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DETERMINING OPTIMUM VOLUME OF COLD AND HOT BLAST AIR IN SINGLE-ROW COKE CUPOLAS

1. INTRODUCTION

In this paper, the term "optimum volume of blast air in coke cupolas" means a volume [$m^3/(m^2 \cdot s)$ – standard operating conditions] of air such that – under given input parameters of the technological process (coke consumption rate, blast air temperature, weight, shape and melting point of the lumps of metallic charge, height of the charge column above the level of tuyéres, etc.) – will produce maximum degree of molten cast iron overheating.

A modern empirical tool used in computation of this optimum volume of blast air are mesh diagrams which on the curves of constant coke consumption rate have some extrema, corresponding to an optimum blast air volume and maximum temperature of molten metal. The drawback of the mesh diagrams is that they cannot provide two very important pieces of information, viz. the information on the height of the column of charge materials filling cupola shaft above the level of tuyéres, and on the shape, size and melting point of the lumps of metallic charge – both being the parameters which have an important influence on the position of extrema on mesh diagrams.

In modern studies of the cupola process two main trends can be distinguished, viz. a new trend – numerical computations, and a traditional one – that is, analytical studies. The aim of the numerical computations is to design a complex physico-chemical (thermal-metallurgical) model in the form of a system of relevant equations, and develop some procedures which would solve these equations (algorithms, software).

The analytical studies, on the other hand, tend to offer, first of all, a functional description of the process most important in cupolas, i.e. the process of heat transfer in cupola shaft (heating, melting and overheating of metal), which depends on the shape, size and melting point of the lumps of metallic charge, on the coke-to-metal ratio, on the volume of air sup-

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plied to cupola blast, and on the height of the charge column above the level of tuyéres. The metallurgical processes are considered in the second place, i.e. against the background of the thermal processes going on.

At this point it should be emphasized that both the research trends outlined above are complementary to each other, and confrontation of the obtained results enables obtaining better insight into the essence of the cupola process.

This study presents a theoretical equation used for computation of the optimum volume of blast air supplied to single-row coke cupolas in relation to: coke consumption rate, height of charge column above the level of tuyéres, the weight, shape and melting point of the lumps of metallic charge, and blast air temperature.

2. DETERMINATION OF GAS TEMPERATURE ON OUTLET FROM THE COMBUSTION ZONE

For considerations disclosed in this study, very important is the temperature of cupola gas leaving the combustion zone. It depends on the theoretical temperature of combustion, i.e. on the temperature which the non-dissociated gas can reach in combustion zone during isobaric-adiabatic combustion without any work input. For computation of this temperature it will be assumed that, when deprived of extra air, carbon contained in coke will burn to CO_2 , while the waste gas will be composed of CO_2 and N_2.

The, referred to 1 kg of coke, physical and chemical heat, coke- and blast air-borne to combustion zone, can be expressed by the following equation

$$q_d = W_u + c_k T_k + L_k c_p T_d \tag{1}$$

where:

- q_d – chemical (W_u) and physical heat of substrates referred to a unit coke weight, J/kg;
- W_u – calorific value of coke, J/kg;
- T_k – coke temperature on inlet to combustion zone, ^{o}C;
- c_k – mean specific heat of coke within the temperature range of 0^{o}C to T_k, J/(kg·K);
- T_d – blast air temperature, ^{o}C
- $L_{k,1}$ – air volume used for burning a unit coke weight in combustion zone (standard operating conditions), m^3/kg;
- c_p – mean specific heat of coke within the temperature range of 0^{o}C to T_d (standard operating conditions), J/(m^3·K).

The heat input q_d is used for preheating of the evolved gas to a temperature T_{sp}, defined as a theoretical temperature of combustion, which can be written down in the form of the following equation

$$q_d = V_{g,1} c'_{g,1} T_{sp} \tag{2}$$

where:

- $V_{g,1}$ – volume of gas evolved on burning a unit coke weight in combustion zone (standard operating conditions), m^3/kg;

$c'_{g,1}$ – mean specific heat of gas for the temperature range of 0°C up to an average gas temperature in combustion zone (gas pressure 0,1 MPa), J/(m^3·K);

T_{sp} – theoretical temperature of combustion, °C.

In equation (2), the heat used for overheating of the molten metal drops and slag moving through the zone of combustion has been initially neglected.

From equations (1) and (2) we obtain a formula for computation of T_{sp}

$$T_{sp} = \frac{W_u + c_k T_k}{V_{g,1} c'_{g,1}} + \frac{L_{k,1} + c_p T_d}{V_{g,1} c'_{g,1}} \tag{3}$$

A member in the right side of equation (3) has been intentionally isolated to allow for an effect of T_d on T_{sp}.

To compute from equation (3) a value of the theoretical temperature of combustion, the following values of the parameters have been adopted: W_u = 28,5·10^6 J/kg, c_k = 1700 J/(kg·K), T_k = 1300°C, $V_{g,1} = L_{k,1}$ = 8,9 · 0,86 = 7,654 m^3/ kg, C_k = 0,86 (carbon content in coke in a fraction of unity), $c'_{g,1}$ = 1693 J/(m^3·K) (for the gas temperature of 2400°C), c_p = 1300 J/(m^3·K) (for the blast temperature T_d = 300°C).

Having substituted the adopted data to equation (3), we obtain

$$T_{sp} = 2370 + 0{,}76\, T_d \tag{4}$$

From (4) it follows that for cold blast (T_d = 0) the value of T_{sp} = 2370°C. This is the temperature much higher than the highest temperature measured for a cold blast in combustion zone, and which usually does not go above 1800°C. Without going in this study any deeper into an analysis of how great are the individual heat losses suffered in combustion zone and the corresponding decrease of the theoretical temperature of combustion, for further studies a coefficient of the decrease of combustion temperature equal to ξ = 0,75 (dimensionless) will be adopted. This enables the highest temperature in the combustion zone $T_{g,1}$ to be expressed by equation

$$T_{g,1} = T_{sp}\, \xi = 1780 + 0{,}57 T_d \tag{5}$$

Then, the decrease of gas temperature in the combustion zone, caused by overheating of both liquid metal and slag, will be evaluated from the following equation of thermal balance

$$V_{g,1} c_{g,1} \Delta T_{g,1} = \frac{100}{K_W} \left(c'_m \Delta T_m + E_{\dot{z}}\, c_{\dot{z}}\, \Delta T_{\dot{z}} \right) \tag{6}$$

where:

$\Delta T_{g,1}$ – decrease of gas temperature in combustion zone due to the temperature of liquid metal and slag increasing by a value of ΔT_m and $\Delta T_{\dot{z}}$, K, respectively;

$c_{g,1}$ – mean specific heat of gas in combustion zone for the temperature range $\Delta T_{g,1}$ (gas pressure 0,1 MPa), J/(m^3·K);

K_W – coke charge consumption rate, $\dfrac{\text{kg coke}}{\text{100 kg Fe}}$ or wt. %;
c'_m – specific heat of liquid metal, J/(kg·K);
$c_{\dot{z}}$ – specific heat of liquid slag, J/(kg·K);
$E_{\dot{z}}$ – slag-to-metal ratio, a fraction of unity.

From the thermal balance given in (6), the following equation is derived

$$\Delta T_{g,1} = \frac{100\, c'_m \Delta T_m + 100 E_{\dot{z}} c_{\dot{z}} \Delta T_{\dot{z}}}{V_{g,1} c_{g,1} K_W} \tag{7}$$

As it follows from the numerous empirical data (e.g. mesh diagrams), the degree of molten metal overheating (and as it should justly be assumed – that of liquid slag, too) increases in a linear way along with the increasing coke consumption rate K_W. Since in equation (7) the degree of metal and slag overheating is placed in numerator, and of coke consumption rate in denominator, for different values of K_W a practically constant value can be expected in the case of gas temperature decrease $\Delta T_{g,1}$,. From equation (7) the value of $\Delta T_{g,1}$ will be computed for the following adopted values of parameters: c'_m = 850 J/(kg·K), $c_{\dot{z}}$ = 1050 J/(kg·K), K_W = 12%, $\Delta T_m = \Delta T_{\dot{z}}$ = 300 K, $E_{\dot{z}}$ = 0,05, $V_{g,1}$= 7,654 m^3/kg, $c_{g,1}$= 1810 J/(m^3·K). The, computed from equation (7), value of $\Delta T_{g,1}$ equals 162 K, which means that it makes about 10% of the value of $T_{g,1}$, determined from equation (5). By multiplying $T_{g,1}$ by 0,9 and rounding the obtained result, we can derive the following equation and use it for computation of the gas temperature on outlet from combustion zone

$$T_{g,2} = 1620 + 0{,}5\, T_d \tag{8}$$

Here, it should be emphasized that many authors have accepted the gas temperature on outlet from combustion zone as equal to 1620°C (cold blast), which confirms that the procedure adopted in deriving equation (8) has been the correct one.

Equation (8) will be used in computation of optimum blast air volume for both cold- -and hot-blast cupolas.

3. THEORETICAL EQUATION FOR DETERMINATION OF OPTIMUM BLAST AIR VOLUME

From the definition it follows that the optimum blast air volume is expected to ensure a maximum degree of molten metal overheating which, in turn, depends on an arrangement of the individual zones in cupola in respect of each other, and specifically on the combustion zone-melting zone design. In this study, for single-row coke cupolas, A. Achenbach condition [1] has been adopted, according to which the highest degree of molten cast iron overheating is obtained in a given cupola and under given input parameters when the lower boundary of the melting zone touches the upper boundary of the combustion zone. Under these conditions, the liquid metal undergoing some preliminary overheating in the melting zone, is next subjected to proper overheating in the combustion zone, as it is flowing along its entire height over the red-hot lumps of coke. If this condition is not satisfied, the degree of molten metal overheating will remain low, and this will be due mainly to the fact that either the lower melting zone boundary is placed below the upper combustion zone boundary (a part of the melting zone is located within the combustion zone), or the lower melting zone boundary is above the upper combustion zone boundary.

In the former case, the reduced degree of molten metal overheating is due to the fact that some of the heat "assigned" in the combustion zone for overheating of molten metal is *de facto* consumed for melting of metal present in this zone. In the latter case, the droplets of molten metal get cold while moving through the layers of coke separating the upper boundary of combustion zone from the lower boundary of a melting zone, because in these layers an endothermic reaction of reduction of a portion of CO_2 to CO takes place.

In single-row coke cupolas, the arrangement of melting and combustion zones in respect of each other depends mainly on the coke consumption rate, on the volume and temperature of blast air, on the weight, shape and melting point of the metallic charge lumps, on the coke reactivity, and – finally – on the height of the charge materials column above the level of tuyéres. The theoretical height of the charge materials column above the level of tuyéres H_m, for the zone arrangement according to Achenbach condition is calculated as a sum of the height of combustion zone (H_s), of melting zone (H_t) and of overheating (H_p), that is, as

$$H_m = H_s + H_t + H_p \tag{9}$$

Because of cupola design, the relation $H_m \le H_u$ holds good (where H_u – effective height of cupola, that is, the tuyéres level – charging door sill distance). In further discussion it will be assumed that $H_m = H_u$.

In deriving an equation which would be useful for computation of the optimum blast air volume, it is necessary to introduce to equation (9) the formulae used for calculation of H_s, H_t and H_p. Since the height of combustion zone depends to a small degree only on the blast air volume [2], in the present study a constant value of the combustion zone has been adopted, while the heights H_t and H_p have been calculated from relationships [3–6].

$$H_t = \frac{100 p_F \bar{r}_m K_{\rho,t} L_f \rho_m}{K_w L_k \alpha_2 \Delta T_{g,2} \rho_{n,m}} \ln \frac{T_{g,2} - T_{m,f}}{T_{g,3} - T_{m,f}} \tag{10}$$

$$H_p = \frac{100 p_F r_m K_\rho c_{m,3} \rho_m}{K_w L_k \alpha_3 (1 - m_{3,1}) \rho_{n,m}} \ln \frac{T_{g,4} - T_{m,o}}{T_{g,3} - T_{m,f}} \tag{11}$$

and:

$$K_{\rho,t} = 1 + \frac{K_w}{100 \varphi_v} \frac{\rho_{n,m}}{\rho_{n,k}} \tag{12}$$

$$K_\rho = 1 + \frac{K_w}{100} \frac{\rho_{n,m}}{\rho_{n,k}} \tag{13}$$

$$\Delta T_{g,2} = \frac{100 L_f}{V_g c_{g,2} K_w} \tag{14}$$

$$m_{3,1} = \frac{100 c_{m,3}}{V_g c_{g,3} K_w} \tag{15}$$

where:

p_F – blast air volume referred to 1 m^2 of an internal cupola cross-section (standard operating conditions), $m^3/(m^2 \cdot s)$;

$\bar{r}_m = \frac{v_{m,o}}{f_{m,o}} \frac{\varphi_v}{\varphi_f}$ – mean total modulus of metallic charge lumps in the melting zone, m;

$V_{m,o}, f_{m,o}$ – initial volume and surface area of metallic charge lumps, respectively;

φ_v, φ_f – dimensionless coefficients for initial volume and surface area of metallic charge lumps, respectively;

K_w – charge coke consumption rate, $\frac{\text{kg coke}}{\text{100 kg Fe}}$ or wt. %;

$\rho_{n,m}$ – bulk density of metal, kg/m^3;

$\rho_{n,k}$ – bulk density of coke, kg/m^3;

L_f – heat of metal fusion, J/kg;

ρ_m – density of metallic charge lumps, kg/m^3;

α_2 – coefficient of heat transfer in the melting zone, $W/(m^2 \cdot K)$;

L_k – air volume consumed to burn 1 kg of coke, calculated from the chemical composition of waste gas (standard operating conditions), m^3/kg;

V_g – gas volume evolved while burning 1 kg of coke, calculated from the chemical composition of waste gas (standard operating conditions), m^3/kg;

$\bar{c}_{g,2}$ – mean specific heat of gas in the melting zone, $J/(m^3 \cdot K)$;

$\Delta T_{g,2}$ – decrease of gas temperature in the melting zone, K;

$\Delta T_{g,2} = T_{g,2} - T_{g,3}$;

$T_{g,2}$ – temperature determined from equation (8);

$T_{g,3}$ – gas temperature on outlet from the melting zone (and on inlet to the heating zone), °C

$T_{m,f}$ – melting point of metallic charge, ^oC;

$c_{m,3}$ – specific heat of a mixture of materials filling the heating zone, $J/(kg \cdot K)$;

α_3 – coefficient of heat transfer in the heating zone, $W/(m^2 \cdot K)$;

$\bar{c}_{g,3}$ – mean specific heat of gas in the heating zone, $J/(m^3 \cdot K)$;

$T_{g,4}$ – gas temperature on upper boundary of the heating zone, ^oC;

$T_{m,o}$ – initial temperature of metallic charge, ^oC;

$r_m = \frac{v_{m,o}}{f_{m,o}}$ – initial modulus of the metallic charge lumps, m.

To ensure that equations (9), (10) and (11) form a coherent thermal system and satisfy *A*. Achenbach postulate, it is necessary to impose onto them the conditions related with boundary temperatures $T_{g,3}$ and $T_{g,4}$, determined by relationships:

$$T_{g,3} = T_{g,2} - \Delta T_{g,2} \tag{16}$$

$$T_{g,4} = T_{g,3} - m_{3,1}(T_{m,f} - T_{m,o}) \tag{17}$$

Equations (9)–(17) serve to compute optimum blast air volume, which will be designated as $p_{F,o}$. The main equation used to compute this volume is derived from equations (9), (10) and (11) for $H_m = H_u$

$$p_{F,o} = \frac{K_w L_k \rho_{n,m}(H_u - H_s)}{100 r_m \rho_m \left[\frac{\varphi \cdot K_{\rho,t} L_f}{\alpha_2 \Delta T_{g,2}} \ln \frac{T_{g,2} - T_{m,f}}{T_{g,3} - T_{m,f}} + \frac{K_\rho c_{m,3}}{\alpha_3(1 - m_{3,1})} \ln \frac{T_{g,4} - T_{m,o}}{T_{g,3} - T_{m,f}} \right]} \tag{18}$$

where: $\varphi = \dfrac{\varphi_v}{\varphi_f}$.

The cupola melting rate corresponding to an optimum blast air volume is computed from the well-known conversion formula proposed by J. Buzek [7]

$$S_{F,o} = 100 \frac{p_{F,o}}{K_w L_k} \tag{19}$$

where $S_{F,o}$ – cupola melting rate corresponding to an optimum blast air volume, kg/(m^2·s)

4. COMPLEMENTARY EQUATIONS

In practical computation of the optimum blast air volume according to equation (18), it is necessary to derive additional equations enabling computation of V_g, L_k, $\bar{c}_{g,2}$, $\bar{c}_{g,3}$, $c_{m,3}$, φ_v, φ_f, Δ_2, Δ_3 and to know exactly the composition of the cupola waste gas. Let us consider now this problem.

In computation of V_g and L_k we can use some equations known from the heat engineering, allowing for a parameter called combustion degree. These equations assume the following form:

$$V_g = 0{,}054(100 + 0{,}65\eta_v)C_k \tag{20}$$

$$L_k = 4{,}45(1 + 0{,}01\eta_v)C_k \tag{21}$$

and

$$\eta_v = \frac{(CO_2)_v}{(CO_2)_v + (CO)_v} 100 \tag{22}$$

where:

η_v – combustion degree, vol. %,
$(CO_2)_v$ – CO_2 content in waste cupola gas, standard operating conditions, vol. %,
$(CO)_v$ – CO content in waste cupola gas, standard operating conditions, vol. %.

Equations (20) and (21) refer to the blast air with standard content of oxygen.

The equation used to compute the mean specific heat of cupola waste gas was derived under the following assumptions [8]:

- cupola waste gas is a mixture of CO_2, CO and N_2 (the small content of H_2, O_2, and H_2O in the gas was intentionally disregarded),
- the specific heat of a gas mixture is equal to the sum of products of the volume content of individual gases in this mixture multiplied by their mean specific heat values c_g,
- a distinction has been made between the mean specific heat typical of the temperature range from 0^oC up to a given gas temperature T_g (generally denoted by c_g) and the mean specific heat typical of any arbitrary range of temperatures T_g' and T_g'' (generally denoted by $\bar{c}_g$).

The equation derived to compute c_g for standard oxygen content in blast air assumes a general form of

$$c_g = A + B \frac{\eta_v}{100 + 0,65\eta_v} \tag{23}$$

where: A and B – constants, compiled in Table 1.

Table 1 also gives the values of c_g, calculated from equation (23) for η_v = 100, 50 and 0%, and the values of enthalpy ($c_g \cdot T_g$).

In the case of gas temperatures different than those stated in Table 1, the values of c_g are calculated from the equation given below

$$c_{g,x} = c_{g,w} - \frac{c_{g,w} - c_{g,n}}{100}(T_{g,w} - T_{g,x}) \tag{24}$$

or from

$$c_{g,x} = c_{g,n} + \frac{c_{g,w} - c_{g,n}}{100}(T_{g,x} - T_{g,n}) \tag{25}$$

where:

$c_{g,x}$ – mean specific heat for temperature range from 0^oC up to a given temperature $T_{g,x}$, J/($m^3 \cdot K$)(pressure of 0,1 MPa);
$T_{g,w}$, $T_{g,n}$ – gas temperatures given in Table 1: $T_{g,w} > T_{g,x}$ and $T_{g,n} < T_{g,x}$;
$c_{g,w}$, $c_{g,n}$ – the values of c_g for temperatures $T_{g,w}$ and $T_{g,n}$, respectively, determined from Table 1.

Table 1. Complementary data to compute the value of the mean specific heat of cupola waste gas

$$c_g = A + B\frac{\eta_v}{100 + 0,65\eta_v}$$

T_g	Value A	Value B	Computed values					
			$\eta_v = 100$		$\eta_v = 50$		$\eta_v = 0$	
			%		%		%	
			c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$
°C	–	–	$\frac{J}{m^3 \cdot K}$	$\frac{MJ}{m^3}$	$\frac{J}{m^3 \cdot K}$	$\frac{MJ}{m^3}$	$\frac{J}{m^3 \cdot K}$	$\frac{MJ}{m^3}$
0	1282.0	103.1	1344.5	0	1320.9	0	1282.0	0
100	1283.7	135.9	1366.1	0.137	1335.0	0.133	1283.7	0.128
200	1288.0	163.8	1387.3	0.277	1349.8	0.270	1288.0	0.258
300	1296.1	185.7	1408.6	0.423	1366.2	0.410	1296.1	0.389
400	1306.8	203.9	1430.4	0.572	1383.7	0.554	1306.8	0.523
500	1318.5	219.4	1451.5	0.726	1401.3	0.700	1318.5	0.659
600	1331.2	231.5	1471.5	0.883	1418.6	0.851	1331.2	0.799
700	1345.5	242.4	1492.4	1.045	1437.0	1.006	1345.5	0.942
800	1358.9	251.8	1511.5	1.209	1453.9	1.163	1358.9	1.087
900	1372.2	259.9	1529.7	1.377	1470.3	1.323	1372.2	1.235
1000	1384.6	267.0	1546.4	1.546	1485.4	1.485	1384.6	1.385
1100	1396.2	274.2	1562.4	1.719	1489.5	1.638	1396.2	1.536
1200	1406.6	279.8	1576.2	1.891	1512.2	1.815	1406.6	1.688
1300	1417.6	285.0	1590.3	2.067	1525.1	1.983	1417.6	1.843
1400	1427.6	289.9	1603.3	2.245	1537.0	2.152	1427.6	1.997
1500	1436.6	293.7	1614.6	2.422	1547.4	2.321	1436.6	2.155
1600	1445.6	297.5	1625.9	2.601	1557.9	2.493	1445.6	2.313
1700	1453.6	301.3	1636.2	2.782	1567.3	2.664	1453.6	2.471
1800	1461.2	305.4	1646.3	2.963	1576.5	2.838	1461.2	2.630
1900	1467.9	308.7	1655.0	3.145	1584.4	3.010	1467.9	2.789
2000	1474.9	311.2	1663.5	3.327	1592.3	3.185	1474.9	2.950
2100	1480.9	314.0	1671.2	3.510	1599.4	3.359	1480.9	3.110
2200	1486.9	316.0	1678.4	3.693	1602.2	3.534	1486.9	3.271
2300	1491.9	318.5	1684.9	3.875	1612.1	3.708	1491.9	3.431
2400	1497.9	320.2	1692.0	4.061	1618.7	3.885	1497.9	3.595
2500	1502.9	321.9	1698.0	4.245	1624.4	4.061	1502.9	3.757

The mean specific heat for any arbitrary range of temperatures $T_{g,x} = T'_g$ and $T_{g,x} = T''_g$ is computed from the following equation

$$\overline{c}_g = \frac{c'_g T'_g - c''_g T''_g}{T'_g - T''_g} \tag{26}$$

where: c'_g, c''_g – the values of mean specific heat for temperatures T'_g and T''_g, J/(m^3·K), respectively.

As it has already been mentioned, using equation (18) in practice requires thorough knowledge of the combustion degree η_v, calculated from the chemical composition of cupola waste gas. Since general theoretical relationships necessary to calculate η_v, are still not available, this parameter can be computed from the empirical equations published in literature.

In this study we shall be using H. Jungbluth equation [9], which assumes the following form

$$\eta_v = \left(\frac{3{,}865}{K_w C_k} + 0{,}15\right)100 \tag{27}$$

Equation (27) will be used for both cold and hot blast, although originally it has been derived for the cold-blast cupolas only. It has been decided to extend its use to hot-blast cupolas after having ascertained that temperature has but only a very insignificant effect on the value of η_v. On the other hand, it should be emphasized that the value of η_v depends very strongly on the physico-chemical quality of coke (its reactivity) and on the coke lumps size.

Using relationships (27) and (23), Table 2 was drawn. It comprises the values of c_g and $c_g{\cdot}T_g$ for coke charge K_w, changing within the range of 10 to 15%.

The following equation has been proposed for use to compute the value of $c_{m,3}$; it allows for the presence of coke and limestone in cupola charge ($CaCO_3$ making 5 wt. % of the coke charge).

$$c_{m,3} = 750 + 8K_w \tag{28}$$

Coefficients φ_v and φ_f are calculated from the following equations for metal pieces in the form of rectangular plates, prisms, cubes, and spheres [4]:

$$\varphi_v = \frac{1}{2} - \frac{1}{6m_b} - \frac{1}{6m_c} + \frac{1}{12m_b m_c} \tag{29}$$

$$\varphi_f = \frac{m_b m_c}{m_b + m_c + m_b m_c} \tag{30}$$

where:

$m_b = \frac{b}{a}$, $m_c = \frac{c}{a}$,

a, b, c – thickness, width and length of a plate, respectively (for cubes and spheres $a = b = c$).

Coefficients α_2 and α_3 will be accepted as equal to 200 and 150 W/(m^2·K), respectively, since literature cannot offer any reliable equation for their computation.

Table 2. A set of values of the mean specific heat of cupola waste gas (the degree of combustion determined from H. Jungbluth empirical equation)

K, %	10		11		12		13		14		15	
T_g, °C	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$	c_g	$c_g \cdot T_g$
0	1326	0	1324	0	1322	0	1320	0	1319	0	1318	0
100	1342	134206.9	1339	133916.2	1337	133665	1334	133445.8	1333	133252.9	1331	133081,8
200	1358	271677.9	1355	270977.2	1352	270371.8	1349	269843.6	1347	269378.7	1345	268966.3
300	1376	412746.8	1372	411555.5	1368	410526.2	1365	409628.1	1363	408837.6	1360	408136.3
400	1394	557747.2	1390	556002.3	1386	554494.9	1383	553179.5	1380	552021.6	1377	550994.6
500	1413	706360.4	1408	704013,6	1404	701986	1400	700216.8	1397	698659.4	1395	697278
600	1431	858350.2	1426	855379,4	1421	852812.9	1418	850573.4	1414	848602.1	1411	846853.6
700	1450	1014721	1444	1011092	1440	1007957	1436	1005222	1433	1002814	1430	1000678
800	1467	1173618	1462	1169309	1457	1165586	1453	1162337	1449	1159478	1446	1156941
900	1484	1335464	1478	1330460	1473	1326137	1469	1322365	1466	1319044	1462	1316099
1000	1499	1499227	1494	1493516	1489	1488582	1484	1484277	1480	1480487	1477	1477126
1100	1514	1665355	1508	1658904	1503	1653331	1499	1648468	1495	1644188	1491	1640391
1200	1527	1832090	1521	1824907	1516	1818702	1511	1813287	1507	1808521	1504	1804293
1300	1540	2001970	1534	1994044	1529	1987197	1524	1981221	1520	1975962	1516	1971297
1400	1552	2172889	1546	2164208	1541	2156708	1536	2150163	1532	2144403	1528	2139293
1500	1563	2344054	1556	2334631	1551	2326489	1546	2319385	1542	2313132	1538	2307585
1600	1573	2517348	1567	2507165	1561	2498368	1557	2490692	1552	2483935	1549	2477942
1700	1583	2691069	1577	2680111	1571	2670644	1566	2662384	1562	2655112	1558	2648663
1800	1592	2866270	1586	2854512	1580	2844354	1575	2835490	1571	2827688	1567	2820767
1900	1600	3040884	1594	3028336	1588	3017496	1583	3008037	1579	2999711	1575	2992325
2000	1609	3217017	1602	3203705	1596	3192204	1591	3182169	1587	3173336	1583	3165500
2100	1616	3392971	1609	3378869	1603	3366686	1598	3356055	1594	3346697	1590	3338396
2200	1623	3569709	1616	3554837	1610	3541989	1605	3530778	1600	3520909	1596	3512156
2300	1629	3745868	1622	3730201	1616	3716665	1611	3704855	1606	3694458	1602	3685237
2400	1635	3924920	1629	3908483	1623	3894282	1617	3881890	1613	3870983	1609	3861308
2500	1641	4102821	1634	4085606	1628	4070734	1623	4057756	1619	4046333	1614	4036200

5. EXAMPLES OF COMPUTATION OF OPTIMUM BLAST AIR VOLUME

Example 1. Remelting of cast iron scrap in cold-blast cupola

Data: H_u = 5 m, H_s = 0,3 m, a = 0,05 m, b = 0,2 m, c = 0,3 m, K_w = 12%, C_k = 0,86, $\rho_{n,m}$ = 2500 kg/m^3, ρ_m = 7000 kg/m^3, $\rho_{n,k}$ = 500 kg/m^3, $T_{m,f}$ = 1150°C, $T_{m,o}$ = 20^{o}C, T_d = 0^{o}C, $T_{g,2}$ = 1620^{o}C, [according to Eq. (8)], α_2 = 200 W/(m^2·K), α_3 = 150 W/(m^2·K).

Supporting computations: $v_{m,o}$ = 3·10^{-3} m^3, $f_{m,o}$ = 0,17 m^2, φ_v = 0,434, φ_f = 0,708, r_m= 0,0176 m, $\overline{r_m}$ = 0,011 m, $K_{\rho,t}$ = 2,38, K_ρ = 1,6, V_g = 6,21 m^3/kg, L_k = 5,82 m^3/kg, $\overline{c}_{g,2}$ = 1708 J/(m^3·K) (for the temperature range of 1600 to 1400^{o}C), $\overline{c}_{g,3}$ = 1602 J/(m^3·K) (for the temperature range of 1400 to 500^{o}C), $\Delta T_{g,2}$ = 236 K, $T_{g,3}$ = 1384^{o}C, $c_{m,3}$ = 846 J/(kg·K), $m_{3,1}$ = 0,71, $T_{g,4}$= 582^{o}C.

Computation of $p_{F,o}$ and $S_{F,o}$,
$p_{F,o}$ = 1,76 m^3/(m^2·s) [105,6 m^3/(m^2·min)],
$S_{F,o}$ = 2,52 kg/(m^2·s) [9072 kg/(m^2·h)].

Example 2. Remelting of cast iron scrap in hot-blast cupola

We assume T_d = 300^{o}C; other input data are left unchanged. Now we calculate new values of the parameters in equation (18) which are subject to changes. $T_{g,2}$= 1620 + 0,5.300 = = 1770^{o}C, $\overline{c}_{g,2}$ = 1730 J/(m^3·K) (for the temperature range of 1800 to 1600^{o}C, $\Delta T_{g,2}$ = 233 K, $\overline{c}_{g,3}$ = 1656 J/(m^3·K) (for the temperature range of 1600 to 700^{o}C, $m_{3,1}$= 0,68, $T_{g,3}$= 1537^{o}C, $T_{g,4}$= 768^{o}C.

From equation (18) we calculate $p_{F,o}$ = 2,57 m^3/(m^2·s) [154,2 m^3/(m^2·min)] and from equation (19) $S_{F,o}$ = 3,68 kg/(m^2·s) [13247 kg/(m^2·h)].

6. CONCLUSIONS

In this study a formula was derived to calculate optimum volume of cupola blast air [m^3/(m^2·s), standard operating conditions], cold or hot, for single-row coke cupolas, assuming that the lower boundary of the melting zone is adhacent to the upper boundary of the combustion zone (the condition of optimum cupola running formulated by A. Achenbach in 1931). Relevant equations and tables have also been developed to make the calculations easier.

From the derived equation (18) it directly follows that the optimum blast air volume is increasing with increasing height of the charge materials column above the lever of tuyéres (H_u), with increasing coke-to-metallic charge ratio (K_w) and heat transfer coefficients (α_2 and α_3); on the other hand, it decreases with increasing modulus of the metallic charge lumps (r_m). From the conducted computations it also follows that $p_{F,o}$ increases with increasing temperature of the blast air supplied to cupola, which is consistent with W. Patterson and F. Neumann conclusions formulated earlier in an empirical study [10]. It has to be remembered, however, that – as admitted very explicitly by those authors themselves, in their studies they had never been able to determine the extrema while using a blast preheated up to 300°C, the main reason being that in the trials they were conducting the fans of a sufficiently high output were not available.

The value of $p_{F,o}$, calculated in this study for a cold-blast cupola, is very close to the value which J. Buzek claims to be an optimum one [7] [Buzek postulate : $p_{F,o}$ = 100 $m^3/(m^2 \cdot s)$].

From computations comprised in this study it also follows that with T_d increasing, the gas temperature in the melting and combustion zones will increase, too, equally as a temperature of the waste gas. The increase of gas temperature in the melting and combustion zones results in an increase of the molten metal overheating degree.

To improve the accuracy of computations made according to equation (18), it is necessary to, first of all, state precisely the values of coefficients α_2 and α_3.

REFERENCES

[1] *Achenbach A.*: Der Giessereischachtofen in Theorie und Praxis. Verlag M. Jänecke, Leipzig, 1931

[2] *Podrzucki C., Kalata C.*: Metalurgia i odlewnictwo żeliwa. Wyd. 2. Wyd. Śląsk, 1976

[3] *Longa W.*: Calculation of Melting Zone Height in Coke Cupolas. Archives of Metallurgy, 43 (1998), Issue 2

[4] *Longa W., Freibe G.*: Berechung der stabilen Höhe der Schmelzzone in koksbetriebenen Kupolofen. Giesserei Forschung, 53 (2001) 2

[5] *Longa W.*: Formulas for Calculation of Gasses and Metal's Temperature in the Heating Zone of Cupola. Metallurgy and Foundry Eng., 23 (1997) 1

[6] *Longa W., Freibe G.*: Wärmetheoretische Berechnungen der Vorwärmzone eines Kupolofens. Giesserei Forschung, 51 (1999) 3

[7] *Czyżewski M.*: Podstawowe wzory Jerzego Buzka, charakteryzujące pracę żeliwiaka. Przegląd Odlewnictwa, (1951) 4

[8] Teoretyczne podstawy obliczania sprawności cieplnej żeliwiaków koksowych. Statutory research work of the Faculty of Foundry Engineering AGH-UST year 2004

[9] *Junghbluth H.*: Die Gesetze des Kupolofenschmelzens. Die Giesserei (1939) 113

[10] *Patterson W.*, Neumann F.: Gesetzmässigkeiten des Schmelzens im Kupolofen. Giesserei (1961) 3

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