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Relationship between stream forces and parameters of the powder injection into metal bath

J. Jezierski*, J. Szajnar
Division of of Foundry, Institute of Engineering Materials and Biomaterials,
Silesian University of Technology, ul. Towarowa 7, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: jan.jezierski@polsl.pl

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ABSTRACT

Purpose: The pneumatic method of introduction of various powders into ladle or metallurgical furnaces is use because of its many advantages. There are no problems with use of injection lances in electric arc furnaces but in inductive furnaces or ladles, especially big ones the problem of metal flowing out of it may appear. This is the reason why the authors have maiden some experiments which results are presented in the article.

Design/methodology/approach: The new lance with a flange was invented and used in powdered material injections experiments. The experimental plan was prepared that contain the most important parameters of pneumatic process. A statistical analysis was made to connect the results of the injection process with its parameters.

Findings: The main conclusion is the influence of carrier gas pressure, lance inside diameter and mass concentration of diphase stream on the obtained results. The next one is that changing of the lance geometry could effectively improve the technological parameters of the process and that the new design of the injection lance is prepared properly.

Research limitations/implications: The limitations of the results is that the experiments were only the “cold model” ones, without presence of molten metal. The only liquid medium used was water for experiments with stream distance measurement. The nest experiments are planned with injection of powder into laboratory induction furnaces for checking the obtained results.

Practical implications: According to the authors, the new lance can be used for introducing a small quantity of the powdered material like modifiers or something like that.

Originality/value: The approach to the problem of diphase stream forces and distance of stream in liquid is according to authors’ knowledge a new one. The lance with flange proposed for those usage is not present in literature and is an originality too. The paper could be interesting for all interested in problems of melting processes improving.

Keywords: Metallic alloys; Casting; Pneumatic conveying; Powder injection; Injection lance

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

When you are melting any alloy in some stage of this process you have to introduce some materials for obtaining the special results like elements content increase, purification of metal (deoxidation, desulphurization etc.) and others. The most often those materials are in form of pieces because of important technological and economic reasons. But when the pieces materials are produced the large amount of fine fractions is obtained too and there are considered the wastes. Utilisation of these fractions is limited because there is not a lot of effective method to enter them into liquid metal [1-4].

For these reasons, these wastes are stored on dumps, increasing their number in many industrial countries.

The next big problem of metallurgy and foundry technology are huge amounts of dusts that very often contain large quantities of useful elements which unfortunately, together with other wastes, are disposed onto a dump.

Therefore the pneumatic powdered material (or dust) injection method has been known and appreciated method of liquid alloys treatment since many years. They can be use for:

– recarburization of cast iron (or decarburization in production of some grades of steel),
– slag foaming for decreasing electrodes damage and energy consumption in EAF's,
– introduction of small amounts of alloy additions,
– modification and spheroidizing of cast iron, rarely used – only with automatic foundry lines with on-stream technique,
– deoxidation, desulphurization, inclusions modification and others purification processes,
– flue dusts back blowing in etc. [5-7].

The best results gives pneumatic recarburization of cast iron in electric arc furnaces, when it is necessary before its spheroidizing - increase of carbon content when you use a large amount of low-carbon steel scrap instead of much more expensive pig iron. On this field Department of Foundry of Silesian University of technology has many successes, which are proven by many industrial applications and devices. That method of introduction is very fast. safe and effective (the effectiveness almost 100% could be obtained) and what is the most its advantage is very economic too. Although pneumatic injection of powdered materials is known and successfully applied for many years, the problem, in some aspects, is not completely solved and understood. Successful solution of some problems e.g. obtaining a good injected particles stream in liquid, small temperature decrease after injection etc. could make possible implementing the method in foundries and metallurgical plants for utilizing of waste materials which would be potentially usable as the raw materials. From this point of view, the great advantages for natural environment would be much appreciated. Application of pneumatic injection method into other than until now areas of technology significantly decreases costs connected with consumption of power, whose large quantities are used in metallurgical and foundry processes. Lesser consumption of power, which is generated often (in Poland mainly) using traditional power industry based on combustion of coal, will affect the environment of more industrialized areas. The main disadvantage of pneumatic method is that the residence times of the particles in liquid bath is sometimes quit short that may cause the poor efficiencies of the material introduced. Therefore the character of the diphase stream (gas-powdered material) is of fundamental importance to these processes. Currently there is no simple method to measure particle trajectories or velocities in a furnace or a ladle because of very high temperatures involved. This is the reason why low temperature model experiments and even computer simulations have been performed [8-10].

The paper include the results of pneumatic injection of powdered materials into liquid medium (water). Design of a chamber feeders and injection lances (especially a new lance with a flange) are shortly presented. The experiments have shown the most important parameters and relationships between them in pneumatic injection process. The influence of particles fraction, velocity of the stream in the lance outlet and parameters of carrier gas (pressure in pipes and in pneumatic feeder) on the technological indexes of the process like effectiveness and rate of assimilation of alloy addition have been presented too.

2. Design of the pneumatic injection stands an its parameters

Because of variety of technological applications the installation of powder injection may be a quit simple or a very complicated stands but always have to include some of the most important parts. One of them is a pneumatic feeder which is the start point of the installation and it is a place where powdered material is introduced into pipeline and mixed with a carrier gas (in the place called mixing chamber) [1,10-12]. The construction of one of the dispensers (invented in Department of Foundry) have been shown on Figure 1.

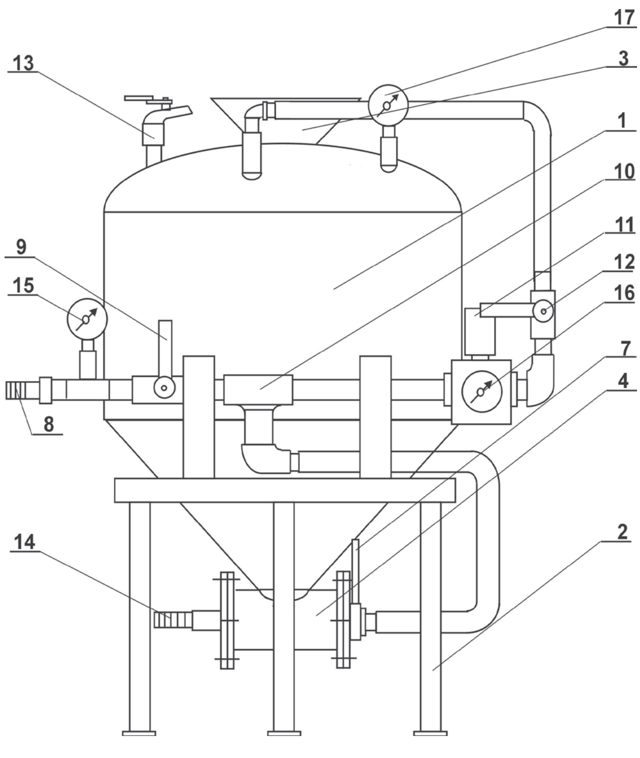

Fig. 1. Scheme of pneumatic transportation feeder.
1- pressure tank, 2- frame, 3- bell valve, 4- mixing chamber, 7- lever, 8- carrier gas supply, 9- valve, 10- gas distributor, 11- pressure regulator, 12- valve, 13- decompressing valve, 14- powder outlet, 15,16,17- manometers [1].

The dispensers can be generally divided into three categories:
a) injectors,
b) fluidizers (conveying of powder being fluidized),

c) combination of injector and mechanical feeders.
Modern setups have normally more than one dispenser what make possible simultaneous injection of several reagents. Such approach make possible to:
a) mix few powders in dispenser to avoid expensive ready-made mixtures,
b) limit vaporization of this elements which have a high partial pressures at liquid alloy temperature.

By simultaneous introduction of several reagents during final stage of injection the same effect may be obtained like by introduction of single but much more expensive reagent and the time of process duration will be smaller.

2.1. Lances and its insertion systems design

The results of injection processes depends among other things on lance construction and its insertion system. Commonly used lances types are presented in fig. 2.

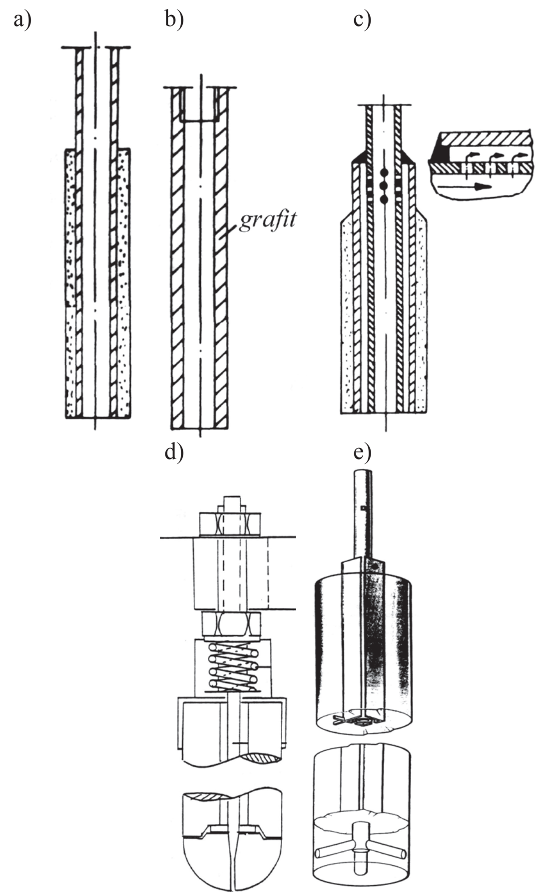

Fig. 2. Injection lances constructions [1].

The lance can be made as follows:
a) monolithic lance – normal steel pipe in ceramic shield),
b) graphite lance (sometimes in form of hollowing electrodes),
c) air-cooled or water-cooled lance,
d) ceramic lance
e) lance with several outlets (for better material distribution).

The basic criteria of a lance choice is its functionality and durability. Problems of lances damages which are comparatively expensive are tried to be avoided making many changes in blowing-in technology: instead of deep submersion – shallow submersion (or non-submerged lances) to the phase separation area between slag and liquid metal bath, or increase of mixture flow rate with decrease of its mass concentration is used. With use of furnaces like cupolas or some EAF's the good approach is to mount in it a permanent lance (or nozzle) when you want to introduce of big amounts of powdered reagents.

2.2. The most important parameters of pneumatic injection

Pneumatic powder injection processes are the very complicated physical-chemical ones, which success is determined by a lot of important parameters. They are connected to liquid metal bath (e.g. its temperature) and carrier gas parameters (e.g. pressures in some points of the installation), powder characteristic(e.g. grain size) and others. The pneumatic injection system should have parameters as follows:

a) constant rate of powder flow,
b) carrier gas consumption as small as possible,
c) short duration time to minimize temperature decrease,
d) easy operation,
e) full air-tightness,
f) possibility to change the injected materials during the process.

The most important parameters are: carrier gas flow rate, powdered material flow rate, mixture mass concentration (material mass flow and gas flow ratio), and velocity of diphase stream (it depends on gas velocity of course) in lance outlet. The appropriate values of that parameters is a key to obtain the best results [1-3].
Carrier gas flow rate is given by equation (1):

$$\dot{V}_N = \frac{\dot{m}_g}{\rho_N} \tag{1}$$

where: $\dot{m}_g$ - powdered material mass flow,
ρ_N –carrier gas density .

Powder flow rate is given by equation (2):

$$\dot{m}_c = \frac{m_c}{t} \tag{2}$$

Mixture mass concentration it is a ratio of powdered material mass flow and carrier gas mass flow and is given by equation (3):

$$\mu = \frac{\dot{m}_c}{\dot{m}_g} \tag{3}$$

Velocity of gas in lance outlet is as follow:

$$w_{śr} = \frac{\dot{m}_g}{A\rho} \tag{4}$$

where: A – lance cross-sectional area.

3. Research topic

Scientific aspect of presented researches has the very important purpose. They should improve the state of knowledge about the two-phase stream (gas-particles) effect in pneumatic powder injection process. The problem of dynamic force of stream while in contact with liquid metal bath surface, is in the author's knowledge, not yet solved. Applying very general, known relationships and descriptions of this phenomenon does give an effect under specific conditions, which are present in the pneumatic injection of the gas-powder mixture into depth of liquid metal.

Therefore, it is necessary to develop the knowledge in an inter-disciplinary approach, with widely understood issues of two-phase gas-powder streams in order to find an answer many questions in this, seemingly, well mastered field of engineering.

The purpose of the researches was, first of all, to find an answer to the question of diphase stream dynamic influence for process technological parameters (mainly using non-submerged lance) of powders into liquid metal bath. In order to better understand the influence of stream dynamics, according to author's knowledge, we have to get acquainted as precisely as possible with phenomena which are present at contact interface of gas-liquid bath. These phenomena are related to forces described in similar processes (in some kinds of moulding machines) as "dynamic pressure force" and such a name is used consequently by authors for describing this parameter.

One of the most important parameters of powder injection process is the range of the particles stream in liquid alloy for the best reagent distribution in whole volume of metal bath. For obtaining of the main purpose of the process, the proper value of diphase stream force is to be provided. Because the researches presented in the paper correspond to "injection" of powders, with the least carrier gas content introduced into liquid bath, the problem of obtaining the optimum range of particles stream has significant meaning.

The previous author's researches within the scope of powders pneumatic injection using the non-submerged lance [13-17] have shown that use a lance of primitive design does not eliminate the introduction of gases into liquid alloys. In this connection, one more purpose of the experiments was to develop a lance of new design (with four slots and a flange), that could make sure that an effect of "stoppage" of carrier gas before it penetrates into depth will be obtained. The lance was invented and its tests in laboratory conditions proved its high effectiveness and usefulness for powder injection without submersion of the lance.

Positive solution of problems being analysed will allow utilization of this method in melting processes in inductive crucible furnaces and ladles, in which traditional application of methods has low efficiency or are impossible to use at all.. Sometimes the procedure is dangerous due to the specific melting conditions and specific geometrical parameters of the ladle or furnace (deep and slender). Because melting technology is very often similar and almost is connected to necessity of adding various elements, it is very important to use an effective and easy method of its introduction (especially of powdered materials which provide the highest effectiveness).

Reaching the planned goals will greatly enrich the scientific and engineering state of knowledge within the field of use pneumatic injection method of various reagents into liquid metal bath, providing the tool ready for application in foundries.

The experiments were so arranged in order to make possible finding the relationship and dependencies between process parameters (mainly the diphase stream range in liquid medium) versus pressure force value which is dependent on many parameters of stream dynamics such as velocity of the carrier gas in lance outlet, mass concentration of two-phase mixture, etc.
Reliable assessment of velocity of powdered particles in gas and powder stream is very important and difficult issue in pneumatic injection technique to be analysed. Applied methods of measurements and calculations of process parameters (especially velocity of particles) require, for their assessment, application of so called "slip coefficient", which produces very often large discrepancies between experimental research and calculated results. Examinations were making based on model experiments with particles motion analysis in two-phase stream (with recording by video camera)), which answered the question what is the real valued of particles velocity and a character of the diphase stream introduced into liquid medium [18-20].

4. Research method and experimental stand

The presented experiments included many inter-disciplinary considerations and research methods due to complexity of physical and chemical phenomena that accompany the processes under analysis.

The main part of the experiments which led to experiencing the effect of the diphase stream force has been done on the basis of carefully selected, experiment plan, which enable decrease of number of experiments with sureness of precision and wide spectrum of variables under analysis.

Research has been carried out under laboratory conditions with use of the pneumatic injection stand shown in fig. 3 with use of the powdered particles of different parameters (especially grain size of particles, density, shape coefficient, etc.).

Because the presented research were the model ones water was used as a model liquid medium and a part of its was made with electronic measurement device instead liquid medium. The stream has attacked the surface of the device and a force value was measured.

Measurement method using an electronic measuring device make possible almost the continuous measurement (10 times per second) and recording the time-dependent force of dynamic pressure. Recording (by the PC computer connected) the force value will allow the analysis of changing of stream force of stream in various moments of powder injection process. Variation of this variable results from the fact that significant fluctuations of stream occur of two-phase mixture under actual conditions of pneumatic conveying. In order to control the process of introduction and the parameters obtained, the optimum value of dynamic pressure force have been provided, which makes possible to achieve the proper infiltration of stream into depth of liquid metal bath and, at the same time, it does not allow to penetrate of essential quantities of carrying gas.

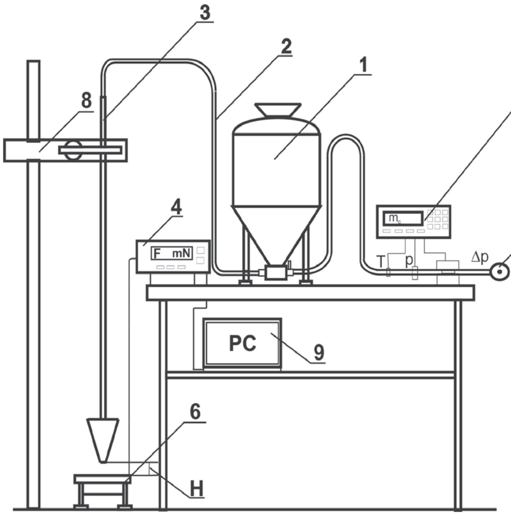

Fig. 3. Research stand of powder injection into induction furnace, 1-chamber feeder, 2-rubber pipeline, 3-injection lance with a flange, 4- electronic diphase stream force recording device, 5- electronic carrier gas flow measuring device, 6- diphase stream force measurement, 7- carrier gas supply, 8- slidable arm, 9- PC computer.

4.1. New invented lance with a flange

The main problem in pneumatic powder injection with non-submerged lance is proper distribution of introduced reagent in liquid medium without introduction of carrier gas and metal bath temperature decreasing. It was the reason for invention of a new design of the injection lance, which will cause significant decrease and even complete elimination of carrying gas introduction into the depth of metal bath. To check its properties the laboratory tests were making with a flange and a four slots made on its outlet, stopping the carrying gas and separating of particles from two-phase stream. Theoretical analysis and general concept and a prototype of the lance are already made and a Polish patent application was prepared and sent to the Polish Patent Office.

However, the lance still have to be tested as well as verified in another conditions. Its design is shown in Figure 4.

The experiments without submersion of the lance have been made because that approach is necessary with inductive furnaces, where use of immersed lance is sometimes impossible at all. The reason is a significant bath agitation, what may cause liquid metal bath flowing out the furnace or major temperature decrease. These problems are not present in the arc furnaces.

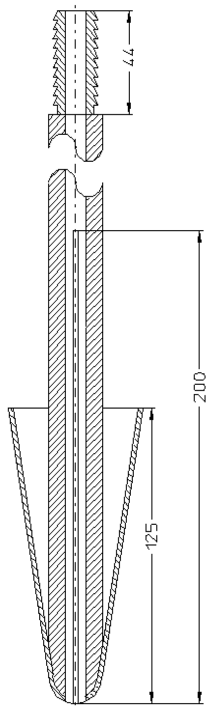

Fig. 4. Scheme of injection lance with flange

4.2. Description of the researches

The single experiment has been carried out as follows:

a) putting into chamber pressure container a weighed portion of material (powdered ferroalloy, polyethylene and others),
b) closing of a bell valve,
c) setting of a distance between a lance outlet and measurement surface of a electronic device,
d) carrier gas flow opening and setting of its parameters,
e) measurement of process parameters as injection time, pressure in important points of conveying installation, gas flow and recording of the stream force value,
f) shut off a gas flow after blowing-in process.

Because the effectiveness of injection processes (and its character in liquid metal) depends on a powder granulation, it was one of the variables which influence was analyzed. The average grain sizes of ferroalloy were:

- fraction 1: $d_a = 0,1$ mm,
- fraction 2: $d_a = 0,5$ mm,

The experiment plan included 12 tests for each fraction separately made. Apart from a grain size there were three another parameters changed during experiments:

a) a carrier gas (compressed air) pressure (three levels of changing: 0,2; 0,3; 0,4 MPa),
b) a gas in powder container pressure (three levels of changing: 0,05; 0,1; 0,15 MPa),
c) a distance between lance outlet and force measuring device (10, 40 and 80mm).

5. Results of the own researches

The one of the most important goals of the researches was finding the relationships between main parameters of the pneumatic powder injection. On the basis of the experiments the equations (5 and 6) have been formed and presented below.

Those equations include the values which have an influent on the diphase stream forces in pneumatic powder injection into liquid metal.

$$F = -4{,}733 \cdot 10^{-1} + 2{,}815\, p_1 + 16{,}68\, p_4 \qquad (5)$$

where: p_1 – pressure of the carrier gas,
p_4 – pressure in the powder dispenser.

As it is seen in fig. 5 the stream force increases when pressure p_1 increases.

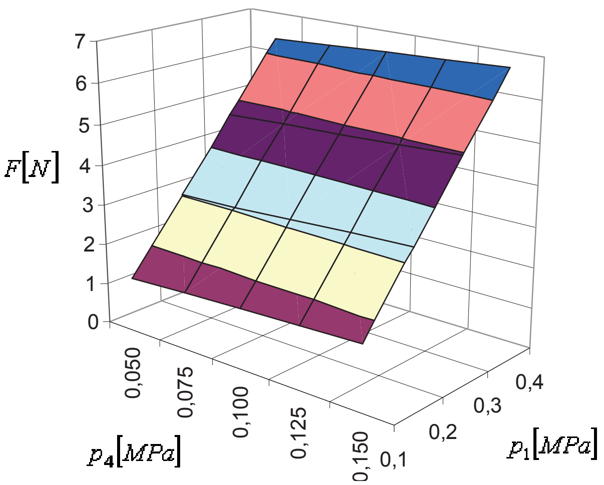

Fig. 5. Diphase stream force as a function of the gas pressures.

The results presented above have been obtained for pneumatic injection of FeSi75 particles with average diameter d_a = 0,1 mm. The analysis of influent of stream mass concentration and carrier gas velocity on the lance outlet on the stream forces caused the equation (6) shown below:

$$F = -6 \cdot 10^{-1} + 1{,}94 \cdot 10^{-2}\, \mu + 1{,}25 \cdot 10^{-1}\, w_k \qquad (6)$$

where: μ - diphase stream mass concentration,
w_k – velocity of the carrier gas in the lance outlet.

That equation shows that when μ and w_k increase the stream force increase too what is shown on the Figure 6.

5.1. Diphase stream range in liquid medium

The obtaining of proper range of diphase stream in liquid metal (fig. 7 and eq.6) is important for the success of pneumatic powder injection process too. The previously made experiments proved [13-17] that the best is the average value (about 40 mm) of distance between lance outlet and liquid metal bath surface. That proportion causes the best stream range in liquid, off course with proper values of other important parameters too.

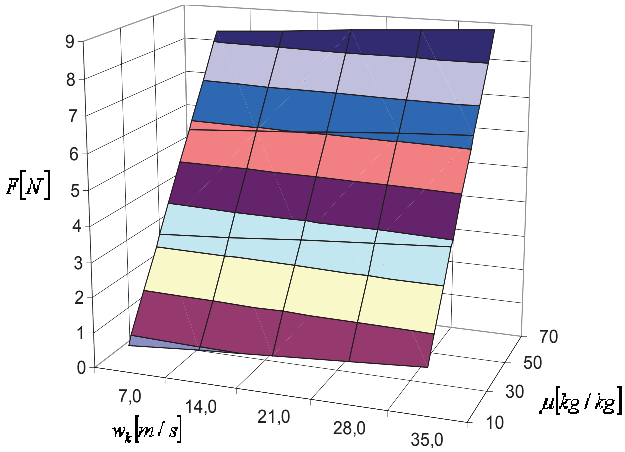

Fig. 6. Diphase stream force as a function of diphase stream concentration and velocity of gas on the lance outlet.

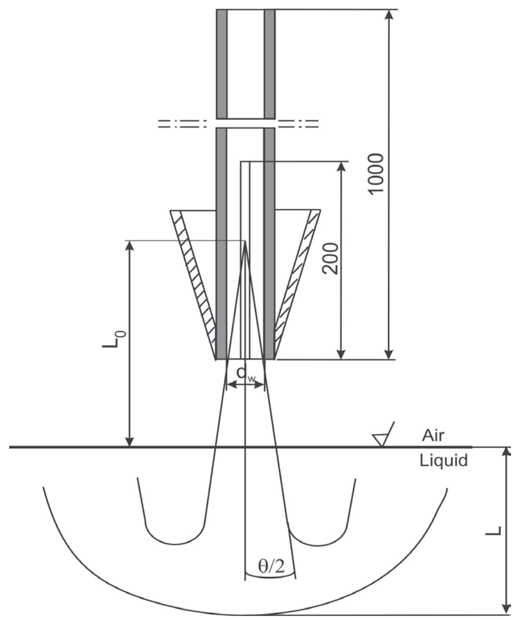

Fig. 7. Jet range in liquid in injection process with non-submerged lance; L_0-distance between liquid surface and virtual start point of conical stream, θ-jet angle, L-jet range in liquid.

The diphase stream range *L* in liquid metal depends mostly on distance between lance outlet and liquid surface *H*, mass concentration of stream μ, velocity of carrier gas w_k and particles grain size d_{cz} that has been shown in equations 8 and 9.

$$L = \left[\frac{3 \cdot \dot{m}_c \cdot w_c \cdot \sin\alpha}{\pi \cdot \tan^2\left(\frac{\theta}{2}\right) \rho \cdot g} + L_0^3 \right]^{\frac{1}{3}} - L_0 \qquad (7)$$

where: w_c – velocity of the powdered material particle, ρ - liquid medium density, θ - stream angle.

$$L = 1,477 \cdot 10^{-1} - 9,388 \cdot 10^{-4} H + 2,568 \cdot 10^{-3} \mu \qquad (8)$$

$$L = 1,513 \cdot 10^{-1} - 9,485 \cdot 10^{-4} H + 1,430 \cdot 10^{-2} w_k - 1,051 \cdot 10^{-2} d_{cz} \qquad (9)$$

The model "cold" experiments with liquid (water) have shown that new lance with flange makes possible to achieve the proper stream range [13,14,15,16,17,21]. The fig. 8 shows one of the photos made during experiments.

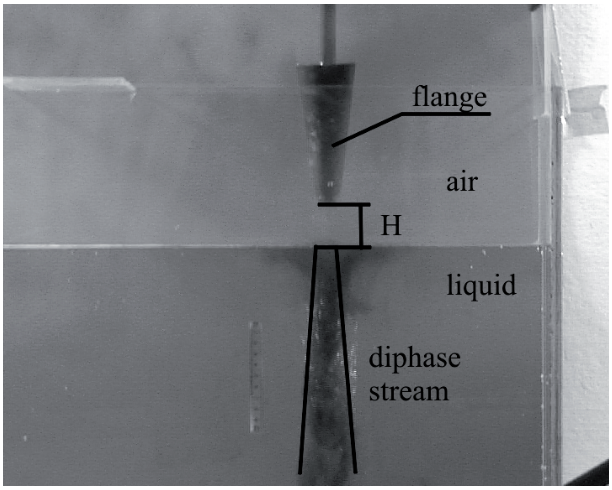

Fig. 8. Diphase stream range in model "cold" (water) experiments with non-submerged lance of new design.

6. Conclusions

The presented paper is the result of author's works in the field of method of pneumatic powder injection into liquid metal bath, which should more complete solve the problem of its possible industrial applications in foundries and metallurgical plants. Moreover the experiments explained some problems of diphase stream dynamics, which fundamentally influences on the results of the process being analyzed.

The non-submerged lance has been chosen because that method is necessary for inductive furnaces, when use of immersed lance is difficult or impossible at all.

In that case the problems of obtaining of high enough powdered particles velocity for proper penetration and distribution in liquid volume appear. Solving of that problems and prevention of carrier gas introduction into liquid metal bath were the main aim of presented work and will be continued in another works in Department of Foundry.

The conducted experiments led to the following conclusions:

1. Use of non-submerged lance could make possible to achieve a proper level of diphase stream force, stream range and introduced powdered material distribution in liquid medium.
2. The carrier gas velocity on the lance outlet has a decisive influence on analyzed during experiments parameters. The mass stream concentration is very important to because together with velocity cause proper kinetic energy of powder particles, which is essential to obtaining big enough stream range in liquid metal bath.
3. The setting of the stream velocity can be done by carrier gas pressure changing or by changing the geometry of the conveying system (both pressure container and injection lance).
4. The highest values of the pneumatic process parameters are obtained with granulation of particles d_a = 0,5 mm and a distance between lance outlet and a liquid bath surface H = 40mm. The use of the finer grains or higher distances requires carrier gas pressure increase.
5. The results show that method of pneumatic injection of powder without lance submersion can be used in foundries at industrial conditions but only for introduction of small quantities of the powdered material.

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Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 11th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005 in Gliwice-Zakopane, Poland on 6th-9th December 2005.

References

[1] K. Janerka, Z. Piątkiewicz, H. Szlumczyk, Review of injection carburizing plants for liquid metal treatment in arc furnaces, Proceedings of the 2nd Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'1993, Gliwice 1993, 126-129.

[2] H. Szlumczyk, Z. Piątkiewicz, K. Janerka, Diphase stream resistance of flow on pneumatic conveyor pipeline contraction, Proceedings of the 2nd Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'1993, Gliwice 1993, 215-218.

[3] Z. Piątkiewicz, H. Szlumczyk. K. Janerka, Pneumatic conveying in industrial applications, Proceedings of the 1st Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'1992, Gliwice 1992, 167-170.

[4] K. Janerka, S. Jura, Z. Piątkiewicz, H. Szlumczyk, Diphase stream parameters influence on carburization rate, Proceedings of the 3rd Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'1994, Gliwice 1994, 155-158 (in Polish).

[5] J. Gawroński, M. Cholewa, J. Szajnar, K. Janerka, Method of pneumatic inserting of reinforcing elements to matrix of

composite casts, Proceedings of the 8th Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'1999, Gliwice-Rydzyna-Pawłowice-Rokosowo 1999, 217-220.

[6] E. Sheepers, J.J. Eksteen, C. Aldrich, Optimisation of the lance injection desulphurization of molten iron using dynamic modeling, Minerals Engineering, 19 (2006) 1163-1173.

[7] J. Buchwalder, K. Scheidig, M, Schingnitz, P. Schmole, Results and trends on the injections of plastics and ASR into the blast furnace, Iron and Steel Institute of Japan – ISIJ International, 46, 12 (2006) 1757.

[8] D. Senk, H.W. Gudenau, S. Geimer, E. Gorbunova, Dust injection in iron and steel metallurgy, Iron and Steel Institute of Japan – ISIJ International, 46, 12 (2006) 1745.

[9] K. Janerka, Parameters of the process in pneumatic liquid metal carburizing, Proceedings of the 12th International Metallurgical & Materials Conference METAL 2003, Hradec nad Moravici, Czech Republic, 2003 (CD-ROM).

[10] D. Bartocha, K. Janerka, J. Suchoń, Charge materials and technology of melt and structure of gray cast iron, Journal of Materials Processing Technology, 162-163 (2005) 465–470.

[11] K. Yamaguchi, Method for simultaneous blow injection of powdered carbon and iron source, Fuel and Energy Abstracts, 39, 1 (1998) 53-53.

[12] J. Jezierski, Pneumatic powder injection into liquid alloys as a tool of quality improving, Proceedings of the 13th Metallurgical and Material Conference, 20-22.05.2004r., Hradec nad Moravici, Czechy, 2004, on CD-ROM.

[13] J. Jezierski, K. Janerka, J. Szajnar, Powder injection into liquid alloys as a tool for its quality improving, Archives of Foundry, 18 (1/2), PAN Katowice, 535-540, 2006 (in Polish).

[14] J. Jezierski, Possibilities of using the fine ferroalloys fractions in its pneumatic introduction into liquid cast iron, Proceedings of the 12th Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'2003, Gliwice- Zakopane 2003,415-418 (in Polish).

[15] J. Jezierski, J. Szajnar, Method and new lance for powder injection into liquid alloys, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 349-352.

[16] J.L. Xia, T. Ahokainen, L. Holappa, Study of flow characteristics in a ladle with top lance injection, International Journal Progress in Computational Fluid Dynamics 1 (2001) 178-187.

[17] K. Janerka, Parameters in pneumatic recarburization process, Proceedings of the 3rd Scientific Conference on Materials, Mechanical and Manufacturing Engineering MMME'2005, Gliwice – Wisła (2005) 531-534 (in Polish).

[18] K. Janerka, Mechanism of mass exchange in pneumatic recarburization of liquid ferrous metals, Proceedings of the 12th Scientific International Conference "Achievements in Mechanical and Materials Engineering", AMME'2003, Gliwice- Zakopane 2003, 415-418 (in Polish).

[19] B. Guo, P. Zulli, H. Rogers, J.G. Mathieson, A. Yu, Three-dimensional simulation of flow and combustion for pulverized coal injection, Iron and Steel Institute of Japan – ISIJ International, 45 (2005) 1272-1281.

[20] M. Asanuma, T. Ariyama, M. Sato et al., Development of waste plastics injection process in blast furnace, Iron and Steel Institute of Japan – ISIJ International 40 (2000) 244-251.

[21] J. Jezierski, J. Szajnar, Diphase stream forces in pneumatic powder injection into liquid metal, Proceedings of 11th Scientific International Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2005, Gliwice-Zakopane, 2005, 431-435, (CD-ROM).