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MASSIVE, VOLUMETRIC AND ENERGETIC EFFECTS OF COAL EXCHANGE BETWEEN COKE AND EXHAUST GASES AT VARIOUS LEVELS OF CUPOLA PROCESSING STACK

EFEKTY MASOWE, OBJĘTOŚCIOWE I ENERGETYCZNE WYMIANY WĘGLA POMIĘDZY KOKSEM A GAZAMI NA RÓŻNYCH POZIOMACH SŁUPA PRZETWOROWEGO ŹELIWIĄKÓW

Formulas for the calculation of mass, volume and energetic effects bound with reaction $\text{CO}_2 + \text{C} = 2 \text{CO}$ have been derived in the paper. The effects occur in the charge coke, which pass from the upper boundary of the heating zone to the lower boundary of the combustion zone as well as in the cupola gases generated in the combustion area and moving through the charge material stack to the upper boundary of the heating region. The formulas include the effects at the lower levels and the maximum effects i.e. occurring between the lower boundary of the combustion zone and the upper melting region.

The presented example of calculations contains full information on the size of analyzed reaction effects and describes its energetic model.

The work contributes to the elaboration of so far inexistent theory of thermal zone and subzone balances of cupolas as well as the method of calculation of gas temperature at the sub- and zone boundaries followed by the kinetics of zone processes, which depend on the temperature of gases

Keywords: cupola, coke, CO_2 reduction; formation of CO, exchange of coal, energy exchange

W pracy wyprowadza się wzory do obliczania efektów masowych, objętościowych i energetycznych, związanych z reakcją $\text{CO}_2 + \text{C} = 2 \text{CO}$. Wymienione efekty zachodzą w koksie wsadowym, przemieszczającym się od górnej granicy strefy podgrzania do dolnej granicy strefy spalania oraz w gazach żeliwiakowych, generowanych w strefie spalania, a następnie przemieszczających się przez słup materiałów wsadowych do górnej granicy strefy podgrzania. Wzory obejmują efekty pomiędzy dowolnymi poziomami oraz maksymalne efekty, tj. zachodzące pomiędzy dolną granicą strefy spalania a górną granicą strefy podgrzania.

Przedstawiony w pracy przykład obliczeniowy zawiera pełną informację o wielkości efektów analizowanej reakcji oraz identyfikuje jej energetyczny model.

Praca stanowi podstawę do zbudowania, dotąd nieistniejącej, teorii bilansów cieplnych strefowych i substrefowych żeliwiaków oraz metody obliczania temperatury gazów na granicach stref i substref, a następnie kinetyki procesów strefowych, zależnych od temperatury gazów.

Denotations

* – upper index in denotations of gas volume and energetic effects informs that the given value refers to 100 kg of metallic charge, i.e. Fe

$(\text{CO}_2)_{v,i}, (\text{CO})_{v,i}$ – CO_2 and CO content in cupola gases at level **i**, respectively, normal conditions, vol.%

C_k – content of C in coke, $\text{kg}_C/\text{kg}_{\text{coke}}$

$G_{co,i}$ – weight of C in CO at level **i** $\text{kg}_C/100 \text{ kg}_{Fe}$

$G_{co_2,i}$ – weight of C in CO_2 at level **i**, $\text{kg}_C/100 \text{ kg}_{Fe}$

i – general denotation of zones and subzones (CO_2 reduction zone); **i=1**; **i=2**; **i=2'**; **i=3**; **i=3'**; **i=4**

i=1 – the lower (conventional) boundary of combustion zone and the lower limit of first reduction area,

i=2 – upper boundary of combustion zone and upper limit of first reduction area as well as lower limit of melting zone and lower boundary of second subzone of reduction,

i=2' – upper boundary of second subzone of reduction and simultaneously upper limit of third subarea of reduction,

i=3 – upper limit of melting zone and upper boundary of third subzone of reduction and also lower limit of heating zone and lower limit of fourth reduction zone,

i=3' – upper limit of fourth reduction subzone and lower limit of neutral subzone,

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$i=4$ – upper limit of heating zone and upper limit of neutral subzone,

$K_{C,i}$ – contribution of coal in charge coke of the processing stack at level i $\text{kg}_C/100 \text{ kg}_{Fe}$

$K_{C,1}$ – share of coal at conventional limit of combustion zone, $\text{kg}_C/100 \text{ kg}_{Fe}$

$$K_{C,i} = K_{w,i} \cdot C_k$$

$$K_{C,4} = K_{w,4} \cdot C_k$$

$K_{w,4}$ – expenditure of charge coke, $\text{kg}_{coke}/100 \text{ kg}_{Fe}$

O_v – share of oxygen in blast air, vol. %

$Q_{C,i}^*$ – thermal chemical energy of coke at level i , $J/100 \text{ kg}_{Fe}$

$Q_{C,4-i}^*$ – decrease of chemical energy of coke between levels 4 and i , $J/100 \text{ kg}_{Fe}$

$Q_{f,g,i}^*$ – thermal physical energy of gases at level i , $J/100 \text{ kg}_{Fe}$

$Q_{f,CO_2,i}^*$ – physical heat of CO_2 at level i , $J/100 \text{ kg}_{Fe}$

$Q(f, CO_2, 1 - i)^*$ – decrease of physical energy between levels 1 and i , $J/100 \text{ kg}_{Fe}$

$Q(f, CO, i)^*$ – physical heat of CO at level i , $J/100 \text{ kg}_{Fe}$

$Q(ch, CO, i)^*$ – chemical heat of CO at level i , $J/100 \text{ kg}_{Fe}$

$Q(f, g, 1 - i)^*$ – decrease of physical heat of gases between levels 1 and i , $J/100 \text{ kg}_{Fe}$

$Q(f, g, 1 - 4)^*$ – decrease of physical energy between levels 1 and 4, $J/100 \text{ kg}_{Fe}$

$V(g, 1)^*$ – volume of generated gases at level $i=1$, in the effect of combustion of coal into CO_2 in amount $K_{C,1}$, normal conditions, $\text{m}^3/100 \text{ kg}_{Fe}$

$V(CO_2, 1)^*$ – volume of CO_2 in gases at level $i=4$, normal conditions, $\text{m}^3/100 \text{ kg}_{Fe}$

$V(g, 4)^*$ – volume of gases at level $i=4$, normal conditions, $\text{m}^3/100 \text{ kg}_{Fe}$

$X_{C,i}$ – increment of coal weight in gases from level $i=4$ to level i (on the expense of charge coal coke), $\text{kg}_C/100 \text{ kg}_{Fe}$

$X_{C,4}$ – maximum weight of coal, which migrated from the charge coke to gases to maintain reaction (1). It refers to the whole height of material stack above the level of bottom nozzles, $\text{kg}_C/100 \text{ kg}_{Fe}$

$\eta_{v,i}$ – degree of gas combustion at level i , counted from bottom boundary of combustion zone (conventional), in unit fraction,

$\eta_{v,4}$ – degree of gas combustion at level $i=4$ (level of upper limit of heating zone), in unit fraction,

$\eta_{v,1}$ – degree of gas combustion at level $i=1$ (level of bottom limit of combustion zone), in unit fraction

1. Introduction

The reaction of reduction of CO_2 belongs to the characteristic and important processes, which go on in

the cupola shaft between the coal contained in the charge coke and CO_2 of the gases:



Reaction (1) is endothermic and brings about slowing down the process of heating, melting and superheating of metal melted as the result of:

– significant decrease of heat amount from the coke combustion in the combustion zone,

– large lowering of temperature of gases migrating through the stack of charge materials containing coke,

– significant decrease of volume of coke pieces.

It also causes an increase of volume of gases (drop of CO_2 , increase of CO).

The reaction is the more efficient the higher the reactivity of coke (ability of coke to the reduction of CO_2 into CO), the smaller the coke pieces and the lower expenditure of blast air. Theoretically reaction (1) proceeds at different intensity at the whole height of material stack filling the cupola shaft above the level of bottom nozzles. The literature data indicate, that reaction (1) practically decays, when gases reach temperature about 900° .

The aim of the present work was to establish the model of reaction (1) in the processing column of cupolas and derivation of its analytical description, which enclose massive, volumetric and energetic effects running in the zones and subzones defined in the work as well as between the sub- and zones (continuation and development of work [1]). The work contains numerous examples of application of the derived formulas. It brings in the basic energetic aspects of the cupola process, which form the basis for the calculations of zone balances, and temperatures of gases at boundaries of individual zones and subzones, which in turn are the basis for the calculation of heights of zones and subzones. The work derives an important element of the analytical thermal theory of the cupola process.

The problem of calculation of massive, volumetric and thermal effects of the coal exchange, proceeding at different levels of the processing stack of cupolas resulting from the reaction $CO_2 + C = 2CO$ between the coke and gases has not been so far described in details in the literature. Out of few contributions [2-6], a formula of calculation of thermal physical energy of gases at the upper limit of the heating zone (outgoing gases), based on work [7] can be referred to in the form of (2) after introducing the SI units and relation $S_r = 1 - \eta_{v,4}$

$$Q(f, g, 4)^* = 33,66 \cdot 10^6 (0,3 + 0,7\eta_{v,4}) K_{C,4} \quad (2)$$

where:

$Q(f, g, 4)^*$ – physical heat of gases at the upper limit of the heating zone (outgoing gases), $J/100 \text{ kg}_{Fe}$

$\eta_{v,4}$ – degree of combustion of outgoing gases, unit fraction (details to be found later)

$K_{C,4}$ – fraction of coal in coke in the metal charge, kg C/100 kg_{Fe}

$33,66 \cdot 10^6$ – thermal effect of combustion of coke coal into CO₂, J/kg_C.

Formula (2) can be derived, when balancing the heat contained in CO₂ and CO of the outgoing gases, which does not reveal the model of energetic phenomena proceeding at the height of the processing stack. As it is to be derived later the $Q(f, g, 4)^*$ heat consists of two fractions, i.e. the loss of coke coal to the gases due to diffusion as well as the loss of physical heat of gases consumed during the formation of CO.

2. Model assumptions

1) The following zones and subzones form in cupolas of stabilized melting process in the column of charge materials filling the cupola shaft above the level of bottom nozzles (rig. 1):

a) zone of coke combustion with oxygen of blast air, and a first subzone of CO₂ reduction zone;

b) melting zone of metallic charge, containing two subzones of CO₂ reduction, the lower one (main) and the upper one;

c) zone of metal heating up to the melting temperature, containing two subzones of CO₂ reduction, i.e. lower one (of decaying reduction) and upper one (neutral – without the CO₂ reduction process).

The mentioned zones (in bold) create a row layout (Fig. 1), in which: the lower limit of the heating zone is adjacent to the upper boundary of the melting area; the lower limit of the melting zone adjoins, in turn, the upper limit of the combustion area. The subzones of reduction and the neutral area also form a row layout. The upper and bottom zone and subzone limits reveal a plain area of contact perpendicular to the cupola axis. The zone and sub zone limits are referred to in the present work as levels (considered from the conventional lower limit of combustion zone) and are generally denoted as bold letter, at which: **i=1** is a level of lower limit of combustion zone and lower limit of first reduction subzone; **i=2** denotes the upper limit of combustion zone and at the same time the upper limit of first subzone of reduction and lower limit of melting area as well as lower limit of second subzone of reduction; **i=2'** refers to the upper limit of the second reduction; **i=3** indicates upper limit of melting zone and upper limit of third reduction subzone

as well as the lower limit of heating zone and lower limit of fourth reduction subzone; **i=3'** denotes the upper limit of fourth subzone of reduction and the lower boundary of neutral subregion; **i=4** is the upper limit of heating zone and upper boundary of neutral subzone (Fig. 1).

2) A very complicated distribution of temperature and chemical composition of gases, not described in literature so far, occurs in the combustion zone. It results from a nonuniform, in the internal cross section of shaft, supply of air blast (side feeding) and the proceeding of the reaction of CO₂ formation and its dissociation (resulting from high temperatures of gases) and decomposition of CO₂ due to the presence of charge coke coal. It is also caused by heating the drops of liquid metal and slag, the formation of slag, losses of physical heat to the furnace walls and other endo- and exothermal processes.

In the present work the final effect of the combustion process of charge coke coal in the combustion zone, i.e. chemical composition of gases at upper limit of the combustion zone. As it follows from the literature data (e.g. [3]) gases at the upper limit of combustion zone, have the highest CO₂ content and temperature in each process: the Co content is on average 5 vol.% [3].

3) At the lower limit of combustion zone, i.e. at the bottom level of nozzles, the coal comprised in the coke gets completely burnt into CO₂ (the conventional lower limit of combustion area). The assumption departs far from the real process but it introduces some order into the considerations, being the point of reference. It does not affect the results of the calculations planned for the upper limit of combustion zone, because the composition of gases for the limit is assumed based on empirical literature data (assumption 2).

4) As it follows from assumption 1, the melting zone contains two subzones of reduction, i.e. the lower one, which can be called the main zone of reduction and the upper one. The sum of heights of both zones gives the height of melting zone, while their boundary of sectioning into subzones is diffused. It can be determined by an assumed share of coke with reference to the metallic charge or assumed contribution of metal melting heat [8]. The share of coke increases in the melting zone towards its lower limit, because of melting the primary pieces of metallic charge. When the metal pieces, at lower limit of melting zone, undergo complete melting, then the homogeneous coke in the continuous way migrates to the combustion zone, currently completing its height.

Let us raise the problem of the quantitative approach to the coal exchange between the coke and gases.

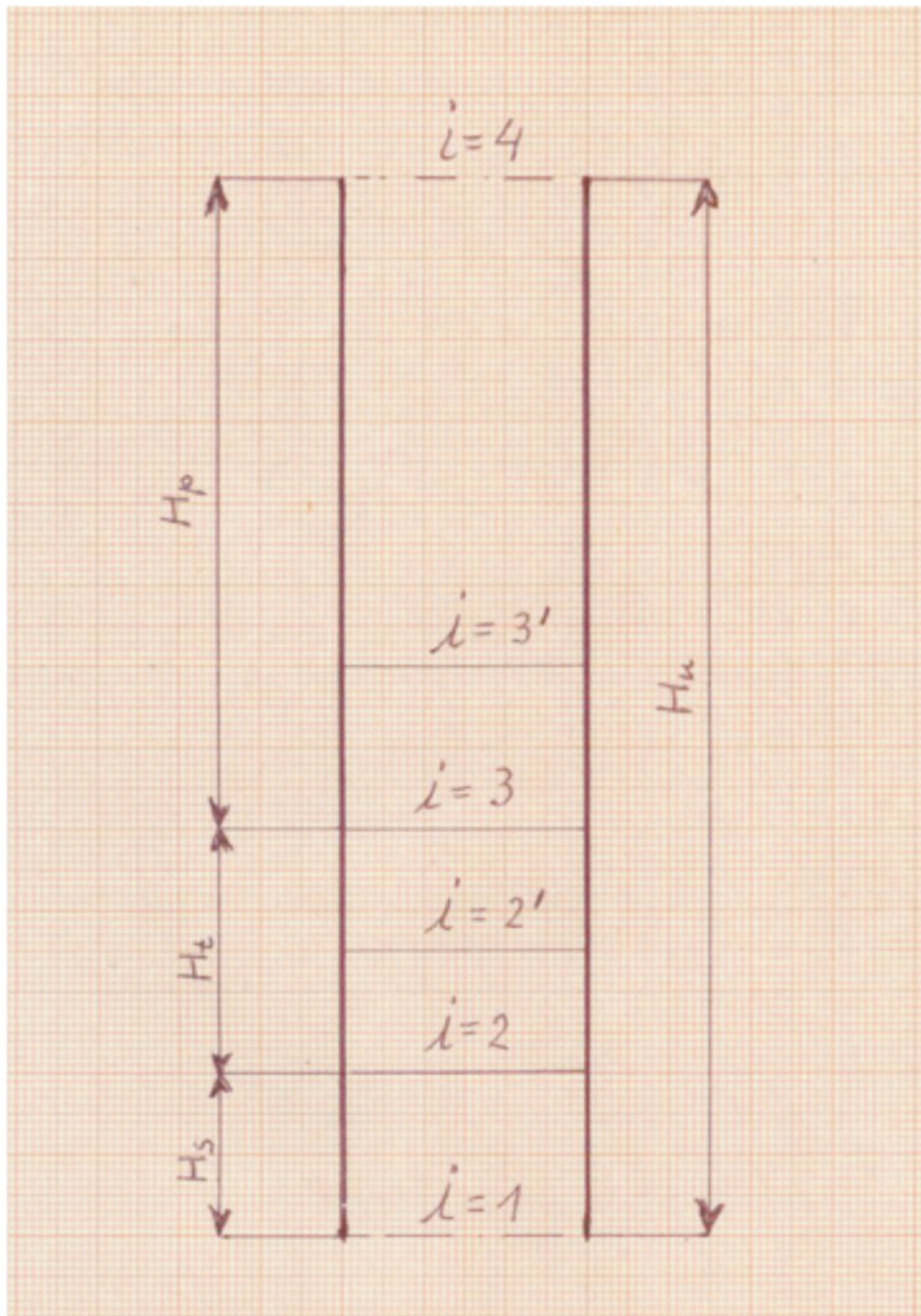


Fig. 1. Scheme of the division of the processing stack of the coke cupolas into technological zones (H_s , H_t , H_p) and subzones of CO_2 reduction. H_u – height of processing stack, m

H_s , H_t , H_p – heights of technological zones: combustion, melting and heating zones, respectively

$i=1$, 2, 3 and 4 – common limits of technological and reduction zones

$i=2'$ and $3'$ – boundaries of reduction zone in melting and heating zones, respectively.

3. Exchange of coal between the charge coke and gases

The coke, which migrates in the cupola shaft towards the combustion zone, gets into contact with concurrently moving gases and it loses to their advantage, part of coal in the way of diffusion (about 25 wt.%, at 12 % expenditure of coke), i.e. part of its chemical energy.

The coal left in the charge coke burns next completely into CO_2 at assessed lower limit of the combustion zone. This gas, (and precisely combustion gas, because of lack of CO), which is a mixture of CO_2 and N_2 reduces part of CO_2 into CO while migrating through the coke of the combustion zone and it is a reason that the content of CO in the gas equals on average about 5 vol.% at the upper limit of combustion zone. The process of reduction

of CO₂ continues in two reduction zones located in the melting zone and in one subarea in the heating zone.

The described levels *i* differ from each other by the chemical composition of gases, expressed with a combustion degree, which is defined by equation

$$\eta_{v,i} = \frac{(\text{CO}_2)_{v,i}}{(\text{CO}_2)_{v,i} + (\text{CO})_{v,i}} = \frac{G_{\text{CO}_2,i}}{G_{\text{CO}_2,i} + G_{\text{CO},i}} \quad (3)$$

where:

$\eta_{v,i}$ – degree of gas combustion at *i* level, counted from the lower limit of combustion zone (conventional), in unit fraction (or in vol.% after multiplication by 100),

$(\text{CO}_2)_{v,i} + (\text{CO})_{v,i}$ – content of CO₂ and CO in cupola gases at level *i* respectively, vol.%,

$G_{\text{CO}_2,i} + G_{\text{CO},i}$ – weight of coal in CO₂ and CO at level *i*, kg_C/100 kg_{Fe} or kg_C

It yields from the first term of the right side of equation (3), that $\eta_{v,i}$ describes the ratio of CO₂ in gases at level *i* to the summary volume of CO₂ and CO in gases at this level. However, it can be concluded from the reaction of CO₂ and CO formation (C+O₂=CO₂) and (C+0,5 O₂=CO) respectively, that $\eta_{v,i}$ can be described with the ratio of weight of coal comprised in CO₂ to the summary weight of coal contained in CO₂ and CO gases, because the same volumes of CO₂ or CO are obtained from 1 kg C (the second term of the right side of equation (3)) Also the $(1-\eta_{v,i})$ difference is the ratio of weight of coal contained in CO to the summary weight of C in CO₂ and CO.

Considering the physical sense of $\eta_{v,i}$ the weight of coal in CO₂ and CO in the gases at level *i* can be written down with the following formulas

$$G_{\text{CO}_2,i} = \eta_{v,i} K_{c,i} \quad (4)$$

$$G_{\text{CO},i} = (1-\eta_{v,i}) K_{c,i} \quad (5)$$

where:

$G_{\text{CO}_2,i}$ – weight of coal in CO₂ at level *i*, kg_C/100 kg_{Fe}

$G_{\text{CO},i}$ – weight of coal in CO at level *i*, kg_C/100 kg_{Fe}

$K_{c,i}$ – share of coal in charge coal of the processing stack at level *i*, kg_C/100 kg_{Fe}

It follows from reaction (1), that the volume of CO (2 kilo-moles) is twice as big as the volume of reduced CO₂ (1 kilo-mole), and the coal comprised in it originates in half from the decomposed CO₂ and in half from the coal of charge coke coal. Hence the increment of coal weight in gases (the loss of charge coke coal) from the conventional lower limit of combustion zone up to level *i* is described with formula

$$X_{C,i} = 0,5 C_{c,i} = 0,5(1 - \eta_{v,i}) K_{c,i} \quad (6)$$

where

$X_{C,i}$ – increment of C weight in gases from level *i*=1 to level *i* due to reaction (1) (on the expense of coal of charge coke), kg_C/100 kg_{Fe}

The maximum weight of coal of charge coke, transferred to gases during the migration of the processing stack through its whole height can be calculated from the following equation, resulting from equation (6) after the substitution *i*=4 i.e. $\eta_{v,i} = \eta_{v,4}$ and $K_{c,i} = K_{c,4}$

$$X_{C,4} = 0,5(1 - \eta_{v,4}) K_{c,4} \quad (7)$$

where:

$\eta_{v,4}$ – degree of gas combustion at upper level of heating zone in unit fraction,

$X_{C,4}$ – maximum coal weight of the charge coke consumed by the gases for reaction (1); it refers to the whole height of processing stack; kg_C/100 kg_{Fe}

The difference describing the share of coal with reference to the metal at the lower conventional limit of combustion zone (*i*=1) can be written as function of $\eta_{v,4}$ and $K_{c,4}$ using expression (7)

$$K_{c,1} = K_{c,4} - X_{C,4} = 0,5(1 + \eta_{v,4}) K_{c,4} \quad (8)$$

where:

$K_{c,1}$ – contribution of coal with reference to the metal at the lower conventional limit of combustion zone, kg_C/100 kg_{Fe}

It results from (8), that the composition of outgoing gases ($\eta_{v,4}$) and expenditure of charge coal (of coke) ($K_{c,4}$) determine values $K_{c,1}$ at the conventional lower zone of combustion.

Formula (8) can also have the following form

$$K_{c,1} = K_{c,i} - X_{C,i} = 0,5(1 + \eta_{v,i}) K_{c,i} \quad (9)$$

The comparison of (8) and (9) derives an important expression to calculate share of coal (coke) in reference to the metal at arbitrary level *i*

$$K_{c,i} = \frac{1 + \eta_{v,4}}{1 + \eta_{v,i}} K_{c,4} \quad (10)$$

where:

$K_{c,i} = K_{w,i} \cdot C_k$ and $K_{c,4} = K_{w,4} \cdot C_k$

$K_{w,i}$, $K_{c,4}$ – share of coke in reference to metal at level *i* and 4, respectively, kg_{coke}/100 kg_{Fe}

C_k – content of coal in coke, kg_C/kg_{coke}

Equation (10) takes the form of eq.(8) for $\eta_{v,i} = 1$ (lower combustion zone; combustion of coke coal into CO₂), while for $\eta_{v,i} = \eta_{v,4}$ (upper limit of heating zone) is simplifies to the form of $K_{c,i} = K_{c,4}$

Based on (9) and (10), an equation for calculation of decrease of coal content in the $\Delta K_{C,4-i}$ processing stack between the upper level of the stack (*i*=4) and the level *i* can be written down as

$$\Delta K_{C,4-i} = K_{c,4} - K_{c,i} = \frac{\eta_{v,i} - \eta_{v,4}}{1 + \eta_{v,i}} K_{c,4} \quad (11)$$

Using the relationship for the calculation of air volume consumed for the combustion of 1 kg of coal [9], eq. (10) may be transformed to find its new physical sense. The mentioned relation resembles the normal content of oxygen in the blast air

$$L_{C,4} = A(1 + \eta_{v,4}) \quad (12)$$

where:

$A = 4,45$ – volume of air required for the combustion of 1 kg C into CO, normal conditions,

$L_{C,4}$ – volume of air consumed in the given process for the combustion of 1 kg coke coal, calculated based on the degree of combustion of outgoing gases, normal conditions, m^3 air blast

For level i equation (12) has form

$$L_{C,i} = A(1 + \eta_{v,i}) \quad (13)$$

Using equation (12) and (13) the ratio (14) can be written as

$$\frac{1+\eta_{v,4}}{1+\eta_{v,i}} = \frac{L_{C,4}}{L_{C,i}} \quad (14)$$

After the substitution of (14) into (10)

$$K_{C,i} = \frac{L_{C,4}}{L_{C,i}} K_{C,4} \quad (15)$$

Relation (16) yields from eq (15)

$$V_d = K_{C,i} L_{C,i} = K_{C,4} L_{C,4} = \text{idem} \quad (16)$$

where:

idem – the same (Latin), word used in the theory of similarity of processes,

V_d – volume of air blast supplied to the cupola, normal conditions, $m^3_{air\ blast}/100kg_{Fe}$

The (16) relation means, that at each level of processing stack, multiplication products of C share in the charge and volumes of air blast are constant value equal to the volume of air blast V_d supplied to the cupola, since its dimension is

$$V_d = K_{C,i} L_{C,i} = \frac{kgC}{100kgFe} \frac{m^3\ air\ blast}{kgC} = \frac{m^3\ air\ blast}{100kg_{Fe}}$$

Let us substitute (10) into (4) (5) and (6) to obtain a developed shape of formulas

$$X_{C,i} = 0,5(1 - \eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (17)$$

$$G_{CO_2,i} = \eta_{v,i} K_{C,i} = \eta_{v,i} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (18)$$

$$G_{CO,i} = (1 - \eta_{v,i}) K_{C,i} = (1 - \eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (19)$$

Equations (18) i (19) can be added to one another

$$G_{g,i} = \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (20)$$

where:

$G_{g,i}$ – content of coal in CO₂ and CO at level i , i.e. summary content of C in gases at level i , $kg_C/100\ kg_{Fe}$

It follows from eq. (20), that the content of coal in the cupola gases increases with the growth of i (value $\eta_{v,i}$ decreases) reaching maximum value $G_{g,4} = K_{C,4}$, which is equal to the contribution of coal in charge cartridges at the upper level of heating zone. Equality (21) results from the comparison of (20) and (10)

$$G_{g,i} = K_{C,i} \quad (21)$$

It can be concluded from (21), that at each level i the content of coal in the gases equals to the content of coal in the charge coke at this level, which confirms the correctness of the balance.

Eq. (22) is obtained from (18) for $\eta_{v,i} = 1$ ($i=1$)

$$G_{CO_2,1} = \frac{1+\eta_{v,4}}{2} K_{C,4} \quad (22)$$

Eq. (22) is identical with eq. (7), which is in accordance with the assumed model, since the coke coal at the lower limit of combustion zone burns completely into CO₂ For $\eta_{v,i} = \eta_{v,4}$ ($i=4$) equations (18) and (4) take form

$$G_{CO_2,4} = \eta_{v,4} K_{C,4} \quad (23)$$

The content of coal in CO₂ contained in the gases leaving the processing stack of cupola is calculated from eq.(23).

Using (22) and (18), the formula for the calculation of C content decrease in CO₂ of gases (diminishing volume of CO₂ between level $i=1$ and arbitrary level i) can be written down as

$$\Delta G_{CO_2,1-i} = G_{CO_2,1} - G_{CO_2,i} = \frac{1-\eta_{v,i}}{2} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (24)$$

When $i=1$, relation $\Delta G_{CO_2,1-1} = 0$ results from eq. (24), while for $i=4$, the equation simplifies to the form

$$\Delta G_{CO_2,1-4} = \frac{1-\eta_{v,4}}{2} K_{C,4} \quad (25)$$

It results from (25) and (5) (for $\eta_{v,i} = \eta_{v,4}$ and $K_{C,i} = K_{C,4}$), that the decrease of coal content in CO₂, between the lower limit of combustion zone and the upper boundary of heating area is equal to a half of coal content in CO at the upper limit of heating zone (formula (5) for $i=4$); half of coal content in CO comes from the decomposition of CO₂ and the other half from the coke.

The loss of part of charge coke coal to the gases brings about the decrease of weight of coke cartridges and their volume as well as the weight and volume of

pieces of coke. Coefficient Z_C characterizing quantitatively the mentioned changes of weight and volumes is defined as

$$Z_C = \frac{K_{w,i}}{K_{w,4}} = \frac{K_{C,i}}{K_{C,4}} = \frac{1+\eta_{v,4}}{1+\eta_{v,i}} = \frac{m_{n,k,i}}{m_{n,k,4}} \quad (26)$$

where:

$m_{n,k,i}$, $m_{n,k,4}$ – weight of coke cartridge at level i and weight of charge coke cartridge for $i=4$, respectively, kg.

Equation (10) is used to write (25); $K_{C,i}$ and $K_{C,4}$ are written as

$$K_{C,i} = \frac{m_{n,k,i}}{m_{n,Fe}} 100 \quad (27)$$

$$K_{C,4} = \frac{m_{n,k,4}}{m_{n,Fe}} 100 \quad (28)$$

where:

$m_{n,Fe}$ – weight of metal charge cartridge, the same in all zones of cupola, kg.

The Z_C coefficient is expressed in weight or volumetric unit fraction or after multiplication by 100 in vol.% or wt.%. If the coke pieces in cartridges are of the same shape, weight and volume, equation (26) can be recorded in the form for calculations as

$$v_{k,i} = v_{k,4} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} \quad (29)$$

where:

$v_{k,4}$, $v_{k,i}$ – primary and current volume of coke pieces, respectively, e.g. in cm^3

After the substitution into (29) $\eta_{v,i}=1$, the formula for calculation of minimum volume of coke pieces is derived.

If the coke pieces have form of spheres or cubes, then their current diameter can be calculated from formula

$$d_{k,i} = d_{k,4} \sqrt[3]{\frac{1+\eta_{v,4}}{1+\eta_{v,i}}} \quad (30)$$

where:

$d_{k,i}$ – current diameter of coke pieces, e.g. cm,

$d_{k,4}$ – primary diameter of coke pieces, e.g. cm,

After the substitution $\eta_{v,i}=1$ into (30), the equation to calculate minimum diameter of spherical coke pieces or side of cubic coke pieces is obtained.

4. The calculation of volume of gases at levels i

The products of coke combustion in cupolas are called in literature “gases”, first of all because of the Co content (the name has also psychological sense, requiring greater caution to avoid explosion). Let us derive a formula for the calculation of volume of dry gases

(not containing water vapour) appeared from the combustion of 1 kg coke into CO_2 and CO. The following items form the summary volume of the gases: CO_2 and CO and N_2 volumes, at which the N_2 volume connected with the combustion of coke coal into CO will be two times smaller than the volume N_2 connected with the combustion of the same mass of coke into CO_2 . For 1 kg of burnt coke, the following equation of balance of volumes of gas components can be written:

$$V_{g,i} = \frac{22,4}{12} \eta_{v,i} + \frac{22,4}{12} (1-\eta_{v,i}) + \frac{22,4}{12} \eta_{v,i} \frac{100 - O_v}{O_v} + \frac{22,4}{12} (1-\eta_{v,i}) \frac{100 - O_v}{2O_v} \quad (31)$$

where:

$V_{g,i}$ – gas volume at level i from the combustion of 1 kg C, normal conditions, m^3 gas/kg $_C$

$22,4/12$ – volume of CO or CO_2 from the combustion of 1 kg C, normal conditions, m^3 CO/kg $_C$ or CO_2 /kg $_C$.

First two terms of right side of balance (31) contain volumes of CO_2 and CO in the gas; third term refers to the volume of nitrogen in the gas bound with the combustion of coal into CO_2 , while the fourth one describes the volume of nitrogen in the gas spent on the combustion of coal into CO.

After a simplification of (31) and a transformation, the relation (32) is derived

$$V_{g,i} = \frac{22,4}{12} \left[1 + (1+\eta_{v,i}) \frac{100 - O_v}{2O_v} \right] \quad (32)$$

For $O_v=21$; 25 and 30 vol.% equation (32) is simplified to the form of:

$$V_{g,C} = 1,87[1 + 1,88(1 + \eta_v)] \quad (33a)$$

$$V_{g,i} = 1,87[1 + 1,50(1 + \eta_{v,i})] \quad (33b)$$

$$V_{g,i} = 1,87[1 + 1,17(1 + \eta_{v,i})] \quad (33c)$$

Let us consider three particular cases of equation (33a), i.e. for $\eta_{v,i}=0$; $\eta_{v,i}=1$ and $\eta_{v,i}=0,5$:

$$\text{First case : } V_{g,C} = 1,87 \cdot 2,88 = 5,386 \quad (34a)$$

$$\text{Second case : } V_{g,C} = 1,87 \cdot 4,76 = 8,9 \quad (34b)$$

$$\text{Third case : } V_{g,C} = 1,87 \cdot 3,82 = 7,14 \quad (34c)$$

After the multiplication of (32) by $K_{C,i}$ and the substitution of equation (10), the full formula of calculation of $V_{g,i}$ is derived

$$V_{g,i}^* = \frac{22,4}{12} \left[1 + (1+\eta_{v,i}) \frac{100 - O_v}{2O_v} \right] \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (35)$$

where:

$V_{g,i}^*$ – volume of gases at level i , normal conditions, $m_g^3/100 \text{ kg}_{Fe}$
 For $O_v = 21 \text{ vol.}\%$ equation (35) simplifies to the form

$$V_{g,i}^* = 5,38(1 + 0,65\eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (36)$$

Based on (1) volume of CO_2 and CO can be written down by equations

$$V_{co_2,i}^* = \frac{22,4}{12} \eta_{v,i} K_{C,i} \quad (37)$$

$$V_{co,i}^* = \frac{22,4}{12} (1 - \eta_{v,i}) K_{C,i} \quad (38)$$

where:

$V_{co_2,i}^*$ – volume of CO_2 in gases at level i , normal conditions, $\frac{m^3 CO_2}{100 \text{ kg}_{Fe}}$

$V_{co,i}^*$ – volume of CO in gases at level i , normal conditions, $\frac{m^3 CO}{100 \text{ kg}_{Fe}}$

The substitution of equation (10) into (37) and (38) enables obtaining a full form of formulas

$$V_{co_2,i}^* = \frac{22,4}{12} \eta_{v,i} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (39)$$

$$V_{co,i}^* = \frac{22,4}{12} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} (1 - \eta_{v,i}) K_{C,4} \quad (40)$$

Volume N_2 in gases can be recorded as difference

$$V_{N_2}^* = V_{g,i}^* - (V_{co_2,i}^* + V_{co,i}^*) \quad (41)$$

After incorporation of equations (35), (39) and (40) into (41) a developed shape of the equation for the calculation of nitrogen volume in the gases is derived

$$V_{N_2}^* = \frac{22,4}{12} \frac{100 - O_v}{O_v} \frac{1+\eta_{v,4}}{2} K_{C,4} \quad (42)$$

For $O_v = 21 \text{ vol.}\%$ equation (42) is simplified to the following form

$$V_{N_2}^* = 3,51(1 + \eta_{v,4}) K_{C,4} \quad (43)$$

To calculate the shares of particular components of gases in the mixture at level i the following formulas are employed

$$(CO_2)_{v,i} = \frac{V_{co_2,i}^*}{V_{g,i}^*} 100 \quad (44)$$

$$(CO)_{v,i} = \frac{V_{co,i}^*}{V_{g,i}^*} 100 \quad (45)$$

$$(N_2)_{v,i} = \frac{V_{N_2,i}^*}{V_{g,i}^*} 100 \quad (46)$$

where:

$(N_2)_{v,i}$ – content of nitrogen in the mixture at level i , normal conditions, $\text{vol.}\%$

The equations for the calculation of decrease of CO_2 content in gases are to be still derived. This decrease from level $i=1$ to level i is defined by equation

$$V_{co_2,1-i}^* = V_{co_2,1}^* - V_{co_2,i}^* = \frac{22,4}{12} \left(\frac{1+\eta_{v,4}}{2} - \eta_{v,i} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} \right) K_{C,4} \quad (47)$$

The first term in the brackets of equation (47) results from equation (39) for $\eta_{v,i}=1$, while another is part of formula (39). After a transformation eq. 48 is obtained

$$V_{co_2,1-i}^* = \frac{22,4}{24} \frac{1-\eta_{v,i}}{1+\eta_{v,i}} (1+\eta_{v,4}) K_{C,4} \quad (48)$$

The decrement of CO_2 volume along the whole processing stack is calculated from (48) after substituting $\eta_{v,i} = \eta_{v,4}$ ($i=4$)

$$V_{co_2,1-4}^* = \frac{22,4}{24} (1-\eta_{v,4}) K_{C,4} \quad (49)$$

As for the CO content in gases, it raises from 0 for $i=1$ to a maximum value for $i=4$; it can be calculated from formula (40) for an arbitrary level i . It results from the comparison of expressions (40) and (48) that the increment of CO volume is twice as high as the decrease of CO_2 volume, which is in accordance with equation (1).

5. Thermal effects of coal exchange between charge coal and gases

The thermal effects connected with reaction (1) will be subsequently described.

The charge coal loses part of coal due to the diffusion to the gases on its way from the upper limit of heating zone towards the bottom boundary of combustion zone. The thermal chemical energy of the coke coal at level i can be calculated from formula

$$Q_{C,i}^* = q_C K_{C,i} = 33,66 \cdot 10^6 \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (50)$$

where:

$Q_{C,1}^*$ – thermal chemical energy of the coke coal at level i $J/100 \text{ kg}_{Fe}$

$q_C = 33,66 \cdot 10^6$ – thermal chemical energy of the reaction of oxidation of coke coal into CO_2 , J/kg_C

Formula (10) was used to write down equation (50).

The following formulas are obtained from eq. (50) for $i=4$ and $i=1$

$$Q_{C,4}^* = 33,66 \cdot 10^6 K_{C,4} \quad (51)$$

$$Q_{C,1}^* = 33,66 \cdot 10^6 \frac{1+\eta_{v,4}}{2} K_{C,4} \quad (52)$$

The thermal chemical energy contained in the coke coal loaded into the cupola can be calculated based on eq. (51), while the thermal chemical energy contained in the coke coal at conventional lower limit of combustion zone, i.e. after the loss of coal to gases at the whole height of processing stack is obtained from eq. (52).

The decrement of thermal chemical energy of the coke coal between levels $i=4$ and i can be calculated from formula

$$Q_{C,4-i}^* = Q_{C,4}^* - Q_{C,i}^* = 33,66 \cdot 10^6 \frac{\eta_{v,i} - \eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (53)$$

The maximum decrease of thermal energy of coke coal is derived from eq. (53) for $i=1$ ($\eta_{v,i}=1$)

$$Q_{C,4-1}^* = 33,66 \cdot 10^6 \frac{1-\eta_{v,4}}{2} K_{C,4} \quad (54)$$

In turn the formula for the calculation of physical energy of CO_2 and physical and chemical one of CO will be derived

At level $i=1$ of the combustion zone, the coke coal, which is a source of thermal energy burns completely into CO_2 in the amount of $K_{C,1}$. The generated CO_2 , migrating through the processing stack undergoes partial reduction into CO , which contains both the physical and chemical energy

Let us write down the equations for the calculation of the physical, thermal energy of CO_2 and CO at level i multiplying the weight of given component of the gas $G_{CO_2,i}$ and $G_{CO,i}$ by its heat of formation.

$$Q_{f,CO_2,i}^* = 33,66 \cdot 10^6 \eta_{v,i} \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (55)$$

$$Q_{f,CO,i}^* = 10,06 \cdot 10^6 (1 - \eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (56)$$

where:

$\frac{120,72}{12} 10^6 = 10,06 \cdot 10^6$ – thermal effect of oxidation of C into CO , J/kg_C

$120,72 \cdot 10^6$ J/kmol C – thermal effect of CO formation

The following formulas can be obtained from eq. (55) and (56) for particular case $i=4$. They confine the physical heat of CO_2 and CO at upper limit of heating zone

$$Q_{f,CO_2,4}^* = 33,66 \cdot 10^6 \eta_{v,4} K_{C,4} \quad (57)$$

$$Q_{f,CO,4}^* = 10,06 \cdot 10^6 (1 - \eta_{v,4}) K_{C,4} \quad (58)$$

After the addition of equations (55) and (56) to each other, the following formula for the calculation of sum

of physical heats of gases (sum of physical heats of CO_2 and CO) at level i can be derived

$$Q_{f,g,i}^* = 33,66 \cdot 10^6 (0,3 + 0,7\eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (59)$$

where:

$Q_{f,g,i}^*$ – summary thermal physical energy of CO_2 and CO (i.e. gases) at level i J/100 kg_{Fe}

Equation (59) simplifies to the form of formula (2) for the particular case, when $i=4$ ($\eta_{v,i} = \eta_{v,4}$)

The decrease of thermal physical energy of CO_2 , from level $i=1$ to level i (resulting from reaction (1), can be written down using equation (55) as a difference of $Q_{f,CO_2,1}^*$ and $Q_{f,CO_2,i}^*$; after the transformation of the difference the following equation can be derived

$$Q_{f,CO_2,1-i}^* = 33,66 \cdot 10^6 \frac{1-\eta_{v,i}}{1+\eta_{v,i}} \frac{1+\eta_{v,4}}{2} K_{C,4} \quad (60)$$

The maximum decrement of thermal physical energy of CO_2 is calculated from (60); after the substitution of $i=4$ equation (61) is obtained

$$Q_{f,CO_2,1-4}^* = 33,66 \cdot 10^6 \frac{1-\eta_{v,4}}{2} K_{C,4} \quad (61)$$

Let us give the formula for the calculation of energetic expenditure of gases for reaction (1) as the difference of physical heat increment of CO and the decrement of physical heat of CO_2 at level i , i.e. the difference of $Q_{f,CO,1-i}^*$ and $Q_{f,CO_2,1-i}^*$

$$Q_{f,g,1-i}^* = -6,77 \cdot 10^6 \frac{1-\eta_{v,i}}{1+\eta_{v,i}} (1+\eta_{v,4}) K_{C,4} \quad (62)$$

where:

$Q_{f,g,1-i}^*$ – difference of physical heat of CO at level i and decrement of physical heat of CO_2 J/100 kg_{Fe}

$$-6,77 = 10,06 - \frac{33,66}{2}$$

Relations (56) and (60) were applied to obtain formula (62).

It results from (62), that the formation of CO consumes the chemical and physical energy of CO_2

For $\eta_{v,i} = \eta_{v,4}$ ($i=4$) equation (62) simplifies to the form of

$$Q_{f,g,1-4}^* = -6,77 \cdot 10^6 (1 - \eta_{v,i}) K_{C,4} \quad (63)$$

Chemical heat contained in the appearing CO can be calculated from relationship

$$Q_{ch,CO,i}^* = 23,6 \cdot 10^6 (1 - \eta_{v,i}) \frac{1+\eta_{v,4}}{1+\eta_{v,i}} K_{C,4} \quad (64)$$

where:

$Q_{\text{ch,CO},i}^*$ – chemical heat of CO at level i , J/100 kg $_{Fe}$
 $23,6 \cdot 10^6$ – heat of reaction of oxidation CO into
 CO_2 , J/kg $_C$

For $i=4$ (chemical heat of CO at the upper boundary of heating zone) equation (64) simplifies to the form of

$$Q_{\text{ch,CO},4}^* = 23,6 \cdot 10^6 (1 - \eta_{v,4}) K_{C,4} \quad (65)$$

6. Examples of calculations

a) Introductory calculations

To perform specific calculations the knowledge of parameters $\eta_{v,i}$ for assumed levels i is required. The problem of theoretical calculations of changeable chemical content of gases, which migrate through the processing stack in the cupola shaft, has not been solved so far. Also the cupolas are not equipped with device for the measurement of chemical composition of gases at various heights of the processing stack. In spite of the mentioned difficulties the derived formulas may be applied for the calculation of the exchange of mass, volume and energy for the defined zone and subzone limits using the available empirical data, model assumptions and applying the following formulas known from the literature:

– formula for the calculation of degree of combustion at level $i=4$, when the chemical composition of outgoing gases is unknown

$$\eta_{v,4} = \frac{3,865}{K_{c,4}} + 0,15 \quad (66)$$

– formula for the calculation of $(\text{CO}_2)_{v,i}$ based on $\eta_{v,i}$

$$(\text{CO}_2)_{v,i} = \frac{34,7 \eta_{v,i}}{1 + 0,65 \eta_{v,i}} \quad (67)$$

– formula for the calculation of $(\text{CO})_{v,i}$ knowing $(\text{CO}_2)_{v,i}$

$$(\text{CO})_{v,i} = 34,7 - 1,65 (\text{CO}_2)_{v,i} \quad (68)$$

– formula for the calculation of $(\text{CO}_2)_{v,i}$ when $(\text{CO})_{v,i}$ is known

$$(\text{CO}_2)_{v,i} = \frac{34,7 - (\text{CO})_{v,i}}{1,65} \quad (69)$$

Relationships (67), (68) and (69) used in literature for the gases at the upper limit of heating zone, are applied in the present work for arbitrary levels i .

The subsequent levels will be now considered.

The lower limit of combustion zone

For the conventional lower limit of combustion zone ($i=1$), $\eta_{v,1}=1$ is assumed, which means that $(\text{CO})_{v,1}=0$,

while the appeared gases (precisely called exhausts) comprise of the CO_2 and N_2 mixture. The $(\text{CO}_2)_{v,1}$ volume is calculated from formula (69)

$$(\text{CO}_2)_{v,1} = \frac{34,7 - 0}{1,65 \cdot 1} = 21 \text{ vol.}\%$$

Upper limit of combustion zone

For the upper limit of combustion zone it is assumed that $(\text{CO})_{v,2}=5$ vol.% and based on formula (69)

$$(\text{CO}_2)_{v,2} = \frac{34,7 - 5}{1,65} = 18\% \text{ is obtained, while } \eta_{v,2} = \frac{18}{18 + 5} = 0,7821 \text{ calculated from formula (3).}$$

Upper limit of heating zone

To obtain $\eta_{v,2'}$ and $\eta_{v,3}$ ($\eta_{v,3'} = \eta_{v,4}$), the value of $\eta_{v,4}$ for the upper limit of heating zone will be at first calculated, followed with the consideration of three cases:

Case 1. The values of $(\text{CO}_2)_{v,4}$ and $(\text{CO})_{v,4}$ are known from the analysis of gases; $\eta_{v,4}$ is calculated from formula (3).

Case 2. Only the $(\text{CO}_2)_{v,4}$ value is known from the analysis of gases; the $(\text{CO})_{v,4}$ is calculated from formula (68) followed by the $\eta_{v,4}$ based on formula (3).

Case 3. To calculate $\eta_{v,4}$ the empirical formula is applied, e.g. well known H. Jungbluth formula (66). Next, the value of $(\text{CO}_2)_{v,4}$ is obtained from formula (67) followed by the value of $(\text{CO})_{v,4}$ from (68) Example: The value of $K_{c,4}$ is known to be 12·0,86 = 10,32 kg $_C$ /100 kg $_{Fe}$; then $\eta_{v,4} = \frac{3,865}{10,32} + 0,15 = 0,5245$;

$$(\text{CO}_2)_{v,4} = \frac{34,7 \cdot 0,5245}{1 + 0,65 \cdot 0,5245} = 13,573 \%$$

$$(\text{CO})_{v,4} = 34,7 - 1,65 \cdot 13,573 = 12,3 \text{ vol.}\%$$

Upper limit of main reduction subzone

To calculate the value of CO at the upper limit of the main reduction subzone ($i=2'$), the difference between the CO content at the upper limit of heating zone and the upper limit of combustion zone, i.e. the CO content increment in the gases must be calculated

$$\delta(\text{CO})_{v,4-2} = (\text{CO})_{v,4} - (\text{CO})_{v,2} \quad (70)$$

Then, the amount of CO at the upper limit of the main reduction subzone assuming the following relation

$$(\text{CO})_{v,2'} = (\text{CO})_{v,2} + 0,85 \cdot \delta(\text{CO})_{v,4-2} \quad (71)$$

In formula (71) coefficient 0,85 was assumed arbitrary. Calculations: $\delta(\text{CO})_{v,4-2} = 12,3 - 5 = 7,3$ vol.%; $(\text{CO})_{v,2'} = 5 + 0,86 \cdot 7,3 = 11,205$ vol.%

Value $(CO_2)_{v,2'}$ is derived from (69): $(CO_2)_{v,2'} = \frac{34,7 - 11,205}{1,65} = 14,24$ vol.%; from (3) the value of $\eta_{v,2'} = \frac{14,24}{14,24 + 11,205} = 0,56$ is obtained.

Upper limit of melting zone

The content of CO at the upper limit of melting zone is calculated from formula:

$$(CO)_{v,3} = (CO)_{v,2'} + 0,1 \cdot \delta(CO)_{v,4-2} \quad (72)$$

Coefficient 0,1 is arbitrary assumed

$$(CO)_{v,3} = 11,205 + 0,1 \cdot 7,3 = 11,9353 \text{ vol.}\%; \quad (CO_2)_{v,3} = \frac{34,7 - 11,9353}{1,65} = 13,8 \text{ vol.}\%; \quad \eta_{v,3} = \frac{13,8}{13,8 + 11,9353} = 0,5362.$$

Upper limit of fourth reduction subzone

The content of CO at the upper limit of fourth reduction subzone is equal to:

$$(CO)_{v,3'} = (CO)_{v,3} + 0,05 \cdot \delta(CO)_{v,4-2} \quad (73)$$

then $(CO)_{v,3'} = 11,9353 + 0,05 \cdot 7,3 = 12,3$ vol.%. = $(CO)_{v,4}$ i $\eta_{v,3'} = \eta_{v,4} = 0,5245$.

b) Fundamental calculations

The fundamental calculations comprise: the change of coal content in the charge coke, change of volume of gases, energetic effects connected with the exchange of coal between the coal of the charge coke and the gases. This requires to assume: $K_{w,4} = 12 \text{ kg}_{\text{coke}}/100 \text{ kg}_{Fe}$; $C_k = 0,86 \text{ kg}_C/\text{kg}_{\text{coke}}$; $K_{C,4} = 12 \cdot 0,86 = 10,32 \text{ kg}_C/100 \text{ kg}_{Fe}$ and value $\eta_{v,i}$: $\eta_{v,1} = 1$; $\eta_{v,2} = 0,7821$; $\eta_{v,2'} = 0,56$; $\eta_{v,3} = 0,5362$; $\eta_{v,3'} = \eta_{v,4} = 0,5245$.

Calculations of coal weight in the charge coke and losses of coal to gases

The coal weight in the charge coke at individual levels is calculated from formula (10). E.g. for $i=2$ the value of $K_{C,2} = \frac{1 + 0,5245}{1 + 0,7821} 10,32 = 8,83 \text{ kg}_C/100 \text{ kg}_{Fe}$. The results using formulas (10), (11), (17)÷(20) and (24) for all levels i are collected in Table 1.

The coke coal loss at the whole height of processing stack amounts to (form. (11) for $\eta_{v,i}=1$): $K_{C,4-1} = \frac{1 - 0,5245}{2} 10,32 = 2,453 \text{ kg}_C/100 \text{ kg}_{Fe}$ $(\frac{2,45}{10,32} 100 = 23,8 \text{ wt.}\%)$

TABLE 1

Coal weight in coke and exhaust gases ($\text{kg}_C/100 \text{ kg}_{Fe}$) (Line 2: column numbers, (in brackets numbers of formulas))

i	$\eta_{v,i}$	$K_{C,i}$	$K_{C,4-i}$	$X_{C,i}$	$G_{CO_2,i}$	$G_{CO,i}$	$G_{g,i}$	$G_{CO_2,1-i}$
	1(3)	2(10)	3(11)	4(17)	5(18)	6(19)	7(20)	8(24)
1	1,0000	7,87	2,453	0,00	7,866	0,000	7,87	0,000
2	0,7821	8,83	1,492	0,962	6,905	1,924	8,83	0,960
2'	0,5600	10,09	0,235	2,219	5,648	4,440	10,09	2,219
3	0,5362	10,24	0,079	2,375	5,491	4,750	10,24	2,375
3'=4	0,5245	10,32	0,00	2,453	5,413	4,910	10,32	2,453

The coke migrating throughout the cupola shaft loses almost 24 % of its mass to the advantage of gases.

Volume of blast air

The calculation of V_d acc. to formula (16) for two values of $K_{C,i}$: $L_{C,i}$ ($\eta_{v,i}=1$ and $\eta_{v,i}=0,56$):

$$V_d = K_{C,1} L_{C,1} = 7,87 \cdot 4,45(1+1) = 70,04 \text{ m}_p^3/100 \text{ kg}_{Fe}$$

$$V_d = K_{C,2'} L_{C,2'} = 10,09 \cdot 4,45(1+0,56) = 70,04 \text{ m}_p^3/100 \text{ kg}_{Fe}$$

As can be seen, both volumes are identical.

Calculation of coal weight consumed in the reaction of CO₂ decomposition

The mass of coal transferred from the coke to the gases is derived from formula (17). E.g. for levels $i=4$ and $i=2'$ they are:

$$X_{C,4} = 0,5(1 - 0,5245)10,32 = 2,453 \text{ kg}_C/100 \text{ kg}_{Fe}$$

$$X_{C,2'} = 0,5(1 - 0,5478) \frac{1 + 0,5245}{1 + 0,5478} 10,32 = 2,298 \text{ kg}_C/100 \text{ kg}_{Fe}.$$

Values $X_{C,i}$ for all the levels are confined in Table 1.

Mass of coal in gases

The weight of coal in gases is calculated from formulas (18), (19), (20) and (24). For example:

$$G_{CO_2,4} = 0,5245 \cdot 10,32 = 5,41 \text{ kg}_C/100 \text{ kg}_{Fe}$$

$$G_{CO,4} = (1 - 0,5245) 10,32 = 4,907 \text{ kg}_C/100 \text{ kg}_{Fe}$$

$$\text{Suma} = 5,4128 + 4,907 = 10,32 \text{ kg}_C/100 \text{ kg}_{Fe}$$

$$G_{g,1} = \frac{1 + 0,5245}{2} 10,32 = 7,87 \text{ kg}_C/100 \text{ kg}_{Fe}$$

$$G_{CO_2,1-4} = \frac{1 - 0,5245}{2} 2,453 \text{ kg}_C/100 \text{ kg}_{Fe}$$

The results of calculations for all levels i are collected in Table 1.

Calculation of coke volume (mass) decrease

$$Z_C = \frac{1 + 0,5245}{2} = 0,7622 \text{ (or 76,22 \%)} \text{ acc. to (26)}$$

The calculation of diameter of spherical coke pieces at lower limit of combustion zone:

$$d_{k,1} = 100 \sqrt[3]{\frac{1 + 0,525}{1 + 1}} = 91,36 \text{ mm acc. to (30)}$$

where:

100 – primary diameter of coke pieces, mm.

Volume of gases

The calculated volumes of gases at selected levels i are:

$$V_{\text{co}_2,1}^* = \frac{22,4}{12} \frac{1 + 0,525}{2} 10,32 = 14,68 \text{ m}^3_{\text{CO}_2}/100 \text{ kg}_{Fe} \text{ acc. to (39) dla } i=1$$

$$V_{\text{co},4}^* = \frac{22,4}{12} (1 - 0,525) 10,32 = 9,16 \text{ m}^3_{\text{CO}}/100 \text{ kg}_{Fe} \text{ acc. to (40) dla } i=4$$

$$V_{N_2}^* = \frac{22,4}{12} \frac{79}{21} \frac{1 + 0,525}{2} 10,32 = 55,24 \text{ m}^3_{N_2}/100 \text{ kg}_{Fe} \text{ acc. to (48) for arbitrary } i$$

$$V_{g,4}^* = 5,38(1 + 0,65 \cdot 0,525) 10,32 = 74,45 \text{ m}^3/100 \text{ kg}_{Fe} \text{ acc. to (36) for } i=4$$

The calculated shares of gases at selected levels i :

$$(\text{CO}_2)_{v,4} = \frac{10,11}{74,45} 100 = 13,6 \text{ vol.\%} \text{ acc. to (44) for } i=4$$

$$(\text{CO})_{v,4} = \frac{9,15}{74,45} 100 = 12,3 \text{ vol.\%} \text{ acc. to (45) for } i=4$$

$$(\text{N}_2)_{v,4} = \frac{55,25}{74,45} 100 = 74,2 \text{ vol.\%} \text{ acc. to (46) for } i=4$$

The summary decrement of CO_2 is equal to:

$$V_{\text{co}_2,1-4}^* = \frac{22,4}{12} \left(\frac{1 + 0,525}{2} - 0,525 \right) 10,32 = 4,58 \text{ m}^3_{\text{CO}_2}/100 \text{ kg}_{Fe} \text{ acc. to (48)}$$

The results of calculations for all levels i are collected in Table 2.

Energetic calculations

The results of calculations for all levels i are collected in Table 3.

Examples

$$Q_{C,1}^* = 33,66 \cdot 10^6 \frac{1+0,5245}{2} 10,32 = 264,78 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc. to (5)}$$

$$Q_{C,4-1}^* = 33,66 \cdot 10^6 \frac{1+0,5245}{2} 10,32 = 82,59 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc. to (53)}$$

TABLE 2

Volumes of exhaust gases in $\text{m}^3/100 \text{ kg}_{Fe}$ (columns from 1 to 5) and in vol.%. (Line 2: column numbers, (in brackets numbers of formulas))

i	$V_{\text{co}_2,i}^*$	$V_{\text{co},i}^*$	$V_{N_2}^*$	$V_{\text{co}_2,1-i}^*$	$V_{g,i}^*$	$(\text{CO}_2)_{v,i}$	$(\text{CO})_{v,i}$	$(\text{N}_2)_{v,i}$
	1(39)	2(40)	3(43)	4(48)	5(36)	6(44)	7(45)	8(46)
1	14,68	0,00	55,24	0,000	69,83	21,00	0,0	79,00
2	12,89	3,59	55,24	1,795	71,64	18,00	5,0	77,10
2'	10,54	8,28	55,24	4,142	74,00	14,35	11,2	74,65
3	10,25	8,87	55,24	4,433	74,30	13,80	11,9	74,35
3'=4	10,10	9,16	55,24	4,580	74,45	13,60	12,3	74,20

TABLE 3

Energetic calculations ($\times 10^{-6} \text{ J/100 kg}_{Fe}$) (Line 2: column numbers, (in brackets numbers of formulas))

i	$Q_{C,i}^*$	$Q_{C,4-i}^*$	$Q_{f,\text{CO}_2,i}^*$	$Q_{f,\text{CO},i}^*$	$Q_{f,g,i}^*$	$Q_{f,\text{CO}_2,1-i}^*$	$Q_{f,g,1-i}^*$	$Q_{ch,\text{CO},i}^*$
	1(50)	2(53)	3(55)	4(56)	5(59)	6(55)	7(62)	8(64)
1	264,78	82,59	264,78	0,00	264,78	0,000	0,00	0,00
2	297,16	50,21	232,39	19,35	251,83	32,375	12,95	45,40
2'	339,47	7,90	190,10	43,53	234,91	74,683	29,87	104,72
3	344,73	2,64	184,84	47,78	232,81	79,942	31,98	112,10
3'=4	347,37	0,00	182,20	49,37	231,75	82,590	33,2	115,81

$$Q_{f,\text{CO}_2,4}^* = 33,66 \cdot 10^6 (0,5245) 10,32 = 182,2 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (55)}$$

$$Q_{f,\text{CO},4}^* = 10,06 \cdot 10^6 (1 - 0,5245) 10,32 = 49,37 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (56)}$$

$$Q_{f,g,4}^* = 33,66 \cdot 10^6 (0,3 + 0,70 \cdot 0,5245) 10,32 = 231,75 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (59)}$$

$$Q_{f,\text{CO}_2,1-4}^* = 33,66 \cdot 10^6 \left(\frac{1 + 0,5245}{2} - 0,5245 \right) 10,32 = 82,5 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (55)}$$

$$Q_{ch,\text{CO},4}^* = 23,6 \cdot 10^6 (1 - 0,5245) 10,32 = 115,81 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (64)}$$

$$Q_{f,g,1-4}^* = -6,77 \cdot 10^6 (1 - 0,5245) 10,32 = 33,2 \cdot 10^6 \text{ J/100 kg}_{Fe} \text{ acc.to (63)}$$

The following boundary effects, connected with the transfer of gases and coke down the cupola shaft result from the presented calculations, for $K_{C,4}=12 \cdot 0,86=10,32 \text{ kgC}/100 \text{ kg}_{Fe}$ and $\eta_{v,4}=0,5245$:

a) chemical heat of coke coal loaded into the cupola is:

$$Q_{C,4}^* = 347,4 \text{ MJ/100 kg}_{Fe}$$

b) coke, when migrating throughout the cupola shaft loses coal, which transfers to the gases by diffusion (reduction of part of CO_2) in amount $X_{C,4}=0,5(1-0,525)10,32=2,451 \text{ kg}_C/100 \text{ kg}_{Fe}$; the calculated loss is: $\frac{2,451}{10,32}100=23,75 \text{ wt.}\%$ of coal contained in the charge coal;

c) loss of thermal, chemical energy equals: $Q_{C,4-1}^*=82,5 \text{ MJ}/100 \text{ kg}_{Fe}$

d) heat of combustion of coke coal at the conventional lower limit of combustion zone amounts to: $Q_{C,1}^*=33,66 \cdot 10^6 \frac{1+0,525}{2} 10,32=264,87 \text{ MJ}/100 \text{ kg}_{Fe}$; the calculated heat is also a physical heat of the formed CO_2 ;

e) volume of reduced CO_2 between levels 1 and 4 is $4,575 \text{ m}^3/100 \text{ kg}_{Fe}$ while the volume of appeared CO is twice as big and equals $9,15 \text{ m}^3/100 \text{ kg}_{Fe}$;

f) expenditure of physical heat of gases consumed during the reduction of CO_2 between levels 1 and 4 is $6,77 \cdot 10^6(1-0,5245)10,32= -33,2 \text{ MJ}/100 \text{ kg}_{Fe}$

g) the physical heat of gases at level $i=4$ is: $33,66 \cdot 10^6(0,3+0,7 \cdot 0,5245) \cdot 10,32=231,7 \text{ MJ}/100 \text{ kg}_{Fe}$

7. Conclusions

A division of processing stack, which fills up the shaft of cupola above the level of bottom nozzles into technological zones and subzones of CO_2 reduction is incorporated in the work. Moreover, the equations for the calculation of the following parameters at arbitrary levels of zones and subzones (levels i), which change due to reaction (1) are derived:

- coal weight, exchanged between the charge coke and the gases migrating concurrently to the coke,
- decreasing weight of coal in the CO_2 and increasing coal mass in the CO of the gases,
- decreasing CO_2 volume and growing volume of CO,
- volumetric shares of gas components
- weight and dimensions of coke pieces
- decreasing thermal, chemical energy of charge coke
- diminishing thermal, physical energy of CO_2 , and raising thermal physical and chemical energy of CO.

The set of calculations of the mentioned parameters for $K_{C,4}=10,32 \text{ kg}_C/100 \text{ kg}_{Fe}$ was completed in the work. They enabled to follow the massive, volumetric and energetic effects connected with reaction (1). The limited volume of the paper did not allow the author to discuss in details its applications e.g. for the calculation of exhaust gas temperature at the limits of the formed zones and subzones, as well as many other parameters, not encountered so far in the thermal theory of cupola process.

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