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Theoretical Investigation of Solar Gasification of Different Types of Lignite Coal

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ABSTRACT:

Scope of this to investigate the steam-gasification in solar assisted gasification reactor of three types of lignite coal that produced in Turkey was investigated. Three different types of lignite coal are TUNCBILEK-B, SEYITOMER and YATAGAN coals respectively. In this gasification process, heat was supplied from solar energy. Process heat can be the use of solar energy, as well as reducing the environmental pollution, increasing the calorific value of the fuel.

Turkey is a rich country in terms of reserve of lignite coal. But these lignite coal reserves have got high ash, humidity and sulphur rates and low calorific value of fuel. Therefore, it is necessary to use these coals with gasification for avoiding the pollutants and increasing the calorific value of the fuel. Moreover, these selected coals are the most suitable fuel type for the gasification process. Because these coals allow sensitive combustion, waste materials are low and suitable for high combustion temperatures.

In this study, exergy and irreversibility calculations related to coal type reactor, heat exchanger and quecher have been made from the data obtained from literature for selected coal. Finally, exergy efficiency expressions for selected three different coal types were obtained and evaluated. As a result, the greatest irreversibility was found in the gasifier and consequently the exergetic efficiency was low (about 40 %). These results gives constrains for designing and efficiently operating solar gasification reactor.

Anahtar Kelimeler: *Coal Gasification, Steam-Gasification, Solar Assisted Gasification, Solar Gasification Reactor, Exergy Efficiency.*

1. INTRODUCTION

Coal is a rich fuel resource in the world and Turkey [1]. Especially Turkey is rich of lignite coal reserves [2, 3]. Today, predicted lignite coal reserves in Turkey is 76 milliard tons and approximately can be expressed as 79 % is visible, 15 % is probable, and 6 % is possible reserve class [4].

Generally, for the case that the difference between of coal production and consumption rates is increasing, it must be paid more attention to using of coal and its products [3].

In a typical coal combustion system, 1 kg CO_2 gas comes out per kWh with greenhouse gasses and pollutants. These emissions considerably reduced by solar fuels which can be used for coal, and can be completely eliminated [5].

Balyaev et. al. (2002), are made analysis of the possibility to use such low-quality coals as alternative energy sources in fluidized bed gasification process. In their work, gasification performance of low-quality coals with different oxygen/nitrogen mixture examined [6]. Cho and Lee (2001) have carried out reactor performance with primary/secondary swirl intensity and direction in coal gasification process. The numerical code was formulated with PSI-cell method, k-ε model for turbulence flow, Monte-Carlo method radiative heat transfer, and eddy dissipation model for gas-phase reaction rate [7]. Steinfeld (2002), studied exergy analysis and economical cost analysis of solar reactors [8]. Epstein et. al. (2001) has carried out the production of zinc from its oxide solar energy. When carbon is used as reducing agent, the main product gases are CO and CO_2 [9].

In this study, gasification reaction calculations of three different lignite coals that produced in Turkey are made (Table 1). Afterwards, thermodynamic analysis of solar assisted gasification reactor was carried out. Finally, irreversibilities and thermal and exergetic efficiencies are estimated for the same system. These results gives constrains for designing and efficiently operating solar gasification reactor.

2. SOLAR COAL GASIFICATION REACTOR

Figure 1 shows a solar coal gasification reactor schematically.

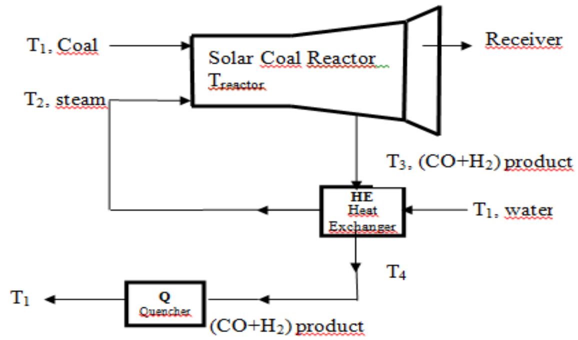

Fig 1. *Solar coal gasification reactor*

Where HE is heat exchanger, Q is quencher. In Figure 1, values are obtained from reference [5] as; T_1=300 K, T_2=1250 K, T_3= $T_{reactor}$=1350 K, T_4=940 K

Lignite is produced in several regions of Turkey (Tuncbilek-B, Seyitomer, Yatagan). In this study, there are only three different lignite coal are investigated. Required values are given in table 1.

Table 1. *Elementary analysis of some lignite in Turkey [10]*

Lignite name and symbol	Tuncbilek-B (T)	Seyitomer (S)	Yatagan (Y)
C (%y)	60,94	63,65	66,34
O (%y)	24	27,88	24,65
N (%y)	1,54	1,79	1,58
S (%y)	2,93	1,02	2,20
H (%y)	5,44	5,66	5,23
H/C (x)	1,0637	1,0596	0,9393
O/C (y)	0,2956	0,3287	0,2788
H_u, Low Heat Value (kW)	13,47	6,91	7,81

The solar concentrating plant is assumed to be a solar tower-reflector system for large-scale collection and concentration of solar energy. The solar tower system uses a field of heliostats to focus the sunrays onto a receiver mounted on top of a centrally located tower. There is a gasification reactor back of the receiver.

Required data for investigated system are obtained from literature. From the data obtained from references [5] and [11], gasification of lignite coal in solar gasification reactor has been analyzed.

3. GASIFICATION OF LIGNITE COAL

For the selected lignite coals, basic and combustion equations is following;

Gasification equation [5]:

$C_1H_xO_y + (1 - y)\ H_2O = [(x / 2) + 1 – y]\ H_2 + CO$

Combustion equation [5]:

$[C + (x / 2)\ H_2 + (y / 2)\ O_2] + [1 + (x / 4) - (y / 2)]\ O_2 = (x / 2)\ H_2O + CO_2$

Where, x = H/C and y = O/C.

The values calculated according to these equations are given in table 2.

Table 2. *Gasification and basic combustion equations for coal types*

(T) coal	Gasification equation	$CH_{1.0637}O_{0.2956} + 0.7044\ H_2O = 1.2362\ H_2 + CO$
	Combustion equation	$C + 0.5318\ H_2 + 1.2659\ O_2 = 0.5318\ H_2O + CO_2$
(S) coal	Gasification equation	$CH_{1.0596}O_{0.3287} + 0.6713\ H_2O = 1.2011\ H_2 + CO$
	Combustion equation	$C + 0.5298\ H_2 + 1.2649\ O_2 = 0.5298\ H_2O + CO_2$
(Y) coal	Gasification equation	$CH_{0.9393}O_{0.2788} + 0.7212\ H_2O = 1.1908\ H_2 + CO$
	Combustion equation	$C + 0.4696\ H_2 + 1.2348\ O_2 = 0.4696\ H_2O + CO_2$

For component i, enthalpy is calculated by the equation (1) [12],

$$\overline{H}_i = \overline{H}_i^0 + m\int_{300}^{T_2}\overline{C}_p dT = \overline{H}_{fi}^0 + \left(\overline{H} - \overline{H}_{300}\right) \text{.......(1)}$$

where forming enthalpy is to reference [12];

$$\overline{H}_f^0 = \overline{H}_{f\,out}^0 - \overline{H}_{f\,in}^0 \text{ ....(2)}$$

Entropy values are calculated by the equation below [12].

$$\overline{S}_i = \overline{S}_{fi}^{\,0} + \left(\overline{S} - \overline{S}_{300}\right) \text{..............................(3)}$$

Where, forming entropy is calculated from main equation for data obtained from reference [12].

$$\bar{S}_f^0 = \bar{S}_{f\ out}^0 - \bar{S}_{f\ in}^0 \quad (4)$$

The values calculated according to these equations are given in table 3.

Table 3. *Thermochemical properties for coal types*

Coal Type	(T) Coal	(S) Coal	(Y) Coal
Formula	$CH_{1.0637}O_{0.2956}$	$CH_{1.0596}O_{0.3287}$	$CH_{0.9393}O_{0.2788}$
$\bar{H}_f^o$ **Forming Enthalpy (kJ/kmol) [11]**	- 522125,5986	-521641,9446	-507083,9592
$\bar{S}_f^o$ **Forming Entropy (kJ/kmolK) [11]**	- 20,518	-20,4294	-17,7649
μ Molar mass (kg/kmol) [11]	17,7933	18,3188	17,4001

4. SECOND LAW ANALYSIS OF THE SYSTEM

Second law (exergy) analysis is applied for calculating maximum exergetic efficiency [5]. In this study, reactor, heat exchanger and quencher are investigated separately.

4.1. Solar Reactor

The solar reactor is assumed to be a cavity-receiver operating at $T_{reactor}$. Its capability to absorb incoming concentrated solar energy is expressed by the solar energy absorption efficiency, $\eta_{absorption}$, defined as the net rate at which energy is being absorbed. Solar reactor parameters and temperature values were taken according to reference [5] as;

$$\eta_{absorption} = \frac{\dot{Q}_{reactor,net}}{\dot{Q}_{solar}} = 1 - \left(\frac{\sigma T_{reactor}^4}{IC} \right) \quad (5)$$

where I is the normal beam insolation; C, the mean flux concentration ratio over the solar reactor's aperture; $T_{reactor}$, the nominal reactor temperature; σ, the Stefan–Boltzmann constant $Q_{reactor\ net}$, absorbed net energy, Q_{solar}, solar energy coming from solar concentration system to reactor [5].

Coal enters the solar reactor at T_1. Only steam is assumed to be preheated from T_1 to T_2 in a heat exchanger. The reactants coal and steam enter the solar reactor and are further heated to $T_{reactor}$. Chemical equilibrium at $T_{reactor}$ is assumed to be achieved inside the reactor. The net power absorbed in the solar reactor should match the enthalpy change of the reaction per unit time. Here, is mass flow rate of coal ($1\ g\ s^{-1}$).

$$\dot{Q}_{reactor,net} = \dot{n}\Delta\bar{H}\,|_{coal@T_1, H_2O@T_2 \rightarrow products@T_{reactor}} \quad (6)$$

From the mass flow equations, calculated mass flow rates form T, S, and Y coals were given in table 4.

Table 4. *Mass flow rates of coals*

Coal type	$\dot{n}_{CHO}$ (g/s)	$\dot{n}_{H_2O}$ (g/s)	$\dot{n}_{H_2}$ (g/s)	$\dot{n}_{CO}$ (g/s)
(T) coal	1	0,7125	0,1389	1,5736
(S) coal	1	0,6594	0,1311	1,5284
(Y) coal	1	0,746	0,1368	1,6091

Heat flux equation for steady state is defined below from references [5] and [12]:

$$\dot{Q} = \sum \dot{n}_{out}(\bar{H}_f^0 + \bar{H} - \bar{H}^0)_{out} \frac{1}{\mu_{out}} 10^{-3} - \sum \dot{n}_{in}(\bar{H}_f^0 + \bar{H} - \bar{H}^0)_{in} \frac{1}{\mu_{in}} 10^{-3}\ [kW] \quad (7)$$

For the equation above, required enthalpy values were obtained from Table 1 and mole rates were calculated basic equation. Where subscripts in and out are inlet and outlet, respectively.

The irreversibility in the solar reactor was calculated with the equation below. In this equation, the first three terms to reference [5] and the last term to reference [13] are calculated.

$$\Delta\dot{S}_{gen} = \frac{\dot{Q}_{solar}}{T_{reactor}} + \frac{\dot{Q}_{radiation\ loss}}{T_1} + \dot{n}\Delta s_{|coal@T_1 H_2O@T_2 \rightarrow products@T_{reactor}} + \dot{n}\Delta s_{mix} \text{......(8)}$$

Where, Δs_{mix} is entropy generation which is born of being formed of mixture phenomena. Δs_{mix} may be expressed as,

$$\Delta s_{mix} = -\sum R_i y_i \ln x_i \text{ and } R_i = R_{mix}\frac{x_i}{y_i} \text{........(9)}$$

$$\Delta s_{mix} = -R_{mix}\sum_{i=1}^{N} x_i \ln x_i \text{ ....(10)}$$

The radiation heat loss by the reactor at $T_{reactor}$ to the surroundings at T_1, ($Q_{reradiation}$) [5];

$$\dot{Q}_{radiation\ loss} = (1-\eta_{absorption})\dot{Q}_{solar} \text{ ....(11)}$$

Irreversibility according to Gouy-Stadola can be defined as;

$$Irr_{reactor} = T_0\Delta\dot{S}_{gen} \text{ ....(12)}$$

The values calculated according to these equations are given in table 5.

Table 5. *Reactor energy, entropy generations and irreversibility for coal types*

Coal type	(T) coal	(S) coal	(Y) coal
$\dot{Q}_{reactor,net}$ (kW)	35,324	33,853	35,3744
$\dot{Q}_{solar}$ (kW)	38,8175	37,201	38,8729
$\dot{Q}_{reradiation}$ (kW)	3,4935	3,3480	3,4985
$\dot{n}\Delta s$ (kW/K)	0,0174	0,0183	0,0170
$\dot{n}\Delta s_k$ (kW/K)	$1{,}396.10^{-3}$	$1{,}0956.10^{-3}$	$1{,}0443.10^{-3}$
$\Delta\dot{S}_{gen}$ (kW/K)	0,059	0,0469	0,05426
Irr, reactor (kW)	17,7	14,07	16,278

4.2. Heat exchanger

The reactants are preheated in an adiabatic countercurrent-flow heat exchanger where some portion of the sensible heat of the products is transferred to the reactants. Water enters at ambient temperature T_1 and exit at T_2; the products enter at T_3 and exit at T_4. It is assumed that the composition of the reactants and products remain unchanged during the heating and cooling processes inside the heat exchanger. Heat transferred from the products, $\dot{Q}_{heat\ exchanger}$;

$$\dot{Q}_{heat\ exchanger} = \dot{n}\Delta h_{|H_2O@T_1 \rightarrow H_2O@T_2} = \dot{n}\Delta h_{|producs@T_3 \rightarrow products@T_4} \text{ ....(13)}$$

Assuming water vapor was ideal gas, enthalpy values were obtained from reference [12] for $\dot{Q}_{heat\ exchanger}$ for T_1=300 K, T_2=1250 K. In the same way, obtained for products ($CO+H_2$) for T_3=1350 K ve T_4=940 K and $\dot{Q}_{heat\ exchanger}$ was calculated

$$\eta_{heat\ exchanger} = \frac{\dot{Q}_{heat\ exchanger}}{\dot{n}\Delta h\,|_{products@T_3 \rightarrow products@T_1}} \text{ ....(14)}$$

entropy generation for heat exchanger;

$\Delta\dot{S}_{\text{gen heat exchanger}} = \dot{n}\Delta h_{|H_2O@T_1 \rightarrow H_2O@T_2} = \dot{n}\Delta h_{|\text{producs}@T_3 \rightarrow \text{products}@T_4}$ ……………………(15)

Reactor irreversibility;

$\text{Irr}_{\text{reactor}} = T_0 \Delta\dot{S}_{\text{gen}}$ ……………………………(16)

For T_0=300 K calculated values were given in table 6.

Table 6. *Exchanger temperatures, entropy generation and irreversibility for coal types*

	(T) coal	**(S) coal**	**(Y) coal**
$\dot{Q}_{\text{heat exchanger}}$(kW) $= \dot{n}\Delta h_{\text{product}T_3 \rightarrow T_4}$	1,655	1,5841	1,6599
$\dot{n}\Delta h_{\text{product}T_3 \rightarrow T_1}$ (kW)	4,0658	3,8888	4,075
$\eta_{\text{heat exchanger}}$	0,40	0,34	0,40
$\dot{n}\Delta s_{H_2OT_1 \rightarrow T_2}$ (kW/K)	$2,105.10^{-3}$	$1,9485.10^{-3}$	$2,204.10^{-3}$
$\dot{n}\Delta s_{\text{product}T_3 \rightarrow T_4}$ (kW/K)	$1,458.10^{-3}$	$-1,3959.10^{-3}$	$-1,463.10^{-3}$
$\Delta\dot{S}_{\text{gen}}$ (kW/K)	$0,647.10^{-3}$	$0,5526.10^{-3}$	$0,741.10^{-3}$
Irr, (kW)	$194,1.10^{-3}$	$165,78.10^{-3}$	$222,3.10^{-3}$

4.3. Quencher

After leaving the heat exchanger, the products are cooled quickly to ambient temperature T_1. The chemical composition of the products remains unchanged upon cooling in the quencher. The power lost during quenching is:

$\dot{Q}_{\text{quencher}} = \dot{n}\Delta h\,|_{\text{products}@T_4 \rightarrow \text{products}@T_1}$ ………..(17)

The irreversibility and entropy generation associated with quenching is:

$\Delta\dot{S}_{\text{gen}} = \frac{\dot{Q}_{\text{quencher}}}{T_1} + \dot{n}\Delta h_{|\text{products}@T_4 \rightarrow \text{products}@T_1}$(18)

$\text{Irr}_{\text{quencher}} = T_0 \Delta\dot{S}_{\text{gen}}$ ……………………………(19)

Values calculated for quencher were given in table 7.

Table 7. *Quencher temperature, entropy generation and irreversibility for coal types*

Coal type	***(T) coal***	***(S) coal***	***(Y) coal***
$\dot{Q}_{\text{quencher}}$ (kW)	2,4103	2,3053	2,4155
$\dot{n}\Delta s_{\text{product}T_3 \rightarrow T_1}$ (kW/K)	$-4,2726.10^{-3}$	$-4,087.10^{-3}$	$-4,2822.10^{-3}$
$\Delta\dot{S}_{\text{gen}}$ (kW/K)	$3,7617.10^{-3}$	$3,5973.10^{-3}$	$3,7694.10^{-3}$
Irr, (kW)	1,128	1,079	1,1308

5. SYSTEM EXERGY CALCULATIONS

5.1. Exergetic Efficiency of Absorber in Solar Reactor Receiver

Absorber exergetic efficiency is given below according to reactor heat energy $E_{Q,reactor}$ and, incoming solar energy exergy $E_{Q,solar}$;

$\eta_{\text{ex,abs}} = \frac{E_{Q,\text{reactor}}}{E_{Q,\text{solar}}}$ ………………………………….(20)

Where;

$E_{Q,\text{reactor}} = \dot{Q}_{\text{reactor,net}} \left(\frac{T - T_0}{T}\right)$………………………(21)

$\dot{Q}_{\text{reactor,net}}$ is taken from Table 5 and $E_{Q,\text{reactor}}$ calculated for all three coals types and for T=1350K ve T_0=300K. For unit area, $e_{Q,\text{solar}}$ can be calculated from [14];

$e_{Q,\text{solar}} = I_e \left(1 - \frac{4}{3}\frac{T_0}{T_s}(1 - 0{,}28 \ln f)\right)$………………(22)

Where I_e=1kW/m^2 , T_0=300K, T_s=5777K and f=$158{,}528.10^{-7}$ for Isparta [15]. For Isparta $e_{Q,\text{solar}}$ = 0.9309 kW/m^2 is calculated.

From here, absorber exergy can be calculated by the equation below according to values taken from Table 8;

$E_{Q,\text{solar}} = e_{Q,\text{solar}} \times A$……………………………….(23)

Table 8. *Absorber parameters for coal types*

Coal Type	$\dot{Q}_{solar}$, (kW)	Required Absorber area,[A](m^2)
(T) coal	38,8175	39,5334
(S) coal	37,2010	35,2691
(Y) coal	38,8729	36,8542

Absorber exergetic efficiencies were given in table 9 for three different coal types.

Table 9. *Absorber exergetic efficiencies for three different coal types*

Coal Type	$E_{Q,reactor}$ (kW)	$E_{Q,solar}$ (kW)	$\eta_{ex,abs}$
(T) coal	27,4467	36,8017	0,74
(S) coal	28,9051	35,2691	0,82
(Y) coal	27,4859	36,8542	0,74

5.2. Reactor Exergetic Efficiency

$$\eta_{eks,r} = \frac{\sum E_{product}}{\sum E_{reactant}} = \frac{E_{ch,product}+E_{ph,product}}{E_{Q,H_2O}+E_{Q,coal}+E_{Q,solar}} \text{.........(24)}$$

Where;

$E_{ch,p}$ =Chemical exergy for products

$E_{ph,p}$ =Physical exergy for products

Calculation of chemical exergy was carried out according to equation below [16]:

$$E_{ch} = \sum x_i \varepsilon_{0i} + RT_0 \sum x_i \ln x_i \text{......................(25)}$$

For the terms in Eq.(25), chemical exergies calculated taking standart exergy values from reference [16] as $\varepsilon_{0,CO} = 275430$ (kj/kmol) and $\varepsilon_{0,H_2} = 238490$ (kj/kmol). Here product mole numbers calculated for three lignite coals according to $x_i = \frac{n_i}{n}$ formula.

Table 10. *Mole numbers calculated for three lignite coals*

Coal	X_{H_2}	X_{CO}
T	0,5060	0,4471
S	0,5456	0,4543
Y	0,5456	0,4543

Although, physical exergy was calculated according to equation below [16, 17].

$$E_{ph} = \frac{\dot{n}(h-h_0-T_0(s-s_0)).10^{-3}}{\mu}\ (kW) \text{.....................(26)}$$

Required values were taken from reference [12] and calculations were made.

The low heat value of fuel can taken equal to the reactant coal exergy. For three different lignite coals, the low heat values were taken from reference [11]. The reactor exergy fluxes calculated based on these values are given in Table 11.

Table 11. *Reactor exergy fluxes for coal types*

Exergies	**(T) Coal**	**(S) Coal**	**(Y) Coal**
E_{ph,H_2} (kW)	1,2532	1,1828	1,2342
$E_{ph,CO}$ (kW)	1,0942	1,0628	1,1189
$E_{ph,product}$ (kW)	2,3474	2,2456	2,3531
$E_{ch,product}$ (kW)	15,9688	15,2562	15,9821
E_{Q,H_2O} (kW)	0	0	0
$E_{Q,coal}$ (kW)	3,47	6,91	7,81
$E_{Q,solar}$ (kW)	36,8017	35,2691	36,8542
$\eta_{ex,r}$ (kW)	%36	%41	%41
Hu (LHV) (kW)	3,47	6,91	7,81

5.3. Exergetic efficiency for heat exchanger

Exergetic efficiency was calculated according to equation below:

$$\eta_{ex,exc} = \frac{\sum E_{product}}{\sum E_{reactant}} = \frac{E_{Q,H_2O}(T_2)+E_{Q,CO}(T_4)+E_{Q,H_2}(T_4)}{E_{Q,water}+E_{Q,CO}(T_4)+E_{Q,H_2}(T_4)} \text{...(27)}$$

Here, physical exergy values were taken from reference [12]. Heat exchanger exergy values calculated for different coal types are given in Table 12.

Table 12. *Exchanger exergies for coal types*

Exergies	(T) coal	(S) coal	(Y) coal
E_{Q,H_2O} (T_2) (kW)	0,8175	0,7565	0,8558
$E_{Q,CO}$ (T_4) (kW)	0,52	0,5051	0,5318
E_{Q,H_2} (T_4) (kW)	0,6096	0,5753	0,6004
$E_{Q,su}$ (T_1) (kW)	0	0	0
$E_{Q,CO}$ (T_3) (kW)	1,2066	1,1719	1,2338
E_{Q,H_2} (T_3) (kW)	1,2532	1,1828	1,2342
$\eta_{ex,exc}$	%79	%78	%80

The exergetic efficiencies for all system are presented in following (Fig. 2.).

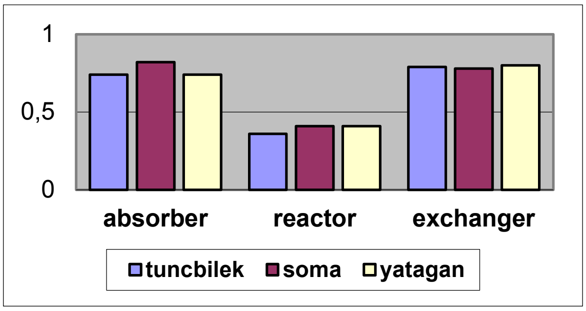

Fig 2. *The exergetic efficiencies vs. the absorber, reactor and exchanger (tuncbilek lignite coal, soma lignite coal, yatagan lignite coal are the exergetic efficiencies*

6. RESULTS

Exergy analyses guides to energy for efficiency use in processes, and helps for determining the major sources of irreversibility for improving the system efficiencies. In this study, solar thermal gasification process of lignite that have high economic value but have pollution effects, analyzed in terms of energy and exergy. In analyses, three types of coal were used. It is seen that for the three types of lignite coals, the maximum exergetic losses were in reactor because of irreversibilities. According to Figure 2, the most exergetic efficiencies for all system components (absorber, reactor, and exchanger) are seen for the Soma lignite coal. However, these systems are the most environmentally friendly systems. However, these systems are the most appropriate to prevent the growth of environmental problems. The system presented in this study provides a promising perspective for the future and encouraging the use of renewable energy systems.

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