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Dalia A. Ali Eng
The British University in Egypt, dalia.amer@bue.edu.eg

Mamdouh A. Gadalla Prof.
The British University in Egypt, mamdouh.gadalla@bue.edu.eg

Fatma H. Ashour Prof.
Cairo University, Faculty of Engineering

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3 authors:

Dalia Amer Ali
The British University in Egypt

Mamdouh Gadalla
Port Said University

Fatma HANAFY Ashour
Cairo University

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Gasification of Coal and Heat Integration Modification for IGCC - Integrated Gasification Combined Cycle

Dalia Amer*,[a], Mamdouh Gadalla[a], Fatma Ashour[b]

[a]Chemical Engineering Department, British University in Egypt, Cairo –Suez Desert Road, Sherouk City Gate 1, Cairo Egypt
[b]Chemical Engineering Department, Cairo University, University Street 1, Giza, Egypt
Dalia.Amer@bue.edu.eg

Use of energy is closely related to the development of an economy. The most useful form of energy in the modern world is electricity. IGCC has higher fuel flexibility (biomass, refinery residues, petroleum coke, etc.) and generates multiple products (electricity, hydrogen and chemicals like methanol and higher alcohols) and by-products - sulphur, sulphuric acid, slag, etc. IGCC plants include coal preparation unit, air separation unit (ASU) to separate oxygen from air to use it in the gasification process, gasification unit where an incomplete combustion for coal is made to produce Syngas, cleaning unit to remove acid gases and CO2 from Syngas and a power station that contains gas turbines and steam turbines to produce electricity (Emun et al., 2010).

In this work Heat Integration study is made to an IGCC plant whose feedstock is coal- water slurry with a flow rate of 3,020 t/d. The study produces a comparison between the capital investment and operating costs of the existing and the integrated IGCC plant and investigates the effect of changing the feedstock content on thermal efficiency, net power and cold gas efficiency.

The Heat Integration considers ΔT_{min} = 1.5 °C as for the existing plant, and results in savings of 47.5 % and 5.4 % as in the required heating and cooling duties. Three different feedstocks with the same flow rate 3020 t/d are used in this work to study their effects on the efficiency of IGCC plant; coal, coal-water slurry and a mixture of 93 % coal and 7 % ricestraw. Thermal efficiencies resulted due to the change in feedstock are 37 %, 36.6 % and 36.8 %, net powers are 337.5 MW, 334 MW and 337 MW while the cold gas efficiencies are 71.5 %, 70 % and 72 % for coal, coal-water slurry and (93 % coal and 7 % ricestraw).

1. Introduction

IGCC uses a coal gasification system to convert coal into a synthesis gas (syngas) and produce steam. The hot Syngas is processed to remove sulphur compounds, mercury and particulate matter before it is used to fuel a combustion turbine generator, which produces electricity. The heat in the exhaust gases from the combustion turbine is recovered to generate additional steam. This steam, along with that from the syngas process, then drives a steam turbine generator to produce additional electricity. Syngas consisted mainly of hydrogen, carbon monoxide, carbon dioxide and water. Syngas is used in petrochemical industries to produce various products such as methanol and ammonia. IGCC plants are major heating and cooling utilities consuming plants and therefore require extensive utility management. There are many ways to make this management; Heat Exchanger Network design and Process Heat Integration are widely used methods (Liew et al., 2014). Feedstock type such as (coal, coal-water slurry or a mixture of coal and biomass) has a great effect on the performance of the IGCC power plants which are thermal efficiency, net power of the plant and cold gas efficiency. Thermal efficiency is a measure of performance of a power cycle and it is function in the plant net power, mass flow rate and lower heating value (LHV) of the fuel used. Cold gas efficiency is a measure of performance of gasification unit and it is function in mass flow rates and lower heating values (LHV) of Syngas and fuel used in the plant. The main objectives of this work are decreasing the heating and cooling utilities consumption of the IGCC plant and increasing the efficiency of IGCC plant by changing the feedstock type.

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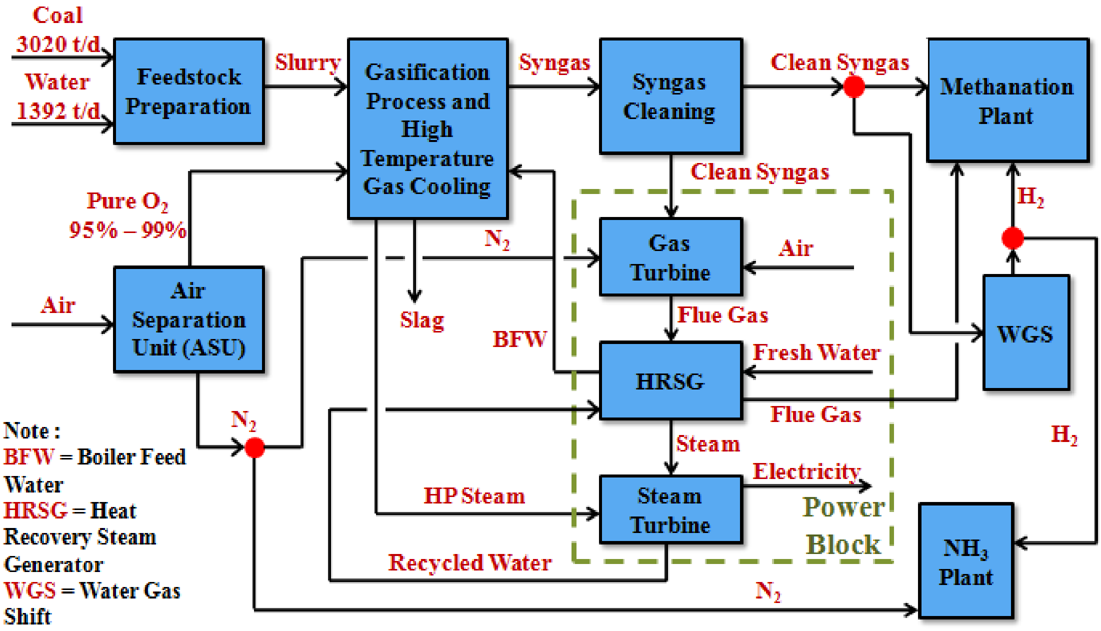

Figure 1: IGCC Block Flow Diagram

2. ΔT_{min} and Heat Exchanger Network of the existing IGCC

Heat Integration study is made for the existing IGCC plant with a coal-water slurry feedstock in order to reach the minimum heating and cooling energy targets and save total annualized cost of the process. ΔT_{min} in this case considers 1.5 °C as shown in Table 1 which is small due to the presence of the ASU in the IGCC plant where a cryogenic process occurred to separate oxygen gas from air in order to use it in the gasification process.

Table 1: ΔT_{min} of the existing IGCC plant with slurry feed

Heat Exchangers Names	T_{hin}(^{o}C)	T_{hout}(^{o}C)	T_{cin}(^{o}C)	T_{cout}(^{o}C)	ΔT_{in}(^{o}C)	ΔT_{out}(^{o}C)
INTRC1 & INTRC1 CW	93.89	33.22	30.56	88.32	5.57	2.66
INTRC2 & INTRC2 CW	114.5	33.3	30.56	100.3	14.2	2.74
INTRC3 & INTRC3 CW	76.53	36.06	30.56	72.41	4.12	5.5
GOXCLR1 & GOXCLR1 CW	267.9	35	30.56	176.7	91.2	4.44
N2CLR1 & N2CLR1 CW	243.9	35	30.56	171.8	72.1	4.44
N2CLR2 & N2CLR2 CW	230.1	35	30.56	171.8	58.3	4.44
GOXCLR2 & GOXCLR2 CW	215.7	35	30.56	169.4	46.3	4.44
HX-2 (AIR-1 to AIR-1A)	20	-170	-181.8	13.04	6.96	11.8
HX3(BOTLPC&BOTLPCA)	-171.3	-179.8	-193.4	-181.4	10.1	13.6
HX-3(N2HPC & N2HPC-A)	-177.1	-179.8	-181.4	-178.6	1.5	1.6
RSC & RSC CW	1438	818.8	215.6	363.3	1074.7	603.2
CSC 1 & CSC1 CW	818.8	402.5	215.6	352.2	466.6	186.9
CSC 2 & CSC1 CW	818.8	402.5	215.6	352.2	466.6	186.9
N2CLR	71.54	-34.44	-37.15	-6.787	78.32	2.71
SG & (Treat to Treat 2)	152.4	140.1	-6.787	93.33	59.07	146.88
ACLR & GTAIRCLR	536.8	502.7	198.3	399.1	137.7	304.4
HX1 (PRD1 & PRD1-A)	415.8	132.2	22.25	69.28	346.52	109.95
HX2 (PRD2 & PRD2-A)	210.4	0	-22.58	22.22	188.18	22.58
HX-3A(PRD2-Bto PRD2C)	0.555	-23.33	-36.37	-3.507	4.062	13.04
HX1 (PRD1 to FD2-A)	427	402	366.7	390.8	36.2	35.3
HX2 (PRD2 to FD3)	507	394	239.2	366.7	140.3	154.8
HX3 (PRD3 to COOLNH3)	472	454	219	239.2	232.8	235

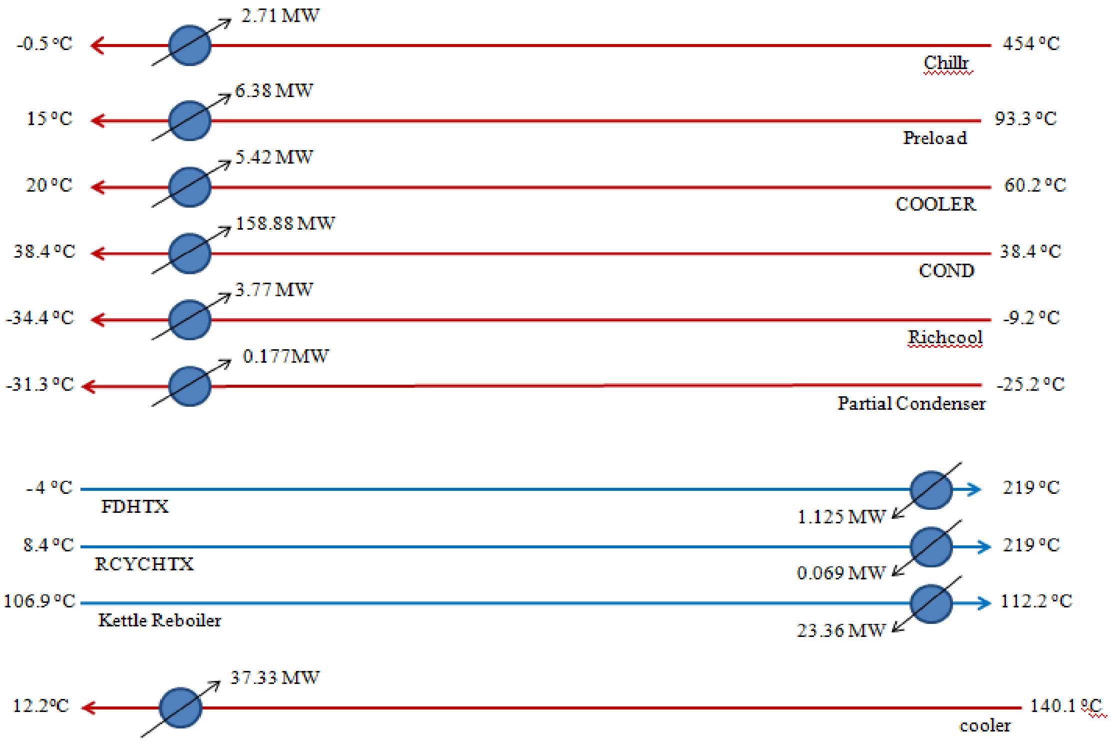

Figure 2: Heat Exchanger Network for the external heaters and coolers only in the existing IGCC plant

The cost of heating and cooling utilities used in the existing IGCC is 12,496,960 $/y as shown in Table 2 Where the cost of cooling water is 0.067 $/t and the high pressure steam cost is 17 $/t (Emun et al., 2010).

Table 2: Cost of heating and cooling utilities for the existing IGCC plant

Utility Name	T_{in}(°C)	T_{out}(°C)	Utility load (kJ/h)	CP (kJ/h°C)	Utility flowrate (kg/h)	Utility cost ($/y)
Cooling water	20	40	9.81×10^8	4.183	11,726,034	6,285,154
HP steam	250	249	8.84×10^7	2.196	40,255	5,474,681
Refrigerant 1	-25	-24	1.62×10^7	4	4,050,000	354,975
Refrigerant 2	-40	-39	1.42×10^7	1.341	10,589,113	382,150

Table 3: All information for the existing IGCC plant

Parameters	Existing IGCC plant
Qh consumed (MW)	24.55
Qc consumed (MW)	214.67
Heating and cooling utilities cost ($/y)	12,496,960
Cost of Bituminous coal ($/y)	35,166,666
Net power of the existing IGCC plant (MW)	322
Electricity selling price ($/y)	188,576,000
Operating and maintenance (O & M) cost (20 % of the electricity selling cost) ($/y)	37,715,200
Total operating cost (heating and cooling duties cost + cost of coal + O&M cost) ($/y)	85,378,826
Cost of additional heat exchanger area ($)	-
Total fixed cost (plant fixed cost + cost of additional heat exchanger area) ($)	892,801,900
Plant life time (y)	10
Annualized fixed cost (total fixed cost / plant life time) ($/y)	89,280,190
Total annualized cost (total operating cost + annualized fixed cost) ($/y)	174,659,016

The cost of Bituminous coal is 52.72 $/t and the cost of electricity is 71 $/MWh (US. Energy Information Administration, 2015). The minimum heating and cooling energy targets are obtained through the Composite Curve as shown in Figure 3.

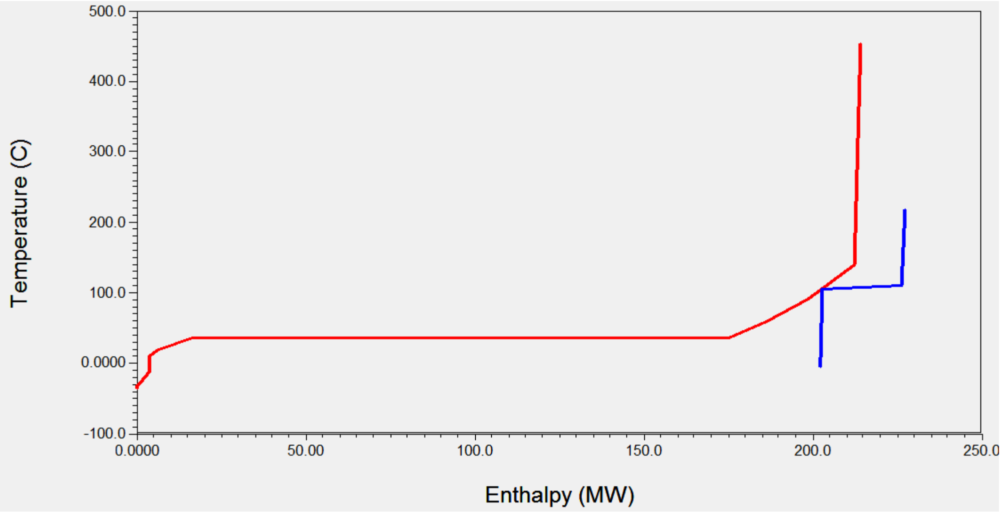

Figure 3: Composite Curve of the IGCC plant at ΔT_{min} = 1.5 °C

The minimum heating and cooling energy targets are 15.38 MW for heating duty and 205.15 MW for cooling duty while the existing IGCC plant consumes 24.55 MW for heating duty and 214.67 MW for cooling duty so; the Heat Integration saves 9.17 MW as heating duty and 9.52 MW as cooling duty. These results are summarized in the following Table 4.

Table 4: Results of Heat Integration of IGCC plant at ΔT_{min} = 1.5 °C

ΔT_{min}(^{o}C)	Qh_{exist} (MW)	Qc_{exist} (MW)	Qh_{min} (MW)	Qc_{min} (Mw)	Qc_{saved} (MW)	Qh_{saved} (MW)
1.542	24.55	214.67	15.38	205.15	9.52	9.17

The Heat Exchanger Network of the Heat integrated IGCC plant is made according to the Pinch Technology method as shown in Figure 4.

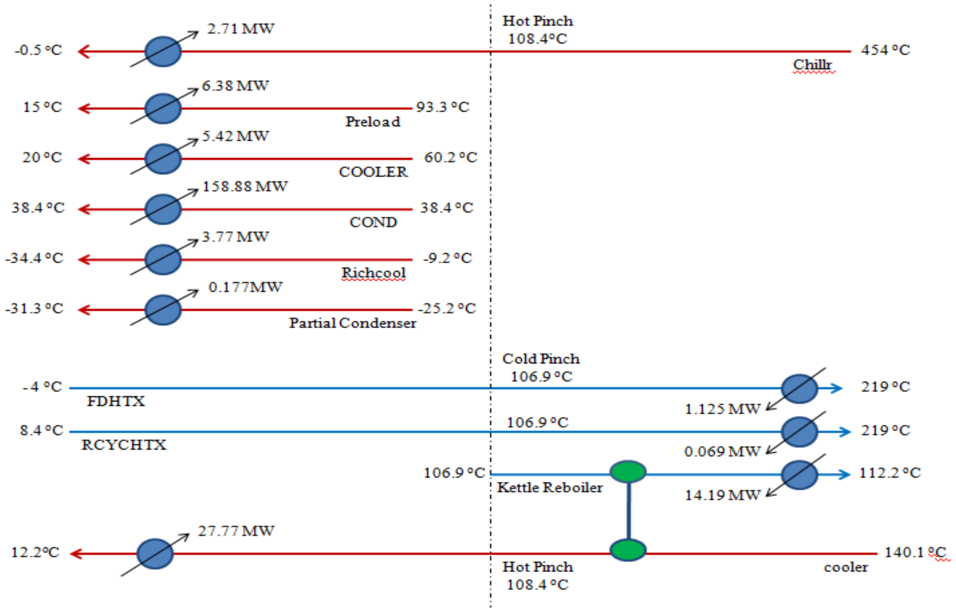

Figure 4: Heat Exchanger Network at ΔT_{min} = 1.5 °C

Table 5 shows the additional area to the IGCC plant after making Heat Integration which equals 9,624 m^2. The cost of this additional heat exchanger area in 2003 is $ 494,545 which is calculated from this equation 1530 * (additional area)$^{0.63}$ and this cost should be multiplied by 1.8 which is the cost index of year 2014 divided by the cost index of year 2003 to get the cost at 2014 that equals $ 890,181.

Table 5: Load and area of the added heat exchanger

Heat Exchanger Name	New load (MW)	Additional Area (m^2)
cooler& kettle reboiler	9.16	9,624

The total cost of heating and cooling utilities is $/y 11,166,760 as shown in Table 6.

Table 6: Cost of heating and cooling utilities for the Heat integrated IGCC plant

Utility Name	T_{in}(°C)	T_{out}(°C)	Utility load (kJ/h)	CP (kJ/h°C)	Utility flowrate (kg/h)	Utility cost ($/y)
Cooling water	20	40	9.81 E8	4.183	11,200,096	6,003,251
HP steam	250	249	8.84 E7	2,196	32,531	4,424,193
Refrigerant 1	-25	-24	1.62 E7	4	4,075,000	357,166
Refrigerant 2	-40	-39	1.42 E7	1.341	10,589,113	382,150

Table 7: A comparison between the results of the existing IGCC plant and the Heat integrated IGCC plant

Parameters	Existing IGCC plant	Heat Integration for existing IGCC plant
Qh consumed (MW)	24.55	15.38
Qc consumed (MW)	214.67	205.15
Heating and cooling utilities cost ($/y)	12,496,960	11,166,760
Cost of Bituminous coal ($/y)	35,166,666	35,166,666
Net power of the existing IGCC plant (MW)	322	322
Electricity selling price ($/y)	188,576,000	188,576,000
Operating and maintenance (O & M) cost (20% of the electricity selling cost) ($/y)	37,715,200	37,715,200
Total operating cost (heating and cooling duties cost + cost of coal + O&M cost) ($/y)	85,378,826	84,048,626
Cost of additional heat exchanger area ($)	-	890,181
Total fixed cost (plant fixed cost + cost of additional heat exchanger area) ($)	892,801,900	893,692,081
Plant life time (y)	10	10
Annualized fixed cost (total fixed cost / plant life time) ($/y)	89,280,190	89,369,208
Total annualized cost (total operating cost + annualized fixed cost) ($/y)	174,659,016	173,417,834

From the previous table it is concluded that the Heat Integration for the existing IGCC plant with slurry feed saves total annualized cost by 1,241,182 $/y.

3. Effect of changing the feedstock on the performance of the IGCC plant

Changing the feedstock has a great effect on the performance of the IGCC plant. In this case three feedstocks with the same flow rate 3,020 t/d are used to study their effects on the performance of IGCC plant. The feedstocks used in this case are dry coal, coal-water slurry and a mixture of 93 % coal and 7 % ricestraw. Thermal Efficiency measures the performance of the power cycle which is obtained from Eq(13). Cold gas efficiency measures the efficiency of a gasification unit and it is obtained from Eq(14). Net power of IGCC plant is obtained from Eq(15) (Emun et al., 2010).

$$\eta t\ (\%) = \frac{Pnet}{(Mfuel * LHVfuel)} * 100 \qquad (13)$$

Where ηt is thermal efficiency, M_{fuel} is the mass flow rate of fuel used such as coal (kg/s), LHV_{fuel} is the lower heating value of the fuel used (MJ/kg) and P_{net} is the net power output (MW).

$$\eta cg\ (\%) = \frac{Msyn * LHVsyn}{Mfuel * LHV\ fuel} * 100 \tag{14}$$

Where η_{cg} is cold gas efficiency, M_{syngas} and M_{fuel} are the mass flow rates of Syngas and fuel used (kg/s) respectively, LHV_{syn} and LHV_{fuel} are the lower heating values (MJ/kg) for syngas and fuel used.

$$Pnet = PGT + PST - PAUX \tag{15}$$

Where P_{net} is net power output (MW), P_{GT} is the net power output from the gas turbine (MW) and P_{ST} is the power output from the steam turbine (MW) and P_{AUX} is the auxiliary power consumption in pumps, compressors, etc. (MW) and here in this case P_{net} is obtained from the simulated IGCC plant on Aspen plus. LHV of coal and syngas are calculated as follows

$$LHV = (XCO * LHVCO) + (XH2 * LHVH2) + (XCH4 * LHVCH4) \tag{16}$$

The effects of changing feedstock on the performance of IGCC plant is shown in Table 8.

Table 8: Effect of changing feedstock on the performance of IGCC plant

Feedstock	Thermal efficiency %	Net power (MW)	Syngas rate (kg/h)	LHV fuel (MJ/kg)	LHV syngas (MJ/kg)	Cold gas efficiency %
Coal	37	337.54	4,398	26.5	10.18	76.53
Coal & ricestraw	36.9	337	3,875	25.18	11.07	77.25
Slurry	36.6	334.29	4,107	26.1	10	76

From the previous Table 3 it is obvious that the coal-slurry feedstock has the lowest thermal efficiency among the others due to the presence of water that consumes a large amount of heating energy to vaporize water during the gasification process. Dry coal has the highest net power due to its high heating value comparing with the other feedstocks (Sofia et al., 2014). The mixture of 93 % coal and 3 % ricestraw has the highest cold gas efficiency as ricestraw is gasified at lower temperatures than dry coal hence it consumes lower heating energy for gasification unit than the other feedstocks also, the presence of ricestraw increases the hydrogen content in the produced syngas that is used in petrochemical industries to produce methanol for example.

4. Conclusions

Heat integration study is made for an IGCC plant with coal-water slurry feed that resulted in savings of 9.17 MW as heating duty and 9.52 MW as cooling duty also saves the operating cost by 1,330,200 $/y and saves total annualized cost by 1,241,182 $/y. Heat Integration increases the fixed capital investment of IGCC plant as it becomes 893,692,081 $ rather than 892,801,900 $ due to the addition cost of the new added heat exchanger. The effect of changing the feedstock on the performance of the IGCC is studied using three feedstocks (coal, coal-water slurry and a mixture of 93 % coal and 7 % ricestraw) and it is concluded that the highest thermal efficiency, net power, and cold gas efficiency are obtained when dry coal feed is used due to the highest heating value for dry coal feed while the lowest thermal efficiency, net power and cold gas efficiency are obtained when coal-water slurry feed is used due to the presence of water that consumes high energy to vaporize water during the gasification process. When ricestraw percent in the feed increases the sulfur content in the produced syngas increases which has harmful corrosive effect on the process equipment.

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