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Co-gasification of coal and biomass wastes in an entrained flow gasifier: Modelling, simulation and integration opportunities

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ABSTRACT

Gasification processes convert carbon-containing material into syngas through chemical reactions in the presence of gasifying agents such as air, oxygen, and steam. Syngas mixtures produced from such processes consist mainly of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4); this gas can be directly utilised as a fuel to produce electricity or steam. Besides, it is regarded as a basic feedstock within the petrochemical and conventional refining industries, producing various useful products like methanol, hydrogen, ammonia, and acetic acid. In this work, a rigorous process model is developed to simulate the co-gasification of coal-biomass blends through an entrained flow gasifier. The proposed model is tested originally for American coal. The model validation is made against literature data and results show good agreement with these practical data, providing a robust basis for integration and retrofitting applications. Effects of critical parameters, comprising gasification temperature, steam/O_2 ratio, and feedstock variability on the syngas composition and gasifier efficiency are studied. The developed model is further applied in a project to revamp an existing Egyptian natural gas-based power plant, replacing its standard fuel with coal-rice straw blends. The revamping project integrates the existing plant with a gasification unit burning a blend of coal and rice straw to replace the conventional fuel used. The feedstock used constitutes a dry Egyptian coal and a coal-rice straw blend (10 wt% rice straw), gathered locally. Different blending scenarios are investigated and the best performance is achieved with coal to rice straw ratio of 90:10 on weight basis, attaining 85.7% cold gas efficiency and significant economic savings. Results showed that the total annualised cost of the revamped process decreased by 52.7% compared with a newly built integrated gasification combined cycle (IGCC) unit.

1. Introduction

Biomass is considered to be sustainable, carbon-neutral, and alternative source of energy with a large potential owing to its low sulphur and nitrogen contents in comparison to conventional fuel resources, and this accordingly lower SO_x and NO_x emissions besides CO_2 foot-print towards meeting global demands and tight environmental concerns (Kuo and Wu, 2016). Numerous types of biomass feedstocks, wastes, products, and technologies are available to be utilised. This in turn highlights the critical need for the development of hierarchical approaches/procedures for the modelling, synthesis, and integration of such biorefinery concepts (Abdelaziz et al., 2015; Tay et al., 2011).

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 like air, oxygen, and/or steam (Lee et al., 2014; Sudiro et al., 2008). The syngas produced from the gasifier is made up mainly of CO, H_2, CO_2, and CH_4; it is eligible to be exploited as a fuel for steam and electricity generation, or as a main feedstock in the chemical process industries to produce various useful products such as methanol, hydrogen, ammonia, and acetic acid (Abdelaziz et al., 2014; Sharma et al., 2015). Coal gasification technology can viably be used in many useful purposes, for instance, the production of syngas that can be completely combusted by air in a gas turbine cycle to produce hot flue gases which transfer heat energy to water and thus generate

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electricity through steam turbine cycles. The clean syngas combusted in turbines/engines at higher temperatures cycles offers higher efficiency than the traditional steam cycles associated with the burning of carbonaceous fuels, allowing more potential efficiency improvements. Yet, the development of more versatile and cost-effective gas-to-liquid conversion technologies that are capable of processing the syngas of a diverse range of compositions is pressing, redirecting insights into complementing coal, renewables, and waste valorisation strategies within natural gas sector (Wood, 2016).

Solid fuel gasification to generate gaseous fuels or high value chemicals is becoming one of the most critical techniques for resources utilisation; in particular, biomass and coal solid fuels are of great importance referring that they are carriers of accumulated solar energy (Sjöström et al., 1999). The coal and biomass co-gasification process provides various environmental and economic gains when compared to standard gasification approaches. It efficiently uses the biomass materials within the energy generation systems at lower production costs, than it can be attained in the current systems of biomass gasification (Howaniec and Smoliński, 2014). In light of this, co-gasification emerged as a promising and important approach in jointly converting carbonaceous fuels into useable heating value gases in a cleaner and more environmentally friendly manner. This is regarded due to the fact that it involves the conversion of a fossil-origin fuel like coal, plastic wastes or fuel-oil, as one of the carbonaceous raw fuel material besides the high potentiality for implementation on a commercial scale (Hernández et al., 2010a).

Among different gasifier types and current available technologies, the entrained flow technology appears to be the most suitable approach to the joint conversion of coal and biomass streams. The main reason is due to the elevated reaction temperature (around 1200–1500 °C) in such configuration and high heating rates which consequently compensates for various reactivities of two fuel resource materials (Valero and Usón, 2006). Additionally, these gasifiers offer high efficiency for syngas production and interesting option to large industrial scale availability/applicability (Vascellari et al., 2015). It is worth mentioning that the current commercialised entrained flow gasifiers are directed primarily to coal and liquid fuels; however, there is still little experience and research efforts with biomass and biomass wastes as potential renewable feedstock (Hernández et al., 2010b).

Simulation and modelling of coal and biomass-derived gasification units is widely studied in literature with different objectives and applications (Adeyemi et al., 2016; Adeyemi and Janajreh, 2015; Meratizaman et al., 2015; Parvez et al., 2016; Tapasvi et al., 2015; Yan et al., 2016; Yi et al., 2012). One essential challenge for designing such a typical gasifier is the process modelling of reaction unit to predict the final composition of syngas generated; this is together with the thermal efficiency of the system (Madzivhandila et al., 2011; Tunå and Hulteberg, 2013). Technically speaking, the syngas quality varies with the exploited oxidising agents. Known examples include air, steam, steam–oxygen, air–steam, and oxygen-enriched air, where between these oxidising agents, air is considered the most commonly adopted agent (Kuo et al., 2014). Furthermore, the accurate modelling of biomass gasification as well as the optimum parameters/conditions prediction are elementary in case of chemical equilibrium achievability. Going forward and due to the deviation of equilibrium data results from experimental sets, the aforementioned assumption is not always valid (Beheshti et al., 2015). Therefore, developing an accurate model in good agreement with real data is important and challenging at the same time.

Coal, petroleum coke, rice straw, wood and blends of coal and biomass can be used as feedstocks for the gasification process. All of these materials consist basically of carbon with different variable amounts of hydrogen, oxygen, and impurities such as sulphur and ash (Lee et al., 2011). The gas produced from the gasifier is normally termed as a producer gas. This producer gas constituents are mainly CO, CO_2, H_2, and H_2O, besides CH_4 and higher hydrocarbons, involving some tar compounds (Svensson et al., 2013). In coal gasification, five principal processes/reactions are involved which are dehydration, pyrolysis, combustion, gasification, water gas shift, and steam-methane reforming. Details of these processes and reactions are discussed below:

1.1. Dehydration

No agricultural waste/product or gasifier feed is found to be completely dry in its natural state. Some water content is always present in its formulation. In the dehydration process, evaporation occurs on any free water content of the feedstock in order to dry the feedstock and produce water vapour that may participate in later chemical reactions.

1.2. Coal pyrolysis

The temperature in the gasifier is typically higher than 1000 °C. When coal is introduced into the gasifier, it first undergoes a pyrolysis process which is a series of physical and chemical complex reactions that start slowly at a temperature from about 150 °C to 700 °C 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 our developed model include CO, H_2, H_2O, CO_2, and CH_4 as in reaction (1), where α is defined as the number of moles of the species post pyrolysis.

$$Coal \rightarrow \alpha_1 CH_4 + \alpha_2 H_2 + \alpha_3 CO + \alpha_4 CO_2 + \alpha_5 H_2O + \alpha_6 Char + \alpha_7 Ash \quad (1)$$

1.3. Volatile combustion reactions

From reaction (1), the volatile matter is seen to include CH_4, H_2, CO, CO_2, H_2O, Char, and Ash. The gases, CH_4, H_2, CO, are combustible gases. Therefore, after the coal pyrolysis process, such combustible gases will react with the gasifying agent (O_2 and steam mixture) which is fed into the gasifier, as shown by the following exothermic reactions (Xiangdong et al., 2013):

$$CO + 0.5O_2 \rightarrow CO_2\ (\Delta H = -\ 283\ MJ/kmol) \quad (2)$$

$$H_2 + 0.5O_2 \rightarrow H_2O\ (\Delta H = -\ 242\ MJ/kmol) \quad (3)$$

$$C + 0.5O_2 \rightarrow CO\ (\Delta H = -\ 111\ MJ/kmol) \quad (4)$$

1.4. Gasification reactions

Exothermic volatile combustion reactions (2), (3), and (4) provide heat energy which is needed 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 shown in the following reactions (Sharma et al., 2015):

$$C + H_2O \leftrightarrow CO + H_2\ (\Delta H = +\ 131\ MJ/kmol) \quad (5)$$

$$C + CO_2 \leftrightarrow 2\ CO\ (\Delta H = +\ 172\ MJ/kmol) \quad (6)$$

$$C + 2H_2 \leftrightarrow CH_4\ (\Delta H = -\ 75\ MJ/kmol) \tag{7}$$

1.5. Water-gas-shift and steam-methane-reforming reactions

Referring to the raised above, the combustion reactions are mainly performed to completion in normal reaction operating constraints. Under high conditions of carbon conversion, the three heterogeneous nature reactions (reactions 5 to 7) can conceivably be reduced instead to two homogeneous reactions in gas phase. These two reactions are water-gas-shift and steam-methane-reforming reactions (reactions 8 and 9); they remarkably play a critical role in obtaining the final equilibrium composition of syngas.

$$CO + H_2O \leftrightarrow CO_2 + H_2\ (\Delta H = -\ 41\ MJ/kmol) \tag{8}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O\ (\Delta H = +\ 206\ MJ/kmol) \tag{9}$$

Reactor configuration and flow arrangement in the gasifier are the main factors affecting the gasification process. In this context, gasifiers can be categorised into the following three types:

(i) Entrained flow gasifiers
In this configuration, very fine coal particles normally flow co-currently with the gasifying agent at high speed, as shown in Fig. 1a. The feedstock type ordinarily used for this gasifier can be dry feed or wet feed (slurry). Entrained flow gasifiers are the most common choice for the gasification of coal. Also, their common licensors are Shell and Texaco gasifiers (Phillips, 2004).

(ii) Fixed bed gasifiers
In the fixed bed gasifiers, the gasifying agent flows counter-currently with coal feed, as depicted in Fig. 1b. The produced syngas contains significant amounts of tars and oils and its temperature is lower than the temperature needed for the gasification of coal (Phillips, 2004).

(iii) Fluidised bed gasifiers
In this type, coal particles are typically suspended in gas flow by adjusting the flowrate of the gasifying agent. Fluidised bed gasifiers have a homogenous temperature during coal gasification process (Minchener, 2005); Fig. 1c illustrates the concept.

Rice is one of the most abundant agricultural crops in Egypt. The local agricultural sector produces around four million tonnes of rice annually, leading to plenty of rice straw wastes. This agricultural waste is produced in enormous amounts in Egypt, reaching up to 3 Mt/y (Abdelhady et al., 2014). The burning process of rice straw is a main reason of released emissions termed locally as the black cloud phenomenon, which causes air pollution. In this concern, finding/seeking solutions and options towards the efficient valorisation of such waste is thus necessary.

In this paper, a rigorous simulation model is developed for the gasification of a blend of coal and rice straw waste materials. To assess robustness and accuracy, the model is tested for real data of coal and validated by using practical data from literature. Applying this process on a blend of coal/rice straw in Egypt serves in two directions, one of which is to replace the conventional burning of rice straw wastes, eliminating a large pollution problem locally in Egypt. The second is to convert biomass wastes into some added-value chemicals. Further, the developed co-gasification model is employed to revamp an existing power-plant for the replacement of its conventional natural gas fuel by a blend of coal/biomass. Such a revamping and integration strategy shall produce electricity with a reduced fuel costs and improved environmental impacts.

2. Methodology

The research develops a rigorous simulation model of an entrained flow gasifier employing commercial Aspen Plus® software (Aspen Technology, 2008). The proposed simulation model is tested for two types of coal origins, American and Egyptian with a mixture of 10% of the Egyptian rice straw; model validation is made with practical data. The new gasifier model consists of three reactors. The first one is a yield reactor where coal pyrolysis occurs, the second reactor is a stoichiometric reactor where gasification reactions take place, and the third reactor is Gibbs reactor in which water-gas and steam-methane reforming reactions occur. The fluid package Peng–Robinson–Boston–Mathias (PR-BM) is adopted for thermodynamic properties estimation. The Gibbs free energy minimisation method of the biomass fuel and oxidant mixture for the C–H–O–N atom blend is applied to predict the thermodynamic composition of the major gas components produced, namely H_2, CO, CH_4, CO_2, H_2O, N_2, and char, near equilibrium. An equilibrium thermodynamic model is hence developed for a biomass gasification system employing the Gibbs minimising approach under the Aspen Plus® simulation environment (Aspen Technology, 2008). Material and energy necessary streams data extracted from the developed model are adopted to estimate the cold gas energy and exergy process efficiencies. Details on the steps of developing the model and its applicability are discussed below.

2.1. Simulation of an entrained flow gasifier

In this model, the thermodynamic property method PR-BM (Peng Robinson-Boston Mathias) is adopted to calculate the physical properties of the mixed conventional components. It is worth mentioning that, it is preferred to use the aforementioned fluid package in case of high gasification temperatures, as occurring in entrained flow gasifiers. The HCOALGEN model is used to calculate the enthalpy of non-conventional components, while the DCOALIGT model is employed to estimate the density for non-conventional components. The HCOALGEN model incorporates a number of empirical correlations for heat of combustion, heat of formation, and heat capacity; other values are retrieved from the available Aspen Plus® database (Aspen Technology, 2008). PROXANAL, ULTANAL, and SULFANAL represent the components attributes for non-conventional components which are essentially required in the HCOALGEN model. The PROXANAL typically gives the weight contents of moisture, fixed carbon, volatile matter, and ash. On the other hand, the ULTANAL gives the weight composition of coal in terms of carbon, hydrogen, nitrogen, sulphur, and oxygen. Going forward, the SULFANAL gives the mass fractions of sulphur divided into pyritic, sulphate, and organic sulphur. The ULTANAL and SULFANAL component attributes are required for the DCOALIGT model. Table 1 reports the component attributes of the American coal incorporated in this model. The same models are used to calculate the enthalpy and density for char and ash. The results of PROXANAL, ULTANAL and SULFANAL for the coal used in this model were determined from the analysis data of original coal and the amount of gasified gaseous product in terms of mass balance.

In the simulation of the gasifier, a three steps steady-state model is developed to tackle the gasification process. Every step is specified by the built-in operating units or the user defined modules, providing a rigorous simulation-based model for further investigation studies. Fig. 2 proposes the simulation model for the coal gasification. The simulation model consists of three reactors: (1)

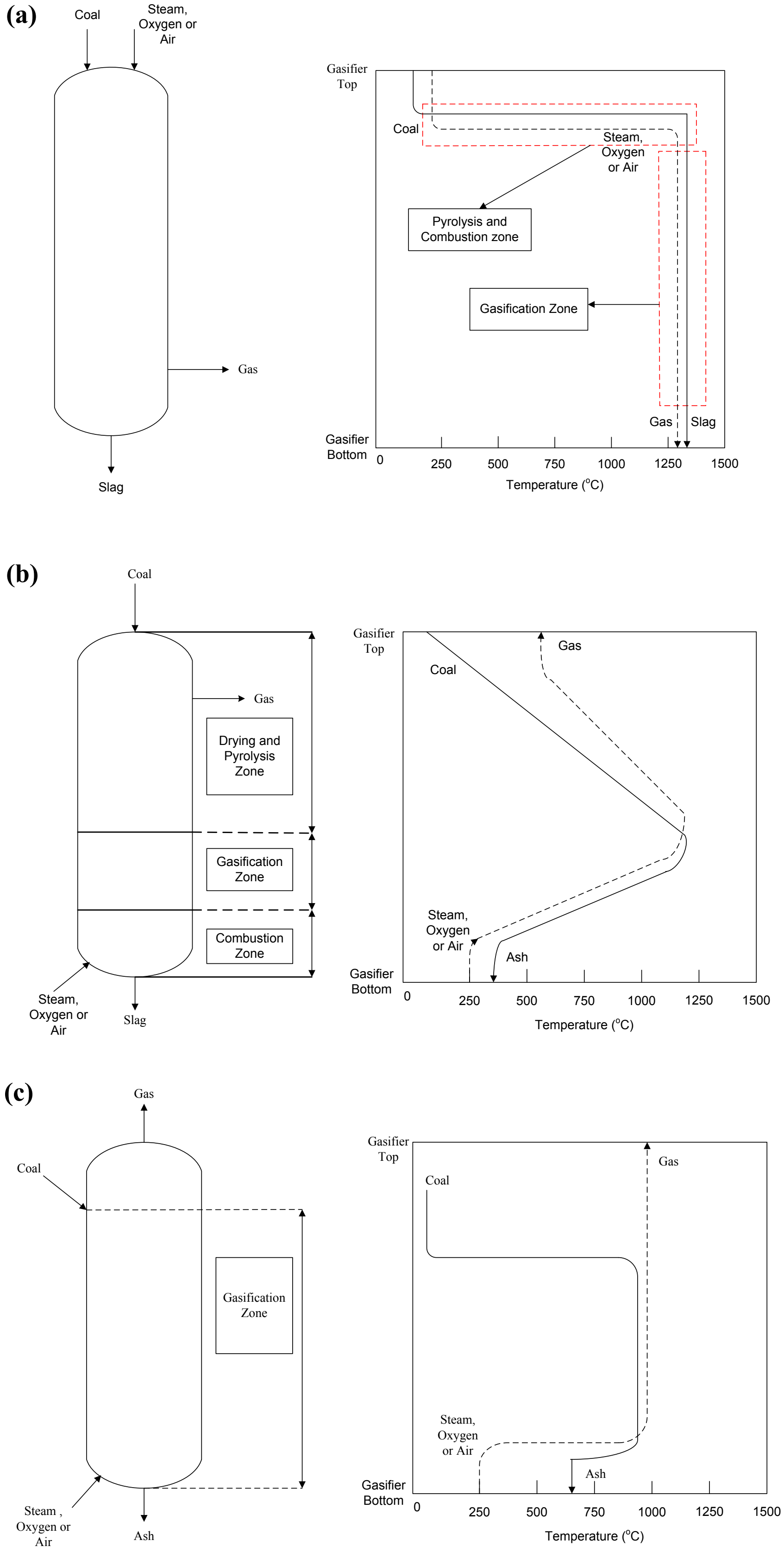

Fig. 1. Schematic of (a) entrained flow gasifier (b) fixed bed gasifier (c) fluidised bed gasifier.

Table 1
Component attribute of the American coal used in developing the model.

PROXANAL		ULTANAL		SULFANAL	
Element	(wt%)	Element	(wt%, dry basis)	Element	(wt%, dry basis)
Moisture (Wet basis)	0.2	Ash	15.5	Pyritic	0.59
Fixed carbon (dry basis)	60.01	C	74.1	Sulphate	0.59
87 Volatile matter (dry basis)	88 24.46	89 H	90 6.21	Organic	0.59
Ash (dry basis)	15.5	N	1.1		
		S	1.77		
		O	1.32		

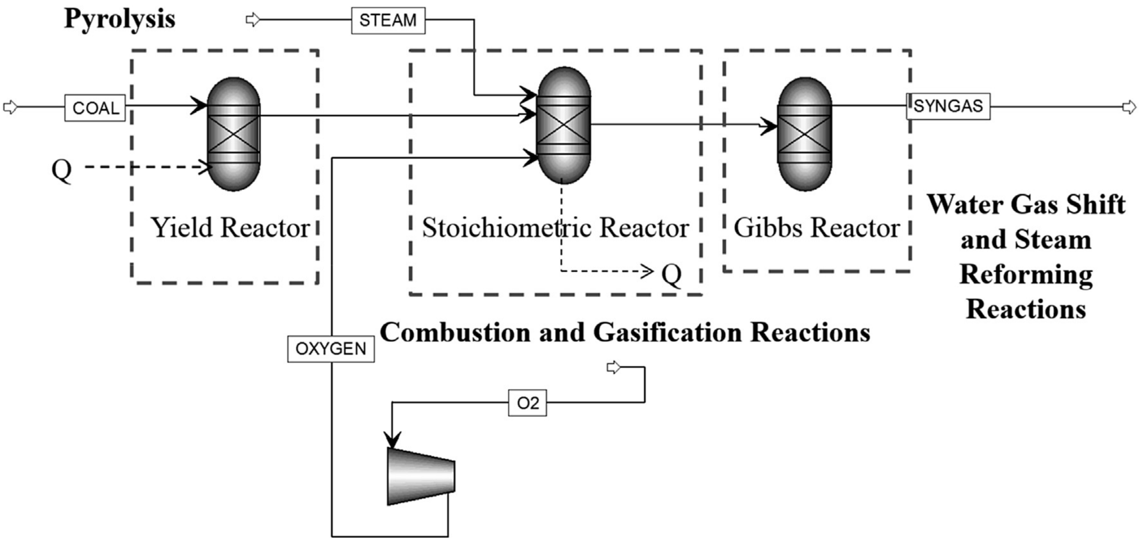

Fig. 2. Flow diagram for coal gasification by using entrained flow gasifier.

yield reactor, (2) stoichiometric reactor, and (3) Gibbs reactor. The yield reactor is proposed to account for (simulate) the coal pyrolysis stage process. Going further, the stoichiometric reactor is selected to model the volatile combustion and gasification reactions. Lastly, the Gibbs reactor is adopted to represent the water-gas and steam-methane-reforming reactions. For given feed properties and conditions, the simulation model converges to determine the compositions/properties of all gasification products, provided that the initial values of the operation conditions, e.g. temperature, pressure, coal flow rate, O_2/coal ratio and steam/coal ratio are introduced. Duties, temperatures and flow rates of reactions' products are also results of the simulation model.

2.2. Model assumptions and operating conditions

The developed model is based on the following assumptions: (i) the system is isothermal, (ii) steady state condition is prevailing, (iii) coal pyrolysis occurs instantaneously and produces light gases which are H_2, CO, CO_2, CH_4, and H_2O, (iv) ash is inert, and (v) no nitrogen oxides are produced. The first three assumptions are based on the characteristics of the entrained flow gasifier configuration in which the residence time of pyrolysis and gasification reactions normally reaches up to 10 s. This is considerably short residence time; therefore, the pyrolysis occurs instantaneously and the temperature can be considered uniform (isothermal) along the gasifier unit. For the fourth assumption, ash is assumed to be inert. This is precisely applied to simplify the gasifier model in the Aspen Plus® environment through eliminating the reactions of ash with O_2. Finally, no nitrogen oxides production is assumed; this can be basically attributed to the complete consumption of O_2 within the pyrolysis and gasification reactions. The temperature of reactors is set to 1227 °C, whereas the pressure of the reactors is defined with a value of 24 atm.

2.3. Model validation

The simulation model is tested for literature data of American coal as given previously in Table 1. The model is then verified with practical data in order to evaluate the gasifier performance. Practical data are collected from some 9 runs in Texaco entrained flow gasifier with different coal mass flowrates, O_2/coal ratios, and steam/coal ratios. Such data of the Texaco entrained flow gasifier are given in Table 2 (Xiangdong et al., 2013). The nine runs of practical data are employed in the simulation model and their results are compared with the existing data from literature.

Table 2
Practical data that are used as feed in this model (Xiangdong et al., 2013).

Run #	Coal rate (kg/h)	O_2/Carbon ratio	Steam/Carbon ratio
1	275.976	0.866	0.241
2	292.248	0.768	0.318
3	295.920	0.813	0.309
4	286.056	0.807	0.323
5	257.804	0.826	0.352
6	315.828	0.774	0.291
7	327.492	0.776	0.282
8	331.668	0.797	0.247
9	316.044	0.787	0.268

Table 3
Simulation model validation with practical data.

Run #	Syngas rate (kg/h)	Model			Practical		
		H_2	CO	CO_2	H_2	CO	CO_2
1	494.75	0.37	0.60	0.013	0.37	0.60	0.013
2	609.63	0.39	0.54	0.015	0.41	0.53	0.015
3	627.94	0.40	0.58	0.014	0.39	0.55	0.015
4	609.29	0.40	0.57	0.014	0.39	0.57	0.014
5	531.51	0.40	0.57	0.022	0.39	0.55	0.022
6	652.23	0.41	0.57	0.013	0.39	0.55	0.013
7	674.20	0.42	0.57	0.012	0.39	0.55	0.012
8	678.10	0.40	0.59	0.010	0.38	0.58	0.012
9	649.47	0.42	0.58	0.011	0.39	0.58	0.011

3. Results and discussion

Table 3 gives the syngas flow rates produced from the model and shows the compositions of gasification gases (CO, H_2, and CO_2) produced from both the model and the literature data of compositions of the gasification gases (practical) that are gathered from 9 runs in the Texaco entrained flow gasifier with different coal mass flowrates. These data are the basis for the model validation, as depicted in Fig. 3.

The results of Fig. 3 illustrate that the model results are in relatively a good agreement with the practical data for the gas compositions of CO, CO_2, and H_2. Accordingly, this model is robust and can be employed to simulate any other entrained flow gasifier with different types of feedstocks and different operating conditions. Thus, the proposed simulation model is applied for further studies on several feedstocks and analysing the effect of many processing parameters on the gasification performances. The following section shows the results of varying some operating and design parameters, outlining their impacts on the performance and products compositions. For every change in the considered parameters, the simulation model is used and all other design variables/parameters are kept fixed.

3.1. *Entrained flow gasifier model with feedstock dry American coal*

The developed simulation model is applied on the same feedstock type (dry American coal) with the same assumptions and reactions. However, the first run only is taken into consideration and its operating parameters are specified as follows: temperature in reactors is 1227 °C, pressure in reactors is 24 atm, dry coal rate is 275.98 kg/h, O_2/coal ratio is 0.87, and steam/coal ratio is 0.24. The results acquired of the model for produced syngas composition and molar flowrates are presented later together with rice straw blend.

(i) Influence of the gasification temperature on syngas composition

For given feedstock properties and conditions, the gasification temperature is changed using the simulation model proposed above. The results of this parameter changes are shown in Fig. 4. The gasification endothermic reactions are enhanced by increasing the gasification temperature. In general, the increase of temperature leads to an increase of H_2 and CO concentrations and a decrease of CO_2 and CH_4 portions (Taba et al., 2012). Accordingly, it would be expected that the concentration of CO and H_2 increases during the proposed runs. However, the presence of endothermic reactions may also lower the gasification temperatures as they are energy intensive process. Besides, an expected decrease in the reactivity of char is encountered. Thus, in the absence of other operating parameters that enhance gasification temperatures such as more steam, the gasification temperature changes have no effect on the concentration of these two components, i.e. CO and H_2. This analysis is found in agreement with the observation spotted in Fig. 4. The same applies to the concentration of CH_4 that seems to be relatively constant.

(ii) Effect of steam/O_2 ratio on H_2/CO ratio, CH_4/H_2 ratio, and syngas flowrate

Fig. 5 exemplifies that by increasing the steam/O_2 ratio, the gasification reaction (5) favours to produce both CO and H_2. In case of further increase in steam/O_2 ratio, the water gas shift reaction (8) favours to produce more hydrogen and carbon dioxide. From the previous two reactions, it appears that the amount of hydrogen produced is larger than carbon monoxide. Consequently, the H_2/CO in syngas increases with increasing the steam/O_2 ratio. This agrees with the finding of simulation results presented in Fig. 5.

Fig. 6 illustrates that reaction (5) is highly affected by increasing steam/O_2 ratio or increasing steam flowrate while

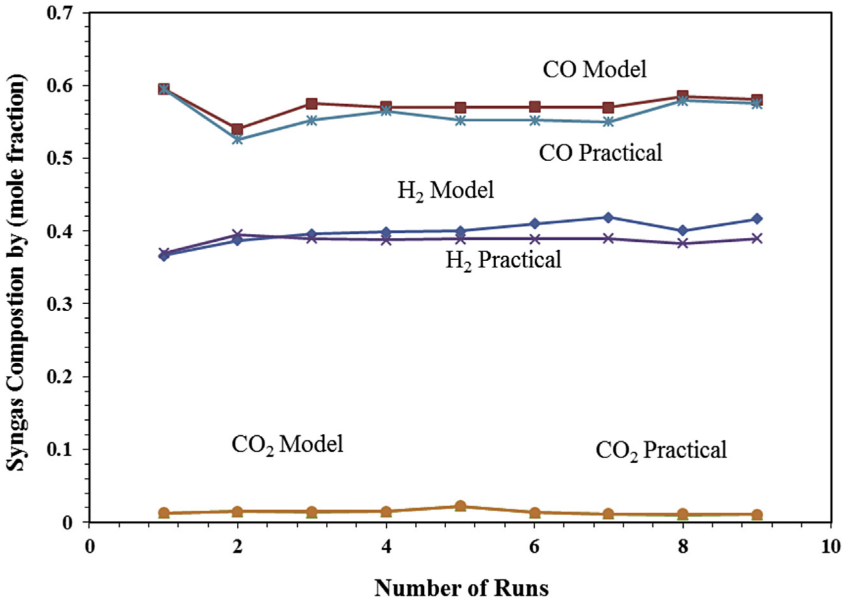

Fig. 3. Graph shows the agreement between model results and practical data.

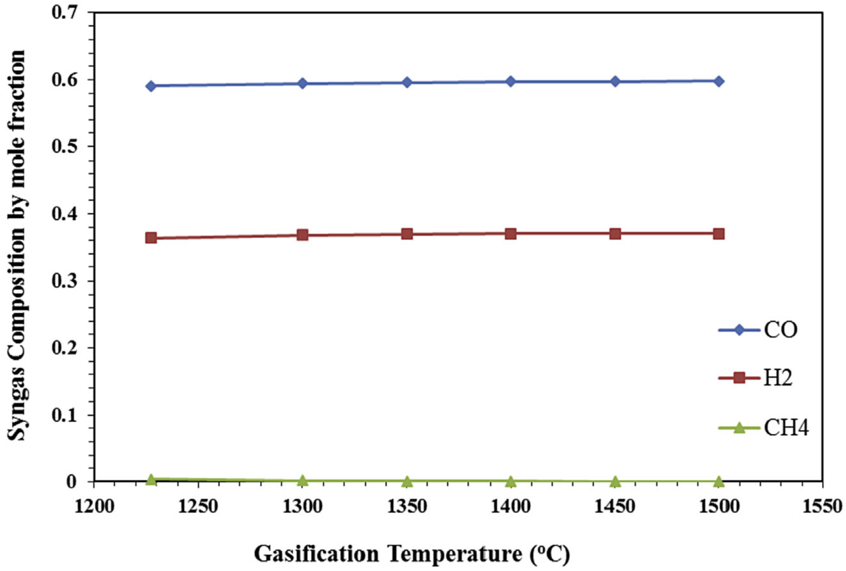

Fig. 4. Effect of changing the gasification temperature on the syngas composition.

fixing O_2 flow rate as it is significant at all pressures. This is because, reaction (5) which is the steam gasification reaction is an endothermic reaction ($\Delta H = +131$ MJ/kmol). So, it tends to decrease the gasification temperature and to face this problem there are two ways that can be used. The first way is feeding gasifier with more O_2 whereas the second way is feeding gasifier with more steam. If O_2 feed is excessive then the process becomes more like combustion than gasification and low heating value gases are produced, while in case of increasing steam flow rate in a suitable way to control the gasification temperature, the flow rates of CO and H_2 increases. On another hand, reaction (7) has lower contribution than the former reaction. Accordingly, the increase in the H_2 production from the steam gasification reaction caused by increasing steam/O_2 ratio is relatively higher than the increase in CH_4 production with higher H_2 concentration. Also, the CH_4/H_2 ratio in syngas decreases with increasing the steam/O_2 ratio (see Fig. 6).

Related to the same parameter changes, Fig. 7 shows that the syngas flowrate increases with increasing steam/O_2 ratio. This could be due to the increase in the production of CO, H_2, CH_4 and CO_2 such that these compounds result from reactions (5), (7), and (8).

(iii) Effect of using a blend of (90% coal and 10% rice straw) on syngas composition and gasifier performance

The above results encounter the use of only coal feedstock. In this section, the simulation model is applied but this time with a feedstock of dry mixture (90% coal and 10% rice straw) to make an efficient-use of rice straw. As mentioned above, rice straw is an agricultural waste, and is produced in enormous amounts in Egypt, reaching up to 3 million tonnes-per-year (Abdelhady et al., 2014). Further, to see the effects of using this feed mixture on the produced syngas composition and the gasifier performance in the context of better waste valorisation, different blends with coal are investigated. The characteristics of the American coal are given as previous in

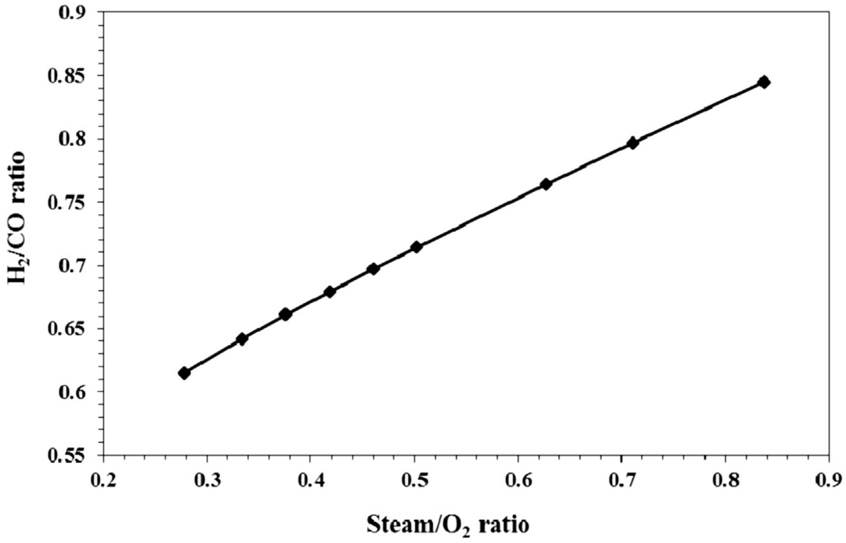

Fig. 5. The effect of changing steam/O_2 ratio on H_2/CO ratio in syngas.

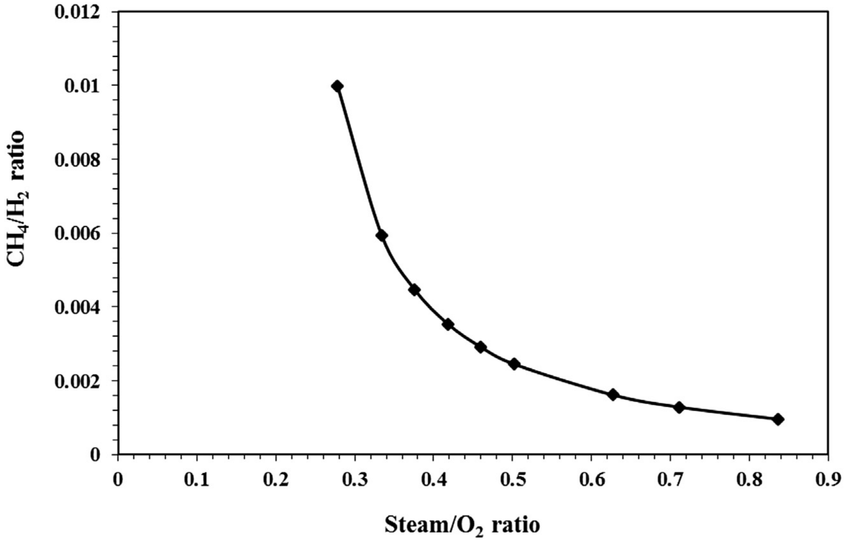

Fig. 6. The effect of changing steam/O_2 ratio on CH_4/H_2 ratio in syngas.

Table 1, while Table 4 provides the characteristics of the rice straw in Egypt (Stahl and Ramadan, 2007) which are used in the simulation of the gasifier model. The characteristics of the rice straw includes three types of analysis; the first analysis is Proximate Analysis which includes the moisture content, fixed carbon, volatile matter, and ash in rice straw. The second analysis is Ultimate Analysis which illustrates the weight percent on dry basis for each element in rice straw like C, H, N, Cl, S, O, for instance. The third analysis is Sulphate Analysis which illustrates the weight percent on dry basis for pyritic, sulphate, and organic in the rice straw. Using the characteristics of rice straw, the biomass feedstock is characterised in Aspen Plus® (Aspen Technology, 2008) using the same manner followed for the American coal.

Again, the model assumptions and the operating conditions are the same as those used in previous analysis with coal rate = 248.37 kg/h and rice straw rate = 27.59 kg/h. Table 5 reports the resulted syngas composition of the blending scenario together with the dry American coal case. This composition value is necessary for the calculation of LHV of syngas and the cold gas efficiency.

Table 5 reveals a decrease in H_2 composition for the case of feedstock blend feed mixture (90% coal and 10% rice straw). This could be due to the presence of higher volatile matter in rice straw than coal, which causes a subsequent reduction in the gasification temperature to be 927 °C than the coal gasification case only where its gasification temperature is 1227 °C, thereby leading to reduction in H_2 production, as shown in the endothermic water-gas reaction (5).

It can be noted that when the gasification temperature decreases, the reaction goes in the reactants direction, hence, H_2 and CO compositions decrease. The concentration of CO_2 increases during the co-gasification process according to the exothermic reaction (2), while the CO concentration decreases according to the endothermic reactions (5) and (6). Meanwhile, when rice straw content increases in the feed, the concentration of H_2S in the

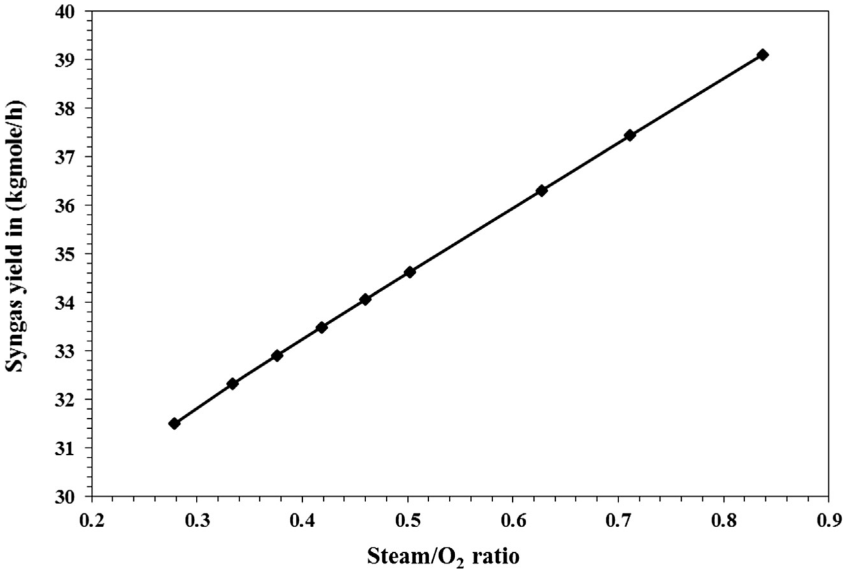

Fig. 7. The effect of changing steam/O_2 ratio on the produced syngas flowrate.

Table 4
Component attributes of rice straw used in the model.

PROXANAL		ULTANAL		SULFANAL	
Element	(wt%)	Element	(wt%, dry basis)	Element	(wt%, dry basis)
Moisture (Wet basis)	10	Ash	20	Pyritic	0
Fixed carbon (dry basis)	20	C	39.2	Sulphate	0
Volatile matter (dry basis)	60	H	3.8	Organic	100
Ash (dry basis)	20	N	0.3		
		Cl	0.9		
		S	0.3		
		O	35.5		

Table 5
Resulted syngas information from the modelled entrained flow gasifier with dry American coal scenario and feedstock (90% American coal and 10% rice straw).

Components	American coal		90% American coal and 10% rice straw	
	Molar flowrate (lbmole/h)	Mole fraction	Molar flowrate (lbmole/h)	Mole fraction
H_2	25.42	0.37	16.67	0.28
CO	41.32	0.60	32.48	0.54
H_2O	1.44	0.02	3.09	0.052
CO_2	0.9	0.013	4.40	0.07
H_2S	0.09	0.0013	0.08	0.0014
CH_4	0.25	0.0036	3.28	0.0546

produced syngas increases as well. This consequently may cause corrosion on the process units. Due to the lower temperature of co-gasification, the CH_4 composition increases according to the exothermic reaction (7).

To tackle the effect on the performance of the modelled entrained flow gasifier, the gasifier efficiency is opted for. Cold gas efficiency (ηCG) measures the typical efficiency of a gasification unit and it is determined by the following equation (Emun et al., 2010):

$$\eta GC = \frac{M_{syngas} \times LHV_{syngas}}{M_{fuel} \times LHV_{fuel}} \tag{10}$$

M_{syngas} is the syngas mass flow rate in (kg/h), M_{fuel} is the hydrocarbon feed coal rate or a mixture of coal and biomass rate in (kg/h), LHV_{syngas} is in (MJ/kg) and LHV_{fuel} is in (MJ/kg). LHV_{syngas} and LHV_{fuel} are calculated from the equation below:

$$LHV_{syngas} = (X_{CO} \times LHV_{CO}) + (X_{H2} \times LHV_{H2}) + (X_{CH4} \times LHV_{CH4}) \tag{11}$$

The terms X_{CO}, X_{H2}, and X_{CH4} are the mass fractions of CO, H_2 and CH_4, respectively. LHV values are set as $LHV_{CO} = 10.1$ 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 feed type (90% coal and 10% rice straw), $LHV_{syngas} = (0.73 \times 10.1) + (0.0267 \times 120) + (0.042 \times 50) = 12.68$ (MJ/kg). On another hand, for a dry coal feed, $LHV_{syngas} = (0.803 \times 10.1) + (0.029 \times 120) + (0.00352 \times 50) = 12$ MJ/kg.

Table 6
The effect of changing the percent of rice straw in feedstock on the performance of the modelled gasifier.

Feed type	Fuel rate (kg/h)	Syngas rate (kg/h)	Fuel LHV (MJ/kg)	Syngas LHV (MJ/kg)	Cold gas efficiency η_{GC} (%)
Dry mixture of (90% American coal and 10% rice straw)	275.976	451.46	25.179	12.687	82.38
Dry American coal	275.976	494.87	26.5	12	79.61

Table 6 illustrates the influence of changing the rice straw percent on the gasifier performance. As can be seen, the dry feed mixture of 90% coal and 10% rice straw shows the higher value of cold gas efficiency. This is because rice straw is gasified at lower temperatures in comparison to dry coal; subsequently, it consumes less heating energy in the gasification unit than for other feedstocks.

3.2. *Entrained flow gasifier with feedstock Egyptian coal (El-Maghara coal)*

In this section, the model is again applied, but this time with a feedstock of dry Egyptian coal that is called El-Maghara coal. Table 7 gives the characteristics of the Egyptian dry coal (El-Maghara). The characteristics of the Egyptian coal is performed as previously discussed and the Sulphate Analysis here illustrates the weight percent on dry basis for pyritic, sulphate and organic in coal. The model assumptions and the operating conditions, and the characterisation procedure in Aspen Plus® (Aspen Technology, 2008) are the same as described in the previous sections. Table 8 shows the produced syngas composition by mole fraction exploiting the local coal El-Maghara, and also blended with the Egyptian rice straw (10%).

(i) Entrained flow gasifier with dry feedstock blend of 90% El-Maghara coal and 10% rice straw
Here, the model is adopted considering a blend of a 90% El-Maghara coal with some 10% rice straw with coal rate = 248.37 kg/h and rice straw rate = 27.59 kg/h. In Table 8, the results of the produced syngas composition by local coal-rice straw blend are given together with the local coal feed scenario; these data are necessary in the calculation of LHV of syngas and the cold gas efficiency.

(ii) Effect of coal type on syngas composition and gasifier performance
The effect of changing the coal type on the syngas produced composition is at this point compared (see Tables 5 and 8). As can be noted, the decrease in H_2 composition in case of dry El-Maghara coal can be assigned to the presence of higher volatile matter present in El-Maghara coal than American coal as the ash percent in El-Maghara coal is 6.5 wt%, while in the American coal it is 5.5 wt%. Nonetheless, the H_2S composition increases, as the sulphur content in El-Maghara coal is higher than American coal. Also, the CH_4 compositions decrease as the carbon percent in EL-Maghara coal is lower than that in the case of the American coal and the H_2 composition decreases due to the presence of higher volatile content in El-Maghara coal. Additionally, the CO and CO_2 compositions increase can be regarded as EL-Maghara coal has higher O_2 content.

For 90% El-Maghara coal and 10% rice straw, Equation (11) results in:

$$LHV_{syngas} = (0.74 \times 10.1) + (0.022 \times 120) + (0.033 \times 50) = 11.76 \text{ (MJ/kg)}.$$

For 90% American coal and 10% rice straw, Equation (11) results in:

$$LHV_{syngas} = (0.73 \times 10.1) + (0.0267 \times 120) + (0.042 \times 50) = 12.68 \text{ (MJ/kg)}.$$

Table 7
Component attributes of El-Maghara coal used in the model (Seddeek et al., 2004).

PROXANAL		ULTANAL		SULFANAL	
Element	(wt%)	Element	(wt%, dry basis)	Element	(wt %, dry basis)
Moisture (Wet basis)	4.9	Ash	6.5	Pyritic	0.59
Fixed carbon (dry basis)	42.5	C	71	Sulphate	0.59
Volatile matter (dry basis)	51	H	5.7	Organic	0.59
Ash (dry basis)	6.5	N	1		
		S	3		
		O	12.8		

Table 8
Resulted syngas composition with feedstock El-Maghara coal scenario and feedstock (90% El-Maghara coal and 10% rice straw).

Components	El-Maghara coal		90% El-Maghara coal and 10% rice straw	
	Molar flowrate (lbmole/h)	Mole fraction	Molar flowrate (lbmole/h)	Mole fraction
H_2	24.72	0.33	13.83	0.24
CO	47.63	0.64	33.18	0.58
H_2O	0.463	0.01	2.51	0.044
CO_2	1.26	0.02	4.39	0.076
H_2S	0.32	0.004	0.26	0.005
CH_4	0.08	0.001	2.62	0.046

The LHV of syngas in case of American coal is higher than El-Maghara coal case with value; this is due to the fact that El-Maghara coal has more volatile matter than the American coal. Add to that, El-Maghara coal is gasified at lower temperatures than the American coal, and thus consuming less heating energy than the other feedstock for gasification unit. The syngas rate and fuel LHV of American coal case is also rather higher with values of 451.5 kg/h and 25.2 MJ/kg in comparison to the El-Maghara coal case with values of 400.3 kg/h and 19.9 MJ/kg, respectively. Over and above, the gasifier revealed the highest cold gas efficiency value of 85.7% for El-Maghara coal blend case in comparison to the American coal blend scenario (82.38%).

4. Revamping modelling 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 it better to move towards the integrated gasification combined cycle IGCC plants and cleaner solutions. The system fuel types can be various such as coal or biomass or a blend of coal and biomass, producing syngas when gasified. To this point, a schematic diagram is proposed in Fig. 8. The scheme proposes the integration of the existing natural gas power plants with an external gasification unit, air separation unit, and cleaning unit. This integrated process represents an economical/environmental alternative to standard power plants. The new equipment will be connected to the existing natural gas power station through a syngas turbines' line in order to generate the same electric power as the natural gas turbines do. Such integration is valuable to tackle any future shortage of natural gas fuel supply or to cope with development projects that promote the use of natural gas as an important petrochemical feedstock. It must be noted that the alternative solution for producing the electricity by burning the coal/biomass blend would be building a complete IGCC unit rather than the integration proposed in this work. For integration, the electric power production rate in MW is the fixed variable for the integration scheme, i.e. conventional plant and integrated plant both produce same electricity rates. On the other hand, if an IGCC unit is newly to be built, the unit will expectedly produce the same power production rate.

Since revamping projects imply structural/capital modifications to replace conventional fuels, costs of installed equipment/components are to be calculated. At the same time, the various operating costs of energy savings, raw materials, biomass feedstock, savings in conventional fuels, electricity productions, etc. have to be estimated. Therefore, capital investment, operation costs and economic parameters of the existing power plant as well as the integrated process are estimated, including:

(1) Capital investments of gasification equipment ($)
(2) Capital cost of syngas turbines ($)
(3) Capital cost of air separation unit ($)
(4) Capital cost of syngas cleaning unit ($)
(5) Operating cost of heating and cooling utilities ($/yr)
(6) Operating costs of raw materials (coal, natural gas, biomass) ($/yr)
(7) Cost of electricity or power production ($/yr)
(8) Operating costs of maintenance (O&M costs) ($/yr)
(9) Payback period (yr)

Once the capital investment of the additional equipment is determined, payback periods can be estimated providing that the total annual cost savings are known. The economic and cost analyses are performed for the revamped process, i.e. existing power plant with additional gasification unit. This economic analysis can be obtained for both the integrated process, i.e. existing power plant with gasification unit, and newly constructed IGCC plant for assessment/comparison.

For an existing power plant in Egypt producing 332 MW of electricity production rate, the simulation model for gasification unit is applied for the revamping objective. The simulation model proposed in previous sections is valuable for the assessment of revamping opportunities of the existing power plant. The model is employed to provide the syngas required for the power plant. For an electricity production of 332 MW, the simulation model is solved to determine raw material flows (coal/rice straw), air flow, flue gas details, dimensions/sizing of equipment, etc.

Table 9 summarises the cost estimation results and economic parameters for the revamped plant burning coal/rice straw blend. Appendix A presents details of cost and economic analysis calculations of the revamped processes. The table also compares the results of the retrofit scenarios, focussing on the new constructed

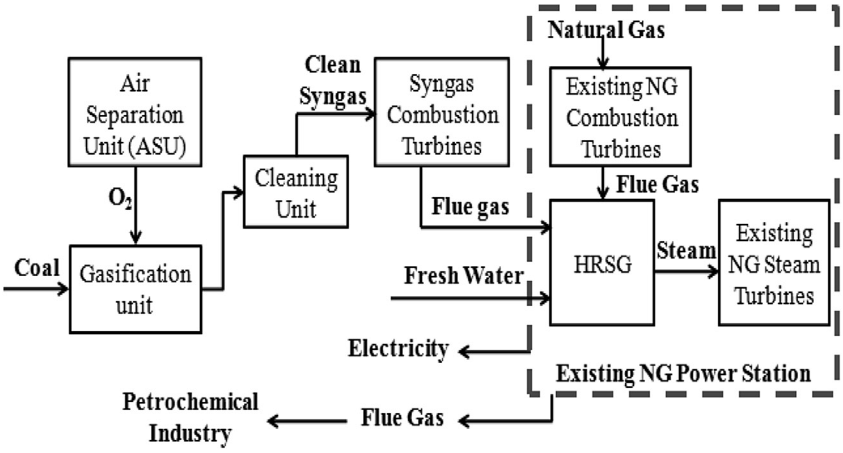

Fig. 8. Revamped natural gas power plant.

Table 9
Economical analysis for the revamped natural gas power plant and the existing IGCC plant.

Parameter	Revamped alternative	New plant
Net power (MW)	332	332
Fixed cost (M$)	170	1398
Natural gas (MMBtu)	3437	–
Coal flow rate (Mt/y)	–	1.01
Cost of natural gas (M$/y)	123.7	–
Cost of coal (M$/y)	–	53.1
Utilities cost (M$/y)	10	12.5
Operating and maintenance cost (M$/y)	32.5	32.5
Total operating cost (M$/y)	95.6	98.1
Difference in cost between natural gas and coal (M$/y)	70.6	–
Price of the generated electricity (M$/y)	162.3	162.3
Plant life (y)	10	10
Annualised fixed cost (M$/y)	17	139.8
Total annualised cost (M$/y)	112.6	237.9
Payback period (y)	1.24	12

IGCC power plant and the proposed revamped natural gas power plant which is integrated with a gasification unit, air separation unit, cleaning unit, and a parallel line containing syngas turbines. Each of the two power plants generates power equals to approximately 332 MW.

It is clear from the table that building a new IGCC plant would require the investment of eight-times more than integrating an IGCC with the existing unit. The total annual operating costs of the integrated plant are less than the original power plant with some 3.5 million dollars. Further, the payback period for this integrated plant is 1.24 year compared with 12 years for the original plant.

5. Concluding remarks

A rigorous model for coal gasification of an entrained flow configuration has been developed. The simulation model was found to be in good agreement with the practical data of Texaco entrained flow gasifier. Co-gasification of several coal feedstock of different origins, and blends of different feedstock/bio-waste materials has been explored, including American/Egyptian coal and coal-rice straw blends. The effect of changing the gasification temperature on syngas composition has been analysed. Results have shown that the compositions of CO and H_2 increased as they are produced from reactions (5) and (6); these endothermic gasification reactions are enhanced by increasing gasification temperature, while CH_4 and CO_2 are produced from the exothermic reactions (7) and (2) which were not affected by the same change. The effects of changing the steam/O_2 ratio at a constant gasification temperature on H_2/CO ratio, CH_4/H_2 ratio in the produced syngas and syngas flowrate have been also analysed. It was found that when steam/O_2 ratio increased, the H_2/CO ratio also increased as reaction (5) favours the production of CO and H_2. On the other hand, reaction (8) prefers the production of more H_2 and $CO_{2.}$

The effect of using a dry mixture of 90% coal and 10% rice straw as feed compared with dry coal on the performance of gasifier and syngas composition has been investigated. For a dry mixture (90% American coal & 10% Egyptian rice straw), the cold gas efficiency has increased to 82.38%, while for the dry coal case it was 79.61% and the syngas composition (H_2 and CO) decreased with 24% and 8.5%, respectively, compared to dry coal scenario. For a feed mixture of 90% Egyptian coal and 10% Egyptian rice straw, the cold gas efficiency was estimated as 85.7%. The revamped Egyptian natural gas power plant decreased the total annualised cost by 52.7% with respect to a newly constructed IGCC power plant. Nevertheless, the payback period decreased to 1.24 years rather than 12 years in case of the construction of a new IGCC power plant. Co-gasification has been proposed and highlighted as a promising solution for waste valorisation with energy recovery, economic savings and pollution reduction.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jngse.2016.11.044.

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