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INDUSTRIAL PUSHER FURNACES: PART 1 - INFLUENCE OF SLAB PREHEATING TO ENERGY CONSUMPTION

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1. SUMMARY

In metallurgy industrial pusher furnace is very important object for energy research because of its large energy consumption. Here, we try to use the combustion products of this furnace for preheating of steel slabs and analyze the effects of such preheating to energy consumption of this furnace.

To represent this furnace we have modeled this furnace with the energy object network that consists of as modules of convective heat exchangers with the constant coefficients of total heat transfer, modules of combustion and modules of stream mixing.

With the injection of oxygen to combustion air and for large sized heat-recovery device of pusher furnace an increase of the slab preheater size gives smaller decrease in energy consumption than without this injection and for heat-recovery devices of smaller size.

2. LIST OF SYMBOLS

a	oxygen percentage in air, %
B	mass-flow rate of fuel, Nm^3/s
C	mass of steel to its oxide, kg/s
c	specific heat capacity, J/kg-K
F	surface, m2
G	mass percentage, %
H_d	lower fuel-heat value, J/kmol
h	ratio of mass flows of high furnace to mixed gasses
k	heat transfer coefficient, W/m^2-K
M	relative molecular mass, kg/kmol
m	mass flow rate, kg/s
N	number of slabs in furnace
O_{2min}	air minimum, Nm3/Nm3 of b
p	furnace over pressure, Pa
Q	heat, W
r	Volumetric composition

s	envelope-layer width, m	λ	coefficient of excess air
T	weight of slab, kg	λ	thermal conductivity, W/m-K
t	temperature, ^0C	μ	flow coefficient
V	gas flow rate Nm3/ Nm3 of b	ρ	density, kg/m^3
W	moisture content, g/Nm3	τ	time, s
Z	heat transmitance coefficient, W/K	ψ	ratio of times of opened door to furnace operation.
a	heat transfer coefficient, W/m^2-K		
ϕ	furnace openings porosity.		

indices

a	average	n	indices
b	fuel	k	correction
c	combustion air, cold	r	heat-recovery device
d	dry	s	slab
e	environment	sc	ceiling
f	combustion products	sg	combustion
g	gas	u	entrance
h	high furnace gas, hot	v	water
i	exit	w	air,
m	mixed gasses	z	wall
O	oxygen	1	inside
o	normal conditions	2	outside
o	furnace openings	j=1-14	1(H_2), 2(CO), 3(CH_4), 4(C_2H_4),5 (C_2H_6)6 (C_3H_6), 7(C_3H_8), 8(C_4H_{10}), 9(CO_2), 10 (N_2), 11 (H_2O), 12(SO_2), 13 (H_2S), 14 (O_2)
p	natural gas, constant pressure		
ph	preheater		
pf	floor		
j	indices		

3. INTRODUCTION

In metallurgy the industrial pusher furnace is very important object because of its large energy consumption. Steel-heating process in pusher furnaces depends on different parameters so as kind and shape of material, kind and quality of fuel, percentage of oxygen in combustion air ect. There is need for flexible work of the furnace. One should take care of the refuse of energy of combustion products. This can be done by use of heat-recovery device (HRD) in which combustion products preheat furnace-combustion air. Here, we try to use additionally the combustion products for preheating of steel slabs and find the effects of such preheating to energy consumption of the furnace [1].

4. MATHEMATICAL MODEL

To represent this furnace (Fig.1) we have used bottom-up analysis as in Ref. 2. We have presented this furnace with the energy object network (Fig.2): modules of heat exchangers, combustion and stream mixing. The applied heat exchangers are purely convective with the constant coefficients of total heat transfer. On the basis of this mathematical model we have developed software POTIS that can be used for the simulation of this furnace operation.

Equations of the combustion module (Appendix 1), the mixing module of oxygen and air (Appendix 2), and equations for mass flow rates of combustion products, air entering HRD and steel slabs are

$$\begin{aligned}
&H_d, O_{2min}, V_f, r_{fj}\ (j=1,2,..,14) = f\,[r_{mj}\ (j=1,2,..,14), a_i, W_w, \lambda],\\
&V_O, V_{wi}, V_{wu}=f(a_u, a_i, O_{2min}, \lambda),\\
&m_f=V_f\,B\,M_f/22.4,\ m_w=V_{wi}\,B\,M_{wi}/22.4,\ m_s=T\,N/\tau \qquad (1)
\end{aligned}$$

where the volumetric data for wet fuels (Appendix 3) are: r_{hj}, r_{nj}, r_{Oj}, r_{wj} $(j=1,2,...,14)$.

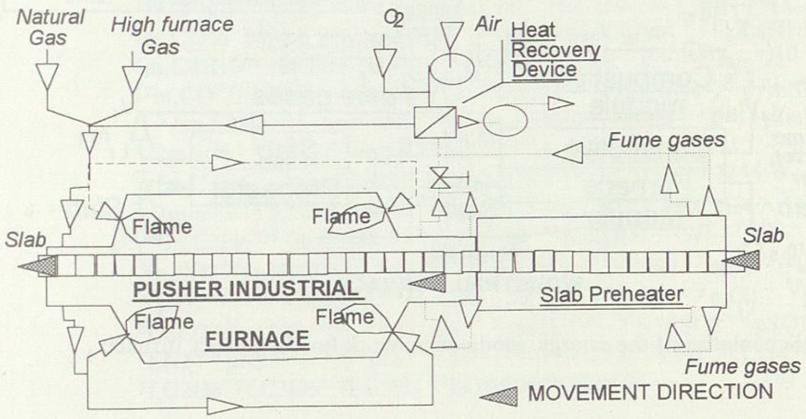

Fig.1 Pusher industrial furnace and slab preheater

Temperature of air with mass flow rate V_{wi} and a_i percentage of oxygen at the exit of the mixing box (mixing of air and oxygen) and combustion temperature is given as

$$\begin{aligned}
&t_{wi}=(V_{wu}c_{pwu}t_{wu}+V_O c_{pO} t_O)/(c_{pwi}V_{wi}),\\
&t_{sg}=(c_{pm}\,t_m+V_{wi}\,c_{pwi}\,t_{ws}+H_d)/(V_f\,c_{pf}). \qquad (2)
\end{aligned}$$

Heat consumption by water for the cooling of furnace, heat lost by radiation (see Appendix 4), by flame through the furnace opening (Appendix 4), through the furnace wall (see Appendix 5), heat obtained by the slab oxidation from exothermic reactions (Appendix 6), temperatures out of convective furnace module (Appendix 7), and temperature correction for this module are given by

$$Q_v=1.1\ m_v\ c_{pv}\ (t_{vi}-t_{vu}),\ Q_r=f(t_{fi},\ t_{sg}, F_{of,u}, F_{of,i},\ \phi_{iu}, \phi_{ii}, \psi_{su}, \psi_{si}),$$
$$Q_{is}=f(\ t_{sg}, t_{fi},\ r_{fj}(j=1,2,..,14),\ p,\ \mu,\ F_{of,u}, F_{of,i},\ t_s,\ \psi_{su}, \psi_{si}),$$
$$Q_z=f(g,\ t_s,\ F_z,\ s_{zj},\ \lambda_{zj},\ F_{sc},\ s_{sc,j},\ \lambda_{sc,j},\ F_{pf},\ s_{pf,j},\ \lambda_{pf,j})\ \text{for } j=1,..,3.,$$
$$Q_k=f(m_s),\ t_{fik}, t_{si}=f(t_{sg},\ t_{su}, m_f, c_{pfa}, m_s, c_{psa}, Z_f),$$
$$t_{fi}=t_{fik}-(Q_v+Q_r+Q_{is}+Q_{ot}+Q_z-Qk)/(m_f\ c_{pf}). \qquad (3)$$

General equations governing preheater (counterflow heat exchanger model) and heat recovery device (see Appendix 8) are

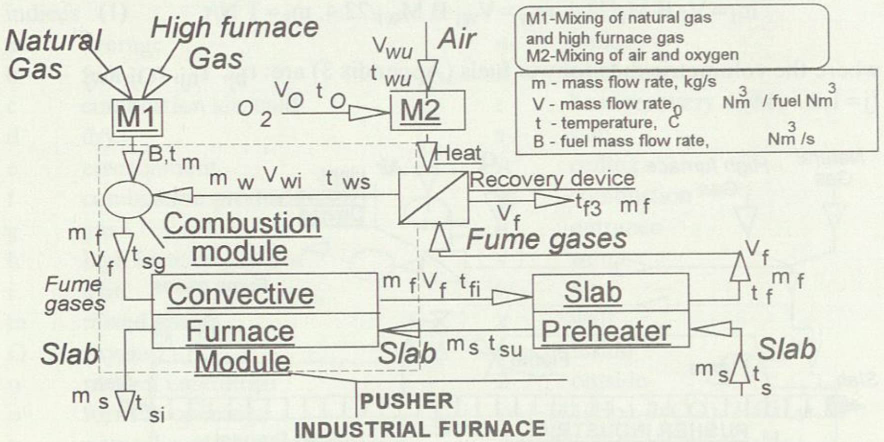

Fig. 2 Schematics of the energy modules network for the pusher furnace

$$t_f, t_{su}=f(t_{fi},\ t_s, m_f, c_{pfa}, m_s, c_{psa}, Z_{ph}),$$
$$t_{f3}, t_{ws}=f(t_f, t_{wi}, m_f, c_f, m_w, c_w, Z_{r1}, Z_{r2}). \qquad (4)$$

Total general equation for the whole furnace with the preheater is

$$B_A=f\,[m_f,\ m_r,\ h,\ a_i,\ T,\ Z_{r1},\ Z_{r2},\ r_{dhj},\ r_{dpj},\ r_{dOj},\ r_{dwi}\ (j=1,2,..,14),\ W_h,\ W_p,\ W_O,\ W_w, a_u,\ \lambda,\ t_{wu},\ t_O,\ t_m,\ t_s,\ t_{vi},\ t_{vu},\ N,\ \tau,\ m_v,\ F_{of,u},\ F_{of,i},\ F_z,\ F_{sc},\ F_{pf},\ \phi_u,\ \phi_i,\ \psi_u,\ \psi_i,\ p,\ \mu,\ s_{zn},\ s_{sc,n},\ s_{pf,n},\ \lambda_{zn},\ \lambda_{sc,n},\ \lambda_{pf,n}\ (n=1,..,3), \alpha_1, \alpha_2\ Z_f,\ Z_{ph}], \qquad (5)$$

5. RESULTS AND ANALYSES

The initial values of different parameters of the example-pusher furnace are given in Appendix 9. When Zp is enlarged form 3 to 30 W/K the fuel consumption is lower 1.376 times when the combustion air is with 21% of oxygen, and 1.071 times when the combustion air has 30% of oxygen (see Fig.3). For the same increase of Zp (see Fig.4) the fuel consumption is lower 1.82 times when Z_{r1}= 10000 W/K and Z_{r2}=30000 W/K and 1.375 times when Z_{r1}=15000 W/K and Z_{r2}=42000 W/K.

REFERENCES

[1] Tomić, M., Bojić,M., "POTIS software for simulation of energy behavior of pusher furnace," Scientific meeting, Institute of Thermal Technology, Technical University of Silesia, Gliwice, Poland, 1994.

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APPENDIX 1 Combustion modules equations with general equation $H_d, O_{2min}, V_w, r_{fj}$ (j=1,2,..,14)= f [r_{mj} (j=1,2,..,14), a_k W_w, λ].

Lower heat value of mixed gas fuel, minimum quantity of oxygen needed, mass flow rates of combustion products, total mass flow rate of wet combustion products and volumetric ratios of wet combustion products are

$$Hd=[H_{d,H2}\ r_{m,H2}+H_{d,CH4}\ r_{m,CH4}+H_{d,C2H4}\ r_{m,C2H4}+H_{d,C2H6}\ r_{m,C2H6}+H_{d,C3H6}\ r_{m,C3H6}+H_{d,C3H8}\ r_{m,C3H8}+H_{d,C4H10}\ r_{m,C4H10}+H_{d,H2S}\ r_{m,H2S}+H_{d,CO}\ r_{m,CO}]\ /\ 100;\ O_{2min}=\{0.5\ [r_{m,CO}+r_{m,H2}]+1.5\ r_{m,H2S}+2.\ r_{m,CH4}+3\ r_{m,C2H4}+3.5\ r_{m,C2H6}+4.5\ r_{m,C3H6}+5.\ r_{m,C3H8}+6.5\ r_{m,C4H10}-r_{mO2}\}\ /\ 100.,\ L_{min}=100.\ O_{2min}/a_k,\ V_{p,CO2}=[r_{m,CO}+r_{m,CO2}+r_{m,CH4}+2\ r_{m,C2H4}+2\ r_{m,C2H6}+3\ r_{m,C3H6}+3\ r_{m,C3H8}+4\ r_{m,C4H10}]/100,\ r_{w,H2O}=0.1244\ W_w\ \lambda\ 100\ O_{2min}/a_k,\ V_{p,H2O}=(r_{m,H2}+r_{m,H2S}+2\ r_{m,CH4}+2\ r_{m,C2H4}+3\ r_{m,C2H6}+3\ r_{m,C3H6}+4\ r_{m,C3H8}+5\ r_{m,C4H10}+r_{m,H2O})+r_{WL})\ /\ 100,\ V_{p,SO2}=r_{m,H2S}/100;\ V_{p,N2}=r_{m,N2}/100.+(100-a_k)\ O_{2min}\ \lambda\ /a_k,\ V_{p,O2}=(\lambda-1)\ O_{2min};\ V_f=V_{p,CO2}+V_{p,SO2}+V_{p,N2}+V_{p,O2}+V_{p,H20},\ r_{f,CO2}=V_{pCO2}\ 100./V_f,\ r_{f,H2O}=V_{pH2O}100./V_f,\ r_{f,SO2}=V_{pSO2}100./V_f,\ r_{f,N2}=V_{pN2}100./V_f,\ r_{f,O2}=V_{pO2}100./V_f,\ r_{f,CO}=r_{f,H2}=r_{f,CH4}=r_{f,C2H4}=r_{f,C2H6}=r_{f,C3H6}=r_{f,C3H8}=r_{f,C4H10}=r_{f,H2S}=0. \qquad (6)$$

APPENDIX 2 Model for a mixing of air and oxygen with general equation is $V_o, V_{wu}, V_{wi}=f(a_u, a_i, O_2min, \lambda)$.

Fresh air has percentage contribution of oxygen a_u. In order to correct contribution of oxygen a_u to a_i we inject pure oxygen to air . Needed quantity of pure oxygen, entrance air (with a_u) and exit air with a_i ($a_i>a_u$) are

$$V_o=100\ \lambda\ (a_i-a_u)O_{2min}/[(100-a_u)a_i],\ V_{wu}=100\ \lambda\ (100-a_i)O_{2min}/[a_i(100-a_u)],\ V_{wi}=\lambda\ 100\ O_{2min}/a_i. \qquad (7)$$

APPENDIX 3 - Calculating wet fuel data out of dry fuel data.

We have volumetric data for the dry fuels: r_{dhi} for i=1,2,..,12 and their content of the moisture W_h. We obtain the wet fuel volumetric data as

$$r_i=r_{dj}/(1+0.001244W_h)\ \text{for } j=1,2,...,12,\ r_j=0.1244\ W_h/(1+0.001244W_h). \qquad (8)$$

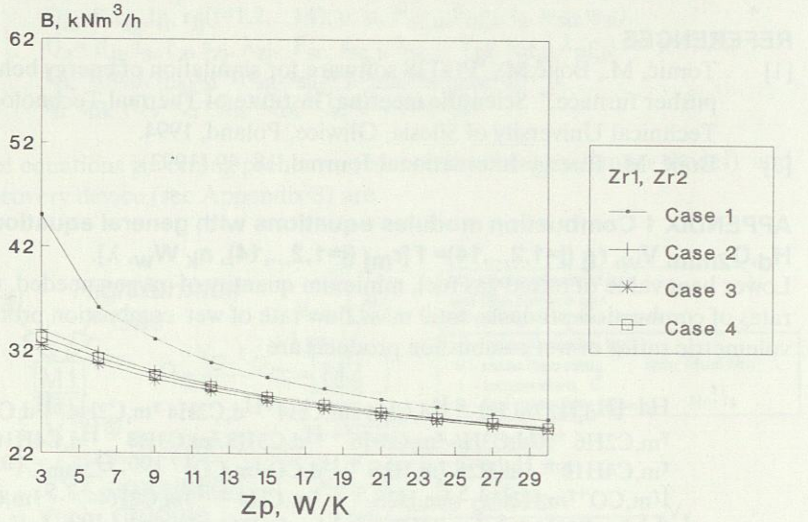

Fig.3 B as a function of $3 \le Z_p \le 30$ and different values of Z_{r1} and Z_{r2}; case 1 (Z_{r1}= 12200 W/K, Z_{r2}=42000 W/K); case 2 (Z_{r1}=12200 W/K, Z_{r2}=50000 W/K); case 3 (Z_{r1}=15000 W/K, Z_{r2}=42000 W/K); case 4 (Z_{r1}=50000 W/K, Z_{r2}=50000 W/K).

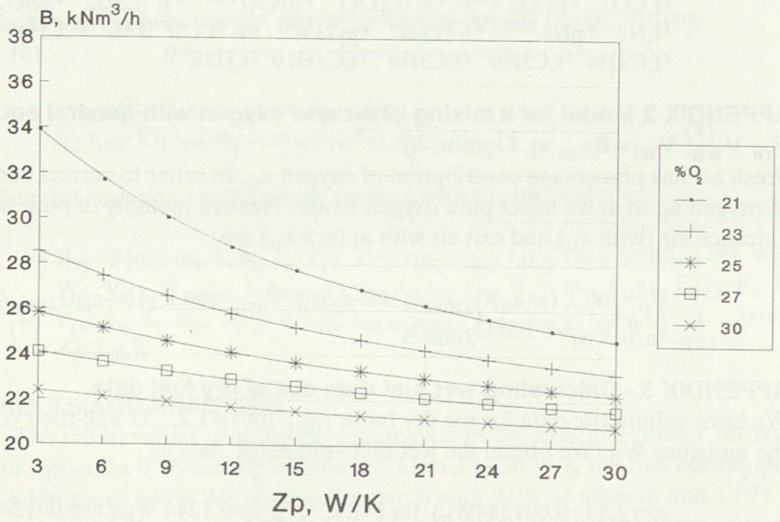

Fig.4 B as a function of $3 \le Z_p \le 30$ and different values of oxygen percentage in combustion air.

APPENDIX 4 - Heat loss by radiation and flame with general equations $Q_r=f(t_{fi}, t_{sg}, F_{of,u}, F_{of,i}, \phi_{iu}, \phi_{ii}, \psi_{su}, \psi_{si})$, $Q_{is}=f(t_{sg}, t_{fi}, r_{fj}(j=1,2,..,14), p, \mu, F_{of,u}, F_{of,i}, t_s, \psi_{su}, \psi_{si})$.

Heat loss by radiation and with flame at furnace slab entrance and exit when these openings are opened is calculated by equations

$$Q_{ru}=20.4\ [(t_{fi}+273.15)/100]^4\ F_{of,u}\ \phi_u\ \psi_u,$$
$$Q_{ri}=20.4\ [(t_{sag}+273.15)/100]^4\ F_{of,i}\ \phi_i\ \psi_i,$$
$$Q_r=Q_{ru}+Q_{ri},\ \rho_0=\rho_0(r_{fj})\ \text{where } j=1,2,..,14,$$
misu=Fof,i m [2p(273.15+tfi)/(273.15 r0)]0.5,
$$m_{isi}=F_{of,u}\ \mu\ [2p(273.15+t_{sg})/(273.15\ \rho_0)]^{0.5},$$
$$Q_{is}=m_{isu}\ c_{pigu}\ (t_{fi}-t_s)\ \psi_{su}+m_{isi}\ c_{pigi}\ (t_{sg}-t_s)\ \psi_{si}. \qquad (9)$$

Appendix 5 - Heat loss through furnace envelope with general equation $Q_z=f(t_{fa}, t_e, F_z, s_{zj}, \lambda_{zj}, F_{sc}, s_{sc,j}, \lambda_{sc,j}, F_{pf}, s_{pf,j}, \lambda_{pf,j})$ for j=1,..,3.

Furnace envelope consist of furnace walls, ceiling and floor and their layers. For average temperature t_{fa} of combustion products, and temperature of environment t_e, the total heat loss through the furnace envelope is

$$k_z=1/(1/\alpha_1+s_{z1}/\lambda_{z1}+s_{z2}/\lambda_{z2}+s_{z3}/\lambda_{z3}+1/\alpha_2),$$
$$k_{sc}=1/(1/\alpha_1+s_{sc,1}/\lambda_{sc,1}+s_{sc,2}/\lambda_{sc,2}+s_{sc,3}/\lambda_{sc,3}+1/\alpha_2),$$
$$k_{pf}=1/(1/\alpha_1+s_{pf,1}/\lambda_{pf,1}+s_{pf,2}/\lambda_{pf,2}+s_{pf,3}/\lambda_{pf,3}+s_{pf,4}/\lambda_{pf,4}+1/\alpha_2),$$
$$Q_z=k_z(t_{fa}-t_e)F_z+k_{sc}(t_{fa}-t_e)F_{sc}+k_{pf}(t_{fa}-t_e)F_{pf}. \qquad (10)$$

APPENDIX 6 - Exothermic slab reactions with general equation $Q_K=f(m_s)$.

Mass of steel that transforms to its oxide and masses of generated of different oxides, mass percentage of oxygen and pure metal is in steel oxide and total heat generated during oxides generation are given by equations

$$G_{O2}=(G_{FeO}\ 16/72+G_{Fe2O3}\ 48/160+G_{Fe3O4}\ 64/232+G_{SiO2}\ 32/60$$
$$+G_{MnO}\ 16/71+G_{CaO}\ 16/56)/100,\ G_{Mk}=1-g_{O2},\ C=0.01\ m_s\ k,\ C_{FeO}=C$$
$$G_{Mk}\ G_{FeO}/100,\ C_{Fe2O3}=C\ G_{Mk}\ g_{Fe2O3}/100,$$
$$C_{Fe3O4}=C\ G_{Mk}\ G_{Fe3O4}/100,\ C_{SiO2}=C\ G_{Mk}\ G_{SiO2}/100,$$
$$C_{MnO}=C\ G_{Mk}\ G_{MnO}/100,\ C_{CaO}=C\ G_{Mk}\ G_{CaO}/100.$$
$$Q_{kov}=C_{FeO}\ Q_{FeO}+C_{Fe2O3}\ Q_{Fe2O3}+C_{Fe3O4}\ Q_{Fe3O4}+C_{SiO2}\ Q_{SiO2}+$$
$$C_{MnO}\ Q_{MnO}+C_{CaO}\ Q_{CaO}. \qquad (11)$$

APPENDIX 7 - The counterflow heat-exchanger model with general equation $t_{wo}, t_{fo}=f(t_{wi}, t_{fi}, m_w, c_w, m_f, c_f, Z)$.

When the mass flows m_h and m_c and the temperatures t_{hu} and t_{cu} of the incoming streams are known, the temperatures t_{hi} and t_{ci} of the exiting streams are determined by the relations

$$a=1/(m_hc_h) - 1/(m_cc_c),\ s=[1-\exp(aZ)]/[1-(m_hc_h)/(m_cc_c)],\ k=[\exp(aZ)-1]/[1-(m_hc_h)/(m_cc_c)],\ t_{hi}=(t_{hu}+t_{cu}k),\ t_{ci}=[t_{hi}-t_{hu}(1-s)]/s \tag{12}$$

Appendix 8 - Heat recovery device equations with general equation

$t_{f3},t_{w3}=f(t_{f0},t_{w0},m_f,c_f,m_w,c_w,Z_{r1},Z_{r2})$.

HRD consist of 3 countercurent heat exchangers. Their equations are

$$\begin{aligned}&t_{f1},t_{w1}=f(t_{f0},t_{w0},m_f,c_f,m_w,c_w,Z_{r1}),\\&t_2,t_{w2}=f(t_{f1},t_{w1},m_f,c_f,m_w,c_w,Z_{r2}/2),\\&t_{f3},t_{w3}=f(t_{f2},t_{w2},m_f,c_f,m_w,c_w,Z_{r2}/2).\end{aligned} \tag{13}$$

Appendix 9 - Initial data of the model.

r_{dhi} ($r_{dh,CO}=28\%$, $r_{dh,H2}=2\%$, $r_{dh,CH4}=0\%$, $r_{dh,C2H4}=0\%$, $r_{dh,C2H6}=0\%$, $r_{dh,C3H6}=0\%$, $r_{dh,C3H8}=0\%$, $r_{dh,C4H10}=0\%$, $r_{dh,H2S}=0.5\%$, $r_{dh,CO2}=10\%$, $r_{dh,O2}=0.5\%$, $r_{dh,N2}=58.5\%$, $r_{dh,SO2}=0\%$, $r_{dh,H2O}=0\%$). r_{dpi} ($r_{dp,CO}=0.5\%$, $r_{dp,H2}=1.5\%$, $r_{dp,CH4}=90.9\%$, $r_{dp,C2H4}=06.\%$, $r_{dp,C2H6}=2\%$, $r_{dp,C3H6}=0.6\%$, $r_{dp,C3H8}=0.8\%$, $r_{dp,C4H10}=0.2\%$, $r_{dp,H2S}=0.2\%$, $r_{dp,CO2}=1\%$, $r_{dp,O2}=0.2\%$, $r_{dp,N2}=1.5\%$, $r_{dp,SO2}=0\%$, $r_{dp,H2O}=0\%$). r_{doi} ($r_{do,CO}=r_{do,H2}=r_{do,CH4}=r_{do,C2H4}=r_{do,C2H6}=r_{do,C3H6}=r_{do,C3H8}=r_{do,C4H10}=r_{do,H2S}=r_{do,CO2}=r_{do,N2}=r_{do,SO2}=r_{do,H2O}=0\%$, $r_{do,O2}=100\%$), r_{dwi} ($r_{dw,CO}=r_{dw,H2}=r_{dw,CH4}=r_{dw,C2H4}=r_{dw,C2H6}=r_{dw,C3H6}=r_{dw,C3H8}=r_{dw,C4H10}=r_{dw,H2S}=r_{dw,CO2}=r_{dw,SO2}=r_{dw,H2O}=0\%$, $r_{dw,O2}=21\%$, $r_{dw,N2}=79\%$,), $W_h = 20$ g/Nm^3 of dg, $W_p = 5$ g/Nm^3 of dg, $W_w = 2$ g/Nm^3 of dg, $W_o = 0$ g/Nm^3 of dg, $h = 0.6$, $a_i=21\ \%$, $a_u = 21\ \%$, $\lambda = 1$, $t_{wu} = t_O = t_m = 20^0C$, $t_s = 1250^0C$, $T = 16848$ kg, $N=36$, $\tau = 9648$ s, $\phi_u = 0.78$, $\phi_i=0.6$, $\psi_u=0.1$, $\psi_i=0.1$, $p= 3$ Pa, $\mu=0.85$, $m_v=1000$ kg/s, $t_{vu}=90^0C$, $t_{vi}=98^0C$, $F_{of,u} = 7.8\ m^2$, $F_{of,i}=9.1\ m^2$, $F_z=524\ m^2$, $F_{sc}=526\ m^2$, $F_{pf}=446\ m^2$, $s_{z1}=0.4$ m, $s_{z2}=0.13$ m, $s_{z3}=0.12$ m, $s_{sc,1}=0.23$ m, $s_{sc,2}=0.03$ m, $s_{sc,3}=0.06$ m, $s_{pf,1}=0.2$ m, $s_{pf,2}=0.25$ m, $s_{pf,3}=0.20$ m, $s_{pf,4}=0.15$ m; $\alpha_1=58.14$ W/m^2-K, $\alpha_2=11.28$ W/m^2-K; $_{z1}=1.459$ W/m-K, $\lambda_{z2}=0.605$ W/m-K, $\lambda_{z3}=0.179$ W/m-K, $\lambda_{sc,1}=1.221$ W/m-K, $\lambda sc,2 = 0.605$ W/m-K, $\lambda_{sc,3}=0.142$ W/m-K, $\lambda_{pf,1}=1.459$ W/m-K, $\lambda_{pf,2}=1.429$W/m-K, $\lambda_{pf,3}=1.395$ W/m-K, $\lambda_{pf,4}=0.142$ W/m-K, $Z_f=50$ W/K, $Z_{ph}=20$ W/K, $Z_{r1}=12200$ W/K, $Z_{r2}= 42000$ W/K, $G_{FeO} = 67.22\%$, $G_{Fe2O3}=28.04\%$, $G_{Fe3O4}=1\%$, $G_{SiO2}=0.72\%$, $G_{MnO}=0.68\%$, $g_{CaO} = 0.2\%$. $Q_{FeO} = 3755$ kJ/kg, $Q_{Fe2O3}=5161$ kJ/kg, $Q_{Fe3O4}= 4810$ kJ/kg, $Q_{SiO2} = 14500$ kJ/kg, $Q_{MnO}=5701$ kJ/kg, $Q_{CaO}=11348$ kJ/kg, $H_{d,H2}= 10760$ kJ/kmol, $H_{d,CH4}= 35797$ kJ/kmol, $H_{d,C2H4}= 59955$ kJ/kmol, $H_{d,C2H6} = 64351$ kJ/kmol, $H_{d,C3H6}=88216$ kJ/kmol, $H_{d,C3H8} = 93575$ kJ/kmol, $H_{d,C4H10} =123552$ kJ/kmol, $H_{d,H2S}= 23696$ kJ/kmol, $H_{d,CO}= 12644$ kJ/kmol.