Evaluation of the usefulness of rotors for aluminium refining

K. Kuglin¹ and D Kalisz¹

¹ AGH University of Science and Technology, Faculty of Foundry Engineering, 23 Reymonta Street, 30-059 Kraków, Poland
E-mail: dak@agh.edu.pl

Abstract. Refining of liquid aluminium by blowing with an inert gas is one of the most effective methods of purifying liquid metal from hydrogen and non-metallic inclusions. In order to improve the efficiency of this process, it is necessary to develop a rotor design. The study compares rotors designed and their usefulness. For this purpose, the theoretical number of nozzles, the amount of gas per nozzle and the gas bubble radius were calculated.

1 Introduction
The process of refining with neutral gas plays an important role in recycling processes and use of secondary materials [1-12]. The type of applied neutral gas depends on the involved contaminations: argon and nitrogen are used for hydrogen removal, a mixture of chlorine and argon or nitrogen is used for removing metallic contaminants.

In industrial practice this process is realized in reactors equipped with a whirling head introducing neutral gas, either continuously or cyclically [1, 5]. The efficiency of the refining process is determined by a number of parameters, but the design of the impeller as most important and decisive for the production of properly dispersed neutral gas bubbles in the liquid metal. This finally guarantees that the liquid metal is thoroughly mixed in the ladle [1-10]. The barbotage refining technology with a whirling head has a number of design variations depending on the number and location of nozzles in the rotor moving with a specific speed. As compared to the traditional refining procedure, the introduction of additional centrifugal force causes the formation of a whirling stream of fine-dispersive neutral gas bubbles in the volume of a metal bath. This phenomenon favors the removal of nonmetallic inclusions to the gaseous bubbles [1-12]. Although numerous research works [5-10] on this issue were conducted, the practical implementation of this technology to the structure of a given foundry still encounters many problems connected with the implementation of such key production parameters as: intensity of mixing and consequently the dispersion of gaseous bubbles in metal, and their connection with the average size of the gas bubble and mass transfer coefficient. The efficiency of the refining process is determined by the type and design of the nozzle, design of the refining system and also surface of the refining gas/metal interface. The design of the whirling head decides about the intake ability and transfer of gas to the system and about the bubble size, though the design of the whirling head and the nozzle is one of the decisive parameter.
2 Comparison of rotor operation
The 3D technique has been used for making whirling heads. As presented in figure 1, the designed whirling heads are equipped with 4, 8 and 12 nozzle outlets, respectively.

![Whirling heads](image)

Figure 1. Whirling head, a)- 4 nozzle outlets, b)- 8 nozzle outlets, c)-12 nozzle outlets

The parameters of the designed impeller are presented in tables 1-3. Table 1 presents characteristic parameters of applied refining system.

Table 1. Characteristic parameters of applied refining system

| No. | Parameters               | Parameters | Pompa       | Propeller |
|-----|--------------------------|------------|-------------|-----------|
| 1   | Nozzle type              | Nozzle type| Pompa Propeller |
| 2   | Nozzle design            | Number of outlets | 4 - 24 | |
|     | Diameter of outlets      | 1 [mm]     | | |
|     | Shape of outlets         | Round      | | |
|     | Shape of nozzle          | Cut cylinder | | |
|     | Shape of ladle           | Cylinder   | | |
|     | Distance between nozzle and bottom of ladle | 110 [mm] | | |
| 3   | Refining system design   | Capacity   | 225 [dm³]  | | |
|     | Number of compartments in system | 1 | | |
|     | Shape of bottom          | round      | | |
|     | Thickness of shaft       | 56 [mm]    | | |
|     | Immersion depth of shaft | 590 [mm]   | | |

Table 2 presents characteristic of gas the basic variants of the tests carried out at the gas flow rate in refining process and impeller revolutions.
Table 2. The basic variants of the tests the gas flow rate and impeller head operations during refining process

| No. | Unit amount of gas to be refined |
|-----|---------------------------------|
|     | [l/min] | [cm³/s] |
| 1   | 10      | 166.67  |
| 2   | 20      | 333.33  |
| 3   | 30      | 500.00  |

| Number of impeller head operations | [r/min] | [obr/s] |
|-----------------------------------|---------|---------|
|                                    | 200     | 3.34    |
|                                    | 300     | 5.00    |
|                                    | 400     | 6.67    |
|                                    | 500     | 8.34    |

As part of the work, it was decided to conduct comparative tests of the calculated mass transfer area for the designed rotors. The following equation was used to calculate the surface area, where : k is number of holes in the head; n is rotary impeller speed [obr/s]; \( V_{ci} \) is unit amount of gas to be refined [cm³/s]:

- Calculation of theoretical number of outlets ( \( k_0 \)) : \( k_0 = k \cdot n \) (1)
- Calculation of gas flowing through the i-th outlet ( \( V_i \)) : \( V_i = \frac{V_{ci}}{k_0} \) (2)
- Calculation of unit radius of a bubble at a temperature of 20°C ( \( r_i [cm] \)) : \( r_i = \frac{3\sqrt{3V_i}}{4\pi} \) (3)
- Calculation of the gas contact surface ( \( A [m^2] \)) : \( A = \frac{3V_{ci}}{r_i} \) (4)

Considering the change of volume of all bubbles of identical diameter with height \( h \) measured from the bottom of the ladle bottom, its value increased in relation to the summaric input surface :

\[
A = A_0 \cdot \frac{1}{L} \cdot \int_0^L \left( \frac{P_0 + \rho_M \cdot g \cdot L}{P_0 + \rho_M \cdot g \cdot (L-h)} \right)^{\frac{2}{3}} \cdot dh
\]  

(5)

\( A_0 \) denotes a summaric real surface of all bubbles with initial diameter \( d_p \), produced at a given gas flow value \( Q \). \( A \) denotes a summaric surface of bubbles, taking into account their increase. To calculate the real surface \( A_0 \), i.e. number of bubbles with diameter \( d_p \), the compression of the introduced gas to pressure \( P_{max} \) should be accounted for: \( Q_{rz} = \frac{P_0}{P_{max}} \cdot Q \)  

(6)

The number of bubbles with diameter \( d_p \) introduced in 1 second: \( n = \frac{6 \cdot Q_{rz}}{\pi \cdot d_p^3} \)  

(7)

Hence the total initial surface of bubbles introduced in 1 second equals to: \( A_0 = n \cdot \pi \cdot d_p^2 \)  

(8)
If the average flow rate of a bubble is $u$, then its outflow time equals to: 
$$t_w = \frac{L}{u}$$
(9)

With this parameter we can calculate the number of bubbles present simultaneously in the metal, and therefore the reaction surface: 
$$A_r = t_w \cdot A$$
(10)

The hydrogen removal rate, expressed by mass, is calculated from the diffusion control formula:
$$\dot{m}_H = \frac{A_r \cdot \rho_{H_2} \cdot k_y \cdot \left\{ [\% H] - \left[ [\% H]\right]_{fr} \right\}}{1400}$$
(11)

[$\% H$, $[\% H]_{fr}$] - hydrogen in liquid aluminium and metal-argon bubble interface.

3 Results of calculations

One of the most important parameters determining impeller usability is the degree to which the gaseous bubbles are dispersed in a volume of liquid metal in the ladle, and which is connected with the contact surface of a gaseous bubble with radius ($r_i$) and liquid metal ($A$). The results of calculations of contact surface for gas $A$ are presented in figures 2-5, results of calculation hydrogen removal $\dot{m}_H$ in kg/s for $[\% H] = 0.001$ are presented in table 3.

![Figure 2: Calculated contact surface $A$ [m$^2$] for a)4, b)8 nozzle rotor with a flow rate equal to 10, 20 and 30 [l/min]](image)

![Figure 3: Calculated contact surface $A$ [m$^2$] for an 12 nozzle rotor with a flow rate equal to 10, 20 and 30 [l/min]](image)

Next the contact surface $A$ was determined in a function of rpm for rotors equipped with 4, 8, 12, 16, 20 and 24 nozzles, and neutral gas flow rate 10, 20 and 30 [l/min].
Figure 4. Calculated contact surface $A \text{[m}^2\text{]}$ at a flow rate equal to 10, 20, 30 [l/min] and a)200, b)400 rpm

Figure 5. Calculated contact surface $A \text{[m}^2\text{]}$ at a flow rate equal to 10, 20, 30 [l/min] and 500 rpm

The calculations reveal that a 12-nozzle rotor is most efficient for all neutral gas flow rates (10, 20, 30 [l/min]). The dynamics of rotations is another equally important parameter. It was observed that the same refining efficiency can be obtained for a smaller number of nozzles and increased number of rotations. For instance, surface $A$ is similar for an 8-nozzle rotor with a flow rate equal to 30 l/min and 500 [rpm] to that for a 12-nozzle rotor with the same flow rate conditions and 300 [rpm].

Table 3. Calculation of rate of nitrogen removal $\dot{m}_H$ in kg/s for [%H] = 0.001.

| Bubble diameter $d_p$ (m) | Volumetric argon flow rate $Q$ (Nm$^3$/s) | 0.001 | 0.005 | 0.01  | 0.05  | 0.1  |
|--------------------------|------------------------------------------|-------|-------|-------|-------|------|
| 0.01                     |                                          | 2.67E-07 | 1.33E-06 | 2.67E-06 | 1.33E-05 | 2.65E-03 |
| 0.03                     |                                          | 2.96E-08 | 1.48E-07 | 2.96E-07 | 1.48E-06 | 9.75E-05 |
| 0.05                     |                                          | 1.07E-08 | 5.33E-08 | 1.07E-07 | 5.33E-07 | 2.09E-05 |
| 0.08                     |                                          | 4.16E-09 | 2.08E-08 | 4.16E-08 | 2.08E-07 | 5.04E-06 |

The results of calculation show how important is the diameter of gas bubble. It only depends on geometry of whirling head. These results relate to the case where the rate determining step of the process is the diffusive transport of the hydrogen in aluminium. If this step turned out to be the reaction on the surface of the bubbles, then the kinetic equation of the second-order reaction should be considered.
4 Conclusions

The design of the rotor decides about the potential of neutral gas transfer to refined liquid metal or alloy. The design and the number of rotations gives information whether or not gas can be introduced to metal; the smaller is the gaseous bubble, the bigger is the contact surface. The calculation of contact surface (A) was based on the assumption of uniform distribution and dynamics of neutral gas flow as well as an ideal round shape of the bubble with a constant predefined radius. This assumption was very simplified as the flowing bubbles collide and coalesce, so the calculated contact surface A [m²] produces overestimated values. According to empirical calculations, the refining efficiency defined by surface A can be modified by using a specific number of rotor revolutions, flow and number of nozzles. In rotors equipped with a bigger number of nozzles the high degree of gaseous bubbles dispersion can be achieved for a smaller number of rotations or gas flow. The same refining efficiency can be achieved by using a constant gas flow with fewer nozzles and by varying the number of rotations of the rotor. For example, for a gas flow of 30 l/min, the same refining efficiency is obtained for 8 and 12 nozzles if the speed is changed from 500 to 300 [rpm].

Acknowledgements

The authors acknowledgement the AGH University of Science and Technology for its financial support within POWR.03.05.00-00-z307/17

References

[1] Bonderek S and Rzadkosz S 1999 Problemy uszlachetniania ciekłych stopów aluminium [in Polish] Metals and Alloys (Krzepnięcie Metali i Stopów) Vol 1(41).
[2] Saternus M 2015 Zanieczyszczenia ciekłego aluminium-metody ich usuwania [in Polish] Obróbka Metali Vol. XXVI(2) pp 115-132
[3] Ransley C E, Talbot D E J and Barlow H C 1957–1958 An instrument for measuring the gas content of aluminium alloys during melting and casting. Inst. Metals Vol 86 pp 212-219
[4] Adamski C and Misiag M 1954 Gazy w metalach nieżelaznych [in Polish] PWT (Warszawa)
[5] Saternus M and Merder T 2018 Physical modeling of aluminium refining process conducted in bath reactor with rotary impeller Metals Vol 8(9)
[6] Saternus M 2018 Determination of RTD curves for aluminium refining process conducted in batch reactor- Physical modeling Arch. Metall. Mater. Vol 63(4) pp 1909-1914
[7] Saternus M 2011 Rafinacja aluminium i jego stopów przez przedmuchiwanie argonem [in Polish] (Gliwice: Wyd. Politechnika Śląska)
[8] Saternus M, Merder T and Warzeczy P 2011 Numerical and physical modeling of aluminium barbotage process Solid State Phenomena Vol 176 pp 1-10
[9] Saternus M and Botor J 2003 Modelling of the continuous refining process of AK-64 alloy Archives of Metallurgy Vol 48(3) pp 321-341
[10] Michalek K, Tkadlečková M, Socha L, Gryc K, Saternus M, Pieprzyca J and Merder T 2018 Physical modelling of degassing process by blowing of inert gas Arch. Metall. Mater. Vol 63(2) pp 987-992
[11] Zak P L, Kalisz D, Lelito J, Szucki M, Gracz B and Suchy J S 2015 Modelling of non-metallic particles motion process in foundry alloys Metalurgija Vol 54(2) pp 357-360.
[12] Gaye H, Huin D, Riboud P 2000 Nitrogen Alloying of Carbon and Stainless Steels by Gas Injection Met. Trans. B 31B pp 905 – 912.