Computer Simulation of The Heat Load Scrutiny For Best Use of Cupula Furnace

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Abstract : *The cupola is a cylindrical steel shell that handles over 90% of iron from a blast furnace in the conversion process to iron castings and steel manufacture. Operational efficiencies of cupola had been tagged to fluctuate between 30% and 50%. The thermal performance limits were mainly experimental. Hence the need for validation employing computer simulation approach. In this work, the cupola or cupolette was designed to handle one ton of charge per heat per day. Mathematical models had been developed by the researchers to validate the stipulation; in there titled "Heat Load Analysis for Optimal Use of Cupola Furnace In Iron Castings and Steel Manufacture" [10]. Alumina (Al_2O_3) refractory was employed as the lining for the furnace. The refractory and shell thicknesses were varied within a reasonable range. The results of the cupola computer simulation confirmed the maximum thermal efficiency of 19.81% when the thickness of the refractory material is 115mm, and steel shell thickness is 5mm. It is worthy to note that the employment of cupola of larger sizes, also simulating the refractory lining of different materials, could tremendously boost the performance of the cupola furnace.*
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Keywords: *Cupola, Blast furnace, Iron castings and steel manufacture, Operational efficiency, Alumina Refractory, computer simulation, and shell thicknesses.*

I. INTRODUCTION

A cupola is essentially a cylindrical steel shell employed in the smelting of scrap metals, and more or less 90% of pig iron used in the production of iron castings [1]. The operating efficiency of the cupola is very paramount. The available heating space is extremely affected by the thermal performance of the cupola furnace. The design and construction of cupola ensure maximum heat conservation and recovery in the workspace, which is a critical factor in its performance[10]. The performance efficiency improvement of the furnaces, as well as the cupola, the optimization of furnace lining thickness by determination of the critical radius of insulation and experimenting with different grades of refractory lining materials, should be considered [2,3,4,5,6].

In this research, only alumina refractory was used in the computational approach to determining the cupola thermal performance and other related parameters. A cupola could melt 15 tons of pig iron per hour, while a cupolette could handle one ton of charge, comprising of pig iron, scrap metal and steel, coke, and flux per heat per day [7, 10]. The available heat in the heating space should be of stringent consideration. The heat is the determinant factor for the operational, thermal, or performance efficiency of the cupola.

The approach to investigating the thermal efficiency of the cupola is through the development of mathematical models that balance the heat load in the different zones of the cupola. Preference would also be placed on the refractory material thickness viz-a-viz the thickness of the steel shell of the cupola.

II. Research Significance

The determination of cupola thermal performance largely has been inclined to design, construction, and experimental procedures. This research investigates the thermal performance concept of cupola through mathematical models development and computer simulation.

III. Relevant Mathematical models

Equation 1 to 25 was re-invoke from the mathematic model used by Briggs and Uzoma in their previous work on heat load analysis for a cupula furnace. The rate of heat transfer through the steel shell given as [10]:

$$\ddot{q}_{rm} = -\frac{2\pi k_2 L}{ln\frac{r_2}{r_1}}(T_2 - T_1) = -\frac{T_2 - T_1}{\frac{n\frac{r_{23}}{r_1}}{2\pi k_2 L}} \quad (1)$$

Heat transfer through the refractory material given as :

$$\ddot{q}_{rm} = -\frac{2\pi k_2 L}{ln\frac{r_2}{r_1}}(T_2 - T_1) = -\frac{T_2 - T_1}{\frac{n\frac{r_{23}}{r_1}}{2\pi k_2 L}} \quad (2)$$

Heat transfer by convection to the internal surface of the furnace lining could be represented as:

$$\hat{q}_{mr} = -h_m(2\pi r_1 L)\big((T_1 - T_m)\big) = -\frac{(T_1 - T_m)}{\frac{1}{2\pi r_1 h_m L}} \quad (3)$$

The heat transfer rate from the surface of the steel shell to the surroundings by convection could express as :

$$\hat{q}_{sa} = -h_a(2\pi r_3 L)\big((T_a - T_3)\big) = -\frac{(T_a 3T_3)}{\frac{1}{2\pi r_3 h_a L}} \quad (4)$$

Rearranging equations 1, 2, 3, and 4, and the expression for the inter-boundaries temperatures T_1, T_2, and T_3 are derived :

$$r_1 h_m T_1 + r_3 h_a T_3 = r_1 h_m T_m + r_3 h_a T_a \quad (5)$$

$$k_1 \ln\left(r_{\underline{3}} r_2\right) T_1 - \left[k_1 \ln\left(\frac{r_3}{r_2}\right) k_2 \ln\left(\frac{r_2}{r_1}\right)\right] T_2 + k_2 \ln\left(\frac{r_2}{r_1}\right) T_3 = 0 \quad (6)$$

$$r_1 h_m \ln\left(r_{3/} r_2\right) T_1 + k_2 T_2 - k_2 T_3 = r_1 h_m \ln\left(r_{3/} r_2\right) T_m \quad (7)$$

The rate of heat flow from the surface of the steel shell to the surrounding air given as[10] :

$$\ddot{q}_r = -\frac{(T_m - T_a)}{\frac{1}{2\pi r_1 h_m L} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L} + \frac{\ln\left(\frac{r_3}{r2}\right)}{2\pi k_2 L} + \frac{1}{2\pi r_3 h_a L}} = -\frac{2\pi L (T_m - T_a)}{\frac{1}{r_1 h_m} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r2}\right)}{k_2} + \frac{1}{r_3 h_a}} \quad (8)$$

The heat load of the system per day represented as :

$$Q_r = Q_{iron} + Q_{rcoke} + Q_{rfluxe} - Q_{RZ} + Q_{HOTAIR} - Q_{exhaust}$$

$$= \left(mc_p \Delta T\right)_{iron} + \left(mc_p \Delta T\right)_{coken} + \left(mc_p \Delta T\right)_{fluxn} + \rho_a \hat{V}_a C_{pair} \Delta T_{hotair} - \rho_{air} \hat{V}_a C_{pair} \Delta T_{exhaust} \quad (9)$$

A cupola or cupolette with the capacity of refining one ton of iron per heat per day has an iron-coke – flux ratio of 0.906: 0.091: 0.00362. On the mass basis of one ton, the ratio in kilogram becomes 906: 91: 3.62 [8, 10]. The heat load expression in Equation 13 can be re-expressed as :

$$Q_r = \left(906 \times C_p \Delta T\right)_{iron} + \left(91 \times C_p \Delta T\right)_{coken} + \left(3.62 \times C_p \Delta T\right)_{fluxn} + \rho_a \hat{V}_a \Delta T_{hotair} - \rho_{air} \hat{V}_a \Delta T_{exhaust} \quad (10)$$

different zones of the cupola being, the stack, the preheat zone, melting zone, reducing zone, combustion zone, and the well can be represented as H1, H_2, H_3, H_4, H_5, and H_6. The dimensional relationships and temperature distribution in the different zones, while the overall cupola height, H given as six meters is represented as follows [10] :

$$STACK, 0 \leq H1 \leq 1m, Temperature = 600^0C$$

$$PREHEATZONE 1m \leq H2 \leq 4m, " = 110^0C$$

$$MELTINGZONE 4m \leq H3 \leq 5m, " = 1600^0C$$

$$REDUCINGZONE 5m \leq H4 \leq 5.2m, " = 1200^0C$$

$$COMBUSTIONZPONE 5.2m \leq H5 \leq 5.6m, " = 1850^0C$$

$$WELL 5.6 \leq H6 \leq 6m, " = 1500^0C$$

The reactions in the reducing zone are endothermic. The average temperatures of the zones over their interfacial boundaries are given as below [10] :

$$\begin{bmatrix} \Delta T_{H1} = [400 - 28] = 380^0C \\ \Delta T_{H2} = [1100 - 28] = 1078^0C \\ \Delta T_{H3} = [1600 - 28] = 1578^0C \\ \Delta T_{H4} = [1850 - 28] = 1822^0C \\ \Delta T_{H5} = [1500 - 28] = 1472^0C \end{bmatrix} \quad (11)$$

Performing heat balance at the different zones :

(i) Stack zone

$$Q_{SZ} = \rho_{air} V_{rs} C_{pair} \Delta T_{H1} \quad (12)$$

(ii) Preheat zone

$$\ddot{Q}_{SZ} = \left(906 \times C_{piron} + 91 \times Cpcoke\rho + 3..62 \times C_{pflux}\right) \Delta T_{H2} \quad (13)$$

(iii) Melting zone

$$Q_{PHZ} = \left(906 \times C_{piron} + 91 \times Cpcoke\rho + 3.62 \times C_{pflux}\right) \Delta T_{H3} \quad (14)$$

(iv) Reducing zone

$$Q_{RZ} = \left(906 \times C_{piron} + 91 \times Cpcoke\rho + 3.62 C_{pflux}\right) \Delta T_{H4} \quad (15)$$

(iv) Combustion zone

$$Q_{CZ} = \left(906 \times C_{piron} + 91 \times Cpcoke\rho + 3.62 \times C_{pflux}\right) \Delta T_{H4} \quad (16)$$

The net amount of heat to melt a ton of the charge expressed as

$$Q_{NET} = Q_{PHZ} + Q_{MZ} + Q_{CZ} - Q_{RZ} + Q_{HOTAIR} - Q_{EXHAUST} \quad (17)$$

If C_{coal} (J/kg) is the calorific value of coal and the mass of coal consumed is m(kg), then the amount of heat provided for smelting operation could be given as :

$$\ddot{Q}_{coal} = \ddot{m} C_{coal} \quad (18)$$

The heat content of the hot air expressed as:

$$\ddot{Q}_{air} = \rho_{air} \ddot{V}_{air} C_{pair} \Delta T_{air} \quad (19)$$

Where,

$$\Delta T_{air} = T_{blast} - T_{exhaust} \quad (20)$$

The heat of formation of carbon dioxide is this expressed as:

$$C(s) + O_2(g) \rightarrow CO_2(g) \Delta H^0_{25^0C} = -\frac{94050 Cal}{mole} \quad (21)$$

Heat evolution due to the oxidation of iron to the highest oxidation state being Fe_2O_3 given as:

$$\Delta H^0_{Fe_2O_3} = -196500 cal/mole of Fe_2O_3 \quad (22)$$

The heat of formation of MnO per mole gave as:

$$\Delta H^0_{MnO} = -35209 Cal/mole \quad (23)$$

The heat of formation of SiO_2 per mole expressed as :

$$\Delta H^0_{SiO_2} = --88618 cal/mole \quad (24)$$

Based on the over-riding stipulated conditions, the thermodynamic efficiency of a cupola furnace system expressed as :

$$\eta_{th} = \frac{Heatutilizedinpreheating + melting + sup\,e\,rheating}{\begin{matrix} Heatduetocalorificvalueofcoke + Heatevolvedduetooxidationof \\ C, Fe, SiandMn + Heatcontentofairblast - Heatutilizedinthereducingzone - Exhaustheat \end{matrix}}$$

$$= \frac{Q_{PHZ} + Q_{MZ} + Q_{QZ}}{Q_{coke} + Q_{oxi} + Q_{hotair} - Q_{RZ} - Q_{exhaust}} \quad (25)$$

IV. INPUT PARAMETERS TO THE ALGORITHMIC CODING

Cupola or cupolette iron : coke : flux ratio = 0.906 : 0.091 : 0.0362

Considering one ton of charge the iron : coke : flux ratio in kilogram = 906 : 91 : 3.62

The charge constituents or compositions are depicted as follows :

%

Properties of constituents

C Si Mn P S

15% Pig Iron No 1 3.5 3.5

0.7 0.17 0.016

20% Pig Iron N0 2 3.5 3.0

0.65 0.11 0.030

30% New Scrap 3.4 2.3

0.5 0.2 0.035

35% returns (gate, risers, etc) 3.3 2.5

0.65 0.16 0.035

Iron Loss Due to Oxidation Reaction

Iron loss due to oxidation reaction is assumed to equal to the carbon that is absorbed in the process of refinement, and it is express as :

(Weight of metal charge)x(Proportion or fraction of constituent in the charge)x(Fraction of element in the charge).

% of carbon in the final analysis :
Pig iron No 1 : 906x(15/100)x0.035 = 4.7565kg
Pig iron No 2 : 906x0.2x0.035 =6.342kg
New scrap : 906x0.3x0.034 =9.2412kg
Returns : 906x0.35x0.033=10.4643kg
Total=30.804kg
% of carbon in the final analysis=(30.804/1000)x100=3.0804%
Iron loss to oxidation reaction=3.0804%=(3.0804/100)x906=27.9084kg
Silicon loss due to oxidation
Silicon loss due to oxidation is about 10%
Pig iron No 1 : 906x0.15x0.025 = 3.3975kg
Pig iron No 2 : 906x0.2x0.03 =5.436kg
New scrap : 906x0.3x0.023 =6.2514kg
Returns : 906x0.35x0.025=7.9275kg
Total=23.0124kg
Silicon loss=23.0124x(10/100)=2.30124kg
Manganese loss due to oxidation
Manganese suffers loss of about 15%
Pig iron No 1 : 906x0.15x0.007 = 0.9513kg
Pig iron No 2 : 906x0.2x0.0065 =1.1778kg
New scrap : 906x0.3x0.005 =1.359kg
Returns : 906x0.35x0.0065=2.06115kg
Total=5.54925kg
Manganese loss=5.54925x(15/100)=0. 83239kg

Carbon loss due to oxidation to carbon dioxide
Volumetric analysis of the exhaust gases:
CO_2 : CO : N_2=12% : 12% :76%
CO_2=1 mole C + 2moles O=12+32=44kg
% of C oxidized=(12/44)x12%=3.273%
Assuming the amount of coke in the combustion zone of the cupola to initiate combustion is 3kg;
Carbon loss to oxidation=(3.273/100)x(91+3)=3.07662kg
The heat of formation of MnO given as :

$$\Delta H_{MnO_3} = -35205 cal / mole$$

One mole of MnO contains 54.99kg of manganese.

$$54.99kg\ of\ Fe = 35205cal = 147861J$$

$$0.83239kg\ of\ Fe = \frac{0.83239 \times 147861}{54.99} = 2238.19J$$

The heat of formation of SiO_2 expressed as :

$$\Delta H^0_{SiO_2} = -88618 cal / mole$$

One mole of SiO_2 contains 28.09kg of silicon.

$$28.09kg\ of\ Si = 88618cal = 372195.6J$$

$$2.3012kg\ of\ Si = \frac{0.83239 \times 372195.6}{28.09} = 11029.26J$$

Ambient temperature, Ta=303K
The temperature of molten iron at the center of the cupola, Tm=1923K
The inner radius of insulation, r_1=0.23m
The outer radius of insulation, r_2=0.34m
The outer radius of steel shell, r_3=0.35m
Thermal conductivity of alumina (Al_2O_3) refractory lining, k_1=0.000056W/mK
Thermal conductivity of steel shell, k_2=0.24713W/mK
Convective heat transfer coefficient of air, h_a=0.025862Wm2K
Convective heat transfer coefficient of molten iron, h_m=3000Wm2K
Cupola height, L=5.65m
The density of air, D_a=1.2kg/m3
The volume of hot air blast, V_r=450m3
Specific heat capacity of hot air blast, C_{pa}=1005J/kg K
The temperature of hot air blast, T_{ha}=973K
Specific heat capacity of iron, C_{piron}=1.6J/kg K
Specific heat capacity of coke, C_{pcoke}=850JkgK
Specific heat capacity of limestone, Cp_{flux}=910JkgK
Exhaust gas temperature, T_{exh}=573K
Calorific value of coke, C_{coke}=15000000J/kg

Table 1: Cupola critical parameters[8]

Melting capacity(tons)	¾-1	2.25-3	6-6.5
Shell diameter(cm)	69	112	168
Shell diameter with lining(cm)	46	76	112
Shell plate thickness (cm)	0.5	0.7	0.8
Cupola height (cm)	565	750	900

V. COMPUTATIONAL ALGORITHMIC CODING

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% COMPUTER SIMULATION OF COMBUSTION AND HEAT LOAD ANALYSIS FOR OPTIMAL USE
% OF CUPOLA FURNACE IN IRON AND STEEL MANUFACTURE
% INITIALIZATION OF PARAMETERS
% Ta--AMBIENT TEMPERATURE (K)
 T3=395.7;
% Tm--TEMPERATURE OF MOLTEN IRON (K)
 Tm=1923;
% r1--INNER RADIUS OF INSULATION (m)
 r1=0.23;
% r2--OUTER RADIUS OF INSULATION(m)
 r2=0.305;
% r3--OUTER RADIUS OF THE STEEL SHELL (m)
 r3=0.35;
% k1--THERMAL CONDUCTIVITY OF OF ALUMINA (Al2O3) REFRACTORY(W/mK)
% ALUMINA AT 1773k
 k1=0.000056;
% k2--THERMAL CONDUCTIVITY OF STEEL SHELL (W/mK)
 k2=0.24713;
% ha--CONVECTIVE HEAT TRANSFER COEFFICIENT OF AIR (W/m2K)
 ha=0.0258621;
% hm--CONVECTIVE HEAT TRANSFER COEFFICIENT MOLTEN IRON (W/m2K)
  hm=3000;
% FILE  TEMP.COM
% SOLVE FOR TEMPERATURES T1, T2 AND T3
 A1=[(r1*hm),0,(r3*ha)];
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A2=[(k1*log(r3/r2)),-((k1*log(r3/r2))+(k2*log(r2/r1))),(k2*log(r2/r1))];
A3=[(r1*hm*log(r3/r2)),k2,-k2];
A=[A1;A2;A3];

b=[(r1*hm*Tm+r3*ha*Ta);0;(r1*hm*log(r3/r2)*Tm)];
Temp=A\b;
disp(Temp)
disp('TEMPERATURE AT THE CURVRD SURFACE OF THE STEEL SHELL, Ta')
fprintf('%20.12f\n',T3)
% CUPOLA ENERGY CONTENT PER UNIT TIME, Q, IN (Watts)
% L--HEIGHT OF CUPOLA (m)
L=5.65;
Q=(((2*pi*L*(Tm-T3))/((1/(r1*hm))+(log(r2/r1)/k1)+(log(r3/r2/k2))+(1/(r3*ha)))))*(24*3600);
disp('HEAT CONTENT OF THE SYSTEM, Qsystem=')
fprintf('%20.12f\n',Q)
% PERFORMING HEAT BALANCE IN THE DIFFERENT ZONES OF THE CUPOLA
% HEAT CONTENT OF THE HOT AIR BLAST, Qhotair (Watts)
% Da--HOT AIR BLAST DENSITY (kg?m3)
Da=1.2;
% VR--VPLUMETRIC FLOW RATE OF THE HOT AIR BLAST, Vr (m/s)
Vr=900;
% Cpa--SPECIFIC HEAT CAPACITY OF THE HOT AIR BLAST (J/kgK)
Cpa=1005;
% Tha--TEMPERATURE OF THE HOT AIT BLAST (K)
Tha=973;
% Qhot=(0.00001157)*(Da*Vr^Cpa*(Tha-T3);
Qhot=Da*Vr*Cpa*(Tha-T3);
disp('HEAT CONTENT OF THE HOT AIR BLAST, Qhotair=')
fprintf('%20.12f\n',Qhot)
% Cpiron--SPECIFIC HEAT CAPACITY OF IRON (J/kgK)
Cpiron=1.65;
% Cpiron--SPECIFIC HEAT CAPACITY OF COKE (J/kgK)
Cpcoke=850;
% Cpiron--SPECIFIC HEAT CAPACITY OF LIMSTONE (W/kgK)
Cpflux=910;
% HEQAT BALANCE IN THE STACK ZONE, Qstack (Watts)
% EXHUAST GAS TEMPERATURE, Texh (K)
Texh=573;
Qstack=Da*Vr*Cpa*(Texh-T3);
% HEAT BALANCE IN THE PREHEAT ZONE, Qphz (Watts)

Qphz=((906*Cpiron)+(91*Cpcoke)+(3.62*Cpflux))*(1373-T3);
disp('HEAT CONTENT OF THE PREHEAT ZONE, Qphz=')
fprintf('%20.12f\n',Qphz)
% HEAT BALANCE IN THE MELTING ZONE, Qmz (Watts);

Qmz=((906*Cpiron)+(91*Cpcoke)+(3.62*Cpflux))*(1873-T3);
disp('HEAT CONTENT OF THE MELTING ZONE, Qmz=')
fprintf('%20.12f\n',Qmz)
% HEAT BALANCE IN THE REDUCING ZONE, Qmz (Watts)

Qrz=((906*Cpiron)+(91*Cpcoke)+(3.62*Cpflux))*(1573-T3);
disp('HEAT CONTENT OF THE REDUCING ZONE, Qrz=')
fprintf('%20.12f\n',Qrz)
% HEAT BALANCE IN THE COMBUSTION ZONE, Qmz (Watts)

Qcz=((906*Cpiron)+(91*Cpcoke)+(3.62*Cpflux))*(2123-Ta);
disp('HEAT CONTENT OF THE COMBUSTION ZONE, Qcz=')
fprintf('%20.12f\n',Qcz)
% HEAT INPUT, Qcal, TO THE SYSTEM DUE TO CALORIFIC VALUE OF COAL (Watts)
% HEAT EVOLUTION DUE TO OXIDATION OF CARBON TO CARBON DIOXIDE ( CARBON LOSS=3.4%, Qcar(Watts)
% Qcar=1.1721;
Qcar=101267.4;
% HEAT EVOLUTION DUE TO OXIDATION OF IRON TO HAEMATITE (IRON LOSS=3.4%,
% Qfe(J)
Qfe=205650.2;
% HEAT EVOLUTION DUE TO OXIDATION OF MANGANESE TO MANGANESE OXIDE
% MANGANESE LOSS=15%, Qmn(J)
Qmn=2238.19;
% HEAT EVOLUTION DUE TO OXIDATION OF SILICON TO SILICON DIOXIDE (SILICON
% LOSS=10%, Qsi(J)
Qsi=11029.267;
% HEAT CONTENT OF COKE PER HEAT PER DAY, Qcoke (J)
% MASS OF COKE, m(KG)
m=94;
% CALORIFIC VALUE OF COKE, Ccoke (J/kg)
Ccoke=15000000;
Qcoke=(m*Ccoke);
disp('HEAT CONTENT OF COKE, Qcoke=')
fprintf('%20.12f\n',Qcoke)
% HEAT ADDITION DUE TO ALL OXIDATION REACTION, QoxiS (wATTS)
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  Qoxi=(Qcar+Qfe+Qmn+Qsi);
  disp('HEAT ADDITION DUE TO OXIDATION REACTION, Qoxi=')
  fprintf('%20.12f\n',Qoxi)
% DETERMINATION OF CUPOLA EFFICIENCY, E(%)
  E=(Qphz+Qmz+Qcz)/(Qcoke+Qoxi+Qhot-Q-Qstack-Qrz);
  disp('CUPOLA EFFICIENCY, E=')
  fprintf('%20.12f\n',E)
```

RESULTS AND DISCUSSIONS

The results of the computational analysis are in Table 2 below:

r_1(m)	r_2(m)	r_3(m)	Thermal Efficiency, E(%)	Shell surface temperature, T_3(K)	Refractory lining thickness, t_{ref}(m)	Shell thickness, t_{ss}(m)
0.23		0.35	19.81	385.7	0.115	0.005
0.23		0.35	19.8	386.5	0.11	0.01
0.23		0.35	19.75	387.5	0.105	0.015
0.23		0.35	19.77	388.5	0.1	0.02
0.23		0.35	19.75	389.6	0.05	0.025
0.23		0.35	19.73	390.9	0.09	0.03
0.23		0.35	19.71	392.3	0.085	0.035
0.23		0.35	19.69	293.9	0.08	0.04
0.23		0.35	19.66	395.7	0.075	0.045

The refractory lining and steel shell thickness were varied within reasonable limits. The maximum thermal efficiency of 19.81% was obtained when the refractory lining thickness was 115mm, and the steel shell thickness was 5mm. Improvement in thermal efficiency could obtainable by changing the type of fuel employed in firing the furnace, proper refractory lining selection, among others.

VI. RECOMMENDATION FOR FUTURE RESEARCH

(i) The computer-simulated algorithmic coding should be modeled with refractories of different

(ii) insulation properties. This procedure is to determine their effectiveness to conserve heat in the workspace. This stuff is one of the major determinant factors controlling the furnace thermal performance.

(ii) Different grades of fuels should be applied, and the thermal performance of the cupola measured.

VII. CONCLUSIONS

The computer simulation determined the cupola thermal performance, in reality, was appreciable at 19.81% employing alumina refractory. Literature-based on the works of other researchers, mainly on design, construction, and experimental approach, estimated 30% to 50%.

NOMENCLATURE

V_{rs} -volumetric of air required per heat (m^3)
T_m—the temperature at the center of the furnace (K)
Q -heat loss from the surface of the steel shell (J)
Q_{iron} -thermal load of iron (J)
Q_{flux} -thermal load of flux (J)
$\ddot{Q}_{coke}$ -thermal load of coke (J)
ΔTi_{hotair} -the temperature difference of the hot air blast and the surroundings (K)
ΔT -the temperature difference of 1ron, coke and the melt (K)
T_a—ambient temperature (K)
T_3—the temperature at the external surface of the steel shell (K)
T_2—interfacial temperature between the lining and the stell shell K)
T_1—the temperature at the inner surface of the lining (K)
R_{th}—thermal resistance (K/W)
r—radial positions from the center of the furnace (m)
L—the height of the furnace (m)
k_2—thermal conductivity of the steel shell K)
k_1—thermal conductivity of the furnace lining W/mK)
A_r -the internal and external surface area of the lining and the steel shell (m^2)
h_m—convective heat transfer coefficient of the hot melt (W/mK)
$\hat{q}_r$ -heat transfer rate per unit mass (Watts)
Q_{SZ} --heat content per unit time of the flue gases in the stack zone (J)
Q_{RZ} --heat content per unit time in the reducing zone (J)
Q_{PHZ} --heat content in the preheat zone (J)
Q_{MZ} --heat content in the melting zone (J)
Q_{CZ} --heat content in the combustion or superheat zone (J)
h_a—convective heat transfer coefficient of the surroundings (W/mK)
ρ_{air} -the density of air (kg/m^3)
C_{piron}—specific heat capacity of iron (J/kg K)
C_{pflux}—specific heat capacity of flux (J/kg K)
C_{pcoke}—specific heat capacity of coke (J/kg K)
$\Delta T_{Overall}$ -the potential thermal difference (K)

H1—stack zone height (m)
H2—preheat zone height (m)
H3—melting zone height (m)
H4—reducing zone height (m)
H5—combustion zone height (m)
H6—well zone height (m)

ΔT_{H1} -the temperature difference of the hot effluent gases in the stack zone (K)

ΔT_{H2} -the temperature difference in the preheat zone (K)

ΔT_{H3} -the temperature difference in the melting zone (K)

ΔT_{H4} -the temperature difference in the reducing zone (K)

ΔT_{H5} -the temperature difference in the combustion zone (K)

ΔT_{H6} -the temperature difference in the well region (K)

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