**Development of correlation between GCV and Proximate Analysis of Indigenous Coals**

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**CENTRE FOR COAL TECHNOLOGY**

**UNIVERSITY OF THE PUNJAB**

**LAHORE**

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**This project is submitted to Centre for Coal Technology,**

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# Summary

Higher heating value (HHV) is very important for quality of coal when used as a fuel. It is often used for estimating the efficiency of treatment and other beneficiation methods and for research purpose. Although it is a costly process and requires special equipment and experts to operate. Whereas proximate analysis data can be obtained easily using an ordinary muffle furnace Therefore, to simplify the task and to reduce the cost of analysis many correlations were developed for determining HHV from proximate analysis of coal. In the present work, an effort has been made to develop a correlation based on proximate analyses data for calculating HHV of coal (air-dried basis). The models presented here is established using analyses of 50 samples of indigenous coal and its importance lies in role of all the major variables affecting the HHV. The developed models appear to be better than the existing models and have the following:

Model 1: HHV (Mj/kg) = 15.788 – 0.215M% – 0.148A% + 0.036V.m% + 6.680F.c%

Model 2: HHV (Mj/kg) = 8.804 – 0.061M% + 0.187V.m% + 0.231F.c% Heating values of basic types of indigenous coal samples were measured and calculated using empirical formulae and results were compared. Remarkable differences were observed in heating value of fifty samples of indigenous coal analyzed. It is determined that further study of these other types is merited for better and more economical utilization of the coal. A significant correlation was also observed between the Heating values proximate contents of the coal.

**Introduction**

Coal is a dark brown to black graphite like material which is present naturally and it can be used as fuel, formed from the fossilized plants and composed of unstructured carbon forms with different organic and some inorganic compounds during coalification. The first coal age which spanned 290 million to 360 million years ago, the formation of coal began during the Carboniferous Period. (Association 2014). There are different ranks of coal according to the age and the process of formation of coal, including anthracite, bituminous, sub bituminous, and lignite. Anthracite is types of coal which contain the highest carbon contents. Its carbon content varies between 86 to 98 percent. This type of coal which is used domestically produces nearly 15,000 Btu's per pound (a Btu, or British thermal unit, is the amount of heat needed to raise the temperature of one pound of water one degree Fahrenheit). The very type of coal is used in steel industry and power generation. Carbon contents in Bituminous coal ranges from 45 to 86 percent and a heat value of 10,500 to 15,500 Btu's per pound. Sub bituminous coal in which carbon contents ranges from 35 to 45 percent ranks just below bituminous coal. The heating value of sub bituminous coal is between 8,300 and 13,000 Btu's per pound. Lignite contains 25 to 35 percent carbon content. Lignite is also used to generate electricity. Sometimes lignite is known as brown coal because of its brown color. The heating value of lignite ranges between 4,000 and 8,300 Btu's per pound. (Powder River Coal Company 2015).

Pakistan is moving towards the large scale use of coal today because huge coal deposits have been found in Pakistan. The Thar coal deposit in Sindh is one of the largest in the world. It contains of 175 billion tons of coal in four sections. Punjab has about 600 million tons of coal deposits. The Salt Range alone has about 500 million tons of coal that can be exploited and used as an energy resource economically. Beside Thar, there are seven other coal fields in Sindh; two of them are developed while the others are un-developed including Thar. KPK (Hangu and Cherat) and Azad Kashmir (Kotli) are also among the developed coal fields. Balochistan has more than ten developed coal fields contributing a major part of coal production in Pakistan. Germany has been developed a process for the up gradation of the Kalabagh iron ore, using indigenous coal of Makarwal. Coal is the best future energy resource for Pakistan. The most important uses of coal are in steel production, cement manufacturing, electricity generation and production of different chemicals and manufacture of gaseous and liquid fuels. Coking coal also known as metallurgical coal is mainly used in steel production. (Pakistan Energy Year Book 2012).

**Heating Value**

Heating value of coal is the heat produced by combustion of a unit quantity of coal in a bomb calorimeter with oxygen under a specified set of conditions prescribed by standard test like (ASTM D-121; ASTM D-2015; ASTM D-3286; ISO 1928). The heating value of coal is neither the part of proximate analysis nor part of ultimate analysis it is one of many physical properties of coal. It is often found in the various sections that deal with the physical properties. (Speight 2005).The heating Value varies on the coalification, geographical age, ranking and location of the coal mines. The heating value is expressed in two different ways on account of moisture present in the coal. Heating value usually expressed as higher heating value (HHV) or gross calorific value (GCV) and lower heating value (LHV) or net calorific value (NCV). Coal contains moisture as an essential component so; difference between both these heating values is the latent heat of condensation of water vapors produced during combustion process. When coal burns the moisture in coal evaporates taking away some heat of combustion which is not available for our use. The higher calorific value presumes that all the vapors produced during combustion process are fully condensed and the lower heating value presumes that the water is removed with the combustion products without being fully condensed. When we say Higher Heating Value or Gross Calorific Value it is the total heat released when burning the coal. When we say Lower Heating Value or Net Calorific Value it is the heat energy available after reducing the loss due to moisture. Coal with greater percentage of volatile matter and fix carbon produces more heating value on combustion as they are the combustible constituents of coal and greater percentage of non-combustibles (moisture and mineral matter) contents lowers the heating value. In bomb calorimeter, the heating value of coal is either determined by an adiabatic process or by static method (isothermal) with the correction made if net heating value is of interest for analysis of coal. The unit is calories per gram, which may be converted to the alternate units. Heating value is the direct indication of heat content (energy value) of coal. The heating value represents the combined heats of combustion of carbon, hydrogen, nitrogen and Sulphur in organic matter and of Sulphur in pyrite and the higher heating value with correction applied if the lower heating value is of interest. The significance of the correlation of heating value with composition in ordinary fuel usage is shown by the development, as early in 1940’s 9 different formulas for calculating heating value of coal from the ultimate analysis and 11 formulas for calculating it from the proximate analysis. Formulas have been proposed within the last three years. The correlation is perhaps of even greater importance for the rationalization and modeling of conversion processes now being developed (Engineering 2014). Much work has been done on measurements of heating value of indigenous coal samples, where the calorific value was found to vary with percentages of fixed carbon, volatile matter, moisture and ash contents. These parameters can be used to estimate the calorific value coal. Some of the models proposed originally for correlation of heating value of coal with its proximate analysis.

**HHV=0.3536FC+0.1559VM−0.0078ASH** (MJ/kg) (Parikh, J.)

**HHV=-0.03(A)-0.11(M)+0.33(VM)+0.35(FC)(**MJ/kg) (Majumder, A.K)

Many equations have been developed for the estimation of higher heating value or gross calorific value (GCV) based on proximate analysis and ultimate analysis. Regression analysis and data for 775 U.S. coal samples (with less than 30% dry ash) were used by Mason and Gandhi (1983) to develop an empirical equation that estimates the calorific value (CV) of coal based on C, H, S, and ash contents (all on dry basis). Their empirical equation, expressed in SI units, is (F. Rafezi 2005).

**CV = 0.472C + 1.48H + 0.193S + 0.107A – 12.29 (MJ/kg) (** F. Rafezi)

Given et al. (1986) developed an equation to calculate the calorific value of U.S. coals from their elemental composition; expressed in SI units, their equation is:

**CV = 0.3278C + 1.419H + 0.09257S – 0.1379O + 0.637 (MJ/Kg) (** F. Rafezi)

Empirical formulae are also available in the literature for the calculation of the heating value of coal based on ultimate and proximate analyses.

HHV=82F+α.V (Goutal)

F= percentage fixed carbon

V= percentage volatile matter

α= a constant depending upon the value of volatile matter expressed as dry ash free basis

This model assumes the coal consisting of volatile matter and fixed carbon, each contributing to heating value of coal. The fixed carbon of different coals is assumed of a fixed composition and hence of fixed heating value. The composition and heating value of the volatile matter differ from coal to coal and are assumed to depend upon the nature of coal as indicated by the volatile matter on dry as free basis. These assumptions limit the utility of the Goutal formula.

The following model have been developed by Central Fuel Research Institute, Dhanbad (CFRI), for the calculation of heating value of Indian coal form their proximate analysis.

For low moisture coals (M≤2%)

HHV = 91.7F+75.6(V-0.1A)-60M

For high moisture coals (M≥2%)

HHV=85.6[100-(1.1A+M) ]-60M

Where M, A, V and F all in air-dried basis.

**Proximate analysis**

Proximate analysis helps to determine the basic characteristics of coal which are important for user to make decision whether or not the coal under reference can be used according to his requirements, (Speight 2001). including Moisture determined by using test method (ASTM D-3173), Volatile matter present in coal consist of certain gases like hydrocarbons, CO,,, , , etc. Which comes out on heating at specific temperature (950±20°C) measured by standard methods i.e., ASTM D-3175 under rigidly controlled conditions and Ash is the residue remaining after the coal combustion under specified conditions and temperature (700-750°C) according to ASTM D- 3174; it is mainly composed of unaltered minerals, oxides and sulfites. Chemical changes during the “*ashing process”* that occurs in the mineral matter produces ash and Fixed Carbon constituents in coal that left behind after the loss of ash, volatile matter and moisture, is referred to as fixed carbon content. The fixed carbon value is basically the value that is used for measuring efficiency of coal on burning.

**Regression Analysis**

It is a [statistical technique](http://en.wikiversity.org/wiki/Multivariate_statistics) which is a multivariate function for examining the [linear correlations](http://en.wikiversity.org/wiki/Linear_correlation) between a single  dependent variable(DV) and two or more independent (IV). This type of analysis is used for forecasting and prediction, and also used to determine the relationships between the dependent variable and independent variables. Many techniques have been developed in Regression analysis of which linear regression analysis and nonlinear regression analysis are vital for the current analysis. Multiple linear regression analysis was conducted in order to get predicted gross calorific value of coal by applying function on combustibles (fix carbon and volatile matter) and non-combustibles (moisture and ash contents) components of coal against calculated gross calorific value of coal respectively (analysis. 2013). In this process dependent variable is illustrated as a function of different independent variables with corresponding coefficients, along with the constant term. Multiple regression analysis requires two or more predictor variables so it is known as multiple regressions (Regression2015).

**Methodology**

50 Representative gross samples weighing about 30 kg each were collected from different coal mines of Punjab, Sindh, KPK and Baluchistan for proximate analysis and GCV test. Samples for proximate analysis were prepared following the ASTM method (D 2013-04) (American Society for Testing and Materials 2008). Gross samples collected from the mines were first crused so that 95% of smaple passed from a four mesh sieve (-4.75 mm) one by one. Determined Air dried loss of each sample used for conducting GCV test and proximate analysis tests by placing weighed quantity of samples in an air drying oven maintained at 40OC for one hour. The air-dried samples were cooled in desiccators, weighted and again placed in the air-drying oven for one hour. The experiment was repeated until the loss in weight of total samples was not more than 0.1% per hour. Each sample was then thoroughly mixed and gradually reduced in size to -60, +80 mesh. The representative sample for proximate analysis and GCV were prepared. Proximate analysis tests were carried out on samples using ASTM test methods and for heating value determination, the adiabatic bomb calorimeter method was used in which a weighed sample is burnt completely in oxygen under controlled conditions. The calorific value is computed from temperature observations made before, during and after combustions by Heating value= m.CpΔT

# Determination of Pearson correlation (r)

Pearson's correlation was calculated by dividing the sum of the xy values (Σxy) (dependent variables and independent variables) by the square root of the product of the sum of the x2 values (Σx2) and the sum of the y2 values (Σy2).(Regression 2015) The resulting formula is:

**r =**

However, the correlation between these parameters was determined by using the software IBM SPSS statistics (version 16.0).

### Coefficient of multiple determination ()

The determination coefficient of a [multiple regression model](http://www.r-tutor.com/node/100) is the result of division for [variances](http://www.r-tutor.com/node/42) of the [fitted values](http://www.r-tutor.com/node/92) and observed values of the dependent variables (Chi Yau 2013).If *yi* is denoted as the observed values of the dependent variable, ý as its [mean](http://www.r-tutor.com/node/35), and  as the fitted value, then the coefficient of determination is:

 **= or =**

Average squared difference between the predictor and the resulted values,was measured by calculating mean squared error. It is somewhat reasonable measure of performance for predictors. In general, any increasing function of the absolute distance would serve to measure the goodness of a predictor (Songfeng Zheng 2013).

**MSE =**

Where,

n = numbers of total experiments performed.

K = number of predictors used in the model.

**Results and Calculations**

In the development of linear regression model for prediction of higher heating value (HHV) of indigenous coal, percentage values of V.m (volatile matter), M (Moisture), F.c (fixed carbon) and ash contents on air dried basis were used as independent variables while HHVs MJ/kg (higher heating values in Mega Joules per kilo gram) were used to target the output dependent variable. The studies included two models; Model 1 contained all the proximate analysis components as predictors of HHV.

**(*Y* = α)**

 While, the predictors of model 2 included fixed carbon, moisture and volatile matter. Ash contents were excluded.

**(*Y* = α**

As the proximate contents of coal (moisture, ash, fixed carbon and volatile matter) are directly related by their percentages as follows;

**Moisture% + Ash% + Volatile matter% + Fixed carbon% = 100**

So, according to above relation for the proximate components of coal, the Model 2 ultimately has ash% as predictor also. Descriptive statistics of the data set considered in the model development are presented in Table 1.

| **Table 1. Descriptive Statistics of coal samples used** |
| --- |
| **Parameters** | **N** | **Minimum** | **Maximum** | **Mean** | **Std. Deviation** |
| **Moisture%** | 50 | 2.170 | 9.940 | 4.07940 | 1.638883 |
| **Ash%** | 50 | 9.570 | 46.500 | 2.81722E1 | 10.293310 |
| **Fixed carbon%** | 50 | 13.720 | 66.440 | 3.50684E1 | 11.588341 |
| **Volatile matter%** | 50 | 13.980 | 48.540 | 3.26800E1 | 9.422630 |
| **GCV MJ/kg** | 50 | 17.300 | 26.400 | 2.20725E1 | 2.436373 |
|  **(Fixed carbon %)** | 50 | 1.137 | 1.822 | 1.52159 | 0.146177 |
| **Valid N (list wise)** | 50 |  |  |  |  |

The relation between higher heating values and proximate analysis components are plotted in figure.1

Figure 1. Effect of Volatile matter and Fixed carbon contents on HHV of coal

 It was observed from the above figure that there is a positive linear relation between HHV, volatile matter content and fixed carbon content. Percentages of moisture and ash exhibits negative relation with HHV of coal samples as shown in figure. 2.

Figure 2. Effect of Moisture and Ash contents on HHV of coal

It means that it is necessary to use a linear model to make a better estimation models.

**(*Y* = α)**

Therefore, on the basis of the considered model structures, multiple linear regression method based modeling was applied to estimate the higher heating values of the coals as the best fit models for the prediction of HHVs. Statistically; it was observed that there was a strong negative correlation between fixed carbon and ash. To see correlation between fixed carbon, ash and all other predictors for higher heating value of coal, Pearson correlation was employed. The results are presented in Table 2.

**Table 2. Relationship among predictors and outcome**

| **Predictors** | **M** | **A** | **V** | **F** | **GCV** |
| --- | --- | --- | --- | --- | --- |
| **M** | **Pearson Correlation** | 1 | .031 | -.014 | -.158 | -.224 |
| **Sig. (2-tailed)** |  | .833 | .925 | .274 | .117 |
| **A** | **Pearson Correlation** |  | 1 | -.329\* | -.625\*\* | -.928\*\* |
| **Sig. (2-tailed)** |  |  | .020 | .000 | .000 |
| **V** | **Pearson Correlation** |  |  | 1 | -.519\*\* | .153 |
| **Sig. (2-tailed)** |  |  |  | .000 | .287 |
| **F** | **Pearson Correlation** |  |  |  | 1 | .731\*\* |
| **Sig. (2-tailed)** |  |  |  |  | .000 |
| **GCV** | **Pearson Correlation** |  |  |  |  | 1 |
| **Sig. (2-tailed)** |  |  |  |  |  |
| \*. Correlation is significant at the 0.05 level (2-tailed). |  |  |
| \*\*. Correlation is significant at the 0.01 level (2-tailed). |  |  |

Results show significant negative correlation between fixed carbon and ash contents of coal. However, the correlation between these parameters, fixed carbon and ash, which appeared to be strongly negative, thus showing that no more different information was obtained due to fixed carbon and ash for prediction of heating value of coal. It refers to a situation in which two or more explanatory variables in a [multiple regression](http://en.wikipedia.org/wiki/Multiple_regression) model are linearly related meaning that one can be linearly predicted from the others. So, model 2 does not contain percentage value of ash contents actually, but indirectly it contains percentage value of ash contents of coal because all proximate components of coal are directly related with each other by their percentage values as follows;

**Moisture% + Ash% + Volatile matter% + Fixed carbon% = 100**

In this situation the [coefficient estimates](http://en.wikipedia.org/wiki/Regression_coefficient) of the multiple regression may change erratically in response to small changes in the model or the data.

Numbers of solutions are present in statistics to overcome multicolinearity problem for regression analysis. Two of these are proposed here as follows;

* One is to change the original values by taking logarithm of one of the collinear predictors shown in Model 1.
* Second is to exclude one of collinear predictors to evaluate the outcome shown in Model 2.

 **Model 1**

| **Table 3. Significance Model fit through regression analyses** |
| --- |
| **Model** | **Sum of Squares** | **df** | **Mean Square** | **F** | **P-value** |  | **Adj.** |
| **Regression** | 271.667 | 4 | 67.917 | 159.243 | .000 | .934 | .928 |
| **Residual** | 19.192 | 45 | .426 |  |  |  |  |
| **Total** | 290.860 | 49 |  |  |  |  |  |

**Table 4. Estimates of regression coefficients for multiple egression models and their significance**

| **Predictors** | **B** | **Std. Error** | **β** | **t** |
| --- | --- | --- | --- | --- |
| **(Constant)** | 15.78 | 6.25 |  | 2.52 |
| **Moisture** | -.21 | .06 | -.145 | -3.31 |
| **Ash** | -.14 | .03 | -.624 | -4.21 |
| **Volatile Matter** | .03 | .03 | .138 | 1.05 |
| **F** | 6.68 | 2.69 | .401 | 2.47 |

\*P < .05. \*\*P < .01. \*\*\*P < .001.

**Model 1 emerged from Multiple Regression**

%Moisture

.215\*

=-.148\*

**HHV**

%Ash

= .036

%Volatile mater

= 6.68\*

%Fixed carbon

 0.93

**Model 1: HHV (Mj/kg) = 15.788 – 0.215M% – 0.148A% + 0.036V.m% + 6.680F.c%**

Model 2

**Table 5. Significance Model fit through multiple regression analyses**

| **Model** | **Sum of Squares** | **df** | **Mean Square** | **F** | **P-value** |  | **Adj.** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Regression** | 269.046 | 3 | 89.682 | 189.120 | .000a | .925 | .920 |
| **Residual** | 21.813 | 46 | .474 |  |  |  |  |
| **Total** | 290.860 | 49 |  |  |  |  |  |

**Table 6. Estimates of regression coefficients for multiple egression models and their significance**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Predictors** | **B** | **Std. Error** | **β** | **t** |
| **Constant** | 8.084 | .75 |  | 10.739 |
| **Moisture** | -.061 | .06 | -.041\* | -0.998 |
| **Volatile matter** | .187 | .01 | .724\*\*\* | 15.236 |
| **Fixed Carbon** | .231 | .01 | 1.101 | 22.860 |

\*P < .05. \*\*P < .01. \*\*\*P < .001.

 Model 2 emerged from Multiple Regression

= -.061

%Moisture

= 0.187

**HHV**

%Volatile mater

%Fixed carbon

= 0.231

 0.925

**Model 2: HHV (Mj/kg) = 8.804 – 0.061M% + 0.187V.m% + 0.231F.c%**

 **Table 7. Resulted data after regression analysis**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sr. No.** | **%Measured values** |  | **Measured** | **Predicted HHV MJ/kg** |
| **M** | **A** | **V.m** | **F.c** | **F.C**  | **HHV MJ/kg** | **Model 1** | **Model 2** |
| 1 | 3.400 | 12.560 | 17.600 | 66.440 | 1.822 | 26.400 | 25.999 | 26.549 |
| 2 | 4.840 | 38.540 | 27.860 | 28.760 | 1.459 | 19.763 | 19.785 | 19.663 |
| 3 | 7.000 | 32.600 | 35.650 | 24.750 | 1.394 | 19.872 | 20.040 | 20.063 |
| 4 | 5.800 | 18.010 | 34.380 | 41.810 | 1.621 | 23.722 | 23.930 | 23.846 |
| 5 | 3.460 | 22.850 | 38.920 | 34.770 | 1.541 | 23.962 | 23.346 | 23.210 |
| 6 | 2.660 | 46.500 | 18.240 | 32.600 | 1.513 | 19.730 | 19.100 | 18.883 |
| 7 | 4.080 | 20.130 | 13.980 | 61.810 | 1.791 | 24.972 | 24.396 | 24.758 |
| 8 | 3.600 | 23.730 | 34.920 | 37.750 | 1.577 | 22.983 | 23.282 | 23.142 |
| 9 | 2.450 | 23.260 | 46.290 | 28.000 | 1.447 | 24.580 | 23.136 | 23.086 |
| 10 | 3.920 | 22.840 | 35.080 | 38.160 | 1.582 | 23.470 | 23.381 | 23.247 |
| 11 | 6.200 | 20.600 | 18.130 | 55.070 | 1.741 | 23.083 | 23.682 | 23.846 |
| 12 | 5.340 | 44.100 | 24.640 | 25.920 | 1.414 | 18.234 | 18.440 | 18.372 |
| 13 | 3.980 | 14.170 | 33.730 | 48.120 | 1.682 | 25.540 | 25.274 | 25.296 |
| 14 | 3.320 | 25.800 | 36.190 | 34.690 | 1.540 | 22.832 | 22.836 | 22.689 |
| 15 | 7.000 | 42.670 | 17.600 | 32.730 | 1.515 | 17.310 | 18.720 | 18.528 |
| 16 | 4.220 | 35.000 | 17.200 | 43.580 | 1.639 | 22.014 | 21.268 | 21.134 |
| 17 | 2.230 | 28.240 | 35.660 | 33.870 | 1.530 | 22.424 | 22.622 | 22.466 |
| 18 | 4.200 | 21.060 | 48.540 | 26.200 | 1.418 | 23.874 | 22.972 | 22.984 |
| 19 | 5.240 | 18.840 | 43.250 | 32.670 | 1.514 | 23.510 | 23.528 | 23.427 |
| 20 | 2.340 | 21.780 | 15.350 | 60.530 | 1.782 | 23.440 | 24.514 | 24.825 |
| 21 | 3.420 | 12.290 | 46.380 | 37.910 | 1.579 | 24.422 | 25.431 | 25.337 |
| 22 | 2.210 | 14.430 | 30.320 | 53.040 | 1.725 | 25.460 | 25.778 | 25.904 |
| 23 | 6.350 | 9.570 | 47.090 | 36.990 | 1.568 | 25.983 | 25.156 | 25.078 |
| 24 | 5.350 | 10.140 | 41.380 | 43.130 | 1.635 | 26.110 | 25.530 | 25.490 |
| 25 | 2.930 | 24.210 | 39.200 | 33.660 | 1.527 | 23.013 | 23.174 | 23.038 |
| 26 | 2.540 | 12.070 | 27.910 | 57.480 | 1.760 | 26.193 | 26.203 | 26.459 |
| 27 | 5.450 | 40.750 | 15.630 | 38.170 | 1.582 | 20.723 | 19.713 | 19.513 |
| 28 | 9.940 | 21.630 | 40.200 | 28.230 | 1.451 | 21.250 | 21.572 | 21.541 |
| 29 | 3.040 | 34.200 | 33.820 | 28.940 | 1.461 | 20.200 | 21.045 | 20.931 |
| 30 | 2.800 | 27.360 | 34.380 | 35.460 | 1.550 | 21.490 | 22.717 | 22.560 |
| 31 | 3.150 | 19.940 | 45.150 | 31.760 | 1.502 | 23.250 | 23.801 | 23.700 |
| 32 | 2.870 | 36.940 | 36.440 | 23.750 | 1.376 | 20.130 | 20.196 | 20.231 |
| 33 | 4.670 | 22.960 | 33.120 | 39.250 | 1.594 | 23.220 | 23.214 | 23.087 |
| 34 | 6.560 | 43.790 | 33.540 | 16.110 | 1.207 | 17.300 | 17.160 | 17.695 |
| 35 | 3.410 | 39.860 | 22.230 | 34.500 | 1.538 | 21.322 | 20.226 | 20.024 |
| 36 | 2.680 | 42.320 | 19.250 | 35.750 | 1.553 | 20.422 | 20.017 | 19.800 |
| 37 | 2.860 | 27.400 | 32.820 | 36.920 | 1.567 | 23.530 | 22.759 | 22.602 |
| 38 | 3.600 | 35.500 | 24.530 | 36.370 | 1.561 | 20.345 | 21.064 | 20.876 |
| 39 | 2.850 | 37.840 | 45.590 | 13.720 | 1.137 | 18.850 | 18.801 | 19.626 |
| 40 | 3.270 | 30.380 | 46.230 | 20.120 | 1.304 | 20.456 | 20.947 | 21.201 |
| 41 | 4.020 | 27.180 | 38.840 | 29.960 | 1.477 | 22.130 | 22.150 | 22.048 |
| 42 | 2.480 | 40.320 | 36.800 | 20.400 | 1.310 | 18.983 | 19.352 | 19.547 |
| 43 | 2.970 | 43.200 | 34.280 | 19.550 | 1.291 | 17.834 | 18.608 | 18.849 |
| 44 | 2.170 | 23.470 | 35.200 | 39.160 | 1.593 | 23.632 | 23.744 | 23.608 |
| 45 | 5.800 | 29.490 | 32.460 | 32.250 | 1.509 | 21.530 | 21.412 | 21.274 |
| 46 | 6.670 | 34.500 | 33.830 | 25.000 | 1.398 | 19.443 | 19.795 | 19.800 |
| 47 | 2.640 | 27.620 | 37.280 | 32.460 | 1.511 | 22.400 | 22.559 | 22.418 |
| 48 | 5.430 | 44.350 | 33.290 | 16.930 | 1.229 | 18.423 | 17.456 | 17.907 |
| 49 | 3.340 | 34.250 | 29.890 | 32.520 | 1.512 | 21.552 | 21.171 | 21.005 |
| 50 | 3.220 | 27.370 | 33.710 | 35.700 | 1.553 | 22.310 | 22.620 | 22.464 |

Figure 3. Correlation between the measured and the experimental values of HHV of indigenous coal

**Table 8. Comparison of HHV (MJ/kg) by models derived from study, A.K Mjumdar and Goutal’s Formula.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sr.No.** | **Measured** | **(Model 1)** | **(Model 2)** | **A.K Mjumdar** | **Gaulat's formula** | **CFRI** |
| 1 | 26.400 | 25.999 | 26.549 | 28.311 | 35.655 | 28.917 |
| 2 | 19.763 | 19.785 | 19.663 | 17.571 | 39.557 | 17.758 |
| 3 | 19.872 | 20.040 | 20.063 | 18.679 | 43.682 | 18.786 |
| 4 | 23.722 | 23.930 | 23.846 | 24.801 | 40.969 | 25.293 |
| 5 | 23.962 | 23.346 | 23.210 | 23.947 | 42.706 | 24.810 |
| 6 | 19.730 | 19.100 | 18.883 | 15.742 | 31.856 | 15.942 |
| 7 | 24.972 | 24.396 | 24.758 | 25.194 | 31.771 | 25.506 |
| 8 | 22.983 | 23.282 | 23.142 | 23.628 | 39.964 | 24.376 |
| 9 | 24.580 | 23.136 | 23.086 | 24.108 | 44.171 | 25.265 |
| 10 | 23.470 | 23.381 | 23.247 | 23.816 | 39.354 | 24.532 |
| 11 | 23.083 | 23.682 | 23.846 | 23.957 | 32.354 | 24.023 |
| 12 | 18.234 | 18.440 | 18.372 | 15.293 | 34.920 | 15.252 |
| 13 | 25.540 | 25.274 | 25.296 | 27.110 | 38.271 | 27.925 |
| 14 | 22.832 | 22.836 | 22.689 | 22.945 | 38.474 | 23.728 |
| 15 | 17.310 | 18.720 | 18.528 | 15.213 | 29.199 | 14.802 |
| 16 | 22.014 | 21.268 | 21.134 | 19.415 | 29.323 | 19.538 |
| 17 | 22.424 | 22.622 | 22.466 | 22.530 | 37.245 | 23.430 |
| 18 | 23.874 | 22.972 | 22.984 | 24.094 | 40.964 | 25.065 |
| 19 | 23.510 | 23.528 | 23.427 | 24.565 | 38.875 | 25.307 |
| 20 | 23.440 | 24.514 | 24.825 | 25.340 | 30.522 | 25.918 |
| 21 | 24.422 | 25.431 | 25.337 | 27.829 | 38.976 | 29.012 |
| 22 | 25.460 | 25.778 | 25.904 | 27.894 | 35.153 | 28.905 |
| 23 | 25.983 | 25.156 | 25.078 | 27.501 | 38.346 | 28.295 |
| 24 | 26.110 | 25.530 | 25.490 | 27.858 | 36.904 | 28.682 |
| 25 | 23.013 | 23.174 | 23.038 | 23.668 | 35.446 | 24.596 |
| 26 | 26.193 | 26.203 | 26.459 | 28.687 | 34.066 | 29.637 |
| 27 | 20.723 | 19.713 | 19.513 | 16.695 | 25.627 | 16.510 |
| 28 | 21.250 | 21.572 | 21.541 | 21.404 | 34.547 | 21.328 |
| 29 | 20.200 | 21.045 | 20.931 | 19.929 | 32.366 | 20.576 |
| 30 | 21.490 | 22.717 | 22.560 | 22.628 | 32.334 | 23.429 |
| 31 | 23.250 | 23.801 | 23.700 | 25.071 | 34.526 | 26.150 |
| 32 | 20.130 | 20.196 | 20.231 | 18.914 | 32.085 | 19.596 |
| 33 | 23.220 | 23.214 | 23.087 | 23.465 | 31.274 | 24.026 |
| 34 | 17.300 | 17.160 | 17.695 | 14.671 | 31.285 | 14.629 |
| 35 | 21.322 | 20.226 | 20.024 | 17.840 | 26.543 | 18.110 |
| 36 | 20.422 | 20.017 | 19.800 | 17.301 | 25.166 | 17.584 |
| 37 | 23.530 | 22.759 | 22.602 | 22.616 | 29.671 | 23.376 |
| 38 | 20.345 | 21.064 | 20.876 | 19.363 | 26.760 | 19.719 |
| 39 | 18.850 | 18.801 | 19.626 | 18.398 | 31.349 | 19.252 |
| 40 | 20.456 | 20.947 | 21.201 | 21.027 | 30.581 | 21.947 |
| 41 | 22.130 | 22.150 | 22.048 | 22.046 | 29.092 | 22.754 |
| 42 | 18.983 | 19.352 | 19.547 | 17.802 | 27.974 | 18.497 |
| 43 | 17.834 | 18.608 | 18.849 | 16.532 | 27.027 | 17.058 |
| 44 | 23.632 | 23.744 | 23.608 | 24.379 | 28.248 | 25.353 |
| 45 | 21.530 | 21.412 | 21.274 | 20.477 | 26.400 | 20.751 |
| 46 | 19.443 | 19.795 | 19.800 | 18.145 | 25.742 | 18.237 |
| 47 | 22.400 | 22.559 | 22.418 | 22.544 | 26.736 | 23.424 |
| 48 | 18.423 | 17.456 | 17.907 | 14.983 | 24.660 | 15.098 |
| 49 | 21.552 | 21.171 | 21.005 | 19.851 | 24.475 | 20.373 |
| 50 | 22.310 | 22.620 | 22.464 | 22.444 | 25.421 | 23.168 |

**Discussion on results**

A comparison of experimental results of higher heating value with those computed by using both equations developed in the present study, and the equations suggested by Majumdar(A.K. Majumder), Gautal’s and CFRI (Central Fuel Research Institute)(O. P. Gupta 2000) by making use of experimental results of proximate analysis of indigenous coals indicate much better fit in of the regression model developed herein compared to that of other models shown in figure 4

Figure 4. Comparison of HHV (MJ/kg) by models derived from study, A.K Mjumdar and Goutal’s Formula.

The value of determination coefficient () for model I and mode II of the present study have been found to be 0.93 and 0.92 respectively, which are reasonably close to its maximum value 1.00. The models developed in the present study have also been tested by taking proximate analysis results of Indian, Indonesian, South African and Afghan coals from the published literature. The results for Indonesian and South African coals show reasonable agreement with their experimental values and those computed by model II of the present study shown in figure 5 And 6 Respectively.

Figure 5. Comparison of Indonesian coal by different models

Figure 6. Comparison of S.A coal by different models

 However, values computed by model I of the present study and those by models by Majumdar, Gautal’s and CRFI (Central Fuel Research Institute) are significant by different than the experimental values. The results for experimental HHV (Higher Heating Value) of Afghan coals and those computed by model II of the present study and by CRFI (Central Fuel Research Institute) models are reasonably close while those computed by model I the present study and other models differ significantly as shown in figure 7.

Figure 7. Comparison of Afghan coal by different models

The HHV computed by model II of this study and CRFI are close to the experimental HHV of Indian coals shown in figure 8.

Figure 8. Comparison of Indian coal by different models

However, the values computed by model I of this study are not very different to the experimental values. The values calculated by Gautal model are far different compared to the experimental results.

# Conclusion

The results of present study have shown that computed values of Indigenous low rank coals (lignite and sub-bituminous) by model I model II fit well with their experimental values while these developed models can reasonably be applied to the higher rank coal compared to the other models available in literature

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