

Technology of Cast Iron and Oxide Materials Cupola Melting with Anthracite Used as a Fuel

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Abstract: Technology of cast iron and oxide materials melting in cupola, which allows to replace completely coke with anthracite, not breaking technologic melting mode is developed. Optimum parameters which make melting process possible at technologically steady level are derived. It is shown that at charge mixture calculation for cupola melting it is necessary to consider quantity of rust in charging and waste of carbon in cast iron connected with it. Method of calculation of inserted metal charge rust weight is given.

Key words: Cupola • Cast iron • Oxide materials • Anthracite • Cast iron and steel scrap

INTRODUCTION

Cupola as a metallurgical aggregate is widely applicable in foundry production and in manufacturing mineral wool products [1-4]. At the same time difficult situation in the industry occurred with the coke provision which is the main fuel for cupolas. Foundry coke is produced at specialized by-product coke plants in conditions of constant coal sources exhaustion (increase in coal ash-content, reduction of coking capacity of coal charge) and an adverse technologic mode of its production [5]. Possibility of foundry coke replacement by cheaper and high quality fuel allow to raise technical and economic indicators of cupolas work. Interesting is the experience received in the USA, related to the formed coke application [6]. Anthracite is increasingly distributed as a fuel, however its application demands deep theoretical study and approbation [7-8].

The main disadvantage of melting process using anthracite is its low thermal stability resulting in its cracking and splitting into small pieces due to fast heating in cupola and big pressure of a batch materials column. It reduces free section of cupola and leads to a melting course breakdown. Cracking occurs due to high mechanical and thermal tensions at fuel piece volume in an oxygen zone where the surface of a piece is warmed up to 2200-2300°C [9].

Problem Statement and Solution: Present research is aimed at development of cast iron and oxide materials cupola melting technology which allows anthracite to replace coke completely and thus not to break technological mode of melting. Experimental melting was carried out in cupola of “Izolit” JSC, Novokuznetsk. The cupola had internal diameter of 1250 mm and two charge hole at height of 3.5 and 5.5 m from the level of the main row tuyeres. It is designed for preparation of oxidized melt from waist blast-furnace slag and rocks such as diabase used in mineral wool production. Anthracite of brand A and lean coals (lean plate large-scale walnut brand) “Krasnogorsky open pit” JSC (the South of Kuzbass) applied as fuel. The cupola is equipped with the radiating and convective recuperator, allowing blasting to be warmed up to 550°C.

Melting is conducted on a coke bed or a bed charge of $H_{\text{жк}} = 1000 \div 1200$ mm height from air injection level. Coke operation charges and batch charges, consisting of metal or blast-furnace slag are loaded in layers into cupola above the coke bed charge. For iron cupolas level of materials loading in to the furnace is located at height from the place of blasting [10]:

$$H_B = (4,25 \div 4,30) \sqrt{D_B}$$

where D_B - cupola internal diameter.

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High level of loading and temperature of a fuel piece in an oxygen zone of cupola does not allow conducting of technologically steady melting using anthracite, calorific efficiency of which is 1.1-1.2 times higher and ash-content is 1.3-1.5 times lower, than coke. Therefore to conduct cupola melting with anthracite charge level of materials in cupola should make $(2,5 \div 2,8)\sqrt{D_B}$ and blasting (the first level of injection) to oxygen zone should be delivered to 450-550°C warm in equal quantities in two horizons with distance between them, making 17.5-20% from cupola diameter. Advantages of transition to the secondary blasting are well-known [9, 13, 16].

To determinate the optimum height of materials loading level we make necessary heat engineering transformations. The temperature T'' of charge leaving a mine heating zone, is defined by expression [9]:

$$T''_{III} = T'_{III} + (T'_r - T'_{III}) \frac{W_r}{W_{III}} Z \quad (1)$$

in which

$$Z = \frac{1 - \exp[-(1 - W_r/W_{III})(\alpha F/W_r)]}{1 - (W_r/W_{III}) \exp[-W_r/W_{III}(\alpha F/W_r)]} \quad (2)$$

Here T' and T'_r - temperature of charge and gas at the entrance of heating zone; W_r and W_{III} - thermal capacities of gas streams and charge; α and F - factor and area of heat exchange between gas and charge, defined from ratios:

$$\alpha = \alpha_v \frac{D_{III}}{7,5(1-\varepsilon)}; \quad (3)$$

$$\alpha_v = 186v_0^{0,9} T_r^{0,3} D_{III}^{-0,75} \quad (4)$$

$$F = 6(1-\varepsilon) H_B / D_{III} \quad (5)$$

D_{III} - average size of charge pieces (slag and metal); v_0 - speed of gas in empty mine; ε - fractional void volume.

If cupolas diameters are identical for cast iron and slag melting only H_B and D_{III} parameters (diameter of slag pieces) are altered in formulas (1) - (5) the others remain constants. The charge heating to melting temperature of about 1200°C is carried out at $H_B = 4$ m height from loading level [10], thus the average D_m size of metal charge pieces for operating cupolas makes about 0,2 m and $D_{III} \approx 0,065 \div 0,085$ m.

Considering that in the equations (1) - (5) only diameter of charge piece and height of loading level are variables, after transformations at $\alpha F = \text{const}$ we receive the demanded ratio:

$$\frac{H_{B,M}}{D_M^{0,75}} = \frac{H_{B,III\pi}}{D_{III\pi}^{0,75}} \quad (6)$$

where indexes of "m" and "III π " correspond to metal and slag charge.

$H_{B,III}$ parameter is defined as follows:

$$H_{B,III\pi} = H_{B,II} - H_{X,K} = (4,25 - 4,30)\sqrt{D_B} - 0,8\sqrt{D_B} = (3,45 - 3,50)\sqrt{D_B} \quad (7)$$

where $H_{B,III}$ is full height of loading level of the furnace; $H_{X,K} = 0,8\sqrt{D_B}$.

After the substitution of the received ratio (7) and values $H_{B,M} = 4$ m, $D_M = 0,2$ m, $D_{III\pi} = 0,065 \div 0,085$ m into the expression (6) we find ratios for the minimum and maximum height of loading level of slag pieces;

$$(H_{B,III\pi})_{\min} = 1,7\sqrt{D_B} \quad (8)$$

$$(H_{B,III\pi})_{\max} = 2,0\sqrt{D_B} \quad (9)$$

which corresponds to full loading height within limits

$$[H_{B,\min} - H_{B,\max}] = (2,5 \div 2,8)\sqrt{D_B} \quad (10)$$

At loading height of $2,5\sqrt{D_B}$ complete heating of charge to melting temperature cannot be obtained, the largest pieces in diameter of $D_{III} > 0,085$ m will fail in a furnace horn, sharply cooling the slag melt. At loading height $2,8\sqrt{D_B}$ increasing is the load of a charge column to the bed charge made of anthracite, the later got worn and crack intensively, the coal fines together with slag melt form thick baffles over the tuyeres, resistance of materials column sharply increases, cupola supply of blast gas decrease, that leads to decrease in temperature of the let out melt.

The second level of inflation should be located at the end of an oxygen zone of the first level of inflation. According to work [11] length L_k of an oxygen zone makes

$$L_k = A d_k \text{Re}^{0,2}, \quad (11)$$

where, $A = \text{const}$; d_k - the average size of fuel pieces, mm; Re - Reynolds's number.

In accordance with the State Standards (GOST 24774-81) cupolas of an average productivity have internal diameter of 900, 1100, 1300 mm. For a coke cupola the length of an oxygen zone makes 350-400 mm [12] that corresponds $L_k = (0,35 \div 0,40) D_B$. Pieces of anthracite descending in the oxygen zone are partially worn and cracked, their average size is approximately two times less

than size of coke pieces, they occupy space between levels of inflation which corresponds to an oxygen zone length $L_{12} = L_k = (0,175 \div 0,20) D_B$.

The third level of inflation for the anthracite fuel cupolas is not reasonable to establish, because small height of bed charge $H_{\text{жк}}$ equals to $0,8\sqrt{D_B}$, doesn't allow oxygen of this blasting level to react completely with the top layer of coke, the temperature of charge in this area falls down and efficiency of melting technology decreases.

The distance between two levels of inflation makes 17,5% from the internal diameter of cupola, i.e. it is less than 175 mm which is inefficient owing to reduction of the general height of oxygen zones or a heating zone. The distance making more than 20% from internal cupola diameter, i.e. more than 200 mm between tuyere belts, is also inefficient, as in this case endothermic reaction of $\text{CO}_2 + \text{C} = 2\text{CO} - Q$ reduction of coke by carbon manages to develop between the first and the second inflation levels which leads to decrease in effective temperature of the heat source and reduction of slag melt overheat temperature.

The analysis of fuel burning showed that the higher is oxygen zone height and the lower is a height of a reduction zone, the higher is melt overheat during its movement from melting zone to the horn.

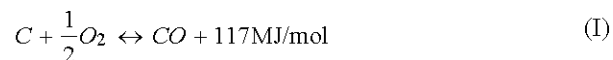
The height of reduction zone reduces to minimum or practically disappears if to mount tuyeres of the second level of inflation with square of section of all holes 5-10% less, than at tuyeres of the first level in 175-200 mm distance from the first level of inflation. It is revealed [13] that the first level of inflation is supplied by tuyeres, where holes section area makes 52-57% of total area of section of tuyeres holes, the area of section of the top level tuyeres holes makes 48-43%. Such a ratio allows to submit approximately identical number of blasting on both horizons of fuel burning zone, as batch column height, located from the second level of inflation, only 5-10% less than height of the column from the first level.

Blasting heating in coke cupola intensifies heat exchange in the melt overheat zone [9, 17]. During the blast heating coke resistance against mechanical abrasion and thermal cracking does not change, than anthracite resistance raises.

Density and the elasticity module of anthracite is 30-40% higher, than coke as the later has large number of pores formed in piece of coal during coking process at the expense of removal of moisture and coal-volatile matters. Therefore to decrease thermal tensions in pieces of

anthracite it is necessary to reduce temperature gradients by its surfaces that can be carried out during blast heating.

Blast heating promotes the reaction of:



Instead of reaction



that reduces temperature of the fuel surface in oxygen zone, temperature gradients and probability of anthracite cracking. The blasting heating to 450-550°C is optimum. The temperature lower than 450°C is insufficient for effective suppression of the reaction (II) and development of the reaction (I). The temperature of an anthracite piece surface in oxygen zone remains high (about 2000°C), that causes considerable temperature gradients, increases probability of cracking of the fuel piece.

Blasting heating to the temperatures over 550°C is inexpedient, as on mine furnaces of the smaller sizes radiating and convective recuperators in which heat exchange pipes from heat resisting steel fail rapidly above this temperature. Big dimensions cowper stoves provide higher and more effective air heating, they can be mounted for big diameter mine furnaces servicing.

During replacement of coke by anthracite and cold blasting application it is established that at the end of melting baffles consisting of slag and fine coal are formed over the tuyeres. Blast pressure and respective resistance of batch column increase in the beginning and at the end of campaign. To avoid these undesirable phenomena the loading height of cupola was reduced and warmed-up blasting was applied.

Provided below are data on time τ of cupola operation to its full stop depending on temperature T of blast heating:

$T, ^\circ\text{C}$	without heating	100	200	300	450	550
τ , day ...	0,3	0,8	1,5	3,0	4,5	5,0

Use of anthracite as cupola fuel has shown good results when melting oxide materials. Industrial cast iron melting process research were carried out in the "Universal" JSC, Novokuznetsk enterprise specialized in pig-iron baths, pipes and other sanitary production. During industrial experiments it was established that for

industrial iron cupolas with horn diameter ($D_t > 1\text{ m}$) high level of loading may lead to considerable sag of coke nozzle therefore experimentally reasonable ratio of anthracite and coke in fuel beds is 60% of anthracite to 40% of coke is recommended. Loading level should not exceed 3.0 m. Blasting has to be warmed up to 450°C and moisturized to 10-15% steam content. Under these parameters it is possible to conduct melting at technologically steady level.

One more problem was revealed during the investigation. In an imperfect economy, the metallic batch used in cupola furnaces at most iron-casting shops is iron and steel scrap, which always contains undesirable impurities. Thus, at the Novokuznetsk facility of LLC Universal, specializing in the production of cast-iron baths, pipe and other plumbing and related supplies, the cast-iron scrap supplied has a considerable content of rust, consisting of ferrous hydroxide $\text{Fe}(\text{OH})_2$. It is smelted in a cupola furnace (diameter 1300 mm) operating with cold blast and equipped with a V14/1400 air-injection system.

After using unconditioned batch in the furnace, the rejection rate of the casting increases, on account of incomplete filling and gas-shrinkage porosity. To establish the reasons for these defects, experimental melts are conducted using batch that consists only of cast-iron scrap (batch *I*) or only of PL and LK iron chunks with the addition of FS45 ferrosilicon (batch *II*). The batch composition is as follows:

Batch composition, %	Content, %				
	C	Si	Mn	P	S
Batch I					
Cast-iron scrap (99.5 %)	3,63	2,90	0,58	0,250	0,012
Batch II					
PL cast iron (70 %)	3,95	0,82	0,60	0,270	0,015
LK cast iron (26 %)	3,70	2,05	0,48	0,260	0,015
FS45 alloy (3.5 %)	0,3	42,4	0,12	0,047	0,024
Mean	3,66	2,53	0,52	0,260	0,012

The composition of the batch and hot metal is analyzed, as well as the discharge temperature of hot metal, the composition and the temperature of waste gases and the fluidity of hot metal in a spiral sample.

Batch samples are taken for each and hot metal samples are taken at each discharge. The content of silicon, carbon, manganese, phosphorus and iron is determined by chemical and spectral analysis.

The mean chemical composition of the resulting hot metal is as follows:

Batch	Content, %					
	C	Si	Mn	P	S	Fe
<i>I</i>	3,32	2,62	0,44	0,280	0,018	93,3
<i>II</i>	3,98	2,28	0,40	0,260	0,016	93,06

Note that batches I and II both contain 0.5% ferrophosphorus

The mean content (%) of element *i* in the batch is calculated as:

$$\bar{C}_i = \sum_{ij} \frac{y_{ij} z_j}{100} \quad (12)$$

where \bar{C}_i - is a mean content of *i*-element in the batch, %; y_{ij} - content of element *i* in *j* component of batch; z_j - content of component *j* in the batch.

Chemical analysis shows that the carbon content in all samples of the final hot meta is 0.25-0.35% (0.31%, on average) less than in the iron scrap for batch I and 0.21-0.42% (0.32%, on average) greater than for batch II.

To determine the quality of rust on the iron scrap, the rust is removed from 10-kg samples of scrap by means of brushes and then the samples are reweighed. The rust content is determined from the formula:

$$\frac{M_1 - M_2}{M_1} \cdot 100 \%, \quad (13)$$

where M_1 and M_2 are the samples masses before and after rust removal.

It is found that the scrap pieces contain 3.1-3.8% rust.

In smelting, the waste gas is collected and analyzed by means of an MRU Vario Plus Industrial portable instrument. The waste-gas composition in smelting with batch *I/II* is as follows:

Gas	Content, %, in gas sample			
	1	2	3	4
CO ₂	11,4	10,2	12,1	11,8
	11,8	10,0	11,6	9,5
CO	16,8	18,5	15,5	15,6
	13,6	16,3	12,6	17,1
H ₂	0,10	0,15	0,10	0,10
	-	-	-	-
O ₂	0,52	0,60	0,38	0,65
	0,64	0,55	0,58	0,47

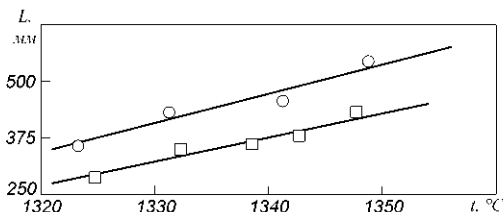
The waste-gas temperature is 450-700°C depending on the measuring time after the last batch charge was introduced. The discharge temperature of the hot metal is 1340-1360°C.

The liquidity *L* of hot metal obtained using batch I is always less by 100-125 mm than the one from batch II, as

shown in the figure. At the same time, the carbon content is lower in the hot metal from batch I. To find the relation between the carbon content in the hot metal and its liquidity, we calculate the carbon equivalent $C_{\text{эж}}$ [14]:

$$C_{\text{ЭЖ}} = C + 0,33\text{Si} + 0,5\text{P}, \quad (14)$$

where C, Si and P - are the carbon, silicon and phosphorous contents in the metal.

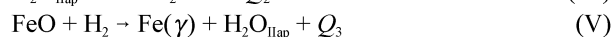
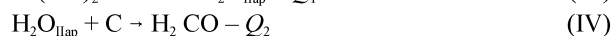
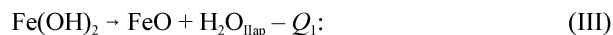


Liquidity of hot metal smelted from batches I (□) and II (○) as a function of the casting temperature.

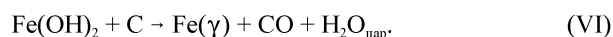
The carbon equivalent of hot metal from batch I is 0.25 - 0.32 % less than that for batch II. With decrease in the carbon equivalent given by Eq. (14), the liquidity of the hot metal declines, as we know from [14].

It is well known [15] that in cupola furnaces, carbon is lost during smelting, that was proved by the results of chemical analysis of hot metal obtained from batch II: the mean loss is 0.32 %.

On smelting with highly contaminated (especially rusty) batch, the following reactions occur in sequence near the charge hole:



The overall reaction may be written as follows:



Thus, according to Eq. (VI), the use of scrap with a high rust content should increase the carbon-monoxide content in the waste gas and lead to the presence of hydrogen.

Mathematical analysis of waste-gas composition shows that the basic components $\text{O}_{2\text{II}}$, CO_2 , CO , O_2 are related as follows [9]:

$$\text{CO} = \frac{2(O_{2\pi} - \text{CO}_2 - \text{O}_2)}{1 + 0,01\text{O}_{2\pi}}, \quad (15)$$

where $\text{O}_{2\text{II}}$ and O_2 - the oxygen contents in the blast and in the waste gases.

Calculation of the CO content from the known $\text{O}_{2\text{II}}$, CO_2 , O_2 contents on the basis of Eq. (15) gives the following results for batch I/II:

Gas	Content, %, in gas sample			
	1	2	3	4
CO_2	11,4	10,2	12,1	11,8
	12,0	10,3	11,6	9,5
O_2	0,52	0,60	0,38	0,65
	0,64	0,55	0,58	18,04
CO	14,85	16,88	13,74	14,23
	13,90	16,71	14,56	18,04
H_2	0,10	0,15	0,10	0,10
	-	-	-	-

Note that oxygen content in the blast is 20.9 %

Comparison shows that the experimental CO content in the waste gases for batch I is 1.37 - 1.95 % higher than the value calculation from Eq. (15) in accordance with reaction (VI). For batch II, controversially, the experimental CO content in the waste gas is 0.3 - 1.94 % than the value given by Eq. (15), on account of partial consumption of oxygen in the oxidation of the manganese and silicon always present in cast iron.

The reduction in Eq. (VI) occurs at the iron-rust boundary - i.e., at the surface of the iron pieces due presence of carbon. Hence, carbon is lost from the cast iron and its discharge content is reduced.

The mass of rust introduced by the metal batch may be calculated on the basis of Eq. (VI). Thus the reduction of one mole of $\text{Fe}(\text{OH})_2$ (molecular mass 90 kg) requires one mole of carbon (molecular mass 12 kg). Then, 100 kg of batch will contain $0,31 \cdot 90 / 12 = 2,325$ kg of rust. Here 0.31 % represents the percentage by which the carbon content in the iron is reduced for batch I.

The experimental results for the rust content is 3.1 - 3.8 kg per 100 kg of batch. This is 0.85-1.55 higher than the calculated value. The discrepancy may be attributed to the removal of rust from the iron scrap by means of metal brushes.

CONCLUSIONS

Oxide materials melting in cupolas using anthracite fuel is possible at materials loading level which makes $(2,5 \div 2,8) \sqrt{D_B}$. Hot blast warmed up to 450-550°C delivery to oxygen zone is to be carried out in equal quantities on two horizons with distance between them, which equals to 17,5-20% of cupola diameter. For cast iron melting recommended is experimentally reasonable ratio of

anthracite and coke in fuel beds namely 60% of anthracite to 40% of coke. Loading level should not exceed 3.0 m. Blasting subjects to warming up to 450°C and moisturizing to 10-15% steam content. Calculating batch for cupola melting it is necessary to consider rust quantity in metal charge and related waste of cast iron carbon.

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