Belkheir Khatemi*, Władysław Longa**

**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 \([\text{m}^3/\text{m}^2\cdot\text{s}] – \text{standard operating conditions}\) 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

$$q_d = W_u + c_k T_k + L_k c_p T_d$$

(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, °C;
- $c_k$ – mean specific heat of coke within the temperature range of 0°C to $T_k$, J/(kg·K);
- $T_d$ – blast air temperature, °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°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

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

(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/(m³·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 \( T_{sp} \)

\[
T_{sp} = \frac{W_u + c_k T_k}{V_{g,1} c_{g,1}'} + \frac{L_{k,1} + c_p' T_d}{V_{g,1} c_{g,1}'}
\]  

(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: \( W_u = 28.5 \times 10^6 \) J/kg, \( c_k = 1700 \) J/(kg·K), \( T_k = 1300°C, V_{g,1} = 8.9 \cdot 0.86 = 7.654 \) m³/kg, \( c_k = 0.86 \) (carbon content in coke in a fraction of unity), \( c_{g,1}' = 1693 \) J/(m³·K) (for the gas temperature of 2400°C), \( c_p' = 1300 \) J/(m³·K) (for the blast temperature \( T_d = 300°C \)).

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

\[
T_{sp} = 2370 + 0.76 T_d
\]  

(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 \( \xi = 0.75 \) (dimensionless) will be adopted. This enables the highest temperature in the combustion zone \( T_{g,1} \) to be expressed by equation

\[
T_{g,1} = T_{sp} \xi = 1780 + 0.57 T_d
\]  

(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

\[
V_{g,1} c_{g,1}' \Delta T_{g,1} = \frac{100}{K_B} (c_{m}' \Delta T_m + E_z c_z \Delta T_z)
\]  

(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 \( \Delta T_m \) and \( \Delta T_z \), 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/(m³·K);
\[ K_W \quad \text{coke charge consumption rate, } \frac{\text{kg coke}}{100 \text{ kg Fe}} \text{ or wt. \%;} \]

\[ c'_m \quad \text{specific heat of liquid metal, } \frac{\text{J}}{(\text{kg} \cdot \text{K})}; \]

\[ c_z \quad \text{specific heat of liquid slag, } \frac{\text{J}}{(\text{kg} \cdot \text{K})}; \]

\[ E_z \quad \text{slag-to-metal ratio, a fraction of unity.} \]

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

\[ \Delta T_{g,1} = \frac{100 c'_m \Delta T_m + 100E_z c_z \Delta T_z}{V_{g,1} c_{g,1} K_W} \]  \hspace{1cm} \text{(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 \frac{\text{J}}{(\text{kg} \cdot \text{K})}, \]

\[ c_z = 1050 \frac{\text{J}}{(\text{kg} \cdot \text{K})}, \]

\[ K_W = 12\%, \quad \Delta T_m = \Delta T_z = 300 \text{ K}, \quad E_z = 0,05, \quad V_{g,1} = 7,654 \frac{\text{m}^3}{\text{kg}}, \]

\[ c_{g,1} = 1810 \frac{\text{J}}{(\text{m}^3 \cdot \text{K})}. \]

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

\[ T_{g,2} = 1620 + 0,5 T_d \]  \hspace{1cm} \text{(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 bound-
ary (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 bound-
ary of combustion zone from the lower boundary of a melting zone, because in these layers
an endothermic reaction of reduction of a portion of CO₂ to CO takes place.

In single-row coke cupolas, the arrangement of melting and combustion zones in re-
spect of each other depends mainly on the coke consumption rate, on the volume and tem-
perature 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 tuyères. The theoretical height of the charge materials column above the level of
tuyères \( H_m \), 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,

\[
H_m = H_s + H_t + H_p
\]  

Because of cupola design, the relation \( H_m \leq H_u \) holds good (where \( H_u \) – effective
height of cupula, that is, the tuyères level – charging door sill distance). In further discus-
sion 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].

\[
H_t = \frac{100 p_F m K_p L_f m_0}{K_n c_2 \Delta T_{g.2} \rho_{n,m}} \ln \frac{T_{g.2} - T_{m, f}}{T_{g.3} - T_{m, f}}
\]  

\[
H_p = \frac{100 p_F m K_p c_{m, m} \rho_{m}}{K_n c_3 (1 - m_{3,1}) \rho_{n,m}} \ln \frac{T_{g.4} - T_{m, o}}{T_{g.3} - T_{m, f}}
\]

and:

\[
K_{p,t} = 1 + \frac{K_w}{100 \rho_v} \frac{\rho_{n,m}}{\rho_{n,k}}
\]  

\[
K_p = 1 + \frac{K_w}{100 \rho_v} \frac{\rho_{n,m}}{\rho_{n,k}}
\]
\[ \Delta T_{g,2} = \frac{100L_f}{V_g c_{g,2} K_w} \]  
(14)

\[ m_{3,1} = \frac{100e_{m,3}}{V_g c_{g,3} K_w} \]  
(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;
- \( \varphi_v, \varphi_f \) – dimensionless coefficients for initial volume and surface area of metallic charge lumps, respectively;
- \( K_w \) – charge coke consumption rate, \( \frac{kg\ coke}{100 \ kg \ Fe} \) 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, \( J/kg \);
- \( \rho_m \) – density of metallic charge lumps, \( kg/m^3 \);
- \( \alpha_2 \) – 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), \( ^\circ C \);
- \( T_{m,f} \) – melting point of metallic charge, \( ^\circ C \);
- \( c_{m,3} \) – specific heat of a mixture of materials filling the heating zone, \( J/(kg\cdot K) \);
- \( \alpha_3 \) – 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, \( ^\circ C \);
- \( T_{m,o} \) – initial temperature of metallic charge, \( ^\circ C \);
- \( r_m = \frac{v_{m,o}}{f_{m,o}} \) – 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:

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

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

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 $H_m = H_u$

$$p_{F,o} = \frac{K_w L_k \rho_{m,m}(H_u - H_4)}{100 \rho_m \rho_m \phi_f \phi_f \varphi_2 \Delta T_{g,2} + \frac{K_p c_{m,3}}{\alpha_2 \Delta T_{g,2}} \ln \frac{T_{g,2} - T_{m,f}}{T_{g,3} - T_{m,f}} + \frac{K_p c_{m,3}}{\alpha_3 (1 - m_{3,1})} \ln \frac{T_{g,4} - T_{m,o}}{T_{g,4} - T_{m,f}}$$

where: $\phi = \frac{\varphi_v}{\varphi_f}$

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

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

where $S_{F,o}$ – cupola melting rate corresponding to an optimum blast air volume, kg/(m²·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 $V_g$, $L_k$, $F_{g,2}$, $F_{g,3}$, $c_{m,3}$, $\varphi_v$, $\varphi$, $\Delta_2$, $\Delta_3$, 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:

$$V_g = 0.054(100 + 0.65\eta_v)C_k$$

$$L_k = 4.45(1 + 0.01\eta_v)C_k$$

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\[ \eta_v = \frac{(CO_2)_v}{(CO_2)_v + (CO)_v} \times 100 \]  

(22)

where:
- \( \eta_v \) – 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°C 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

\[ c_g = A + B \frac{\eta_v}{100 + 0.65\eta_v} \]  

(23)

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

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

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

\[ c_{g,x} = c_{g,w} - \frac{c_{g,w} - c_{g,n}}{100} (T_{g,w} - T_{g,x}) \]  

(24)

or from

\[ c_{g,x} = c_{g,n} + \frac{c_{g,n} - c_{g,w}}{100} (T_{g,x} - T_{g,n}) \]  

(25)

where:
- \( c_{g,x} \) – mean specific heat for temperature range from 0°C up to a given temperature \( T_{g,x} \), J/(m³·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

<table>
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<th>Value A</th>
<th>Value B</th>
<th>Computed values</th>
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<td>$\frac{\text{MJ}}{\text{m}^3}$</td>
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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

$$
\bar{c}_g = \frac{c'_g T'_g - c''_g T''_g}{T'_g - T''_g}
$$

(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 $\eta_v$, calculated from the chemical composition of cupola waste gas. Since general theoretical relationships necessary to calculate $\eta_v$, 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

$$
\eta_v = \left( \frac{3.865}{K_w C_k} + 0.15 \right) 100
$$

(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 $\eta_v$. On the other hand, it should be emphasized that the value of $\eta_v$ 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 $c_g T_g$ 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).

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

(28)

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

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

(29)

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

(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 $\alpha_2$ and $\alpha_3$ 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)

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5. EXAMPLES OF COMPUTATION OF OPTIMUM BLAST AIR VOLUME

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

Data: \( H_u = 5 \text{ m}, H_s = 0,3 \text{ m}, a = 0,05 \text{ m}, b = 0,2 \text{ m}, c = 0,3 \text{ m}, K_w = 12\%, C_k = 0,86, \\)
\( \rho_{n,m} = 2500 \text{ kg/m}^3, \rho_m = 7000 \text{ kg/m}^3, \rho_{n,k} = 500 \text{ kg/m}^3, T_{m,f} = 1150\text{°C}, T_{m,o} = 20\text{°C}, \\)
\( T_d = 0\text{°C}, T_{g,2} = 1620\text{°C}, \) [according to Eq. (8)], \( \alpha_2 = 200 \text{ W/(m}^2\text{·K)}, \alpha_3 = 150 \text{ W/(m}^2\text{·K)}. \)

Supporting computations: \( \nu_{m,o} = 3\cdot10^{-3} \text{ m}^3, f_{m,o} = 0,17 \text{ m}^2, \varphi_v = 0,434, \varphi_f = 0,708, \\)
\( r_m = 0,0176 \text{ m}, T_m = 0,011 \text{ m}, K_{p,f} = 2,38, K_p = 1,6, V_g = 6,21 \text{ m}^3/\text{kg}, L_k = 5,82 \text{ m}^3/\text{kg}, \\)
\( \tau_{g,2} = 1708 \text{ J/(m}^3\text{·K)} (\text{for the temperature range of 1600 to 1400}°\text{C}), \tau_{g,3} = 1602 \text{ J/(m}^3\text{·K)} (\text{for the temperature range of 1400 to 500}°\text{C}), \Delta T_{g,2} = 236 \text{ K}, T_{g,3} = 1384°\text{C}, c_{m,3} = 846 \text{ J/(kg·K)}, \\)
m_{3,1} = 0,71, \( T_{g,4} = 582°\text{C}. \)

Computation of \( p_{F,o} \) and \( S_{F,o} \),

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

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

We assume \( T_d = 300°\text{C}; \) 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\cdot300 = = 1770°\text{C}, T_{g,3} = 1730 \text{ J/(m}^3\text{·K)} (\text{for the temperature range of 1800 to 1600}°\text{C}, \Delta T_{g,2} = 233 \text{ K}, \tau_{g,3} = 1656 \text{ J/(m}^3\text{·K)} (\text{for the temperature range of 1600 to 700}°\text{C}, m_{3,1} = 0,68, T_{g,3} = 1537°\text{C}, \\)
\( T_{g,4} = 768°\text{C}. \)

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

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 tuyères (\( H_u \)), with increasing coke-to-metallic charge ratio (\( K_w \)) and heat transfer coefficients (\( \alpha_2 \) and \( \alpha_3 \)), 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 pre-
heated 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 $p_{E,o}$ 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] \[Buzek postulate : p_{E,o} = 100 \text{ m}^3/(\text{m}^2\cdot\text{s})\].

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 $\alpha_2$ and $\alpha_3$.

REFERENCES

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

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