Background and principles of self-organizing jet-emulsion metallurgical unit

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Abstract. The basic principles laid in the creation of a new jet-emulsion process and metallurgical unit were considered. Development of self-organizing oscillator reactor, bottom feed of the prepared in it combustible mixture to the column reactor and a large deviation from the thermodynamic equilibrium allow dissipative structure to be created, and thus control the ratio of reducing and oxidizing processes, the carbon content in the metal.

1. Introduction

The authors on the basis of their multi-year research set a goal of describing in a compact and consistent manner the basic principles which were laid in the creation of a new jet-emulsion metallurgical process and a unit.

The idea, later realized in the self-organizing jet-emulsion process, appeared in 1983-85, when our research team began to study and comprehend the just appeared in the Russian translation of basic works on the theory of self-organization by I. Prigogine [1] and G. Haken [2], and then the examples [3] of practical application synergy concept and principles.

There was an idea to try to create a new process and machine, in which to some extent these principles could be implemented. Beside, the analysis of development and status of traditional metallurgy showed that the tendency to increase the single capacity of units in combination with the accepted in the iron production principle of charge materials pelletizing led to the clunkiness and energy inefficiency of the multistage technological scheme.

The idea of charge pelletizing is in contradiction with the principle of global energy saving (entropy) as a huge reaction surface of ore materials, crushed at the stage of enrichment, is reduced by one thousand times at a high cost of material and energy resources in agglomeration of coke production. Heating and melting of agglomerated materials require a significant residence duration and, consequently, a large amount of aggregates. The processes occur in the vicinity of the state of thermodynamic equilibrium.

Eliminating this irrationality and saving the large initial reaction surface of the charge aggregates was the first task, which was to be implemented in combination with the principles of self-organization, the most important of which is a large deviation from thermodynamic equilibrium,
Gauss’s principle of least constraint (Le Chatelier-Brown) and the circular congruence. These principles, as it turned out later, we managed to implement constructively with the right technological parameters.

In more detail the sequence of the development and implementation of the idea of creating a new process we described in our monograph [4]. Below we explain the basic principles of the functioning of the process and the unit.

2. Basic principles
To implement the task of creation of a greater reaction surface we used the principle of charge dispersion by the counter gas jets followed by the organization of the forced movement of the formed gas slurry under pressure. As it turned out later with the scientists from the Institute of Thermal Physics SB RAS (Novosibirsk), the flow rate of the forced two-phase medium in the channel is in a substantially non-linear dependence on the gas content [5], as shown in Figure 1.

\[
\alpha_g = \frac{\nu_g}{\nu_g + \nu_{kp}},
\]

where \(\nu_g\) – the amount of gas, \(\nu_{kp}\) – volume of the condensed phase, and then to a change in the outflow of a two-phase medium in the connecting channel, which in turn leads to a change in pressure in the spherical reactor. The process “runs” on the right-hand member of the nonlinear dependence of the sound velocity \(C\) from the gas content (Figure 1), the outflow velocity of the two-phase medium from the connecting channel 3 (Figure 2) can be changed by several times.

The result is a possibility of creating a stationary oscillatory mode at any given pressure level. Figure 3 shows the nature of the agreed processes of vibrational pressure \(P\) and volumetric gas content \(\alpha_g\) in the reactor-physical model of the oscillator, and Figure 4 shows an example of recording in real time the pressure in the piston pump fuel supply of oil plasticized charge in the spherical reactor of the pilot unit. It can be seen here that in the real high-temperature reactor, with an inner diameter of 2 meters, due to the above-described two-phase gas-dynamic effect of locking jets the pressure of two atmospheres was created. Due to changes in the consumption of substance flows at the input and output, as well as changes in the diameter of the connecting channel 3 (Figure 2), a fixed level of pressure support in this reactor can be set.
Thus, based on the reactor-oscillator a stimulus flow (a kind of carb-compressor) was created, by which (in combination with the transition process in the area of the gas suspension and emulsion) it was possible to organize the internal transport of the working mixture through all elements of the unit, including heat-utilizing installations (waste heat boiler, gas turbine, fluidized bed, smoke reformer in the synthesis gas). This creates conditions for using deep fuel energy source (70-80%). High pressure and isolation from the atmosphere of the process allowed the energy of the expansion of the working mixture to be fully used (8.31 J/mol), i.e. “cork the imp inside the bottle”, which helped to make the reaction mixture work in the right mode and perform different process operations, thanks to that the unit has a certain degree of flexibility.

Another important decision was the lower supply of the prepared in the reactor-oscillator of the working mixture to the column reactor, on the slag-metal boundary. At the same time, the kinetic energy of the ejected from the connecting channel 3 jets is spent on the intensive bubbling gas slag emulsion together with embedded therein particles of ore materials, turning into the potential energy of pressure, forms a “pillow”, a kind of a failing grid, which maintains a high post (about 2-3 m) of...
gas-slag-metal emulsion and gas-suspension (zones 6 and 7 in Figure 2). In zone 5a there are mainly regenerative processes occurring on the very developed contacts surfaces, on the iron oxide films, on CO bubbles and on the surface of oxide slag – solid carbon, according to the reactions:

$$(\text{FeO}) + \{\text{CO}\} = [\text{Fe}] + \{\text{CO}_2\};$$

$$(\text{FeO}) + \text{C}_s = [\text{Fe}] + \{\text{CO}\};$$

$$\text{C}_s + \{\text{CO}_2\} = 2\{\text{CO}\}.$$  

In the initial stages of continuous steelmaking process hearth and converter types [6, 7], an important and essential advantage of this process, together with the lack of intermediate energy and raw material losses, considered the existence of separate chambers (zones) for the implementation of the necessary technological operations (decarbonization, desulfurization, dephosphorization, etc.). However, at that time, due to the flow of the process is close to equilibrium and, consequently, low rates of chemical reactions, these cameras were produced quite cumbersome, and the unit as a whole capital-intensive.

Due to entering of the bottom feed mixture into the zone of gas suspensions and emulsion, and keeping the large deviation from the thermodynamic equilibrium, we manage to create (instead of physically realizable chambers) definite zones in the form dynamic dissipative structures that exist only under the condition of a certain kinetic mode. The desulfurization is achieved due to a large reaction surface on the gas bubbles and the dephosphorization problem can be solved by controlling the particle size distribution in the raw materials fed to the metal-slag boundary. On the problem of carbon content control we shall focus separately.

One of the important dissipative structures discussed in more detail in [8, 9], is a gravitational separator of metal, slag and gas, which is formed in the upper half of the column reactor (zone 6 and 7 in Figure 2). Due to the influence of the gravitational component and close to the parabolic distribution of emulsion speed vector in the cross section of the column reactor there is a separation of particles according to their density. Because of this phenomenon, the reduced iron particles having a density in two to three times greater than the particles of iron oxide, “slide” on the flow periphery and form the near-wall layer with negative (reverse) velocity (zone 7). We visually observed this phenomenon on a physical model.

Thus, taking into account counter gravitational and aerodynamic forces in the upper half of the column reactor (zone 6) there is a separation of metal and slag, and also uneven (in density, chemical composition and gas content) parameter distribution along the unit height takes place. Distributed content of iron oxides in height, which plays an important role in control over the ratio of oxidation and reduction processes, is also due to the nature of non-equilibrium thermodynamic processes,
including the intensity of the flow of matter and energy coming from below through the connecting channel 3 from the reactor-oscillator 2.

3. Control over the metal chemical composition

Now, after getting acquainted with the basic principles of the functioning of the process and the role of dissipative structures, we can concentrate on the control over chemical composition of the metal, primarily carbon. To do this, let us turn again to the zone model (Figure 2).

Stressing that chemical reactions occur in non-equilibrium conditions with removal of the reaction products, we shall note that the reduction reactions of iron oxide by solid carbon

\[
(Fe_2O_3) + C_{sol} = 2(FeO) + \{CO\};
\]

\[
(FeO) + C_{sol} = [Fe] + \{CO\};
\]

\[
C_{sol} = [C],
\]

occur in zone 6 (the upper part of the column reactor), and the reactions with the carbon dissolved in metal

\[
(Fe_2O_3) + [C] = 2(FeO) + \{CO\};
\]

\[
(FeO) + [C] = [Fe] + \{CO\},
\]

take place at the boundary of zones 5 and 8 (turbulent layer on the boundary metal-slag) and have a velocity an order of magnitude greater rate [10], than reactions (1, 2). The zones 5 and 8 are separated by dynamic “pillow” (zone 4) from zone 6. The proportion of iron oxides processed at the boundary slag-metal (zones 5 and 8) can be increased by rising the fractions of larger ore materials and additional induction heating of the forehearth, and in zone 6 to raise the reduction potential due to supplying coke fines or coal to the column reactor to the upper level of gas-slag emulsion. Thus, possibility for creation the above-described dynamic dissipative structures under certain gasdynamic modes allows the speeds ratio of redox processes to be controlled separately and, consequently, control over the carbon content in the produced metal.

Most of the experimental melts in the pilot unit of the new process at Zapsibmetkombinat gave the carbon content in the range 0.2-1.7%, and after some melts the carbon content was 0.04-0.10%, but this was due either to long taphole opening, or a significant slag overoxidation due to excess of oxygen. It should be noted that the pilot unit could not realize continuous but continuous periodical mode, also in the actual technology, due to the low inertia of the process, the implementation of such mode (with periodic release and leaving the “swamp” in the forehearth) is possible.

The following table 1 shows two examples of the direct production of metal with carbon contents 0.44 and 1.72%, corresponding to these values of concentration of iron oxides in the slag, and the main control values: mass ratio of the charge to mass ratio of reducing agents.

| Experiment No. | C   | FeO  | Fe_2O_3 | Mass ratio charge / reductant | Notes                                      |
|---------------|-----|------|---------|-------------------------------|-------------------------------------------|
| 20            | 0.44| 37.84| 8.36    | 2.89                          | Slag on the level of the connecting channel |
| 20            | 34.04| 5.45 |         |                               | Slag from the wall of the column reactor at a height of 2 meters from the connecting channel |
| 29            | 1.72| 6.56 | 2.29    | 2.31                          | The slag on the metal release              |
Also the concentrations of iron oxides are given in two slag samples taken after the experiment No. 20 (on the occasion of the machine stopping for reconstruction) at the upper edge of the forehearth and at the height of 2 m on the inner wall of the column reactor, indicating that the iron oxide content is distributed along the reactor height.

4. Comparison with the known processes of direct reduction

In the last 20-25 years, a lot of attention is paid to the development of direct reduction processes (see the review in [4]). More than 100 direct reduction plants have been built or are in the process of construction. Among the solid-phase direct reduction processes “Midrex” is the most advanced but, in fact, this process is hardly straightforward, as the same global energy illogic related to pelletization is repeated as in the conventional technology. Moreover, if the iron in the blast furnace is obtained in the liquid form, in this process the solid intermediate is produced. We should not forget that the arc energy used for the subsequent pellets or briquettes melting comes mainly from thermal power plants, where the thermal efficiency of about 37%, that is, only one tonne of coal reaches the arc, while the blast furnace coke consumption is less than 400 kg/t. In the solid phase reduction the economy is obtained only due to the lack of coke production, but only rich ores can be processed by this process.

In this sense, the liquid-phase reduction processes are being developed: Romelt [11], Hismelt, Ausmelt, DIAS, etc. [4], and have certain advantages. In these processes, which do not require sintering, dusts may be processed, including poor ores and metal-containing waste (sludge, scale). As a reducing agent energy coal is used; the constructive decisions on the use of exhaust gas energy are developed.

However, by none of the known processes the direct reduction of steel cannot be obtained. Cast iron with a carbon content of 2 to 4% is produced. This is due to the fact that the processes are close to thermodynamic equilibrium, and the metal and slag contact with each other for a long time in. Independent control over the metal composition and slag as well as the period of their residence in these units is practically impossible.

Among the combined processes of direct reduction Corex process should be mentioned, which was industrially implemented and has achieved some progress. But it also turned out to be rather clunky, it also has failed to avoid the stage of pelletizing. For the pre-reduction of oxidized pellets in this unit a shaft furnace with volume of 1000 cubic meters is used installed over the liquid-phase reduction unit. All together this building is about 100 m high.

It is interesting to draw an analogy with the considered in this article unit SER, which, due to the refusal of the agglomeration stage, the role of the preparatory unit plays a spherical reactor-oscillator with volume only a few cubic meters. It is also the compressor, which prepares and pushes the mixture through all devices of the unit.

5. Design and technological features of SER unit

After such comparison in the conclusion of the paper we shall consider the main features of the design and technological solutions in SER unit.

The basis of the technological scheme of the unit (Figure 5) is as follows: charge supply system 1-5; reactor-oscillator 6; a connecting channel with a gas-dynamic self-locking 7; refining sump 8; forehearth simultaneously acting as a first stage of wet gas purification 9; and skull cooling system 10, a channel for gas flow 11; slag tank 13 with a granulator 14; the heat utilization system in the fluidized bed or the flue gas reformation in the synthesis gas 17 and gas cleaning system 18.
Figure 5. Technological mini-module scheme based on SER process.

Use as a refining sump of the vertical column reactor with bottom feeding of the reaction gas suspension in combination with a significant deviation of processes from thermodynamic equilibrium is the major factor that determines the possibility of separating the iron metal flow flowing along the periphery of the column reactor and settling in the forehearth 9 (Figure 5), and iron depleted slag flow withdrawn via an inclined channel 11 into the slag receiver 13.

Dustlike charge consisting of a mixture of metal oxides and solid reductants is effectively dispersed in the reaction chamber 6. This creates a suspension of gas volume fraction of the order of 0.99. As an effect of dependence of the speed of the two-phase medium flow on the gas content (Figure 1), in the connecting channel 7 aerodynamically lockable gate is formed (jet braking), and in combination with the feedback in gas content (by changing the conditions of chemical reactions, as well as the supply conditions in the batch and oxygen feeding into the reactor) it is possible to create a stationary oscillatory mode (self-organizing reactor-oscillator). The created in reactor-oscillators 6 a high pressure potential and the total process isolation from the atmosphere, allows products through reactions to be pushed through all energy utilization devices, located after the main technological device, without the usage of high flow boosters.

Figure 6 shows a general view of the experimental unit SER in the converter shop of the West Siberian Metallurgical Combine.
In the foreground there is a column reactor, at the top of the “stack” is a system of metering and feeding the batch into the reactor-oscillator located at the bottom in the closed chamber.

Based on the considered unit a mini-mill of a new structure in the from of operating independently from each other and in parallel processing units can be designed, instead of succession of large units in the smelting cycle. The implementation of the principle of continuity eliminates the need for heavy removable equipment (casting ladles, heavy-duty bridge cranes, heavy foundations, etc.). The units can be placed in a relatively light buildings, enabling fast return on investments. The modules may operate independently from each other and be stopped in a few minutes. The proposed development opens the possibility for creating a mini-metallurgy of “full cycle”, without use of scrap, shortages and price of which is steadily rising. At the same time the problem of obtaining primary metal without non-oxidized impurities (copper and nickel) is solved, as well as using the powdered metal waste (scale, sludge, small chips, etc.). Creation of own mini industry is also very important for the machine-building plants, many of which have metallurgical industry in an outdated state.

6. Conclusions
- The basic principles that were laid in the creation of a new jet-emulsion process and metallurgical unit are considered.
- It is shown that due to the lower supply of the prepared in the reactor-oscillator working mixture (gas suspension) into the a column reactor, as well as a large deviation from thermodynamic equilibrium, there are dissipative structures, allowing the ratio of reducing and oxidizing processes to be controlled, and, consequently, control over carbon content in metal.
- The features of the structure and functioning of the SER unit are considered, allowing the described principles to be implemented.
- Thanks to the capacities of direct the processing in this unit of dusty ores and wastes (without agglomeration), the framework for designing of compact mini-mills with a full production cycle, from ore to steel, is developed.

7. References
[1] Nikolis G and Prigoshin I 1979 *Self-organization in Nonequilibrium Systems* (M.: Mir) p 512
[2] Khaken G 1980 *Synergy* (M.: Mir) p 406
[3] Kurdyumov S P and Malinetskii G G 1983 *New in Life, Science, Technology, Series “Mathematics, Cybernetics”* (M.: Knowledge) 6 p 48
[4] Tsymbal V P et al 2014 *The Process of SER – Metallurgical Jet Emulsion Reactor* (M.: Metallurgy) p 488
[5] Nakoryakov V E et al 1990 *Wave Dynamics of Gas and Liquid-vapor Environments* (M.: Energoatomisdat) p 248
[6] *Proc. Meet. On Continuous Process of Smelting Ferrous and Nonferrous Metal* (1975) (M.: Nauka) pp 14–28, 55–64, 160–167.
[7] Bigeev A M 1986 *Continuous Steelmaking Processes* (M.: Metallurgy) p 136
[8] Tsymbal V P et al 2014 *Proc. XIII Int. Cong. Steelmakers* (M.: Polevskoy) p 472–477
[9] Tsymbal V P et al 2015 *Metallurgist* 59 (3) 119–125
[10] Telegin I A et al 1993 *Ferrous metallurgy* 6 10–4
[11] Roments V A 2005 *Process Romelt* (M.: MISis) p 400