Experimental verification of mathematical models adequacy of the new continuous metallurgical process JEP

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Abstract. A comparative analysis of the experimental data obtained at a large-scale experimental installation and the results of modeling and optimization in the “Engineering-Metallurgy” system for various technological options in the unit of spray-emulsion type is carried out in the paper.

1. Introduction
Metallurgy is one of the most resource-intensive industries. Currently, the multistage scheme for metals production is the most common one, which includes agglomerate and steelmaking operations. The need to reduce the energy and materials consumption in metallurgical industry requires the improvement of traditional schemes of iron and steel production and the creation of new metallurgical processes and units for direct production of metals. Over the past 10 years, more than 100 plants of direct reduction have been built and some are still being constructed in the world implementing a variety of principles. Promising in this direction is the development of spray-emulsion processes and units, for which large phase-separation surfaces and high rates of physico-chemical interactions are typical. Such processes include the continuous metallurgical process of the spray-emulsion reactor (JEP) developed by the teams of researchers from Department of Information Technologies in Metallurgy (currently the Department of Applied Information Technologies and Programming) and West Siberian Metallurgical Combine (EVRAZ ZSMK) under the supervision of Doctor of Technical Sciences, Professor V.P. Tsymbal [1-3].

The process is based on the idea of implementing the principles of synergetics and nonequilibrium thermodynamics, which allowed theoretical foundations and a universal design of the unit to be created, which makes it possible to implement various technologies [4-5].

2. Structure, functions and purpose of the development system
The experimental JEP unit was constructed at KKTs-2 ZSMK and was intended for the adjustment of developed technologies. Its main technological equipment is a technological unit, including reactor of a spray type and an emulsion-type refining clarifier, a feed system, a process gas supply system, a control system, an automated experiment system, and auxiliary systems consisting of a cooling system for the unit body and a product outlet. The general view of the pilot plant is shown in figure 1.

On the pilot plant 40 series of experiments were carried out, the results of which confirmed the advantages of the process and the spray-emulsion unit: high rates of heat and mass transfer processes (100 ÷ 200 times higher than in the converter); small sizes and low material consumption (10 ÷ 20 times less than in traditional metallurgy); low through energy consumption (15 ÷ 18 GJ/t);
environment friendly and non-waste technologies; controllability, universality and mobility, the possibility of implementing various technology options [6].

![Figure 1. General view of the pilot installation of JEP.](image)

To develop, research and optimize these technologies using the MS Excel and Delphi, the development system “Engineering-Metallurgy” was created, in which a mathematical description of the interconnection of flows and processes parameters is implemented using a complex of mathematical deterministic models based on the first and second laws of thermodynamics [7-8].

The instrumented system “Engineering-Metallurgy” made it possible to implement multivariate calculations, to carry out research and solve interrelated optimization problems in determining the best conditions for the processes during the adjustment of technologies on a pilot plant.

The control actions for each experiment were calculated with the help of the system, which resulted in the implementation of the following technology options: metal production from cast iron and scale, direct metal production from pulverized ores and wastes, processing of titanium-magnetite concentrate to produce the conditioned titanium slag, production of manganese alloys from poor dust-like manganese ores [9 -10].

The first 5 series of automated experiments were aimed at obtaining steel from cast iron using gaseous oxygen. Subsequent experiments after structural changes in the feed system of the charge to the first reactor were carried out without cast iron. Six series of experiments were conducted to develop the technology of direct reduction of pulverized materials, such as manganese concentrate, manganese concentrate – scale, scale.

In the next series of experiments the main attention was paid to the development of technology of iron direct reduction from a mixture of sludge and scale. At the same time, as the main task, the calculated and experimental choice of rational ratios of ore and reducing agents in the charge was made. These experiments helped to obtain a certain experience in controlling the process and determine the most rational ratio of 1:1 converter slag and scale for the ore part with the supply of plasticized charge, which confirmed the correctness of calculation results using the development system.

Also, experiments on processing titanium-magnetite concentrates for production of a conditioned titanium slag were successfully carried out.
One of the important tasks of conducting experiments was checking the adequacy of software-implemented mathematical models. A comparative analysis of the most representative experimental and calculated data is given in table 1 and in figure 2.

![Carbon content comparison](image1)

![Manganese content comparison](image2)

![Content of FeO comparison](image3)

**Figure 2.** Comparative analysis of calculated and experimental data.

The adequacy of the models was estimated using a relative error, which was defined as the ratio of the root-mean-square deviation of the actual carbon and manganese content in the metal and FeO in the slag, calculated from the model to the mean value of the carbon, manganese and FeO content. The results of the calculations showed that the relative errors in the content of carbon, manganese in the metal and FeO in the slag are 15.5, 21.1 and 18.4%, which corresponds to the deviation from actual values for the carbon concentration 0.13%, manganese – 0.14%, FeO – 3.44%.

3. Conclusions
Experiments on adjustment of the technology of the spray-emulsion process at the pilot installation confirmed the adequacy of the models. Relative errors in the content of carbon, manganese in the metal and FeO in the slag can be considered quite acceptable in the conditions of adjustment of technology options in the presence of a large number of interferences, technical and technological limitations.
| No. | Exp. No. | Technology | Consumption, kg/s (m³/s) | Data | Composition of metal, % | FeO |
|-----|----------|------------|--------------------------|------|------------------------|-----|
|     |          |            | Cast iron | Charge | Oxygen | C | Mn | Si | P | S | Al |
| 1   | 3        | cast iron  | 20       | 4      | 1.78   | act. | 1.03 | 0.03 | 0.03 | 0.13 | 0.045 | - | 28.0 |
|     |          | + scale    |          |        |        | calc. | 1.15 | 0.05 | 0.02 | 0.023 | 0.018 | - | 25.00 |
| 2   | 7        | Mn conc.   | -        | 6.5    | 1.06   | act. | 1.6 | 20.0 | 20.4 | -   | - | 3.5 | 11.8 |
|     |          |            |          |        |        | calc. | 1.43 | 21.13 | 22.2 | 0.021 | 0.02 | - | 11.85 |
| 3   | 8        | Mn conc.   | -        | 5.06   | 0.67   | act. | 0.11 | 25.9 | 33.5 | -   | - | 0.94 | 2.6 |
|     |          |            |          |        |        | calc. | 0.51 | 29.1 | 34.5 | 0.018 | 0.019 | - | 1.19 |
| 4   | 10       | Mn conc. + | -        | 5.9    | 0.92   | act. | 0.3 | 9.0   | 6.5   | -   | - | 8.0 | 4.5 |
|     |          | scale      |          |        |        | calc. | 0.55 | 11.44 | 7.98 | 0.019 | 0.019 | - | 3.98 |
| 5   | 11       | Mn conc.   | -        | 3.4    | 0.78   | act. | 2.57 | 9.6  | 5.8   | -   | - | 2.7 | 12.0 |
|     |          |            |          |        |        | calc. | 2.21 | 10.11 | 6.19 | 0.023 | 0.021 | - | 12.8 |
| 6   | 12       | scale      | -        | 4.5    | 0.97   | act. | 0.55 | 0.03 | 0.01 | 0.013 | 0.01 | - | 38.0 |
|     |          |            |          |        |        | calc. | 1.00 | 0.1  | 0.06 | 0.015 | 0.013 | - | 31.0 |
| 7   | 13       | Mn charge  | -        | 4.5    | 0.89   | act. | 0.56 | 3.53 | 7.5   | 0.070 | 0.023 | - | 6.76 |
|     |          |            |          |        |        | calc. | 0.40 | 4.19 | 8.3   | 0.029 | 0.021 | - | 5.34 |
| 8   | 16       | scale      | -        | 5.45   | 0.72   | act. | 0.22 | 6.91 | 15.37 | 0.085 | -   | - | 17.9 |
|     |          |            |          |        |        | calc. | 0.58 | 7.44 | 18.53 | 0.025 | 0.024 | - | 16.89 |
| 9   | 18       | scale      | -        | 6.06   | 0.75   | act. | 0.69 | 0.26 | 0.3   | 0.1   | -   | - | 28.35 |
|     |          |            |          |        |        | calc. | 1.03 | 0.31 | 0.34 | 0.026 | 0.022 | - | 27.13 |
| 10  | 20       | scale      | -        | 5.4    | 0.78   | act. | 0.44 | 0.02 | 0.06 | 0.03  | -   | - | 37.84 |
|     |          |            |          |        |        | calc. | 0.77 | 0.031 | 0.076 | 0.023 | 0.022 | - | 33.15 |
| 11  | 24       | scale +    | -        | 4.8    | 0.81   | act. | 1.57 | 0.025 | 0.12 | -   | - | 0.01 | 19.46 |
|     |          | charge     |          |        |        | calc. | 1.19 | 0.031 | 0.14 | 0.02 | 0.021 | - | 20.12 |

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