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Predictive equations for CO_2 emission factors for coal combustion, their applicability in a thermal power plant and subsequent assessment of uncertainty in CO_2 estimation

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ABSTRACT

The emission of carbon dioxide varies systematically with the rank and type of coal combusted. Hence use of a single default emission factor proposed by IPCC (Inter Governmental Panel on Climate Change) for entire categories coals may not be appropriate option to obtain a reliable estimate of carbon dioxide emission level or towards the preparation of national carbon dioxide inventory. Even predictive equations developed based on the coals of different origin may not work well with coals of a specific origin. Several linear predictive equations were thus developed separately for coking and non-coking coals of Indian origin for the estimation of carbon dioxide emission utilizing basic coal parameters such as VM, FC, GCV and NCV on different basis. Large numbers of authenticated data set were used for multiple regression analysis and good correlations were obtained. Those equations were also validated with different data sets of Indian coals. Its applicability towards estimation of CO_2 emission from power plant was also studied and uncertainty in CO_2 estimation is revealed. The developed equations may be utilized to get a realistic estimate of carbon dioxide emission with specific cases where Indian coals are mostly used.

1. Introduction

Fossil fuels (coal, oil, and natural gas) accounted for 85% of world's primary energy supply, accounts for 70% of world's electricity and heat generation, and over 94% of energy for transportation. The production and use of fossil fuels contribute to 80% of anthropogenic (man-made) green house gas (GHG) emissions worldwide and fossil fuel power generation currently accounts for over one-third of global annual carbon dioxide emissions [1]. Given expected increase of population, economic growth, and energy demand, a continuous rise in emissions is expected unless fundamental technology change occurs in world energy system dominated by fossil fuels.

Like most of the countries coal is the most abundant, affordable source of energy in India and likely to continue as the major source of energy for foreseeing future. Coal utilization in combustion processes is expected to increase significantly in this century, its use nearly tripling between 2005 and 2030. India ranked fifth in carbon dioxide emission in 2005, and is likely to be world's third largest emitter of carbon dioxide by 2015 [2,3]. It is to be noted that currently almost 60% of the electrical energy is producing from coal [4], which contributes about 71% of the total GHG emissions in India.

It is understood that for proper assessment of the emission levels and their impact on environment/living being, a reliable national inventory on GHG emission is essential. It provides a crucial reference point for other assessment tools like climate change indicators and mitigation strategies. It may also help in developing medium to long term action plan for climate change research in the country.

Emission estimates from combustion of fossil fuels basically require three input parameters, viz., carbon dioxide emission factor (CEF), gross (GCV) or net (NCV) calorific value (energy conversion factor), and carbon stored/un-oxidized during its utilization. To prepare the national inventory, the energy conversion factor is required to convert the consumption data by weight to heat units. In conjunction with the CEF value, this provides the amount of carbon dioxide emission from different coal types. The CEF can be expressed as the amount of carbon dioxide emission per unit weight of the fuel combusted, or as the amount of emission per unit heat value of the fuel, which could be either GCV/higher heat value (HHV) or NCV/lower heat value (LHV). The former does not provide a reliable basis for the comparative evaluation of various ranks of coals, primarily because of the variation in the elemental composition like carbon, hydrogen, sulphur, oxygen, and particularly the

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extraneous mineral matter. As the heat value, either the GCV or NCV is predominantly a function of the carbon content, the latter definition with NCV as the unit of heat value has been accepted as the international norm. The Indian National Inventory for the base year 1990 [5] was prepared using the values of 20.5 TJ/kt and 17.6 TJ/kt for NCV for coking and non-coking, respectively, and a single value of 25.8 t C/TJ for CEF for entire coking and non-coking coal. IPCC 1996 (Inter Governmental Panel on Climate Change) indicated a single default value of 19.98 TJ/kt for NCV and 25.8 t of C/TJ for CEF for entire coking and other bituminous coals. Keeping in view the different types and nature of coal extracted from varying depth of different mines across India having wide variation in ash, moisture and petrographic make up, an extensive study have been carried out in this institute for the refinement of the IPCC default values for the Indian coals and the estimation of NCV and CEF for each category of coal separately (Table 1) analyzing large volume of authenticated data on Indian coals. The refined values were used for the subsequent national inventory estimation. During estimation of the India-specific figures for NCV and CEF [4] the production pattern of different grades of coals under the broad category of coking or non-coking coals were duly considered.

Several authors attempted estimation of carbon emission factor of coals from easily measurable quality parameters and predictive equations were developed to get the CEF from VM, FC, GCV, NCV, etc., of the coal on different basis, viz., as received (ar), dry basis (db), air dried (ad), dry mineral matter free (DMF)/dry ash free (daf) [6–10]. The equations developed so far did not work well while estimating CEF of different categories of Indian coals. Moreover, estimation of carbon dioxide emissions from fuel combustion needs the data like amount of fuel burned, carbon content of the fuel, fraction of carbon oxidized and in most of the utilities carbon dioxide emission estimation is rarely possible as the determination of carbon content are not done routinely.

Hence in this study, attempts have been made to develop predictive equations to estimate CEF on unit mass basis, net energy basis and gross energy basis for the Indian coking and non-coking coals separately from the easily measurable quality parameters, such as, VM, FC, GCV and NCV. The equations predicting the CEF values may find applications in estimating the emissions from the utilities in a straightforward way after combining the fuel consumption data in mass units or in energy unit and per cent of carbon oxidized in the process. These predictive equations may help in reducing the uncertainties in emission estimates from the key sources like power, cement, etc., where a single numerical value of CEF is being used covering a wide range of coals within the same coal type.

The above exercise was finally linked to a study in an efficient super thermal power station, where CO_2 was estimated both from stack measurement and input–output carbon balance. The basic objective of this study was three fold: (i) to quantify measured and estimated CO_2 from plant study as well as CO_2 emissions calculated from selected predictive equations in terms of emission coefficients (on per kg of coal and per kWh of electricity produced), (ii) to assess uncertainties in CO_2 emission estimates, and (iii) subsequently, to calculate total possible emission from Indian power plants.

Table 1
Conversion and emission factor of Indian coking and non-coking coal.

	IPCC default		India-specific			
	1996		1994–1995		1999–2000	
	NCV	CEF	NCV	CEF	NCV	CEF
	TJ/kt	t C/TJ	TJ/kt	t C/TJ	TJ/kt	t C/TJ
Coking coal	19.98	25.8	24.18	25.53	24.06	25.53
Non-coking coal	19.98	25.8	19.63	26.13	19.14	26.19

2. Methodologies

2.1. Methodologies of data collection and calculation of CEF

The Central Fuel Research Institute (now, Central Institute of Mining and Fuel Research) has generated large number of coal data during the last six decades and reported in various technical reports and Indian coal volumes. Out of these huge data, those generated since last one and half decade and from the collieries which are still in working condition and likely to produce coal in coming years were considered. The entire data set was segregated into two categories, i.e., non-coking and coking coal on the basis of carbon content on dry mineral matter free basis (DMF) – non-coking ($74 < C < 84$), coking ($84 < C < 92$). To assure integrity of the data the experimental GCV was cross checked with that calculated from the elementary data using the formula proposed by Mazumdar [11].

Different types of moisture levels are normally used both for scientific classification and commercial purposes. Accordingly, in this study the elementary coal data of coking coals were first converted in to various bases, such as, (1) air dried (2) dry (3) dry mineral matter free (DMF). In the case of non-coking coals the elementary data were converted to '60% relative humidity (RH) at 40 °C' basis, because the 60% RH basis is used for grading of Indian non-coking coals.

The properties of coking coals varies in quality from field to field and hence 180 nos. of samples for development of predictive equations and 69 separate samples for validation were considered in this study covering entire grades of Indian coking coals as per grading system based on ash value (Table 2). Similarly for the non-coking coals the study covers the major sources of Indian non-coking coals. The total nos. of non-coking coal data were 1214 and 361 for predictive equation development and for validation, respectively. For both coking and non-coking coal categories segregation of data set for predictive equation development and validation was made ensuring grade wise representation of data in both sets with more or less uniform distribution within each of the grades. It was also ascertained that variation of coal quality parameter in both the data sets (used for predictive equation development and validation) to remain within the similar range. For commercial transaction of Indian non-coking coals the useful heat value (UHV) is considered, which is estimated from the formula:

$$UHV = 8900 - 138(\text{Ash} + \text{Moisture}) \quad (1)$$

where ash and moisture are determined at 60% RH at 40 °C.

Table 2
Categorization of coking coal and non-coking coal.

Sl. no.	Class	Grade	Grade specification
1	Coking coal on the basis of ash contents	Steel Gr. I	Ash content <15%
		Steel Gr. II	15% ⩽Ash content <18%
		Washery Gr. I	18% ⩽Ash content ⩽21%
		Washery Gr. II	21% ⩽Ash content ⩽24%
		Washery Gr. III	24% ⩽Ash content ⩽28%
		Washery Gr. IV	28% ⩽Ash content ⩽35%
2	Non-coking coal on the basis of useful heat value (UHV) kcal/kg	A	UHV >6200
		B	6200⩾ UHV >5600
		C	5600⩾ UHV >4940
		D	4940⩾ UHV >4200
		E	4200⩾ UHV >3360
		F	3360⩾ UHV >2400
		G	2400⩾ UHV >1300