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CRITERION ASSESSMENT OF THE EFFICIENCY OF INJECTION EQUIPMENT DURING THE INJECTION OF POWDERED FERROALLOYS

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***Summary**. The purpose of the work is determining the efficiency of injection equipment with the injection of ferroalloys of different fractional composition, density and flow deep into the iron-carbon melt, taking into account the parameters of injection equipment (length and diameter of the pipeline and pressure in the powder-feeder). The analytical review of the literature is performed, which confirmed the advantage of powder injection in a teeming ladle compared to traditional technologies of deoxidation and alloying. Based on known mathematical models adapted to specific technological conditions, mathematical modeling is carried out, which takes into account a number of important parameters for technology, including fractional composition, density and consumption of powder ferroalloy, taking into account the parameters of injection equipment. The optimal diameter of the pipeline is determined. Nomograms of the lowest level of carrier gas consumption are designed. With the help of nomograms, it is possible to control the operation mode of injection equipment in obtaining pulsationless transportation of gas-powder mixture depending on the ferroalloy fraction, its flow rate and density, taking into account the diameter of the pipeline. Based on the results of mathematical modeling, the criterion for assessment the efficiency of injection equipment has been deduced, that makes it possible to determine quickly the pulsationless transport of gas-powder mixture depending on the fraction of powder reagent and pipeline diameter. The consumption of carrier gas depending on the fraction of powder reagent and the diameter of the pipeline, which can be used to control the operation mode of injection equipment in order to obtain pulsationless transport of gas-powder mixture has been determined*

***Key words**: out-of-furnace processing, steel, injection, deoxidation, alloying.*

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Statement of the problem. Application of injection technologies is one of the main directions of progressive development of steel production. This is due to the fact that significant acceleration of physical and chemical reactions occurs with the intensification of mixing of metal, slag and gas, as well as with the increase in the specific surface of the reacting phases. The greatest effect of intensification of metallurgical processes is achieved by simultaneous acceleration of melt flows and increase of the phase's reaction contact while grinding solid reagents into powder, crushing liquid into drops, and gas into small bubbles. Therefore, metal blowing in the steel melting unit or in the ladle with simultaneous injection of powders ensures the maximum contact of blown solid particles with the liquid melt, high speed of their interaction and the degree of use.

In this regard, the injection of powder materials and liquid iron-carbon fusion for various purposes (desulfurization, dephosphorization, deoxidation, etc.) has found its application in solving certain technological tasks.

Analysis of available investigation results. The authors of paper [1] note that metal alloying by blowing powders makes it possible to obtain more stable content of alloying and high degree of their assimilation: aluminum is 80–90%, boron – 85–93% (at consumption of 0.026-0.043 kg/t of ferrobor), selenium – 71–77% (0.28–0.44 kg/t of ferroselenium), carbon – 90–100% (0.4–1.0 kg/t of carbonizer). FeMn, FeSi, FeV, FeTi, FeNb are also blown.

The interaction of the gas-powder jet with metal is preceded by the transportation of the powder from the pneumatic compressor through pipelines to the lance, which is immersed or not immersed into the metal [2]. The problem of pneumatic transport is good enough explained in special literature, and the calculations of such systems are given in papers [3–5].

However, in order to ensure a uniform supply of the gas-powder mixture with a given flow rate, it is necessary to carry out time-consuming calculations in the entire range of gas flows, which should be applied to the fluidization of the powder, to maintain the necessary pressure in the feeder and to transport the gas-powder mixture.

The objective of the paper. The objective of this paper is to investigate the effective operation of injection equipment when introducing ferroalloys of different fractional composition, density and consumption into the depth of iron-carbon fusion, taking into account parameters of the injection equipment (length, diameter of the pipeline and pressure in the feeder).

Statement of the problem. The basics of calculating the injection blowing complex with chamber feeder are described in the paper [5].

As the theory of pneumatic transport shows, the size of solid particles is one of the most important characteristics and is included as determining parameter in the calculation equations. The theory of pneumatic transport makes it possible to estimate the critical flow rate at which particles do not precipitate on the pipe walls:

$$u_{cr} = 5{,}6 d_{tube}^{0{,}34} \cdot d_{part}^{0{,}36} \sqrt{\frac{\rho_{part}}{\rho_{gas}}} \cdot W^{0{,}25}, \text{ m/s}, \quad (1)$$

where:
d_{tube} is pipeline diameter, m;
d_{part} is powder size, m;
$W = \frac{m_{part}}{m_{gas}}$ is the ratio of mass consumption of powder and gas, kg/s;
ρ_{part} is powder density, kg/m^3;
ρ_{gas} is gas density kg/m^3.

Pulsationless uniform transportation of powder on horizontal sections of the pipeline is possible provided that the speed u_o of the gas-powder jet at the exit from the chamber feeder at the beginning of the pipeline exceeds critical u_{cr}, at which the deposition of powder particles on the walls of the pipeline begins, i.e. $u_o > u_{cr}$. At the exit from the chamber feeder at the beginning of the pipeline, the velocity u_o is:

$$u_o = \frac{m_{gas} \cdot R \cdot T_{gas}}{p \cdot S}, \text{ м/с}, \quad (2)$$

where:
m_{gas} is consumption of gas (argon), kg/s;
R is the universal gas constant, 8.314 J/(mol K);
T_{gas} is carrier gas temperature, K;
S is cross-sectional area of the pipeline, m^2;
P is the absolute pressure in the feeder. In general, the pressure in the feeder is: $P = \Delta p_1 + \Delta p_2 + \Delta p_3 + \Delta p_4 + \Delta p_0$, Pa,
where:
Δp_1 – losses for overcoming the force of gravity of metal column (ferrostatic pressure), Pa;
Δp_2 – frictional pressure losses during the movement of the gas-powder mixture in the transport pipeline and nozzle channel), Pa;
Δp_3 – pressure losses associated with dispersion of solid particles), Pa;

Δp_4 – pressure losses associated with the weighing of powder column with height *H* (*H* is the difference in the levels of entry and exit of gas-powder mixture). The value Δp_4 is positive if the entry is lower than the exit, and negative when the entry is higher than the exit: p_0 is atmospheric pressure.

However, the inequality does not answer questions concerning the possibility of system operation when using powdered ferroalloys with different physical parameters.

After transformation of the above given expressions, we get the following inequality:

$$d_{tube}^{2,34} \cdot d_{\text{part}}^{0,36} < \frac{4m_{gas}^{1,25} RT_{\text{gas}}}{5{,}6 m_{\text{part}}^{0,25} P\pi} \cdot \sqrt{\frac{\rho_{\text{gas}}}{\rho_{\text{part}}}}. \tag{3}$$

However, for more convenient application of the above given inequality, criterion for evaluating the efficiency of the injection equipment when injecting powdered ferroalloys is derived.

$$K_{eff} = \frac{4\, R m_{\text{gas}}^{1,25} T_{\text{gas}}}{5{,}6\ \text{P}\ \pi d_{\text{tube}}^{2,34} d_{\text{part}}^{0,36}} \cdot \sqrt{\frac{\rho_{\text{gas}}}{\rho_{\text{part}}}}. \tag{4}$$

If the criterion is more than one, there will be no deposition of powder on the walls of the pipeline, while the condition of pulsationless transport of the gas-powder mixture will be fulfilled, and if the value is less than one, the powder will spread over the pipeline walls.

Analysis of numerical results. To assess the determination of reliable data acquisition according to the above mentioned formula, calculations are carried out taking into account the following initial parameters of powdery materials and injection equipment:

Table 1

Transportation process parameters

Parameters title	Units of measurement	Minimum	Maximum
Powder fraction, d_{part}	mm	0.1	3.0
Diameter of the pipeline, d_{tube}	mm	15	50
Gas consumption*, m_{gas}	m^3/h	60	120
Powder consumption, m_{part}	kg/min	10	110
Ferroalloy density, P_{part}	kg/m^3	2.2	9.3
Feeder pressure, P	atm.	3.0	12.0

*Argon with 1.78 kg/m^3 density is used as a carrier gas. The density of ferroalloys: the minimum value is 2.2 kg/m^3 silicocalcium density (30–33% mass fraction of the alloying element); the maximum value is 9,3 kg/m^3 ferromolybdenum density (60–70% mass fraction of alloying element) [6].

Investigation results. Analysis of the calculation data showed that the maximum value, at which the efficiency criterion was obtained less than one, is at the maximum powder fraction (3.0 mm) and maximum pipeline diameter (50 mm). The exception was the version where the minimum powder consumption (10 kg/m^3) and its density (2.2 kg/m^3) were noted, but at the same time the maximum gas consumption (120 m^3/h) was noted, which did not allow the powdery reagent to spread over the pipeline walls. This circumstance indicates the fact that for the effective operation of the injection equipment, it is necessary to determine the required flow rate of the carrier gas depending on the fractional composition of the powdered reagent, its flow rate and density, taking into account the use of pipelines with different diameters.

The dependence of argon consumption on the fractional composition of powdered ferroalloy and pipeline diameter (the lance nozzle) is shown on the nomograms (Fig. 1 and 2).

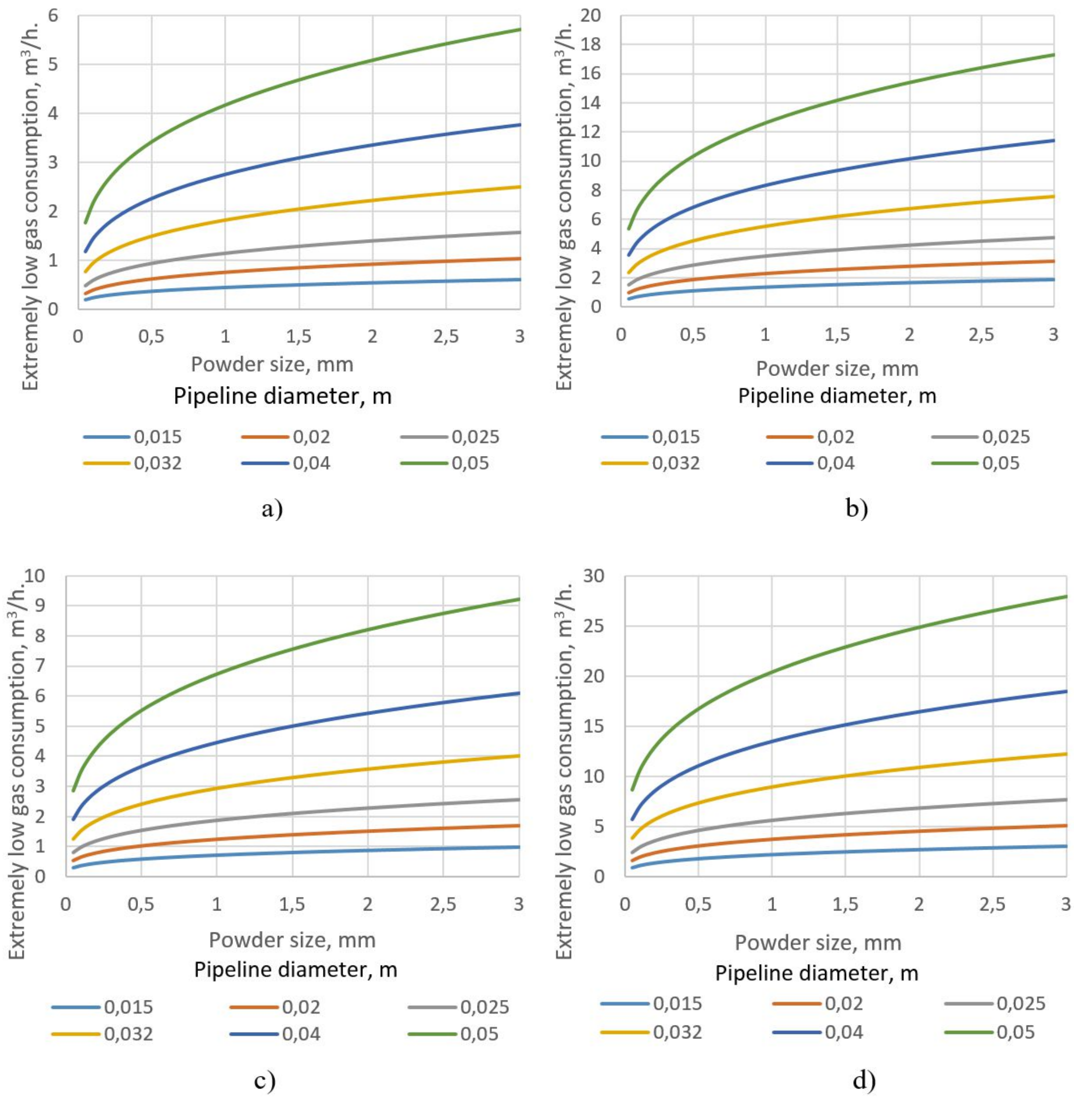

Figure 1. Dependence of argon consumption on consumption of ferroalloy powder of its fractional composition and density (2.2 kg/m^3): a) powder consumption 10 kg/min., pressure in the feeder 3 atm.; b) powder consumption 110 kg/min., pressure in the feeder 3 atm.; c) powder consumption 10 kg/min., pressure in the feeder 12 atm.; d) powder consumption 110 kg/min., pressure in the feeder 12 atm

Analysis of the nomogram data shows that with the increase in the fractional composition of ferroalloys, the consumption of carrier gas increases. Particularly noticeable increase occurs with the increase of the pipeline diameter from 32 mm to 50 mm. This circumstance indicates the fact that the optimal diameter of the pipeline used for the injection of powdered ferroalloy of the investigated fraction (0.05–3.0 mm) is 15, 20, 25 and 32 mm. It should also be noted that the increase in gas consumption contributes to the increase of the density of ferroalloy and its consumption (Table 2).

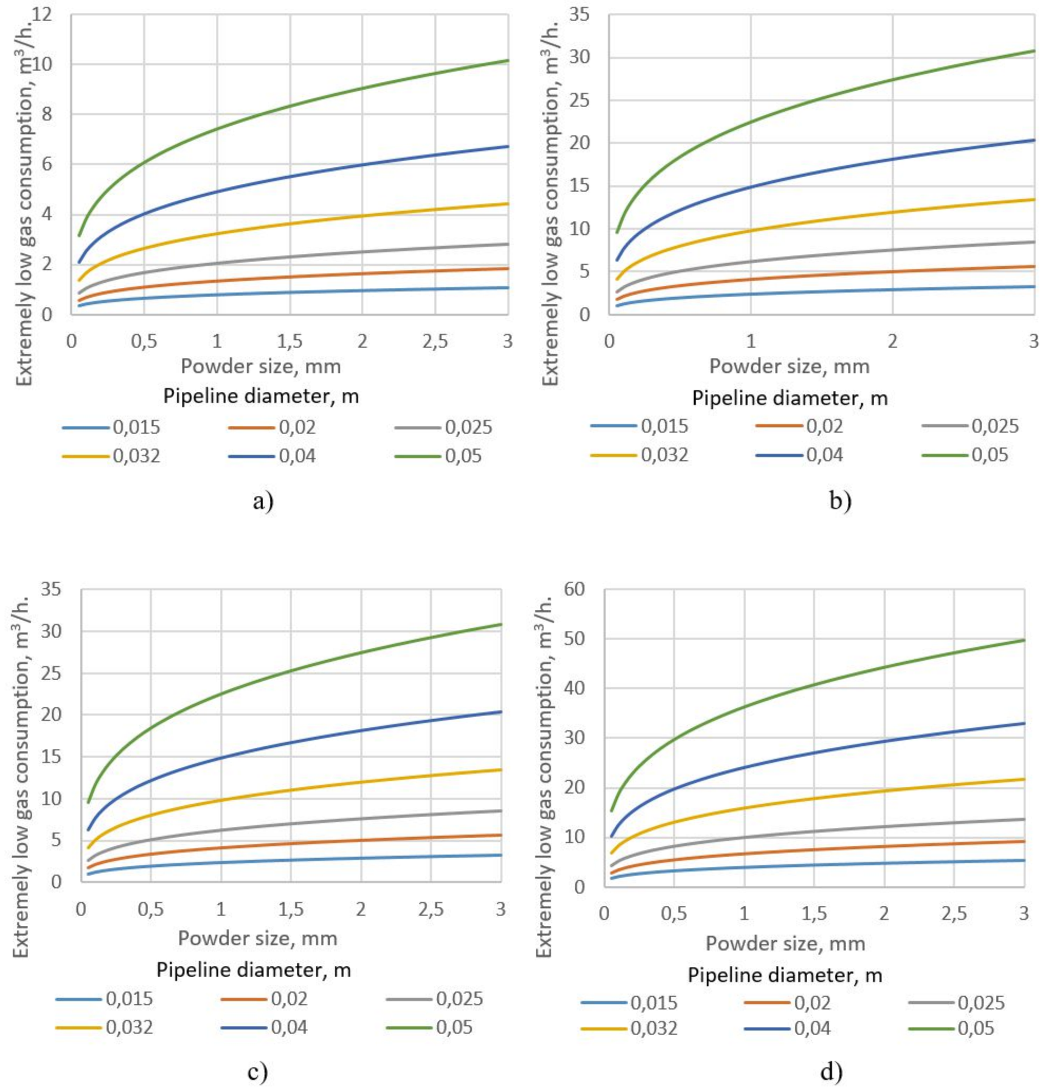

Figure 2. Dependence of argon consumption on consumption of ferroalloy powder of its fractional composition and density (9.3 kg/m^3): a) powder consumption 10 kg/min., pressure in the feeder 3 atm.; b) powder consumption 110 kg/min., pressure in the feeder 3 atm.; c) powder consumption 10 kg/min., pressure in the feeder 12 atm.; d) powder consumption 110 kg/min., pressure in the feeder 12 atm

Table 2 shows that with the increase of powder consumption within the range from 10 to 110 kg/min. and density from 2.2 to 9.3 kg/m^3, the consumption of argon increased by 1.63 times (from 0.19 to 0.31 m^3/h) and by 1.58 times (from 0.34 to 0.54 m^3/h), when blowing powder with the fraction of 0.05 mm through the pipeline with 15 mm diameter. Such tendency can be observed when ferroalloy with 3.0 mm fraction is introduced through the pipeline with investigated diameters. It should be noted that in gas consumption table, the carrier must be perceived as extremely low, that is, as a starting point for the beginning of blowing the metal with gas-powder mixture with further possible increase. The increase in gas consumption is possible if weak mixing is noted in the ladle during visual observation.

As the pressure in the feeder increases, gas consumption increases. However, this parameter depends on the ratio of mass consumption of powder and gas. This indicates the disadvantage of this method. The given parameter must be pre-calculated taking into account frictional pressure losses during the movement of gas-powder mixture, overcoming the gravity force of metal, pressure losses associated with the acceleration of solid particles, pressure losses associated with weighing the powder with H height, atmospheric pressure.

Table 2

Dependence of argon consumption on ferroalloy consumption of its fractional composition and density, taking into account the pipeline diameter

Powder consumption, kg/min.	Pressure in the feeder, atm.	Ferroalloy fraction, mm	Argon consumption for pipelines with different diameters, m^3/h.					
			15	20	25	32	40	50
with ferroalloy density 2.2 kg/m^3								
10	3.0	0.05	0.19	0.32	0.49	0.77	1.17	1.77
		3.0	0.61	1.04	1.57	2.49	3.77	5.70
	12.0	0.05	0.57	0.98	1.48	2.34	3.55	5.37
		3.0	1.85	3.15	4.77	7.55	11.43	17.29
110	3.0	0.05	0.31	0.52	0.79	1.25	1.89	2.86
		3.0	0.99	1.68	2.54	4.02	6.09	9.22
	12.0	0.05	0.93	1.58	2.39	3.79	5.73	8.67
		3.0	2.99	5.09	7.71	12.20	18.46	27.94
with ferroalloy density 9.3 kg/m^3								
10	3.0	0.05	0.34	0.57	0.87	1.38	2.08	3.15
		3.0	1.09	1.85	2.80	4.43	6.71	10.15
	12.0	0.05	1.02	1.74	2.64	4.17	6.31	9.56
		3.0	3.29	5.61	8.50	13.44	20.34	30.78
110	3.0	0.05	0.54	0.93	1.41	2.22	3.36	5.09
		3.0	1.75	2.99	4.53	7.16	10.84	16.40
	12.0	0.05	1.65	2.82	4.26	6.74	10.20	15.44
		3.0	5.32	9.07	13.73	21.71	32.86	49.73

Conclusions. The criterion for evaluating the efficiency of the injection equipment is derived. This criterion makes it possible to determine quickly the possibility of pulsationless transport of the gas-powder mixture fraction from 0.05 to 3.0 mm, depending on the pipeline diameter (lance nozzle). The optimal pipeline diameter is 15, 20, 25 and 32 mm. Nomograms of extremely low consumption of carrier gas are constructed. Due to the nomograms, it is possible to control the mode of operation of the injection equipment in obtaining pulsatioless transport of gas-powder mixture, depending on:

- the ferroalloy fraction no more than 0.05 to 3.0 mm;
- the consumption of ferroalloy powder within the range from 10 to 110 kg/min.;
- the density of the ferroalloy from 2.2 to 9.3 kg/m^3;
- the pipeline diameter from 15 to 32 mm.

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КРИТЕРІАЛЬНЕ ОЦІНЮВАННЯ ЕФЕКТИВНОСТІ РОБОТИ ІНЖЕКЦІЙНОГО ОБЛАДНАННЯ ПІД ЧАС ВВЕДЕННЯ ПОРОШКОПОДІБНИХ ФЕРОСПЛАВІВ

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Резюме. *Визначено ефективність інжекційного обладнання при введенні феросплавів різного фракційного складу, густини та витрати вглиб залізовуглецевого розплаву з урахуванням параметрів інжекційного обладнання (довжина і діаметр трубопроводу та тиск в живильнику). Виконано аналітичний огляд літературних джерел, за результатами якого підтверджено перевагу інжекції порошкових реагентів у ківш порівняно з традиційними технологіями розкислення й легування. Ґрунтуючись на відомих математичних моделях, адаптованих до конкретних технологічних умов, виконано математичне моделювання, що враховує низку важливих для технології параметрів, зокрема фракційного складу, густини та витрати порошкового феросплаву з урахуванням параметрів інжекційного обладнання. Визначено оптимальний діаметр трубопроводу, який забезпечує стабільно високу подачу порошку газом у безпульсаційному режимі. Побудовано номограми гранично низької витрати газу носія. За допомогою номограм можна керувати режимом роботи інжекційного обладнання в отриманні безпульсаційного транспорту газ-порошкової суміші залежно від фракції феросплаву, його витрати та густини з урахуванням діаметра трубопроводу. За результатами математичного моделювання виведено критерій оцінювання ефективності роботи інжекційного обладнання, за рахунок якого можливе оперативне визначення безпульсаційного транспорту газопорошкової суміші залежно від фракції порошкового реагента й діаметра трубопроводу. Визначено витрати газоносія залежно від фракції порошкового реагента й діаметра трубопроводу, які можна використовувати для керування режимом роботи інжекційного обладнання з метою отримання безпульсаційного транспорту газо-порошкової суміші.*

Ключові слова: *позапічна обробка, сталь, інжекція, розкислення, легування.*

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