

# Advantages of Melting Cast Iron in Gas Cupola Furnaces

V. Grachev

A.N. Frumkin Institute of Physical Chemistry and Electrochemistry of the Russian Academy of Sciences, 29 Bldg 1, Bolshaya Ordynka St., Suite # 104, 119017 Moscow, Russia

\* Corresponding author. E-mail address: chernitsa@vernadsky.ru

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## Abstract

The author has developed and patented several types of gas cupola furnaces, which, due to replacing coke with gas, do not emit carbon monoxide, sulfur dioxide and coke dust. The author has defined the optimal modes of gas-and-air mixture combustion, i.e. the optimal coefficient of air discharge and gas mixture escape speed in melting cast iron. It has been experimentally proved that from the point of view of obtaining the maximum temperature, the optimal was the process with some lack of air, i.e. with  $\alpha = 0.98$ . The results of metallurgical studies used in the article allowed to develop an optimal structure of the gas cupola furnace with a heterogeneous refractory filling, and to establish the optimal composition of the filling. For the first time the optimal composition of the filling is given: 40% of chamotte, 30% of high-alumina refractory, 30% of electrode scrap. It has been noted that when gas cupola furnaces were used, the main environmental advantage was the reduction of dust emission into the atmosphere, CO and SO<sub>2</sub> content.

**Keywords:** Innovative Foundry Technologies and Materials, Heat Treatment, Gas Cupola Furnace, Gas Combustion Mode, Heterogeneous Refractory Filling

## 1. Introduction

Some 100 mln t of castings of ferrous and non-ferrous alloys is produced worldwide. In 2016, China occupied the leading place in the production of castings – 47.2 mln t, followed by India (11.35 mln t), the USA (9.4 mln t), Japan (5.2 mln t), Germany (5.17 mln t), Russia (3.9 mln t), Republic of Korea (2.61 mln t), Mexico (2.56 mln t), Brazil (2.1 mln t), and Italy (2.08 mln t) [1].

Cupola furnace remains the basic unit for melting cast iron. Smelting in cupolas is characterized by high gas and dust content in the air of the shop floor and the surrounding area. During cupola furnaces' operation, in the average 1,000 m<sup>3</sup> of gases (which contain 3–20 g·m<sup>-3</sup> of dust, 5–20% of harmful CO, and 5–17% of CO<sub>2</sub> (greenhouse gas)) are emitted per ton of iron. Environmental aspects are described by Boldin [2]. When gas

cupola furnaces are used, coke-related emissions – toxic carbon monoxide and dust – are absent.

There is a great interest in the problem worldwide. Cherny [3] and Grachev [4–6] studied electrochemical mechanism of the phase interaction, the experience of their introduction, based on long-term observations. Similar studies were performed by Kuhn and Volianik [7], National Academy of Sciences of Ukraine [8], Küttner North America and Düker [9]. However, the Gas Institute of the National Academy of Sciences of Ukraine has not yet introduced it on an industrial scale. And the most successful are the studies performed by the Düker GmbH.

## 2. Experiment procedure

The world's first gas cupola with ledges in the stack and with an external chamber were installed at the Penza Compressor Plant, and later at other plants of Russia, after which they were installed at the Italian company Acciaierie e Ferriere Pugliesi (AFP) under a license [6, 10]. Based on the research and numerous semi-industrial and industrial experiments with gas cupola furnaces with ledges in the stack, with a plate in the stack and with an external superheater chamber (Fig. 1), where cast iron is melted on an industrial scale for obtaining complex compressor castings, defects have been identified, and tasks for further research have been set [11]. These cupolas were introduced into production and patented in Belgium [12, 13], France [14, 15], Italy [16], Sweden [17], and England [18]. The results are summarized by Grachev [19, 20].

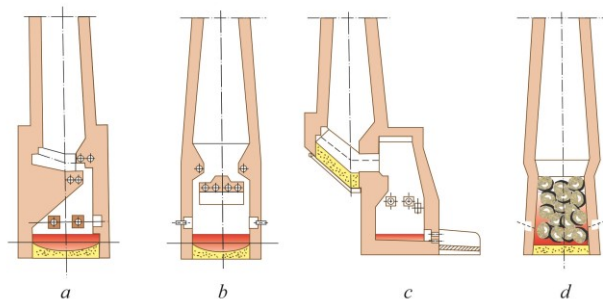


Fig. 1. Gas cupola furnaces: with ledges in the stack (a), with a plate in the stack (b), with an external chamber (c), with a heterogeneous filling (d) [5]

The operational experience at the AFP metallurgical plant in Italy showed that these cupola furnaces could be used to obtain a wide range of grades of grey cast iron, including high-carbon cast iron (3.8–3.9% C), with the temperature up to 1,510 °C and sulfur content 0.015% [20]. The use of high quality refractory linings ensures reliable operation of the cupola furnaces. The cupola furnaces worked 16 hours a day, and one cupola furnace had worked for 12–15 campaigns in a row without repair, after which the lining of the arch was replaced. The lining of the cupola was replaced after each 90 campaigns. The throughput of the cupola furnaces was 8 t·h<sup>-1</sup> (with the design throughput of 6 t·h<sup>-1</sup>).

The experience of introducing gas cupola furnaces has shown that it is necessary, first, to provide the desired temperature of the cast iron, i.e. to find the optimal thermal regime, and, second, to study interaction of the phases, i.e. metal, slag and gas phase in the changed conditions, and to develop the optimal technological process of melting cast iron in a gas cupola furnace on this basis.

The studies were carried out by means of gas cupolas with a capacity of 3 t·h<sup>-1</sup> and 7–10 t·h<sup>-1</sup>, and various system designs.

## 3. Results and discussion

In order to determine the influence of operation conditions (coefficient of air discharge and the gas mixture escape speed) on

the temperature and the composition of the gas phase, a series of experiments were performed using various cupolas (Fig. 2).

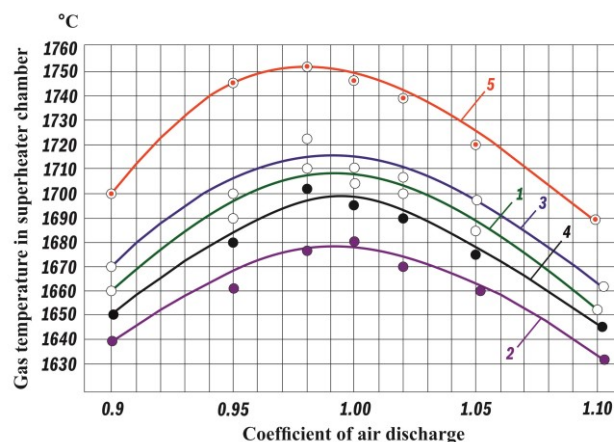


Fig. 2. Dependence of the gas temperature in the superheater chamber on the coefficient of air discharge when burning gas in a multi-nozzle burner system: 1 – gas cupola furnace with the capacity of 3 t·h<sup>-1</sup> (unloaded stack); 2 – same (loaded stack); 3 – gas cupola furnace with the capacity of 7–10 t·h<sup>-1</sup> (unloaded stack); 4 – same (loaded stack); 5 – gas cupola furnace with the capacity of 7–10 t·h<sup>-1</sup>. Curves 1–4 – gas mixture escape speed  $u = 49.2 \text{ Nm}\cdot\text{s}^{-1}$  (unloaded stack), curve 5 – gas mixture escape speed  $u = 91.9 \text{ Nm}\cdot\text{s}^{-1}$ .  $\text{Nm}\cdot\text{s}^{-1}$  – speed in meters per second under normal conditions ( $t = 20 \text{ }^\circ\text{C}$ ,  $p = 0.1 \text{ MPa}$ ) [21]

In all series of experiments, the temperature was measured by tungsten-molybdenum thermocouples fitted with special rebars and protective covers made of aluminum oxide.

Gas samples were taken by rapid passing the gases under pressure in the furnace through the sampling tube. This ensured their quick entering the cooled part of the sampling tube, where the gas composition was recorded.

The above data show that in all cases, with increasing speed of the gas-and-air mixture, gas temperature increases, and stabilizes upon reaching the rate of 75 m·s<sup>-1</sup>.

When studying gas combustion modes, it has been recognized that the coefficient of air discharge  $\alpha = 0.98$  and gas mixture escape speed of 75 Nm·s<sup>-1</sup> were optimal for cold blast gas cupola furnaces.

The physical-chemical processes were studied on an experimental gas cupola furnace with heterogeneous refractory bed charge with the capacity of 0.7 t·h<sup>-1</sup>, and a laboratory gas cupola furnace with the capacity of 20 kg·h<sup>-1</sup>.

For heterogeneous refractory bed charge a variety of materials was used: scrap of graphitized electrodes, fire clay and high-alumina refractories. Special attention was paid to using the benefits of a gas cupola furnace with heterogeneous filling, resulting from presence of carbon material between pieces of the refractory. The benefits are separation of pieces of the refractory material, protecting them from sticking together and localization of carbon right where it is needed – in the areas of temperature fluctuations increasing carbon burn-out and reducing iron, silicon and manganese burn-out (as shown by our laboratory studies).

Attempts to make a refractory bed charge of refractory materials with higher refractory properties were unsuccessful: the refractory materials softened, stuck together, and the passages for gases decreased, which disrupted stability of melting.

On an experimental cupola furnace with heterogeneous refractory bed charge, meltings were performed under extreme conditions: with the use of only refractories, with the use of only carbon material. It has been found that making a refractory charge of high-alumina refractory materials with high porosity of the layer in cold state did not ensure refractory bed charge stability and knock-out capacity. Refractory bed charge made of 100% coke has also been found unacceptable: when leaving the burners, the products of gas combustion reacted with carbon in the coke, the temperature decreased abruptly, and the melting stability was impaired. Testing a charge of 40% coke and 60% refractory also

yielded unsatisfactory results. Stability of melting and sufficient temperature of cast iron were not achieved. Therefore, for further study, the authors adopted the ratio of carbonaceous material and refractory not exceeding 40% and 60%, respectively.

It has been found that the temperature of gases in refractory bed charge decreased upon increasing the share of carbonaceous material in the refractory bed charge, but remained high enough. The temperature of cast iron with the presence of 10–15% of electrode scrap was high enough (about 1,480 °C). Stability of operation was ensured in all cases. However, with the content of 10–15%, knocking out the refractory bed charge after melting was complicated.

In order to study the influence of refractory bed charge composition on the smelting characteristics, many meltings were made, most representative of which are shown in Table 1.

Table 1.

Results of experimental meltings in a gas cupola furnace with heterogeneous refractory bed charge

Indicators		Melting index								
		24.3	24.8	15.9	8.9	16.8	28.11	2.3	31.3	16.4
Composition of bed charge, % by weight	Fireclay	50	-	80	50	-	82	30	50	40
	HAR	50	-	-	-	64	-	30	25	30
	Coke	-	-	20	-	36	-	-	-	-
	Electrode scrap	-	100	-	50	-	18	40	25	30
Temperature of cast iron, °C		1,495	1,400	1,440	1,380	1,390	1,450	1,400	1,400	1,450
Amount of slag,% from metal loaded		7.4	-	5.6	4.1	4.9	4.8	-	4.2	4.4
Contents in the slag	FeO <sub>2</sub>	1.08	-	7.9	7.8	3.8	8.6	-	7.18	7.1
	Fe <sub>2</sub> O <sub>3</sub>	24.4	-	12.2	11.3	14.3	9.6	-	14.4	9.8
Iron burn-out by analysis of slag, % by weight of loaded metal		1.32	-	0.82	0.57	0.63	0.64	-	0.66	0.54
Elements burn-out, % of the original content	C	42.8	-	+4.5	+0	+8.6	+6.2	+0	2.94	+0
	Si	1.72	-	6.3	3.4	+4.2	2.4	+4.8	+9.9	5.1
	Mn	35.2	-	6.1	10.7	10.8	6.1	10.3	12.2	9.62
Consumption, % from metal loaded	Refractory	3.5	-	1.5	-	1.67	-	-	1.8	1.5
	Carbon material	-	5.0	1.1	-	0.90	-	-	0.9	1.0

Note: HAR – high-alumina refractory materials.

The above data show that making the refractory bed charge of refractories only (melting 24.3) did not ensure stability of operation, and significantly impaired smelting characteristics. Carbon burn-out was 42.8%. In this melting, the charge mixture consisting of 100% recycled material was melted. The obtained cast iron contained 2% of carbon. The Si burn-out was insignificant due to the influence of temperature conditions. The manganese burn-out amounted to 40.7%. Obviously, adding oxides would also result in its reduction, and their absence eliminated the effect of temperature conditions, and allowed restoring due to the carbon dissolved in the metal. Consumption of the refractory material in this case was quite significant (3.5%).

Melting with the use of refractory bed charge consisting of 100% electrode scrap, unlike melting with the use of refractory bed charge consisting of 100% coke, was not stopped prematurely, and the temperature of cast iron in the melting 24.8 reached 1,400 °C, but the consumption of electrode scrap was 5% of loaded metal. Taking into account the cost of commercial carbon materials, which is 5–6 times higher than that of coke, this process should be considered unacceptable.

Meltings with the use of fire clay and coke mixture yielded good results. Melting 21.12 is of special interest. The charge mixture consisted of 100% scrap steel, and we obtained cast iron, or, more precisely, intermediate product, which contained 1.5% of C, 0.19% of Mn, and 0.61% of Si. The content of carbon increased from 0.3 to 1.5%. Other meltings were made with the use of the charge that consisted of pig iron (up to 40%), and iron scrap (recycled) with the same chemical composition.

It has been found that increasing the content of coke in refractory bed charge resulted in decreasing temperature and reducing burn-out. With the coke content as much as 20%, carbon content increases. Iron burn-out reduces from 1.32 in case of melting without coke, to 0.82% with the presence of 20% of coke. In this case, consumption of the refractory material and coke was low (1.5% and 1.1%, respectively). Introducing electrode scrap instead of coke (melting 8.9) was more favorable from the metallurgical point of view. The Fe burn-out reduced to 0.57%. Comparison of the meltings 15.9 and 28.11 is exemplary in this respect; with almost equal amount of the refractory material, coke was replaced with electrode scrap; the temperature of cast iron remained virtually the same, and the amount of slag and elements

burn-out decreased (Fe burn-out decreased from 0.82 to 0.64%). These facts show that the use of carbon materials of a quality higher than that of coke is advisable. However, their high cost restricts their usage. Therefore, meltings were made with a reduced amount of electrode scrap. It has been found that it was sufficient to introduce about 5% of electrode scrap for its positive influence on the melting process. Consumption of electrode scrap was 0.3%, of coke – 0.7%.

As a result, the optimum composition was determined – melting 16.4. During melting, refractory bed charge was partially consumed. For refilling it, 1.5% of recycled metal of the refractories and 1% of carbon material were added to the charge.

Meltings in this mode yielded good results, metal temperature was 1,420–1,450 °C by the immersion thermocouple in the bucket, elements burn-out was insignificant. With lower content of C and Si in the charge, there was C and Si burn-on. Manganese burn-out was insignificant.

The metallurgical parameters obtained in a gas cupola furnace with heterogeneous refractory bed charge are much higher than those obtained in conventional gas cupola furnaces. When melting with the use of charge consisting of 100% scrap iron in a gas cupola furnace, Fe burn-out is 1.47%, even when the air heated up to 600 °C. That is almost three times higher than melting in a gas cupola with heterogeneous refractory bed charge.

Thus, the optimum composition of refractory bed charge was determined, which allowed making the conclusion that the most advanced and optimum option of a gas cupola furnace developed by the author was a cupola furnace with refractory filling consisting of a mixture of refractory materials and coke, or other carbonaceous material. According to the electrochemical studies and analysis of the process kinetics, carbonaceous material is a necessary component of melting cast iron in gas cupola furnaces.

## 4. Conclusions

Using gas cupola furnaces for melting cast iron in foundry production has the following advantages over coke cupola furnaces:

- (1) The possibility of steady melting of a wide range of cast irons with various carbon and low sulfur content, including spheroidal graphite irons; better mechanical properties of cast iron, lower sensitivity to changing wall thickness;
- (2) Emission of dust into the atmosphere is reduced 20 times, CO content – 50 times, and SO<sub>2</sub> content – 11 times. It is the main environmental advantage of gas cupola furnaces.

Research of cast iron melting process in a gas cupola furnace allowed making following conclusions:

- (1) The optimum mode of burning gas in a gas cupola furnace is burning with the air discharge coefficient of 0.98 and gas mixture escape speed of 75 Nm·s<sup>-1</sup>.
- (2) The established mode of burning gas allows steady smelting of cast iron with high enough temperature; but for obtaining cast iron with the required composition, carbon is to be introduced into the interacting phases. This can be done in the fourth type of gas cupola furnace – with refractory bed charge. The optimum composition of the carbonaceous refractory filling has been determined experimentally: 40%

of chamotte, 30% of high-alumina refractory, 30% of electrode scrap.

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