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Theoretical thermal efficiency of conventional steam reforming of groundnut shell

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Abstract

The aim of the study was to determine the theoretical thermal efficiency of conventional steam reforming of groundnut shell (CSR-GS) using the 'DH ratio' factor. It was found that the energy cost of CSR-GS is dominated by the enthalpy of heating liquid water from 298 K (25 °C) to reforming temperature. Thus, energy cost increases with the increase in steam-to-carbon ratio. It was concluded that the conventional steam reforming of groundnut shell has poor thermal efficiency at all the investigated steam-to-carbon ratios and temperatures (700 to 1200 K). However, at a steam-to-carbon ratio of 1 combined with a temperature of 700 K, the DH ratio was 1.0, which is almost more thermodynamically advantageous than water splitting.

1. Introduction

Hydrogen is the cleanest fuel known to mankind with no greenhouse gas emissions since the only biproduct of burning hydrogen fuel is water vapor. The applications and uses of hydrogen cannot be overemphasized, as they are many ranging from power production, synthetic fertilizers production, refinery operations, metal processing, food processing, chemicals production, glass production, and electronics industries to mention a few [1-3].

For over 70 years, conventional steam reforming has been the leading technology of hydrogen production. The technology is fully matured and accounts for 48% of global hydrogen production, while other techniques (oil/naphtha, coal gasification, electrolysis, and other processes) represent 52% of hydrogen production combined [4][5].

Global demand for hydrogen is projected to increase in both the chemical and energy sectors. Approximately, 90% of worldwide hydrogen production comes from the use of fossil fuels as feedstock, which arguably contributes to climate change and global warming [4][6-8]. Thus, it is crucial to finetune hydrogen production from sustainable and renewable resources to minimize its environmental footprint.

Since the eighties of the previous century, groundnut production has been rising due to the expansion in its production area and productivity. More than half the production of groundnut in West Africa is produced in Nigeria, which represents 10% of the global groundnut production [9]. Groundnut shell is a leftover product of the groundnut industry. Therefore, and due to the large production quantities of groundnut, using groundnut shells as a feedstock for hydrogen production might be a suitable utilization for this widely available organic residue.

Many researchers have investigated thermodynamic stimulation of hydrogen production using diverse fuel and feedstocks ranging from shale gas [1][2] to methane [11] and including propane [12], hydroxy acetone [13], acetic acid [14], and urea [15] (Table 1). The thermodynamic analysis gives more insight into a system's overall performance

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and this undoubtedly leads to finding the sources of losses owing to irreversibility in each process in a system. Furthermore, these simulations play a vital role in making economic and useful process modifications or operational changes [16]. Thus, the main aim of this research was to investigate the theoretical thermal efficiency of conventional steam reforming of groundnut shell.

Table 1. Summary of some previous work methodology and/or software used for thermodynamic analysis/stimulation of hydrogen production

Title	Reference	Methodology and/or software used
Chemical equilibrium analysis of hydrogen production from shale gas using sorption enhanced chemical looping steam reforming	[1]	Gibbs free energy minimization method with CEA and Aspen Plus
Effect of hydrocarbon fractions, N_2 and CO_2 in feed gas on hydrogen production using sorption enhanced steam reforming: thermodynamic analysis	[2]	
Thermodynamic analysis of hydrogen production from conventional steam reforming of groundnut shell	[10]	
Thermodynamic analysis of hydrogen production via sorption-enhanced steam methane reforming in a new class of variable volume batch-membrane reactor	[11]	Gibbs free energy minimization method
Hydrogen production by sorption enhanced steam reforming of propane: a thermodynamic investigation	[12]	Gibbs free energy minimization method with Matlab language and Lagrange's undetermined multiplier method
Comparative analysis on sorption enhanced steam reforming and conventional steam reforming of hydroxyacetone for hydrogen production: thermodynamic modeling	[13]	Gibbs free energy minimization principle and response reactions (RERs) method
High hydrogen yield and purity from palm empty fruit bunch and pine pyrolysis oils	[14]	Gibbs free energy minimization method with The FORTRAN program EQUIL
Thermodynamics of hydrogen production from urea by steam reforming with and without in situ carbon dioxide sorption	[15]	Gibbs free energy minimization method with The code EQUIL from the CHEMKIN II package
Thermodynamic analysis of steam reforming of glycerol for hydrogen production at atmospheric pressure	[17]	Gibbs free energy minimization method with CHEMCAD
Thermodynamic analysis and optimization for steam methane reforming hydrogen production system using high temperature gas-cooled reactor pebble-bed module	[18]	Gibbs free energy minimization method with a mathematical model and MATLAB
Thermodynamic analysis of steam reforming of methane with statistical approaches.	[19]	Gibbs free energy minimization method with statistical modeling

2. Materials and Methods

2.1. Feedstock composition and simulation conditions

The elemental composition of the groundnut shell feedstock was obtained from the literature [20] (Table 2). The feedstock is readily available in Nigeria as agricultural waste and is among the few biomasses with high hydrogen composition [10][20].

Based on the mentioned feedstock composition, stimulation conditions were arranged with eight steam-to-carbon ratios (S:C) (1 to 8), temperature (700 K to 1200 K), and pressure (1 bar). where 'C' represents moles of carbon in the feed, and 'S' the moles of water feed as a liquid at 298 K (25°C) that will transform to steam at reforming temperature

Table 2. Composition of groundnut shell used for stimulations [20]

Feed	Composition (% based on dry weight)
C	50.9
O	40.4
H	7.5
N	1.2
S	0.02
Total	100

2.2. Thermodynamic analysis

Thermodynamic equilibrium calculations of conventional steam reforming of groundnut shell (CSR-GR) were performed using Chemical Equilibrium Applications (CEA) software developed by NASA [21]. The software uses a solution method based on the minimization of Gibbs energy function of a feed mixture to determine the mole fractions of the equilibrium mixture of products.

The thermal efficiency of the process was evaluated using the DH ratio factor. 'DH ratio' is the enthalpy of generating 1 mol of hydrogen via the considered equilibrium process divided by that of generating 1 mol of hydrogen via thermal water splitting from reactants in their natural state at 298 K (25°C) and ending with products at reaction temperature. DH ratio can also be described as the measure of energy expenditure of producing hydrogen through the groundnut shell-water system compared to the energy gained by the evolution of heat from combusting this hydrogen with oxygen, signifying its final use in a fuel cell or combustion process [1][15]. A DH ratio greater than one (>1) denotes an inefficient process from an energy perspective, since the energy needed to generate hydrogen is greater than the energy released through hydrogen oxidation or combustion in a heat or power-generating device. On the other hand, a DH ratio of less than one (<1) denotes an efficient and theoretically economical hydrogen-generating process from an energy viewpoint. Enthalpy calculations were made based on the following equations [1][2].

$$\Delta H_{GS} = H_{feed\ GS}\ at\ T_R - H_{feed\ GS}\ at\ 298\ K\ (kJ)\ (1)$$

$$\Delta H_{H20} = H_{feed\ H2O\ Vapour}\ at\ T_R - H_{feed\ H2O\ Liquid}\ at\ 298\ K\ (kJ)\ (2)$$

$\Delta H_{Reactants} = \Delta H_{GS} + \Delta H_{H2O}$ (3)

Reaction Enthalpy change $\Delta H_{Reaction}$:

$$\Delta H_{Reaction} = H_{Product\ mixture}\ at\ T_R - H_{Reactants\ mixture}\ at\ T_R\ (kJ)\ (4)$$

Total enthalpy change of process ΔH_{Total} is

$$\Delta H_{Total} = \Delta H_{Reactants} + \Delta H_{Reaction}\ (kJ)\ (5)$$

Thus,

$$DH_{Ratio} = \Delta H_{Total} / \Delta H_{WSP}\ (6)$$

$$\Delta H_{WSP} = 0.5 \times H_{O_2}\ at\ T_R + H_{H_2}\ at\ T_R - H_{H_2O\ liquid}\ at\ 298\ K\ \left(\frac{kJ}{mol\ H_2}\right)\ (7)$$

Where ΔH is the change in enthalpy, H is the enthalpy of relevant species formation at the indicated temperature, GS stands for groundnut shell, T_R reaction temperature, and WSP for water splitting.

3. Results and Discussion

3.1. DH ratio of conventional steam reforming of groundnut shell

DH ratio value was higher than 1 for all the investigated steam-to-carbon ratios except for S:C ratio of 1, where the DH ratio was 1.0 and 1.4 at the temperature of 700 and 750 K respectively (Fig. 1 A). The DH ratio value of 1.0 at 700 K is almost more thermodynamically advantageous to water splitting. The noticed DH ratio increases with temperature increase is expected, since a higher S:C ratio means that more energy is required to heat the excess steam [1][2][15]. Another disadvantage of operating at a high S:C ratio is that a higher reactor volume will be required with increased catalyst deactivation incidents due to pore blockage [1][22][23].

3.2. Effect of steam-to-carbon ratio on total and reaction DH of conventional steam reforming of groundnut shell

Both the total DH (fig. 1 B) and reaction DH (fig. 1 C) increased with the increase of steam-to-carbon ratio. The total DH at S:C ratio of 1 and 950 K was 5950 kJ while that of 2 at similar operating conditions and temperature was 14143 kJ. This is equivalent to 58 % rise in energy demand between steam-to-carbon ratio of 1 and 2 at exactly same operating conditions. At the temperature of 900 K, which corresponds to the temperature of maximum hydrogen yield for both steam-to-carbon ratio of 7 and 8 [20], the reaction DH at steam-to-carbon ratio of 7 and 8 were 24146 and 27863 kJ respectively, which is equivalent to 13 % increase. The behaviour of the total and reaction DH in the present study is similar to that previously reported in [1][2][15].

3.3. Effect of individual enthalpies on conventional steam reforming of groundnut shell

The heating demand of the groundnut shell was the same for all the investigated steam-to-carbon ratios as their molar input remained unchanged (Fig. 1 D). On the other hand, the heating demand of water increased with the increase in S:C ratio (Fig. 1 E). Overall, the heating demand of conventional steam reforming of groundnut shell is dominated by the enthalpy of water. The observed unchanged heating demand of feedstock and increased energy demand with the increase in steam-to-carbon ratio is in agreement with previous studies conducted on different feedstocks [1][2][15].

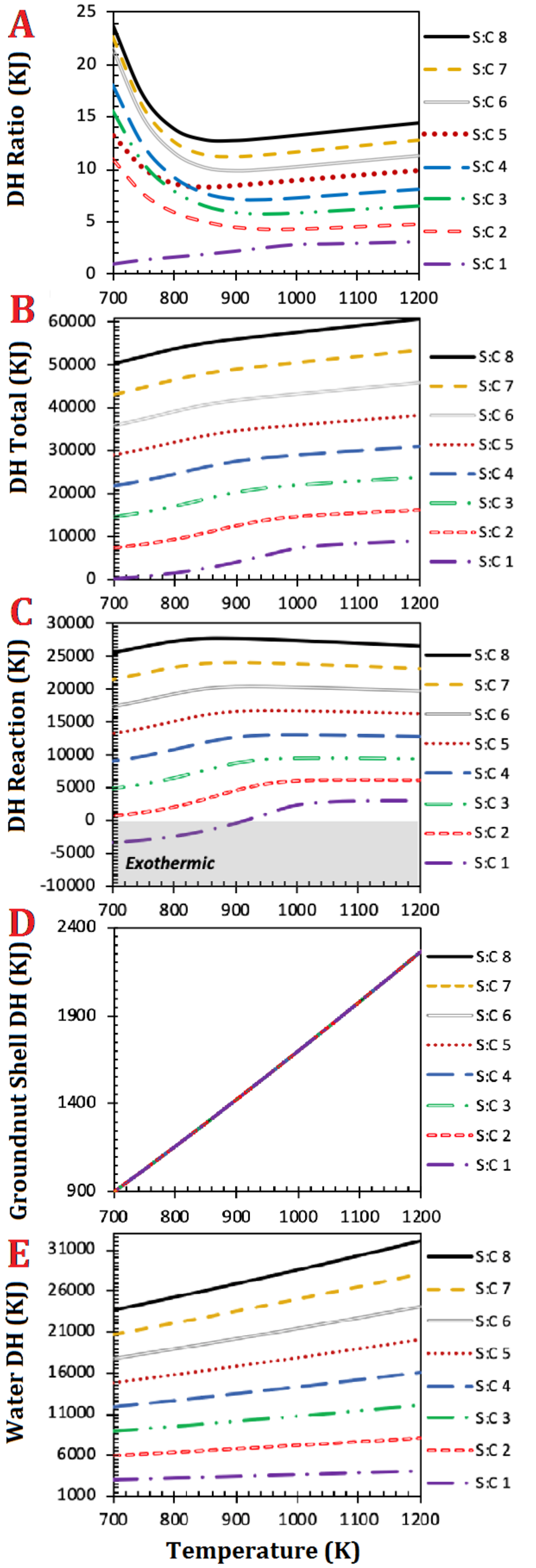

Figure 1. DH Ratio (A), Total (B), Reaction (C), groundnut shell (D), and water (E) under various reforming temperatures and varied Steam-to-Carbon ratios.

4. Conclusion

This study shows that the conventional steam reforming of groundnut shell has poor thermal efficiency under the investigated conditions. The energy demand of conventional steam reforming of groundnut shell is dominated by the enthalpy of heating liquid water from 298 K (25°C) to reforming temperature. Thus, energy demand increase with the increase in steam-to-carbon ratio. Therefore, more studies should be conducted to investigate other advanced reforming processes of groundnut shell such as sorption-enhanced steam reforming, chemical looping steam reforming, and sorption-enhanced chemical looping steam reforming and to assess the potential of this feedstock in hydrogen production.

Conflict of interest statement

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Data availability statement

The authors declared that all related data are included in the article.

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