EXPERIMENTAL INVESTIGATIONS, REGRESSION AND COMPUTATIONAL, MODELING AND ANALYSIS OF EFFICIENT AND EFFECTIVE TECHNIQUES FOR FUEL/ENERGY CONSERVATION IN IRON FOUNDRIES

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ABSTRACT

This paper deals with development of efficient and effective techniques for fuel/energy conservation in iron foundries. The authors conducted series of experimental investigations on a self-designed and developed 200kg LDO fired rotary furnace installed in a foundry.

Initially the furnace was operated as under existing conditions. The specific fuel consumption was 0.415 liters/kg and energy consumption was 4.110 kwh/kg. The technique of oxygen enrichment and reducing combustion volume was applied. Initially the 6.9% oxygen enrichment of 75% of theoretically required air, and later on 7.5-8.5% oxygen enrichment of 60-65% of theoretically required air was done which lead to specific fuel consumption of 0.208 liters/kg and specific energy to 2.0403 kwh/kg. This effective technique significantly reduced specific fuel and energy consumption by 53.855% and 53.863% respectively

The modeling and regression analysis of oxygen consumption per heat has been carried out.The average and percentage variations between experimentally investigated and calculated values of fuel consumption are within acceptable range of±5% hence are acceptable.

Keywords Rotary furnace, Excess air percentage, Preheated air temperature, Oxygen enrichment, Mat lab, Energy consumption.

1. Introduction

The present exercise is an attempt in energy conservation in ferrous foundries through experimental investigations and regression and computational, modeling and analysis of oxygen enrichment of combustion volume of rotary furnace. In rotary furnace for melting of cast iron, the input parameters are (1) charge weight, (2) fuel (LDO), (3) flame temperature, (4) Preheated air volume, (5) Preheated air temperature, (6) Duration of a particular heat.(7)oxygen consumption. These parameters need to be controlled for optimal specific fuel and energy consumption. Figure-1 shows the layout of a rotary furnace and its accessories.

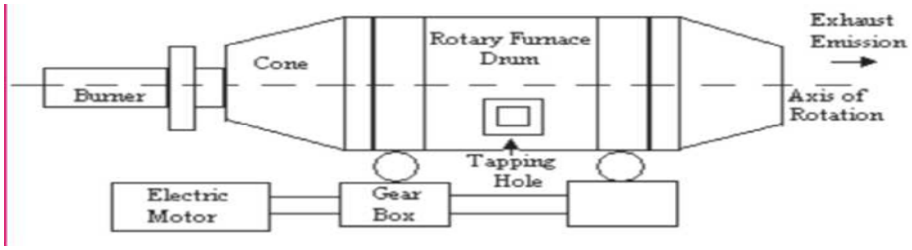

Fig. 1: Layout of Rotary furnace.

2. Melting Operation

The process of melting the charge in rotary furnace is carried out in the following steps:

(i) Preheating of oil and furnace-

(ii) Charging– After pre heating, the furnace is charged.

(iii)Rotation-After sufficient pre heating and charging, the furnace is rotated at desired speed.

(iv) Melting- The flame starts coming out of the exit end, which is initially yellowish in colour. After approximately 1 hour, the colour of flame changes to white indicating that metal has been thoroughly melted. The temperature of the molten metal is measured using pyrometer. If it is approximately 1250 to 1300°C, the rotation of furnace is stopped.

(v) Tapping-The tape hole is slightly lowered and opened and metal is transferred into ladles, which are pre heated prior to the transfer of molten metal to avoid heat losses.

(vi) Inoculation-The Ferro silicon and Ferro manganese approx. 600 grams per heat are added in molten metal contained in the ladles.

(vii)Pouring –The ladles are then carried to moulds and pouring is completed

3. Experimental investigations

The series of experimental investigations conducted are given in subsequent sections

(1) Operating furnace under existing conditions of operation

the furnace was operated under existing conditions of operation without oxygen enrichment. The charge per heat is 200.0 kg. In first heat, as furnace was started from room temperature, the melting time, fuel and energy consumption were more. In subsequent heats, the melting time, fuel and energy consumption were reduced. 1liter of LDO is equivalent to 9.9047kwh/kg of energy. Observations are given in table 1.

S N	Heat no	Rpm	Time min	Fuel liters	Specific Fuel (lit/kg)	Melting Rate (kg/hr)	Flame temp.°C	Preheated air cons. m^3	Energy consumption kwh/kg
1	1	2.0	50.0	92.0	0.460	240.0	1310.0	1320.0	4.556
2	2	2.0	47.0	90.0	0.450	255.3	1314.0	1290.0	4.457
3	3	2.0	46.0	87.0	0.435	260.8	1325.0	1240.0	4.308
4	4	2.0	46.0	86.0	0.430	266.0	1334.0	1220.0	4.259
5	5	2.0	45.0	83.0	0.415	266.0	1350.0	1175.0	4.110

Table 1- Specific fuel and energy consumption of furnace under existing conditions of operations without oxygen enrichment of combustion volume

Graphical representation

the graphical representation of energy consumption under existing conditions of operation is shown in figure 2

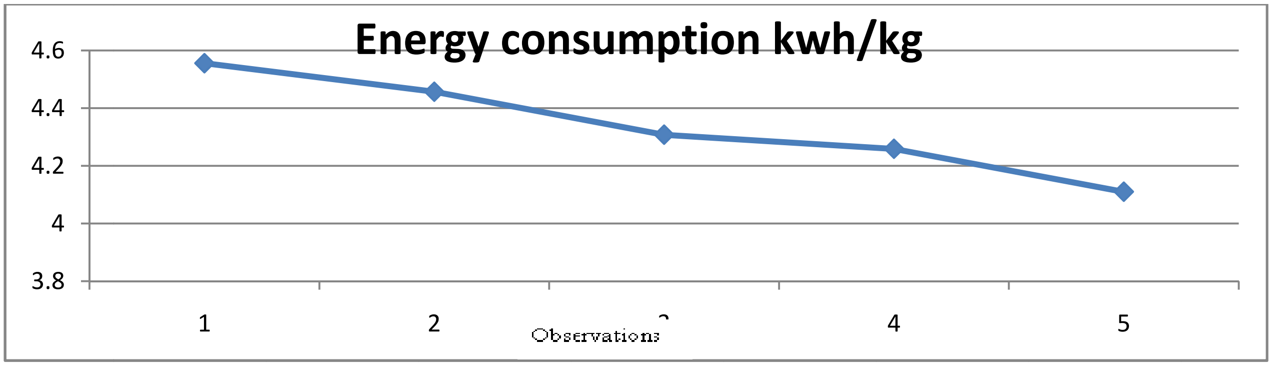

Fig. 2- The graphical representation of energy without oxygen enrichment of combustion volume

(2) Effective techniques -Oxygen enrichment of combustion volume

If the combustion volume is more than more fuel and time shall be required for reaching to a certain temperature. Hence it is thought to optimize the combustion volume by reducing the amount of air and supplying oxygen externally. Several experiments were conducted, gradually reducing air to its theoretical requirement and even lesser in steps of 5.0 to 10.0% and supplying oxygen externally in steps of 1.0 to 2.0 % and its effect on flame temperature, time, fuel, melting rate, and fuel consumption was studied. The effect was significant only when air was reduced to 75.0% of its theoretical requirement and approx.7.0% oxygen was supplied externally.

(i)Effect of 6.9% oxygen enrichment of combustion volume

The data on preheated air temperature, flame temperature, time of heat, fuel consumption /heat, oxygen consumption/heat, preheated air consumption/heat and melting rate were collected from self designed and developed rotary furnace operating in a ferrous foundry. Charge weight in each heat was 200kg. The 6.9%oxygen enrichment of 75.3-75.4% of combustion volume is made to reduce the specific fuel and for energy conservation. The relevant observations are presented in Table-2.

Sn	Preheat air temp °C	Flame temp °C	Time/ Heat Min	Fuel consumption Liters	Melting rate Kg/hr	Sp.Fuel Consumption Lit./kg	Preheat air vol. m^3	Oxygen Consumption /heat m^3	Energy consumption kwh/kg
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	Y	
1	410	1710	33	56	363	0.280	459.5	39.0	2.7733
2	418	1722	32	56	375	0.280	459	39.0	2.7733
3	428	1730	32	55	375	0.275	451	38.5	2.7237
4	449	1746	31.5	54	385	0.270	443	38.0	2.6742
5	454	1752	31	53	387	0.265	434.5	37.0	2.6247
6	458	1754	30.5	52	393.44	0.260	426.7	36.6	2.5752
7	460	1755	30.5	52	393.44	0.260	426.5	36.5	2.5752

Table2- Experimental oxygen consumption (6.9%oxygen enrichment of 75.3-75.4%) of theoretically required preheated air and its affect on inputs

Graphical representation

the graphical representation of effect of 6.9% oxygen enrichment of combustion volume on energy consumption is shown in figure 3

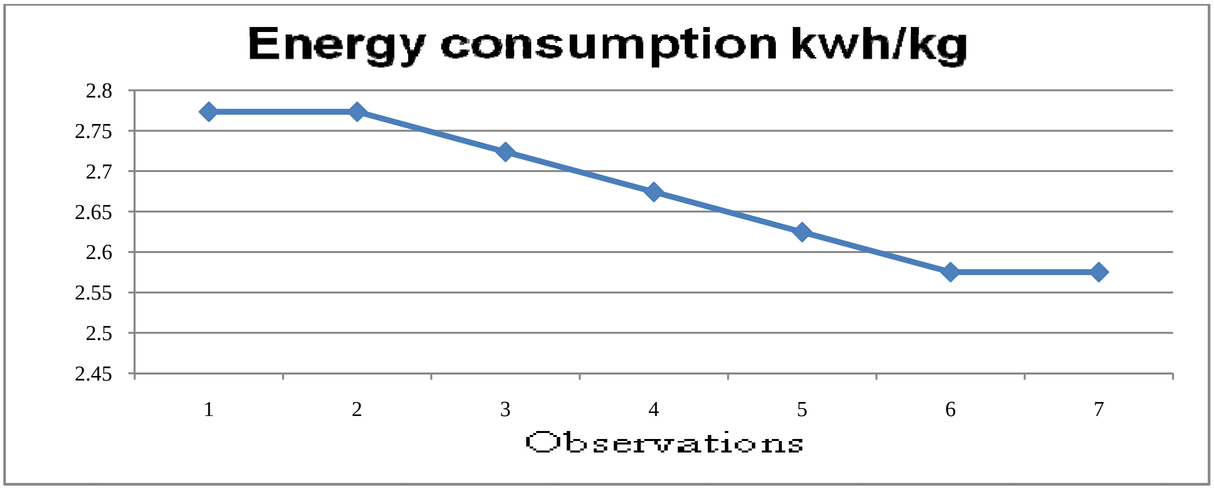

Figure 3- The graphical representation of energy consumption with 6.9% oxygen enrichment of combustion volume

3. Industrial Results and Modeling

Statistical methods such as cluster analysis, pattern recognition, design of experiments, factor analysis, and regression analysis are some of the statistical techniques which enable one to analyze the experimental data and build empirical models to obtain the most accurate representation of physical situations

(i)Development of model 1(Table 1)

The oxygen enrichment has been taken as output parameter Y, and all other parameters viz. excess air, preheated air temperature, fuel/heat; time/heat etc. has been taken as input parameters. X= f[x_1, x_2, x_3, x_4, x_5 x_6 x_7]. Regression modeling as given in matrices of MATLAB 7.0 is used. Oxygen consumption is function of all input parameters and can be expressed as

O_2=f[(preheated air temp)(flame temp.)(Time)(Fuel)(Melting rate)(Specific fuel)(Preheated air volume)]

Mathematically it can be represented as

$$O_2 = C_0 (PHAT)^{C_1} (FT)^{C_2} (T)^{C_3} (F)^{C_4} (MR)^{C_5} (SF)^{C_6} (PHAV)^{C_7} \text{----------} (1)$$

or

$$\ln[O_2] = \ln C_0 + C_1 \ln(PHAT) + C_2 \ln(FT) + C_3 \ln(T) + C_4 \ln(F) + C_5 \ln(MR) + C_6 \ln(SF) + C_7 \ln(PHAV) \text{----------} (2)$$

Where C_0, C_1, C_2, C_3, C_4, C_5, C6 and C_7 are constants to be determined using Mat lab. The following steps are followed in **MATLAB;** the first column is always taken as unity.

1. Output melting rate [Y] and inputs [X] were converted in natural log terms

2 X^T=Transpose of [X] was determined.
3 X^T Transpose of [X] was multiplied with [X] to get the product [X^T X].
4. The inverse of product [X^T X] = $[X^T X]^{-1}$ was obtained.
5. X_t Transpose of [X] was multiplied with output Y to get the product=[$X^T Y$]
6. Step 4 $[X^T X]^{-1}$ was multiplied with step 5 [X^T Y] to obtain the product of$[X^T X]^{-1}$and [X^T Y].The final matrices is of the form

β_o constant C_o =antilog β_o
β = β_1 $C_1 = \beta_1$
β_2 $C_2 = \beta_2$
β_3 $C_3 = \beta_3$
β_4 $C_4 = \beta_4$
β_5 $C_5 = \beta_5$
β_6 $C_6 = \beta_6$
β_7 $C_7 = \beta_7$

The values are β_o =6.6118, β_1 = - 0.2926, β_2 = 0.5508, β_3 = - 0.2240, β_4 =-0.1386, β_5 = -.0689644, β_6=0.0000010, β_7= 0.0406391.

The values of constants are
C_o =antilog β_o = -40.172189, C_1= β_1=-0.009366, $C_2 = \beta_2$ =0.0000105., $C_3 = \beta_3$ = 0.7527703.
$C_4 = \beta_4$ =--2.7395490, $C_5 = \beta_5$ = --0.0689644, $C_6 = \beta_6$=0.0000010, $C_7 = \beta_7$= 0.0406391.
Putting these values in eqn. (1)
$[O_2]= C_o (PHAT)^{C_1} (FT)^{C_2} (T)^{C_3} (F)^{C_4} (MR)^{C_5} (SF)^{C_6} (PHAV)^{C_7}$
$\mathbf{[O_2]= -40.172189(PHAT)^{-0.009366}(FT)^{0.0000105}(T)^{0.7527703}(F)^{--2.7395490}(MR)^{--0.0689644}(SF)^{0.0000010} (PHAV)^{0.0406391}}$
---------------------------(3)

(ii) Testing of model 1- Comparison of experimental and modeled values of 6.9%oxygen enrichment of 75.3-75.4% of theoretically required preheated air

The model developed is tested and comparison of actual experimental results and modeled results of oxygen consumption/heat of 6.9%oxygen enrichment of 75.3-75.4% of theoretically required preheated air is given in Table3.

Sn	Experimental values	Modeled value	Actual variation	% variation
1	39.0	38.9951	-0.0049	-0.012564
2	39.0	39.000161	+0.000161	+0.0004128
3	38.5	38.39430	-0.1057	-0.2745454
4	38.0	38.00910	+0.00910	+0.023947
5	37.0	36.99900	-0.000999	-0.0027
6	36.6	36.60098	+0.00098	+0.00267
7	36.5	36.5002375	+0.5002375	+1.37051

Table3-Comparison of actual experimental values and modeled values of oxygen consumption/heat
Maximum variation =+0.5002375, Maximum% variation=+1.37051, Average variation =+0.0549256, Average % variation =1.1077304

The comparison of experimental oxygen consumption and modeled oxygen consumption (table 2) is shown in Fig.4.

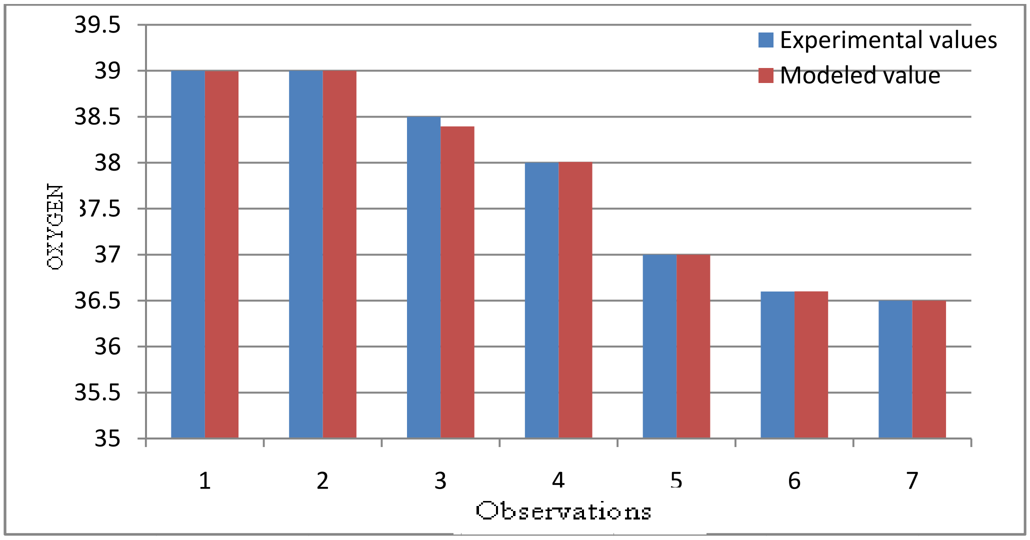

Fig 4- Comparison of experimental and modeled 6.9 %oxygen enrichment (table 2)

4. Results

the average variation is +0.0157331 and the average percentage variation between experimental and modeled values of oxygen enrichment of combustion volume is. It is within permissible limits hence acceptable.

5. Further Expérimental investigations- Increasing Oxygen enrichment of combustion volume

Again the experiment was continued, further reducing volume of air to (60 -65)% of its theoretical requirement and increasing additional oxygen supply to 7.5%- 8.5 %, maintaining the with same charge of 200.0 kg. The experiment was conducted, operating furnace in similar conditions in consecutive heats..The observations taken during experiment are given in table 4

Heat No	Preheated air temp °C	Flame Temp °C	Time Min.	Fuel liter	Melting rate kg/hr	Specific fuel cons. lit/kg	Preheated air consumption m^3	Oxygen consumption m^3	Energy consumption kwh/kg
1	424.0	1745.0	32.0	48.0	375.00	0.240	319.0	49.3	2.3771
2	430.0	1752.0	32.0	47.0	375.00	0.235	319.0	49.0	2.3276
3	437.0	1755.0	32.0	46.5	375.00	0.232	317.0	48.0	2.2978
4	448.0	1762.0	31.5	45.8	380.95	0.229	313.0	46.8	2.2681
5	465.0	1770.0	31.0	45.0	387.00	0.225	310.0	46.0	2.2285
6	470.0	1772.0	30.5	44.6	393.44	0.223	309.0	45.0	2.2087
7	472.0	1773.0	30.5	43.8	393.44	0.219	302.0	45.0	2.1691
8	474.0	1776.0	30.4	42.9	394.73	0.214	297.0	43.0	2.1196
9	475.0	1778.0	30.1	42.0	398.67	0.210	295.0	41.5	2.0799
10	476.0	1778.0	30.1	41.6	398.67	0.208	294.0	40.0	2.0403

Table4- Experimental oxygen consumption (7.5%- 8.5 %, oxygen enrichment 60 -65% of theoretically required preheated air and its affect on inputs

(i)Graphical representation

the graphical representation of effect of7.5%- 8.5 %, oxygen enrichment of combustion volume on energy consumption is shown in figure 5

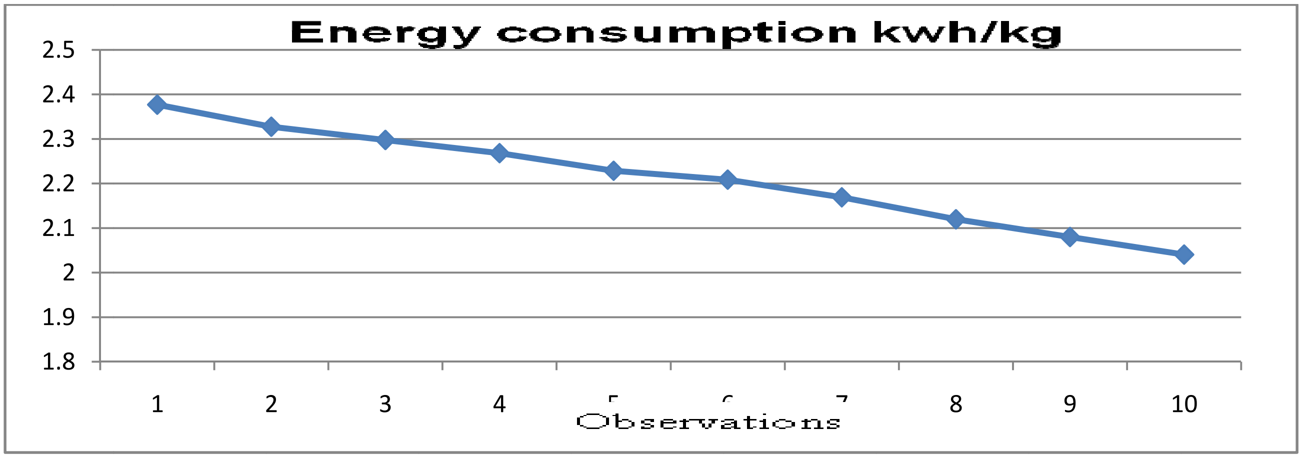

Figure 5- The graphical representation of energy consumption with 6.9% oxygen enrichment of combustion volume

(ii) Development of model 2

following exactly the similar steps, the values of constants are

C_o =antilog β_o =2.1914×10^{-241}, $C_1 = \beta_1 = -0.1041$, $C_2 = \beta_2 = 8.77$, $C3 = \beta_3 = 54.1816$, $C_4 = \beta_4 = 0.4769$
$C_5 = \beta_5 = 52.9360$, $C_6 = \beta_6 = 2.1878$, $C_7 = \beta_7 = -1.2217$.

Putting these values in eqn. (1)

$[O_2] = C_0 (PHAT)^{C1} (FT)^{C2} (T)^{C3} (F)^{C4} (MR)^{C5} (SF)^{C6} (PHAV)^{C7}$

$[O_2] = 2.1914 x 10^{-241} (PHAT)^{-0.1041} (FT)^{8.77} (T)^{54.1816} (F)^{0.4769} (MR)^{52.9360} (SF)^{2.1878} (PHAV)^{-1.2217}$ -------------- (4)

(iii)Testing of model 2 -Comparison of experimental and modeled values of 7.5-8.5% oxygen enrichment of 60 % of combustion volume

The model developed is tested and comparison of actual experimental and modeled results of oxygen consumption/heat of 7.5-8.5% oxygen enrichment of 60 % of theoretically required preheated air is given in Table 5

Sn	Experimental values	Modeled value	Actual variation	% Variation
1	49.3	49.5491	+0.2491	+0.50527
2	49.0	48.4489	-0.5511	-1.12469
3	48.0	47.8613	-0.1387	-0.288958
4	46.8	47.4884	+0.6884	+1.47094
5	46.0	45.9849	-0.0151	-0.032826
6	45.0	45.1453	+0.1453	+0.32288
7	45.0	44.4406	-0.5594	-1.243111
8	43.0	43.1141	+0.1141	+0.265348
9	41.5	41.2142	-0.2858	-0.688674
10	40.0	40.3347	+0.3347	+0.83675

Table 5 -Comparison of actual experimental and modeled results of oxygen consumption/
The average Actual variation is-0.0185 and percentage variation is +0.022359

(iv)Graphical representation

The comparison of experimental oxygen consumption and modeled oxygen consumption (table4) is shown in Fig. 6

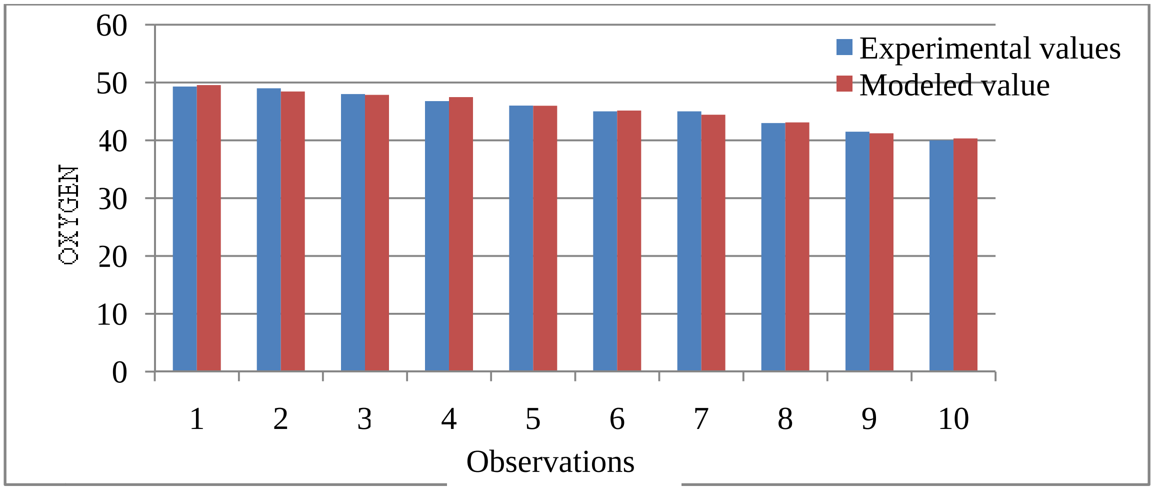

Fig 6 Comparison of experimental and modeled 7.5%- 8.5 %, oxygen consumption (table4)

6. Modeling using regression analysis

The another model is developed for fuel consumption using regression analysis as given in subsequent sections

(i) Effect of 7.5%- 8.5 %, oxygen enrichment of combustion volume on specific fuel

The graphical representation of effect of oxygen enrichment of combustion volume (m^3) on specific fuel consumption as per observed values table3 is shown in fig 7

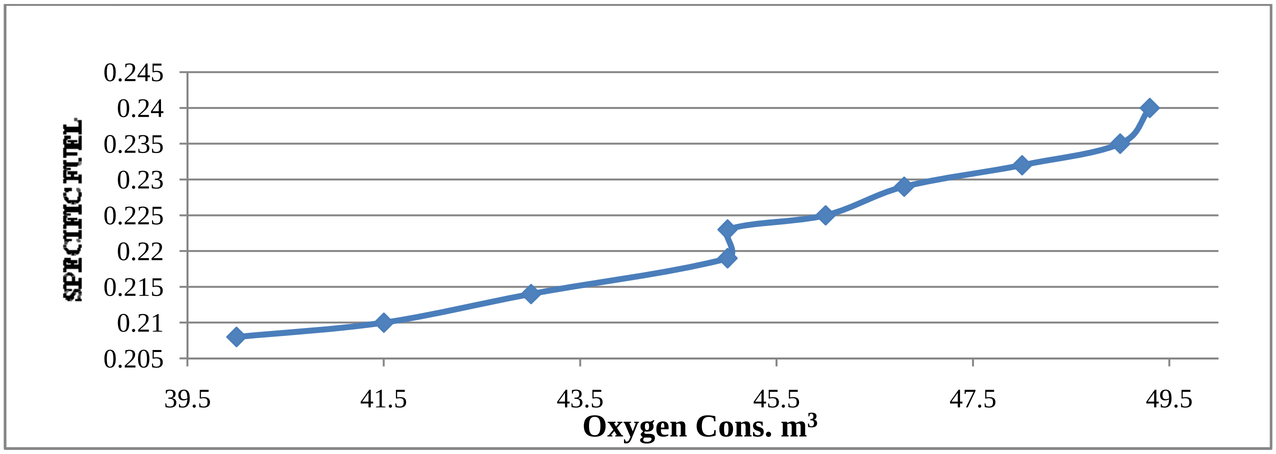

Fig 7 The graphical representation of effect of oxygen (m^3) on specific fuel consumption

Calculations

The calculations of oxygen and specific fuel consumption are given in table6–Y= specific fuel consumption, X= oxygen consumption

Sn	X	$x=X-\bar{x}$	x^2	Y	$y=Y-\bar{y}$	y2	xy
1	49.3	3.94	15.5236	0.240	0.0165	0.00027225000	0.06501
2	49	3.64	13.2496	0.235	0.0115	0.00013225000	0.04186
3	48	2.64	6.9696	0.232	0.0085	0.00007225000	0.02244
4	46.8	1.44	2.0736	0.229	0.0055	0.00003025000	0.00792
5	46	0.64	0.4096	0.225	0.0015	0.00000225000	0.00096
6	45	-0.36	0.1296	0.223	0.0005	0.00000025000	0.00018
7	45	-0.36	0.1296	0.219	0.0045	0.00002025000	0.00162
8	43	-2.36	5.5696	0.214	0.0095	0.00009025000	0.02242
9	41.5	-3.86	14.8996	0.21	0.0135	0.00018225000	0.05211
10	40	-5.36	28.7296	0.208	0.0155	0.00024025000	0.08308
∑	453.6	0.00	87.684	2.235	-5.6E-17	0.00104250000	0.2976

Table.6 – The calculations of oxygen and specific fuel consumption. $\bar{x}$=45.36, $\bar{y}$=0.2235
Regression equation of specific fuel consumption vs. oxygen consumption.

X is oxygen, Y is specific fuel. Equation of Y on X
$(Y - \hat{y}) = b_{yx} (X - \hat{x})$ $\hat{y} = 0.2235$, $\hat{x} = 45.36$

$Y - 0.2235 = b_{yx} (X - 45.36)$ ------------------- (4)
Where $b_{yx} = r\frac{\sigma y}{\sigma x} = \frac{\Sigma xy}{\Sigma x^2} = \frac{0.2976}{87.684} = 0.003394$, Putting it in (1)

$Y - 0.2235 = 0.003394 (X - 45.36)$ ------------------- (5)
Or $Y = 0.003394 X + 0.069548$---------- (6)

Specific fuel consumption = 0.003394 (oxygen) +0.069548------(7)

Testing of model – developed by regression analysis
The calculated values, (by reregression equation) observed values, variation and % variation of specific fuel based on oxygen consumption, are given in table 7

Sn	X	Yobse- -rved	Y calculated	Variation	% Variation
1	49.3	0.240	Y=0.003394(49.3)+0.069548= 0.236872	− 0.003128	− 1.320%
2	49.0	0.235	Y=0.003394(49)+0.069548 = 0.235854	+.000854	+0.3621%
3	48.0	0.232	Y = 0.003394(48) +0.069548 = 0.23246	+0.00046	+0.19788%
4	46.8	0.229	Y 0.003394(46.8) +0.069548 = 0.22838	− 0.006128	− 0.2683%
5	46.0	0.225	Y = 0.003394(46) +0.069548 = 0.22567	+0.000672	+ 0.29777%
6	45.0	0.223	Y = 0.003394(45) +0.069548 = 0.222278	−0.000722	−0.324818%
7	45.0	0.219	Y = 0.003394 (45) +0.069548 = 0.222278	0.0003278	+0.01474%
8	43.0	0.214	Y = 0.003394 (43) +0.069548 = 0.21549	+0.00149	+0.69144%
9	41.5	0.21	Y = 0.003394(41.5) +0.069548 = 0.210399	+0.000399	+0.189639%
10	40	0.208	Y = 0.003394(40) +0.069548 = 0.205308	−0.002692	−1.310%

Table 7-The calculated values, observed values, variation, % variation of specific fuel based on oxygen consumption using regression analysis

8. Results: The average variation= **+0.0003717**, the average % variation= **−0.14695%**
The variation of observed values and calculated values of specific fuel, based on oxygen consumption, as per regression analysis are more clearly presented in figure 8 where blue line represents its observed values and red line the calculated values-

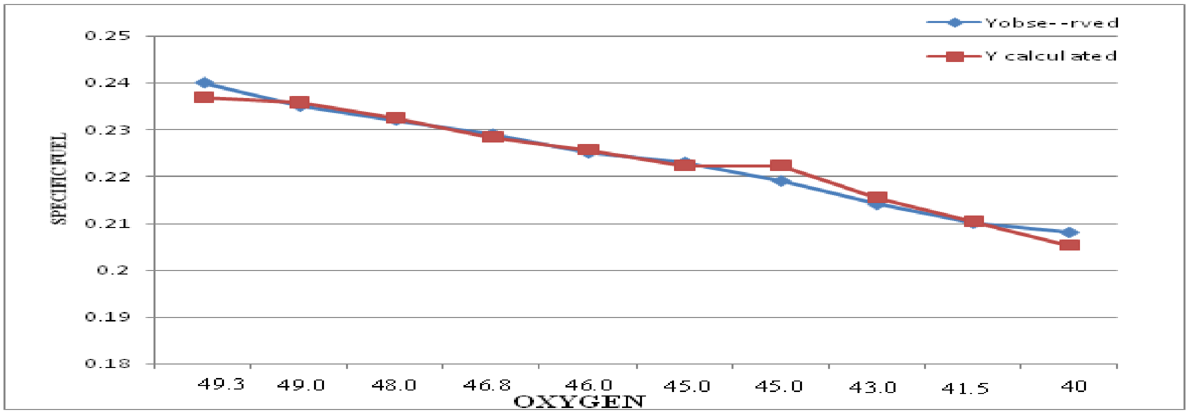

Fig 8-The observed and calculated values of spec. fuel based on oxygen consumption, table 5

The prediction of specific fuel consumption based on oxygen consumption is given in table 8-

Sn	Predictor	Regression coefficient	Regression Equation
1	Specific fuel consumption	b_{yx} = 0.003394	Y= 0.003394X +0.069548 Specific fuel=0.003394(oxygen consumption +0.069548

Table 8- The prediction of specific fuel consumption based on oxygen consumption

From figure 8 and tables, it is evident that the variation between calculated values and observed values of Spec. fuel based on oxygen consumption is -0.14695%. It is within acceptable range of ± 5%, hence the regression analysis and regression equations, are acceptable.

9. The summarized results

The result are summarized below-

(a) The comparison of experimental and modeled oxygen consumption are given in table 9

6.9% oxygen					7.5%- 8.5 %, oxygen		
Sn	Output parameter	Experimental	Modeled (Mat lab)	% variation	Experimental	Modeled (mat lab)	% variation
1	Average oxygen consumption.m^3	37.8	37.78552	0.0383	45.36	45.3185	0.0914

Table 9 -The comparison of experimental and modeled oxygen consumption

(b) The comparison of specific fuel (lit/kg) and energy (kwh/kg/) consumption on experimental investigations, (using effective technique) are given in table 10

Sn	Output parameter	Operating under existing conditions	Operating furnace by6.9% oxygen enrichment of combustion volume	Operating furnace by 7.5%- 8.5 %, oxygen enrichment of combustion volume	Absolute reduction	Percentage reduction
	Specific Fuel	0.415	0.2707	0.2235	0.1915	53.855
	Specific Energy	4.110	2.68120	2.2137	1.8962	53.863

Table10–The comparison of specific fuel (lit/kg) and energy (kwh/kg/) consumption based on experimental investigations only

(c) The comparison of specific fuel (lit/kg) and energy (kwh/kg/) consumption based on experimental investigations(using effective technique) and regression-modeling are given in table 10

Sn	Output parameter	Operating under existing conditions	Operating furnace by 6.9% oxygen enrichment of combustion volume	Operating furnace by 7.5%- 8.5 %, oxygen enrichment of combustion volume	Regression Modeling 7.5%- 8.5% oxygen enrichment of combustion volume	%variation Experimental and /Regression modeling
	Specific Fuel	0.415	0.2707	0.2235	0.22349	0.004474
	Specific Energy	4.110	2.68120	2.2137	2.21360	0.0045173

Table10 -The comparison of specific fuel (lit/kg) and energy (kwh/kg/) consumption based on experimental investigations and regression-modeling

(d)The graphical representation of effect of oxygen enrichment of combustion volume on fuel conservation is shown in figure9 and on energy conservation in figure 10

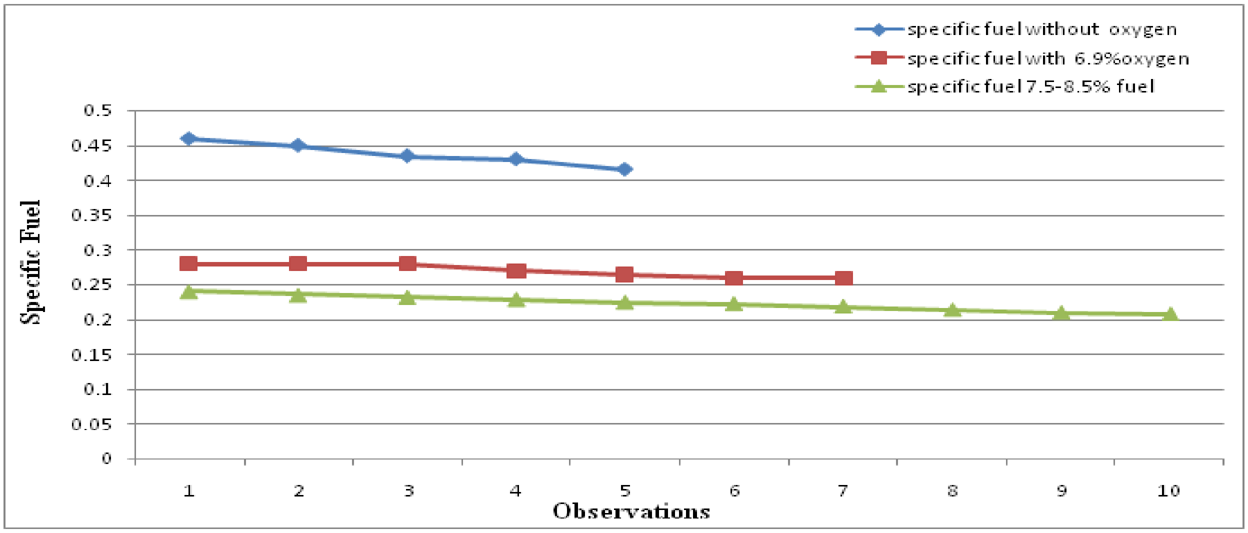

Figure 9- effect of oxygen enrichment of combustion volume on specific fuel conservation

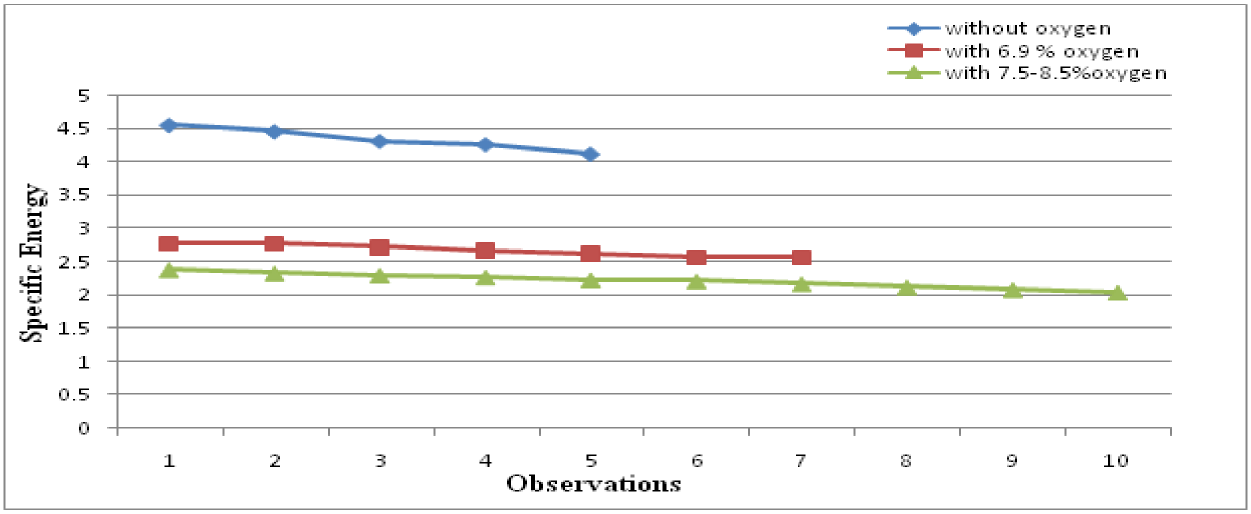

Figure 10 -effect of oxygen enrichment of combustion volume on specific energy conservation

10. Conclusions

on basis of above experimental investigations, regression, computational modeling and analysis, the following conclusions are drawn

(1)The oxygen enrichment and reducing of combustion volume significantly reduces the specific fuel/energy consumption. The minimum specific fuel consumption was0.415 liter/kg, without oxygen enrichment which reduce to 0.260 liter/kg with 6.9% and then to 0.208 liter/kg with 7.5-8.5% oxygen enrichment.
(2) The oxygen consumption/heat has been optimized using computational technique (Mat lab). The average and percentage variations between experimentally investigated and modeled value for 6.9% oxygen enrichment are +0.0549256 and +1.1077304,and for 7.5-8.5% oxygen enrichment are -0.0185 1nd +0.022359% respectively. These variations are within acceptable range of±5% hence are acceptable. Computational technique (Mat lab) is capable of modeling the rotary furnace parameters with sufficient accuracy
(3)The statistical techniques (regression analysis) have been made for analysis of effect of 7.5-8.5% oxygen enrichment oxygen enrichment of combustion volume on specific fuel consumption. The average and percentage variations between experimentally investigated and calculated values of fuel consumption for 7.5-8.5% oxygen enrichment are +0.0003717 and-0.14695percentage respectively. Statistical technique (regressions analysis) is also capable of modeling the efficient and effective techniques with sufficient accuracy
(4) The oxygen enrichment and reducing combustion volume has proven to be an efficient and effective technique for fuel/energy conservation in iron foundries

Recommendations

the LDO fired rotary furnace, under these operating parameters is recommended for ferrous foundries for fuel/energy conservation.

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