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## Simulation and Optimization Study on Exploitation of Coal/Biomass (Rice Husk) Synergy for Production of Syngas

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**Abstract** This study was motivated by the quest for zero greenhouse gas emission and improved energy efficiency in producing syngas. Syngas, a multi-purpose chemical/fuel in several industries can be produced from renewable (fossil-based) and non-renewable (biomass) sources. The transformation of coal and rice husk into syngas was respectively investigated. However, to probe the synergetic effect of rice husk on coal gasification, a blend of the feedstock was simulated. The process was designed to produce 50kT of syngas annually with production rate of 6772kg/hr and operating period of 315 days. It was simulated using ASPEN PLUS and a pinch analysis targeted at maximizing H<sub>2</sub> yield while minimizing energy requirement was carried out. It was found that, under same process condition, gasification of rice husk gives a syngas with 57.87 %vol. H<sub>2</sub> and an enthalpy of  $-7.6 \times 10^6$  J/kg; gasification of coal produces a syngas with 47.68 %vol. H<sub>2</sub> and an enthalpy of  $-6.8832 \times 10^6$  J/kg and co-gasification of the blended (coal and rice husk) feedstock gives 52.54 %vol. H<sub>2</sub> and an enthalpy of  $-7.3 \times 10^6$  J/kg. The pinch analysis indicated that the co-gasification model with a highly rich syngas with 60.40 %vol. H<sub>2</sub> (92.9% yield) resulting in an increase in H<sub>2</sub> yield of 12.9% and CV of  $-7.3 \times 10^6$  J/kg. The optimization based on the pinch analysis led to a significant drop in energy requirement from 241MW to 122.05MW resulting in 49.13% energy saving. Besides, reduction in GHG emission, this work would generate more revenue and create jobs from revitalization of the Nigerian coal industry and efficient utilization of rice husk industrially.

**Keywords** Syngas, Biomass, Rice husk, Coal, Optimization, Simulation

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### 1. Introduction

From the agrochemical sector to steel manufacturing, from petroleum refineries to chemical production - many sectors of the chemical process industries would grind to a halt overnight without one crucial ingredient: Synthesis gas [1]. In its simplest form, Synthesis gas is composed of two diatomic molecules, Carbon monoxide and Hydrogen [2], which provides the building blocks upon which an entire field of fuel science and chemical technology is based. The gaseous mixture of CO and H<sub>2</sub> has had many names depending on how it was formed. These include: producer gas, town gas, blue water gas, synthesis gas, syngas, etc. Both components of synthesis gas (H<sub>2</sub> and CO) are cryogenic industrial gases, that is, they liquefy at temperatures below -150 °C [3]. Therefore synthesis gas cannot easily be compressed for storage, meaning that the processes that use it as feedstock must be located nearby, preferably within battery limits. The major industrial routes for syngas manufacture result in substantially different ratios of H<sub>2</sub>: CO, usually within the range 1:1 to 5:1, as the range of possible products from syngas feedstock is also wide; it is the stoichiometry of the final product that largely influences the choice of which syngas route, immediately upstream, is best. Other factors include the purity of the CO (as this might affect the catalyst life of the downstream process) and the desired scale of operation. Some syngas- derived products are presented in Figure 1.



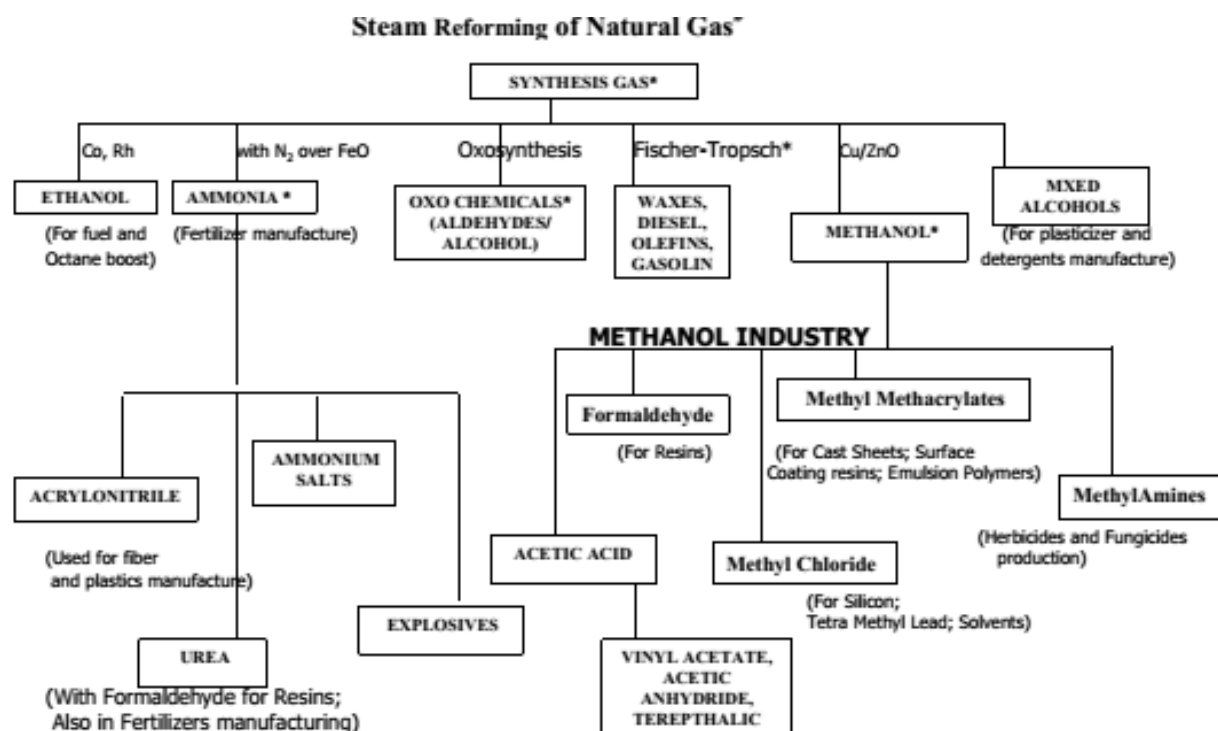


Figure 1: Synthesis gas routes to vast range of viable products [4]

Hydrogen production and it constitutes the largest use, by far, of synthesis gas. Hydrogen is mainly consumed by ammonia production, refinery operations, and methanol production [5]. It is also a component in the peroxide, solvents, certain polymers, and not least, as rocket fuel. Ammonia ( $\text{NH}_3$ ) synthesis is the largest user of synthesis gas by tonnage and first in value of production. A major percentage of  $\text{NH}_3$  is used to make fertilizers. It is also used in the production of explosives (hydrazine, nitriles, etc) and a long list of other chemicals including Ammonium nitrates, Phosphates and Sulphates. Others are nitric acid, urea, organic amines, Caprolactam, and Acrylonitrile as fibers and plastic intermediates [6]. A fourth major industrial use of the ever-versatile synthesis gas is in a group of reactions called Oxosynthesis. The oxosynthesis process (also known as hydroformylation) involves the reaction of CO and  $\text{H}_2$  with olefinic hydrocarbon to form an isomeric mixture of normal- and iso- aldehydes. It is an industrial synthetic route for the conversion of olefins (in the  $\text{C}_3 - \text{C}_{15}$  range) to produce solvents, synthetic detergents, flavorings, perfumes and other healthcare products, as well as other high value commodity chemicals [2]. Another example of synthesis gas use is the Fischer – Tropsch synthesis process, in which a wide range of olefins, paraffins and oxygenates (oxygen-containing hydrocarbons). The iso-synthesis reaction converts syngas over a Thorium or Zirconium-based catalyst at relatively extreme conditions to isobutene and isobutane. This reaction has often been considered a variation of Fischer-Tropsch synthesis; however, there are major differences between the two synthetic processes [7]. Iso-synthesis is selective to  $i\text{-C}_4$  hydrocarbons whereas FTS forms a range of olefins according to the ASF distribution. Only trace amounts of oxygenates (water, methanol, isobutanol, DME, etc.) are formed under iso-synthesis reaction conditions.

The syngas composition, most importantly  $\text{H}_2/\text{CO}$  ratio, depends on the production technology and feedstock. It is used primarily as a feedstock for downstream manufacture processes and can be produced from any hydrocarbon feedstock via reforming or gasification process. Coal gasification is the oldest method and has the established technology for syngas production [8,9]. It was the major consumer of coal. However, this method has negative impact on the environment due to greenhouse gas (GHG) emission coupled with other technological issues. This attracted research on gasification involving other feedstock to improve efficiency and performance of the process. Specifically, several types of biomass have been investigated to substitute coal. These include: sugarcane residue [10], rice husk [11], sawdust [12], almond shells [13], almond [14], wheat straw [15] and food waste [16]. Recently, there has been a growing interest in co-gasification of various biomass



and coal mixtures such as: cedar wood and coal [17], coal and saw dust [18], coal and pine chips [19], coal and silver birch wood [20], coal, pine, and polyethylene [21] and coal and birch wood [22]. The impact of biomass in coal gasification has been studied [23]. The process produces syngas with improve H<sub>2</sub>/CO ratio suitable for liquid fuel synthesis coupled with low GHG emission due to low carbon footprint on the environment [17]. Moreover, biomass contains inorganic matter found to catalyze gasification of coal [24]. Meanwhile, only a handful of research articles are available on synergetic effect of biomass/coal gasification. This work seeks to investigate this synergism in order to achieve zero GHG emission and improved energy efficiency. It also optimizes co-gasification process to ensure hydrogen-rich syngas with high calorific value is produced.

Nigeria has huge deposits of coal and heaps of rice husks littered if not burnt off at all nooks and crannies of the country. Exploitation of these resources would promote revitalization of the Nigerian coal industry thus creating thousands of job opportunities for Nigerians. The utilization of agricultural waste (rice husk) creates additional income to farmers while ensuring cleaner environment. Computer based simulation has been popular nowadays for different chemical engineering purposes. This paper is designed to present co-gasification of rice husk/coal using renowned ASPEN PLUS software. To achieve the desired result, making some assumptions and using hypothetical reactors were necessary to enable the author perform the simulation of co-gasification process. Though it is not a real life production environment, it can give relief from making wide range of experiment without making the small scale reactors or plant [25]. The simulation as presented next are developed based on the models from the literature.

## 2. Research Methodology

In this section, design basis, assumptions and specifications and chemical reactions required are presented. However, to determine the progress of simulation study as described herein, material and energy balance was carried out paving way to optimization study using pinch analysis.

### 2.1. Design Basis, Assumptions and Specifications

In order to carry out this study, design basis with proper justifications coupled with assumptions and specifications based on literature are necessary. The co-gasification process was simulated using ASPEN PLUS based on these data.

#### 2.1.1. Design Basis

The co-gasification plant was designed to produce 50kT of syngas annually with production rate of 6772kg/hr and operating period of 315 days. The co-gasification process was simulated using ASPEN PLUS. The choice of 315 days as operating period favors plant's maintenance or start-up within the year. Furthermore, Aspen Plus package was chosen because it can handle both solid phase stream and liquid-vapour phase streams with accurate result.

#### 2.1.2. Assumptions and Specifications

The plant was designed to utilize a blend of coal and rice husk as co-gasification feed stream for the production of syngas. Pre-treatment of the feedstock will not be simulated as they were assumed to have uniform composition. However, several analyses showed that the composition of coal and rice husk varies especially in sulphur content. Consequently, data for specifications of the feedstock (coal and rice husk) in terms of composition as well as moisture/volatility/ash and sulphur contents were based on ultimate analysis (Table 1), proximate analysis (Table 2) and sulphur analysis (Table 3) respectively.

**Table 1:** Ultimate analysis (% wt) of coal and rice husk by dry ash free basis

Ultimate Analysis	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)
Coal	78.03	4.06	4.66	1.69	1.97
Rice Husk	36.1	1.94	37.8	3.8	-

**Source:** Boharapi *et al* [26]

Table 1 shows that coal is richer than rice husk in carbon and hydrogen contents. However, the oxygen content of rice husk is over six times higher than that of coal.



**Table 2:** Proximate analysis (% wt) of coal and rice husk

Proximate Analysis	Moisture (%)	Fixed Component (%)	Volatile Matter (%)	Ash (%)
Coal	9.07	54.44	36.97	7.59
Rice Husk	8.44	9.3	71.4	19.3

Source: Hoffman [27]; Panda [28]

Meanwhile, rice husk is more volatile than coal and richer in ash content as shown in Table 2.

**Table 3:** Sulphur analysis (% wt) of coal

Sulphur Analysis	Pyritic	Sulphate	Organic
Coal	0.91	0.15	0.91

Source: Hoffman [27]

The co-gasification process was assumed to be steady state isothermal process and the reactors operated at adiabatic condition as such no heat loss throughout the whole process. In addition, all reactions are assumed to reach equilibrium and specific heat capacity ( $C_p$ ) of species was independent of operating pressure at which reaction takes place. However, the transformation of coal and rice husk to syngas is a chemical process. The chemical reactions associated with the co-gasification of these feedstocks are presented next.

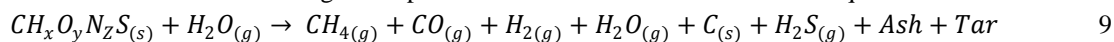
## 2.2. Chemical Reactions in Co-Gasification Process

This study incorporated these reactions at the appropriate stages in which they occurred in the gasifier, pyrolysis reactor, desulphurizer, two absorbent regenerators and water gas shift reactor. Most of the reactions in each reactor happened simultaneously as side reactions. However, the reaction mechanisms reported by various researchers are considered. In the gasifier, Boharapi *et al.* [26] reported that the following reactions took place:

- i. Partial oxidation of carbonaceous material as shown in Equation 1
 
$$2C_{(s)} + O_{2(g)} \rightarrow 2CO_{(g)} \quad 1$$
- ii. Water gas reaction producing syngas as shown in Equation 2
 
$$C_{(s)} + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)} \quad 2$$
- iii. Methanation reaction producing methane (natural gas) as shown in Equation 3
 
$$C_{(s)} + 2H_{2(g)} \rightarrow CH_{4(g)} \quad 3$$
- iv. Gasification reactions producing in each case methane and hydrogen in addition to carbon (IV) oxide as shown in Equations 4 and 5 respectively
 
$$2C_{(s)} + 2H_2O_{(g)} \rightarrow CH_{4(g)} + CO_{2(g)} \quad 4$$

$$C_{(s)} + 2H_2O_{(g)} \rightarrow 2H_{2(g)} + CO_{2(g)} \quad 5$$
- v. Steam reforming reaction producing syngas as shown in Equation 6
 
$$CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3H_{2(g)} \quad 6$$
- vi. Boudouard reaction a dissociation of a molecule of carbon (II) oxide producing carbon (tar) in addition to carbon (II) oxide as shown in Equation 7
 
$$2CO_{(g)} \rightarrow CO_{(g)} + C_{(s)} \quad 7$$
- vii. Shift conversion producing hydrogen and carbon (IV) oxide as shown in Equation 8
 
$$CO_{(g)} + H_2O_{(g)} \rightarrow H_{2(g)} + CO_{2(g)} \quad 8$$

These transformations in the gasifier produce the over-all reaction shown in Equation 9.



Similarly, in the pyrolysis reactor, Surjosatyo *et al.* [29] reported that the following reaction involving tar ( $C_nH_x$ ) and hydrocarbon ( $C_mH_y$ ) occurred. However, these reactions are catalyzed.

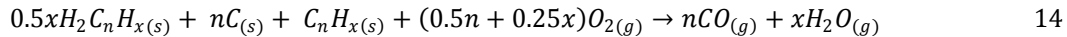
- i. Dissociation of tar to hydrocarbon and hydrogen as shown in Equation 10
 
$$pC_nH_{y(s)} \rightarrow qC_mH_{y(s)} + rH_{2(g)} \quad 10$$
- ii. Tar and steam producing syngas as seen in Equation 11.
 
$$C_nH_{x(s)} + nH_2O_{(g)} \rightarrow (n + 0.5x)H_{2(g)} + nCO_{(g)} \quad 11$$
- iii. Tar and carbon (IV) oxide producing syngas as shown in Equation 12
 
$$C_nH_{x(s)} + nCO_{2(g)} \rightarrow (0.5x)H_{2(g)} + 2nCO_{(g)} \quad 12$$



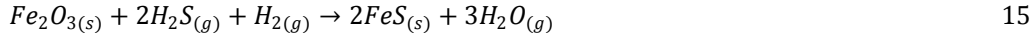
iv. Tar dissociates to carbon and hydrogen as shown in Equation 13



The over-all reaction in the pyrolysis reactor is presented in Equation 14



In the desulphurizer (Sulphidation), Portzer *et al.* [30] reported that the only reaction taking place as shown in Equation 15 involving iron (III) oxide and hydrogen sulphide in the presence of hydrogen.



Two regenerators for sulphur (IV) oxide and oxygen were required for the co-gasification process. The reactions occurring in these regenerators as reported by Portzer *et al.* [30] are:

i. Regeneration of sulphur (IV) oxide to produce harmless elemental sulphur as shown in Equation 16.



ii. Regeneration of oxygen to produce sulphur (IV) oxide as shown in Equation 17.



In the water gas shift reactor, Hoffman [27] reported that a catalyzed reaction involving steam and carbon (II) oxide to produce carbon (IV) oxide and hydrogen as shown in Equation 18



These equations were incorporated appropriately in simulating the co-gasification plant. In the next section, description of the process indicating the process flow diagram (PFD) the plant is presented.

### 2.3. Design Process Description

The process flow diagram for co-gasification plant is presented in Figure 2. This was developed based on the design basis and assumptions incorporating reactions and other necessary information sourced from literature. The plant consists of four units: Gasification, Gas Cooling or Heat Recovery Steam Generator (HRSG), Gas Cleaning and Water Gas Shift (WGS). The plant utilized rice husk and coal for syngas production. However, water, steam and oxygen were also utilized where necessary in ensuring high yield of hydrogen-rich syngas and relatively low amount of sulphur as by-product. The pre-treatment plant was intentionally excluded as the main raw materials (rice husks and coal) were considered to be pre-treated (*vide supra*). These feedstocks were mixed in equal proportion and fed into a dryer (**D-100**) using two conveyors (**CV-100** and **CV-101**). At the Gasification unit, both feeds were co-gasified at temperature of 700°C and pressure of 32.04 bar in a gasifier (**G-100**) using continuous steam generated from the HRSG unit. To avoid undesired Nitrogen dilution and ensure high yield of hydrogen, only steam (not air/oxygen) was used as gasifying agent [26]. In addition, the steam was also useful in the cooling unit thus ensuring efficient management of utility.

The gasifier (**G-100**) is also involved in cracking char, one of the gasifying products. Fjellerup *et al.* [31] reported that char accumulated on the bed in a porous form can be reduced to tar in the presence of steam. The raw syngas leaving the gasifier is fed into a cyclone (**CY-100**) for ash removal and the un-cracked char is removed from the bottom of the gasifier as residue [26]. The ash-free raw syngas is sent to the cooling unit. The HRSG unit which generates steam which subsequently gets to the cooling unit has a quencher super-heater heat exchanger, as well as medium pressure (MP) and high pressure (HP) steam coolers. There are series of heaters, steam turbine and compressor in this unit. Thus, the raw syngas flowed through a quencher (**Q-200**), a super-heater (**HX-100**) and coolers (**C-200** and **C-201**) before half of it is recycled and compressed back to **Q-200** to quench the gas and maintain the temperature difference between hot and cold stream before entering the wet scrubber. The recirculation of the raw gas enables heat to be recovered where mechanical work is produced in the gas compressor (**CO-200**). The processed, pure water feed is utilized for the generation of power from the steam turbine (**STUR-400**) and heater series where steam is formed for gasification process.

However, to eliminate tar and ammonia from the raw syngas, subsequent gas cleaning process was required [32]. Hence, the raw syngas was mixed with steam and de-aerated water in the water scrubber (**SC-200**) at 144°C and 26 bar. The wet scrubber scrubbed secondary tars to a pyrolysis reactor (**R-200**) at the condition of 120°C and 20 bar where tar cracking reaction occur in the absence of oxygen and it is assumed that the secondary tars are fully converted to raw syngas.



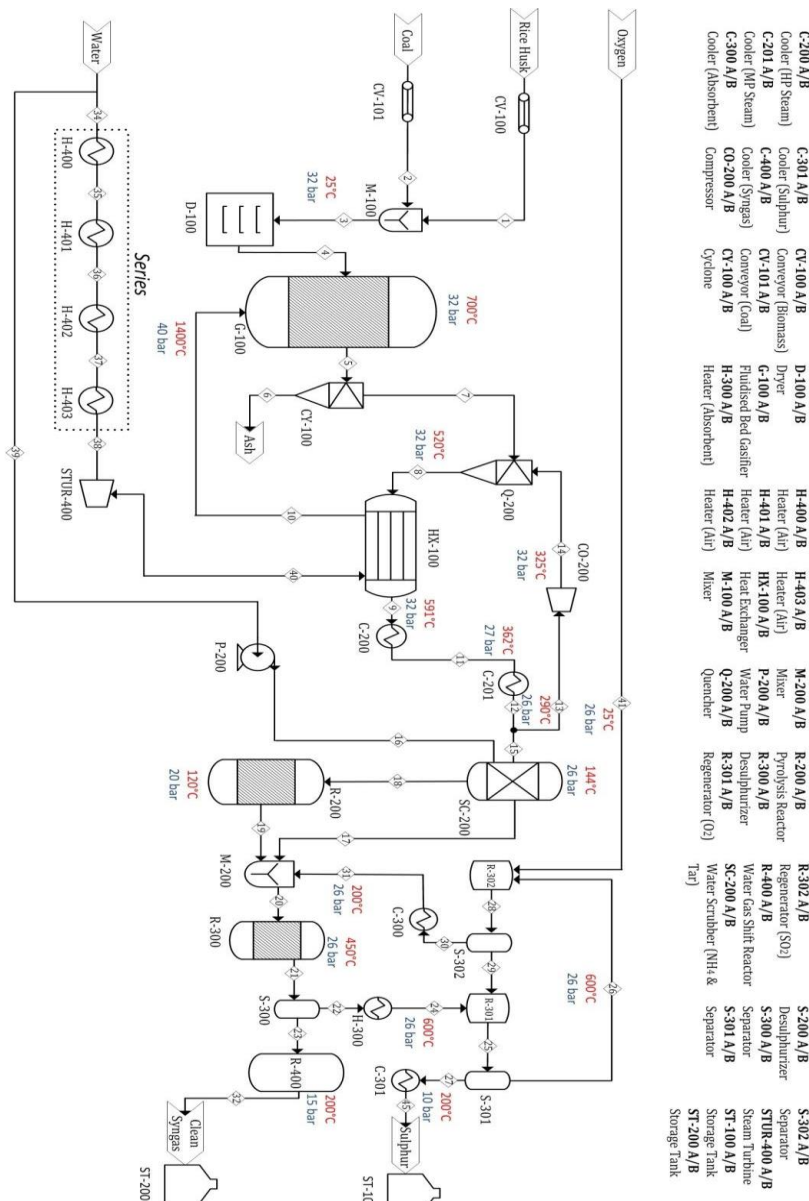


Figure 2: Process Flow Diagram of Rice Husk/Coal Gasification Process

The syngas needs to be cooled to certain temperature prior to desulphurization and this requires high cost and complex design to achieve. However, the HRSG unit has been designed to generate power from **STUR-400** and **CO-200** via a heat-integrated system in preparation for gas cleaning treatment [33]. Desulphurization took place in (**R-300**) at 450°C and 26 bar using absorbent (Fe<sub>2</sub>O<sub>3</sub>) generated from the regenerators (**R-301** and **R-302**) in a recirculation loop. Molten sulphur condensed out continuously in the SO<sub>2</sub> regenerator (**R-301**) from recirculating SO<sub>2</sub> gas stream generated from the O<sub>2</sub> regenerator (**R-302**). The sulphided absorbent is fed into the multistage reactors and it is heated (**H-300**) to 600°C to form the regenerated sorbent, where subsequently this partially regenerated sorbent is passed into **R-302** and oxygen is added to the regenerated gas for maximum conversion before it is cooled (**C-300**) and fed back into **R-300**. The recirculation loop allows clean syngas to be recovered using a condensing separator (**S-300**) and clean syngas with hydrogen 50 vol% proceeds to its last cleaning step. The catalyst packed reactor (**R-400**) operated at 200°C and 15 bar where the water gas shift reaction took place produce more hydrogen at which a cleaner syngas with about 60 vol% was produced. The simulation was also carried out using only coal as feedstock as well as rice husk in order to investigate the synergetic effect of the blended feedstock. The materials and energy balances were evaluated and the result from this study simulation was compared the result from literature.

## 2.4. Process Optimization

The optimization study was carried out to maximise hydrogen yield and minimise utility cost via heat integration. The capital cost is constant as the equipment sizing remains unchanged. However, the variables that are manipulated are mostly equipment with possible exergy loss such as mixer, gasifier, reactors, heat exchangers, heaters and coolers. Parameters adjusted are: flow ratio, exit temperature, operating pressure, feed ratio and fractional conversion of reactions. Meanwhile, for efficient and feasible design, the minimum approach of heat exchangers was manipulated within a constraint. However, H<sub>2</sub>/CO ratio was subsequently altered resulting to unavoidable increase in H<sub>2</sub> and reduction in CO. Lastly, the safety parameters such as flammability point and storage pressure of the product is also maintained at specific range. The optimized parameters with respect to the objective, manipulated variable and constraints were reported.

### 2.4.1 Pinch Analysis

Heat integration, also known as energy integration or heat integration is a technique used for **minimizing energy consumption and maximizing heat recovery in the plant**. Heat energy network (HEN) is used to indicate the calculation of minimum heating and cooling requirements which reveal significant energy savings. The methodology is summarized in a flowchart in Figure 3.

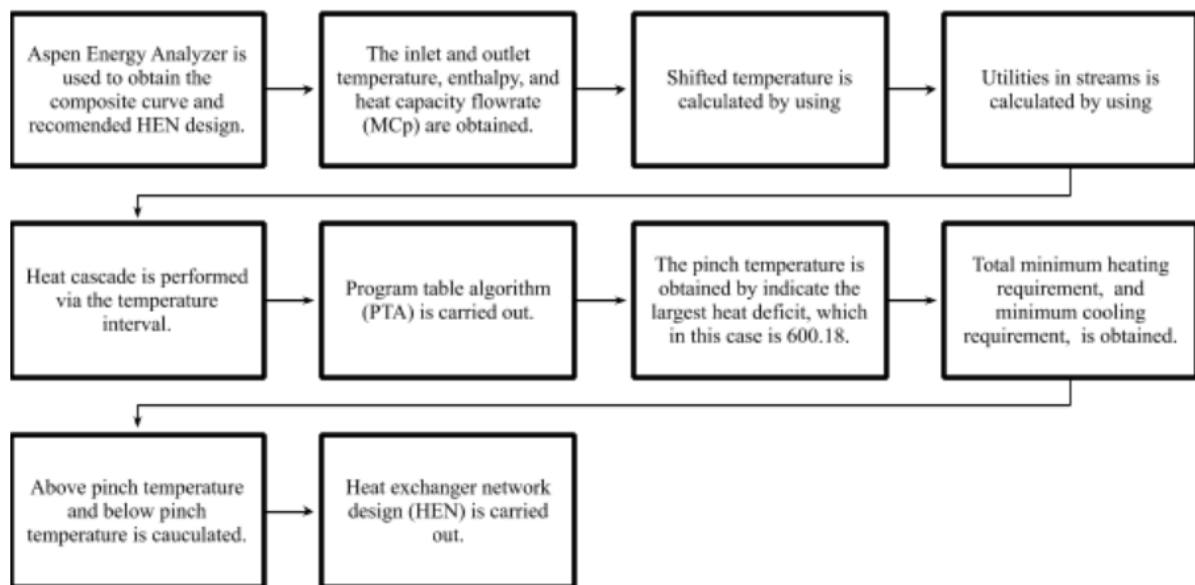


Figure 3: Flowchart for pinch analysis work flow

The main objective to perform energy integration is to improve the energy efficiency of the co-gasification plant which includes heat exchangers, heaters as well as coolers to heat and cool the process streams to specific desired temperatures. Reactor such as pyrolysis reactor, desulphurizer and water gas shift reactor which require duty were taken into consideration.

## 3. Results and Discussion

The results of the simulation study are presented and discussed in this section. Section 3.1 discussed the effect of the feedstock on the syngas composition. The plant was subjected to optimization study and pinch analysis carried out. The optimized model for the co-gasification was compared with existing plants operating with similar technologies.

### 3.1 Effect of Feedstock on Syngas Composition

The syngas compositions obtained from the aspen base cases prior optimization are presented in this section. Table 4 indicates the effects of coal as the only gasification feedstock on syngas composition.



**Table 4:** Syngas composition from coal gasification process

Component	Mole fraction in syngas
H <sub>2</sub> O	0.0790227
N <sub>2</sub>	0.00286112
O <sub>2</sub>	0.00279509
H <sub>2</sub>	0.476844
CO <sub>2</sub>	0.196718
CO	0.104068
CH <sub>4</sub>	0.1376907
total flow (kg/hr)	6763.2
temperature (°C)	30
enthalpy (J/kg)	-6.8832 x10 <sup>6</sup>

It can be seen that the conventional gasification (using coal alone) produces a syngas with about 48% hydrogen. The plant was equally simulated using rice husk alone as feedstock for gasification and syngas composition was tabulated as presented in Table 5

**Table 5:** Syngas composition from rice husk gasification process

Component	Mole fraction in syngas
H <sub>2</sub> O	0.108382
N <sub>2</sub>	0.00739048
O <sub>2</sub>	0.00135899
H <sub>2</sub>	0.578746
CO <sub>2</sub>	0.174862
CO	0.121417
CH <sub>4</sub>	0.00784383
total flow (kg/hr)	6717.78
temperature (°C)	30
enthalpy (J/kg)	-7.6304x10 <sup>6</sup>

Obviously rice husk gasification under the same technologies and operating conditions as coal gasification produced a syngas with about 58% hydrogen, which is quite better than that of coal. However, the synergetic effect of both feedstocks was exploited as blended feedstock of coal and rice husk in a ratio of 1:1 gave a syngas composition presented in Table 6.

**Table 6:** Syngas composition from co-gasification of rice husk and coal

Component	Mole fraction in syngas
H <sub>2</sub> O	0.0910
N <sub>2</sub>	0.0052
O <sub>2</sub>	0.0026
H <sub>2</sub>	0.5354
CO <sub>2</sub>	0.188
CO	0.112
CH <sub>4</sub>	0.0661
total flow (kg/hr)	6717.78
temperature (°C)	30
enthalpy (J/kg)	-7.3212×10 <sup>6</sup> J/kg

The result shows that the addition of rice husk (biomass) to the conventional coal gasification process improves the quality of the syngas in terms of the hydrogen composition and heating value. The three cases investigated are shown in Figure 4.





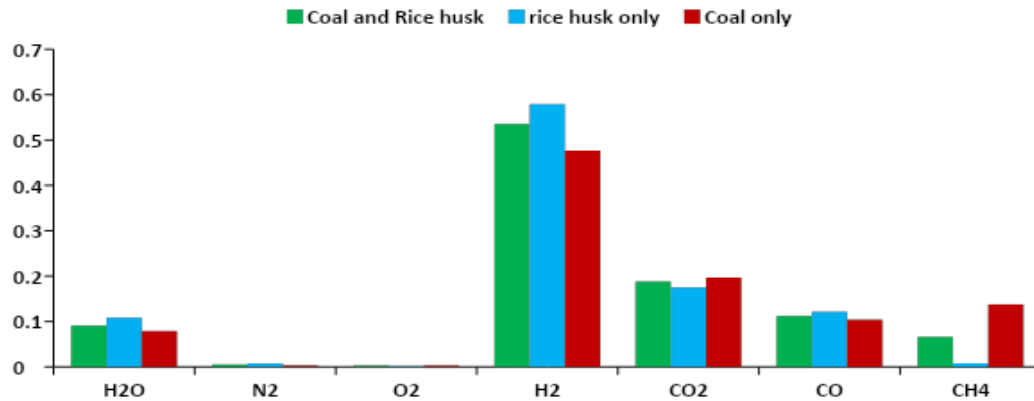


Figure 4: Effect of feedstock on syngas composition

Obviously, the synergetic effect of the blended feedstocks (co-feeding of coal and rice husk) was exploited such that while reducing environmental impact and plant operating cost through minimized fossil fuel (coal) usage also produces syngas richer in H<sub>2</sub> and with improved calorific value (CV) than that of the conventional gasification plant utilizing coal. The plant was subjected to optimisation study and the outcome was reported as presented next.

### 3.2. Optimisation of Co-Gasification Plant

The co-gasification plant was subjected to optimisation study by adjustment of manipulated variables and the outcome was tabulated as presented in Table 7. It shows the list of the optimization parameters in terms of the objectives, manipulated variables and constraints before and after optimization. It found that an increase in hydrogen yield of 12.9% from 82.3% of base case to 92.9% was achieved.

Table 7: Optimization parameters and results

Parameters	Unit	Before	After	Remark
<b>Total energy requirement</b>	MW	241.87	122.05	energy saving of 49.13%
<b>Product:</b>				increase yield by 12.9%
H <sub>2</sub> yield	%	82.3	92.9	
H <sub>2</sub> fraction	mol/%	52.5	60.6	minimum 60 mol% H <sub>2</sub> as saleable gas
<b>Manipulated variable:</b>				
<b>Units:</b>				
Number of heat exchangers	unit	1	2	
Number of heater/cooler	unit	11	10	
Mixer, M-200 pressure	bar	26	20	
Cooler, C-300 exit temperature	°C	200	20	
Steam turbine, ST-400 pressure	bar	45	40	
<b>Gasifier:</b>	°C	1400	1340	
Steam temperature				
Steam to feed ratio (S:F)	-	2.20	2.18	mass flowrate was used conversion rate for H <sub>2</sub> S
<b>Reactor:</b>				
R-301 fractional conversion	%	98	85	
R-400 fractional conversion	%	25	85	conversion rate for H <sub>2</sub> O
Constraint: E-200 minimum temperature approach	°C	914.1	880.7	more than 880°C, power generation at ST-400
E-400 minimum temperature approach	°C	N/A	160.3	more than 161°C for sufficient cooling
Hydrogen rich product gas temperature	°C	30.0	57.5	less than 70°C due to flammability of product
H <sub>2</sub> /CO ratio	-	3.2	21.8	the ratio increase, with increase in H <sub>2</sub> yield



### 3.3. Pinch Analysis

The optimization of the co-gasification plant was performed based using pinch which involves energy integration. The calculated flowrate of the utilities is tabulated in Table 8 indicating LP steam with  $4.58 \times 10^5$  kg/h as the highest flowrate among all the utilities and cold water with  $1.15 \times 10^5$  kg/h as the lowest flowrate. This is attributed to the fact that majority of the heating equipment were utilizing LP steam and the temperature difference (30 °C to 800 °C) as the driving force was the highest. However, of all the equipment in the plant, only one utilizes cold water as coolant hence the lowest flowrate among all the utilities. As a co-generation plant, energy consumption of this plant is reduced by using the power generated from steam turbine for equipment such as cyclone and compressor. The heat integration provides reduction of cooler or heater number with the installation of a more efficient heat exchanger technology. Hence, operating cost can be reduced.

**Table 8:** Heating and cooling utilities

Equipment	Heat Duty (kJ/h)	Utility used	T <sub>in</sub> , °C	T <sub>out</sub> , °C	ΔT, °C	Specific heat capacity, kJ/ kg °C	Flowrate required (kg/h)
C-301	1.1E-04	Cooling Water	600.00	200.00	400.00	0.56	0
C-300	2.8E+08	Cooling Water	604.18	200.00	404.18	2.77	184710.74
H-300	1.1E+08	LP Steam	450.00	600.00	150.00	1.33	554117.31
Hx-200	2.5E+06	Cooling Water	200.00	30.00	170.00	10.67	1364.72
H-400, H-401, H-402, H-403	2.4E+07	LP Steam	20.00	1580.00	1560.0	40.17	383.69
C-200	7.0E+06	Cold Water	590.48	290.00	300.48	2.04	11467.39
HX-100	1.6E+06	MP Steam	524.65	590.48	63.83	2.16	11467.39
R-200	2.1E+07	MP Steam	-67.00	120.00	187.00	204.03	819.84
G-100	1.7E+08	LP Steam	199.98	450.00	250.02	193.39	3533.36
R-400	3.4E+06	Cooling Water	450.00	200.00	250.00	299.47	59.29
C-202	2.8E+03	LP Steam	800.00	30.00	770.00	0.05	72.20

The energy savings are shown in Table 9 for hot and cold stream are 49.13 % and 0 % respectively. As the cooling water used to cool down the ash is recycled repeatedly causing only small amount of water required with small duty insignificant when compared to the hot utilities to heat up the water in order to generate the steam for gasifier. Hence, the 0 % of energy saving in hot utilities as indicated.

**Table 9:** Energy saving from hot and cold utilities

Detail	Cold Utilities (MW)	Hot Utilities (MW)
Before Heat Integration:	241.87	43.54
After Heat Integration:	122.05	43.54
Total Heat Reduced:	118.82	0.00
Total Saving (%):	49.13	0.00

### 3.4. Comparative Study of Co-Gasification Plants

This study was compared with existing plants: Foster wheeler, Uhde and Fraunhofer. Syngas composition of the after optimization of the co-gasification scenario as reported is shown in Table 10 and presented in Figure 5 for clarity. The result of our plant after optimization study with H<sub>2</sub> yield of 60% is indicated in last column.

**Table 10:** Syngas composition from existing and optimised simulation plants

Plant/component	Foster wheeler	Uhde	Fraunhofer	Simulation
H <sub>2</sub>	11 vol%	30.1 vol%	14 vol%	60.40%
CO	22 vol%	32.1 vol%	18 vol%	2.77%
N <sub>2</sub>	46.5 vol%	0.4 vol%	39 vol%	0.53%
CO <sub>2</sub>	11.5 vol%	-	16 vol%	271%
O <sub>2</sub>	-	-	-	0.045%
H <sub>2</sub> S	-	0.03 vol%	-	-



CH <sub>4</sub>	-	4.7 vol%	3 vol%	7.2%
H <sub>2</sub> O	-	-	10 vol%	2.06%
C <sub>6</sub> H <sub>6</sub>	-	770ppm	-	-
NH <sub>3</sub>	-	90ppm	-	-
H <sub>2</sub> /CO ratio	0.74	0.91		21.805

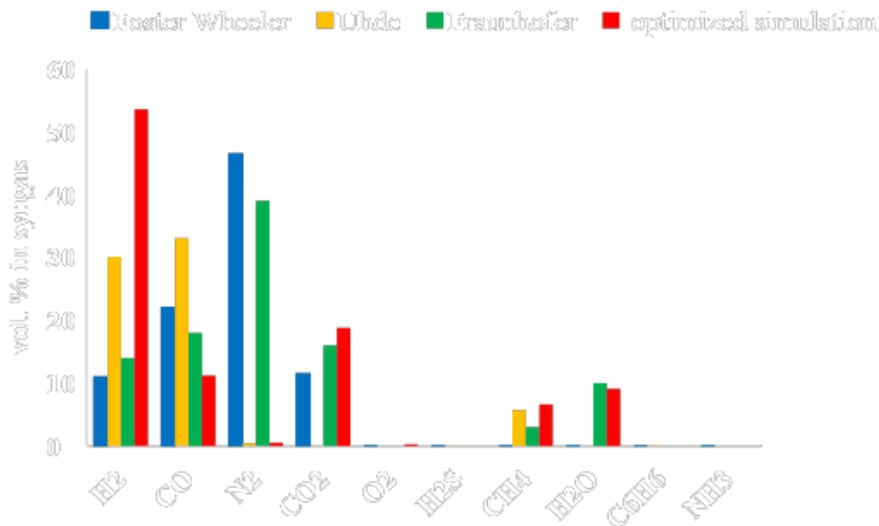


Figure 5: Syngas composition (after optimization) comparison with existing plants

The optimized simulation plant has a substantial advantage based on hydrogen-rich syngas production compared to conventional plants even if the efficiency of this model drops after actual plant erection. Figure 5 shows the comparison of the syngas composition of the co-gasification scenario before and after optimization. The comparison study of these existing plants operating with similar technology with that of optimized simulation plant revealed the synergetic effect of biomass on co-gasification when optimized gives syngas with 60.4% H<sub>2</sub>.

#### 4. Conclusion and Recommendations

The study seeks to investigate the effect of gasification feedstock on syngas. This was carried out in a simulation plant utilizing these feedstocks (coal and rice husk) individually. The synergetic effect of biomass (rice husk) on coal gasification was investigated with a blended coal/rice husk feedstock on the same plant. It was found that co-gasification of biomass (rice husk) with coal raised the efficiency of the proposed gasification plant and as well and reducing the greenhouse gases emissions. This work shows that hydrogen-rich syngas was obtained from the co-gasification of coal and biomass (rice husk) compared with the conventional coal gasification. The increase in hydrogen yield from 47.68% vol H<sub>2</sub> to 52.54% vol H<sub>2</sub> was attributed to introduction of rice husk. This was better shown when the gasification plant was simulated using coal alone producing syngas with 47.68% vol of H<sub>2</sub> while that of rice husk alone gives 57.87% vol H<sub>2</sub>. Although a better hydrogen yield was obtained with rice husk alone, it is not readily available in Nigeria for industrial production. Hence, blending rice husk with coal will reduce rice husk consumption rate as well as the operating cost of the plant.

Furthermore, exploitation of sub-bituminous coal and rice husk at a ratio of 1:1 to achieve high gas yield, low tar and char yield, as well as high thermal efficiency with effective HRSG and desulphurization gas cleaning technology when compared with others. This is in tuned with our quest for energy efficiency and zero/reduced GHG emission. Pinch technology which involves energy integration was employed for optimization study of the plant. This led to further increase in hydrogen content of the syngas as 60.40% vol H<sub>2</sub> was reported. The increase in energy saving after optimization is mainly as a result of the application of the principles of pinch technology analysis to enhance process to process heat exchange with a significant drop in energy requirement from 241MW (before pinch analysis) to 122.05MW (after pinch analysis) resulting in a total energy saving of 49.13%.



The role of biomass on coal gasification is invaluable in achieving low GHG emission and energy efficiency. In view of the results obtained from the study, the authors recommend that:

- Economic analysis, process control / instrumentation scheme and a HAZOP assessment with the aim of justifying the profitability and safety of this plant should be carried out. These aspects of plant design were not beyond the scope of this work.
- Further studies should be conducted with other bio-sourced feedstock.

## References

- [1]. Ulber, D. (2015). A guide to methane reforming. *Chemical Engineering Journal*, 122 (1): 40-46.
- [2]. Spath, P. L. and Dayton, D. C. (2003). Technical and Economics Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas. <http://www.osti.gov/bridge>. Accessed: July 2, 2020.
- [3]. Younger, A. H. (2004). *Natural Gas Processing Principles and Technology: Part 1*. Alberta: Thimm Engineering Inc.
- [4]. Obonukut, M. E., Alabi, S. B. and Bassey, P. G. (2016) Steam reforming of natural gas: Value addition to natural gas utilization in Nigeria. *Journal of Chemistry and Chemical Engineering*, 10(1): 28-41
- [5]. Vergis, M. T. (2007). Economics of Steam Methane Reformation and Coal Gasification for Hydrogen Production. Master Thesis, University of Florida, USA.
- [6]. Considine, D. M. (1974). *Chemical and Process Technology Encyclopedia*. New York: McGraw-Hill, 1077p.
- [7]. Feng, L. X., Zhong, D., Liu, Z., Dady burjor, D. B. and Kugler, E. L. (1998). Higher Alcohols from Synthesis Gas Using Carbon-Supported Doped Molybdenum-Based Catalysts. *Industrial and Engineering Chemistry Research* 37(10): 3853-3863
- [8]. Ishi, S. (1982). Coal gasification technology. *Energy*, 15(7): 40-48.
- [9]. Hotchkiss, R. (2003). Coal gasification technologies, *Proceedings of the Institution of Mechanical Engineers Part A*, 217(1): 27-33.
- [10]. Gabra, M., Pettersson, E., Backman, R. and Kjellstrom, B. (2001). Evaluation of cyclone gasifier performance for gasification of sugar cane residue—part 1: gasification of bagasse. *Biomass and Bioenergy*, 21(5): 351-369.
- [11]. Boateng, A. A., Walawender, W. P., Fan, L. T. and Chee, C. S. (1992). Fluidized-bed steam gasification of rice hull. *Bioresour Technol*, 40(3): 235-239.
- [12]. Lv, P. M., Xiong, Z. H., Chang, J., Wu, C. Z., Chen, Y. and Zhu, J. X. (2004) An experimental study on biomass air-steam gasification in a fluidized bed,” *Bioresour Technol*, 95(1): 95-101.
- [13]. Rapagna, S., Jand, N., Kiennemann, A. and Foscolo, P. U. (2000). Steam-gasification of biomass in a fluidised-bed of olivine particles,” *Biomass and Bioenergy*, 19(3): 187-197.
- [14]. Rapagna, S. and Latif, A. (1997). Steam gasification of almond shells in a fluidised bed reactor: the influence of temperature and particle size on product yield and distribution. *Biomass and Bioenergy*, 12(4): 281-288.
- [15]. Ergudenler, A. and Ghaly, A. E. (1993). Agglomeration of alumina sand in a fluidized bed straw gasifier at elevated temperatures *Bioresour Technol*, 43(3): 259-268.
- [16]. Ko, M. K., Lee, W. Y., Kim, S. B. K., Lee, W. and Chun, H. S. (2001). Gasification of food waste with steam in fluidized bed. *Korean Journal of Chemical Engineering*, 18(6): 961-964.
- [17]. Kumabe, K., Hanaoka, T., Fujimoto, S., Minowa, T. and Sakanishi, K. (2007). Cogasification of woody biomass and coal with air and steam. *Fuel*, 86(5-6): 684-689.
- [18]. Velez, J. F., Chejne, F., Valdes, C. F., Emery, E. J. and Londono, C. A. (2009). Cogasification of Colombian coal and biomass in fluidized bed: an experimental study. *Fuel*, 88(3): 424-430.
- [19]. Pan, Y. G., Velo, E., Roca, X., Manyá, J. J. and Puigjaner, L. (2000). Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel*, 79(11): 1317-1326.



- [20]. Collot, A. G., Zhuo, Y., Dugwell, D. R. and Kandiyoti, R. (1999). Co-pyrolysis and co-gasification of coal and biomass in bench-scale fixed-bed and fluidized bed reactors *Fuel*, 78(6): 667-679.
- [21]. Pinto, F., Carlos, F. and Andre R. N. (2003). Effect of experimental conditions on co-gasification of coal, biomass and plastics wastes with air/steam mixtures in a fluidized bed system. *Fuel*, 82(15-17): 1967-1976.
- [22]. Brage, C., Yu, Q., Chen, G. and Sjoström, K. (2000). Tar evolution profiles obtained from gasification of biomass and coal. *Biomass and Bioenergy*, 18(1): 87-91.
- [23]. Sjoström, K., Chen, G., Yu, Q., Brage, C. and Rosen, C. (1999). Promoted reactivity of char in co-gasification of biomass and coal: synergies in the thermochemical process. *Fuel*, 78(10): 1189-1194.
- [24]. Brar, J. S., Singh, K., Wang, J. and Kumar, S. (2012). Cogasification of coal and biomass: a review. *International Journal of Forestry Research*, 2012: 1-10.
- [25]. Obonukut, M. E., Bassey, E. N. and Etuk, B. R. (2015). Study of the Contribution of Carbon IV and Carbon II Oxides in Methanol Synthesis with Modified Kinetic Model. *International Journal of Scientific Research and Education* 3 (9): 4485-4494.
- [26]. Boharapi, A. B., Kale, G. R. and Mahadwad, O. K. (2015). Co-Gasification of Coal and Biomass - Thermodynamic and Experimental Study. *International Journal of Research in Engineering and Technology*, 2319-1162
- [27]. Hoffman, Z. (2003). Simulation and Economic Evaluation of Coal Gasification with Sets Reforming Process for Power Reduction. BSc. Project, Louisiana State University, USA.
- [28]. Panda, C. (2012). Aspen Plus Simulation and Experimental Studies on Biomass Gasification. MSc. Thesis, National Institute of Technology, Rourkela.
- [29]. Surjosatyo, A., Vidian, F. and Nugroho, Y. S. (2010). A review on gasifier modification for tar reduction in biomass gasification. *Mechanical Journal*, 31: 62-77.
- [30]. Portzer, J. W. and Gangwal, S. K. (2015). Hot-Gas Desulfurization with Sulfur Recovery. Research Triangle Institute.
- [31]. Fjellerup, J., Ahrenfeldt, J., Henriksen, U. and Gobel, B. (2005). Formation, Decomposition and Cracking of Biomass Tars in Gasification. MSc. Thesis, Technical University of Denmark.
- [32]. Botha, F. J. (2012). Simulation of a syngas from coal production plant coupled to a high temperature nuclear reactor. MSc. Thesis, Faculty of Engineering of Stellenbosch University.
- [33]. Ajay, K., Mohanta, K. and Parkash, V. (2012) Properties and industrial applications of rice husk. *International Journal of Emerging Technology and Advanced Engineering*, 7(3): 15-29.

