UDC 669.169

Possibility of Improving Technologies of Liquid-Phase Reduction of Iron

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Liquid-phase reduction processes are the new and effective alternative to the coke-agglomerate-blast furnace technology of ironmaking. To date, there is no doubt in the efficiency of a large number of processes of liquid-phase reduction of iron. We have developed mathematical models which make it possible to select the most effective technology for specific conditions on the basis of certain criteria of optimization and speed limits. We created a dynamic simulator of liquid-phase reduction process which provides the development and improvement of the methods of process control.

Keywords: IRONMAKING, LIQUID-PHASE REDUCTION PROCESSES, MATHEMATICAL MODELS, OPTIMIZATION, PROCESS CONTROL

Introduction

The last decade was marked by a significantly increased interest in the process of liquid-phase reduction of iron. Many processes have passed the stage of pilot testing and are prepared to explore a commercial scale. The first industrial plants are constructed. Authors of new developments show convincing evidence for the benefits of these processes over conventional coke-agglomerate-blast scheme of cast iron, but few hope that in the near future mass replacement of blast furnace by liquid-phase reduction units will start soon . The issue here is not in the least unit capacity of new aggregates compared to the blast furnaces what is often referred to. There are much less restrictions to increase unit capacity in units of liquid-phase reduction than that of blast furnace. The determining factors are the psychological barriers and economic considerations. The benefits of the revolutionary change is the dominant technology of cast iron - not so clearly large enough to justify a complete overhaul of the entire structure of the existing production where existing mass produced equipment can operate successfully for many years in the multitemporal exhaustion of technologically interconnected units.

However, the potential benefits of new processes are significant. Liquid-phase reduction process does not require coking coal and iron ore agglomerate, can process any technological waste, including high in zinc, lead, alkalis, phosphorus and other harmful pollutants. They are much easier to manage than the blast furnace. Emissions of air pollutants are reduced by 5-10 times compared to coke-agglomerate-blast technology. During the processing of the accumulated large reserves of (several million tons) of oily scale mixed with slurry near many metallurgical plants liquid phase reduction processes ensure significantly lower cost price of cast iron than in the smelting of cast iron in a blast furnace. When working on iron ore concentrate economic benefits from the use of new processes is somewhat smaller, but remains very high.

For the first time the reality and effectiveness of liquid-phase reduction processes was practically proved in 1985 in an industrial scale, but experienced in fact on the installation on at Novolipetsky MC. The authors of this technology, called later Romelt process, were employees of the Moscow Institute of Steel and Alloys (MISA) [1]. At present, except for the Romelt process such processes as HIsmelt, DIOS, Ausiron are ready for commercial development [2-4]. However, none of the technologies of liquid-phase reduction processes of mass industrial applications are still pending.

For creating universal multipurpose most effective for specific conditions of liquid-phase reduction of iron technology we implemented:

- Development of methods and computer programs of computational analysis of the process parameters of liquid-phase reduction including features and constraints of its multi-purpose use;

- Study of the effect of different factors on the performance and effectiveness of universal technology of liquid-phase reduction
- Justification of technological and design parameters of the universal unit of liquid-phase reduction.

The most realistic initial commercial development of liquid-phase reduction processes could be carried out within an integrated blast furnace at a steel plant on the site of decommissioned inefficient furnace, in order to maximize its infrastructure and heat the blast for liquid-phase reduction processes by means of furnace gas through the existing heater. Heating blast gives you access to low-oxygen and even anoxic liquid-phase reduction technology, which significantly improves its effectiveness. Structurally liquid-phase reduction processes can be implemented using mostly standard equipment of blast and converter plants [5].

Results and Discussion

Without solving the problem of operational management in dynamics of the process of melting and without the development of methods of preventing emergency situations liquid-phase reduction processes cannot be recommended for commercial development . This was confirmed by the experience of pilot operation of the Romelt unit [2]. Development of the technology in the smelting unit liquid-phase reduction processes is possible with an electronic simulator, which could fairly reliably reproduce the dynamics of the process, given the nature and properties of the fluctuations of the charge materials. The creation of such a simulator required the development of dynamic mathematical model of the process.

The model includes deterministic and probabilistic parts. Deterministic part simulates control channels presented in the form of a combination of elementary parts of the theory of automatic control. Probabilistic models the part given to the output of liquid-phase reduction process disturbances and includes a noise generator that simulates the typical process disturbances.

Deterministic part of the model allows to assess the response to changes liquid-phase reduction process parameters which are controlled and subject to dynamic regulation. These parameters primarily include such expenses: iron ore and flux materials, coal, blast at the bubbling, air blast at afterburning.

Purpose of regulating technological mode of liquid-phase reduction process is to ensure the maximum performance of the unit, which is proportional to the heat coming into the slag bath, and preventing accidental foaming slag, which is made possible by the increasing concentration of FeO in slag to 6-8% and is associated with an increase in the arrival of iron ore materials in the slag bath and decline in the rate of FeO recovery by reducing slag temperature.

Main source of high-temperature heat into the slag bath is heat exchange with the afterburning zone, which can efficiently control by calculating the current material and heat balance from data on the parameters of the blast and the exhaust gas.

The heat transfer rate depends on the temperature of food on the intensity of post-combustion and slag splashing in the afterburning zone. Power of splashing is determined by consumption of bubble blowing. A factor that may limit the heat is excessive amount of coal in the slag bath that leads to blockage in the area of the surface of the slag splashing and reduce the degree of post-combustion of the gas above the surface of the slag due to the presence of carbon coal in the reburning zone.

Direct control of the amount of coal in the slag bath is impossible. In addition to the approximate visual estimates of the surface state of slag, not enough coal in the slag can be identified by computational analysis of liquid-phase reduction process on reducing the intensity of the reduction of iron at high enough temperature of the slag bath. Indirect evaluation of excessive amounts of coal in the slag bath is possible in view of changes in the degree of post-combustion of gas in the working space of liquid-phase reduction process unit and the heat transfer rate. Although generally we assume a fairly wide range of variation in the amount of coal in the slag bath, the estimated control of the value with the described analysis of the dynamics of the process, as well as heavy loading of coal into the furnace and the gas supply must be considered an essential element of melting.

Unit capacity of liquid-phase reduction process is determined on the one hand, by the temperature of the slag bath, and on the other hand - the content of iron oxides in slag. Permanent direct control of slag temperature is impossible but its indirect control by estimating heat removal on the caisson plates cooled slag zone [2], supplemented by an analysis of the current calculation of the heat balance of the process is real.

Temperature control of the slag must be, above all, the degree of change in the post-combustion of gas in the working space of liquid-phase reduction process unit and the heat transfer between the zone of post-combustion and slag bath. The proposal to regulate the temperature of the slag bath by changing oxygen content in a bubble blowing, so as to influence the coming of heat from coal combustion in the lower tuyeres [2] is not valid. During Romelt process oxygen of bottom air has virtually no possibility, as already noted [5], to burn coal in the volume of the slag bath. In areas where bubbling blast leaves on a surface of slag, the coal is also too little. Therefore, the oxygen bubble blast provides combustion of gas and coal particles already in the zone of afterburning. If the practice confirmed the positive effect of increasing the concentration of oxygen in the lower blast on the temperature of slag, the cause of this effect can be explained by an increase of the gas temperature in the post-combustion zone and inhibition of the endothermic process of reduction of iron from slag.

The biggest problem with the process control of liquid-phase reduction of iron is an assessment of the current content of iron oxides in the slag. To provide high performance unit of liquid-phase reduction it is desirable to maintain the content of FeO in slag at the level of 4-5%. But the rise of the FeO content of up to 6% creates a real threat of emergency foaming of slag, which if it starts, is extremely difficult to stop.

Periodic sampling of slag for its analysis is mandatory, but significant delay of the analysis and the possibility of a fairly rapid increase in the content of FeO in the slag forces to work in practice with FeO content of 2-3%, which reduces the capacity of the unit. Using a dynamic simulator of liquid-phase reduction for the design monitoring of FeO content in the slag will optimize melting mode and improve safety of the machine of liquid-phase reduction.

It should be noted that the simulation model does not yet take into account the effects of some minor technological factors on the temperature in the area of post-combustion, heat transfer rate and temperature of the slag, for example - the impact of rarefaction in the workspace area by the amount of post-combustion air leaks, and through it - for all the parameters. This will require clarifying on the already existing unit.

Internal connection between the two most important process parameters - temperature and slag content of iron oxides in it - is important for the regulation of the processes of liquid-phase reduction of iron. This relationship contributes to the relative stabilization of the temperature of the slag bath. Increasing the temperature reduction of iron slag intensifies, leading to the cooling of the slag, and vice versa. The process is stabilized at new levels of performance and content in the slag.

Inverse relationship, where the primary is a change in the content of FeO in the slag, demonstrates one of the manifestations of instability in liquid-phase reduction. Reduction of FeO by significantly reducing joining slag to bath of iron ore materials, leading to the initial increase in the temperature of slag, a slight increase and then decrease in unit output due to a fall in the concentration of FeO in slag to a critical level, the growth temperature of slag until the emergence of operational problems and the need to take appropriate induced technological measures.

In the case of a substantial increase in the arrival of the iron oxides in the slag to bath, and other input parameters unchanged process slag bath temperature falls, which, in the end, reduces the intensity of the reduction of iron and promotes the accumulation of FeO in slag up to an accident - uncontrolled foaming slag (**Figure 1**).

The authors of Romelt process as one of the reasons for the increase of the FeO content in slag refer to increase in the number of large pieces of charge materials [2]. By itself, an increase in lump size of the charge, while delaying the dissolution of iron materials in slag , helping to increase the proportion of solid particles in the slag, have almost no effect on either the temperature of the slag bath or the content of FeO in slag. However, it significantly increases the risk of accidental foaming of slag with the same FeO content in it.

Liquid-phase reduction process in which there is an area of calm slag, is constantly in a state of unstable equilibrium. At the interface of iron and slag there, on the one hand, a large amount of dissolved iron oxides in slag, and on the other hand - a huge reduction potential of dissolved carbon in the iron. The reduction reaction is slow here only because of the limited interface of iron and slag and difficulties with the formation at the interface between the gas phase nucleation. The appearance on the surface of pieces of iron materials that do not have time to dissolve, create active sites of reduction with the release of increased amounts of gas, promotes the beginning of mixing iron and slag and serves as "trigger mechanism" for emergency foaming of slag.

Thus, the main task of operational management of liquid-phase reduction is to regulate the loading into the furnace of iron materials in strict accordance with the advent of heat in the slag bath. Without the use of ACS with a dynamic simulator of liquid-phase reduction in the loop to ensure reliable operation of the unit of liquid-phase reduction is extremely difficult.

Another aspect of the use of dynamic simulator of liquid-phase reduction process is to optimize the feedback gain control of deviations from the monitored parameters of melting from specified values, for example, while maintaining the cast iron temperature at the desired level by changes in iron ore materials flow. Dynamic delay of channel temperature control of cast iron in its continuous release is sufficiently large. Therefore, this regulation by exception can be either too weak and not effective enough or too powerful, that will lead to overshoot and the destabilization of the process.

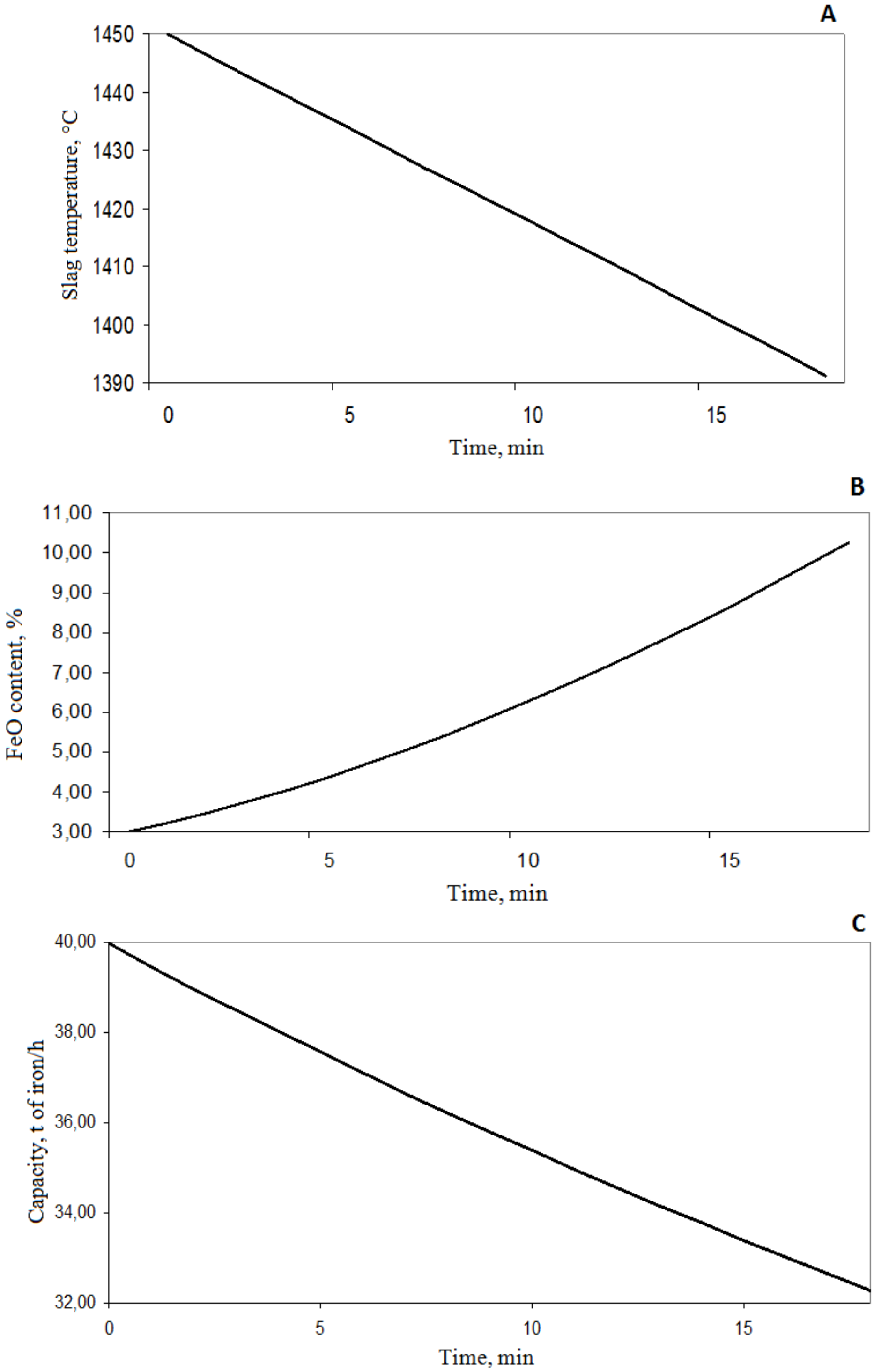

Figure 1. Example of liquid-phase reduction parameter changes after a step increase in load to the furnace ore materials from 58 to 66 t/h

The optimal value of the feedback factor can be determined at the operating unit, but it will lead to a significant loss, since this would require several research periods, and for a long time, the industrial unit will be managed efficiently enough. Moreover, changes in the nature of uncontrolled disturbances in case of change of the quality of used iron ore materials and coal each time will necessitate repetition of industrial research.

Using a dynamic simulator of liquid-phase reduction enables fast and cost-effective find optimal values of the feedback. For this simulator which can work with any desired acceleration time must be adapted to the particular technology and the specific conditions of the liquid-phase reduction unit. The universality of the mathematical model, which was the basis for the creation of the simulator enables to use a simulator without changing the structure of the model in all conditions of liquid-phase reduction technology implementation. Dynamics of the process is taken into account automatically. Setting of the simulator of liquid-phase reduction requires only achieving a believable simulation of uncontrolled disturbances which are mainly associated with dosing errors of materials and fluctuations in their composition.

To achieve the required adequacy of the model to the real process it is sufficient to achieve approximately equal values of the decay time of the autocorrelation function to zero adjustable parameter for real and simulated processes by adjusting the corresponding coefficients in the simulator of random perturbations of the process.

In the simulator we implemented the program of simple proportional regulation to the temperature deviation from the set point of iron. Changing the value of the feedback factor in periods of simulation lasting several days and evaluating the results of the regulation according to the mean-square temperature deviation of cast iron and content of FeO in the slag, it is possible to find the best value for the specific conditions of the feedback factor. An example of such search is shown in **Figure 2**. In this example the optimal value of the feedback factor was $K_f = 20$ kg minute change rate of ore material by 1 ° C cast iron temperature deviation from the set point (1450 ° C).

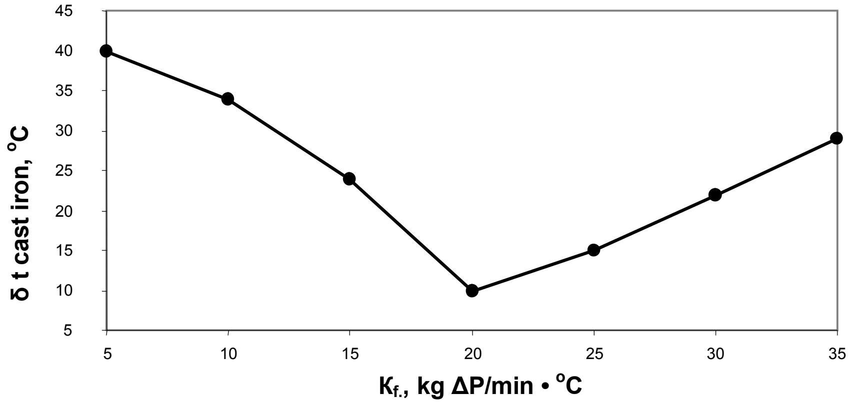

Figure 2. Dependence of the standard deviation of cast iron temperature (δt_c) on the value of feedback gain control channel "consumption of ore materials - temperature of cast iron"

Conclusions

Although liquid-phase reduction processes are not yet perceived by investors as a real alternative to the blast furnace in the future they will become leading technology of obtaining primary metal from ore materials.

In the industrial development of this technology operational control of melting must be managed through the control loop of the dynamic process model.

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* Published in Russian

February 14, 2012

Возможности совершенствования технологии жидкофазного восстановления железа

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Процессы жидкофазного восстановления (ПЖВ) являются новой и эффективной альтернативой коксо-агло-доменной технологии производства чугуна. К настоящему времени нет сомнений в работоспособности большого числа процессов жидкофазного восстановления железа. Разработанные нами математические модели дают возможность выбирать для конкретных условий наиболее эффективную технологию, исходя из определённых критериев оптимизации и установленных ограничений. Созданный нами динамический имитатор процесса жидкофазного восстановления обеспечивает разработку и совершенствование методов управления процессом.