Modelling and Prediction of NOx emissions from coal fired boilers: Case study

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Abstract – *As India modernizes and as the population shifts to urban areas, the country has also shifted from using traditional biomass and waste to relying on other energy sources, including fossil fuels. India is strongly fossil fuel dependent and coal is the major fossil fuel in India. The country was ranked as the third-largest global coal producer, consumer, and importer of coal in 2012, and coal plays a pioneer role in the power sector. Due to growing energy demand dependence on coal is increasing day by day. Despite having significant coal reserves, India has experienced increasing supply shortages as a result of a lack of competition among producers, insufficient investment, and systemic problems with our mining industry Combustion of coal produces emissions of Nitrogen (NO&NO_2) commonly referred to as NOx which causes harmful environmental problems such as acid rain and smog. In this article a mathematical model based on dimensional analysis is developed to establish the relationship between boiler operational parameters and Nitrogen oxides (NOx) formation. Dimensional analysis works on the proper selection of parameters affecting the process (NOx formation).It operates on the dimensions of the selected parameters rather than their values. In dimensional analysis, it is not necessary to identify details of the actual combustion equipment e.g. its design, combustion air distribution system, positions of burners, etc. and what will be the effect on combustion of fuel if parameters like humidity changes; All these effects are reflected in the model through measured values of quantities that are used to build up the model. The experiment is based on on-line measurements of selected operational parameters for the given boiler.*

Key Words: dimensional analysis, nitrogen oxides

1. INTRODUCTION

Coal is the major fossil fuel in India and plays a key role in the energy sector [2]. Coal meets about 61% of the commercial energy needs and about 72% of the electricity produced in India comes from coal. The combustion of coal produces various pollutants, such as oxides of carbon (COx), oxides of sulphur (SOx), oxides of nitrogen (NOx) and particulates .These pollutants degrades the environmental quality by causing acid rain ,ozone hole depletion and climate change. Climate change affects agriculture, ecosystem, human health and habitat of the entire living beings. Hence it is the responsibility of these industries to check these emissions and keep them to minimal level. Fly-ash particulates can be removed by fitting electrostatic precipitators and SO_2 by installing a flue gas desulphurization plant. The best way to reduce CO_2 emissions is to improve power generation efficiency. However, no practical methods exist for reducing NOx, leading to increased research into this area. During the combustion process in a coal-fired power plant, nitrogen from the coal and air is converted into nitric oxide (NO) and nitrogen dioxide (NO_2); together these oxides of nitrogen are commonly referred to as NOx.

2. DIMENSIONAL ANALYSIS

Dimensional analysis is a means of simplifying a physical problem by appealing to dimensional homogeneity to reduce the number of relevant variables [1]. It is based on the Buckingham Pi-theorem. Dimensional analysis works on the proper selection of parameters affecting the process (NOx formation).It operates on the dimensions of the selected parameters rather than their values. In dimensional analysis, it is not necessary to identify details of the actual combustion equipment e.g. its design, combustion air distribution system, positions of burners, etc. and what will be the effect on combustion of fuel if parameters like humidity changes; All these effects are reflected in the model through measured values of quantities that are used to build up the model.

3.MATHEMATICAL MODELLING BY DIMENSIONAL ANALYSIS

According to Buckingham pi theorem if a problem involves n relevant variables & m independent dimensions then it can be reduced to a relationship between n – m non-dimensional parameters $\pi_1 \ldots\ldots \pi_{n-m}$.

Accordingly the parameters selected as input variables are as follows:

- Volume of combustion air, $Q_a(m^3/s)$
- Mass flow rate of coal, $\dot{m}c$ (kg/s)
- Temperature of combustion air, $T_a(K)$
- Volume of Nitrogen oxides, $NO_x(kg/m^3)$
- Boiler performance, $P_B(kgm^2/s^3)$
- Calorific value of fuel, $Q_C(m^2/s^2)$

Here the number of selected parameters = 6
Number of basic dimensions = 4
∴ Number of dimensionless arguments = 6-4 = 2
∴ the dimensionless arguments are π_1 and π_2
It is possible in dimensional analysis to express the selected parameters including NOx formed in a functional form as follows:

$$f(Q_a, \dot{m}_c, T_a, NO_x, P_B, Q_c) = 0 \qquad (1)$$

The parameters expressed in the functional form have fudamental dimensions of length, mass and time.The above parameters can be expressed as follows:

$$\pi = Qa^{x_1} \dot{m}_c^{x_2} T_a^{x_3} NO_x^{x_4} P_B^{x_5} Q_C^{x_6} \qquad (2)$$

The relation for dimensional arguments π_1 and π_2 will be obtained from dimensional matrix A as prescribed below:

Table-1: Parameters and Dimensions

	Q_a	$\dot{m}_c$	T_a	NO_x	P_B	Q_C
	x_1	x_2	x_3	x_4	x_5	x_6
M	3	0	0	-3	2	2
S	-1	-1	0	0	-3	-2
Kg	0	1	0	1	1	0
K	0	0	1	0	0	0

Dimensional matrix A will be formulated from table 1 such that determinant of A ≠0. ∴ Matrix A will be formulated by choosing variables x_1, x_2, x_3, and x_5

$$[A] = \begin{bmatrix} 3 & 0 & 0 & 2 \\ -1 & -1 & 0 & -3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_5 \end{bmatrix}$$

$$|A| = -4 \neq 0$$

For the matrixes with A and D dimensions and vector matrixes of unknown parameters B and E the following equation can be applied:

$$[A][B] = (-1)[D][E]$$

By expanding A, B, D, E the following set of linear equations is obtained:

$$\begin{bmatrix} 3 & 0 & 0 & 2 \\ -1 & -1 & 0 & -3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = (-1) \begin{bmatrix} -3 & 2 \\ 0 & -2 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_4 \\ x_6 \end{bmatrix}$$

$$\left.\begin{aligned} 3x_1 + 2x_5 &= 3x_4 - 2x_6 \\ -x_1 - x_2 - 3x_5 &= 2x_6 \\ x_2 + x_5 &= -x_4 \\ x_3 &= 0 \end{aligned}\right\} \qquad (4)$$

Values for x4 and x6 will be assumed such that its determinant also should not be zero:

$$\begin{bmatrix} x_4 \\ x_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} = 1 \neq 0$$

By substituting the values of x4 and x6 in the linear equations we obtain the values of π_1 and π_2 as tabulated in table 2:

Table-2: Dimensionless arguments and their values

	x_1	x_2	x_3	x_4	x_5	x_6
π_1	1	-1	0	1	0	0
π_2	0	1	0	0	-1	1

$$\pi_1 = \frac{x_1 * x_4}{x_2} \qquad (5)$$

$$\pi_2 = \frac{x_2 * x_6}{x_5} \qquad (6)$$

i.e.

$$\pi_1 = \frac{Q_a * NO_x}{\dot{m}_c} \qquad \pi_2 = \frac{\dot{m}_c * Q_C}{P_B} \qquad (7)$$

The term π_1 contains NOx term and hence it can be expressed as a function of π_2 i.e.

$$\pi_1 = \varphi(\pi_2) \qquad (8)$$

Also π_1 and π_2 is expressed in the power function form to get relation between dimensionless arguments in Xcel as follows:

$$\pi_1 = A\pi_2{}^B \qquad (9)$$

4. EXPERIMENTAL ANALYSIS

Table3:- Parameters and their values obtained from online measurements

Slno.	Qa (m3/s)	ṁc (kg/s)	Ta (k)	PB (kgm2/s3)	QC (m2/s2)	NOx (kg/m3)
1	81.6326531	9.75	531	80000000	23250000	0.000314262
2	81.6326531	11.22	535	81100000	23250000	0.000314262
3	79.3632653	10	532	80400000	23250000	0.000324984
4	78.0081633	9.722	532	80300000	23250000	0.000319602
5	78.0081633	9.444	533	80000000	23250000	0.00031837
6	76.4163265	9.167	533	80000000	23250000	0.000310154
7	104.734694	13.33	541	118000000	23250000	0.000353288
8	107.673469	13.83	554	117000000	23250000	0.000345072
9	114.938776	15.06	561	123000000	23250000	0.000361504
10	73.6979592	3.222	529	58300000	23250000	0.000425178
11	72.5632653	3	535	56200000	23250000	0.000422302
12	74.8326531	2.689	537	56000000	23250000	0.000396627
13	73.9265306	2.719	536	56000000	23250000	0.000398065
14	74.6040816	2.939	539	56000000	23250000	0.000408746
15	112.489796	11.94	540	125000000	23250000	0.000429286
16	111.346939	13.25	536	127000000	23250000	0.000314262
17	113.387755	11.94	536	130000000	23250000	0.000330694
18	68.4816327	3.639	543	62000000	23250000	0.000435243
19	68.7102041	3.889	535	62000000	23250000	0.000443828
20	68.4816327	3.528	531	62000000	23250000	0.00044161
21	67.1183673	3.722	534	62000000	23250000	0.000453934
22	84.1632653	5.361	524	73000000	23250000	0.000449826
23	68.7102041	5.25	543	77000000	23250000	0.000414908
24	84.3265306	5.25	533	81000000	23250000	0.000425178
25	84.1632653	5.25	566	81000000	23250000	0.000414908
26	110.693878	13.61	527	121000000	23250000	0.000365612
27	78.6857143	14.44	559	81500000	23250000	0.00033891
28	116.571429	13.89	538	130000000	23250000	0.000361504

5. RESULTS OBTAINED

Dimensionless arguments π_1 and π_2 is computed by substituting values from table 3 onto equations in 7

Table4:- Dimensionless arguments and their values

Sl.no	π_1	π_2
1	0.002631184	2.83359375
2	0.002286456	3.216584464
3	0.002579178	2.891791045
4	0.002564451	2.814900374
5	0.002629761	2.7446625
6	0.002585451	2.664159375
7	0.002775807	2.626461864
8	0.002686558	2.748269231
9	0.002759019	2.846707317
10	0.009725249	1.284931389
11	0.010214547	1.241103203
12	0.011037814	1.116415179
13	0.010822942	1.128870536
14	0.010375679	1.220209821
15	0.004044413	2.22084
16	0.002640914	2.425688976
17	0.003140423	2.135423077
18	0.008190746	1.364625
19	0.007841485	1.458375
20	0.008572045	1.323
21	0.008185736	1.39575
22	0.007061896	1.707441781
23	0.005430174	1.585227273
24	0.006829293	1.506944444
25	0.006651431	1.506944444
26	0.002973623	2.615144628
27	0.001846771	4.119386503
28	0.003033912	2.484173077

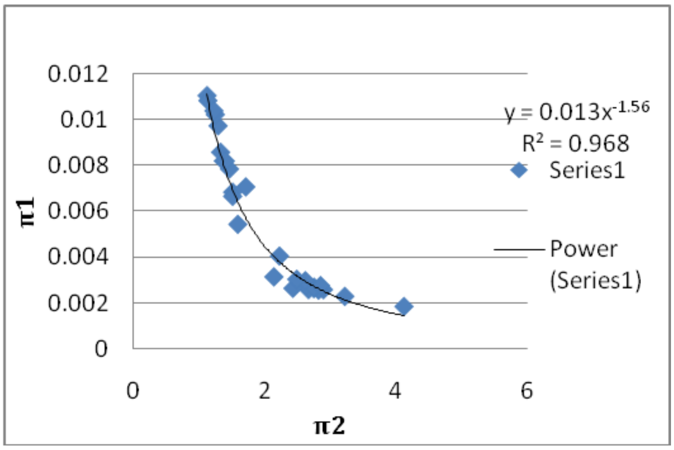

Fig -1: plot of π_1 vs. π_2

From fig 1 we obtain the values of A and B of equation9 as

A= 0.013

B= -1.56

Substituting A and B in eqn 9 we get the formula for NOx (kg/m³) as below:

$$\pi_1 = 0.013\pi_2^{-1.56} \qquad (10)$$

$$\left(\frac{Q_a * NO_x}{\dot{m}_c}\right) = 0.013\left(\frac{\dot{m}_c * Q_C}{P_B}\right)^{-1.56} \qquad (11)$$

$$NOx(kg/m^3) = 0.013 * \frac{\dot{m}_c^{-0.56}}{Q_a} * \left(\frac{Q_u}{P_B}\right)^{-1.56} \qquad (12)$$

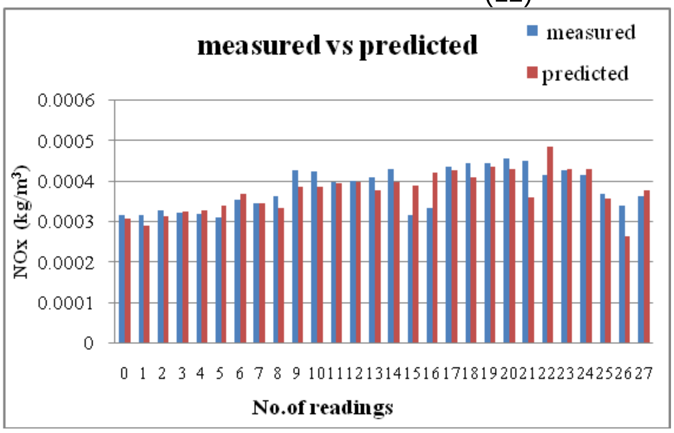

Chart -1: Measured NOx vs. Predicted NOx

Table 4:- Measured NOx vs. Predicted NOx values and their errors

Sl.no	NOx measured (kg/m³)	NOx predicted (kg/m³)	Error (%)
1	0.000314262	0.0003058	2.692671
2	0.000314262	0.000288759	8.11507
3	0.000324984	0.000312538	3.829555
4	0.000319602	0.000322401	-0.8757
5	0.00031837	0.000325774	-2.32562
6	0.000310154	0.000338151	-9.02677
7	0.000353288	0.000366829	-3.83294
8	0.000345072	0.000344925	0.042673
9	0.000361504	0.000333063	7.867288
10	0.000425178	0.00038438	9.595523
11	0.000422302	0.000383714	9.137659
12	0.000396627	0.0003934	0.813593
13	0.000398065	0.000395756	0.580135
14	0.000408746	0.000375442	8.147921
15	0.000429286	0.000397436	7.41921
16	0.000314262	0.000388274	-23.551
17	0.000330694	0.000419167	-26.7536
18	0.000435243	0.000425334	2.276476
19	0.000443828	0.000408436	7.974311
20	0.00044161	0.000432777	2.000115
21	0.000453934	0.000428527	5.597018
22	0.000449826	0.000359424	20.09712
23	0.000414908	0.000484104	-16.6774
24	0.000425178	0.000426881	-0.40052
25	0.000414908	0.000427709	-3.08526
26	0.000365612	0.000356767	2.419256
27	0.00033891	0.000262105	22.66225
28	0.000361504	0.000374602	-3.62312

6. CONCLUSION

Modelling of NOx emissions from a 150 MW power plant, based on dimensional analysis has been done. The predicted value goes well in accord with the measured values and it has been tabulated in table 4 along with the errors. In four cases error has risen by more than ±10% and it can be attributed to the error incurred while taking the online observations. During the equation formulation based on dimensional analysis one can observe that the variable combustion temperature gets excluded. As already stated above even if the parameter gets excluded it's effected will be reflected through the other parameters which makes the model.

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REFERENCES

[1] Maria Camogurska, "*Modelling of nitrogen oxides formation applying dimensional analysis*," Chemical and Process Engineering. Vol.32 (3) pp.175-184, 2011.

[2] M.A.Habib and M.Elshafei. "*Influence of combustion parameters on NOx production in an industrial boiler*." Science Direct, Computers and fluids37, pp 12 – 23, 2008.

