PHYSICAL MODELLING OF MIXING IN OCCURRING STEELMAKING LADLE DESIGNED FOR SINGLE- AND DUAL-PLUG BLOWING PROCESS

Tomasz MERDER [1], Jacek PIEPRZYCA [1]

[1]Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Katowice, Poland, EU
tomasz.merder@polsl.pl

Abstract

Introduction of argon to the bath is a commonly used secondary metallurgy treatment. The most economical technique of secondary metallurgy is the ladle process at the ladle furnace station. The introduction of inert gas (argon) into the metal bath takes place using purging plugs placed in the bottom of the ladle. Such argon blowing process through the metal bath via a purging plugs proceeds with the intensity necessary to cause the circulation of liquid steel. This movement is necessary to homogenize the temperature and to achieve a state of near chemical homogenization of the liquid steel after introduction of the alloy addition. Another positive effect of gas injection is the adhesion of non-metallic inclusions to the bubbles or their capture by bubbles and removal from the metal bath to the slag.

The work presents the research carried out using the water ladle model in which there is a possibility of simultaneous blowing the bath through one, two or three purging plugs installed in the bottom and additional lance support from the top. Different configurations of bath gas introduction (through one or two plugs) were analyzed using different flow rate of gas. As a result of the research, visualization of the mixing process of the alloy additive and mixing curves at different process parameters were obtained. These results allowed to analyze the mixing process of the alloy additive.

Keywords: Secondary metallurgy, steel, ladle, physical modelling

1. INTRODUCTION

The modern metallurgy uses mixing of metal bath in almost all stages of liquid metal production. For this purpose various metallurgical aggregates are used. During the smelting of steel in the oxygen converter, steel is mixed with oxygen introduced through the lance or additional plugs. Additionally, the metal movement is often supported by inert gas blown by purging nozzle in the bottom of the converter. The new electric furnaces contain purging plug and oxygen lances. However, the mixing of baths is most widely carried out at secondary treatment stations. At this stage of steel production, new techniques for motion the liquid steel were developed, both at atmospheric pressure and in vacuum. The simplest and most economical technique of secondary treatment of steel is the ladle process, carried out in the ladle furnace (LF) [1,2].

The intended mixing targets are achieved when blowing chemically or neutral active gas. Their presence and movement in the bath forces a more or less intense movement of liquid metal. The blowing of argon into the metal bath through the purging plug proceeds with the intensity necessary to cause a turbulent flow able to create the circulation of liquid steel. This movement, in turn, is necessary to homogenize the temperature and to achieve the state similar to chemical homogenization of the liquid steel after the introduction of the alloy addition and to support the flotation of inclusions and non-metallic precipitates [2-4].

The presence and movement of gas bubbles in the steel supports the movement of media to the places where the desired chemical reactions take place. The low proportion of the gas phase ensures bubble flow, in which the gas occurs in the form of small, single bubbles, whose velocity of rising up depends on their size and does not depend on the diameter of the tank. The increase in gas proportion causes the generation of more amount of bubbles, which as a result of collisions and coalescence take the form of a spherical bowl. Therefore, the intensity and configuration of argon injection is an important technological parameter that can result in a significant reduction in production costs while maintaining identical or higher quality parameters [4-5].

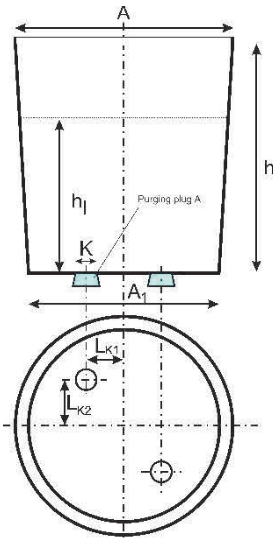
Identification and description of phenomena occurring in liquid metals, which is associated with the selection of appropriate process parameters, often in the conditions of their turbulent flows, creates a number of problems, because they are nontransparent phases. In this case, the use of numerical simulation methods in commercial research applying commercial programs as well as building physical models of devices are nowadays a modern research tool for metallurgical processes involving liquid metallic phases [6-11].

The work presents the research carried out using the water ladle model in which there is possibility of simultaneous blowing the bath using one, two or three purging nozzles installed in the bottom and additional support with the lance from the top. These studies are a continuation of the research presented in publications [12-13].

2. OBJECT OF THE RESEARCH STUDY AND RESEARCH METHODOLOGY

The studied object is a steel ladle with a capacity of 50 t liquid steel. Due to the characteristic dimensions of the real object for the ladle model (**Table 1**), a decreasing linear scale S_L = 1: 5 = 0.2 was assumed. The model is built in accordance with the requirements of the theory of kinematic and dynamic similarity, it also fulfills the condition of geometrical similarity [14]. There is the possibility of simultaneous blowing the bath through one or two purging plugs installed in the bottom and additional lance support from the top.

Table 1 Scheme and design parameters of the physical model ladle

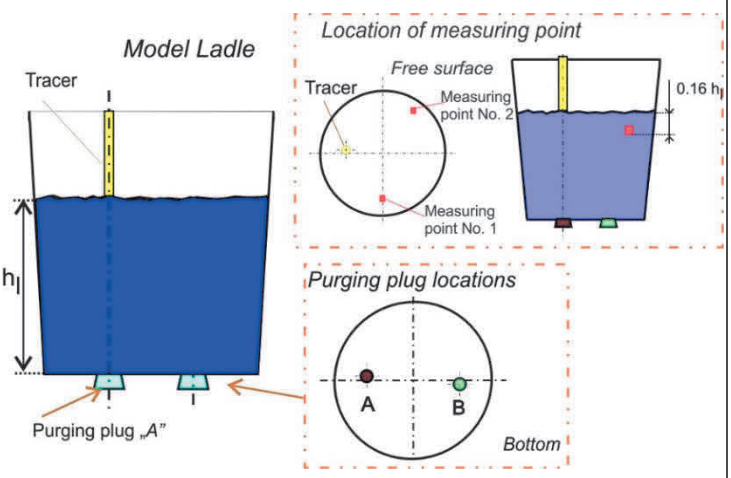
<table>
<tr><th>Scheme</th><th>Design parameters</th><th>View of the test model</th></tr>
<tr><td>
</td><td><table>
<tr><th><i>Parameter</i></th><th><i>Symbol</i></th><th><i>Unit</i></th><th><i>Value</i></th></tr>
<tr><td>Volume (to the liquid steel level)</td><td>V</td><td>(m³)</td><td>0.057</td></tr>
<tr><td rowspan="2">Diameter</td><td>A</td><td rowspan="7">(m)</td><td>0.511</td></tr>
<tr><td>A₁</td><td>0.386</td></tr>
<tr><td>Height</td><td>h</td><td>0.66</td></tr>
<tr><td>Height (to the liquid steel level)</td><td>h_l</td><td>0.44</td></tr>
<tr><td>Purging plug diameter</td><td>K</td><td>0.023</td></tr>
<tr><td rowspan="2">Purging plug position</td><td>L_{K1}</td><td>0.094</td></tr>
<tr><td>L_{K2}</td><td>0.096</td></tr>
</table></td><td></td></tr>
</table>

The research was carried out using a physical water model of the ladle (**Table 1**). The test stand is equipped with a precise gas flow regulation system and a device for precise addition of the tracer. In visualization (qualitative) studies, the tracer was an aqueous solution of $KMnO_4$. Whereas, in quantitative experiments involving the determination of mixing characteristics, $KMnO_4$ was replaced with aqueous NaCl solution. The identical precise amount of tracer was introduced into the ladle model for each variant of the experiment. The image of flows was recorded in two planes - central and lateral. This arrangement of the cameras allowed uninterrupted observation of the model liquid circulation. In the described model, signals constituting the basis for plotting the mixing curves are generated by conductometers of G Instruments type GCT20K [15], which are installed at selected points of the model workspace. The voltage generated in half-second intervals by the conductometers is the equivalent of changes in the tracer concentration in water. The recorded signals from the measurement sensors (conductometers) are further developed to plot the mixing curves.

According to the assumptions of the research plan, the appropriate conversion of the gas flow (argon) from real conditions to model conditions was made. What is more according to the guidelines, the calculation of dynamic similarity condition of gas flow in the model to the real condition was done based on the modified Froude`s criterion [12-13].

Table 2 presents the designations of plugs installed in the bottom of the model and the place of introduction of the tracer. The "A" shaped element is the main plug, a tracer (alloy additions in the industrial conditions) is placed centrally over it, while the "B" shaped body is a plug that supports the mixing process. **Table 2** shows the determined particular variants of experiments (parameters of the bath blowing process) depending on the configuration of the method of gas stream introduction to the ladle model.

Table 2 The assumed blowing process parameters of bath stirring under industrial conditions and their values computed for testing conditions on water model and designation of purging plugs (physical model)

<table>
<tr><th>Designation of purging plugs (physical model)</th><th>Experiment variants</th></tr>
<tr><td>
</td><td>
<table>
<tr><th rowspan="3">Experiment variant</th><th rowspan="3">Method for gas introducing / purging plug</th><th>Industry scale 1:1</th><th>Model scale 1:5</th></tr>
<tr><th colspan="2">The intensity of gas</th></tr>
<tr><th>($m^3 \cdot h^{-1}$)</th><th>($l \cdot min^{-1}$)</th></tr>
<tr><td rowspan="2">P1</td><td>A</td><td>10.8</td><td>1.2</td></tr>
<tr><td>B</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">P2</td><td>A</td><td>9.72</td><td>1.1</td></tr>
<tr><td>B</td><td>1.08</td><td>0.12</td></tr>
<tr><td rowspan="2">P3</td><td>A</td><td>8.64</td><td>0.96</td></tr>
<tr><td>B</td><td>2.16</td><td>0.24</td></tr>
<tr><td rowspan="2">P4</td><td>A</td><td>7.56</td><td>0.84</td></tr>
<tr><td>B</td><td>3.24</td><td>0.36</td></tr>
<tr><td rowspan="2">P5</td><td></td><td>6.48</td><td>0.72</td></tr>
<tr><td></td><td>4.32</td><td>0.48</td></tr>
<tr><td rowspan="2">P6</td><td>A</td><td>5.4</td><td>0.6</td></tr>
<tr><td>B</td><td>5.4</td><td>0.6</td></tr>
</table>
</td></tr>
</table>

3. RESEARCH RESULTS

3.1. Visualization

The research was conducted in series, recording their course using high resolution cameras. Film sequences were created from the recorded film material containing the appropriate amount of information. Then, the sequences were divided into individual frames, from which a series of frames with the same time parameters was selected for individual variants of the experiment. **Figure 1** presents exemplary results of visualization tests of the mixing (distribution) process of the tracer in the working space of the ladle model for individual variants of the experiment.

During the visualization research, the different character of the mixing of the model liquid in the model of the steel ladle was found, depending on the division of the stream of gas blown into individual purging plugs. In the P1 variant, a strong rinsing of the wall of the ladle model by the injected gas was observed. The picture shows the "push" of the tracer towards the ladle axis. This phenomenon should be considered unfavorable, causing excessive wear of the refractory lining in this zone and the risk of secondary contamination of steel by endogenous inclusions. With the reduction of the gas stream on the A plug the limitation of this unfavorable phenomenon takes place.

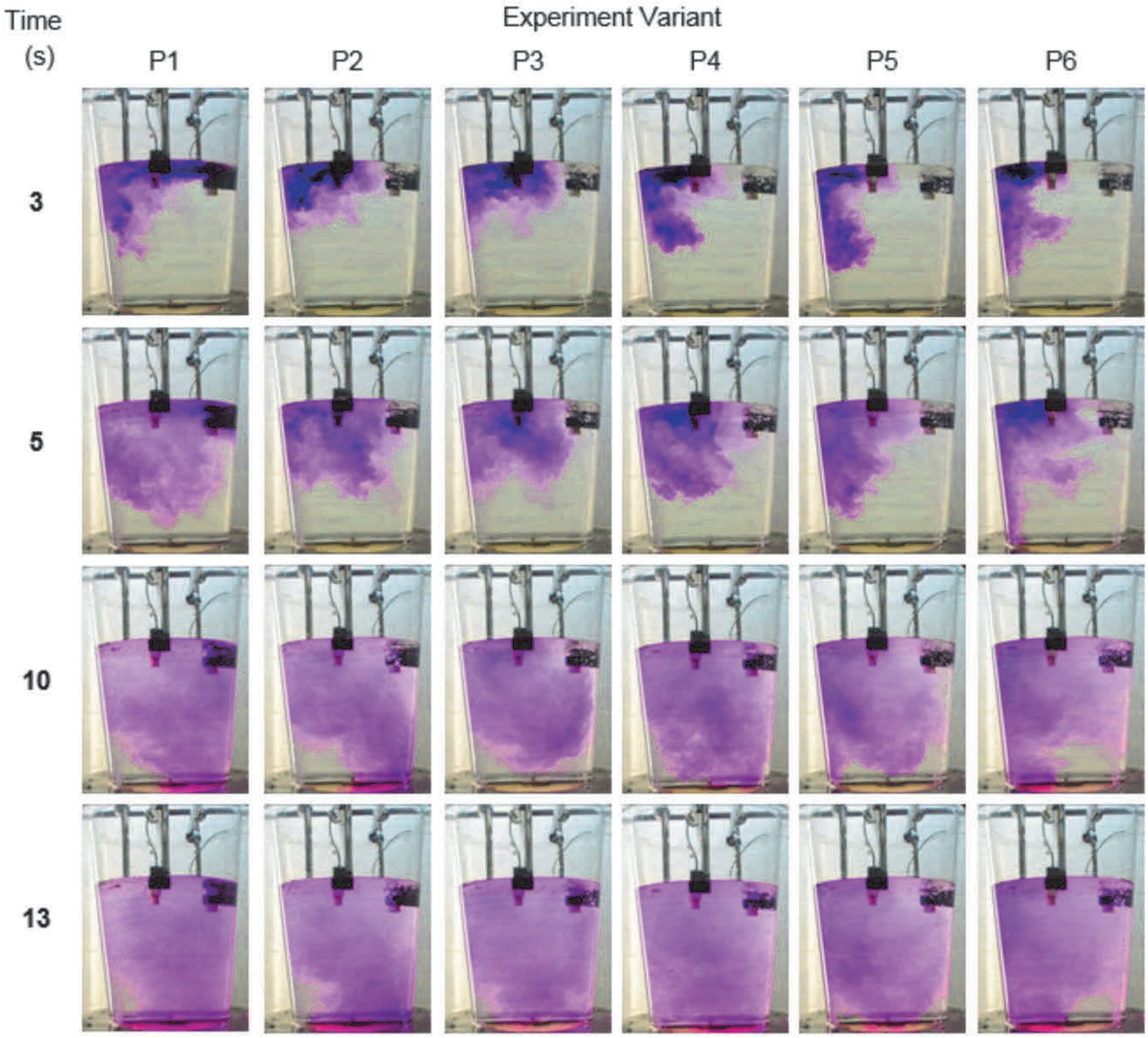


Figure 1 Exemplary results of visualization

The way of creation of the circulating zones of a model liquid in the volume of the ladle model should in principle be considered as correct in each variant. The process of homogenizing the model liquid in the volume of the steel ladle model is most efficiently carried out in variants P3 and P4 of the experiment. Along with the equalization of gas flow in purging plugs, the course of this process is disturbed. This fact should be explained by the decrease in the energy of gas flow currents, caused by their interaction with each other.

3.2. Mixing curves

Figure 2 shows the example of a characteristic (variant P3) showing changes in dimensionless tracer concentration during argon injection to the metal bath.

Obviously there is a different bath mixing efficiency for the considered variants of the experiment, since different tracer distribution is observed in **Figure 1**. In addition, the spatial distribution of the tracer concentration and the mixing curves (see **Figure 2**) reveal two important features. The tracer migrates in the bath mainly under the influence of forced convection observed as a circulating movement of the liquid.

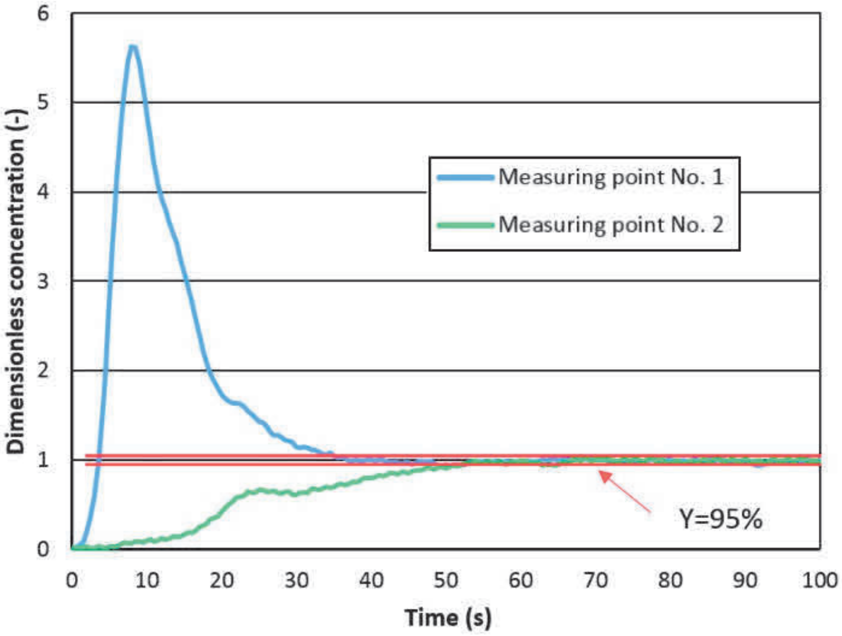


Figure 2 Exemplary changes of dimensionless concentration of the tracer - variant P3

Dimensionless concentration of tracer can be defined as:

$$C_b = (C_t - C_0)/(C_\infty - C_0) \qquad (1)$$

where: C_t - tracer concentration at time t, (μS·cm^{-1}),
C_0 - tracer concentration at the beginning of the measurement, (μS·cm^{-1}),
C_∞ - tracer concentration at the end of the measurement, (μS·cm^{-1}).

When the point place of monitoring the tracer concentration changes is applied, the fact it should be taken into account that the concentration of the tracer at this point does not reflect its concentration outside the sampling site.

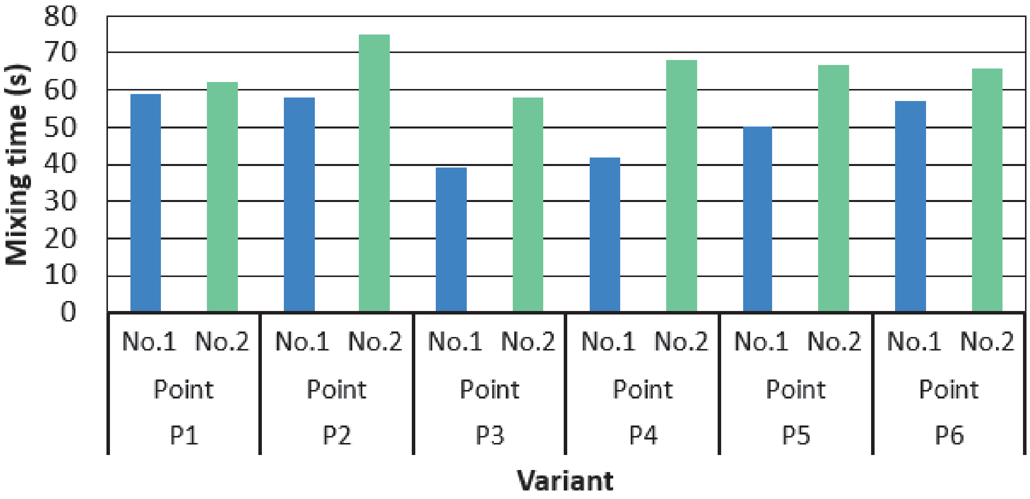


Figure 3 The forecasted tracer mixing time for the analyzed variants

The obtained data also show that the determined mixing time depends on the location of the monitoring site (in the zone of so-called stagnation flows or the dead zone it is much longer). Therefore, it was assumed that the longest one should be taken as the total mixing time. **Figure 3** presents the summary of the mixing time data depending on the gas flow rate and the configuration of its introduction (for variants of the experiment).

4. CONCLUSION

Analysis of the presented results of research carried out on water model allows to state:

- Mixing the tracer (alloy additive) depends on the method (proportion) of the separation of the introduced gas stream into individual plugs.
- Measured mixing times depend on the monitoring site as well as the gas introduction method (chemical homogenization time of the metal bath is spatially determined by the characteristics of the ladle).
- The reduction of the gas stream (separation into two plugs) results in a larger number of bubbles with smaller diameters, which favors the favorable course of the argon blowing process.
- At high gas flow rate (especially variant P1) an adverse effect of the gas column on the side wall of the ladle is noted (the flow distorts the gas column towards this wall increasing the resistance force on the wall). This may cause hydrodynamic erosion of the ladle refractory lining, and consequently promote the formation of endogenous non-metallic inclusions.
- When using one plug (variant P1) during the process of blowing steel with inert gas, the purging plug should be moved by approx. 10% in the direction of the ladle axis. However, when using two plugs, the best solution is variant P3 or P4.

ACKNOWLEDGEMENTS

This work was supported by Polish Ministry for Science and Higher Education under internal grant BK221/RM0/2018 for Department of Extractive Metallurgy and Environmental Protection, Silesian University of Technology, Poland.

REFERENCES

[1] STOLTE, Gerd. *Secondary metallurgy - fundamentals processes applications*, Woodhead Publishing, Dusseldorf 2002.

[2] GHOSH, Ahindra. *Secondary steelmaking*; *principles and application*, CRC Press USA, 2000.

[3] SZEKELY, Julian, CARLSSON, Goran, HELLE, Lars. *Ladle metallurgy*. Germany: Springer-Verlag New York Inc., 1989.

[4] SAHAI, Yogeshwar, GUTHRIE, Roderick I. L. The formation and role of bubbles in steelmaking operations, *Proceedings of the International Symposium on Modern Developments in Steelmaking*, Jamshedpur, India,1981.

[5] ENGH, Abel T. *Principles of metal refining*, Oxford University Press, 1992.

[6] AOKI, J., THOMAS, B. G., PETER, J., PEASLEE, K. D. Experimental and theoretical investigation of mixing in a bottom gas-stirred ladle. *AISTech 2004 Conference,* Nashville, TN, Assoc. Iron Steel Technology, Warrendale, PA, 2004, pp. 1045-1056.

[7] LI, Yang, DENG, Anyuan, LI, Huan, YANG, Bin, WANG, Engang. Numerical study on flow, temperature, and concentration distribution features of combined gas and bottom-electromagnetic stirring in a ladle. *Metals,* 2018, vol. 76, no. 8, pp. 1-19. DOI:10.3390/met8010076.

[8] LIU, Zhongqiu, LI, Linmin, LI, Baokuan. Modeling of gas-steel-slag three-phase flow in ladle metallurgy: part I physical modeling. *ISIJ International*, 2017, vol. 57, no. 11, pp. 1971-1979.

[9] MAZUMDAR, Dipak, DHANDAPANI, Palani, SARVANAKUMAR, Rajagopal. Modeling and optimisation of gas stirred ladle systems. *ISIJ International*, 2017, vol. 57, no. 2, pp. 286-295.

[10] GRYC, K., MICHALEK, K., HUDZIECZEK, Z., TKADLEČKOVÁ, M. Physical modelling of flow pattern in 5-strand asymmetrical tundish with baffles. *In METAL 2016: 25 International Conference on Metallurgy and Materials.* Ostrava: TANGER, 2010, pp. 42-46.

[11] WARZECHA, Marek, JOWSA, Jan, WARZECHA, Piotr, PFEIFER, Hubert. Numerical and experimental investigations of steel mixing time in a 130-t ladle. *Steel Research International,* 2008, vol. 79, no. 11, pp. 852-860.

[12] MERDER, T., PIEPRZYCA, J., WARZECHA, M. The influence of porous plug type on argon blowing process. *In METAL 2017: 26 International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2017, pp. 188-193.

[13] MERDER, Tomasz, PIEPRZYCA, Jacek, WARZECHA, Marek, WARZECHA, Piotr. Application of high flow rate gas in the process of argon blowing trough steel. *Archives of Metallurgy and Materials*, 2017, vol. 62, no. 2A, pp. 905-910.

[14] MICHALEK, Karel. *Vyuziti fyzikálního o a numerickeho modelovani pro optimalizaci metalurgickych procesu [The use of physical modeling and numerical optimization for metallurgical processes*]. Ostrava: Vysoka Skola Banska, 2001.

[15] Information materials G Instruments 2017. Available from http://www.ginstruments.com/condtx.htm.