Arch. Metall. Mater. **64** (2019), 2, 653-658

DOI: 10.24425/amm.2019.127594

J. PIEPRZYCA*#, T. MERDER*, M. SATERNUS*, K. GRYC**, L. SOCHA**

THE INFLUENCE OF PARAMETERS OF ARGON PURGING PROCESS THROUGH LADLE ON THE PHENOMENA OCCURING IN THE AREA OF PHASE DISTRIBUTIONS: LIQUID STEEL-SLAG

Purging the liquid steel with inert gases is a commonly used treatment in secondary metallurgy. The main purposes for which this method is used are: homogenization of liquid steel in the entire volume of the ladle, improvement of mixing conditions, acceleration of the absorption process of alloy additives and refining of liquid steel from non-metallic inclusions. The basic processing parameters of this treatment are: gas flow rate and the level of gas dispersion in liquid steel. The level of gas dispersion depends on the design and location of the porous plug in the ladle. Therefore, these parameters have a significant impact on the phenomena occurring in the contact zone of liquid steel with slag. Their improper selection may cause secondary contamination of the bath with exogenous inclusions from the slag, or air atmosphere due to discontinuity of the slag and exposure of the excessive surface of the liquid steel free surface. The article presents the results of modelling research of the effect of liquid steel purging with inert gases on phenomena occurring in this zone.

The research was carried out using the physical (water) model of steel ladle. As a modelling liquid representing slag, paraffin oil was used, taking into account the conditions of similarity with particular reference to the kinematic viscosity. The results of the conducted research were presented in the form of visualization of phenomena occurring on the surface of the model liquid free surface in the form of photographs. The work is a part of a bigger study concerning modelling of ladle processes.

Keywords: steelmaking, ladle, slag, physical modelling

1. Introduction

Physical modelling is currently one of the most popular tool used for determining the basic parameters of the process and discover phenomena occurring in metallurgical processes. It is really convenient to build and use such models due to accessibility of modelling media (mainly water) and conducting research in laboratory in standard temperature instead of high temperature existed in industry. Physical modelling is commonly used to model processes occurring in steel metallurgy (in blast furnace [1,2], ladle [3-8], tundish [8-14] and mold [15]) and nonferrous metallurgy mainly aluminium [16-19].

Ladle refining is fully responsible for temperature and composition homogenization, degassing, deoxidation, desulphurization and removal of inclusions [20-23]. As was mentioned above the process was studied by some researchers; however still it is not fully understood.

During the process gas (argon) is injected into the liquid steel through the top lance or porous plugs (one or more) installed in the bottom of the ladle. Argon created gas bubble column in the liquid steel, meanwhile bubbles rising up the surface they induce recirculation flow in the ladle, what as a result give effective mixing. It is obvious that processing parameters will affect the process, the most important factors are: gas flow rate, the height of the liquid steel, plug position and slag layer, which plays crucial role in the refining of liquid steel.

There were some investigation results concerning especially the phenomena occurring in the slag-metal interface. Jardon-Perez and coworkers [6] pointed out that a higher flow velocity in the plume area (the upper part of the gas bubble column) can enhance the undesirable slag eye creation. Cho et. al. [24] stated that the presence of slag layer considerably changes the flow behavior, mainly due to reduction of the momentum from the rising bubbles in the plume and increasing the mixing time in the ladle. Okumura and Sano [25] give evidence that higher bath depth provides better circulation and tends to reduce mixing time and also that the height of the liquid steel determines the size of the slag eye opening in the ladle [26]. A lower bath depth probably cause larger slag eye opening, in the same time a larger area of steel is exposed to the atmosphere interaction. Owusu et. al. [26] reported that the rising gas bubbles in the area of plume play a significant role in the creation of turbulence within the two phase region. Krishnapisharody and Irons [27] measure eye size by physical modelling at various conditions of gas flow rate and depth of fluids. It is really important to understand the motion of slag layer if the high strength steel with very low level of sulphur

* SILESIAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIALS ENGINEERING AND METALLURGY, 8 KRASIŃSKIEGO STR.,40-019 KATOWICE, POLAND,
** THE INSTITUTE OF TECHNOLOGY AND BUSINESS IN ČESKÈ BUDEJOVICE, FACULTY OF TECHNOLOGY, OKRUŽNI 517/10, ČESKÈ BUDEJOVICE, CZECH REPUBLIC
# Corresponding author: jacek.pieprzyca@polsl.pl

is possible to produce. In the article the physical modelling is used to observe the effect of liquid steel purging with argon on phenomena occurring in the area of liquid steel – slag interface. The research results are a continuation of the broader research program presented in the article [28].

2. Object of the research study

Physical water model of a steel ladle with a capacity of 50 t of liquid steel working at the ladle furnace stand was used for the research. Due to the characteristic dimensions of the real object, a reducing linear scale S_L = 1:5 = 0.2 was applied for the ladle model. Fig. 1 presents the scheme of the model, whereas the most important parameters of the model are shown in Table 1. More detail of the model can be found in article [28].

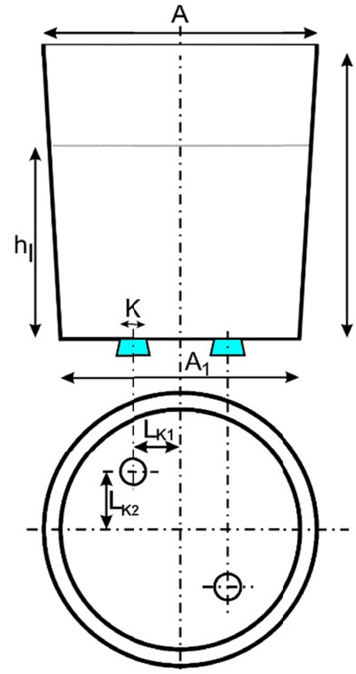

Fig. 1. Scheme of the ladle model

TABLE 1

Design parameters of the ladle model (scale 1:5)

Parameter	Symbol	Unit	Value
Volume (to the liquid steel level)	V	m^3	0.057
Diameter	A	m	0.511
	A$_1$		0.386
Height	h		0.66
Height (to the liquid steel level)	h$_l$		0.44
Purging plug diameter	K		0.023
Purging plug position	L$_{K1}$		0.094
	L$_{K2}$		0.096

The model is built in accordance with the requirements of the theory of dynamic and kinematic similarity. It also fulfills the condition of geometrical similarity [29]. There is the possibility of simultaneously purging the bath through one, two or three porous purging plugs installed in the bottom and additional lance support from the top.

The basic criterion for the similarity of the model to the real object is the Froude's number (Fr). However, it is not completely sufficient. It determines the free flow of fluid under the influence of gravity. In the steel ladle, however, there is a two-phase flow (liquid and gas phase). Therefore, the most commonly used solution in this case is the use of a modified Froude's number [30,31].

In accordance with the assumptions of the research program, appropriate calculations of the gas (argon) flow rate from real object to model conditions (see Table 2) were made based on the modified Froude's criterion following the equation:

$$Q' = \left(\frac{c'}{c}\right)^{-\frac{1}{2}} \cdot S_L^{\frac{5}{2}} \cdot Q \qquad (1)$$

where: Q' – volumetric stream of gas flow for the water model, m^3×s^{-1}, Q – volumetric stream of gas flow for the industrial reactor, m^3×s^{-1}, c' – constant for the water model, c – constant for the industrial reactor, S_L – linear scale.

TABLE 2

The assumed processing parameters of purging process of steel with inert gas (argon) under industrial conditions (scale 1:1) and their values calculated for research conditions on water model (scale 1:5)

Experiment variant	**Method for gas introducing /purging plug**	**Industry scale 1:1**	**Model scale 1:5**
		Flow rate of gas	
		[m^3×h^{-1}]	**[dm^3×min^{-1}]**
P1	A	10.8	1.2
	B	—	—
P2	A	9.72	1.1
	B	1.08	0.12
P3	A	8.64	0.96
	B	2.16	0.24
P4	A	7.56	0.84
	B	3.24	0.36
P5	A	6.48	0.72
	B	4.32	0.48
P6	A	5.4	0.6
	B	5.4	0.6

The designation of porous plugs installed in the bottom of the model is shown in Fig. 2. The "A" purging plug is the main plug, the tracer (simulating alloy additions in industrial conditions) is introduced centrally above it, while the "B" purging plug is a plug that supports the mixing process. Both plugs installed in the model have the same dimensions.

In the modelling research, the phenomenon of disruption of the slag continuity and exposure of the liquid steel free surface in the steel ladle was analyzed [32]. Water was used as the medium for simulating the liquid steel, whereas for modelling the slag layer on liquid steel, paraffin oil was applied (see Table 3).

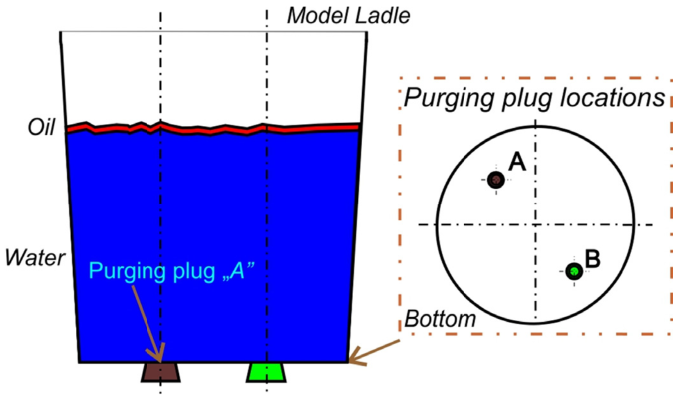

Fig. 2. Designation of purging plugs in physical model of the steel ladle

TABLE 3

Parameters of liquids used in the modelling research

Modelling and real media	Density, kg×m^{-3}	Kinematic viscosity, m^2×s^{-1}
Water	998.2	$1 \cdot 10^{-6}$
Oil	830	$1.5 \cdot 10^{-5}$
Air	1.225	$1.5 \cdot 10^{-5}$

Research of slag continuity was carried out by introducing a 10 mm layer of paraffin oil onto the surface of the modelling liquid (water). Its properties were selected according to the conditions of similarity.

The course of the experiment was recorded in several planes by means of cameras.

3. Results and discussion

Fig. 3 presents the results of visualization research of the formation of slag eyes on the surface of the model liquid surface. The analysis of these results concerned the effect of the inert gas flow rate and the configuration of the purging porous plugs operation on the size of the surface of forming slag eyes. During the experiments the expected increase in slag eyes area with the increase of the gas flow rate was observed.

In order to quantify this phenomenon, the summaric surface area of the formed slag eyes for particular gas flow variants was determined. Then they were referenced to the total value of the free surface of the modelling liquid. In this way, the percentage share of the slag eye surface in the surface of the liquid free surface was obtained. The results of these calculations are presented in Table 4.

To mathematically determine the trend of the effect of the inert gas flow rate on the surface size of the formed slag eyes, the research results for porous plug A are presented graphically. The graph shows that the increase in the percentage of slag eye surface in the total surface of the liquid steel free surface under the influence of the outgoing gas bubbles is exponentially growing according to the equation shown in Fig. 4.

Determination of the above mathematical dependence of the growth of the slag eye surface on the flow rate of the gas stream allows to conclude that with the expansion of the gas flow rate, the expansion of the slag eye surface increases. From this point of view, it seems more beneficial to insert gas bubbles through two purging porous plugs, since the sum of their surfaces at a given gas flow rate should be smaller than the eye slag surface created when introducing the same amount of gas through one purging porous plug. This phenomenon is illustrated in Fig. 5.

The slag eye created in the variant P1, where the gas was introduced by one porous purging plug, covers a larger surface of the modelling liquid free surface than the sum of the eye slag

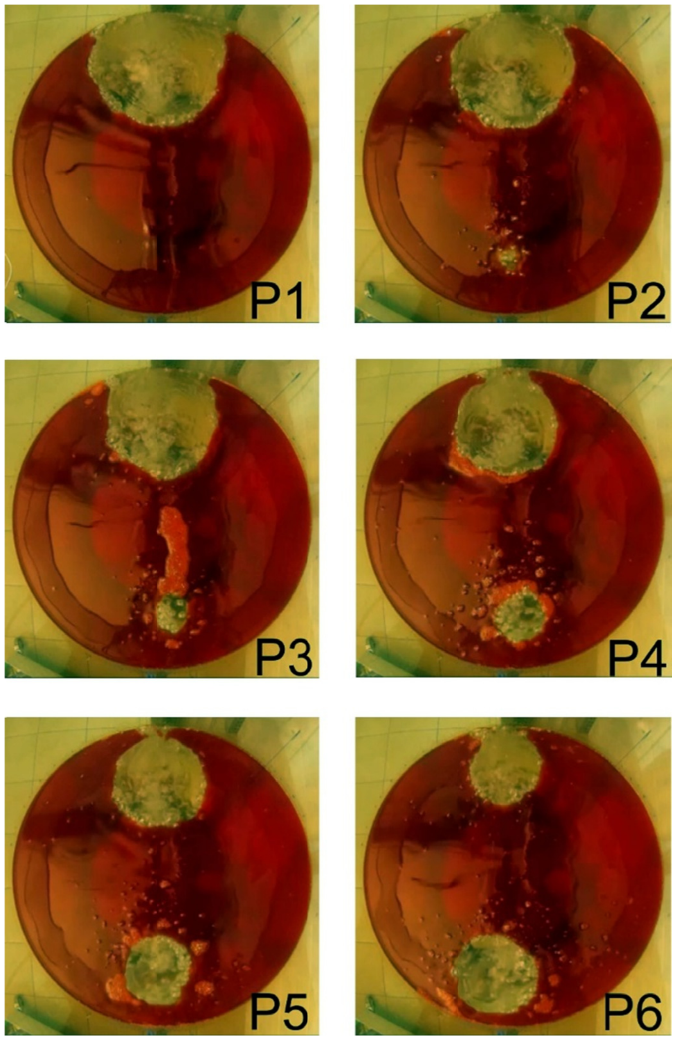

Fig. 3. The influence of flow rate of gas and configuration of purging plugs work on the size of slag eye – upper view

TABLE 4

Percentage share of the slag eye in the surface of the whole free surface of the modelling liquid

Percentage of eye slag area on the free surface, %	Value					
	Experiment variant					
	P1	P2	P3	P4	P5	P6
above the purging plug A	17.8	16.8	14.2	12.6	9.5	6.8
above the purging plug B	—	0.6	1.7	2.7	5.1	7.8

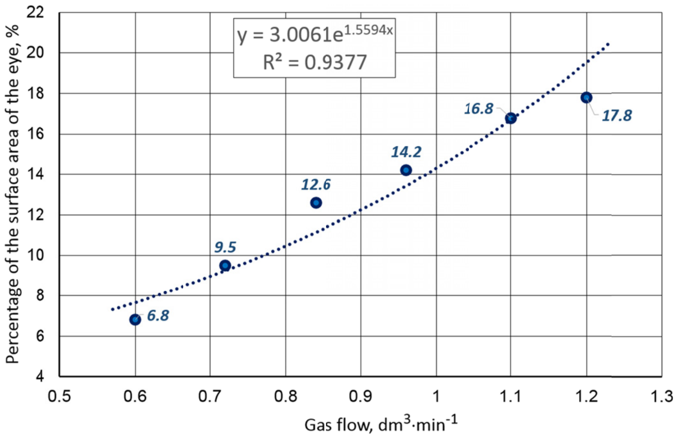

Fig. 4. The influence of the flow rate of gas on the percentage participation of the slag eye area in the entire surface (for porous purging plug A) of the modelling liquid free surface

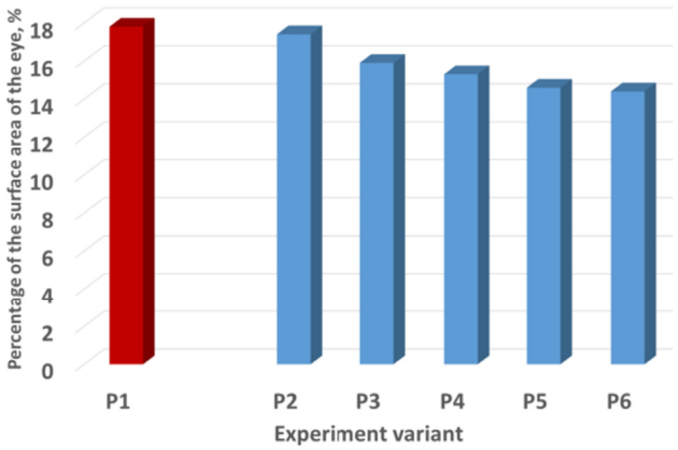

Fig. 5. The value of the total surface area of the slag eye in the particular variants of the experiment

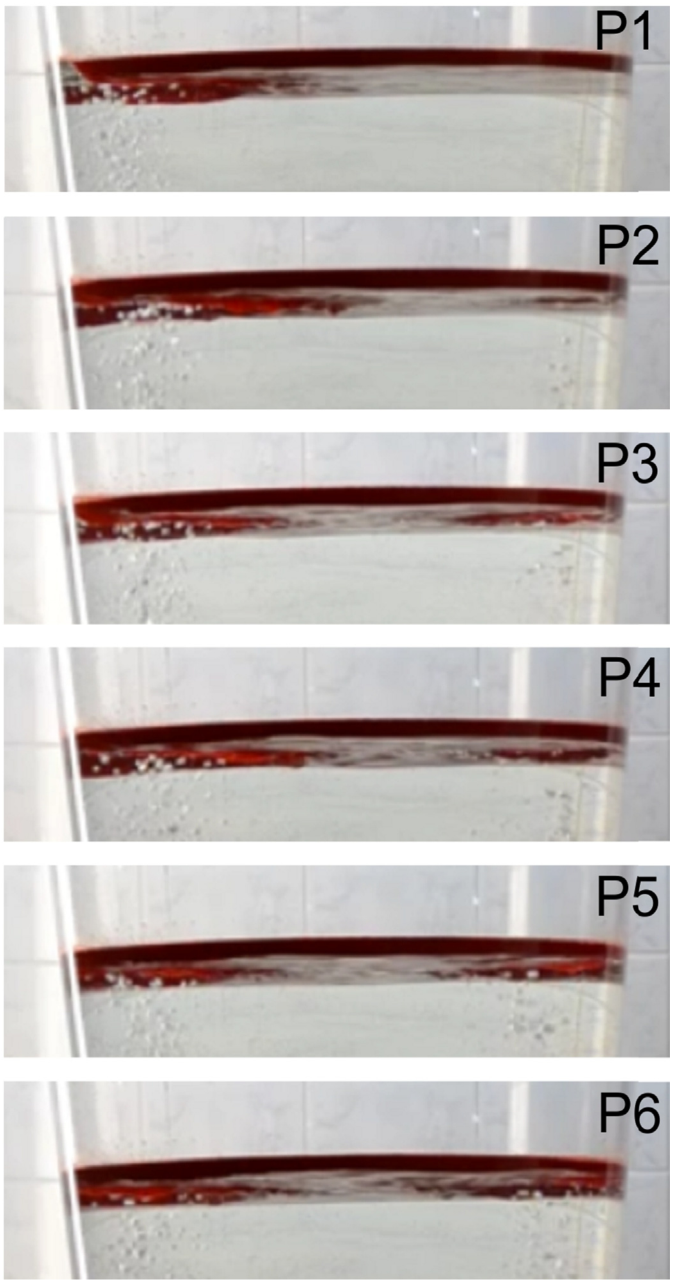

Fig. 6. The influence of the flow rate of gas and configuration of purging plugs work on the behavior of slag surface – side view

area in the other variants with two purging plugs, at the same value of gas stream in all variants.

However, when analyzing the problem from the point of view of the danger of secondary contamination of steel with atmospheric gases, it was found that the size of the generated slag eyes in any variant of the experiment does not exceed the standard values.

Another problem is the danger of secondary contamination of the bath with inclusions from slag. For analysis of this issue it was used the observation of the behavior of the modelling liquid at the border of the metal-slag division (see Fig. 6). During the modelling research, no breaking out of drops of the slag layer and their penetration in the modelling liquid were observed. Therefore, the gas flow rate used from this point of view is safe.

The results of the tests were supplemented with the results illustrating the mechanism of the gas bubble cone (gas column) formation and their dispersion level in the modelling liquid for the considered variants (see Fig. 7). It was observed that in case of variant P1 only one cone is created, and it is not so wide in the upper side. When applying two purging plugs the homogenization is better, because in two places the cone of gas bubbles is created, however variants P2 and P4 seems to be characterized by the widest cone of gas bubbles created by plug A. In variants P5 and P6 the size of cone of gas bubbles created by purging plug A and B seems to be comparable.

4. Summary

The results of laboratory tests presented in the article enable to formulate the following statements and conclusions:

- In the research concerning the influence of the inert gas flow rate on the size of the forming slag eyes, the expected increase in their area was observed along with the increase of the gas flow rate. This increase is exponential.

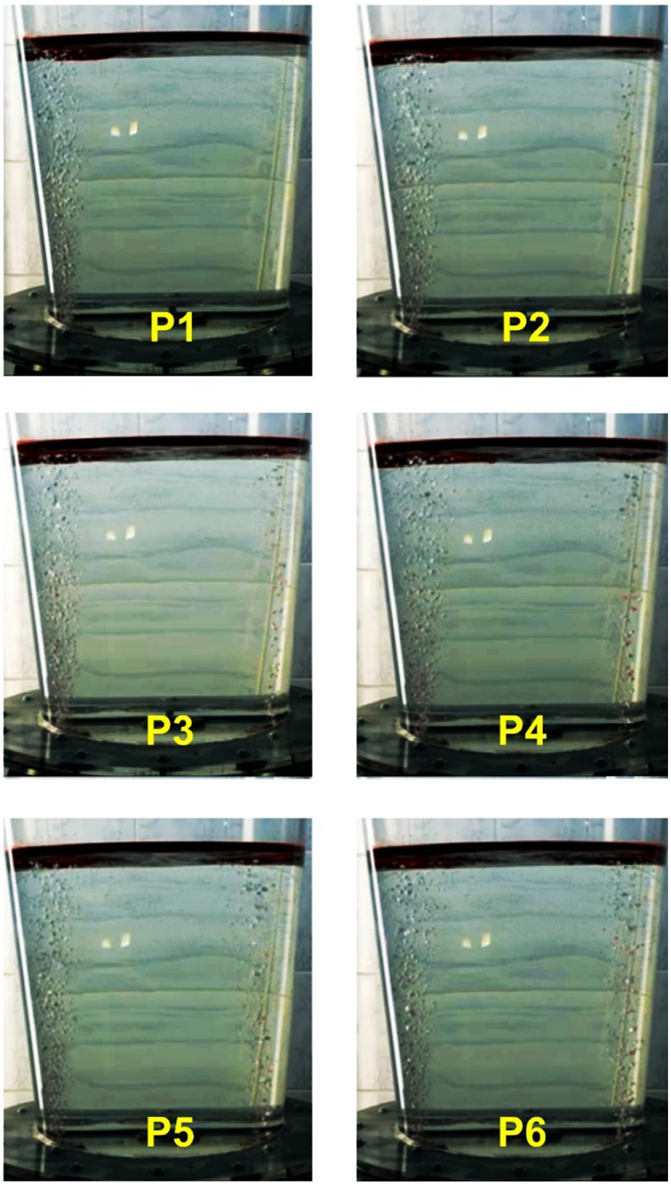

Fig. 7. Mechanism of creation of bubble gas cone (gas column) and their level of dispersion in modelling liquid for the studied variants of experiment

- Analyzing the issue from the point of view of the danger of secondary contamination of steel with atmospheric gases, it was found that the size of the generated slag eyes does not exceed the standard values.
- The risk of secondary contamination of the bath with inclusions from slag also in the range of studied gas flow rates is minimal.
- The correct way of creating the circulation zones of modelling liquid in the volume of the steel ladle model for the entire range of the gas flow rate was observed.

Acknowledgement

This paper was created with the financial support of Polish Ministry for Science and Higher Education under internal grant BK221/RM0/2018 for Faculty of Materials Engineering and Metallurgy, Silesian University of Technology, Poland.

REFERENCES

[1] B. Panic, Archives of Metallurgy and Materials **59** (2), 795-800 (2014).
[2] K. Janiszewski, B. Panic, Metalurgija **63** (3), 339-443 (2014).
[3] D. Mazdumar, R.I.L. Gutrie, ISIJ International **35** (1), 1-20 (1995).
[4] D. Guao, G.A. Irons, Metallurgical and Materials Transaction B **31**, 1447-1455 (2010).
[5] K. Seon-Hyo, R.I. Fruehan, Metallurgical Transactions B **18**, 673-680 (1987).
[6] L.E. Jardon-Perez, A.A. Villeda, A.N. Conejo, C. Gonzalez-Rivera, M.A. Ramirez-Argaez, Materials and Manufacturing Processes **33** (8), 882-890 (2018).
[7] R.P. Nunes, J.A.M. Pereira, A.C.F. Vilela, F.T.V. der Laan, Journal of Engineering Science Technology **2** (2), 139-150 (2007).
[8] M. Michalek, K. Gryc, J. Moravka, Metalurgija **48** (4), 215-218 (2009).
[9] A. Kumar, S.C. Koria, D. Mazdumdar, ISIJ International **44** (8), 1334-1341 (2004).
[10] K. Chattopadhyay, M. Isac, R.I.L. Guthrie, ISIJ International **50** (3), 331-348 (2010).
[11] K. Chattopadhyay, M. Hasan, M. Isac, R.I.L. Guthrie, ISIJ International Metallurgical and Materials Transactions B **41**, 225-233 (2010).
[12] S. Lopez-Ramirez, J.J. Barretto, J. Palafox-Ramos, R.D. Morales, D. Zacharias, Metallurgical and Materials Transactions B **32** (7), 615-627 (2001).
[13] H. Lei H., Metallurgical and Materials Transactions B **46** (6), 2408-2413 (2015).
[14] T. Merder, J. Pieprzyca, M. Saternus, Metalurgija **53** (2), 155-158 (2014).
[15] Y. Kwon, J. Zhang, H.-G. Lee, ISIJ International **46** (2), 257-266 (2006).
[16] E. Mancilla, W. Cruz-Mendez, I.E. Garduno, C. Gonzalez-Rivera, M.A. Ramirez-Argaze, G. Ascanio, Chemical Engineering Research and Design **118**, 158-169 (2017).
[17] E. R. Gonzalez, R. Zenit, C. Gonzalez-Rivera, G. Trapaga, M.A. Ramirez-Argaez, Metallurgical nad Materials Transactions B **44**, 974-979 (2013).
[18] J.L. Camacho-Martinez, M.A. Ramirez-Argaez, A, Juarez-Hernandez, C.Gonzalez-Rivera, G. Trapaga-Martinez, Materials and Manufacturing Processes **27**, 556-560 (2012).
[19] M. Saternus, J. Botor, Metalurgija **48**, 175-179 (2009).
[20] J. Szekely, G. Carlsson, L. Helle, Ladle Metallurgy, Springer-Verlag, Germany, 1989.
[21] E.T. Turkdogan, Fundamentals of steelmaking, The Institute of Materials, London 1996.
[22] P. Cavaliere, Ironmaking and Steelmaking Processes, Springer-Verlag, Germany 2016.
[23] M. Warzecha, J. Jowsa, P. Warzecha, H. Pfeifer, Steel Research Int. **79** (11), 852-860 (2018).

[24] S.H. Cho, S.H. Hong, J.W. Han, B.D. You, Materials Science Forum **490**, 510-511 (2006).

[25] K. Okumura, M. Sano, ISIJ International **41**, 234-241 (2001).

[26] K.B. Owusu, T. Haas, P. Gajjar, M. Eickhoff, P. Kowitwarangkul, H. Pfeifer, Steel Research, 1800346, 1-10 (2018).

[27] K. Krishnapisharody, G.A. Irons, Metallurgy and Materials Transaction B **37**, 763-769 (2006).

[28] T. Merder, J. Pieprzyca, Physical modelling of mixing in occurring steelmaking ladle designed for single- and dual-plug blowing process, METAL 2018, Brno, Czech Republic 163-169 (2018).

[29] K. Michalek, The use of physical modelling and numerical optimization for metallurgical processes, Vysoka Skola Banska, Ostrava, Czech Republic 2001.

[30] L. Zhang, S. Yang, K. Cai, J. Li, X. Wan, B.G. Thomas Metallurgical and Materials Transactions B **38** (1), 63-83 (2007).

[31] H. Chanson, The Hydraulics of Open Channel Flow, Arnold, London 1999.

[32] Report from research No 1001/2/2018/RM2-03.