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Exergy Analysis of Hydrogen Production from Palm Oil Solid Wastes using Indirect Gasification

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Abstract

Background: The extraction of oil from African palm fruits (*Elaeis guineensis*) generates solid wastes such as Empty Fruit Bunch (EFB), mesocarp fibers, palm frond, palm trunk and palm kernel shell, which exhibit great capability to be employed for producing value-added products, such as hydrogen. **Objectives:** In this work, exergy analysis of hydrogen production from EFB was carried out using indirect gasification and purification with selexol in order to evaluate overall efficiency of this process. **Methods/Analysis:** Based on operational conditions (mass flow, temperature and pressure), the process was modeled using a commercial process simulation software, physical and chemical exergies of streams were calculated, stage and overall irreversibilities and exergy efficiencies were found. Stages that require improvements were identified and sensibility analysis was implemented to increase overall exergy efficiency. **Findings:** It was found that 36 t/h of EFB produce 2.5522 t/h of hydrogen with an overall exergy efficiency of 20%. **Novelty/Improvement:** Sensibility analysis suggested that process efficiency in terms of exergy could be improved by recycling selexol to hydrogen separation stage, which led to increase the products exergy to 469,747.05 MJ/h.

Keywords: Empty Fruit Bunch, Exergy Analysis, Hydrogen, Palm Oil, Solid Waste

1. Introduction

Palm oil industry has grew over the last decades driven by population growth and increased energy demand.[1] African palm oil (*Elaeis guineensis*), native to the north-western region of Africa (Guinea-Bissau), is a perennial monocotyledonous tropical plant whose oil is now the primary source of edible vegetable oil.[2] It has become the world's number one fruit crop because of its unparalleled productivity. This is the highest oil yielding plant among perennial oil yielding crops, producing palm oil and palm kernel oil.[3] The increase in palm oil production has resulted in the generation of a large amount of biomass wastes, which are mainly obtained from plantation and milling activities.[4,5] Improper disposal of palm oil waste cause: (i) contamination of groundwater through leaching or run-off water, (ii) attraction of air or vector-borne diseases, and (iii) non-exploitation of full potential of residues. Due to numerous disadvantages of the existing disposal technique, researchers are urged to explore the potential uses of PALMOIL solid residues.[6] Wastes from PALMOIL mill and plantation are consisting of Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), Palm Mesocarp Fiber (PMF), PALMOIL Frond (POF) and Palm Oil Trunk (POT) are feasible to be used as a source of renewable energy.[7] EFB is the most abundant and available biomass generated from the palm oil industry throughout the year during threshing of bunches.[5] Value-added products can be developed from this ligno-cellulosic biomass such as hydrogen gas.[1,8] Generally, biomass conversion technology can be classified into three main categories, namely thermo

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chemical, biological and physical conversion.[9] In the process of conversion of biomass for thermal, there are a number of ways such as combustion, gasification and pyrolysis.[10] In Gasification process biomass feedstock is converted into higher heating value fuel.[11] On the other hand, exergy analysis is a method for quantifying the efficiency of a variety of energy transfer processes.[12] It has been implemented to industrial process due to its concept incorporates both first and second laws of thermodynamics and provides a feasible approach for efficient energy planning.[13] The aim of this study was to applied exergy analysis to hydrogen production from EFB in order to determine overall exergy efficiency and identify process stages that exhibit highest irreversibility's.

2. Material and Methods

2.1 Process Description

The process of hydrogen production from EFB via indirect gasification is shown in Figure 1. Palm oil biomass composition is given in Table 1. The feedstock is milled and dried in order to reduce particle size and remove liquid content. Then, dried biomass is sent to Gibbs reactor, where synthesis gas is obtained. Solid impurities after reaction are separated from gas phase by cyclone equipment. Solid wastes pass through a combustion process to produce heat, which is recycled to gasification stage. Before entering to High Temperature Shift (HTS) reactor, synthesis gas is cooled. In this reactor, methane is converted to CO and H_2. Then, CO is sent to Low Temperature Shift (LTS) reactor in order to produce CO_2 and H_2. Finally, hydrogen is separated from water by condensation and its purification is performed using selexol, which dissolves undesired components such as CH_4, CO and CO_2. Selexol stream passes through desorption column to reuse it in this process.

Table 1. Composition of palm oil biomass (EFB)

Component	Composition* (%)
Water	49.7237
Cellulose	23.9873
Hemicellulose	11.9936
Lignin	11.9936
Ashes	2.30135

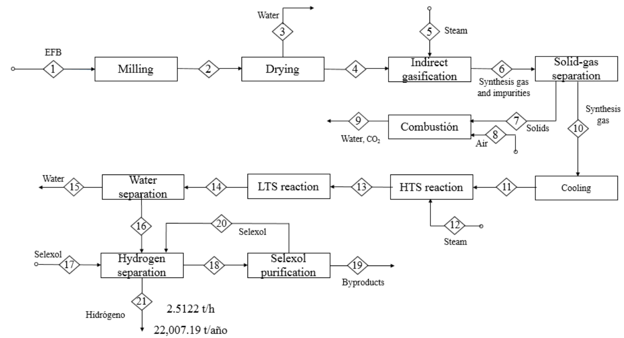

Figure 1. Block diagram of hydrogen production process from EFB.

2.2 Exergy Analysis

Exergy analysis is based on the second law of thermodynamics, whose effects are due to kinetic and potential energy changes that are neglected; the general exergy rate balance is expressed as:

$$\dot{E}x_{destroyed} = \dot{E}x_{work} + \dot{E}x_{heat} + \dot{E}x_{stream} \quad (1)$$

The exergy transfer as work of a system is equal to work when there are no changes in volume:

$$\dot{E}x_{work} = \dot{W} \quad (2)$$

The exergy transfer as heat is given by Equation 3.

$$\dot{E}x_{heat} = \sum\left(1 - \frac{T_0}{T}\right)Q \quad (3)$$

Exergy of stream is defined by two components: chemical and physical exergy, as described by the Equation (4).

$$\dot{E}x_{stream} = \dot{E}x_{phy} + \dot{E}x_{chem} \quad (4)$$

The physical exergy is given by:

$$\dot{E}x_{phy} = \left(\dot{H} - \dot{H}_0\right) - T_0\left(\dot{S} - \dot{S}_0\right) \quad (5)$$

When the stream behaves as ideal gas with constant heat capacity, Equation (6) is used.

$$\dot{E}x_{phy,gas} = C_P(T - T_0) - T_0\left(C_P Ln\frac{T}{T_0} - RLn\frac{P}{P_0}\right) \quad (6)$$

On the other hand, if the stream includes solid or liquid phases, the following equation is required:

$$\dot{E}x_{phy,liq-sol} = C_P\left[(T - T_0) - T_0 Ln\frac{T}{T_0}\right] - V_m\left(P - P_0\right) \quad (7)$$

Chemical exergy is the work obtained when a substance achieves thermodynamic equilibrium through chemical reactions. These exergies are usually found in literature; however, they can be calculated with Equation (8).

$$\dot{E}x_{chem} = \Delta G_f^0 + \sum V_i Ex^0_{Ch-i} \quad (8)$$

In case of mixture, it is defined by its components and respective compositions

$$\dot{E}x_{chem} = \sum_i y_i \times Ex^0{}_{ch,i} + RT_0 \sum_I y_i \times \ln\ln\left(y_I\right) \quad (9)$$

Exergy can enter the system in two ways: mass flow or utilities required by the system (i.e. heating or cooling).

$$\dot{E}x_{in} = \dot{E}x_{stream} + \dot{E}x_{utilities} \quad (10)$$

The exergy that leaves the system is associated with product and waste streams as is defined by Equation (11).

$$\dot{E}x_{out} = \dot{E}x_{stream,products} + \dot{E}x_{stream,wastes} \quad (11)$$

The irreversibilities of this process are represented by destroyed exergy, which is calculated by Equation (12).

$$\dot{E}x_{destroyed} = \dot{E}x_{inlet} - \dot{E}x_{stream,products} \quad (12)$$

The exergy efficiency is given by Equation (13).

$$n = 1 - \frac{\dot{E}x_{destroyed}}{\dot{E}x_{in}} \quad (13)$$

3. Results and Discussion

3.1 Process Simulation

Operation conditions (temperature and pressure) of production process are summarized in Table 2. Hemicelluloses and lignin were considered as xylose and dextrose, respectively. As is known, lignin is an organic polymer, not a polysaccharide; however, this consideration did not significantly affect any results. In addition, Selexol solvent was assumed as ethylene glycol because this commercial solvent is made up of a mixture of polyethylene glycol dimethyl ethers. Figure 2 displays process flow diagram of hydrogen production from EFB.

Table 2. Stream operation condition of hydrogen production process

Stage	Temperature (K)	Pressure (bar)
Milling	303.15	1
Drying	374.15	0
Gasification	1,075.15	60
Solid separation	-	60
HTS reaction	647.15	55
LTS reaction	547.15	55
Liquid separation	313.15	45
Absorption	-	40
Selexol purification	363.15	1

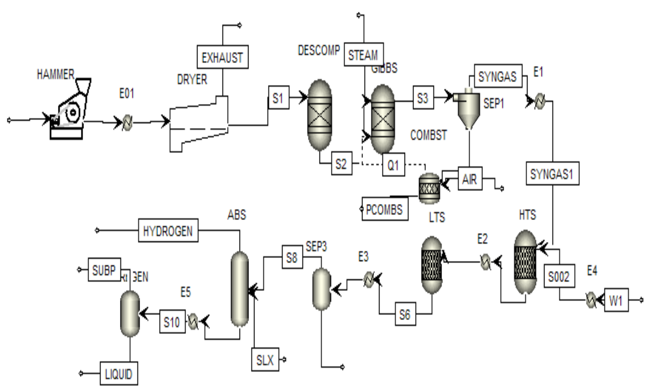

Figure 2. Process flow diagram of hydrogen production from palm oil solid wastes (EFB).

3.2 Exergy Analysis

Exergy analysis offered information about stages that are inefficient and affect significantly the overall efficiency of the process. Table 3 shows mass flow, chemical exergy and physical exergy of streams.

Irreversibilities or destroyed exergy of process stages were calculated using equations previously described. As it is observed in Figure 3, the stage that most contributes to total irreversibilities is absorption process, in which selexol dissolves undesired components.

Figure 4 shows that total exergy of input is higher than total exergy of products; therefore, this is the stage with most irreversibilities. In addition, it can be observed that absorption exhibits highest value for exergy of wastes. If these residues are used (corresponding to carbon dioxide in 98%), it could substantially increase the overall exergy efficiency.

The overall efficiency of this process based on exergy analysis was relatively low (20%) as shown in Figure 5, which can be attributed to that it is considered solid wastes from first separation stage as not used stream. However, indirect gasification technology proposes that this stream can be used to generate an industrial service (heat). In addition, selexol from absorption stage is also assumed as waste, although it is proposed its recirculation in order to increase overall exergy efficiency.

Table 3. Chemical and physical exergies of process streams

Stream	Massflow (Kg/h)	Chemical exergy (MJ/h)	Physical exergy (MJ/h)
1	36,000	337,829.1546	5.5554
2	36,000	355,590.2516	9,044.71
3	18,000	18,321.0423	8,829.1
4	18,000	339,174.3513	215.572
5	15,030	36,059.0719	28,133.3
6	33,030	409,955.4473	126.758
7	5,090	171,031.1209	23,650.200
8	20,951	895,111.4858	20,951.500
9	26,041	932,366.3826	52,354.800
10	27,940	325,879.4628	61,211.11
11	27,940	286,272.7528	21,604.4
12	3,500	6,265.5655	4,419.91
13	31,440	305,091.5764	23,533.1
14	31,440	312,313.2914	21,709
15	5,603	3,155.6075	76.55
16	25,837	311,106.7133	21,129.3
17	55,000	1,069,385.2050	130.205
18	78,325	1,081,130.5311	1,776.240
19	23,539	25,328.4819	7,490.460
20	54,786	1,064,084.4617	1,010.780
21	2,512	298,715.9239	16,394.200

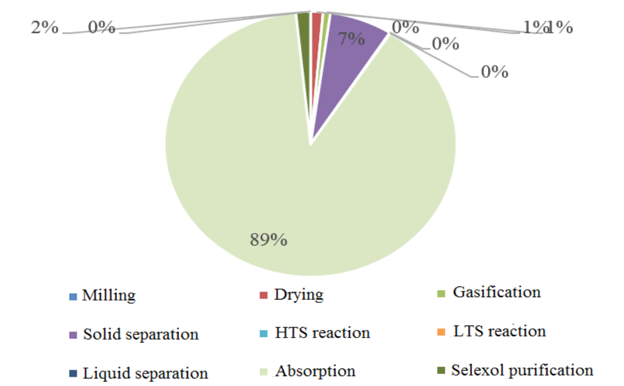

Figure 3. Contribution of process stages to total irreversibility.

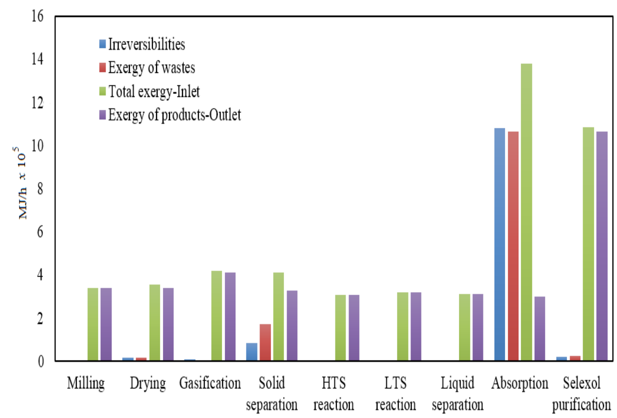

Figure 4. Exergy analysis results per stage of the process.

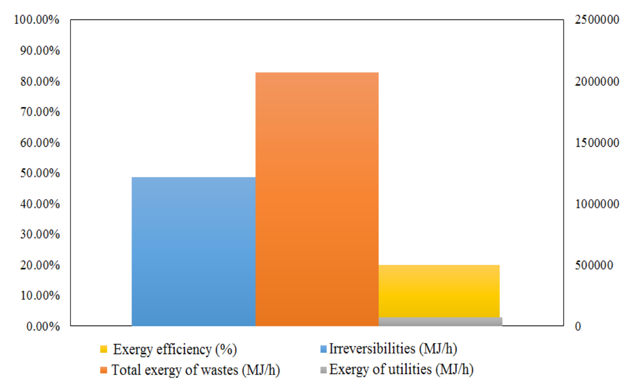

Figure 5. Exergy analysis results for production of hydrogen from palm oil solid wastes (EFB), using indirect gasification.

3.3 Sensibility Analysis

Figure 6 shows overall exergy efficiency variations when exergy efficiency of absorption stage increases from 0 to 100 %. If Selexol stream that has captured CO_2 is not considered as waste, the overall exergy efficiency increases dramatically.

As is presented in Figure 7, overall exergy efficiency increases until 25.55 % when exergy efficiency of solid separation stage is 100%.Likewise, overall efficiency is positively affected when selexol that has absorbed CO_2 is considered as product because it can be recalculated to this process in Figure 8.

Finally, it is observed that huge amount of $CO_2$is waste of hydrogen production from EFB, with a mass flow of 23,491.227 kg/h; hence, different alternatives have to be considered for reducing it. One of them could be electrochemical conversion process with catalyst based on copper, carbon and nitrogen NANO particles to produce ethanol with a 63% productivity yield.[14]

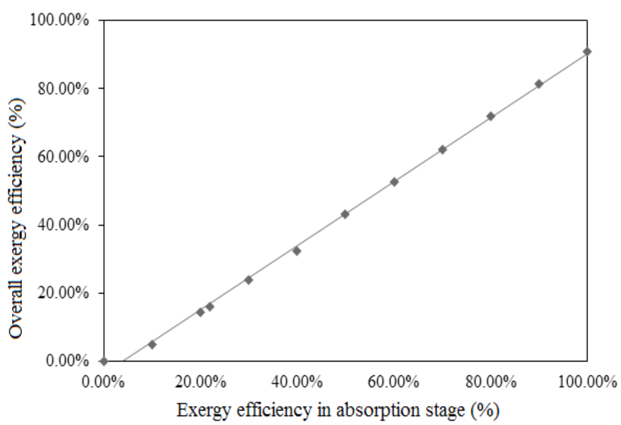

Figure 6. Overall exergy efficiency versus exergy efficiency in absorption stage.

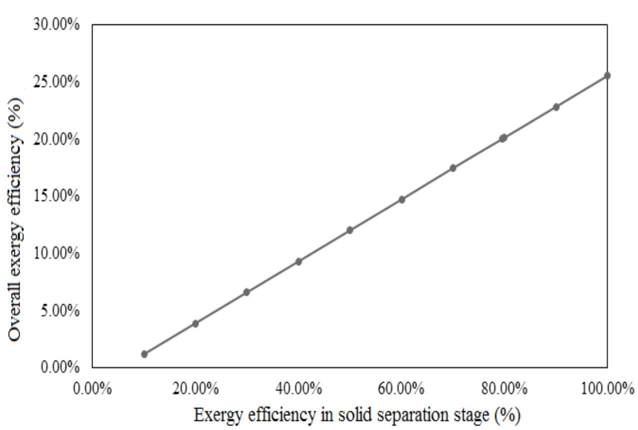

Figure 7. Overall exergy efficiency versus exergy efficiency in solid separation stage.

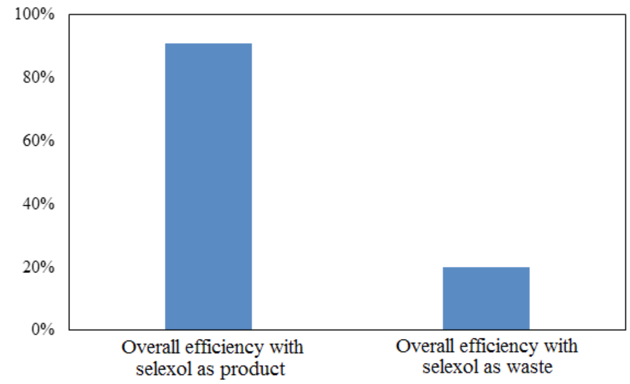

Figure 8. Comparison of overall exergy efficiencies when selexol is considered as product and waste. *Wet basis

4. Conclusion

In this work, exergy analysis was performed to hydrogen production process from empty fruit bunch as palm oil biomass. From 36 t/h of EFB, it was obtained 2.55 t/h of hydrogen with an overall exergy efficiency of 20%. The stages that exhibited highest destroyed exergy were absorption and solid separation. Total irreversibility was calculated in 1,081,775.994 MJ/h and 89% of this value was attributed to absorption stage. From sensibility analysis, it was purposed the use of wastes generated in hydrogen separation. Therefore, when selexol is recycled, exergy of products is incremented to 469,747.0448 MJ/h, which enhances overall exergy efficiency.

5. Acknowledgments

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