Heat Integration Analysis of Gasification Process for Hydrogen Production from Oil Palm Empty Fruit Bunch

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A heat integrated flowsheet has been designed for hydrogen production from oil palm empty fruit bunch (EFB) via steam gasification with in-situ CO₂ capture. The process energy requirement and cost are calculated from the mass balances, energy balances and the economic model of flowsheet. The flowsheet calculation and cost minimization are carried out using MATLAB. The flowsheet under investigation includes steam generation unit, gasification unit and gas cleaning unit. For heat integration studies on the flowsheet, the pinch analysis is employed to obtain the energy efficient and self-sustained system. The heat integration study is carried out using SPRINT software. The analysis shows that considerable saving can be obtained for steam production using heat integration application as there is a large amount of available waste heat from the gas cleaning and cooling units. The results show that the minimum hot utilities required is 601.85 kJ/h and the minimum cold utilities is 13.82 kJ/h for the case of minimum temperature difference of 10 K. Furthermore, a feasible heat exchanger network that fulfills these requirements has been presented. Moreover, the cost of hydrogen production decreases from 1.91 to 1.84 US$/kg of H₂ by applying heat integration approach in the flowsheet.

1. Introduction

Malaysia is the largest exporter of palm oil with the production of empty fruit bunch (EFB) with more than 17 million tonnes/year (Shuit et al., 2009). Biomass steam gasification for hydrogen production is not only in favor of more hydrogen but also economical than other conventional gasifying methods and pyrolysis (Balat, 2008). Furthermore, hydrogen purity can be increased in the product gas with in situ CO₂ capture technique using CaO as sorbent (Florin and Harris, 2008). The hydrogen production cost can be reduced with energy efficient system through increasing thermal integration of the system (Eljack et al., 2005). Lutterbacher et al., (2009) presented a model for hydrothermal gasification of biomass for upgrading of biomass to synthetic natural gas (SNG). The model incorporated the flowsheet mass, energy balances and heat and power integration. The thermo economic analysis showed that high efficiency process could be attained using heat integrated configurations. Heyne et al., (2010) also reported a study on SNG production from gasified biomass using integrated flowsheet design using ASPEN PLUS. They used pinch analysis method for the calculation of optimal internal heat recovery within the

The objective of the present work is to apply process integration in the flowsheet design for enriched hydrogen production from EFB via steam gasification with CO$_2$ capture in a single pass fluidized bed gasifier. The feasibility of the process is investigated via parametric studies of energy recovery on the hydrogen cost using MATLAB. Pinch analysis approach is employed to integrate heat sources and sinks, to determine energy targets and to identify potential improvement in the flowsheet to obtain lower production cost and increased energy efficiency and self-sustainability.

2. Process Development

The process flowsheet diagram was presented by authors in earlier work (Inayat et al., 2010). EFB is used as the feedstock biomass and is pretreated i.e. dried and ground. The gasifier operates at atmospheric pressure and assumed to be at steady state condition (Inayat et al., 2010). Steam is used as the gasification agent, produced in a steam generator and superheated using super heaters. The product gas from the gasifier is cooled down by passing it through a scrubber, and hydrogen recovered and purified using a pressure swing adsorption (PSA) unit. The steam gasification process is an endothermic process which requires external energy that is supplied using heaters.

3. Cost Minimization

The minimum hydrogen production cost is solved subject to the process constraints (Inayat et al., 2010) as formulated below.

$$\text{Minimize } \text{hydrogen production cost} = \frac{\sum \text{Total cost}}{\sum \text{Total hydrogen production}}$$

Subject to:  Total Cost  
Total Hydrogen Produced  
Reaction Kinetics  
Mass Balances  
Energy Balances  
H$_2$ mol% > 80 %  
H$_2$ yield > 15 g/h (0.015 kg/h)  
H$_2$ Efficiency > 80 %  
Thermodynamic Efficiency > 80 %

Bounds:  850 < Temperature (K); < 1150; 2.0 < Steam/biomass ratio < 4.0;  
0.2 < Sorbent/biomass ratio < 1.6
The optimization is carried out using MATLAB optimization solver named fmincon. The minimum production cost of 1.91 US$/kg is obtained at 1150 K, steam/biomass ratio of 4 and sorbent/biomass ratio of 0.87. The hydrogen yield and purity at the optimal condition are 0.0179 kg/h and 79.91 mol% respectively.

4. Heat Integration

Heat integration study using SPRINT software is next applied to improve the system’s energy efficiency and self-sustainability. The SPRINT is commercial process heat integration software developed by University of Manchester, United Kingdom. For heat integration studies on the flowsheet, the pinch analysis is employed to obtain the required minimum utilities. The stream data are extracted from the energy balance of the flowsheet at the optimum conditions with minimum hydrogen production cost calculated in the previous section. The energy balance on the flowsheet is shown in Figure 1.

![Sankey diagram of energy balance for the flowsheet. Temperature: 1150 K; Steam/biomass ratio: 4; Sorbent/biomass ratio: 0.87](image)

The stream data are shown in Table 1. The table shows that energy required for cold streams C1 and C2 are 305 and 1115 KJ respectively. C1 is the stream for super heated steam generation and C2 is the energy required to the gasification process. H1 is the hot stream from scrubber.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Name</th>
<th>Supply Temp. (K)</th>
<th>Target Temp. (K)</th>
<th>Energy (kJ/h)</th>
<th>Heat Capacity Flowrate (kW/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H1</td>
<td>900</td>
<td>298</td>
<td>832</td>
<td>1.38206</td>
</tr>
<tr>
<td>2</td>
<td>C1</td>
<td>298</td>
<td>523</td>
<td>305</td>
<td>1.35556</td>
</tr>
<tr>
<td>3</td>
<td>C2</td>
<td>298</td>
<td>1150</td>
<td>1115</td>
<td>1.30869</td>
</tr>
</tbody>
</table>
There is 832 kJ of energy available for heat integration as shown in Figure 1. The calculation is performed with the minimum temperature difference of 10 K. The composite curves for hot streams and cold streams are generated using SPRINT, given in Figure 2. It can be calculated based on the composite curves that the minimum hot utilities required is 601.85 kJ/h and minimum cold utility is 13.82 kJ/h.

**Figure 2: Composite curves for hot streams (red) and cold streams (blue)**

Furthermore, Heat Exchanger Network (HEN) has been developed and optimized using SPRINT as shown in Figure 3. There are three heat exchangers required to fulfil minimum amount of hot and cold utilities with the temperature difference of 10 K.

**Figure 3: Optimized heat exchanger network**
Based on the matching in the developed HEN, the heat integrated process flowsheet design as shown in Figure 4 is proposed. The production cost of hydrogen is recalculated for the heat integrated flowsheet. It is observed that by using heat integration, the hydrogen cost decreases from 1.9105 to 1.8405 US$/kg of H₂. So, using heat integration application, the flowsheet not only becomes energy efficient and self-sustained but also offers lower hydrogen production cost.

![Figure 4: Integrated process flowsheet design](image)

A comparison of hydrogen production cost between the current study and others on similar processes is shown in Table 2. The results indicate that this system has the potential to offer low production cost for hydrogen production from EFB in Malaysia.

**Table 2: Comparison of hydrogen production cost**

<table>
<thead>
<tr>
<th>H₂ cost (US$/kg)</th>
<th>Process</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.69</td>
<td>Pine wood blocks gasification and CO shift</td>
<td>Lv et al., (2008)</td>
</tr>
<tr>
<td>1.91</td>
<td>Palm oil empty fruit bunch steam gasification with in-situ CO₂ capture</td>
<td>(Current study)</td>
</tr>
<tr>
<td>1.84</td>
<td>Palm oil empty fruit bunch steam gasification with in-situ CO₂ capture</td>
<td>(Current study)</td>
</tr>
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</table>
5. Conclusion

A heat integration study has been carried out on the flowsheet design for H₂ production from EFB via steam gasification with in-situ CO₂ capture. The minimum production cost is solved to be 1.9105 US$/kg of H₂. For heat integration studies on the flowsheet, the pinch analysis is employed to obtain the energy efficient and self-sustained system using SPRINT software. The analysis shows that considerable saving can be obtained for steam production using heat integration application. Moreover, using the heat integration the H₂ production cost can be reduced to 1.8405 US$/kg.

References

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Smjeikal Q., Sarlej M. and Stehlík P., 2009, New unit for clean energy production from contaminated biomass (1 to 3 MW,)-example of process design, Chem. Eng. Trans., 18, 57-62