www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2020.131300
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2020
Issue 2/2020
43 – 48
7/2

Efficiency of Aluminum Oxide Inclusions Removal from Liquid Steel as a Result of Collisions and Agglomeration on Ceramic Filters

D. Kalisz *, K. Kuglin
AGH University of Science and Technology, Faculty of Foundry Engineering, Krakow, Poland
ul. Reymonta 23, 30-059 Kraków, Poland
* Corresponding author. E-mail address: e-mail: dak@agh.edu.pl

Received 17.10.2019; accepted in revised form 03.01.2020

Abstract

Filtration is one of the most efficient methods of removing Al_2O_3 inclusions from liquid steel. The efficiency of this process depends on the physicochemical parameters of liquid metal, inclusion and properties of the applied filters. The particles attracted during filtration undergo agglomeration, collisions and chemical reactions on the filter surface, with the emphasis on the mechanism of particle collisions and the role of material from which the filter was made. The aluminum oxide inclusions collide with the filter surface and as the growing process continues, the particles also collide with the previously adsorbed inclusions. At the interface of particle and filter the mixing of the metal bath is most intense, being a result of a sudden change of flow direction and breaking up the stream of liquid metal which is in a direct contact with material. The efficiency of filtration is defined not only by the behavior of individual particles but of all population. The simulations revealed that only a small fraction of these particles adheres directly to the filter material; most of them stick to the former ones. Attention should be also paid to the fact that some of the inclusions which contacted the filter walls do not form a permanent connection and are then entrained by metal. Authors solved the problem of agglomeration and collisions of Al_2O_3 inclusions with the ceramic surface of the filter with the PSG method, mainly used for the analysis of agglomeration of inclusions during steel refining in the ladle.

Keywords: Filtration, Nonmetallic inclusions, Efficiency of collisions, PSG method

1. Introduction

The removal of non-metallic inclusions from liquid steel is a process in which the inclusions go to a different phase and permanently bond with it. This can be liquid slag or a surface of ceramic material [1-3]. The removal and adhesion of non-metallic inclusions to the surface of ceramic filter is one of the most efficient methods of eliminating and separating liquid and solid inclusions from liquid metal. The filtration method has been successfully applied to refining liquid metals and alloys, especially aluminum. It was also used in steel metallurgy, but in this case the filtration takes place directly before casting in the tundish [4-7]. Initially, filtration was used for cleaning liquid metals of low melting temperature from solid contaminations. Foam filters were used for this purpose, and only after successful attempts at producing high quality aluminum casts, iron alloys started to be filtered. Many types of filters are used for filtration. They differ in their structure, active area and efficiency. Two basic groups of filters, which considerably differ in their filtration mechanisms, can be distinguished: flat filters and volume filters [4-13].

The surface of flat filters is much bigger than their thickness. Contaminations are captured on the filter entry only by the straining mechanism. Inclusions which are bigger than the openings in the filter entry are captured, therefore this method is used only for removing big agglomerates. After adsorbing the first big inclusions, filter cake is formed therefore then only the smaller inclusions can be adsorbed. Gradually as the filter openings are narrowed, even as small inclusions as 1-5 µm can be removed [9-15]. Unlike the first case, the volume filters make use of both the filtration effect on the filter entry and deep filtration, which depends on the size of the holes, their cross-section, distributions and filtration material. During deep filtration the process takes place over the whole filter length and lies in the adhesion of non-metallic inclusions and bonding to the ceramic filter walls. During depth filtration the inclusions surround the ceramic material and the particles agglomerate forming bridges with edges anchored on the filtration canals [16-17]. The efficiency of the process depends on a number of parameters, e.g. temperature of metal, chemical composition of filtration material and non-metallic inclusions, wettability, shape and distribution of canals in the filter. If the inclusion moves along the straight wall of the canal, the probability of capturing it is smaller than in canals having a bigger number of walls. The smaller is the cross section of the canal, the bigger is the probability that the filter captures the inclusions.

High temperature strength regimes (to 1700°C) have to be met by ceramic filters. This and the associated higher prices of filters complicate the filtration of steel. For this reason, initially the filtration was used for the production of steel alloys only for specialist and demanding casts. A considerable increase of filtration of steel (and not only) was recorded only at the beginning of the 21st century, and was dictated by a particularly drastic increase of metal prices and mass popularity of continuous metal casting technology. During filtration of liquid steel the filter should have higher resistance to high temperatures and the penetrating operation of the liquid metal bath. Therefore, because of the intensity of metal flow the ceramic foam filters were not applicable to steel metallurgy [4-15].

Monolithic ceramic filters with dominating deep filtration mechanism, are most suitable for cleaning steel from non-metallic inclusions. They are also called multi-hole, canal or sieve filters. These filters differ in shape and distribution of filter holes. Due to the difficult work conditions in which ceramic filters operate in the process of continuous steel casting, the scope of materials from which they can be made is limited. Canal filters are made of aluminum oxide with ceramic bonding, aluminum oxide with graphite, zircon or quartz oxide. The aluminum oxide-based materials are efficient for filtration purposes. Their resistance to thermal shocks is not very high, but their other properties, i.e. high temperature, hardness and resistance of surface to erosion speak for their applicability. The thermal shock resistance can be improved by adding zircon oxide. Sinters made of fine aluminum oxide with a small amount of magnesium oxide or other compounds counteracting the growth of grains exhibit the highest strength and resistance to creep strength.

For selecting an appropriate size of holes in the filter, a compromise between efficiency of filtering and admissible pressure loss should be reached. The initial quantities of flowing off steel require bigger holes at the filter entry to avoid clogging. In the further part of the filter the canals may have a smaller diameter to maximize the efficiency of filtering. The design of the filter, number and diameter of canals and the associated hydraulic flow conditions of steel determine the mechanism and efficiency of filtering. A higher efficiency of cleaning steel from non-metallic inclusions at uniform thicknesses of filter are obtained thanks to a smaller diameter of canals and thinner layers of ceramics between them. During steel production the filter should be place on the way of the flowing off steel to remove the inclusions and provide appropriate flow intensity. The most suitable place for the filter is the tundish. The volume of the tundish usually constitutes 10% of the main ladle. Liquid steel has high temperature and easily reacts with the environment, therefore the refractory lining of the tundish is made of high-aluminum and zircon, so that the chemical composition of steel remains the same upon its contact with the lining. The distribution of ceramic filters in the tundish is very important. The filter should be placed in a way maximizing the efficiency of precipitates removal. Commonly the upper and lower diaphragms are placed in the ladle to modify the steel flow. They should also form a zone in which steel flows horizontally without turbulences. This creates conditions for an outflow of part of the non-metallic inclusions no matter whether the steel is filtered or not. The filter can be placed before or after the diaphragm [16-21].

2. Mechanism of filtration of Al_2O_3 precipitates

Depending on the chemical composition of steel and the amount of added deoxidants in relations to the original oxygen content, solid or liquid inclusions are formed. Deoxidation with aluminum is associated with solid inclusions. When aluminum, manganese and silicon or calcium participate in the process, liquid inclusions at liquidus temperature for steel are obtained [22-26]. Despite the applied technologies of refining with neutral gas and modification with calcium, the removal of aluminum oxide still creates a problem, especially in the case of steel where high metallurgical purity is required, e.g. deep processed steels, in such cases the presence of aluminum oxide inclusions disqualifies these materials from further processing. The mechanism of aluminum oxide filtration lies in dynamic collisions of particles from the filter surface, where the mixing of liquid metal bath is highest, which stems from a rapid change of flow direction and breaking of the stream. The efficiency of filtering is determined by the behavior of individual particles. Only a small fraction of particles directly adheres to the filter, most of them adhere to the former ones. It should be considered that some of the inclusions which had contact with the filter walls do not form a permanent connection but are entrained by metal. This effect is expressed by the collision efficiency coefficient β [26-30].

3. Collision mechanism

The process of inclusion attraction on the filter Surface being a result of colliding spherical particles can be described with an equation derived for colliding spherical particles by Saffman and Turner (1). It was assumed in this model that collisions of two particles ri and rj in liquid steel have a much smaller radius of collision than the smallest turbulence [31-33]:

$$N_{ij} = 1{,}3\left(r_i + r_j\right)\cdot\left(\varepsilon/v\right)^{1/2} n_i n_j \qquad (1)$$

where:

r – radius of particle and filter j [m],
ε – energy of mixing [$m^2 \cdot s^{-3}$],
υ – kinematic viscosity [$m^2 \cdot s^{-1}$],
n – „i" and „ j" particles content [m^{-3}].

On the assumption that a particle of inclusion r_i has a much smaller radius than particle r_j, one may consider that this situation may correspond to the agglomeration of particles on the ceramic filters.

In the tundish conditions there is a definite population of particles of radius r and number in steel volume v , i.e. density n. The efficiency of filtration of a definite population of inclusions in the course of turbulent collisions can be analyzed with the Particle Size Grouping (PGS) method worked out by T. Nakaoka and others [33] and used in works [26, 28-30, 33]. The calculations in the model were based on the population balance equation (2):

$$\frac{dn_k}{dt} = \frac{1}{2}\sum_{i=1;i+j=k}^{i=k-1}\left(1+\delta_{ij}\right)N_{ij} - \sum_{i=1}^{\infty}\left(1+\delta_{ik}\right)N_{ik} \qquad (2)$$

where :

δ_{ij}– Kronecker delta (δ_{ij} = 1 for i = j, δ_{ij} =0 for i ≠ j),
N_{ij} – number of collisions between particles *i* , *j* in 1 m^3 in one second,
N_{ik} – number of collisions between particles *i, k* in 1 m^3 in one second,
n_k – volume density of particles of dimension „k",
a - radius of particle [m].

As the solution of the population balance equation for k determined by the successive natural numbers is hard to calculate, a method was used to divide particles into definite size groups M so that the population balance equation is calculated only for these size classes. Nakaoka et all [33] in their work operate on dimensionless parameters: nk – density related to the density of N_0 smallest particles.

If the mechanism of turbulent collisions is assumed, the reduced time t* is expressed as:

$$t^* = 1{,}3\cdot\alpha\cdot r_1^3\cdot\left(\frac{\varepsilon}{v}\right)^{\frac{1}{2}}\cdot N_0\cdot t \qquad (3)$$

N_0 – initial density of particles of basic dimensions,
α - agglomeration coefficient
t* - non dimensional time.

4. Calculations

The presented calculation procedure was designed for simulating the effect of nonmetallic inclusions removal from liquid steel through collision-based agglomeration. The PSG method was adapted to the analysis of the effect of colliding aluminum oxide inclusions with the surface of the corundum ceramic filter. It was assumed in the simulations that the collisions of the aluminum oxide particle with the ceramic surface were effective, i.e. inclusion was arrested on the filter surface, and the successive inclusions grew on the already existing surface. The results of the simulation have been graphically presented, showing the change of the number of particles in a function of surrogate time. It was assumed that the whole population of inclusions in the volume of liquid steel had a uniform radius.

The calculations were realized for particles with initial radius r = 1, 2, 5, 10, 15, 20 µm, diversified energy flows ε: 0.1; 0.01; 0.001; 0.00001 [$m^2 \cdot s^{-3}$], coefficient of viscosity for steel equal to $7.857 \cdot 10^{-7} m^2 \cdot s^{-1}$, agglomeration coefficient equal to 1, initial number of Al_2O_3 particles: 100000; time t*= 8.646·t was assumed after Taniguchi et al. [33]. Exemplary calculations are presented in figures 1-8.

Figures 1-2 illustrate curves of vanishing Al_2O_3 inclusions as a consequence of collisions with the filter surface for mixing energy ε=0.1[$m^2 \cdot s^{-3}$].

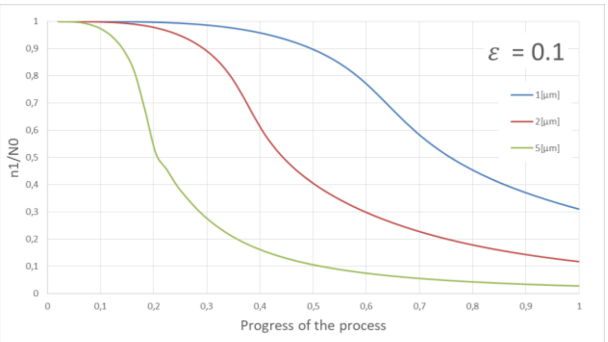

Fig. 1. Al_2O_3 inclusions colliding with a filter surface for particle radius: 1; 2 and 5µm, N_0=100000/m^3

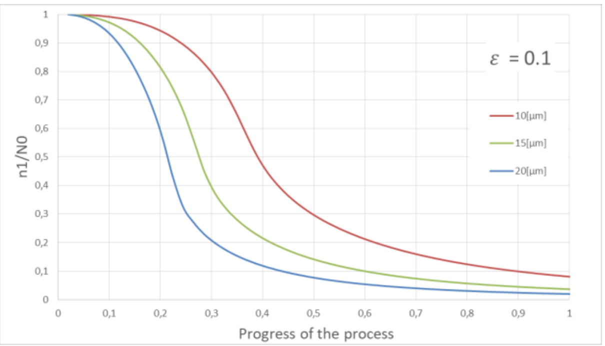

Fig. 2. Al_2O_3 inclusions colliding with a filter surface for particle radius: 10; 15 and 20µm, N_0=100000/m^3

Figures 3-4 illustrate curves of vanishing Al_2O_3 inclusions as a consequence of collisions with the filter surface for mixing energy $\varepsilon=0.01[m^2 \cdot s^{-3}]$.

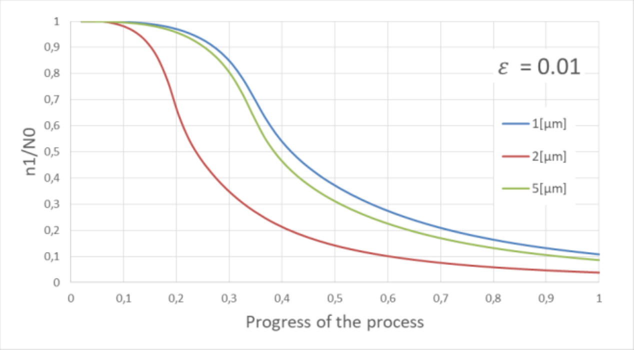

Fig. 3. Al_2O_3 inclusions colliding with a filter surface for particle radius: 1; 2 and 5µm, N_0=100000/m^3

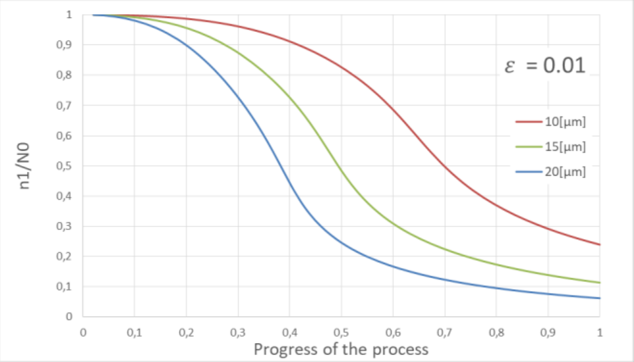

Fig. 4. Al_2O_3 inclusions colliding with a filter surface for particle radius: 10; 15 and 20µm, N_0=100000/m^3

Figures 5-6 illustrate curves of vanishing Al_2O_3 inclusions as a consequence of collisions with the filter surface for mixing energy $\varepsilon=0.001$ $[m^2 \cdot s^{-3}]$.

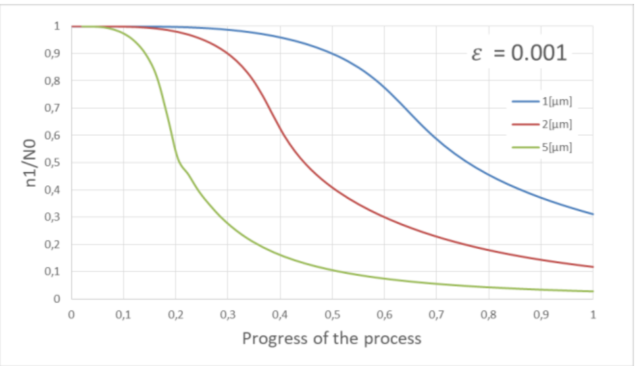

Fig. 5. Al_2O_3 inclusions colliding with a filter surface for particle radius: 1; 2 and 5µm, N_0=100000/m^3

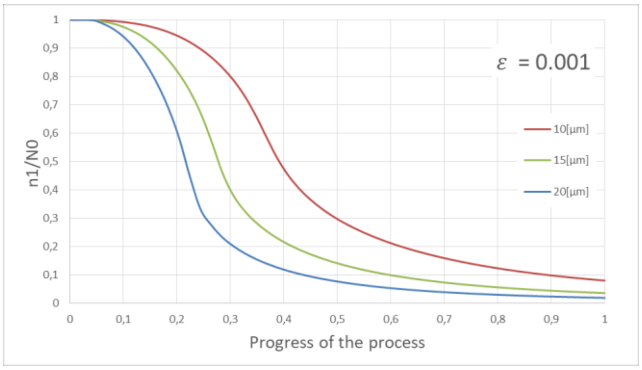

Fig. 6. Al_2O_3 inclusions colliding with a filter surface for particle radius: 10; 15 and 20µm, N_0=100000/m^3

Figures 7-8 illustrate curves of vanishing Al_2O_3 inclusions as a consequence of collisions with the filter surface for mixing energy $\varepsilon=0.00001$ $[m^2 \cdot s^{-3}]$.

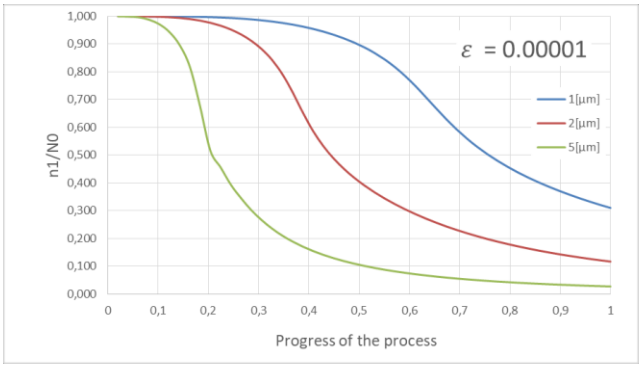

Fig. 7. Al_2O_3 inclusions colliding with a filter surface for particle radius: 1; 2 and 5µm, N_0=100000/m^3

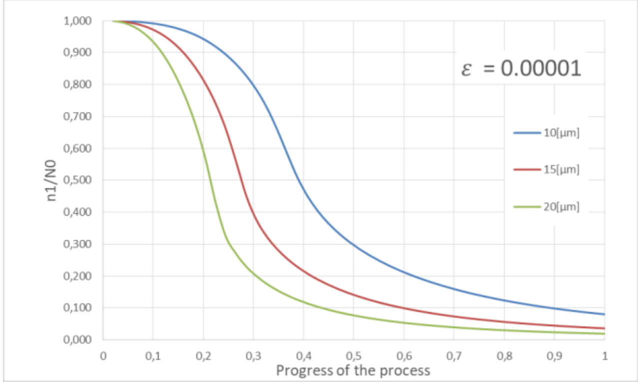

Fig. 8. Al_2O_3 inclusions colliding with a filter surface for particle radius: 10; 15 and 20µm, N_0=100000/m^3

It was observed in all cases that small particles with radius 1, 2µm showed little ability to agglomerate as a result of collision with ceramic filters. As expected, their removal in the process of filtration in the initial stage was hindered. This effect was especially well visible for low and very low energy of mixing (figs. 5 and 7). The removal of small particles was much slower than for particles with radius 15 and 20µm. The filtration process could be intensified by increasing the energy of mixing. In the case of particles with radius 1 and 2μm, their increase only slightly improved the efficiency of removal of these particles. They could be removed in the course of the process as a consequence of collisions within the filters and on the existing surfaces, where the inclusions were adsorbed and bounded.

5. Conclusions

1. The analyzed effect of aluminum oxide particles colliding with filter surface does not mean that these particles were removed. For doing so, one should account for the surface effects which have influence on adhesion and solid bounding particles with the ceramic surface.
2. The assumed uniform number of analyzed particle population does not fully reflect the conditions in the tundish, where the whole spectrum of inclusion sizes occur.
3. The analysis of plots reveals that the removal of process of particles from ceramic filters is very efficient for inclusions with radius 15 and 20 μm, and the increase of energy of mixing accelerates the collisions of inclusions with the ceramic surface.
4. The plots illustrate the dynamics of the filtration process. It was observed that in the final stage of the process there always remains a certain amount of inclusions which did not undergo collisions and stayed in liquid steel. This effect is especially well visible in the case of small inclusions and for a low energy of mixing.

References

[1] Kalisz, D. & Kuglin, K. (2019). The influence of adsorbed Al_2O3 inclusions on the viscosity behavior of mould slag, *Archives of Foundry Engineering.* 19(2), 67-74. DOI:10.24425/afe.2019.127118.

[2] Bulko, B., Molnar, P., Demeter, P., Baricova, D., Pribulova, A. & Mutas P. (2018). Study of the Influence of Intermix Condition on Steel Cleanliness. *Metals.* DOI:10.3390/met8100852.

[3] Żak, P.L., Kalisz, D., Lelito, J., Szucki, M., Gracz, B. & Suchy, J.S. (2015). Modeling of non – metallic particles motion proces in foundry alloys. *Metallurgija - Journal for Theory and Practice in Metallurgy.* 54(2), 357-360.

[4] Janiszewski, K. & Panic, B. (2014). Industrial Investigations of the liquid steel filtration. *Metalurgija.* 53(3), 339-342.

[5] Janiszewski, K. (2013). Refining of liquid steel in a tundish using the method of filtration during its casting in the CC machine. *Archives of Metallurgy and Materials.* 58(2), 509-517. DOI: 10.2478/amm-2013-0029.

[6] Socha, L., Bažan, J., Martinek, L., Fila, P., Balcar, M. & Lev, P. (2010). Laboratory Verification of Resistance of Refractory Materials for Ceramic Filters. *METAL.* Rožnov p. Radhoštěm, Czech Republic, 90-95.

[7] Warzecha, M. & Merder, T. (2013). Numerical analysis of the nonmetallic, inclusions distribution and separation in a two strand tundish. *Metalurgija - Journal for Theory and Practice in Metallurgy.* 52(2), 153-156.7.

[8] Aubrey, L.S. & Brockmeyer, J.W. (1986). Steelmaking Proc. Conf. Washington 6-9.04. 1986, 977-991.

[9] Bažan, J., Bužek, Z., Roučka, J., Strańsky, K., Lev, P. (1998). About the mechanism of filtering molded copper and foam filters. Materials of the VIII International Scientific Conference „Iron and Steelmaking", Mala Lučivna, 23-25.09.1998, 168-171. (in Czech).

[10] Bagherian, E.R., Ariffin, M.K. & Sulaiman, S. (2015). Development of a ceramic foam filter for filtering molten aluminium alloy in castin process. *IJRET: International Journal of Research in Engineering and Technology*. 04, 03, 27-43.

[11] Asłanowicz. M., Ościłowski. A., Stachańczyk. J. & Wieliczko, P. (2007). Evaluating the effectiveness of heat – resistant cast steel filtration from the results of structure examinations. *Archives of Foundry Engineering.* 7(1), 97-102.

[12] Bruna, M., Bolibruchova, D. & Kantorik, R. (2008). Filtration of aluminium alloys and its influence on mechanical properties and shape of eutectical silicium. *Archives of Foundry Engineering.* 8(2), 13-16.

[13] Chojecki A., Dobosz St. (2006). Alloy filtration through ceramic filters. Transactions of VSB – Technical University of Ostrava, 1, 87-92. ISSN 1210-0471.

[14] Ali, S., Mutharasan, R. & Apelian, D. (1985) Physical refining of steel melts by filtration. *Metallurgical Transactions* B. 16(4), 725-742.

[15] Svjażin, A.G., Romanowicz, D.A. (1996). Hutnik – Wiadomości Hutnicze 1996, nr 5.

[16] Weidner, A., Krewerth, D., Witschel, B., Emmel, M., Schmidt, A., Glining, J., Volkova, O., Aneziris, C.G. & Bierman, H. (2016). Microstructure of non-metallic inclusion identified in cast steel 42CrMo4 after metal melt filtration by novel foam filters. *Steel Research*. 87(8), 1038-1053.

[17] Uemura, K., Takahashi, M., Koyma, S. & Nitta, M. (1992). Filtration mechanism of non – metallic inclusions in steel by ceramic loop filter, *ISIJ Int.* 32, 150-156.

[18] Geiger, G.H., Poirier, D.R. (1973). Transport Phenomena in Metallurgy, Addison-Wesley Publishing Company, Inc., 1973, 91-97.

[19] Scheidegger, A.E. (1974). The Physics of Flow through Porons Media, 3rd Edition, University of Toronto Press, 1974, 124-155.

[20] Bulkowski, L., Galisz, U., Kania, H., Kudliński, Z., Pieprzyca, J. & Barański, J. (2012). Industrial tests of steel filtering process, *Archives of Metallurgy and Materials*. 57(1), 363-369.

[21] Kawecka-Cebula, E., Kalicka, Z. & Wypartowicz, J. (2006). Filtration of nonmetallic inclusion in steel. *Archives of Metallurgy and Materials*. 51(2), 261-268.

[22] Iwanciw, J., Podorska, D. & Wypartowicz, J. (2011). Simulation of oxygen and nitrogen removal from steel by means of titanium and aluminium, *Archives of Metallurgy and Materials*. 56(3), 635-644. DOI: 10.2478/v10172-011-0069-x.

[23] Podorska, D., Drożdż, P., Falkus, J. & Wypartowicz, J. (2006). Calculation of oxide inclusions composition in the

steel deoxidized with Mn, Si and Ti. *Archives of Metallurgy and Materials*. 51(4), 581-586.

[24] Kalicka, Z. (1998). *The role of dispersion systems in the description of liquid steel refining.* Kraków: AGH Wydawnictwo Naukowo – Dydaktyczne.

[25] Lis, T. (2009). *High purity steel metallurgy.* Gliwice: Wydawnictwo Politechniki Śląskiej.

[26] Kalisz, D.(2013). *Thermodynamic characteristics of the non-metallic phase in liquid steel.* Kraków: Wydawnictwo Naukowe Akapit.

[27] Tozawa, H., Kato, Y., Sorimachi, K. & Nakanishi T.(1999) Agglomeration and flotation of alumina clusters in molten steel. *ISIJ Int.* 39(5), 426-434.

[28] Kalisz, D. & Żak, P.L. (2016). PSG method for simulating of Al_2O_3 inclusion in liquid steel, *Acta Physica Polonica A.* 130(1), 157-159. DOI: 10.12693/APhysPolA.130.157.

[29] Kalisz, D. & Żak, P.L. (2016). Analysis of Agglomeration of Al_2O_3 Particles in Liquid steel, *Archives of Metallurgy and Materials*. 61(4), 2091-2096. DOI: 10.1515/amm-2016-0336.

[30] Kuglin, K. & Kalisz, D.(2017). Effect of energy mix on the phenomenon of agglomeration of non – metallic inclusion particles in liquid steel. *Transactions of Foundry Research Institute*. 57(1), 11-18. DOI: 10.7356/iod.2017.02.

[31] Saffman, P.G. & Turner, J.S. (1956). On the collision of drops in turbulent clouds. *Journal of Fluid Mechanics.* 1(1), 16-33. DOI: 10.1017/S0022112056000020.

[32] Linder, S. (1974). Hydrodynamics and collisions of small particles in a turbulent metallic melt with special reference to deoxidation of stell. *Scandinavian Journal of Metallurgy*. 3, 137-150.

[33] Nakaoka, T., Taniguchi, S., Matsumoto, K., Johansen, S.T. (2001). Particle – size grouping method of inclusion agglomeration and its application to water model experiments. *ISIJ Int.* 41, 1103-1111. DOI: 10.2355/isijinternational.41.1103.