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Exergy analysis of low and high temperature water gas shift reactor with parabolic concentrating collector

Murat OZTURK

*Department of Physics, Science-Literature Faculty, Suleyman Demirel University,
Cunur Campus, Isparta
Turkey*

Abstract

Energy is one of the building blocks of modern society. The growth of the modern society has been fueled by cheap, abundant energy resources. Since the Industrial Revolution, the world concentrated on fossil fuels to provide energy needed for running factories, transportation, electricity generation, homes and buildings. In parallel to the increase in the consumption of energy, living standards increased. High living standards of today are owed to the fossil fuels. But, the utilization of fossil fuels in different applications has caused global warming, climate change, melting of ice caps, increase in sea levels, ozone layer depletion, acid rains, and pollution. Nowadays, total worldwide environmental damage adds up to US\$5 trillion a year. On the other hand, fossil fuels are not infinite. World will be out of fossil fuels in the future. Alternatives to the use of non-renewable and polluting fossil fuels have to be investigated. One such alternative is solar energy. Solar energy is the only sources from which we can use more energy than at present, without adding new thermal energy into atmosphere. It may be used in many applications, such as active and passive space heating and cooling, industrial process heating, desalination, water heating, electric generating and solar reactor as a new perspective. Parabolic trough collectors generate thermal energy using solar energy. They are the most deployed type of solar concentrators. Especially, they are very suitable for application of middle temperature solar power systems. Storing of the solar energy is not a good way using the solar energy due to entropy generation process associated with the heat transfer. Instead of that, solar energy can be used to produce hydrogen using solar reactor. Several technologies to produce hydrogen from fossil fuels have already been developed. Although hydrogen itself is clean and has zero emission, its production from fossil fuels with existing technologies is not. It also relies on fossil fuels that no one exactly knows when they will run out. Hydrogen production with renewable energies (e.g., solar, wind, etc.), therefore, can be a viable long-term, may be, an eternal solution. Among renewable energies, solar energy is cost competitive with other conventional energy generation systems in some locations, and is the fastest growing sector. The conventional energy analysis (based on the first law analysis of thermodynamics) does not give the qualitative assessment of the various losses occurring in the components. So

exergy analysis (based on the second law analysis thermodynamic) is used to get a clear picture of the various losses quantitatively as well as qualitatively. Exergy is the maximum amount of work that can be obtained if a material or some form of energy is converted to its inert reference state. Also, exergy is the minimum amount of work to be supplied if a material or form of energy has to be produced from the inert reference system. The reference system includes, in addition to physical parameters such as temperature and pressure, references for chemical elements. Exergy analysis of cylindrical parabolic solar reactor is particularly useful in their design. Exergy analysis provides the basis for choosing the operating parameters of the solar reactors. The requirements for greater conversion efficiency and the introduction of new devices have led to the need for improved methods of prediction of design parameters. Performance analysis of cylindrical parabolic reactors through exergy analysis has led the designer to improve the design parameters.

Water Gas Shift (WGS) reaction is a main step in hydrogen and ammonia production. Also, it has been used for detoxification of town gas. On the basis of thermodynamic and kinetic considerations, the WGS reaction is usually performed by two stages, first at a high-temperature stage, in the range of 593-723 K, and the other low-temperature stage, in the range of 473-523 K. The high-temperature water gas shift (HT-WGS) reaction uses $\text{Fe}_2\text{O}_3/\text{Cr}_2\text{O}_3$ as catalyst, while the low-temperature water gas shift (LT-WGS) reaction is normally performed on $\text{CuO}/\text{ZnO}/\text{Al}_2\text{O}_3$ catalyst. By using parabolic concentrating collectors which are simple technology, H_2 and CO_2 can be produced by applying water-gas shift reaction with H_2O and CO which emitted to atmosphere by any reaction under 475 K. Produced hydrogen can be used in energy generation systems or chemical industries while carbon dioxide can be used in green houses or carbon industry. The WGS reaction has the advantage of producing long term storable energy carriers from solar energy. This conversion also enables solar energy transportation from the sunbelt to remote population centers.

This chapter presents a second law analysis based on an exergy concept for the simple solar cylindrical parabolic reactor for better evaluation. Also this paper presents the methodology of detailed exergy analysis of the solar cylindrical parabolic reactor and distribution of the exergy losses for HT-WGS, between 593 and 723 K and LT-WGS, between 473-523 K. Exergy analysis of the solar energy conversion processes help to define the optimum system that covers the imposed thermal and economical constraints. It is found that the main exergy loss takes place at the collector-receiver assembly. The analysis and results in this study can be used for evaluating the component irreversibilities of solar cylindrical parabolic reactor. Exergy analysis of solar reactor systems provides more meaningful and useful information than energy analysis for researchers and wind energy companies before making decisions .

Keywords: Solar reactor, water-gas shift reaction, exergy analysis, cylindrical parabolic collector, solar energy.

1. Introduction

Energy is defined as the capability of doing work in thermodynamic. Energy constitutes one of the main inputs for sustainable economic and social development. Energy consumption is increasing simultaneously with increasing industrialization, population, urbanization, and technological improvement (Spalding et al., 2005). In order to achieve a sustainable development, which supports economic and social development, energy supply and

demand at minimum amount and cost with the minimum destructive effect on the environment should be set as the main objective. Building an economy based upon a clean, renewable fuel is critical to securing a livable planet for future human generations.

There are a lot of energy sources in the world, such as coal, petroleum, natural gas, solar energy, wind, biomass, hydropower, etc. These sources of course, can be classified in several ways. According to the United Nations classification, primary energy sources are classified as renewable and non-renewable. Renewable energy is defined as an energy from the supply of which is partly or wholly regenerated in the course of the annual solar cycle and/or the supply which is considered unlimited for all intents and purposes. For example, solar, wind, biomass, hydropower, tidal power, wave power, etc. However, non-renewable energy is defined as energy form, the supply of which can not be regenerated such as coal, petroleum, natural gas, etc. It should be pointed out that, non-renewable energy sources are limited, besides they are pollutant for environment. Therefore, renewable energy sources are good alternatives to the non-renewable energy sources (Dincer & Mark, 1999). Compared to the non-renewable energy sources, others are much clean, bides, inexpensive. Some of the renewable energy sources require considerably much amount of money for installation but they are clean sources (e.g. hydropower, geothermal energy etc.). It is obvious that, solar energy being inexpensive and clean energy sources compared to the non-renewable energy sources seems to hold much promise for the future. One of the reasons for the use of solar energy is to reduce the environmental pollution and cost for its control.

Today, renewable energies supply 14% of the world primary energy demand. The primary source of all renewable energies except geothermal energy is solar radiation. The amount of solar energy striking the earth's surface is 5.4×10^{24} J per year (Sorensen, 2004). The world primary energy demand is approximated to be 11000 Mtoe (million ton of equivalent oil) in 2006 (IEA, 2004). Thus the solar energy intercepted by the earth is approximately 11500 times greater than the world's total primary energy demand in the year 2006. Solar energy should be transformed into usable energy forms in order to be utilized. Solar energy is mainly exploited in two ways. It can be converted to either heat or electricity. Converting solar energy to heat is possible by using solar thermal energy technologies. Converting solar energy directly to electricity is achievable by using photovoltaic cells (PV). Also there are indirect ways of converting solar energy into electricity by using solar thermal energy technologies. Energy (heat or electricity) obtained from solar energy technologies can be used for many purposes including the following: drying, heating, cooking, cooling, desalination (Kalogirou, 1997), generating electricity (Mills, 2004), (Trieb, Lagni β & Klai β , 1997) and chemical reactor.

Key advantages of solar thermal systems are as follows (European Solar Thermal Industry Federation [ESTIF];

- reduces the dependency on imported fuels
- improves the diversity of energy supply
- saves scarce natural resources
- saves CO₂ emissions at very low costs
- curbs urban air pollution
- is proven and reliable
- is immediately available
- owners of systems save substantially on their heating/cooling bills
- creates local jobs and stimulates the local economy
- inexhaustible

Solar radiation is converted into thermal energy in the focus of solar thermal concentrating systems. These systems are classified by their focus geometry as either point-focus concentrators (central receiver systems and parabolic dishes) or line-focus concentrators (parabolic-trough collectors (PTCs) and linear Fresnel collectors). PTCs focus direct solar radiation onto a focal line on the collector axis. A receiver tube with a fluid flowing inside that absorbs concentrated solar energy from the tube walls and raises its enthalpy is installed in this focal line. The collector is provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTCs can only use direct solar radiation, called beam radiation or Direct Normal Irradiance (DNI), i.e., the fraction of solar radiation which is not deviated by clouds, fumes or dust in the atmosphere and that reaches the Earth's surface as a parallel beam.

PTC applications can be divided into two main groups. The first and most important is Concentrated Solar Power (CSP) plants. There are currently several commercial collectors for such applications that have been successfully tested under real operating conditions. Typical aperture widths are about 6 m, total lengths are from 100 to 150 m and geometrical concentrating ratios are between 20 and 30. Temperatures are from 300 to 400 °C. CSP plants with PTCs are connected to steam power cycles both directly and indirectly. Although the most famous example of CSP plants is the SEGS plants in the United States, a number of projects are currently under development or construction worldwide.

The other group of applications requires temperatures between 100 and 250 °C. These applications are mainly industrial process heat (IPH), low-temperature heat demand with high consumption rates (domestic hot water, DHW, space heating and swimming pool heating) and heat-driven refrigeration and cooling. Typical aperture widths are between 1 and 3 m, total lengths vary between 2 and 10 m and geometrical concentrating ratios are between 15 and 20.

2. Availability of Solar Energy

The sun's energy is created in the interior regions as a result of a continuous fusion reaction, a process in which four hydrogen protons are combined to form one helium atom by releasing energy. Almost 90% of this energy is generated in the region 0.23 times the radius of the sun and then transferred by radiation up to a distance of about 0.7 R (where R is the radius of the sun) from the center. Outside this region there is the convective zone where the temperature is in the range of 6000 K. The energy created in the interiors is dissipated by radiation from the outer surface at an effective temperature of about 5762 K into space. Thus, the sun with its radius 6.9×10^8 m and mass 1.991×10^{30} kg is almost an inexhaustible source of energy for the earth. The radiation emitted by the sun propagates through space with a velocity of 3×10^8 m/s and takes about 8 minutes to travel the average distance of 1.5×10^{11} m between the earth and the sun to reach the earth's atmosphere.

2.1. Extraterrestrial Solar Radiation

The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (i.e., 1.5×10^{11} m), measured outside the earth's atmosphere, is called the solar constant, I_{sc} . The currently accepted value of this constant, given in different units, is 1353 W/m², 429.2 Btu/(ft².h), 4871 KJ/(m².h) and 1.937 cal/(cm².min).

The effective temperature of the sun's surface (T_s) can be determined from utilizing the value of the solar constant in the fourth power black-body radiation law (Tiwari, 2003).

$$q = \left(\frac{r}{R} \right)^2 \sigma T_s^4 \quad (1)$$

where q is the radiative flux normal to the sun's beam outside the earth's atmosphere based on the mean earth-sun distance, 1353 W/m^2 ; r is the radius of the solar disc, $6.9598 \times 10^8 \text{ m}$; R is the mean earth-sun distance, $1.496 \times 10^{11} \text{ m}$; σ is Stefan-Boltzmann constant, $5.6697 \times 10^{-8} \text{ W/m}^2\text{K}^4$. Then, the effective temperature of the sun's surface is determined as, $T_s = 5762 \text{ K}$. As the earth moves about the sun in a slightly elliptical orbit, the distance between the earth and the sun varies from the 98.3% of the mean distance when the earth is closest to the sun to the 101.7% of the mean distance when the earth-sun distance is maximum. It is apparent from Equation (1) that for the fixed value of T_s , the extraterrestrial radiation varies inversely as the square of the earth-sun distance. The intensity of extraterrestrial radiation varies approximately by $\pm 3.4\%$ about the solar constant (Saying, 1979). That is, from a maximum value of 1399 W/m^2 on December 21 to a minimum of 1310 W/m^2 on June 21. To illustrate the absorption of solar radiation by ozone, oxygen, water vapor and carbon dioxide, the solar spectrum measured on the ground level for an air mass $m=1$, a clear atmosphere, a reducible water of 20 mm and the equivalent path of ozone 3.4 mm at normal pressure and temperature are given in Figure 1.

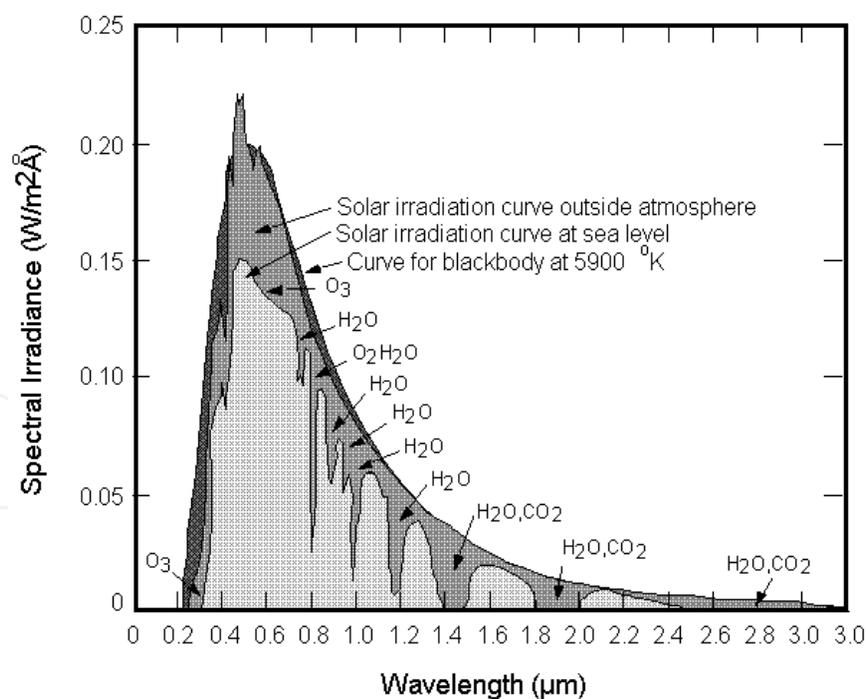


Fig. 1. Spectral distribution of extraterrestrial solar radiation based on the solar constant ($I_{sc} = 1353 \text{ W/m}^2$), (Goswami et al., 1999)

2.2 Atmospheric Attenuation Effect

In passing through the earth's atmosphere the solar radiation is absorbed and scattered by the atmospheric material, approximately 99% of which is contained within a distance of about 30 km from the earth's surface. As a result of atmospheric scattering, some of the solar radiation is reflected back into the outer space, while some of the scattered radiation reaches the earth's surface from all directions over the sky as diffuse radiation. The part of the solar radiation that is neither scattered nor absorbed by the atmosphere reaches the earth's surface as beam, which is called the direct radiation. The direct component of the intensity solar radiation is represented by the symbol, I_D and the diffuse term by I_d .

The solar radiation from the sun arrives to the earth with a $1/2^\circ$ cone. When passing through a turbid atmosphere with large aerosol there is a broadening of the angular cone through which the sun's rays arrive, caused by forward scattering. This is referred to as circumsolar radiation, I_{CS} . Under turbid sky conditions a significant amount of energy is translated into a cone of near 5° about the sun's center. This radiation, which has the same general angular time variations as the primary direct component from the sun, is focusable with some types of collectors. On the other hand, this energy is not all available to highly concentrating collectors, such as parabolic trough collectors.

The extent of absorption and scattering of radiation by the atmosphere depends on the length of the atmospheric path traversed by the sun's beam and the composition of the atmosphere. The atmospheric path traversed by the beam is shortest if the sun is directly overhead (i.e., the sun is at zenith). In general, the beam follows an inclined path in reaching the earth's surface. To take into account the effect of inclination on the length of the path traversed by the sun's ray through the atmosphere, a dimensionless quantity, m , called the air mass is defined as

$$m = \frac{m_a}{m_{a,ex}} \quad (2)$$

where m_a is mass of the atmosphere in the actual path of the beam, $m_{a,ex}$ is mass of atmosphere which would exist if the sun were directly overhead. Clearly if m is equal to 1, corresponds to the case when the sun is directly overhead and if m is equal to 0, the case of no atmosphere (Goswami et al., 1999). For most practical purposes the air mass is approximated by a flat earth model and related to the solar altitude angle, β and the solar zenith angle ψ by the following simple relation.

$$m \cong \frac{1}{\sin \beta} = \frac{1}{\cos \psi} \quad (3)$$

A more accurate representation of m is obtainable by making use of the spherical earth model; the resulting expression is given as

$$m \cong \frac{L}{H} = \left[1 + 2\eta + (\eta \cos \psi)^2 \right]^{1/2} - \eta \cos \psi \quad (4)$$

where L is path of the beam through the atmosphere, H is thickness of atmosphere (1.524×10^5 m), η is R/H and is 41.8 if radius of the earth (R) is equal to 0.6372×10^7 m. The absorption and scattering of solar radiation by the atmospheric materials take place in a selective manner. The ozone, water vapor, carbon dioxide, nitrogen, oxygen, aerosols or dust particles, water droplets in the clouds and other constituents of the atmosphere all participate in the attenuation of solar radiation by absorption and/or scattering (Kreider and Kreith, 1975).

The ozone in the atmosphere is concentrated in a layer between 10 to 30 km above the earth's surface, with the maximum concentration occurring between about 25 to 30 km. Ozone is a very strong absorber of solar radiation in the ultraviolet range between 0.2 to 0.29 μm , relatively absorber in the range between 0.29 to 0.34 μm and has a weak absorption in the range 0.44 to 0.7 μm . There is a variation in the concentration and total content of ozone both geographically and seasonally. The total ozone content may vary from 3.8 mm of ozone (i.e., at normal temperature and pressure) at upper latitudes to about 2.4 mm over the equator. Also, the total amount in the upper latitudes may vary from 3.0 to 5.0 mm (Bayazitoglu, 1986).

The reducible water content of the atmosphere varies from a low value of 2 mm (i.e., the height of water in mm if the water vapor in the air column above the ground per unit area were condensed into liquid) to about 50 mm for hot, very humid summer days without cloud formation. The water vapor in the atmosphere absorbs solar radiation strongly in wavelengths beyond about 2.3 μm . In the range of wavelengths between 0.7 to 2.3 μm , there are several absorption bands.

The oxygen absorption of solar radiation occurs in a very narrow line centered at 0.762 μm . Carbon dioxide is also, a strong absorber of solar radiation in wavelengths beyond about 2.2 μm and has band absorption at selective wavelengths in the range from 0.7 to 2.2 μm .

The scattering of solar radiation by air molecules, water droplets contained in the clouds, and aerosols or dust particles also attenuates the direct solar radiation passing through the atmosphere. The air molecules (i.e., nitrogen, oxygen and other constituents) scatter radiation in very short wavelengths comparable to the size of molecules; such scattering is called the Rayleigh scattering. Water droplets, aerosols and other atmospheric turbidity scatter radiation in wavelengths comparable to the diameters of such particles. Therefore, an increase in the turbidity or dust loading of the atmosphere and/or the coverage of the sky by clouds increases the scattering of solar radiation. As a result of scattering, part of the direct radiation is converted into diffuse radiation. The higher the turbidity and cloud coverage, the larger is the scattering of radiation in the long wavelengths, which in turn causes the whiteness of the sky.

The atmospheric dust loading which has even smaller percentage contribution by weight than water drops, can particularly change the direct solar radiation. The atmospheric dust loading varies over a range of several decades as a result largely of volcanic action. The solar radiation, first, passes through an upper dust layer from 15 to 25 km, and later enters into a lower layer of dust and water vapor in the 0 to 3 km region.

3. Estimation of Solar Radiation Data

3.1.2 Hourly Total Radiation on a Horizontal Surface

3.1.2.1 Extraterrestrial Radiation

The radiation that would be received in the absence of the atmosphere is called extraterrestrial radiation. It can be calculated between hour angles 1 w and 2 w as follows in J/m^2 (Duffie and Beckman, 1991):

$$I_o = \frac{12.3600}{\pi} \cdot G_{sc} \cdot \left(1 + 0.033 \cdot \cos \frac{360 \cdot n}{365} \right) x \left[\cos L \cdot \cos D (\sin w_2 - \sin w_1) + \frac{\pi \cdot (w_2 - w_1)}{180} \cdot \sin L \cdot \sin D \right] \quad (5)$$

where G_{sc} is solar constant in the value of 1367 W/m^2 , n is the number of day in a year ($1 \leq n \leq 365$), L is latitude of the location, D is the declination angle, w is the hour angle and is the angle between the longitude of the considered location and the line connecting the center of the earth. The hour angle is zero at local solar noon and changes by 15° per hour ($360/24$) for earlier or later than noon. It has positive sign for afternoon hours, negative sign for morning hours.

The calculation of the length of a day is necessary to determine the solar gain for hourly basis. It enables to know the sunrise and sunset hours for a particular day. Hour angle at sunset can be determined by:

$$w_s = \arccos(-\tan L \cdot \tan D) \quad (6)$$

and the length of the day (the number of daylight hours) is expressed as follows:

$$N = \frac{2}{15} \cdot w_s \quad (7)$$

3.1.2.2 Estimation of Hourly Radiation from Daily Data

The calculation of the performance for a system in short-time bases makes necessary the use of daily solar radiation data. Thus, daily radiation or monthly average daily radiation by meteorological data can be used to calculate the hourly radiation. Statistical studies have lead to r_t ratio, the ratio of hourly total to daily total radiation (Tiwari, 2003).

$$r_t = \frac{I}{H} = \frac{\pi}{24} (a + b \cdot \cos w) \cdot \frac{\cos w - \cos w_s}{\sin w_s - \frac{\pi \cdot w_s}{180} \cdot \cos w_s} \quad (8)$$

where w is the hour angle in degrees for the time in question. The coefficients a and b are given by:

$$a = 0.409 + 0.5016 \cdot \sin(w_s - 60) \quad (9)$$

$$b = 0.6609 + 0.4767 \cdot \sin(w_s - 60) \quad (10)$$

3.1.2.3 Beam and Diffuse Component of Hourly Radiation

The fraction hourly diffuse radiation on a horizontal surface can be expressed by the Erbs correlation (Duffie and Beckman, 1991):

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ \left(\begin{array}{l} 0.9511 - 0.1604 \cdot k_T + 4.388 \cdot k_T^2 \\ -16.638 \cdot k_T^3 + 12.336 \cdot k_T^4 \end{array} \right) & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \quad (11)$$

where k_T is the hourly clearness index and is expressed as a function of the extraterrestrial radiation as follows:

$$k_T = \frac{I}{I_o} \quad (12)$$

Consequently, hourly beam radiation on a horizontal plane can be written by using the hourly diffuse and the total radiation data as follows:

$$I_b = I - I_d \quad (13)$$

3.1.3 Hourly Total Radiation on a Tilted Surface

One of the most important factors to gain the maximum available solar radiation for a certain season or month is the tilt angle. There are several suggestions on the collector tilt angle as dependent on the latitude of the place where the collector is located. It will be make a seasonal suggestion; for summer period $T=L-15$, for winter period $T=L+15$ and for whole year period $T=L$.

It is necessary to define the ratio of total radiation on the tilted surface to that on the horizontal surface R :

$$R = \frac{I_T}{I} \quad (14)$$

where I_T is total radiation on a tilted surface and I is total radiation on a horizontal surface. Similar for beam radiation

$$R_b = \frac{I_{b,ts}}{I_{b,hs}} \quad (15)$$

where $I_{b,ts}$ is beam radiation on a tilted surface and $I_{b,hs}$ is beam radiation on a horizontal surface. The ratio of beam radiation on a tilted surface to that on a horizontal surface can also be determined by the other equation for the northern hemisphere (Duffie and Beckman, 1991):

$$R_b = \frac{\cos(L-T) \cdot \cos D \cdot \cos w + \sin(L-T) \cdot \sin D}{\cos L \cdot \cos D \cdot \cos w + \sin L \cdot \sin D} \quad (16)$$

A tilted surface also receives solar radiation reflected from the ground and other surroundings. By using a simple isotropic diffuse model, that is the assumption of that the combination of diffuse and ground reflected radiation is isotropic, total solar radiation on a tilted surface can be calculated as (Saying, 1979):

$$I_T = I_b \cdot R_b + I_d \cdot \left(\frac{1 + \cos T}{2} \right) + I_g \cdot \rho_g \cdot \left(\frac{1 - \cos T}{2} \right) \quad (17)$$

where $(1 + \cos T)/2$ term is the view factor to the sky, $(1 - \cos T)/2$ term is the view factor to ground for tilted surface and ρ_g is the diffuse reflectance for the surroundings.

4. Parabolic Trough Solar Collector

Parabolic trough technology has proven to be the most mature and lowest cost solar thermal technology available today (Price et al., 2002) and are efficiently employed for high temperature (300–400 °C) without any serious degradation in the efficiency. One of the major advantages of parabolic trough collector is the low-pressure drop associated with the working fluid when it passes through a straight absorber/receiver tube. The receiver is an important component for solar energy collection and subsequent transformation. Conventional line-focusing receiver designs incorporate transparent enclosure and selective surfaces to reduce convection and radiation losses. The thermal losses from the receiver of a concentrating solar collector significant influence the performance of the collector system under high temperature operation. Investigation of heat loss from the receiver and heat transfer from the receiver to the working fluid are very important in determining the performance of solar parabolic trough collector. The parabolic solar concentrator has three main parts, namely;

- Absorber
- Glass Envelope
- Reflector

4.1 Absorber

The selective surface is necessary if the losses are to be saved. There is a considerable difference between the absorptivities of absorber surface with and without a special coating. The absorber tube is coated with a spectrally selective material to maximize solar absorption and minimize thermal emission from its surface. The absorptance and emittance of some type of coating are listed in Table 1.

Type of coating	Absorptivity (α)	Emissivity (ϵ)	Ratio (α/ϵ)
Black nickel on galvanized steel	0.89	0.12	7.42
Black chromium on duty nickel	0.92	0.085	11
Black nickel (Zn or Ni oxides and sulfur on bright nickel)	0.93	0.11	8.46
Black nickel	0.88	0.066	13.3
Nextel black paint	0.97	0.97	1
PbS (on Al)	0.89	0.20	4.45
CuO (on Al)	0.85	0.11	7.23
Ebanol C on copper	0.91	0.15	5.69
Stainless steel, 16% Cr, heated 3 hr at 600 °C	0.75	0.10	7.5
Aluminium treated with KMnO ₄	0.80	0.35	2.29
Platinum black	0.95	0.91	1.04

Table 1. Absorptivity emissivity ratio for some coatings (Saying, 1979)

4.2 Glass Cover

A glass envelope was put around the tubular absorber to decrease the losses to the surroundings. This glass forms a gap between the absorber and itself. As a result, the gaps acts as insulation and reduce the convective losses. Surely, it will decrease the convective losses further if air in this gap is evacuated by a vacuum pump. Type of the glass is an important factor affecting the percent of radiation transmitted to the absorber. The reason of using pyrex can be explained as the behavior of the glass below 2.5 microns. Pyrex glass can transmit almost 91% of the incident (short wave) radiation while not allowing long wave radiation emitted by the absorber. Some of the common glazing materials are given in Table 2.

Glass	Transmissivity (τ)	Absorptivity (α)	Reflectivity (ρ)
High transparent pyrex	0.90	0.02	0.08
Common window glass	0.87	0.04	0.09
Regular plate (1/4 inc)	0.77	0.16	0.07
Heat absorbing plate (1/4 inc)	0.41	0.53	0.06
Double window glass	0.76	0.04+0.04	-
Double regular plate	0.60	0.07+0.10	-

Table 2. Transmissivity, absorptivity and reflectivity of glazing materials (Saying, 1979)

4.3 Reflector

The reflector is one of the most important components of the parabolic solar concentrator. Reflectors can be situated at an optimum angle to gain the greatest possible level of sunlight that can be achieved onto the panel. This idea of using this type of reflector is a lot simpler and less complicated than the existing concentrators, for example the parabolic concentrator. In Table 3, some of the reflectors are given with their reflectivity values.

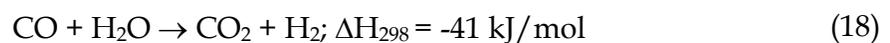
Materials	Reflectance
Silver (unstable as front surface mirror)	0.94 ± 0.02
Gold	0.76 ± 0.03
Aluminized acrylic, second surface	0.86
Various aluminum surfaces-range	0.82 - 0.92
Copper	0.75
Back-silvered water-white plate glass	0.88
Aluminized type-C Mylar (from Mylar side)	0.76

Table 3. Solar reflectance values for reflector materials (Goswami et al., 1999)

5. Water-Gas Shift (WGS) Reaction

The water-gas shift (WGS) reaction is a main step in hydrogen and ammonia production. It has been used for detoxification of town gas (Kodama, 2003). On the basis of thermodynamic and kinetic considerations, the WGS reaction is usually performed two stages. First at a high-temperature stage is the range of 320-450 °C, and the other low temperature stage is the range of 200-250 °C (Eskin, 1999). The high temperature shift (HTS) reaction uses Fe₂O₃/Cr₂O₃ as catalyst, while the low-temperature shift (LTS) reaction is normally performed on CuO/ZnO/Al₂O₃ catalyst (Kodama, 2003).

Recently, the renewed interest in the removal of CO by the WGS reaction has grown significantly because of the increasing attention to pure hydrogen production for its use in fuel cell (Newsome, 1980). The WGS reaction,



is limited by its thermodynamic equilibrium.

6. The model of solar reactor

The simple solar reactor arrangement is schematically shown in Figure 2 some typical properties used in the following illustration are shown in it. This solar reactor system with the use of solar energy consists of two subsystems: the parabolic through solar collector subsystem and WGS chemical reactor, reformer. The cold air enters at a temperature of 200 °C and exists at a temperature of 600 °C. The hot air enters the reformer where it heats up CO and H₂O at a temperature of 350 °C. So that, WGS reaction occurs at this temperature in the reformer.

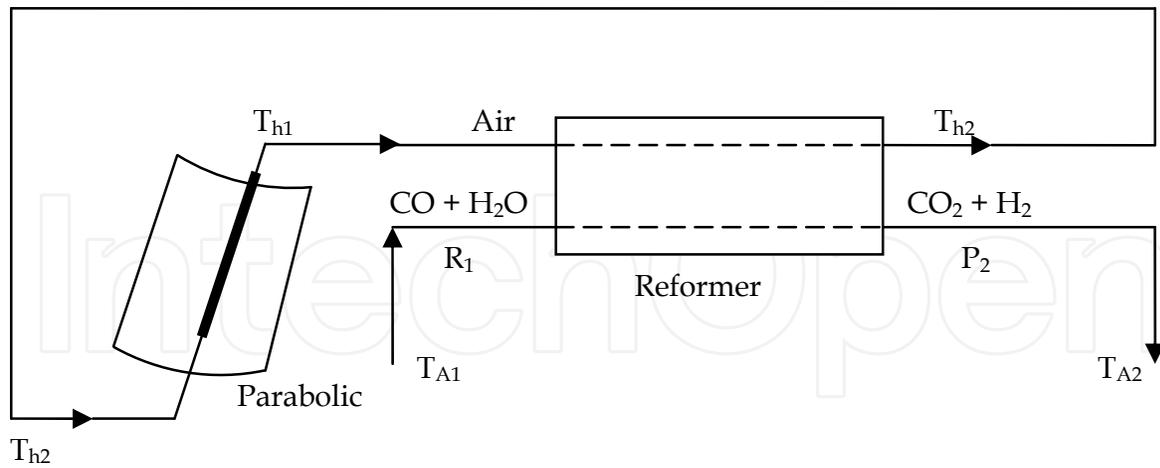


Fig. 2. WGS Chemical reactor

7. The Theory of Exergy

Exergy as a concept emerged as corollary to the second law of thermodynamics and can be expressed simply as the amount of available energy a system possesses with respect to a specified reference level. This reference level is often taken to be that of the environment. When taken as such, the exergy of a system represents the maximum amount of work that can be extracted from the system if it were allowed to completely return to equilibrium with the environment in a reversible manner. Conversely, looking at it from the opposite vantage, exergy is a measured of the minimum amount of energy required to create a given system from materials in equilibrium with the environment.

While its rigorous definition is based upon the reversible work available in a system, the term exergy is also frequently used to describe transfer of work to or from a system. Hence, when one talks about the power consumption of a piece of equipments, this can be expressed in terms of the rate of exergy consumption. Indeed, the colloquial use of the energy in industry can in most cases is replaced by more appropriate term exergy. The distinction between exergy as a property signifying the available reversible work of a system and exergy as a work transfer that evokes change in a system (either reversible or irreversibly) can be the source of some confusion.

7.1 Exergy analysis of solar reactor

Exergy analysis is an effective and illuminating form of second law analysis (Hua et al., 2005). Exergy is defined as the maximum amount of work that can be produced by a stream of material or a system as it comes into equilibrium with its environment. Exergy may be loosely interpreted as a universal measure of the work potential or quality of different forms of energy in relation to a given environment.

The exergy transfer can be associated with mass flow, with work interaction and with heat interaction (Lian, 2006). Dynamic and kinetic exergy are two more forms of exergy that exist in renewable energy sources technology (Singh, 2000).

The exergy associated with heat interaction is given by the equation (Magal, 1994):

$$E = \int_o^f \left(1 - \frac{T_o}{T_s} \right) d\dot{Q} \quad (19)$$

where T_0 is the ambient temperature, T is the temperature at which the heat transfer takes place, o denotes the dead state, f denotes the final state and \dot{Q} is the infinitesimal heat transfer rate at the boundary of the control mass (Haught, 1984). Total irreversibility of WGS solar reactor which is given Figure 2 is

$$I_{total} = I_{solar} + I_{collector} + I_A + I_{CH} \quad (20)$$

where I_{solar} , $I_{collector}$, I_A , I_{CH} is solar, parabolic collector, air and chemical reaction in the reformer irreversibility, respectively.

7.2 Exergy Analysis of Solar Radiation

Exergy balance of solar radiation is

$$E_{solar} = E_G - Ex_{solar} \quad (21)$$

where E_{solar} is irreversibility of solar radiation, E_G is the global irradiance, $E_G = f\sigma T_s^4$ where f is the dilution factor and T_s is the solar temperature which is 5777 K, Ex_{solar} is the exergy released by the solar irradiance (You and Hu, 2002)

$$Ex_{solar} = I_e \left(1 - \frac{4T_0}{3T_s} (1 - 0.28 \ln f) \right) \quad (22)$$

where I_e is the direct irradiance, T_0 is the ambient temperature.

7.3 Exergy Analysis of Cylindrical Parabolic Collector

Exergy balance of solar cylindrical parabolic collector is

$$E_{collector} = Ex_{solar} - Ex_Q \quad (23)$$

where $E_{collector}$ is irreversibility of cylindrical parabolic collector, Ex_Q is the exergy transfer accompanying

$$Ex_Q = Q_s^u \left\{ 1 - \frac{T_0}{T_{h1} - T_{h2}} \ln \left[\frac{T_{h1}}{T_{h2}} \right] \right\} \quad (24)$$

where, T_{h1} , T_{h2} are the temperature of the solar heat carrier entering and exiting the heat exchanger(s), respectively and Q_s^u is the useful transferred solar heat,

$$Q_s^u = I_e (\alpha\tau) F_k + (\alpha\varepsilon) F_k \frac{\sigma T_c^4}{C} - (\varepsilon\bar{\rho}) F_k \frac{\sigma T^4}{C} - U_L F_k \frac{T - T_o}{C} \quad (25)$$

where $\alpha\tau = \alpha_a \tau_c / [1 - \rho_c (1 - \alpha_a)]$ and α_a is the absorptivity of the absorber, τ_c is the transmissivity of the cover, and ρ_c is the fraction backscattered by the cover, $\alpha\varepsilon = \alpha_a \varepsilon_c / [1 - \rho_c (1 - \alpha_a)]$ and ε_c is the emissivity of the cover, $\varepsilon\bar{\rho} = \varepsilon_a (1 - \rho_c) / [1 - \rho_c (1 - \alpha_a)]$ and ε_a is the emissivity of the absorber, σ is the Stefan-Boltzmann constant, $\bar{\rho}$ is the average reflectivity, U_L is the heat loss coefficient, F_k is termed as collector efficiency factor which is close to 1 for a well designed receiver or collector, T is the fluid temperature, T_c is the cover temperature, T_o is the ambient temperature, C is the concentration ratio (You and Hu, 2002).

7.4 Exergy analysis of reformer

Total exergy analysis of reformer consists of exergy analysis of air at heat reformer and chemical and physical exergy analysis of reactants and products.

7.4.1 Exergy analysis of air at heat reformer

Exergy balance of air in heat reformer is

$$E_{air} = E_{EnA} - E_{ExA} \quad (26)$$

where E_{air} is irreversibility of air at heat reformer, E_{EnA} and E_{ExA} are exergy of entering and exiting air, respectively and they are calculated from (Kotas, 1985),

$$E_{EnA} = n_A \tilde{\varepsilon}_{ph,EnA} \quad (27)$$

$$E_{ExA} = n_A \tilde{\varepsilon}_{ph,ExA} \quad (28)$$

where n_A is the mol number and $\tilde{\varepsilon}_{ph,EnA}$ and $\tilde{\varepsilon}_{ph,ExA}$ are the physical exergy of the entering and exiting air, respectively. In the general form of physical exergy of gases is (Kotas, 1985)

$$\tilde{\varepsilon}_{ph} = \tilde{C}_p^h (T - T_0) - T_0 \tilde{C}_p^s \ln(T/T_0) + RT_0 \ln(P/P_0) \quad (29)$$

where R is the universal gas constant. Physical exergy of entering air, at $P=P_0$ is

$$\tilde{\varepsilon}_{ph,EnA} = \tilde{C}_{p,En}^h (T_{h1} - T_0) - T_0 \tilde{C}_{p,En}^s \ln(T_{h1}/T_0) \quad (30)$$

where $\tilde{C}_{p,En}^h$ is mean isobaric heat capacity for enthalpy of entering and $\tilde{C}_{p,En}^s$ is mean isobaric heat capacity for entropy of entering air. Physical exergy of exiting air, at $P=P_0$ is

$$\tilde{\varepsilon}_{ph,ExA} = \tilde{C}_{p,Ex}^h (T_{h2} - T_0) - T_0 \tilde{C}_{p,Ex}^s \ln(T_{h2}/T_0) \quad (31)$$

where $\tilde{C}_{p,Ex}^h$ is mean isobaric heat capacity for enthalpy of exiting air and $\tilde{C}_{p,Ex}^s$ is mean isobaric heat capacity for entropy of exiting air. Mol number of entering air given in Equation (27) and (28) is

$$n_A (h_{A,En} - h_{A,Ex2}) = (H_{ph,P_2} - H_{ph,R_1}) + (H_{d,P_2}^0 - H_{d,R_1}^0) \quad (32)$$

For air, the following assumption can be written

$$(h_{A,En} - h_{A,Ex}) = (T_{h1} - T_0) \tilde{C}_{p,En}^h - (T_{h2} - T_0) \tilde{C}_{p,Ex}^h \quad (33)$$

Assuming the reactants and products to behave as ideal gases;

$$H_{mixture} = \sum_i (n_i \tilde{h}_i) \quad (34)$$

where n_i is mol number of i^{th} reactant. Hence from Equation (34)

$$H_{d,P_2}^0 - H_{d,R_1}^0 = (\tilde{h}_{CO_2}^0 - \tilde{h}_{H_2}^0) - (\tilde{h}_{CO}^0 - \tilde{h}_{H_2O}^0) \quad (35)$$

The change in the physical enthalpy can be expressed as,

$$H_{ph,P_2} - H_{ph,R_1} = (T_{A2} - T_0) (\tilde{C}_{p,CO_2}^h + \tilde{C}_{p,H_2}^h) - (T_{A1} - T_0) (\tilde{C}_{p,CO}^h + \tilde{C}_{p,H_2O}^h) \quad (36)$$

where T_{A1} and T_{A2} are chemical compositions temperature at the entering and exiting of the solar cylindrical parabolic collector, respectively.

7.4.2 Chemical and physical exergy analysis of reactants and products

Chemical and physical exergy balance of reactants and products is

$$Ex_{Re} = Ex_{Pu} + E_{ch,ph} \quad (37)$$

where Ex_{Re} is chemical exergy of reactants and Ex_{Pu} is chemical exergy of product and $E_{ch,ph}$ is the irreversibility of chemical reaction (Kotas, 1985).

$$Ex_{Re} = n_{Re} (\tilde{\varepsilon}_{ch,Re} + \tilde{\varepsilon}_{ph,Re}) \quad (38)$$

$$Ex_{Pu} = n_{Pu} (\tilde{\varepsilon}_{ch,Pu} + \tilde{\varepsilon}_{ph,Pu}) \quad (39)$$

The molar standard chemical exergy from the reactants and products is calculated from [15]

$$\tilde{\varepsilon}_{ch} = \sum_i x_i \tilde{\varepsilon}_i^0 + \tilde{R}T_0 \sum_i x_i \ln x_i \quad (40)$$

where x_i is the mole fraction. It follows from the Gibbs-Dalton rules that the physical exergy of a mixture of N components can be evaluated from:

$$\tilde{\varepsilon}_{ph} = \sum_{i=1}^N x_i \tilde{\varepsilon}_i^{\Delta T} + RT_0 \ln(P/P_0) \quad (41)$$

where P is the total pressure of the mixture. Using tabulated of the mean molar isobaric exergy capacity \tilde{C}_p^ε , Equation (41) can be written in the following form,

$$\tilde{\varepsilon}_{ph} = (T - T_0) \sum_{i=1}^N x_i \tilde{C}_{p,i}^\varepsilon + \tilde{R}T_0 \ln(P/P_0) \quad (42)$$

8. Exergetic Efficiency

Systems or devices designed to do work by utilization of a chemical reaction process, such as solar power plants, have irreversibilities and losses associated with their operation. Accordingly, actual devices produce work equal to only a fraction of the maximum theoretical value that might be obtained in idealized circumstances.

The real thermodynamic inefficiencies in a thermal system are related to exergy destruction and exergy loss. An exergy analysis identifies the system components with the highest exergy destruction and the processes that cause them. However, only a part of the exergy destruction in a component can be avoided. A minimum exergy destruction rate for each

system component is imposed by physical, technological, and economic constraints. The difference between the total and the unavoidable exergy destruction rate represents the avoidable exergy destruction rate, which provides a realistic measure of the potential for improving the thermodynamic efficiency of a component. Exergy loss of the system components is

$$Ex_{loss} = \frac{Ex_{in} - Ex_{out}}{Ex_{in}} \times 100\% \quad (43)$$

where Ex_{in} is the entering exergy in the system and Ex_{out} is the exiting exergy from the system. The performance of systems intended to do work can be obtained as the ratio of the actual work developed to the maximum theoretical work. This ratio is a type of exergetic (second law) efficiency. Exergy efficiency of the each component based on the second law of the thermodynamics is

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}} \times 100\% \quad (44)$$

Energy efficiency does not meet searchers' need and does not give a complete understanding of any process. Thus, use of exergy efficiency analysis is more appropriate, because it mentions not only losses but also internal irreversibilities which can be improved for overall performance of a process (Moran, 1989). In many cases, the internal irreversibilities are more significant and more difficult to deal with than external losses (Dincer, 2007).

Also, exergy efficiency of solar water-gas shift reactor is

$$\eta_{reactor} = \frac{(n_A \times \tilde{\epsilon}_{H_2}^0) / 3600}{Ex_{total\ received}} \times 100 \quad (45)$$

where $Ex_{total\ received}$ is exergy received from the solar energy.

9. Case Studies

To illustrate the principle of this approach, the following two case studies, low temperature water-gas shift reaction (LT-WSR) and high temperature water-gas shift reaction (HT-WSR), are investigated. For general assumption, the ambient temperature for exergy evaluation is assumed to be 293.15 K and neglecting the losses of heat in the reformer. Water is chosen as the working fluid in the solar cylindrical parabolic collector. Assuming that, $T_s=5777$ K, standard spectrum with $f=1.3 \times 10^{-5}$, $I_e=900$ Wm⁻², $(\alpha\tau)F_k=0.8$, $(\epsilon \bar{\rho})F_k=0.8$, $(\alpha\epsilon)F_k=0.8$, $U_L=20$ W/m²K, $\sigma =5,67 \times 10^{-8}$ W/m²K⁴.

9.1 Parabolic Trough Collector with LT-WSR

Water is chosen as the working fluid in the solar cylindrical parabolic collector. Mean isobaric heat capacity for enthalpy and entropy for entering and existing air at given temperature are given in Table 4. Assuming that, $E_G=800 \text{ W/m}^2$, $I_e=600 \text{ W/m}^2$, $C=16.76$, $T_c=708 \text{ K}$, $T_{h1}=673 \text{ K}$, $T_{h2}=473 \text{ K}$. The thermodynamic parameters of selected case study are listed in Table 5. Substituting the calculated values of enthalpy changes in Eq. (34), n_A is 3.69 kmol. For the reactants and products, $\tilde{\epsilon}_{ph,EnA}$ is 3880.2 and $\tilde{\epsilon}_{ph,ExA}$ is 1092.1 kJ/kmol, respectively.

$\tilde{C}_{p,En}^h$ (at 673.15 K)	29.36 kJ/kmolK
$\tilde{C}_{p,En}^s$ (at 673.15 K)	29.86 kJ/kmolK
$\tilde{C}_{p,Ex}^h$ (at 473.15 K)	29.02 kJ/kmolK,
$\tilde{C}_{p,Ex}^s$ (at 473.15 K)	29.44 kJ/kmolK,

Table 4. Mean isobaric heat capacity for enthalpy and entropy for air at given temperature

Properties	CO	H ₂ O	CO ₂	H ₂
\tilde{h}	283150	0	0	242000
\tilde{C}_p^h	29.32 (at 373 K)	33.15 (at 373 K)	44.08 (at 623 K)	29.28 (at 623 K)
$\tilde{\epsilon}^o$	275430	11710	20140	238490
\tilde{C}_p^ϵ	3.17 (at 373 K)	3.55 (at 373 K)	14.78 (at 623 K)	9.52 (at 623 K)

Table 5. Thermodynamic properties of reactants and products (Magal, 1994; Moran, 1989)

Table 6 presents the results of the exergy analysis for solar cylindrical parabolic reactor plant with low temperature water-gas shift reaction under consideration. The first column gives the input exergy of each component and second column gives the output exergy. The difference between the first and second column is irreversibility which is given in third column. The fourth column gives the exergy loss and the fifth column give the efficiency of each components of the solar chemical reactor based on the second law of thermodynamics.

Subsystem	Exergy received (kW)	Exergy delivered (kW)	Irreversibility (kJ)	Ex _{loss} (%)	η_{II} (%)
Solar	$E_G=800$	$Ex_{solar} = 559$	$E_{solar}=241$	30.12	69.88
Collector	$Ex_{solar} = 559$	$Ex_Q = 73.48$	$E_{collector}=485.52$	86.85	13.15
Air	$E_{EnA} = 3.97$	$E_{ExA} = 1.12$	$E_{air}=2.85$	71.78	28.22
Chemical	$Ex_{R1} = 82.18$	$Ex_{P2} = 77.97$	$E_{ch}=4.21$	5.12	94.88
Reformer	$(E_{En,A} + Ex_{R1}) = 86.15$	$(E_{Ex,A} + Ex_{P2}) = 79.09$	$E_{reformer}=7.06$	8.19	91.81
Reactor	$Ex_{total \text{ received}} = 559$	$Ex_{total \text{ delivered}} = 132.49$	$E_{total}=426.51$	76.29	23.71

Table 6. Exergetic analysis of each components of the solar cylindrical parabolic reactor

It can be seen from the Table 6, the percentage exergy loss in the collector subsystem has the greatest value, 86.85%. In other words, exergetic efficiency (η_{II}) in the collector subsystem has the minimal value. Moreover, it is known that exergy loss does not imply that it is lost forever; a good amount of it can be recovered for future use. Hence, in the solar cylindrical reactor, it is the solar collector assembly, where the effort has to be concentrated to reduce the exergy loss. Total exergetic efficiency of the solar chemical reactor is 23.71%. Exergy received of the solar cylindrical parabolic collector is equal to exergy received of collector but exergy delivered of this process is equal to exergy delivered of collector plus chemical and physical exergy difference of entering and existing products. The main reason of low efficiency of device driven by solar radiation lies in the impossibility of full absorption of the insulation (Petela, 2005). To obtain high quality energy, at high temperature, the absorbing surface has to be at high temperature, which produces a large loss of energy by emission from the surface. This factor influences exergy efficiencies.

9.2 Parabolic Trough Collector with HT-WSR

Water is chosen as the working fluid in the solar cylindrical parabolic collector. Mean isobaric heat capacity for enthalpy and entropy for entering and existing air at given temperature are given in Table 7. Assuming that, $E_G=900$ W/m², $I_e=700$ W/m², $C=21.84$, $T_c=808$ K, $T_{h1}=773$ K, $T_{h2}=573$ K. The thermodynamic parameters of selected case study are listed in Table 8. Substituting the calculated values of enthalpy changes in Eq. (34), n_A is 2 kmol.

For the reactants and products, $\tilde{\epsilon}_{ph,EnA}$ is 5654.2 and $\tilde{\epsilon}_{ph,ExA}$ is 2345.6 kJ/kmol, respectively.

$\tilde{C}_{p,En}^h$ (at 773.15 K)	29.53 kJ/kmolK
$\tilde{C}_{p,En}^s$ (at 773.15 K)	29.97 kJ/kmolK
$\tilde{C}_{p,Ex}^h$ (at 573.15 K)	29.19 kJ/kmolK,
$\tilde{C}_{p,Ex}^s$ (at 573.15 K)	29.65 kJ/kmolK,

Table 7. Mean isobaric heat capacity for enthalpy and entropy for air at given temperature

Properties	CO	H ₂ O	CO ₂	H ₂
\tilde{h}	283150	0	0	242000
\tilde{C}_p^h	29.57 (at 473 K)	33.93 (at 473 K)	45.44 (at 723 K)	35.33 (at 723 K)
$\tilde{\epsilon}^o$	275430	11710	20140	238490
\tilde{C}_p^ϵ	6.33 (at 473 K)	7.22 (at 473 K)	17.81 (at 723 K)	11.21 (at 723 K)

Table 8. Thermodynamic properties of reactants and products (Magal, 1994; Moran, 1989)

Table 9 presents the results of the exergy analysis for solar cylindrical parabolic reactor plant with low temperature water-gas shift reaction under consideration. The first column gives the input exergy of each component and second column gives the output exergy. The

difference between the first and second column is irreversibility which is given in third column. The fourth column gives the exergy loss and the fifth column give the efficiency of each components of the solar chemical reactor based on the second law of thermodynamics.

Subsystem	Exergy received (kW)	Exergy delivered (kW)	Irreversibility (kW)	Ex _{loss} (%)	η _{II} (%)
Solar	E _G =900	Ex _{solar} = 652	E _{solar} =248	27.55	72.45
Collector	Ex _{solar} = 652	Ex _Q = 148.2	E _{collector} =503.8	77.26	22.74
Air	E _{EnA} = 3.14	E _{ExA} = 1.83	E _{air} =1.31	41.72	58.28
Chemical	Ex _{R1} = 83.1	Ex _{p2} = 82.63	E _{ch} =0.56	0.56	99.44
Reformer	(E _{En,A} + Ex _{R1}) = 86.24	(E _{Ex,A} + Ex _{p2}) = 84.46	E _{reformer} =1.87	2.16	97.84
Reactor	Ex _{total received} = 652	Ex _{total delivered} = 185.56	E _{total} =466.44	71.54	28.46

Table 9. Exergetic analysis of each components of the solar cylindrical parabolic reactor

It can be seen from the Table 9, the percentage exergy loss in the collector subsystem has the greatest value, 77.26%. Total exergetic efficiency of the solar chemical reactor is 28.46%.

10. Conclusion

Exergy analysis is now a well accepted tool for process optimization. Exergy analysis do a better job of quantifying the efficiency of energy conversation processes than those traditionally accepted based on the energy efficiency. Exergy analysis reflects more accurately the true performance of a technological system. Also, minimizing the exergy destroyed throughout the industrial chain can decrease the total impact of a process upon the environment. The motivation for the present study lies in the increased in utilization of medium temperature heat sources such as solar energy and in the increased interest and success in applying exergy analysis as a measure of system performance. It is argued that irreversibility analysis represents suitable basis for the evaluation of the usefulness of medium temperature heat.

The exergy analysis of solar energy conversation systems is particularly useful in their design and provides the basis for choosing the operating range. Also, exergy analysis is now a well-accepted tool for process optimization. The motivation for the present study lies in the increased utilization of medium temperature heat sources such as solar energy and in the increased interest and success in applying exergy efficiency as a measure of system performance. It is argued that exergy analysis represents suitable basis for the evaluation of the usefulness of medium temperature solar reactor.

The requirements for greater exergy efficiencies and introduction of new solar devices have led to the need for improved methods of predicting design parameters. In this study, exergy analysis applied to the solar cylindrical parabolic reactor. Irreversibility rates of solar radiation, cylindrical parabolic collector and reformer, obtained in the analysis of solar chemical reactor system are given some significant information for scientists and designers before decision making.

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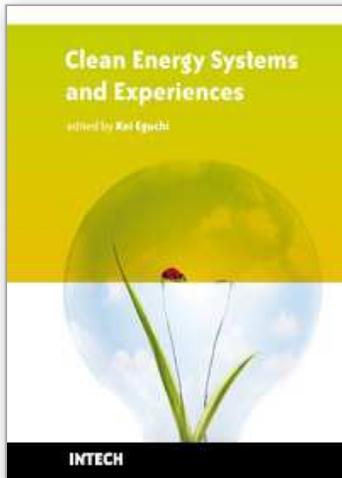
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51000 Rijeka, Croatia
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Phone: +86-21-62489820
Fax: +86-21-62489821

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