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# Modelling of Coal-Biomass Blends Gasification and Power Plant Revamp Alternatives in Egypt's Natural Gas Sector

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Recently, there has been a growing research interest in the co-gasification of biomass with coal to produce syngas and electricity in a sustainable manner. Co-gasification technology do not only decrease potentially the exploitation of a significant amount of conventional coal resources, and thus lower greenhouse gases (GHG) emissions, but also boost the overall gasification process efficiency. In the present work, a rigorous simulation model of an entrained flow gasifier is developed using the Aspen Plus® software environment. The proposed simulation model is tested for an American coal and the model validation is performed in good agreement with practical data. The feedstocks used in the proposed gasifier model are dry Egyptian coal and a blend of an Egyptian coal and rice straw that is gathered locally. The proposed gasifier model mainly consists of three reactors. The first one is a yield reactor where the coal pyrolysis occurs, the second reactor is a stoichiometric reactor where the gasification reactions arise, and the third reactor is a Gibbs reactor where the water-gas and steam-methane reforming reactions take place. The influence of using a feed mixture of 90 % coal and 10 % rice straw on the gasifier efficiency is investigated. The developed model provides a robust basis for revamping of an existing Egyptian natural gas-based power plant to replace its standard fuel with a coal-rice straw blend, in case of low natural gas supply. The model is further employed to assess different revamping scenarios and alternatives within the natural gas power plant. For a dry blend of (90 % Egyptian coal and 10 % rice straw), the cold gas efficiency is estimated as 85.7 %, while for dry Egyptian it is calculated as 79.61 %. The revamped Egyptian natural gas power plant decreases the total annualized cost (TAC) by 52.7 % with respect to a new constructed integrated gasification combined cycle (IGCC) plant. Besides, the payback period decreases to 1.24 y rather than 12 y in case of the construction of a new IGCC power plant.

## 1. Introduction

Gasification is an incomplete combustion process that converts any carbon-containing material into syngas through chemical reactions that take place in the presence of gasifying agents such as (air, oxygen, and/or steam) (Lee et al., 2014). The syngas produced from gasifier consists mainly of carbon monoxide, hydrogen, carbon dioxide, and methane; it can be used as a fuel to generate electricity or steam. Also, it could be utilised as a basic or main feedstock in the petrochemical and refining industries (Gadalla et al., 2015) to produce various products such as methanol, hydrogen, ammonia, ethylene, and acetic acid (Amer et al., 2015). Coal gasification technology has many useful uses and applications such as syngas production that can be completely combusted by air in gas turbine cycles to produce a hot flue gas which transfers the heat energy to water and generate electricity via electric power generation unit operations. In addition, syngas can be used in petrochemical industry as chemical building block, manufacturing of synthetic natural gas that can be used as pipeline gas supplies, and producing hydrogen for fuel cell applications (Breault, 2010).

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### 1.1 Gasification feedstock

Coal, petroleum coke, and even blends of coal and biomass for renewable energy production (Čuček et al., 2010) are ordinarily used as feedstock for gasification process. All of these materials consist mainly of carbon with varying amounts of hydrogen, oxygen, and impurities such as sulphur and ash (Pinto et al., 2015).

### 1.2 Processes and reactions in the gasifier

In coal gasification, the principal processes that normally take place within the gasifier unit are dehydration, pyrolysis, combustion, gasification, water gas shift, and steam-methane reforming (Xiangdong et al., 2013).

#### 1.2.1. Dehydration

In this process, evaporation occurs for any free water content of the feedstock to dry the feed.

#### 1.2.2. Coal pyrolysis

The temperature in the gasifier unit is typically higher than 1,000 ºC. When coal is fed into the gasifier, it first undergoes the pyrolysis process which is a series of physical and chemical complex reactions that start slowly at a temperature from about 150 ºC to 700 ºC and take place in the absence of air or $O_2$. Products from this process are high molecular weight char and volatile matters that in this model include CO, $H_2$, $H_2O$, $CO_2$, and $CH_4$, as shown in Eq(1), where α is the number of moles of the species after pyrolysis.

$$\text{Coal} \longrightarrow \alpha1\ CH_4 + \alpha2\ H_2 + \alpha3\ CO + \alpha4\ CO_2 + \alpha5\ H_2O + \alpha6\ \text{Char} + \alpha7\ \text{Ash} \tag{1}$$

#### 1.2.3. Volatile combustion reactions

From Eq(1), the volatile matter is composed of $CH_4$, $H_2$, CO, $CO_2$, $H_2O$, Char, and Ash. These gases, $CH_4$, $H_2$, CO, are combustible gases. So, after the coal pyrolysis process, these combustible gases will react with the gasifying agent ($O_2$ and steam mixture) that is fed into the gasifier, as presented in Eqs(2)-(4).

$$CO + 0.5\ O_2 \longrightarrow CO_2 \quad (\Delta H = -\ 283\ \text{MJ/kmol}) \tag{2}$$
$$H_2 + 0.5\ O_2 \longrightarrow H_2O \quad (\Delta H = -\ 242\ \text{MJ/kmol}) \tag{3}$$
$$C + 0.5\ O_2 \longrightarrow CO \quad (\Delta H = -\ 111\ \text{MJ/kmol}) \tag{4}$$

#### 1.2.4. Gasification reactions

The exothermic volatile combustion reactions (2), (3), and (4) provide heat energy which is required for the endothermic gasification reaction. The remaining char reacts with steam and $CO_2$ to produce syngas that consists mainly of CO and $H_2$, as illustrated in Eqs. (5)-(7).

$$C + H_2O \longrightarrow CO + H_2 \quad (\Delta H = +\ 131\ \text{MJ/kmol}) \tag{5}$$
$$C + CO_2 \longrightarrow H_2O \quad (\Delta H = +\ 172\ \text{MJ/kmol}) \tag{6}$$
$$C + 2\ H_2 \longrightarrow CH_4 \quad (\Delta H = -\ 75\ \text{MJ/kmol}) \tag{7}$$

#### 1.2.5. Water-gas shift and steam-methane reforming reactions

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad (\Delta H = -\ 41\ \text{MJ/kmol}) \tag{8}$$
$$CH_4 + H_2O \longrightarrow CO + 3\ H_2 \quad (\Delta H = +\ 206\ \text{MJ/kmol}) \tag{9}$$

## 2. Modelling and simulation of an entrained flow gasifier

The component attributes of the American coal used in developing this model are given in Table 1. HCOALGEN model is adopted to calculate the enthalpy of coal and DCOALIGT model is employed to estimate the density of coal (Xiangdong et al., 2013).

*Table 1: Component attribute of the coal used in the model*

| PROXANAL Analysis | | ULTANAL Analysis | | SULFANAL | |
|---|---|---|---|---|---|
| Element | (wt%) | Element | (wt%, dry basis) | Element | (wt%, dry basis) |
| Moisture (wet basis) | 0.20 | Ash | 15.50 | Pyritic | 0.59 |
| Fixed Carbon (dry basis) | 60.01 | C | 74.10 | Sulphate | 0.59 |
| Volatile Matter (dry basis) | 24.46 | H | 6.21 | Organic | 0.59 |
| Ash (dry basis) | 15.50 | N | 1.10 | | |
| | | S | 1.77 | | |
| | | O | 1.32 | | |

### 2.1 Simulation approaches

Figure 1 depicts the designed flow sheet for the coal gasification model which consists of three reactors yield, stoichiometric, and Gibbs. The yield reactor is used to simulate the coal pyrolysis process, while the stoichiometric reactor is adopted to model the volatile combustion and gasification reactions. Finally, the Gibbs reactor is used for the water-gas and steam-methane reforming reactions.

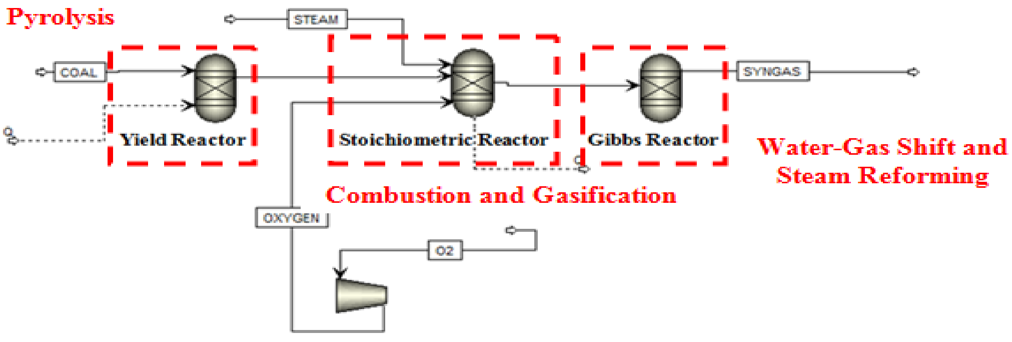


*Figure 1: Flow diagram of coal gasification through an entrained flow gasifier*

**2.2 Model validation**

This model is verified with practical data in order to evaluate the gasifier performance and accuracy issues. The results from this model is compared to the practical data that are collected from 9 runs in Texaco entrained flow gasifier with different coal mass flowrates, $O_2$/coal ratios, and steam/coal ratios (Xiangdong et al., 2013).

**2.2.1. Model assumptions**

The following are the main assumptions used to develop the model:

- The system is isothermal and steady state.
- Coal pyrolysis occurs instantaneously and produces light gases which are $H_2$, CO, $CO_2$, $CH_4$, and $H_2O$.
- Ash is inert.
- No nitrogen oxides are produced.

**2.2.2. Model basis and operating conditions**

The thermodynamic fluid package used for the simulated case is PR-BM. This thermodynamic package is suitable for high temperature gasification processes, as the alpha which is a parameter in this thermodynamic package, depends on temperature. This accordingly improves the correlation of the pure component vapor pressure at very high temperatures (Xiangdong et al., 2013). The temperature of reactors is set at 1,500 K = 1,227 °C and pressure of reactors is maintained at 24 bar. Model results are shown in Figure 2.

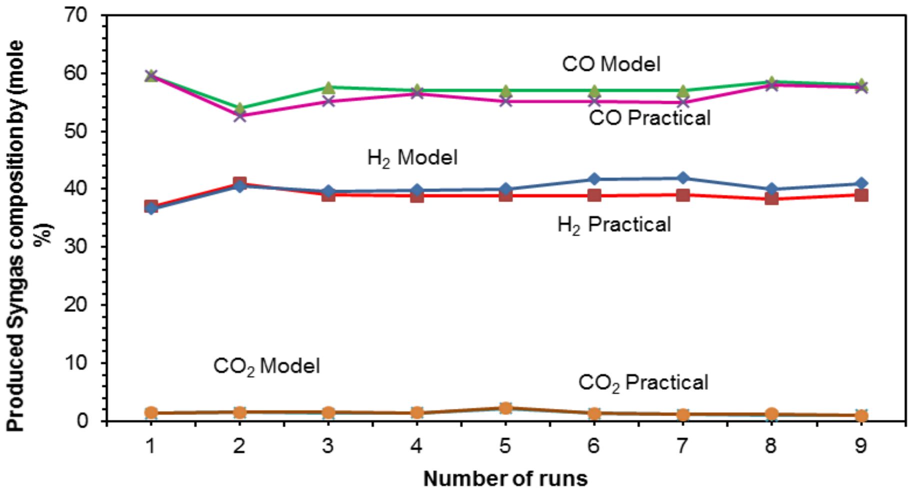


*Figure 2: Agreement between model results and practical data*

As illustrated in Figure 2, it can be observed that the model results show high agreement with the practical data. Therefore, this model can accurately predict the actual performance and also be employed to simulate any other entrained flow gasifier with different types of feedstocks and different operating conditions.

**2.3 The effect of using a blend of (90 % coal and 10 % rice straw) on the gasifier performance**

In this section, the developed model is applied but this time with feedstock dry mixture of (90 % El-Maghara coal and 10 % rice straw) in order to make an efficient-use of rice straw that is produced in massive rate in Egypt up to 3 Mt/y. Additionally, the model is applied to investigate the effects of using this feed mixture on the produced syngas composition and the gasifier performance. Over and above, the cold gas efficiency ($\eta_{CG}$) measuring the efficiency of the gasifier is calculated from Eq(10) (Emun et al., 2010).

$$\eta_{CG}\,(\%) = \frac{\mathrm{Msyngas} \cdot \mathrm{LHVsyngas}}{\mathrm{Mfuel} \cdot \mathrm{LHVfuel}} \cdot 100 \tag{10}$$

$M_{syngas}$ is the syngas mass flow rate in (kg/h), $M_{fuel}$ is the hydrocarbon feed coal rate or a blend of coal and biomass rate in (kg/h), $LHV_{syngas}$ is in (MJ/kg), and $LHV_{fuel}$ is in (MJ/kg). Nonetheless, $LHV_{syngas}$ and $LHV_{fuel}$ are estimated from Eq.(11) (Emun et al., 2010).

$$\mathrm{LHV\ syngas} = (X_{CO} \cdot LHV_{CO}) + \left(X_{H_2} \cdot LHV_{H_2}\right) + (X_{CH_4} \cdot LHV_{CH_4}) \tag{11}$$

$X_{CO}$, $X_{H2}$, and $X_{CH4}$ are the mass fractions of CO, $H_2$, and $CH_4$, respectively. $LHV_{CO}$ = 10.1 MJ/kg, $LHV_{H2}$ = 120 MJ/kg, $LHV_{CH4}$ = 50 MJ/kg, and $LHV_{coal}$ = 26.5 MJ/kg (Sudiro et al., 2008). For a dry El-Maghara coal; for dry coal feed; $LHV_{syngas}$ = (0.803·10.1) + (0.029·120) + (0.00352·50) = 12 MJ/kg and for a blend of (90 % El-Maghara coal and 10 % rice straw); $LHV_{syngas}$ = (0.74·10.1) + (0.022·120) + (0.033·50) = 11.76 (MJ/kg). Table 2 reports the effect of changing the feedstock coal type on the performance of the gasifier.

*Table 2: The effect of using a blend of (90 % coal and 10 % rice straw) on the performance of the gasifier*

| Feed type | Fuel rate (kg/h) | Syngas rate (kg/h) | LHV fuel (MJ/kg) | LHV syngas (MJ/kg) | Cold gas efficiency $\eta_{GC}$ (%) |
|---|---|---|---|---|---|
| Dry El-Maghara coal | 275.976 | 494.870 | 26.50 | 12.00 | 79.61 |
| 90 % El-Maghara coal and 10 % rice straw | 275.976 | 400.286 | 19.90 | 11.76 | 85.70 |

From Table 2, it is concluded that the dry feed mixture of (90 % coal and 10 % rice straw) revealed the highest cold gas efficiency, as rice straw is gasified at lower temperatures than dry coal. Hence, it consumes lower heating energy for the gasification unit than the other feedstocks.

## 3. Retrofit of an Egyptian natural gas power plant

Due to the increase in the price of natural gas and the need for a cleaner technology to produce electricity, power industry finds that it is better to go towards IGCC plants. The system fuel types such as coal or biomass or a blend of coal and biomass are gasified to produce syngas which consists mainly of carbon monoxide and hydrogen. As schematically outlined in Figure 3, the option concept is that the existing natural gas power plants would install an external gasification unit, an air separation unit, and a cleaning unit that will be connected to the existing natural gas power station through a syngas turbines line to generate the same power as the natural gas turbines.

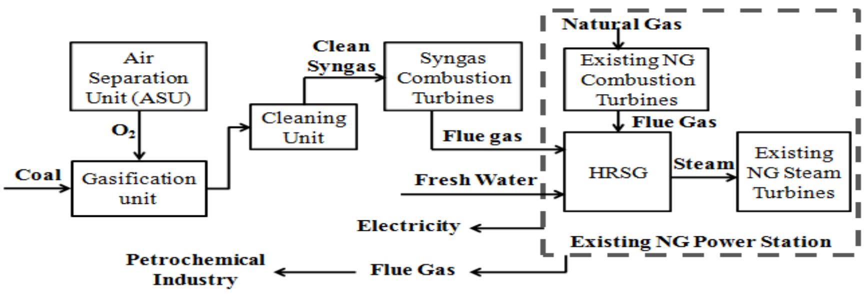


*Figure 3: Revamped natural gas combined cycle power plant*

Table 3 presents a comparison between an alternative new constructed IGCC power plant and the proposed revamped natural gas power plant. Each of the two power plants generates a power of 332 MW.

*Table 3: A comparison between the existing natural gas power plant and the retrofit alternative with syngas turbines line, gasification unit, air separation unit, and cleaning unit*

| Parameter | Revamped Natural gas plant | New constructed IGCC Plant |
|---|---|---|
| Net power (MW) | 332 | 332 |
| Fixed cost ($) | 169,925,967 | 1,398,227,393 |
| Natural gas (MMBtu) | 3,437 | ----------- |
| Coal flow rate (t/y) | -------- | 1,006,667 |
| Cost of natural gas ($/y) | 123,733,080 | ----------- |
| Cost of coal ($/y) | --------- | 53,101,666 |
| Utilities cost of the revamped plant ($/y) | 10,000,000 | 12,496,960 |
| Operating and Maintenance (O&M) cost ($/y) | 32,462,222 | 32,462,222 |
| Total operating cost ($/y) | 95,563,888 | 98,060,848 |
| Difference in cost between natural gas and coal ($/y) | | 70,631,414 |
| Cost of the generated electricity ($/y) | 162,311,111 | 162,311,111 |
| Plant life time (y) | 10 | 10 |
| Annualized fixed cost ($/y) | 16,992,597 | 139,822,739 |
| Total annualized cost for the revamped natural gas power plant ($/y) | 112,556,485 | 237,883,587 |
| Payback period of the revamped natural gas power plant (y) | 1.24 | 12 |

The fixed cost of a gasification unit in 2007 is $ 28,000,000 (Swanson et al., 2010) and this cost should be multiplied by 1.03 which is the cost index (CI) of year 2015 (543)/CI of year 2007 (525.7). So, the cost in 2015 becomes $ 28,921,438. The fixed cost of the air separation unit in 2007 is $ 19.5,000,000 and this cost in 2015 is estimated as $ 20,141,716. The fixed cost of the cleaning unit in 2007 is $ 29,000,000 and this cost in 2015 is calculated as $ 29,954,347. The fixed cost of the syngas turbines in K$ in year 2003 which equals to $ 67,302,400 is calculated through Eq(12) (Gadalla et al., 2005) and this cost in 2015 becomes $ 90,908,466.

$$\text{Fixed cost of syngas turbine (K\$)} = 195.1 * \text{Power (MW)} + 2529.2 \tag{12}$$

Fixed cost of the added units in 2015 equals to $ 169,925,967 which is calculated through Eq(13) as follows:

$$\text{Fixed cost (\$)} = \text{Air separation unit} + \text{gasification unit} + \text{syngas cleaning} + \text{syngas combustion turbines} \tag{13}$$

The fixed cost of the IGCC power plant in 2013 is $/kW 4,400 ( U.S. Energy Information Administration, 2013) and this cost should be multiplied by 0.957 which is the CI of 2015 (543)/CI of 2013 (567.3). Hence, the cost in 2015 becomes $1,398,227,393. The operating and maintenance cost (O&M) is almost 20 % of the total price of electricity generated from power plant. Withal, the total operating cost is calculated through Eq(14):

$$\text{Total operating cost} \left(\frac{\$}{\text{y}}\right) = \text{heating and cooling utilities cost} + \text{raw material cost} + O\&M\ cost \tag{14}$$

The payback period of the revamped natural gas power plant is calculated through Eq(15):

$$\frac{\text{Fixed cost of the added units to the existing natural gas power plant (\$)}}{\left[\begin{pmatrix}\text{Cost of electricity generated from the power plant} \left(\frac{\$}{\text{y}}\right) \\ + \text{Difference in cost between coal and natural gas} \left(\frac{\$}{\text{y}}\right)\end{pmatrix} - \text{Total operating cost of the revamped natural gas power plant} \left(\frac{\$}{\text{y}}\right)\right]} \tag{15}$$

On the other hand, the payback period of the new constructed IGCC power plant is calculated through Eq(16):

$$\frac{\text{Fixed cost of the new constructed IGCC power plant (\$)}}{\left[\left(\text{Cost of electricity generated from the power plant} \left(\frac{\$}{\text{y}}\right) + \text{Cost of coal} \left(\frac{\$}{\text{y}}\right)\right) - \text{Total operating cost of the new constructed IGCC power plant} \left(\frac{\$}{\text{y}}\right)\right]} \tag{16}$$

The cost of electricity generated from the power plant is calculated via Eq(17):

$$\text{Cost of electricity} \left(\frac{\$}{\text{y}}\right) = \text{Net power (kW)} * \frac{\$\ 1}{\text{L.E } 9} * \text{price of electricity(L.E/kWh)} * \text{working hours in year} \tag{17}$$

The cost of electricity in Egypt’s oil and gas sector is around L.E/kWh 0.55, the annual working hours = 8,000 h/y and $1 = L.E 9. The price of natural gas in 2014 is $/MW 15.35 and the price of coal in 2015 is $/t 52.75. The (MW) of natural gas that is needed to produce 332 MW is calculated as follows: 1 kW.h corresponds to

0.286 $m^3$ natural gas and 332,000 kW.h corresponds to 94952 $m^3$ natural gas, such that 0.30039 MW / 28.31 $m^3$ * 94952 $m^3$ = 1007.51 MW.

## 4. Conclusions

A simulation model of an entrained flow gasifier was developed using Aspen Plus commercial software. The proposed simulation model was tested for two types of coal origins, American and Egyptian; the model validation was performed with practical data and found to be in very good agreement. The developed model provided a robust basis for revamping an existing Egyptian natural gas-based power plant to replace its standard fuel with a coal-rice straw blend in case of low natural gas supply for the power plant. The revamped Egyptian natural gas power plant decreased the total annualized cost by 52.7 % with respect to a new constructed IGCC power plant. Nevertheless, the payback period decreased to 1.24 y rather than 12 y in case of the construction of a new IGCC power plant. Co-gasification was proposed and highlighted as a promising solution for waste valorisation with energy recovery, economic savings, and pollution reduction.

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