Special issue of the 2nd International Conference on Computational and Experimental Science and Engineering (ICCESEN 2015)

PSG Method for Simulating Agglomeration of Al_2O_3 Inclusions in Liquid Steel

D. Kalisz* and P.L. Żak
AGH University of Science and Technology, Faculty of Foundry Engineering,
W.S. Reymonta 23, 30-059 Kraków, Poland

A quantitative description of the non-metallic inclusions removal from liquid steel is the most important element of secondary metallurgy. Authors made an attempt at calculating balance of Al_2O_3 particles during turbulent flow, which represents the steel refining conditions. For this purpose a special program was worked out. The agglomeration of non-metallic inclusions in liquid steel was modeled with the particle grouping method. Calculations were performed for steel with 300 and 500 ppm oxygen content. Then the quantity of generated aluminum oxide was calculated. Various mixing rates of the melt, corresponding to the actual conditions in the ladle, were applied. Simulations were performed for 6 groups of particles for the initial size of inclusions 1, 3, and 5 µm. The size interval for each group was predefined very strictly. The diameter increase and particle number reduction of the successive groups were graphically presented in plots. In the initial phase the rate of particle removal was very high, especially when high mixing energies were involved. This calculation procedure realistically describes the agglomeration and elimination of non-metallic inclusions in the secondary metallurgical processes and can be implemented for modeling this type of processes.

DOI: 10.12693/APhysPolA.130.157
PACS/topics: 61.66.Dk, 61.82.Bg, 81.30.Mh, 94.20.Qq

1. Introduction

Deoxidization of melt is a process accompanied by non-metallic inclusion formation — products of steel and oxygen reaction are removed in the course of refinery processes. There are three major mechanisms used for removing inclusions from steel: fluctuation, agglomeration, and adhesion, with special emphasis on agglomeration. The agglomeration mechanism was described by many numerical models. Saffman and Turner [1] proposed a turbulent collision model with the participation of spherical particles acting on the principle of raindrops in a cloud, Linder [2] worked out deoxidization model with deoxidization plots, based on the Saffman and Turner model. Nakanishi and Szekely used the Saffman and Turner model to determine a dependence of deoxidization coefficient on mixing energy ε. This subject was also investigated in [3–8]. Under real conditions three mechanisms of inclusions removal co-exist. Clusters of non-metallic particles concentrate in large sets of inclusions and have a negative impact on the properties of steel products. On the other hand, large agglomerations of large-diameter inclusions can be removed from liquid steel more easily [9–20]. Nakaoka [3] claimed that an adverse effect may take place during refining operations, i.e. agglomerates are decomposed into smaller clusters. This phenomenon takes place while intensely mixing liquid melt. In this case the frequency of such events depends on the intensity of mixing and so the speed of the particles and the matrix, leading to collisions with other particles of the ladle; this results in the lack of coherence of the agglomerates [4, 5].

Modeling of non-metallic inclusions removal through agglomeration encounters a number of difficulties relating to complex calculations of particles transport in equations describing balance of population, especially when the particles significantly differ in size. In view of the unsolved issues relating to the mechanism of non-metallic inclusion agglomeration, authors proposed another solution in which the aluminium oxide inclusions are removed by grouping particle sizes, as previously used in papers [3, 12].

Direct observations of the behavior of Al_2O_3 inclusions on the surface of low-carbon steel deoxidized with aluminium and containing 200 ppm of oxygen, presented in works [4, 5] allowed to identify a large number of individual Al_2O_3 particles of 1 µm and bigger clusters composed of this phase. The particles start colliding almost immediately, though after about 2 min, 200 µm aggregates are formed. The removal of Al_2O_3 inclusions by the clustering of solid particles into larger agglomerates in the refining processes was a starting point for a computer simulation performed in this paper.

2. Particle clustering method

When applying the population balance equation along with the collision frequency equation, the solution can be obtained by considering the size of each particle separately. In the presence of a great number of non-metallic inclusions in the steel deoxidization processes, calculations are impossible. In this situation the particle size grouping (PSG) method can be used as it mainly refers to the clustering of solid particles into agglomer-

*corresponding author; e-mail: dak@agh.edu.pl

ates [3]. In this method the set of particles is divided into M groups. The volume of particles in each group varies from v_1 to v_M, and their diameters from a_1 to a_M. The following relation exists for the volumes of inclusions:

$$\frac{v_k}{v_{k-1}} = R_v = \text{const.} \tag{1}$$

A particle is represented by a_k, which means that the particle diameter stays between two threshold values

$$\text{Th}_k = \frac{a_{k-1} + a_k}{2}, \tag{2}$$

$$\text{Th}_{k+1} = \frac{a_k + a_{k+1}}{2}. \tag{3}$$

If particles belonging to two groups meet, a new particle of different size is formed. It was assumed in the paper that $R_v = 2$, which means that the critical particle is formed by two one level lower particles v_{k-1}. Agglomeration formed by particles classified within $k-1$ group gives a new particle of different size than that group. The new particle is classified to group k if its size exceeds the classification threshold. Otherwise it is again classified as $k-1$. This means that one particle is formed of two particles, which causes the total decrease of the number of particles in the liquid metal area, and remaining in the group of the particles decreases the number of its elements. When the assumption that collision of particles from the interval $i_{c,-1}$ to $k-1$ generates a particle k is met, the population balance equation has the following form [3]:

$$\begin{aligned}\frac{\mathrm{d}n_k^*}{\mathrm{d}t^*} = &\sum_{i=i_{c,k-1}}^{k-1} \xi_{i,k-1}(r_1^* + r_{k-1}^*)^3 n_i^* n_{k-1}^* \\ &+ \sum_{i=1}^{i_{c,k-1}} \zeta_{i,k}(r_i^* + r_k^*)^3 n_i^* n_k^* \\ &- \sum_{i=i_{c,k}}^{M-1} (1+\delta_{ik})\,(r_i^* + r_k^*)^3 n_i^* n_k^*,\end{aligned} \tag{4}$$

where $n_k^* = n_k/N_0$ — density of particles of a given size is referred to the initial density of particles N_0, $t^* = 1.3 \propto r_1^3(\varepsilon/v)^{1/2} N_0 t$, $t*$ — dimensionless time of turbulence collision, ε — turbulent energy dissipation [m^2 s^{-3}], v — kinematic viscosity [m^2 s^{-1}], r_1 — radius of elementary monomers, N_0 — initial number of particles in a unit of volume, N_M — number of basic particles clustering to form agglomerations, ξ, ζ — correction coefficients for particle density in group, $\xi_{i,k-1} = (v_i + v_{k-1})/v_k$, $\zeta_{i,k} = v_i/v_k$, $r_k^* = r_k/r_1$, $i_{c,k-1}$ — critical size of a particle, δ_{ij} — Kronecker's delta ($\delta_{ij} = 1$ for $i = j$, $\delta_{ij} = 0$ for $i \neq j$).

Member of the right side denotes:

- participation of collisions, where particles "k" are formed from particles "k-1",
- participation of collisions with small particles, where particles "k" remain particles "k",
- participation of collisions, where particles "k" become larger particles than "k".

3. Results of calculations

The oxygen content in liquid steel after preliminary deoxidization stays on a level of 300–500 ppm, i.e. about 6×10^{14} of Al_2O_3 particles of size 1 µm can be found in 1 m^3 of steel. The following data were assumed for calculations: coefficient $\alpha = 1$, initial number of particles $N_0 = 50000/\text{m}^3$. Literature abounds in discrepancies on the assumed time value. Zhang et al. [13] assumed $t^* = 2.37{\times}10^6{\times}t$. This value depends on a number of factors, i.e. size of the particle, energy of mixing and number of particles in a unit of volume. Authors calculated the reduced time $t^* = 8.646 \times t$ for the number of particles of about 6×10^{14} and energy of mixing $\varepsilon = 0.0001$ m^2/s. The value of energy of mixing — assumed after Taniguchi et al. [8] — corresponds to the conditions of metallurgical processes taking place in a ladle. Exemplary calculations for Al_2O_3 particles of radius 1, 3, and 5 μm are presented in the paper. The distribution of particle clusters' density was exemplified on 6 groups. Oxide particle agglomeration curves for the initial particle of 1–5 µm and the initial number of particles in the system $N_0 = 50000/\text{m}^3$ are presented in Figs. 1–3.

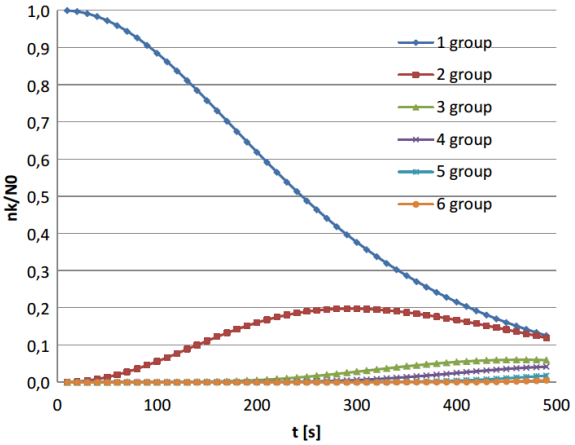

Fig. 1. Al_2O_3 particle agglomeration curves for initial size 1 μm, where $N_0 = 50000/\text{m}^3$.

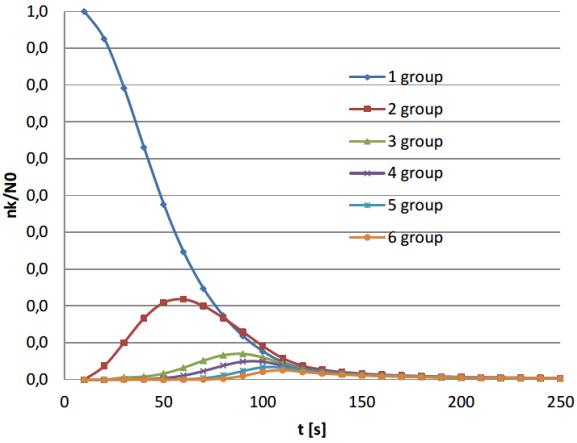

Fig. 2. As in Fig. 1, but for initial size 3 μm.

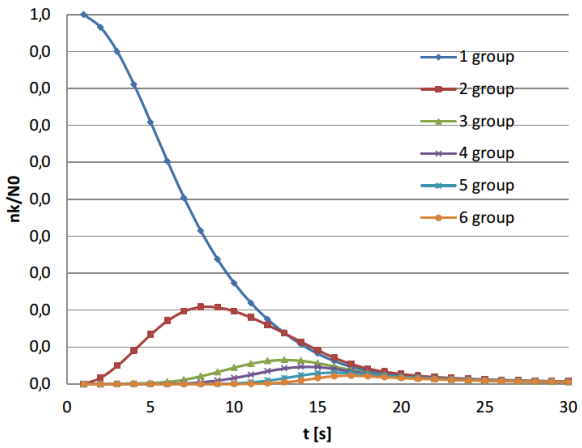

Fig. 3. As in Fig. 1, but for initial size 5 μm.

For a small initial size of Al_2O_3 particles (1 μm) (Fig. 1) even at considerable increase of precipitated particles and their transition to higher size groups is slower than in particle having bigger initial size (Figs. 2 to 3). This process is six times slower as compared with particles of initial size equal to 5 µm. At the first stage of the agglomeration process, the decreasing amount of inclusions in the first group is very fast (Figs. 2 to 3), till 80% of particles of the first group are removed in 80 s (Fig. 2), whereas for the initial size of particles of 1 to 5 µm this process takes place in 12 s (Fig. 3). At the further stage the density of particles in the first group minimally decreases, which is caused by a small amount of inclusions in them.

4. Conclusions

The presented model visualizes the dynamics of aluminum oxide in a melt during refining processes. The agglomeration of non-metallic particles does not mean that they were removed from liquid steel. Inclusions outflow and are assimilated by slag. Then they adhere to the ceramic lining, which has not been accounted for in the presented model. As a result of agglomeration, bigger and bigger particles are formed. The assumed number of basic (smallest) particles remains constant during agglomeration, though they are clustered differently. They form agglomerates consisting of particles, the number of which increases with the process duration. This process accelerates considerably for particles of larger radius (Fig. 3). The model accounts for the removal of particles belonging to a given group by collision with particles of the same group, lower group or all higher groups. It does not take into account the removal of smaller particles due to the transition to slag after they have been carried by the stream of gas to the division surface. The plots represent the dynamics of the agglomeration process in its initial stage. After the assumed time elapses about 1% of particles of each group is left. Their removal lasts much longer as the probability of a collision considerably increases.

Acknowledgments

This study was conducted within the framework of the project Reg. No. 11.170.318 task 14 at financial support of Ministry of Science and Higher Education Republic of Poland.

References

[1] P.G. Saffman, J.S. Turner, *J. Fluid Mech.* **1**, 16 (1956).

[2] S. Linder, *Scand. J. Metall.* **3**, 137 (1974).

[3] T. Nakaoka, S. Taniguchi, K. Matsumoto, S.T. Johansen, *ISIJ Int.* **41**, 1103 (2001).

[4] H. Yin, H. Shibata, T. Emi, M. Suzuki, *ISIJ Int.* **37**, 936 (1997).

[5] H. Yin, H. Shibata, T. Emi, M. Suzuki, *ISIJ Int.* **37**, 946 (1997).

[6] T. Ishii, N. Kubo, K. Bose, M. Iguchi, *ISIJ Int.* **41**, 1174 (2001).

[7] A.K. Sinha, Y.A. Sahai, *ISIJ Int.* **33**, 556 (1993).

[8] S. Taniguchi, A. Kikuchi, T. Ise, N. Shoji, *ISIJ Int.* **36**, 117 (1996).

[9] J. Iwanciw, D. Podorska, J. Wypartowicz, *Archiv. Metall. Mater.* **52**, 999 (2011).

[10] J. Iwanciw, D. Podorska, J. Wypartowicz, *Archiv. Metall. Mater.* **52**, 635 (2011).

[11] P.L. Zak, D. Kalisz, J. Lelito, M. Szucki, B. Gracz, J.S. Suchy, *Metalurgija* **54**, 357 (2015).

[12] D. Kalisz, *The Thermodynamic Characteristic of the Non-Metallic Phase Formation in the Liquid Steel*, Sci. Publ. Co. Akapit, AGH-UST, Krakow 2013, p. 193.

[13] L. Zhang, W. Pluschkell, B.G. Thomas, in: *85th Steelmaking Conf., Nashville, TN (USA)*, Eds.: D.L. Kanagy, D.J. Fuga, M.A. Baker, Vol. 85, ISS, Warrendale, PA 2002, p. 463.

[14] L. Zhang, B.G. Thomas, in: *7th Europ. Electric Steelmaking Conf., Venice (Italy)*, Associazione Italiana di Metallurgia, Milano 2002, p. 2.77.

[15] U. Lindborg, K. Torssell, *Trans. ASME* **242**, 94 (1968).

[16] A. Chojecki, *Analysis of the process of floating up of nonmetallic inclusions to the surface of liquid metals*, Metalurgia i Odlewnictwo, Krakow 1982, p. 78.

[17] L. Zhang, B.G. Thomas, in: *ISS Tech 2003 (Conf. Proc.), Indianapolis, IN (USA)*, ISS Tech, 2003, ISS-AIME, Warrendale, PA 2003, p. 141.

[18] H. Tozawa, Y. Kato, K. Sorimachi, T. Nakanishi, *ISIJ Int.* **39**, 426 (1999).

[19] M. Suzuki, R. Yamaguchi, K. Murakami, M. Nakada, *ISIJ Int.* **41**, 247 (2001).

[20] K. Higashitani, K. Yamauchi, Y. Matsuno, G. Hosokawa, *J. Chem. Eng. Jpn.* **16**, 299 (1983).