ANALYSIS OF THE GAS-SOLID JET IN PNEUMATIC POWDER INJECTION PROCESS

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Abstract
The new approach to the pneumatic powder injection process analysis was presented in the article. The experiments with the high speed camera recording of the pneumatic powder injection process were carried out. The results were analysed and some interesting conclusions appeared. The two-phase jet character as well as some of its parameters were analyzed. They were compared with literature data as well as with some previously made by authors experiments. The commonly used indexes (e.g. slip velocity during two-phase jet movement) calculated in a typical way were compared and verified with these obtained during experiments described in the article.

Keywords:
two-phase jet, powder injection, injection lance, pneumatic conveying

1. INTRODUCTION
The use of the powder injection into metal bath technology has been known as an efficient method for metallurgical processes intensifying since many years and a lot of articles have been published [1,2,3]. Some authors described the phenomena during various kind of powdered materials introduction e.g. recarburizers [4], some grades of ferroalloys [5,6], reagents introduced for sulfur, phosphorus and other impurities removal [7,8]. However, not many experiments were focused on the problems appearing when the gas-solid jet goes out the lance outlet and introduces liquid, through its surface. Some initial experiments were conducted [9,10] but the recording equipment, computers and software were not good enough to carry out the precise analysis of the gathered data. The experiments described in this article were based on the high speed camera recording which outstanding feature i.e. recording speed and high resolution jointly with professional software for recorded material analysis made possible the observations of the phenomena which were earlier beyond the reach of the scientists. The authors prepared quite a complex experimental plan based on the previously made experiments described among others in [11,12] and the initial stage of it was described here in the article. The experiments with high speed camera following by the recorded material analysis were conducted to find the main parameters of two-phase gas-powder jet. The same parameters were traditionally calculated and both results were compared. The authors were mostly interested in a solid particles velocity or actually so-called slip velocity, which is the difference between gaseous and solid phase velocity of the two-phase jet. The recorded films were analyzed visually, too, what drawn to the interesting in the authors’ opinion conclusions, which were described further in the paper. Some remarks for further experiments were made, too. The next stage of the researches should finally prove that the two-phase jet character has a significant influence on the powder injection into liquid alloys process efficiency.

2. RESEARCH STAND AND EXPERIMENTAL PROCEDURE
The experiments were prepared analogically to those described in the previous authors’ works cited earlier. The only significant but crucial modification was high speed camera recording of the two-phase jet going out the injection lance. Both the research stand and experimental procedure were shortly described below.
2.1. **Research stand**

The research set-up used in these experiments was similar one to those used in previously reported works. Its outlook was shown in the fig. 1 below. The most important part of it is the high speed camera Phantom v210 by Vision Research with the maximum speed of 300,000 frames per second (with low resolution). This equipment was good enough to record the powder particles movement on the lance outlet with proper picture quality and then to process it in professional software. The TEMA Lite package which allows automatic selected points of the recorded area tracking and movement parameters estimation was used for image analysis purpose.

![Fig. 1. The research set-up for two-phase jet recording](image)

The main elements of the set-up are: 1- pneumatic powder feeder, 2- carrier gas flow meter, 3- carrier gas pressure reducer, 4- gas shut-off valve, 5- gas pressure inside feeder reducer, 6- halogen lamp, 7- powder injection lance, 8- high speed camera, 9- powder receiver

2.2. **Experimental procedure**

Two powdered materials: polypropylene powder of fraction 0.4 – 0.8mm and ferrosilicon Si75 of fraction 0.2 – 0.4mm were used during the experiments. The installation shown in the fig. 1 is equipped with high-pressured chamber feeder with bottom unloading. Its construction allows to regulate two-phase jet parameters by means of changing of two pressures values: \( p_1 \) – pressure of carrier gas (compressed air) supplying feeder’s mixing chamber, \( p_4 \) – pressure of gas inside the feeder above the powdered material which role is to regulate transportation efficiency. The \( p_1 \) pressure range was 0.1 – 0.3 MPa and \( p_4 \) pressure 0.02 – 0.1MPa for comparison with earlier works. This resulted in 15 experiments for each powdered material. The mass of material used in every single test was set 200 g.

The single test was performed as follows:
- pneumatic feeder charging,
- carrier gas flow open and its parameters adjusting,
- high speed camera calibration: exposure time, recording buffer start and trigger adjusting (to be sure the whole process will be successfully recorded),
- start the injection process together movie recording,
- recording the additional measurements e.g. gas flow and injection time,
- injection stopping, switching off the recording and carrier gas supply cut-off.

Recording was performed with use of dedicated PCC Control Software which perfectly cooperates with TEMA software used in further analysis.

3. RESULTS DISCUSSION

After recording all the experiments (15 tests for each material) thorough analysis was performed to find velocity, acceleration and displacement of the selected and representative particles. Below in fig. 2 the snapshots set of the particles jet for the polypropylene injection example and various pneumatic process parameters were shown.

![Fig. 2. The snapshots of two-phase air-polypropylene powder jet for p₁ = 0.1 MPa and various p₄, from left to right p₄ = 0.02, 0.04, 0.06, 0.8, 0.1 MPa](image)

During the powder material injection into molten alloy probably the most important parameter is velocity of the solid particles. It depends mainly on the gas velocity on the lance outlet. The difference between carrier gas and particles velocity so-called slip velocity sometimes is described as the quotient c/w, where c - solid phase velocity and w - gaseous phase velocity. On the experimental basis it is estimated that in the pneumatic conveying the ratio c/w (so called slip coefficient) equals 0.5 – 0.8. For the powder injection processes because the mass concentration μ < 10 slip coefficient is determined close to the highest 0.8 value. After the movies were recorded the powder particles were tracked and the graphs showing velocity of selected particles were prepared. The velocity changings of polypropylene grains for the experiments which were shown as the snapshots in fig. 2 (for p₄ = 0.02, 0.06 and 0.1 MPa) were shown in fig. 3 below.
Fig. 3. Polypropylene particles velocity changings for the following pneumatic parameters: $p_1 = 0.1 \text{MPa}$ and various $p_4$, from top to bottom $p_4 = 0.02, 0.06, 0.1 \text{MPa}$
Common analysis of fig. 2 and 3 shows that particles velocity increases with the pressures $p_1$ and $p_4$ increase. It is visible both from the particles velocity analysis and from their movement recorded on films that particles jet is non-uniform in terms of the velocity. It is a result of the gas velocity profile (the highest velocity in the jet axis and zero at the walls) but the dynamic phenomena occurring between particles what is visible on recorded films, too. The bounced back grains go slower and their track change what causes the particles jet cone expands.

The comparison of the velocity of gas and particles on the lance outlet calculated using standard formulas and average velocity of the polypropylene particles read from the films gave interesting results. The graph in fig. 4 shows three values together:

- $v_g$ – calculated carrier gas velocity, m/s,
- $v_p$ – calculated particles velocity $v_p = 0.8v_g$, m/s,
- $v_{avg}$ – average particles velocity read from the films, m/s.

![Graph showing comparison of calculated and read velocity](image)

**Fig. 5. Comparison of the calculated and read from films gas and polypropylene particles velocities;**

$v_g$ – calculated velocity of the carrier gas, $v_p$ – calculated velocity of the solid particles, $v_{avg}$ – average velocity of the solid particles read from the films

The analysis drawn to the conclusion that real polypropylene particles velocity is merely $34.0 \text{ - } 64.8\%$ of the calculated gas velocity on the lance outlet, so the slip coefficient $\frac{c}{w} = 0.34 \text{ - } 0.65$ what is the value much lower than this mentioned in the literature for powder injection and used by authors, too.

4. **CONCLUSIONS**

The results of the experiments described in this article presented the first initial stage of the complex experimental plan launched by authors. Its realization should significantly widen the knowledge in the character of the two-phase gas-solid particles jet in powder injection into liquid alloys process. The results shown the significant differences between real particles movement parameters and the values calculated using the formulas. This is particularly visible for so-called slip velocity what indicates that carrier gas flowing accelerates the material particles to a much lesser extent that was previously thought. The next step is computer modeling (just started) in which on the basis of data gathered during described experiments (and previously made, too) the jet introducing the liquid alloy model will be analyzed. For the numerical models validation purposes they will be compared to the model powder injection into water experiments previously made by authors. Only after the models are correct the modeling for the liquid alloy conditions will be
launched. The last experimental stage will be set of laboratory melts with the powder injection and high speed camera recording of the jet introducing the liquid metal bath. The technological process indexes such an efficiency or introduced material yield will be linked to two-phase jet parameters. The authors hope that it will give the full view of the two-phase jet character and the on-surface phenomena during powder injection influence on the efficiency of the carried on processes.

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LITERATURE


