The Analysis of Two-Phase Jet in Pneumatic Powder Injection into Liquid Alloys

J. Jezierski, K. Janerka

Abstract—The results of the two-phase gas-solid jet in pneumatic powder injection process analysis were presented in the paper. The researches were conducted on model set-up with high speed camera jet movement recording. Then the recorded material was analyzed to estimate main particles movement parameters. The values obtained from this direct measurement were compared to those calculated with the use of the well-known formulas for the two-phase flows (pneumatic conveying). Moreover, they were compared to experimental results previously achieved by authors. The analysis led to conclusions which to some extent changed the assumptions used even by authors, regarding the two-phase jet in pneumatic powder injection process. Additionally, the visual analysis of the recorded clips supplied data to make a more complete evaluation of the jet behavior in the lance outlet than before.

Keywords—injection lance, liquid metal, powder injection, slip velocity, two-phase jet

I. INTRODUCTION

THE powder injection into liquid metal alloys process has been worldwide known and successfully utilized since tens of years and a lot of papers describing its industrial applications have been published e.g. Holtzer [1], Senk [2] or Leontev [3] who additionally described the process development history. Many authors worked on the phenomena appearing during various kind of solid particles introduction including recarburizers as Janerka [4], ferroalloys as Jezierski [5,6,7], reagents introduced for sulfur, phosphorus and other impurities removal as Scheepers [8], Jezierski [9] and Limmaneevichitr [10]. Most experiments were focused on what happens in the liquid alloy volume after successful powdered material introduction. The particles dissolution process was analyzed by Kosowski [11] then diffusion, particles movement e.g. floating, jet distribution inside liquid medium as by Janerka [12]. However few experiments were focused on the first process stage when the jet goes out the lance outlet and is introduced into liquid, through its surface. However, such experiments were conducted by Engh [13] or Farias [14] but those years the equipment, computers and software were not good enough to record and analyze the data.

High speed cameras make vertiginous career in various researches for several years. Their outstanding features i.e. recording speed and high resolution along with professional software for recorded material analysis make possible the observations of the phenomena which were earlier beyond the reach of the scientists. High speed cameras entered the flow analysis area, too, what is proved by numerous articles reporting their use. In the pneumatic conveying scope, where the powder injection into liquid alloys method is applied, a lot of papers appear such Yan [15], Zheng [16] or Jaworski [17]. Among the others, the papers describing the powder injection experiments were published, too e.g Davis [18]. However, such comprehensive experiments started by the authors in the aspect of pneumatic powder injection have not been launched so far. Based on the previously made experiments described among others in Jezierski [19,20], they started a multistage research plan. The first stage, described in this paper was based on the experiments with high speed camera followed by the recorded material analysis to obtain the main parameters describing two-phase gas-powder jet. The same parameters were calculated in a traditional way knowing some installation data and the results were compared. The authors were mostly interested in such parameters as solid particles velocity or actually so-called slip velocity, which is the difference between gaseous and solid phase velocity and mass concentration of the two-phase jet. The recorded films were analyzed visually, too, which led to the interesting in the authors' opinion conclusions, described further in the paper.

II. EXPERIMENTAL PROCEDURE

Based on their vast research experience and industrial applications of the pneumatic powder injection process, the authors planned the analogical experiments to those conducted earlier and described in Jezierski [19,20]. In the experiments reported there were no direct jet movement parameters measurement and only calculations were used. So the purpose of the new, to some extent repeated experiments, was to check how close the calculations results will correspond to those obtained with the high speed camera use.

A. Research Stand

The research stand was the updated version of this used in experiments previously made by authors and thoroughly described in Jezierski [22]. The assembled updated research set-up was shown in fig. 1 below.

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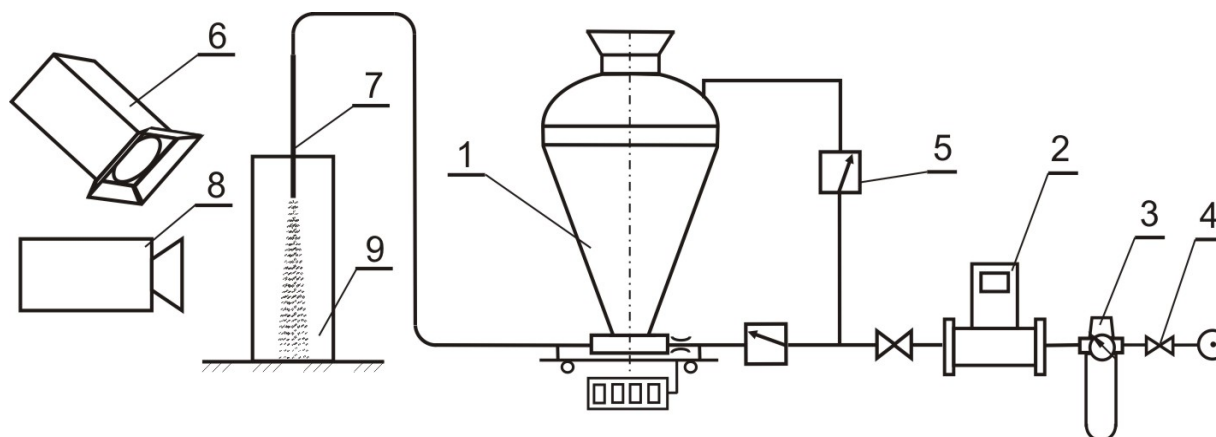
Fig. 1 The research set-up for two-phase jet recording: 1- pneumatic feeder, 2- gas flow meter, 3- pressure reducer, 4- shut-off valve, 5- gas pressure inside feeder reducer, 6- halogen lamp, 7- injection lance, 8- high speed camera, 9- powder receiver

The most important extension of the research stand potential 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 solid particles movement on the injection lance outlet with good picture quality and then to have it processed by professional software. The TEMA Lite package which allows automatic selected points of the recorded area tracking and movement parameters estimation was used by the authors.

B. Experiments Description

The preliminary tests were conducted to find the best high speed camera working parameters. On their results basis the following exposure parameters for the high speed camera experiments were chosen: resolution: 160x352 pixels; maximum speed: 20,000 frames per second; exposure time: 49.4 μs. These parameters in given lighting conditions (special 1500W halogen lamp) ensure good recording quality and a created file capacity possible to next comfort work.

C. Materials Used in the Experiments

Two powdered materials of different features were used for the experiments. These were: polypropylene powder of fraction 0.4 – 0.8mm and ferrosilicon Si75 of fraction 0.2 – 0.4mm. These materials were used because the authors used them in previous model experiments, where the polypropylene powder was injected into water as in Janerka [12] and the ferrosilicon as an alloy addition injection into liquid cast iron as in Jezierski [22]. The experiments conducted and described in this paper are, as previously mentioned, continuation of the authors' earlier work and should draw to the complete two-phase jet character influence on the efficiency of the powder injection into liquid alloys problem solving.

D. Pneumatic Powder Injection Parameters

The powder injection installation shown in the fig. 1 is equipped with high-pressured chamber feeder with bottom unloading. Its construction allows to regulate the pneumatically transported particles jet parameters by means of changing of two pressures values: p_1 – pressure of compressed air supplying feeder's mixing chamber, where the powdered material from feeder mixes with carrier gas and p_4 – pressure of gas inside the feeder above the powdered material which role is to regulate transportation efficiency. For comparison with earlier works purpose the p_1 pressure range was 0.1 – 0.3 MPa and p_4 pressure 0.02 – 0.1MPa what resulted in 15 experiments for each powdered material. The mass of material used in particular test was set 200 g and it was enough to record proper video with not too high capacity.

E. The single test description

The single test was performed as follows:

- feeder charging with weighed material portion,
- carrier gas supply open and pressure parameters adjusting,
- high speed camera adjusting: exposure time, recording buffer start and trigger adjusting, to be sure the whole process would be recorded,
- feeder's mixing chamber opening (injection process beginning) and start the trigger to record movie,
- recording the additional measurements e.g. gas flow and transportation time,
- feeder's mixing chamber closing, switching off the recording and carrier gas supply cut-off after injection process. Recording was performed with the use of dedicated PCC Control Software which perfectly cooperates with TEMA software used in further analysis. The example of the screen during analysis where the representative particles were chosen is shown in fig. 2 next page.
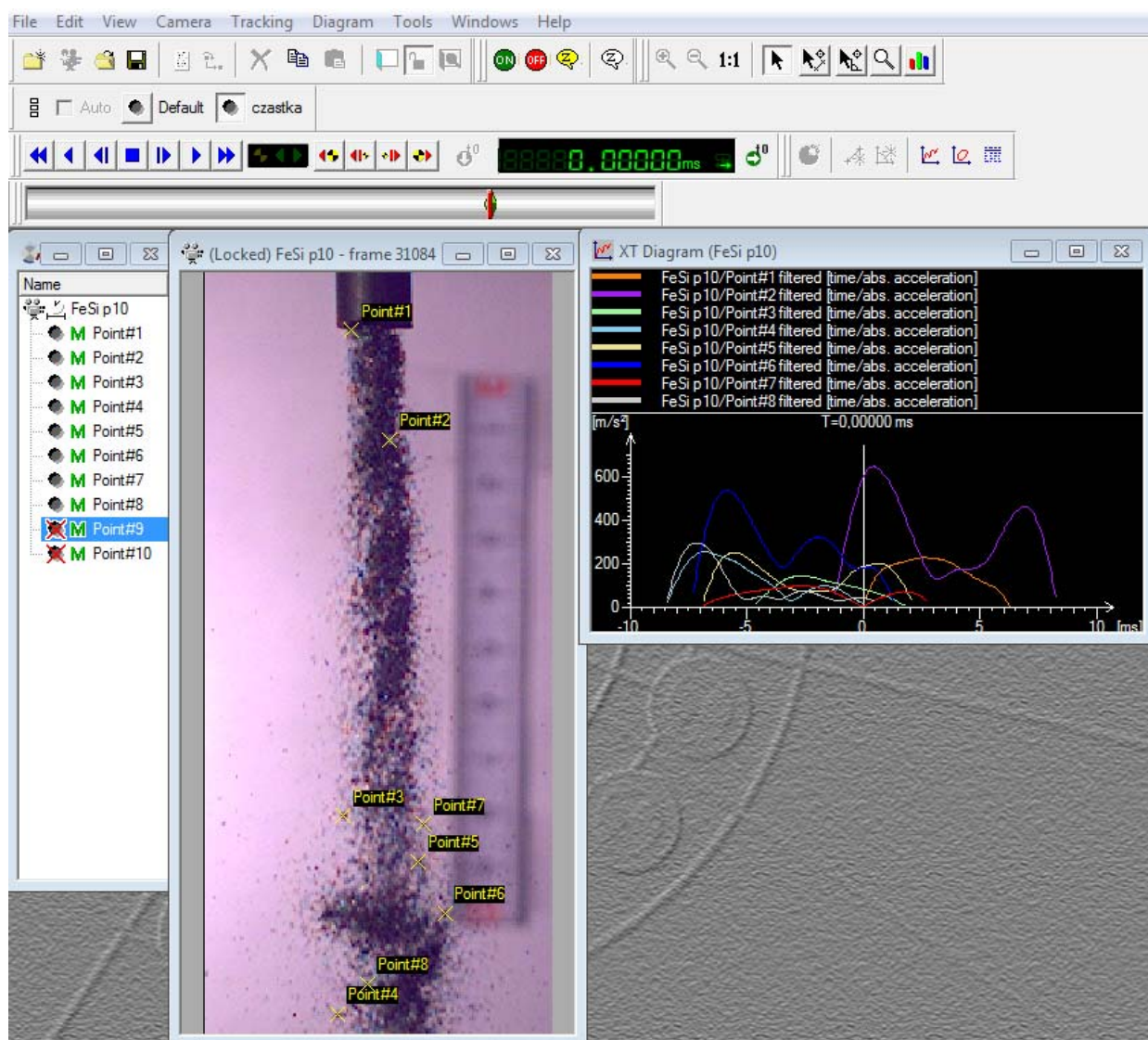
Fig. 2 Screenshot from TEMA software where: a- performed test window, b- movie panel, c- points tracking panel, d- tools panel, e- movie window, f- graphs (particle acceleration on this sample)

III. DISCUSSION

When all the experiments were successfully recorded (15 tests for each material), a thorough analysis was performed to find velocity, acceleration and displacement of the chosen particles (8 particles for each sample movie accordingly to the software version restriction).

Below in fig. 3 the snapshots set of the particles jet for the ferrosilicon injection example and various pneumatic process parameters were shown.
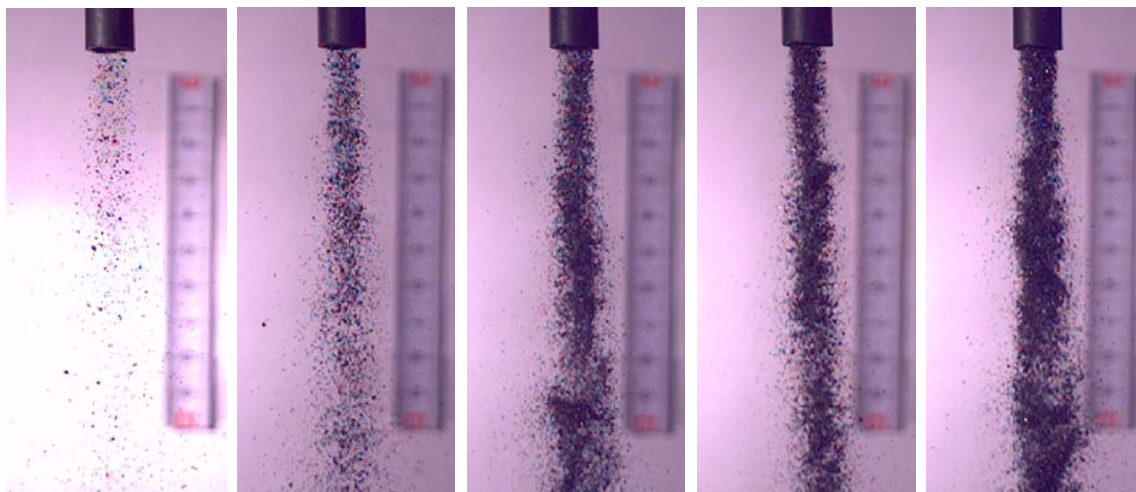
Fig. 3 The snapshots of two-phase air-FeSi75 powder jet for $p_1 = 0.1$ MPa and various p_4, from left to right $p_4 = 0.02, 0.04, 0.06, 0.8$ and 0.1 MPa

A. Gas and particles velocity on the lance outlet- slip velocity

In pneumatic powder injection processes one of the most important parameter is injected particles velocity. It is dependent mainly on the gas velocity on the lance outlet and the difference between carrier gas and particles velocity is commonly called slip velocity and sometimes it is described as these values quotient i.e. 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 c/w ratio (so called slip coefficient) = 0.5 – 0.8 and the value is bigger when mass concentration of the solids in two-phase jet is smaller. For the powder injection processes when mass concentration $\mu < 10$ slip coefficient is determined close to the highest 0.8 value.

After the films were recorded the particles were next tracked (automatically or manually when automatic tracking was impossible due to problems with too closely situated adjoining particles) and the graphs showing velocity of all representative particles were prepared. In fig. 4 and 5 (next page) were shown the velocity changings of ferrosilicon grains for the experiments which were shown as the snapshots in fig. 3.
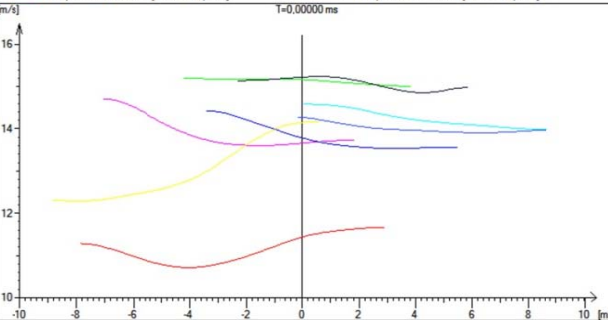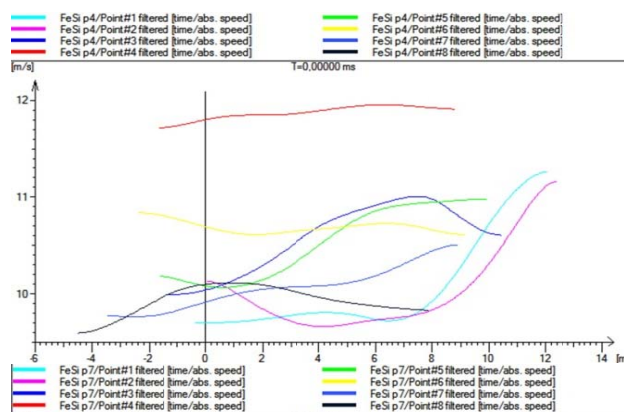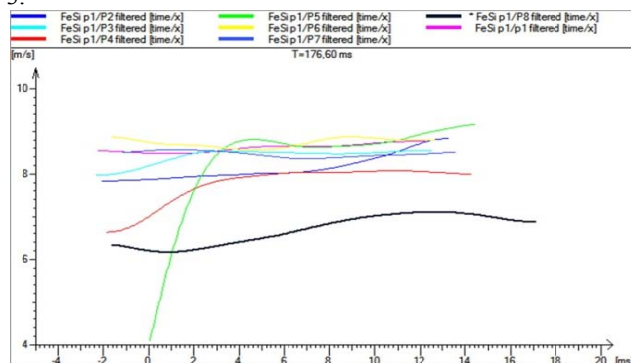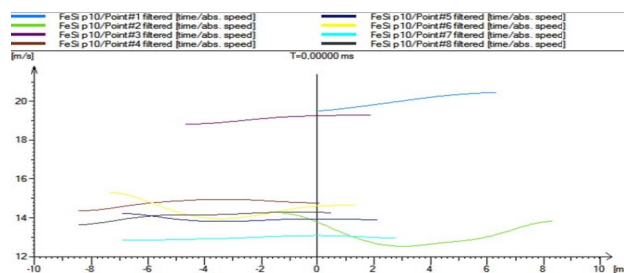

Fig. 4 FeSi grains velocity changings for the following pneumatic parameters: $p_1 = 0.1$MPa and various p_4, $p_4 = 0.02, 0.04$ and 0.06 MPa (analogically to fig. 3)
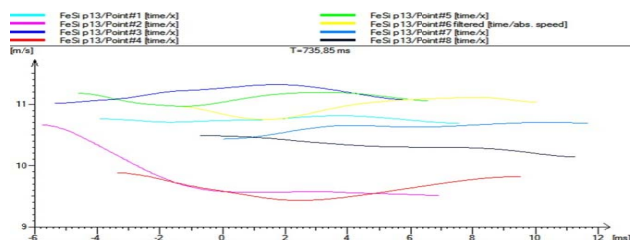
Fig. 5 FeSi grains velocity changings for the following pneumatic parameters: $p_1 = 0.1$ MPa and various p_4, for $p_4 = 0.8$ and 0.1 MPa (analogically to fig. 3)

Common analysis of fig. 3, 4 and 5 shows that particles velocity increases with the pressures p_1 and p_4 increase. However, for the boundary case when the pressure inside the feeder $p_4 = 0.1$ MPa and pressure of the carrier gas jet $p_1 = 0.1$ MPa the velocity drop is visible in fig. 4e. The material is introduced by air into mixing chamber too fast to be grabbed by too small carrier gas jet.

In this case the geometry of the feeding set-up is its bottleneck. 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 both of the gas velocity profile (the highest velocity in the jet axis and zero at the walls) and of the dynamic phenomena occurring between grains what is visible on 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 according to Piątkiewicz [23] and average velocity of the ferroalloy read from the films give interesting data. The data set is shown in fig. 6, where: vg – calculated carrier gas velocity, m/s, vp – calculated solid particles velocity vp = 0.8vg, m/s, vp avg – average particles velocity read from the films, m/s.

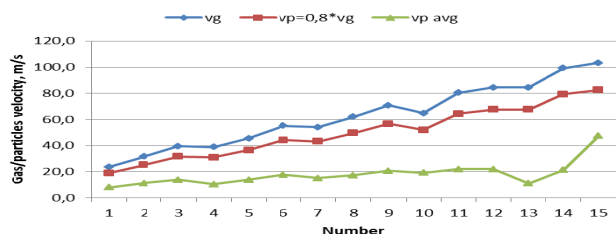

Fig. 6 Comparison of the calculated and read from films gas and ferrosilicon particles velocities; vg – calculated velocity of the carrier gas, vp – calculated velocity of the solid particles, vp avg – average velocity of the solid particles read from the films

The analysis led to the conclusion that real particles velocity is merely 13.1 – 46% of the calculated gas velocity on the lance outlet, so the slip coefficient c/w = 0.13 – 0.46 what makes a much lower value than the mentioned in the literature and used by authors, too.

B. Mass concentration of the gas-powder jet

Mass concentration of the gas-solids jet calculated as a quotient of particles mass flow and carrier gas mass flow varied from 1.03 to 5.07 during the experiments was quite small. In the fig. 7 (next page) the dependence of average grains velocity (read from films) on two-phase jet mass

concentration and various pressure in the feeder p_4 was presented. The concentration value decreases because of the carrier gas flowing through installation increase for three pressure levels $p_1 = 0.1$, 0.2 and 0.3MPa. The only exception is a case where due to material flow suppression for starting pressure value $p_1 = 0.1$ MPa the mass concentration in the second test for $p_1 = 0.2$ MPa was higher (the last picture in fig. 7). However, in the next test it decreased according to the whole experiment tendency.

When comparing fig. 7 and 3 one may assume that two-phase flow mass concentration highly increases in the latter with the increase of pressure inside feeder p_4. However, despite optical particles jet thicken, higher gas flow causes that mass concentration of the mixture is for the test with $p_4 = 0.1$ MPa even slightly lower than in the previous tests. This parameter analysis confirms both literature data and the earlier authors' experiences that when two-phase flow mass concentration $\mu < 10$ the problems with transportation uniformity do not appear during powder injection processes.
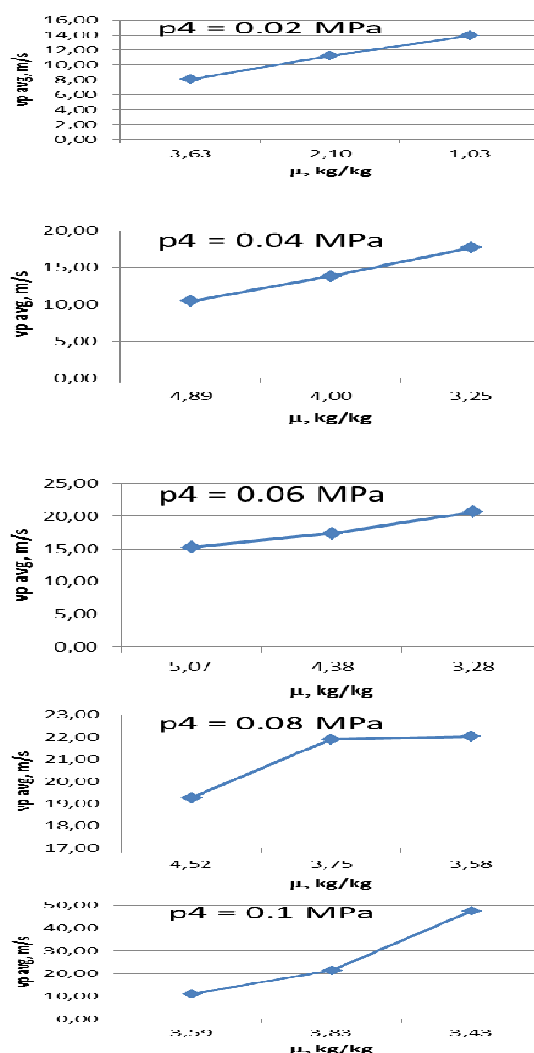

Fig. 7 Dependence of the solid particles on two-phase jet mass concentration for the various air pressure levels inside conveying feeder

IV. Summary and remarks for the next stage

The experiments described in the article presented the first stage of the complex experimental plan. Its realization should widen the knowledge in the character of the two-phase gas-solids jet during powder injection into liquid alloys process. The preliminary experiments stage emphasized the significant differences between the real parameters read from the films recorded particles movement and the values calculated from the well-known formulas. This is particularly visible for so-called slip velocity which indicates that carrier gas flowing accelerates the material grains to a much lesser extent that was previously thought. Wrong grains velocity on the lance outlet estimation causes wrong jet range inside liquid alloy estimation what in industrial conditions may cause non-uniform distribution of the material inside its whole volume. The next experimental stage has been the already started computer modeling in which on the basis of data gathered during described experiments (and also performed previously) 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 the 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 it will give a 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.

Acknowledgment

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