Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 114 (2017) 6478 – 6489

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

Coal quality effects on the performance of an IGCC power plant with CO_2 capture in India

Mohammad Mansouri Majoumerd[a,b,]*, Han Raas[c], Kuntal Jana[d], Sudipta De[d], Mohsen Assadi[b]

[a]*International Research Institute of Stavanger (IRIS), P.O. Box 8046, N-4068 Stavanger, Norway*
[b]*Faculty of Science and Technology, University of Stavanger, 4036 Stavanger, Norway*
[c]*Enssim Software, Kieftskamp 15, 7006 JE Doetinchem, The Netherlands*
[d]*Department of Mechanical Engineering, Jadavpur University, Kolkata 700 032, India*

Abstract

Ever increasing power demand coupled with CO_2 emission from coal-based power plants is a critical challenge for worldwide energy sector. This is even more critical for a country like India where a large coal reserve exists and about 60% of the total power produced is from coal. Meeting energy demand and simultaneously satisfying CO_2 emissions target, India has to develop power from coal using more advanced technology than existing subcritical pulverized coal fired one. IGCC with CO_2 capture emerges as a prospective option for using coal with reduced CO_2 emissions. In collaboration under Indo-Norwegian cooperation program, an assessment of expected performance of a possible IGCC configuration with typical Indian coals is explored. In this paper, results of preliminary investigation through simulation for a baseline configuration of IGCC with CO_2 capture are presented. A comparison between expected performances for three typical coals is reported to show the effect of coal quality on IGCC performance in an Indian context.

Keywords: IGCC; CO_2 capture; Coal quality; Performance analysis; Indian coal

* Corresponding author. Tel.: +47 453 91 926; fax: +47 51 87 52 00.
E-mail address: mohammad.mansouri@iris.no

doi:10.1016/j.egypro.2017.03.1784

1. Introduction

Presently, coal is the main primary energy source for electricity generation [1]. The total electricity generated globally was 23322 TWh in year 2013 out of which 41.3% was produced from coal [2]. A similar trend is also observed in India, as coal is the largest primary source of electricity generation. In India, the total installed capacity of electricity generation is 285 GWe and coal-based thermal power is 168 GWe as on 31.03.2014 [3]. This trend will continue in near future, as the estimated coal reserve in India is 301 Gt [3]. Hence, replacement of coal is not possible in near future though it contributes to maximum greenhouse gas (GHG) emissions. During the transition period from fossils to renewables, utilization of coal in a more sustainable way is a promising option.

As mentioned above, a critical aspect of power generation from coal is high greenhouse gas emissions and India is the fourth largest GHG emitter in the world (6% of the total GHG emissions in year 2011) after China, United States and the EU [4]. Net greenhouse gas emissions from India are 1727 Mt and the electricity sector contributes maximum (37.8%) of this GHG emissions in 2007 [5]. After the Kyoto Protocol and the 21st Conference of Parties (COP21) in Paris, almost all countries agreed to reduce the GHG emissions to achieve the goal of limiting global average temperature increase within 2 K compared to the pre-industrial age [6]. India is also adopting policies to reduce its GHG emission by 33-35% by 2030 using various measures including cleaner energy production and creating additional carbon sink [7].

For cleaner energy production, knowledge transfer from developed countries plays an important role. Hence, India has started to work in collaboration with these countries in the context of clean energy to decarbonize its energy sector. The Indo-Norwegian Cooperation Programme in Higher Education and Research (INCP) is an example of such collaborative initiatives. The “Road map for decarbonization of Indian energy system: exploring innovative solutions” project is a collaboration under the INCP initiative receiving financial supports from the Research Council of Norway (RCN) and University Grants Commission (UGC) in India. Amongst different topics for research on energy systems, one of the topics identified for further collaboration is the need for base-load power generation in India and use of coal in a more environment-friendly way. In this regard, integrated gasification combined cycle (IGCC) power plants has been selected for which feasibility studies using various Indian coal types are being performed. Working on this topic and evaluation of the feasibility of this concept in India is also perceived as a sort of continuation of previously co-funded EU H2-IGCC project (2009-2014) [8] and using existing knowledge and transferring it to India.

In this paper, the aim is to evaluate the effects of variation of typical Indian coal quality on the overall performance of the baseline IGCC plant with CO_2 capture. For this purpose, the quality of produced syngas using different coals are compared in terms of composition and heating value. In addition, the effects of coal quality variation on the overall efficiency and specific emissions of the plant are evaluated.

Nomenclature

AGR	acid gas removal
Ar	argon
ASU	air separation unit
BFD	block flow diagram
C	carbon
CH_4	methane
CMD	coal milling and drying
CO	carbon monoxide
COP	Conference of Parties
CO_2	carbon dioxide
DEPG	dimethyl ether of polyethylene glycol
DGAN	diluent gaseous nitrogen

EU	European Union
f	fuel
GHG	greenhouse gas
GOX	gaseous oxygen
GT	gas turbine
HHV	higher heating value
HP	high pressure
HRSG	heat recovery steam generator
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
IGCC	integrated gasification combined cycle
INCP	Indo-Norwegian Cooperation Program in Higher Education and Research
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
MAC	main air compressor
NOx	nitrogen oxides
N_2	nitrogen
O_2	oxygen
PC-SAFT	perturbed-chain statistical associating fluid theory
PGAN	pure gaseous nitrogen
RCN	Research Council of Norway
RH	re-heat
SCGP	Shell coal gasification process
SH	superheat
SR	Schwarzentruber and Renon
ST	steam turbine
SWGS	sour water-gas shift
TEG	triethylene glycol
TIT	turbine inlet temperature
TOT	turbine outlet temperature
UGC	University Grants Commission
W_{aux}	auxiliary power demand
W_c	gas turbine's compressor power demand
$W_{p,HRSG}$	pumping power demand in the heat recovery steam generation unit
W_{st}	steam turbine shaft power output
W_t	gas turbine shaft power output
η_{el}	generator electrical efficiency
η_m	generator mechanical efficiency
η_{net}	overall plant efficiency

2. IGCC plant's configuration

The primary objective of this work is to explore the opportunity to use IGGC power plants with CO_2 capture in India as a cleaner coal technology compared to the existing power production technology from coal, i.e. pulverized coal power plants (mainly sub-critical units). For this purpose, a configuration of the plant optimized through implementation of the European Union co-funded H2-IGCC project (2009-2014) [8] has been used as the baseline configuration of the plant for this study.

The impact of variation of coal quality on the performance of the selected plant configuration with CO_2 capture has been investigated. For this purpose, three coals with different characteristics as listed in Table 1 are considered in this study. These coal types represent typical qualities that are used in Indian coal-fired power plants.

Table 1. Various properties of different Indian coal samples.

Coal sample	Coal A	Coal B	Coal C
Proximate analysis (wt% air dried basis)			
Moisture	7.9	8.1	8.3
Ash	36.4	36.4	26.7
Volatile matter	25.3	24.8	28
Fixed carbon	30.4	30.6	37
LHV (MJ/kg)	15.53	14.94	20.10
HHV (MJ/kg)	16.36	15.73	20.96
Ultimate analysis (as received)			
C	43.1	42.5	52.6
H	2.8	2.62	2.9
S	0.35	0.18	0.3
N	0.86	0.08	1.4
O	4.94	6.5	5.1
Main ash composition (wt%)			
SiO_2	56.9	57.5	62.6
Al_2O_3	27.5	25.3	25.9
FeO_3	9.4	12.0	5.2
CaO	1.41	1.36	1.10
MgO	0.49	0.52	0.30
SO_3	0.54	0.86	0.05
Na_2O	0.47	0.20	0.37
K_2O	1.11	0.87	2.17
TiO_2	1.92	1.12	1.60
P_2O_5	0.34	0.26	0.70

The block flow diagram (BFD) of the IGCC configuration with CO_2 capture unit is shown in Fig.1. A brief outline of the plant is presented here. However, readers can refer to [9] for additional description of the baseline configuration. Except sulfur recovery unit that is not covered by this study, the plant consists of seven major sub-systems including:

- Air separation unit (ASU);
- gasification block including coal milling and drying (CMD), gasification, syngas cooling and scrubbing;
- sour water-gas shift (SWGS) reaction unit;
- acid gas removal (AGR) unit and CO_2 capture unit;
- CO_2 compression and dehydration unit;

- gas turbine (GT), and
- heat recovery steam generator (HRSG) and steam cycle.

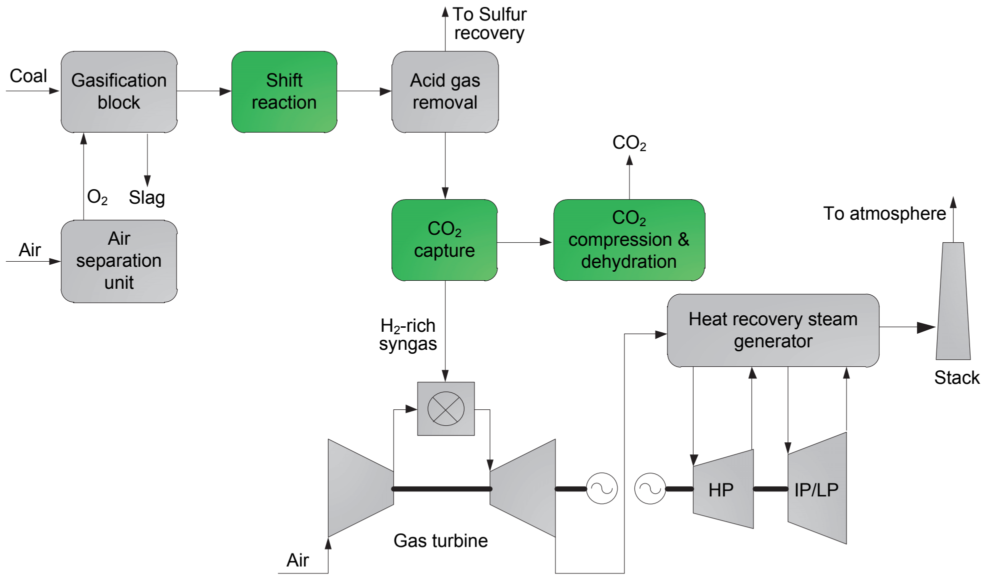

Fig.1. The block flow diagram of an IGCC power plant with CO_2 capture.

(1) Air separation unit: the cryogenic ASU is considered for providing oxygen to the gasification block, as this technology is currently the only proper alternative for large-scale O_2 production available in the market. This unit is considered as a stand-alone unit generating gaseous oxygen (GOX) with 95% purity from air supplied by an intercooled main air compressor (MAC). Note that the overall plant efficiency could be improved with higher degree of integration between the MAC and the GT compressor due to higher isentropic efficiency of the GT compressor compared to the MAC [10]. However, the stand-alone unit was selected mainly due to adverse process control effects of integrated GT-ASU leading to reduced availability of the entire plant. Lower efficiency of the non-integrated case somehow could be mitigated by selecting the intercooled MAC. Apart from GOX, the ASU also produces two nitrogen streams viz. pure gaseous nitrogen (PGAN) mainly used to convey gasifier dense phase coals dust and diluent gaseous nitrogen (DGAN) that is less pure nitrogen (impurities approximately 1 mol%).

Please also note that typically in IGCC plants either syngas dilution with DGAN/steam or syngas saturation with water (or a combination of both) is considered to control NOx emissions from diffusion flame burners. However, syngas dilution is not required here due to pre-mixed combustion of the undiluted H_2-rich syngas. Accordingly, as there is no need for injection of DGAN into the GT combustion chamber, heat integration between the GT compressor bleed air and diluent nitrogen from the ASU is not possible and there by the overall plant efficiency cannot be enhanced.

(2) Gasification block: gasification of coal takes place in a slagging entrained-flow, oxygen-blown, dry-fed gasifier based on Shell coal gasification process (SCGP). This technology is selected due to its high cold gas efficiency, desired operating pressure level and higher calorific value of the raw syngas produced. Moreover, SCGP shows a relatively constant behavior for a wide range of coal quality meaning that the quality of produced syngas even when low-rank coal is gasified is higher compared to syngas produced by slurry-fed slagging entrained flow gasifiers [11].

A key parameter governing the overall plant pressure is the operating pressure at the inlet of the fuel gas valve of the GT combustor. This pressure is set to be about 30 bar to avoid gas turbine humming. A calculated 15 bar total design pressure loss upstream to the gas turbine leads to a gasifier design working pressure of 45 bar in this study. The selection of the SCGP technology is also justified by availability of a validated gasification model. The readers are referred to [11] to access validation data for gasification simulation. Different technical assumptions (input data) for modeling and simulation of the gasification block are listed in Table 2.

Table 2. Technical variables for simulation of the gasification block for different coals.

Coal sample code	Coal A	Coal B	Coal C
Operating temperature (°C)	1550	1550	1550
Operating pressure (bar)	45.0	45.0	45.0
Temperature Margin to the 25 Pa.s slag viscosity point (K)	100	100	100
Carbon conversion (%)	99.3	99.3	99.3

(3) Sour water-gas shift reaction unit: the SWGS process converts carbon monoxide (CO) in the raw syngas to CO_2 by shifting CO with water in the presence of H_2S over a catalytic bed according to the following reaction:

$$CO_{(g)}+H_2O_{(g)} \xleftrightarrow{44\frac{MJ}{kmole}} CO_{2(g)}+H_{2(g)} \quad (1)$$

(4) Acid gas removal unit and CO_2 capture unit: for H_2S removal and CO_2 capture, a double-stage SELEXOL^{TM} system (using dimethyl ether of polyethylene glycol or DEPG solvent) is considered. Due to high partial pressures of acid gases and better H_2S/CO_2 absorption selectivity, physical absorption of H_2S and CO_2 is preferred over chemical, amine-based absorption processes. Hydrogen sulfide in the syngas is removed by a counter-current flow of solvent in the first absorption column. The syngas leaving the H_2S absorber enters the second stage where CO_2 is captured in a similar way to the first stage. The overall CO_2 design capture rate is approximately 90%.

(5) The CO_2 captured from the process is compressed in an intercooled compressor, dried from water content, after-cooled, liquefied and finally pumped up to a final pressure of 110 bar. The final pressure is appropriate for permanent geological storage of captured CO_2. The drying process is performed to reduce the corrosion risk in the transport pipeline. The dehydration unit based on tri-ethylene glycol (TEG) reduces the water content in the captured CO_2 line to less than 20 mg/kg.

(6) Gas turbine: the GT block includes a compressor, combustion chamber and expander and generates electric power using a generator. The lower calorific value of the fuel gas (i.e. undiluted hydrogen-rich syngas) compared to natural gas, the latter being typically the fuel for designing the engine, requires engine modifications to maintain compressor stability margins. To evaluate the impact of the fuel change on the selected gas turbine technology in IGCC application, various simulation setups with different boundary conditions such as turbine inlet temperature (TIT), turbine outlet temperature (TOT) etc. were considered in [12]. To keep modifications at a reasonable level that can be performed relatively easy on the engine, a re-staggered expander is considered to cope with changes in the fuel gas properties. Simulations for this study is performed based on the data for the re-staggered expander.

(7) A triple pressure level HRSG with reheat and a steam turbine (ST) to generate steam and power was considered downstream of the gas turbine.

A brief list of assumptions for thermodynamic modeling and simulation of major sub-systems of the selected IGCC system with CO_2 capture is presented in Table 3.

Table 3. Technical input data for different sub-systems of the IGCC power plant with CO_2 capture.

Sub-system	Parameter (unit)	Amount
ASU	Delivery pressure/temperature of GOX by ASU (bar/°C)	1.2/10
	Delivery pressure/temperature of PGAN by ASU (bar/°C)	5.0/10
	MAC polytropic efficiency (%)	85
	GOX compressor polytropic efficiency (%)	78
	HP PGAN compressor polytropic efficiency (%)	78
	Inter-cooling temperature (°C)	40
SWGS	Sour syngas inlet temperature for both SWGS reactors (°C)	250
	Steam-to-CO ratio	2.4
	Overall adiabatic conversion of CO (%)	~98
	Overall pressure loss (% of inlet pressure)	8
AGR	Solvent pumps polytropic efficiency (%)	70
	Compressor isentropic efficiency (recycle gas) (%)	85
	Mechanical and electrical efficiencies (%)	98
	Coefficient of performance for refrigeration pump	2.2
	Solvent temperature at absorber inlet (°C)	5
	Pressure loss in $1^{st}/2^{nd}$ absorber (bar)	0.5/0.5
	H_2S removal efficiency (%)	99.99
	CO_2 co-absorbed in H_2S absorber (mol% of inlet)	~1
	Overall H_2 co-absorption (mol% of inlet)	~2
	Overall CO co-absorption (mol% of inlet)	~3
	CO_2 capture (%)	~90
GT	Ambient air pressure (bar)	1.013
	Ambient air temperature (°C)	15
	Relative humidity (%)	60
	TIT (°C)	1267
	GT outlet pressure (bar)	1.1
	Compressor pressure ratio	18.2
	Generator electrical/mechanical efficiency (%)	99/99.5
HRSG	HP/IP/LP (bar)	140/43/4
	SH and RH temperature (°C)	530
	HP/IP/LP ST isentropic efficiency (%)	88.5/89/91
	ST and generator mechanical efficiency (%)	99.5
	Gas side HRSG pressure drop (bar)	0.04
	Condenser pressure (bar)	0.04
	Generator electrical efficiency (%)	98.2
	Pump polytropic efficiency (%)	70
	Pump mechanical efficiency (%)	95
	Evaporator pinch point IP/LP (K)	10/10
	Super heater pinch point (K)	32
	Economizer pinch point (K)	10
	Approach point temperature (K)	5

3. Simulation tools efficiency indicators

In order to obtain reliable results and to utilize the possibility of incorporating detailed component characteristics into relevant sub-system models, a combination of the following simulation tools are used for modeling the IGCC power plant with CO_2 capture:

- Detailed modeling of the gasification block including various processes such as CMD, gasification, raw syngas cooling and scrubbing, is performed using the Enssim software tool [13]. As mentioned earlier in this article, selection of this software is justified by the fact that the gasification model was previously validated against real plant operational data and the validation results for the SCGP technology is available in [11].

- The ASU and SWGS sub-systems are modeled using Aspen Plus [14] and the Peng-Robinson equation-of-state was selected for the properties method. The AGR unit and CO_2 capture unit is also modeled in Aspen using perturbed-chain statistical associating fluid theory (PC-SAFT) equation-of-state. The compression of captured CO_2 and dehydration of CO_2 stream are modeled in Aspen Plus using Peng-Robinson equation-of-state, and Schwarzentruber and Renon (SR polar) equation-of-state, respectively.

- The power block including the GT, and the triple-pressure steam cycle are modeled in IPSEpro, a commercial heat and mass balance software tool [15].

As different software tools have been used for simulation of different sub-systems, proper matching between those tools enables simulation of the entire plant. Data exchange between software tools was performed manually to find the optimal match.

4. Performance indicators

In general, coal properties including ash content, ash composition and coal reactivity have significant effects on the gasification process and consequently on the entire IGCC power plant. Generally, a coal with low ash content (e.g. Coal C in this article) is favorable for the IGCC power plant as it produces smaller amounts of fly ash and bottom slag and thereby the risk of plugging and fouling of downstream heat transfer surfaces is reduced [16]. The coal with lower ash content is also favorable as the coal feed is lower for the same amount of produced syngas compared to a coal with higher ash content. Coal reactivity determines the gasification temperature and consequently influences the amount of oxidizing agent necessary for gasification. The higher coal reactivity is desired as it requires less oxygen production by ASU to reach desired gasification temperatures. The slag viscosity must be sufficiently low for a slagging gasifier to be able to be operated at the required gasification temperature. Usually the slag viscosity at a temperature 100 K below gasifier temperature should be equal or higher than the slag fluid point (that is at a slag viscosity of 25 Pa.s). In order to satisfy this criterion, mostly a fluxing medium is required. For the Indian coal, being characterized by a relatively high melting acidic ash, limestone is needed as a fluxing agent. This agent is admixed to the coal upstream the coal mill. To evaluate the effects of coal quality on the gasification process, the properties of produced syngas including its composition and heating value have been investigated.

In addition, to highlight the effects of coal quality variation on the performance of the IGCC power plant with CO_2 capture two main indicators are used in this article, namely the overall plant's efficiency (LHV%) and specific CO_2 emissions (kg of CO_2 emissions per each MWh of electricity production). Following equation 2 is used in this article for estimation of the overall efficiency of the IGCC plant based on the boundary that is depicted in Fig.2.

$$\eta_{net}=\frac{(W_t+W_c)\eta_m\eta_{el}+W_{st}\eta_m\eta_{el}-W_{p,HRSG}-W_{aux}}{\dot{m}_f\times LHV_f}\times 100 \tag{2}$$

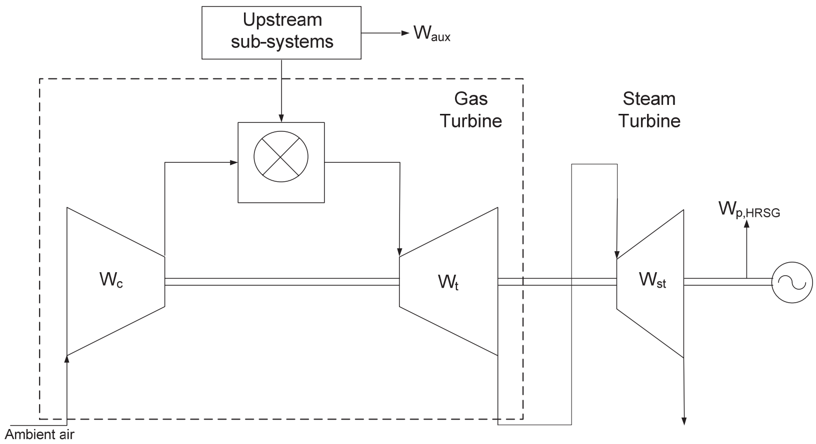

Fig.2. The boundary for efficiency calculation of the entire IGCC plant.

5. Results and discussion

Table 4 presents properties and composition of raw syngas produced from different Indian coals upstream of the SWGS reaction unit. Results of the simulation show that Coal A and Coal B are similar in terms of heating values of the produced syngas and the raw syngas derived from Coal C has the highest calorific value. The raw syngas temperature in Table 4 is the scrubber temperature. This temperature, which is lower for Coal C than those of the other two coals, is the dew point temperature corresponding to pressure and composition of syngas.

Table 4. Results of gasification simulation with properties and composition of the raw syngas prior to the SWGS unit for different coals.

Properties/Composition	Coal A	Coal B	Coal C
Specific O_2 demand (kg/kg coal a.r.)	0.784	0.764	0.756
Specific N_2 demand (kg/kg coal a.r.)	0.237	0.235	0.242
Specific calcareous flux demand (kg/kg coal a.r.)	0.084	0.076	0.100
Specific drying heat demand (kJth/kg coal a.r.)	254	258	271
Temperature (°C)	179.3	178.9	165.9
Pressure (bar)	43	43	43
LHV (MJ/kg)	6.31	6.12	8.29
HHV (MJ/kg)	6.55	6.34	8.64
Flow rate (kmole/s)	6.12	6.27	4.87
Ar (mol%)	0.974	0.980	0.834
H_2 (mol%)	12.6	11.8	17.6
CO (mol%)	42.1	42.04	50.4
H_2O (mol%)	25.6	25.9	18.4
CO_2 (mol%)	9.72	10.60	4.42
H_2S (mol%) [a]	0.135	0.071	0.111
N_2 (mol%)	8.83	8.59	8.22

Raw syngas produced from Coal C has higher CO and H_2 and lower CO_2 content compared to other two coals. This feature is more specifically advantageous if the plant needs to be operated without the CO_2 capture unit, as the amount of Coal C required to produce the GT fuel gas is significantly lower than necessary amounts of Coal A and

Coal B. In case of the IGCC plant with CO_2 capture, i.e. the selected plant in this study, high CO content in the raw syngas requires more intermediate pressure (IP) steam for the water-gas shift reaction that is often withdrawn from the HRSG. This can reduce the advantage of Coal C compared to other two coals.

Given the general information provided in terms of coal reactivity and ash content, Coal C seems to be a better feedstock compared to other Indian coals. Coal B can be an appropriate fuel as it produces significantly lower hydrogen sulfide (please note that this study does not include sulfur recovery unit). Nevertheless, a techno-economic study is required to identify clearly, which one of coals are more suitable for this power generation concept.

The composition and other properties of the fuel gas (hydrogen-rich syngas), corresponding to three different coals, prior to the gas turbine burner are presented in Table 5. Hydrogen contents in all of the fuel gases are more than 80 mol%. Similar to composition and properties of the raw syngas, fuel gases from Coal A and Coal B have similar characteristics. Higher heating value of the Coal C results in a lower mass flow rate of the fuel gas necessary to keep the turbine inlet temperature of the GT at a certain level compared to other two coals. This, in consequence, causes a more stable GT compressor operation with greater margin to the surge condition compared to operation on fuel gas produced from Coal B and Coal C.

Table 5. Properties and composition of the raw syngas prior to the GT for different coals.

Properties/Composition	Coal A	Coal B	Coal C
Temperature (°C)	30	30	30
Pressure (bar)	25	25	25
LHV (MJ/kg)	24.68	24.81	29.54
HHV (MJ/kg)	29.09	29.24	34.83
Flow rate (kmole/s)	4.00	4.02	3.81
Ar (mol%)	1.30	1.34	0.93
H_2 (mol%)	80.14	80.25	83.75
CO (mol%)	1.24	1.27	1.17
H_2O (mol%)	0.04	0.04	0.04
CO_2 (mol%)	4.17	4.14	3.88
H_2S (mol%) [a]	Trace	Trace	Trace
N_2 (mol%)	13.09	12.97	10.23

[a] The H_2S content in the syngas is lower than volumetric part per billion (ppbv).

Estimated performance parameters of simulations for different coals are shown in Table 6. The IGCC plant with CO_2 capture using Coal C has the highest overall efficiency and Coal B has the lowest one by 3.5 percentage points lower efficiency than that of Coal C.

Because of using same GT technology with fix characteristics (including components efficiencies) in simulations, variation of coal quality does not affect the GT power output very much. Higher GT power output for Coal A and Coal B than for Coal C is mainly due to greater hot gas flow rates in case of using Coal A and Coal B. Using different coals with different quality, however, significantly affects the power produced by the steam turbine. The higher ST power output using Coal A and Coal B is mainly due to higher water content of the produced raw syngas (see Table 4) that reduces the IP steam extraction from the steam cycle to achieve the desired CO conversion within the SWGS unit. Moreover, lower quality coals have generally higher available moisture that results in higher steam production within the gasification block.

Table 6. Performance results of the IGCC power plant with CO_2 capture for different Indian coals.

Power	Coal A	Coal B	Coal C
Power production			
GT power (MWe)	322.2	322.0	317.4
ST power (MWe)	225.9	227.6	189.3
Power demands			
Gasification power (MWe)	9.38	9.74	7.02
Pumping power (MWe)	4.30	4.10	3.59
Syngas cleaning compression and pumping power (MWe)	13.2	13.6	11.72
ASU compression power (MWe)	92.0	94.8	62.9
CO_2 compression power (MWe)	25.6	26.5	22.0
AGR refrigeration power (MWe)	10.9	12.4	9.87
Generator power output (MWe)	548.1	549.6	506.7
Auxiliary power demand (MWe)	155.4	161.1	117.0
Net power output (MWe)	392.7	388.5	389.
Overall efficiency (LHV%)	31.0	30.2	33.7

The increase in the ST power output in case of using Coal A and Coal B, however, could not offset the increase in the auxiliary power demand. Higher ash contents in Coal A and Coal B compared to Coal C result in higher oxygen demand and thereby drastically increase ASU power demand to maintain the gasifier temperature when using Coal A and Coal B compared to Coal C. The auxiliary power increases by coal quality reduction (from Coal C to Coal A and Coal B) primarily due to the increasing oxygen demand but also because of increasing CO_2 content that should be captured and compressed.

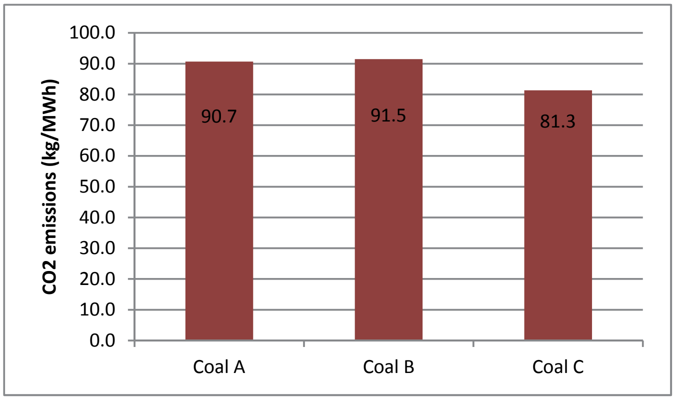

Fig.3. The specific CO_2 emissions from the IGCC plant with CO_2 capture.

The specific CO_2 emissions of the plant using different coals are shown in Fig.3. As shown in this figure, Coal B has the highest specific emissions with 91.5 kg of CO_2 emissions per MWh.

6. Conclusions

To explore innovative low carbon Indian energy systems under the Indo-Norwegian Cooperation Programme in Higher Education and Research (INCP-2014), a possible IGCC configuration with CO_2 capture for Indian coals is studied. Collaborating Norwegian group was a partner in similar studies in the context of the EU H2-IGCC project. However, quality of coals are different from previous studies with respect to calorific value, sulfur content and ash content. The effects of coal quality for three general coals that are typically used for power generation in India is studied on the overall performance of the IGCC power plant with CO_2 capture.

Simulation is performed to assess the performance of the IGCC plant with CO_2 capture using different software tools including Enssim, Aspen Plus and IPSEpro. Results show that the quality of the produced syngas from gasifier significantly depends on coal types. Raw syngas produced from Coal C has higher CO and H_2 (and consequently higher calorific value) and lower CO_2 content compared to other two coals. The IGCC plant with CO_2 capture using Coal C has the highest overall efficiency (33.7 LHV%). The efficiency of the plant using Coal B is the lowest one with 3.5% lower than that of Coal C. Specific CO_2 emission is also the lowest for Coal C with 81.3 kg CO_2/MWh.

Given the results of simulations, Coal C seems to be a better feedstock compared to other Indian coals. Nevertheless, a techno-economic study is required to evaluate if IGCC technology can compete with its rival, i.e. pulverized coal technology and which one of Indian coals studied here is more suitable for IGCC power plants.

Acknowledgements

Authors are grateful to the Research Council of Norway (RCN) and the University Grants Commission (UGC) of India for financial support of INCP-2014/10086 project. Authors also gratefully acknowledge the technical support of Dr. Pinaki Sarkar, Principal Scientist, CIMFR - Digwadih Campus, Dhanbad, Jharkhand, India.

References

1. IEA, *World energy outlook*, 2015, International Energy Agency: Paris, France.
2. IEA, *Key world energy statistics*, 2015, International Energy Agency: Paris, France.
3. *Energy statistics*, 2015, Central Statistics Office, Ministry Of Statistics and Programme Implementation, Government of India: New Delhi, India.
4. EPA. *Global greenhouse gas emissions data*. Available from: https://www3.epa.gov/climatechange/ghgemissions/global.html
5. INCCA, *India: Greenhouse gas emissions 2007*, 2010, Indian Network for Climate Change Assessment (INCCA), Ministry of Environment and Forests, Government of India: New Delhi, India.
6. UNFCCC, *Synthesis report on the aggregate effect of the intended nationally determined contributions*, 2015, United Nations Framework Convention on Climate Change (UNFCCC): http://unfccc.int/focus/indc_portal/items/9240.php.
7. *India's climate and energy policies*. 2015 06.08.2016]; Available from: http://www.c2es.org/docUploads/india-factsheet-formatted-10-2015.pdf.
8. H2-IGCC. *Low emission gas turbine technology for hydrogen-rich syngas Under the 7th Framework Programme FP7-239349*. 02.08.2014]; Available from: www.h2-igcc.eu.
9. Mansouri Majoumerd, M., De, S., Assadi, M., Breuhaus, P., *An EU initiative for future generation of IGCC power plants using hydrogen-rich syngas: Simulation results for the baseline configuration.* Applied Energy, 2012. 99: p. 280-290.
10. Gazzani, M., Macchi, E., Manzolini, G., *CO_2 capture in integrated gasification combined cycle with SEWGS – Part A: Thermodynamic performances.* Fuel, 2013. 105: p. 206-219.
11. Mansouri Majoumerd, M., Raas, H., De, S., Assadi, M., *Estimation of performance variation of future generation IGCC with coal quality and gasification process – Simulation results of EU H2-IGCC project.* Applied Energy, 2014. 113: p. 452-462.
12. Mansouri Majoumerd, M., Breuhaus, P., Smerekar, J., Assadi, M., Basilicata, C., Mazzoni, S., Chennaoui, L., Cerri, G. *Impact of fuel flexibility needs on a selected GT performance in IGCC application*. in *ASME paper GT2012-68862*. 2012. ASME Turbo Expo, Copenhagen, Denmark.
13. *Enssim®*, 2009, Enssim Software: Doetinchem, The Netherlands.
14. *Aspen Plus version 8.8*, 2009, Aspen Technology Inc.: Cambridge, MA, USA.
15. *IPSEpro version 6.0*, 2013, Simtech Simulation Technology (Simtech): Graz, Austria.
16. Yun, Y., Yoo, Y.D., Chung, S.W., *Selection of IGCC candidate coals by pilot-scale gasifier production.* Fuel Processing Technologies, 2007. 88: p. 107-116.