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ECONOMICS OF REMOVAL OF COAL MOISTURE IN THERMAL POWER GENERATION WITH WASTE HEAT RECOVERY

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ABSTRACT

The techno-economic aspects of coal drying with cost effective waste heat recovery mechanism is one of the challenging issues faced while using lignite or high ash brown coal for direct combustion in coal fired thermal power plant. Coal being hygroscopic in nature, re-adsorbs considerable moisture even after conventional drying post wet coal washing condition affecting boiler performance. Particularly moisture in coal affects the pulverization where pulverized coal (PC) firing is adopted. In this paper the impact of coal moisture on useful heat value for PC fired steam generation is evaluated for some typical steam coals so that related change in direct firing coal throughput can be estimated for application of suitable online coal drying mechanism. This assessment can be further used to determine usefulness of pre-combustion coal drying methods like integrated drying and partial coal gasification method, particularly for coal processed through dry or wet coal washing to improve the heat value with the exhaust flue gas immediate upstream of stack.

Keywords: drying, moisture, ash, pulverized coal, cost, flue gas, heating value, waste heat recovery.

1. INTRODUCTION

Electric power generation in India is predominantly being sourced from low grade sub-bituminous or lignite coal, presently being consumed by direct combustion in utility furnaces, where primary issues are increasing users' end cost, decreasing fuel quality and tightening environmental emission standards. Currently, the cleaning of the majority of run-of-mine (ROM) coal is conducted by heavy or medium separation jigs and flotation. These techniques use water as a separating medium though washability characteristics of Indian coals are significantly poor. The use of wet separation techniques result the generation of large amounts of coal slurry that usually needs to be dewatered at significant costs. Besides, the economic and energy efficient mechanisms of coal drying is essential as sometimes, combined coal ash and moisture is more than 50% of the “as received” coal by weight. Therefore, suitable drying system on flue gas waste heat recovery will add on to profitability, reducing power generation cost and emission penalties.

2. THE PULVERIZED COAL FIRED SYSTEM

The PC firing is a proven technology to burn coal under suspension through the pneumatic conveyance to the furnace of the boiler. By the coal pulverizer, semi-crushed coal is further reduced to the desired fineness (60-85% passes through 200 mesh BIS sieve). By pulverizing the coal, the surface area increases resulting quicker preheating and better combustibility. The heat produced during grinding can reduce the moisture content significantly, particularly during high speed pulverizing. The primary function of a pulverizer is to dry, grind and pneumatically convey the PC to the furnace. The pulverizer performance is typically measured by PC fineness and flow rate to furnace. However, not even a proper fineness and defined output guarantee the optimum use of the pulverizer in terms of overall boiler performance, that is also governed by coal-air mixture temperature and PC throughput velocity at furnace entry, the particle size distribution to maintain the combustion efficiency and the environmental impact with emission regulations [1 & 2].

As such, mill drying capacity is limited by Primary Air (PA) fan power to supply hot air and the PA temperature determined by Air Pre Heater (APH) inlet flue gas temperature - an increase of this will result in efficiency loss of the boiler and too much of hot PA may cause fire within mill under certain conditions. However, the higher PA inlet temperature can be attained through economizer gas by-pass, the steam coiled APH or by

Besides, for variation of coal quality, coal moisture, and quantity of coal to be pulverized, separation of coal fines is more important that depends on proper drying of coal in pulverizing system [6]. Improper drying results in agglomeration of coal fines within the pulverizer that increases recirculation within the grinding zone and reduces the net coal throughput to the boiler furnace.

Table –1: Ultimate Analysis of typical Mahanadi Coalfields Ltd. (MCL). coal (Sourced by - INDAL CPP, Hirakud, India**)**

MCL Coal	Carbon	H_2	O_2	N_2	Sulfur	Ash	Moisture	HHV, MJ/kg	LHV, MJ/kg
%Wt (ar)	28.921	1.833	5.431	0.543	0.272	48	15	10.878	10.11
%Wt (mf)	34.025	2.157	6.39	0.639	0.319	56.47	0	12.8	12.32
%Wt (daf)	78.165	4.954	14.68	1.468	0.734	0	0	29.4	28.31
Weight stack Kg/Kg coal	CO_2 – 1.06	Evaporated Moisture	O_2 - 0	2.847	SO_2 – 0.005		0.315	Wet Stack gas – 4.227	Dry Stack gas – 3.912
Stoich. Air Flow m^3/Kg Coal - 2.883		Stoic. Air-Coal Ratio: 3.712	CO_2% (By vol. of wet Flue gas with SR combustion: 16.81				CO_2% (By volume of dry Flue gas with complete SR combustion: 19.14		

Partial Flue Gas Recirculation ([1]PFGR©) through pulverizer [1&3] where high ash-moisture significantly affect the pulverizer performance.

Sometimes, the variation in the “as fired” coal goes beyond the worst variety coal intake design limitations of pulverizing capacity putting capacity restriction to sustain the boiler thermal load demand. The coal with high ash, lower heat value and higher moisture calls for more coal throughput. Not all the PC-fired power plants are running with stand by pulverizing capacity to sustain the higher throughput with lower grade of coal [1]. Again, coal blending as cost compromising measures may turn out to be a renegotiation of deliverables in terms of utility efficiency and emission penalties as high heating value coal is, sometimes, accompanied by considerable trace elements of mercury and chlorides [4].

3. EFFECT OF MOISTURE IN PC FIRING

The PC throughput is largely affected by the amount of inherent and surface moisture present in the coal. Due to climatic variations, there is change in "as received" to "as fired" moisture in ROM coal which needs correction for optimizing the coal feeding. But, the total coal flow in the boiler is controlled through coal feeders which work either in gravimetric or volumetric mode of operation irrespective of correction for moisture factor that changes the demand of "as received" to "as fired” coal. The separation of moisture from coal is dependent on the drying capacity of the pulverizing system. Improper drying may originate imbalance in flow through PC pipes and furnace may suffer from loss of ignition (LOI) [1, 5].

[1] PFGR [© C. Bhattacharya @ 2007]: Partial Flue Gas Recirculation Through Pulverizer (An extended FGR based NOx control technology)

The impact of the coal moisture (% wet basis) on useful heat value and percentage loss of "as received" heat value in pre – combustion drying at different coal moisture percentages are computed considering the combustion at stoicheometric air-coal ratio and represented graphically with respect to typical steam coals chosen as widely used non-coking variety of coals available in India with following composition (derived from proximate and ultimate analysis of the coal sample) given in Table 1 - 3 and Figure 1 - 7 where: %wt (ar): As received basis; %wt (mf): Moisture free coal (N_2 stream dried above 60^0C); %wt (daf): Dry ash free basis [Calculated with Normal Dry Atmospheric (21% O_2 at 1.01325 bar pressure & 0^0C temperature) and moisture is not included in hydrogen and oxygen [7, 8, 9].

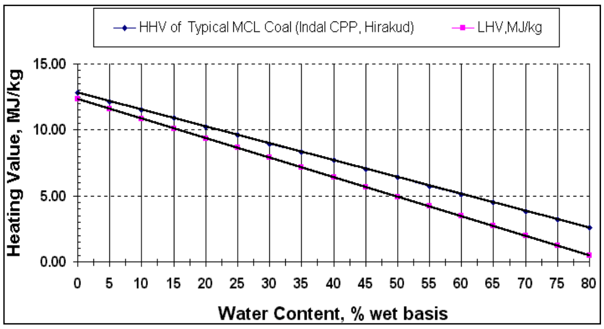

Fig.1: Change in Useful Heat value with coal – moisture of MCL Coal

3.1 Findings of coal of MCL

The Mahanadi Coalfields Ltd. (MCL) coal of Coal India Ltd (CIL) is a high ash-moisture low rank sub-bituminous Indian coal, comparatively low priced with lower available heat value. A 5% (% wet basis) in process decrease in “as received” coal moisture will improve the “as fired” coal net useful heat value from 10.11 MJ/kg to 10.847 MJ/kg. The HHV and LHV decrease linearly with increase in moisture content (% wet basis) and the linear relationship can be given by y = - 0.128x + 12.798 and y = - 0.1477x + 12.324 respectively.

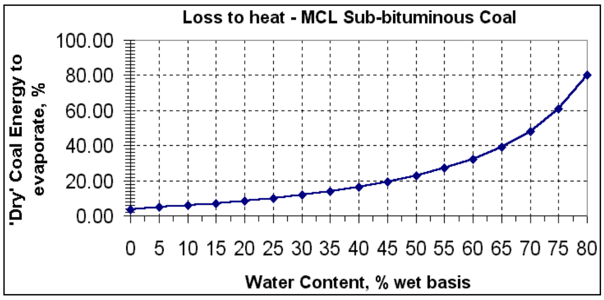

Fig. 2: Percentage Heat Value lost to dry up MCL coal (wet basis)

The percentage coal energy lost to dry up the coal closely follows an exponential pattern ($y=3.9301e^{0.0361x}$) and to reduce the coal moisture (% wet basis of "as received" coal) to residual 2% will consume 15.3% of useful heat value $[(HHV_{2\%m} - HHV_{ar})/HHV_{ar}]$. Similarly, a 1% (% wet basis) increase in coal moisture will deteriorate the "as received" coal heat value to 10.75 MJ/kg as found from figure 1, 2 and table – 1. Part of this analytical procedure has already been published in referred publication – [3].

The percentage fuel energy lost to dry up this coal also follows an exponential pattern i.e. ($y = 3.3539 e^{0.0297x}$) and to reduce the coal moisture (% wet basis of "as received" coal) to residual 2% will consume 21.74% of useful heat value $[(HHV_{2\%m} - HHV_{ar}) / HHV_{ar}]$. Similarly, a 1% (% wet basis) increase in coal moisture will deteriorate the "as received" coal heat value to 19.282 MJ/kg as shown in Figure 3, 4 and Table - 2.

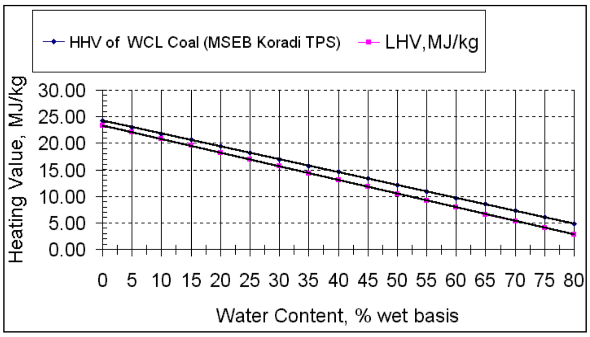

Fig.3: Change in Useful Heat value with coal – moisture of WCL Coal.

Table 2: Ultimate analysis of typical WCL Coal (Sourced by - MSEB – Koradi TPS, India)

WCL Coal	Carbon	H_2	O_2	N_2	Sulfur	Ash	Moisture	HHV, MJ/kg	LHV, MJ/kg
%Wt (ar)	47.85	3.20	8.16	1.03	1.16	19.10	19.50	19.526	18.346
%Wt (mf)	59.44	3.98	10.14	1.28	1.44	23.73	0.00	24.255	23.382
%Wt (daf)	77.93	5.21	13.29	1.68	1.89	0.00	0.00	31.801	30.655
Weight stack Kg/Kg coal	CO_2 – 1.753	Evaporated Moisture	O_2 – 0.0	4.805	SO_2 –0.023	-----	0.483	Wet Stack gas –7.065	Dry Stack gas – 6.582
Stoich. Air Flow m^3/Kg Coal: 4.866		Stoichiometric Air-Coal Ratio: 6.264		CO_2% (By volume of wet Flue gas in SR combustion: 16.70				CO_2% (By volume of dry Flue gas in SR combustion: 18.82	

Table –3 Ultimate Analysis of typical ECL. coal (Sourced by –Durgapur TPS / DVC, India)

ECL Coal	Carbon	H_2	O_2	N_2	Sulfur	Ash	Moisture	HHV, MJ/kg	LHV, MJ/kg
%Wt (ar)	49.65	3.09	4.34	1.07	0.45	39.45	1.95	20.398	19.671
%Wt (mf)	50.64	3.15	4.43	1.09	0.46	40.23	0.00	20.804	20.111
%Wt (daf)	84.73	5.27	7.41	1.83	0.77	0.00	0.00	34.809	33.650
Weight stack Kg/Kg coal	CO_2– 1.819	Evaporated Moisture	O_2 – 0.0	5.037	SO_2 – 0.009	-----	0.298	Wet Stack gas –7.163	Dry Stack gas – 6.865
Stoich. Air Flow m^3/Kg Coal: 5.10061		Stoicheometric Air-Coal Ratio: 6.566			CO_2% (By volume of wet Flue gas in SR combustion: 17.39			O_2% (By volume of dry Flue gas in SR combustion: 18.68	

3.2 Findings of coal of WCL

The coal of Western Coalfields Ltd. (WCL) of CIL is a Medium - high ash-moisture bituminous grade 'D' Indian coal, with average available heat value. A 5% (% wet basis) in process decrease in "as received" coal moisture will improve the "as fired" coal net useful heat value 18.35 MJ/kg to 19.64 MJ/kg. Here also, the HHV and LHV decreases linearly with increase in moisture content (% wet basis) and the linear relationships can be represented by y = - 0.2426x + 24.256 and y = - 0.2582x + 23.382 respectively.

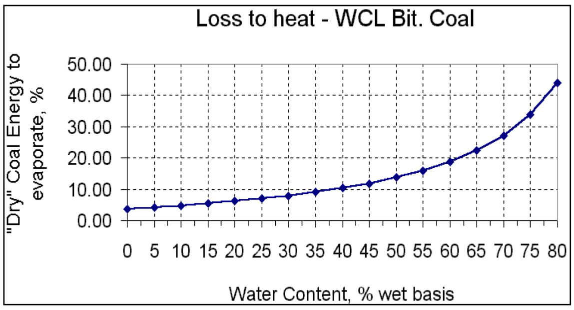

Fig. 4: Percentage Heat Value lost to dry up WCL coal

3.3 Findings of coal of ECL

The coal from Eastern Coalfields Ltd. (ECL) of CIL is a high ash-low moisture bituminous grade 'D' non-long flame non-coking Indian coal, with a higher average available heat value. ECL has more than 135 mines some of which are open cast pits. Here also, the HHV and LHV decreases linearly with increase in moisture content (% wet basis) and the relationships can be represented by linear algebraic equations as y = - 0.208x + 20.804 and y = - 0.2255x + 20.111 respectively. The percentage fuel energy lost to dry up this coal also follows an exponential pattern ($y = 3.2289e^{0.0322x}$). Similarly, a 1% (% wet basis) increase in coal moisture will deteriorate the "as received" coal heat value to 20.17 MJ/kg as evident from figure 5, 6 and Table -3.These theoretical mathematical modeling of effect on heat value with coal moisture at stoicheometric combustion condition is already published in paper reference [3] and [6].

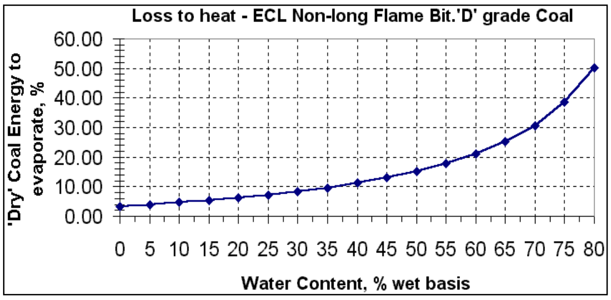

Fig.5: Change in Useful Heat value with coal – moisture

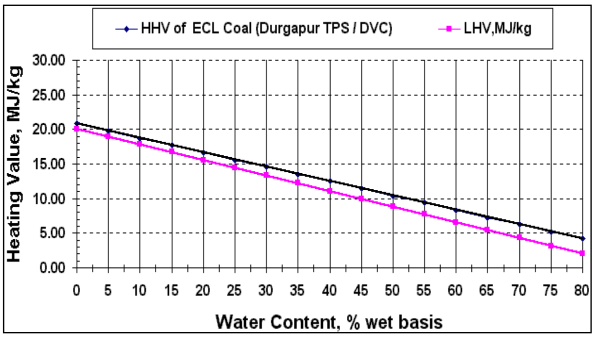

Fig. 6: % Heat Value (dry coal) lost to dry up ECL coal.

4. MOISTURE IMPACT ON VARIOUS COAL GRADES

From the coal analysis reports, the economic impact is assessed both in wastage in coal procurement cost and potential savings opportunity in total coal consumption.

The above empirical relationships outlined for three grades of low quality sub-bituminous coals to study the waste heat quantity to dry up the "as received" coal and suggested outcome from extrapolation of the formulation under a general specified condition of PC fired thermal power generation of a 250 MWe with tangential firing sub-critical steam generation unit is provided in Table – 4.

Integrated Environmental Control Model (IECM) software [7] developed by Carnegie Melon University, USA is a useful tool to determine "as received" coal throughput requirement with specific plant configuration and presumed plant performance and efficiency level. It is used for quantitative analysis of coal throughput requirement with specific plant configuration and presumed plant performance and efficiency level. The detail of the assumed software based configuration with various assumptions of the plant is as given in Table - 5.

The drying energy requirement and effect of drying impact factor (λ) with higher grade of coal is shown in plotted graph in figure - 7. It is evident that high rank coal will have less impact of moisture. However, removal of moisture is more difficult for higher-grade coal than a lower one with respect to time required to dry up for same flow rate of drying medium.

5. ECONOMICS OF COAL MOISTURE

From the above mentioned coal analysis reports for different typical experimental coals considered, the economic impact is assessed [Table – 6] in terms of potential savings opportunity of total coal consumption (Case considered: Effect of 2% decrease in "as fired" coal moisture). This economic analysis is based on the most proven base load coal fired power plant of 250Mwe size with tangential firing sub-critical steam generation arrangement.

Table 4: Impact factor: λ [HHV/LHV Vs. Moisture; % Dry coal energy loss vs. evaporative moisture load (% wet basis)]

Ref. Coal	HHV: $Y=M_Hx+C_H$	M_H	C_H	LHV : $Y=M_L x +C_L$	M_L	C_L	% Dry Coal Energy Loss: $y = k.e^{\lambda x}$	R^2 – Value	K – Value	λ- value	Remarks
MCL	y = - 0.128x +12.798	-0.128	12.798	y=-0.1477x +12.324	-0.1477	12.324	$y= 3.930.e^{0.0361x}$	0.997	3.9301	0.0361	High ash-moisture low rank subbit. G
WCL	y= - 0.2426x +24.256	-0.2426	24.256	y=-0.2582x +23.382	-0.2582	23.382	$y=3.354.e^{0.0297x}$	0.9904	3.3539	0.0297	Medium-high ash-moisture bit. D'
ECL	y = -0.208x +20.804	-0.208	20.804	y= -0.2255x +20.111	-0.2255	20.111	$y=3.229.e^{0.0322x}$	0.9943	3.2289	0.0322	High ash-low moisture bit. 'D'

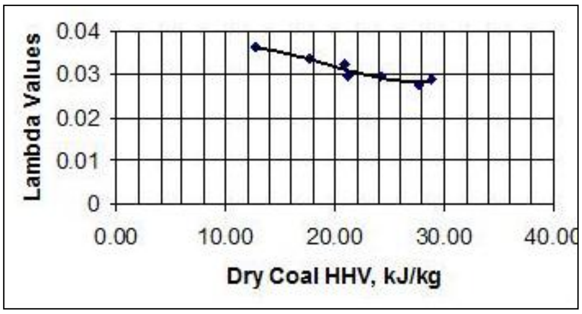

Fig.7: Change in coal moisture impact factor (λ) with dry coal HHV

Table 6 – The Coal Moisture Economics

Reference Coal	MCL Coal	WCL Coal	ECL Coal
Coal Rank	Non-coking Gr. F	Non-coking Gr. D	Non-coking Gr.D
"As Recd" HHV (MJ/Kg)	10.878	19.526	20.398
Coal Price Unit	Rs. ('07)	Rs. ('07)	RS. ('07)
Coal Price / MT	440.00	1210.00	1360.00
As Received Coal Moisture (wt %)	15.00	19.50	1.95
Ref. Case : 2% decrease in "As Fired" coal moisture			
As fired coal Moisture (wt %)	13.00	17.50	0.0
"As fired" LHV with 2% less moisture[wt%(ar)] in coal (MJ/Kg)	10.404	18.889	20.111
Waste heat recovery savings in equivalent "As Received" coal quantity in MTPD	139.45	85.79	212.38

The waste heat recovery savings in equivalent "as received" coal savings per day is calculated for 2% decrease in coal moisture (% wet basis) by considering the improvement in "as fired" coal throughput heat value in terms of total fuel heat input requirement to sustain the steam generation demand in a day.

Coal India Limited (under Ministry of Coal /Govt. of India) fixes the prices of coal relative to the market prices and the typical Indian coal prices in Table – 6 are taken on pithead supply basis without consideration of transportation & other associated costs from last such revision made on 12.12.2007 [10,11].

Coal drying is a cost effective measure to improve the heat value, minimize the end use cost and to reduce the GHG effect in combustion. Wet coal is difficult to transport due to freezing in colder climates. High moisture content reduces the friability of coal, difficulty in pulverization and blending. Moisture in coal impedes the classification and pneumatic conveyance; chokes the coal bunkers with formation of rat-holes [12, 13, and 14]. The Coal drying rate with a steady flow of drying medium occurs in three phases that initiate with warming up of moist coal, followed by a constant rate of drying with time and ultimately a falling rate of drying at a lesser residual moisture.

Table - 5: Assumptions on pc fired TPS boiler configuration and performance parameters

Gross Electrical Output, MWg		250.0	
Net Electrical Output, MW		233.4 (MW Output for reference only)	
Boiler Use (MW):	14.63	Cold-Side ESP Use(MW):	1.965
Base Plant Power Requirements (MW):			16.595
Unit Type - Sub-Critical		Boiler Firing Type - Tangential	
Steam Cycle Heat Rate, HHV: kJ/kWh			8313.84
Excess Air For Furnace; % stoich.			20.00
Gas Temp. Exiting Economizer; °C			371.1
Ambient Air Temperature; °C			25.0
Ambient Air Humidity: kg H2O/kg dry air			1.800e-02
Conc. of Carbon in Collected Ash; %			0.0
Primary Fuel Energy Input (MW)			676.77
Gross Plant Heat Rate, HHV;(kJ/kWh)			9746.6
Net Plant Efficiency, HHV; (%)			34.49
Boiler Efficiency, %			85.30
Leakage Air at Preheater: % stoich.			19.00
Gas Temp. Exiting AP Heater, °C			148.9
Ambient Air Pressure; kPa			101.353
Oxygen Content in Air/Oxidant – vol%			20.37
Percent of Burned Carbon as CO; %			0.0
Total Plant Energy Input;(MW)			676.7
Net Plant Heat Rate, HHV:(kJ/kWh)			10438.7
Electricity Price (Base Plant) $/MWh			749.8

Obviously, higher-grade coals, like bituminous are harder to dry up than lower ones, like lignite [15, 16].

Coal drying mechanism is also available on waste heat recovery from hot flue gas prior discharge through stack by generating hot air stream (regenerative or recuperative APH) or generation of induction heating process steam for coal drying purpose. Coal drying is also possible with heat trapped from stack gas by recuperated nitrogen from air separation unit supplying oxygen in oxy-fuel firing and used for coal drying in raw coal bunker. The hot nitrogen gas drying is more suitable for in bunker drying minimizing self-ignition and chute jamming. Pre-combustion coal slurry drier is also tested with auxiliary heating arrangement [17].

But, any indirect heat exchange mechanism for coal drying has an inherent limitation on coal moisture removal capacity in the pulverizing process which compromises on overall boiler efficiency [18, 19].

The PFGR© system can overcome these system limitations. In this system, part of the flue gas is recirculated back into the primary air circuit of pulverizer collected through a Gas Recirculation (GR) Fan after tapping from an appropriate location in the boiler convective pass [3, 6]. It may be further improved by integrating coal drying arrangement with waste heat recovery from flue gas upstream of stack [6].

6. CONCLUSIONS

Study reflects a wide range of drying application to mitigate the issue of coal moisture to enhance steam generator performance [6, 19].

It also shows an opportunity in reduction in equivalent NOx generation in the combustion process that needs pilot scale field assessment for retrofitting viability against stricter emission penalties going to be enforced in future [20, 21].

ACRONYMS AND ABBREVIATIONS

TPS–Thermal power Station; VM-Volatile matter of coal; BIS - Bureau of Indian Standards; FGR – Flue Gas Recirculation; CEA – Central Electricity Authority, INDIA; MWe– Mega Watt electricity; NETL – National Energy Technology Laboratory, USA; IEA-International Energy Agency; NOx–Nitrogen Oxides; SOx – Sulfur oxides; N_2–Nitrogen; O2 – Oxygen; CO2 – Carbon Dioxide; MTPD–Metric Tonnes per Day; HHV–Higher Heating Value; LHV–Lower Heating value; SR- Stoicheometric Ratio; MCR- Maximum Continuous Rating.

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NOMENCLATURE

Symbol

λ Coal moisture impact factor as percentage useful heat value loss to dry up coal moisture

Subscripts

m moisture
ar as received

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