sunny day.

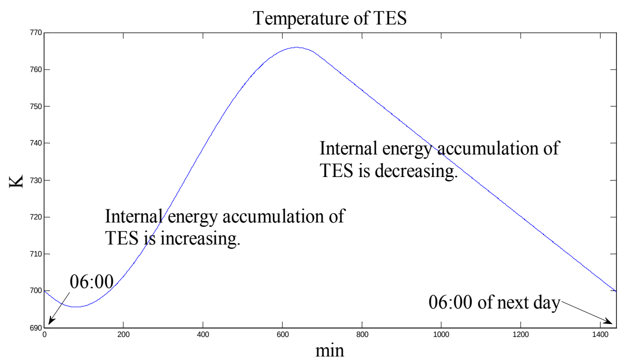

Figure 6. Temperature of TES for length of a sunny day.

is 46.95%. The subsystem energy efficiencies are 75%, 84.96%, 94.98% and 29.25% for parabolic dish subsystem, receiver subsystem, TES tank and Stirling engine, respectively. The largest percentage energy loss is 47.12% occurred in parabolic dish subsystem, followed by 25.59% in Stirling engine, 21.26% in receiver subsystem and 6.03 % in TES tank. However, the results of the exergy analysis show a different behavior. The overall exergy efficiency of the whole system is 30.53%, while the subsystem energy efficiencies are 52.9%, 79.26%, 88.58% and 47.60% for parabolic dish subsystem, receiver subsystem, TES tank and Stirling engine, respectively. The largest percentage exergy loss is 67.80% occurred in parabolic dish subsystem, followed by 15.79% in receiver subsystem, 9.52% in Stirling engine and 6.89% in TES tank.

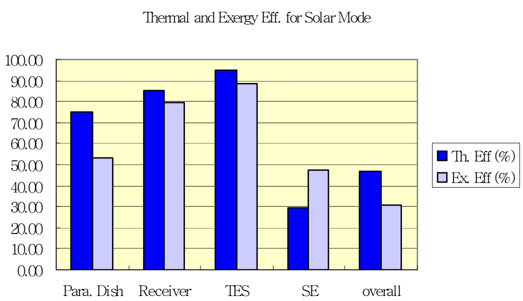

Figure 7. Comparison of energy and exergy efficiency for solar mode.

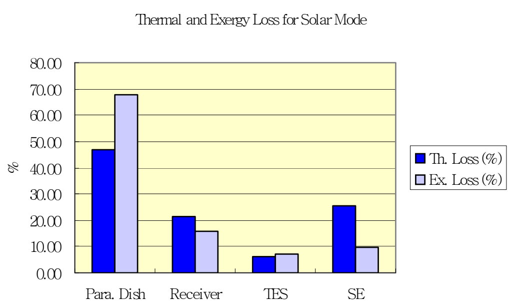

Figure 8. Comparison of energy and exergy loss for solar mode.

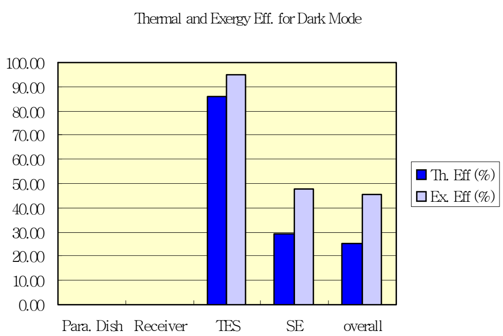

Figure 9. Comparison of energy and exergy efficiency for dark mode.

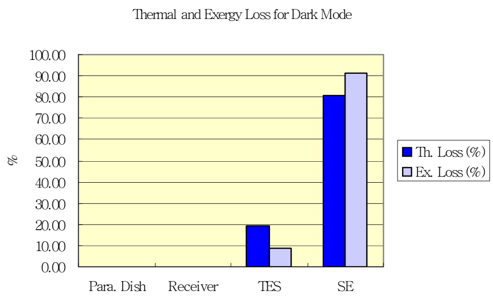

Figure 10. Comparison of energy and exergy loss for dark mode.

It is found that the TES thermal storage power of 99.718 kW can generate net output electricity of 25 kW for the new CSP plant in dark mode. The overall energy efficiency of the whole system is 25.07%. The subsystem energy efficiencies are 85.71% and 29.25% for TES tank and Stirling engine, respectively. The largest percentage energy loss is 80.93% occurred in Stirling engine, followed by 19.07% in TES tank. The overall exergy efficiency of the whole system is 45.26%, while the subsystem energy efficiencies are 95.08% and 47.60% for TES tank and Stirling engine, respectively. The largest percentage exergy loss is 91.02% occurred in Stirling engine, followed by 8.98% in TES tank.

It can be seen that although Stirling engine has low energy efficiency and large loss, the system overall efficiency is not lessened with the help of TES. The TES offers great contribution in both energy and exergy efficiency. Furthermore, for high overall efficiency the most significant components requiring careful design and selection are the parabolic dish subsystem and Stirling engine.

4. Conclusions

In this study, the exergy and energy analysis of the new CSP plant is considering two modes: solar and dark. The CSP plant using molten salt and filler as thermal energy storage material is under developing. It is consisted of a parabolic dish concentrator, receiver, TES tank, and Stirling engine. The theoretical model is built and verified. The validation reveals that the Stirling engine of the new CSP using TES as an energy buffer can continue to run at full capacity all day long. Furthermore, the analysis results show that although Stirling engine has low energy efficiency and large loss, the system overall efficiency is not lessened with the help of TES. The TES offers great contribution in both energy and exergy efficiency. Furthermore, in CSP design the most significant components requiring careful design and selection are the parabolic dish subsystem and Stirling engine.

5. Acknowledgements

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