THE PROCESSING OF EXPERIMENTAL DATA FROM THE PHYSICAL MODEL OF A FDU REFINING UNIT

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Abstract

The present paper describes a method for processing experimental data obtained on a physical model of a refining unit, the Foundry Degassing Unit (FDU). For different refining gas flow rates and rotor rotation speeds of the FDU, the concentration of oxygen removed was measured depending on time. A large number of experiments were carried out with different rotor types and under different conditions. After examining the character of the data obtained, a method was proposed to evaluate the performance of different rotor types in degassing at a given gas flow rate at different rotor speeds. This method is based on interpolating several degassing curves in such a way that the resulting characteristic can be expressed by a single parameter. This final parameter then allows the degassing efficiency (refining capacity) to be quantified. In this unique way, the degassing efficiency of different rotor types can then be objectively compared. Furthermore, the parameter thus obtained can be used to determine the expected time at which the desired decrease in the concentration of undesirable gas in the bath will occur. Attention is also paid to the possible deviation that occurs when a large amount of experimental data is reduced to a single parameter by the described approximation.

Keywords: Physical modelling, aluminium, degassing, experimental data, parameterization

1. INTRODUCTION

The requirements for product quality improvement are constantly placing emphasis on a better understanding of the processes taking place during the manufacturing process. There are various ways in which the progress of metallurgical processes can be studied. One of these is the modelling method, which aims to imitate the behaviour of a real system. If certain requirements are met, the model can then be used to retrospectively predict the behaviour of the real system as various conditions change [1]. In recent years, this topic has attracted numerous researchers [2-14].

Physical modelling is usually carried out on scale models of operating equipment and at normal ambient temperatures. This modelling method uses the theory of physical similarity between two systems [1,15]. The results obtained can then be interpreted for the actual conditions of the operating equipment, provided certain conditions are met and after appropriate conversions. However, it is worth mentioning that, although the physical modelling method has clear benefits for aluminium refining technology, approximate physical modelling is often involved that does not fully meet the requirements for compliance with the theory of similarity

between two systems [1,15]. Therefore, it is good to approach the results obtained in a sober way and to verify the findings under operating conditions in the next step. Physical modelling usually focuses on describing the kinetics of degassing under different conditions, e.g. when changing the rotational speed and flow rate of the refining gas [9,10,14] or the working height of the rotor [11], or when using different gas injection techniques into the melt [9,12]. Finally, physical modelling can be used to test and mutually compare the efficiency of various rotor shapes. This topic was the subject of numerous studies in the past, e.g. [5-8,10,13].

The efficiency of rotors is often judged by the time of removing a certain percentage of oxygen from the water [5,11]. The objective of this work was to develop a more sophisticated methodology for evaluating physical modelling data, the purpose of which was to reasonably simplify large datasets of measured results on a physical model in order to evaluate and more easily compare rotor efficiency under different conditions. By means of the methodology presented, the time of degassing to the desired concentration can also be determined retrospectively, which could reduce the number of time-consuming experiments in the future. To develop the methodology, data from a physical model of the FDU refining unit used in the operating conditions of MOTOR JIKOV Slévárna a.s. were used. The physical modelling was carried out as part of research aimed at optimizing the refining technology in order to increase the quality of aluminium castings [14,16,17]. A number of rotors of different shapes and materials were examined as part of the modelling. In this paper, the development of the methodology will be presented on a dataset measured using a single rotor.

2. EXPERIMENTAL PROCEDURE

The experimental measurements were carried out on a physical model of the FDU refining unit, which is shown with a description of the individual components in **Figure 1.** Due to the acceptable dimensions of the refining basin, the model was constructed at a scale of 1:1. The container of the physical model was made of Plexiglas and its dimensional diagram is shown in **Figure 2.** The degassing of the aluminium melt, i.e. the removal of dissolved hydrogen using nitrogen as refining gas, was simulated through the physical model. In this case, liquid aluminium was replaced by water, hydrogen by oxygen, and nitrogen by argon. A comparison of the properties of the different media is provided in **Table 1**. Thus, the basic principle of the physical modelling of the removal of dissolved hydrogen from the aluminium melt was the removal of dissolved oxygen from water using argon. InPro6860i/12/120/mA Ex optical probes of the METTLER-TOLEDO company were selected for the continuous measurement of oxygen content, allowing dissolved oxygen content measurements to up to 26 ppm. For physical modelling purposes, special software was developed to monitor the oxygen concentration in the water and record the data. A more detailed description of the model design and measurement methodology is provided in the reference [14].

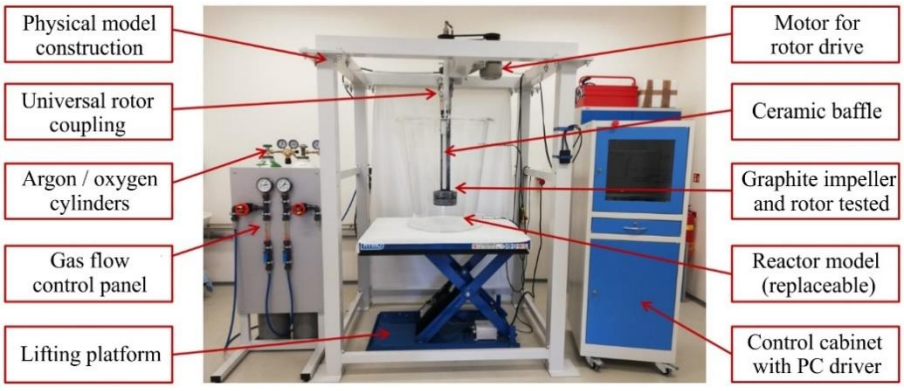


Figure 1 Description of the physical model workplace

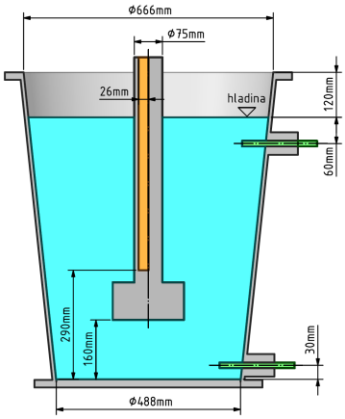
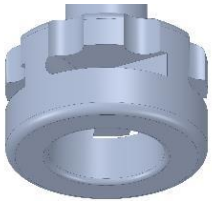


Figure 2 Dimensional diagram of the container

Table 1 Comparison of the parameters of the media used

	Industry	Physical model	Rotor type
Inert gas (-)	Nitrogen	Oxygen	
Liquid (-)	Aluminium	Water	
Density (kg·m^{-3})	2.345	0.998	
Dynamic viscosity (Pa·s)	1005	1000	
Surface tension (N·m^{-1})	0.868	0.072	
Froude´s number (-)	0.121	0.121	

For the development of the evaluation methodology, a series of experiments were selected using one type of rotor with a constant working height (160 mm) and 0% wear (see **Table 1**). Under the defined conditions, measurements were carried out on the physical model, which included 35 experimental variants. The parameters of each variant are shown in **Table 2**.

Table 2 Parameters of experiments on the physical model

Rotor speed (rpm)	275					300					325					350					375					400					425				
Ar flow rate (Nl·min^{-1})	13	15	17	19	21	13	15	17	19	21	13	15	17	19	21	13	15	17	19	21	13	15	17	19	21	13	15	17	19	21	13	15	17	19	21

3. DESCRIPTION OF THE EXPERIMENTAL DATA EVALUATION METHOD

3.1 Processing of the measured data

The experimental data in the form of degassing curves were obtained by measurements (see **Figure 3**). These data were subjected to standardization and processed in the Matlab programme. For further processing of the data, the degassing curves for the same gas flow rates and different rotor speeds were combined into one group of curves forming a surface. All data were considered only up to the time of t = 200 s, even though experiments were continued until a concentration of 1 ppm oxygen in the water was reached. Rotor speeds were considered in the rpm dimension, which is consistent with operational practice, although from the point of view of physical analysis, it would be more accurate to consider angular velocity in rad-s^{-1}, or more precisely s^{-1}.

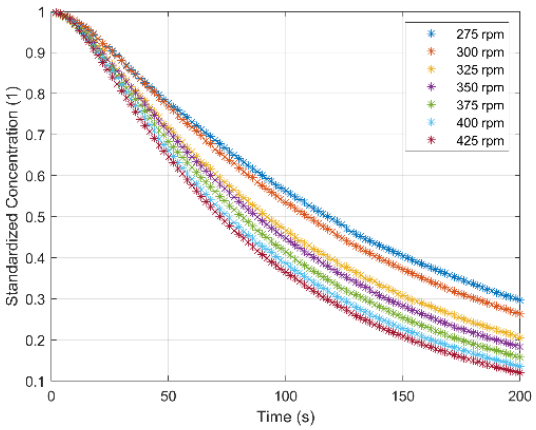


Figure 3 Measured standardized data for a gas flow rate of 17 Nl·min^{-1}

3.2 Processing of surfaces for individual gas flows

A 3D representation can be introduced, where the x-axis will be time (s), the y-axis (second horizontal axis) will be rotor speed (rpm), and the vertical z-axis will be the measured standardized concentration (1). Such a graph (**Figure 4**) captures the measured degassing modes for only one rotor and one gas flow. The measured standardized concentrations over time are shown by blue points. A surface was sought that would approximate the experimental data while still keeping its mathematical description in x, y, z coordinates as simple as possible - expressed in terms of the fewest possible number of parameters, ideally one. A parametric description of this function will be looked for, in such a way that the whole group of degassing curves can be described by a single parameter. Due to the nature of the decreasing surface and the initial value of 1 (standardized concentration), an exponential decreasing function appears to be appropriate. The equation of this surface was determined to be of the form (1), more specifically of the form (2).

$$z = e^{(\frac{x \cdot y}{a})}, \tag{1}$$

$$conc.stand. = e^{(\frac{t \cdot rpm}{a})} \tag{2}$$

where the only unknown surface parameter is the parameter *a*. Using the "fit" function, Matlab found the best-fit parameter a for each such surface sought. **Figure 4** shows the original measured data and the interleaved replacement surface. At this stage of processing, each set of measurements for one rotor and one gas flow is replaced by one parameter *a*. It is worth pointing out that the proposed shape of the concentration replacement function contains the product of time and speed, this physically corresponds to a dimensionless number, the obtained parameter *a*, can also be considered as dimensionless, as the resulting relative concentration. The degassing curves can be retrospectively shown as sections through the replacement surface, resulting in **Figure 5**, which shows the original measured data and the newly replaced curves. Each of the curves could be individually replaced more accurately, but in this case, it is a joint replacement of all the displayed data (sections of a common surface).

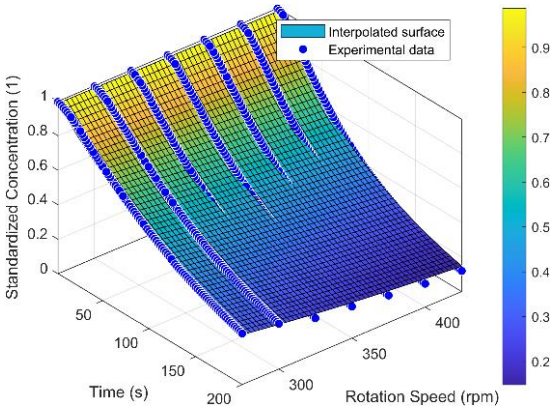


Figure 4 Measured data and interleaving with replacement surface, gas flow 17 Nl·min^{-1}

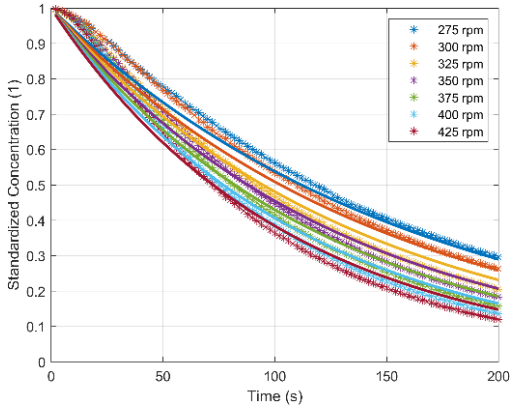


Figure 5 Measured data and interleaved curves, gas flow 17 Nl·min^{-1}

3.3 Determination of expected degassing times

Using the appropriate parameter *a*, the degassing time for the desired concentration can be retrospectively calculated according to the formula:

$$t = \frac{ln(conc.stand.)}{rpm} a \tag{3}$$

Where *t* is the expected degassing time (s), *conc. stand*. is the desired resulting standardized concentration (1), *rpm* is the rotor speed and *a* is the appropriate parameter of the replacement surface corresponding to the

rotor and gas flow. For example, the inserted standardized concentration value of 0.3 means that 70 % of the original gas content has been degassed.

3.4 Determination of replacement function deviations from experimental data

The next step in considering the above-mentioned procedure of replacing the experimental data with replacement functions is to determine the deviations of the original data and the new interpolated ones. A comparison of the original values with the interpolated ones in terms of the difference in relative concentrations can be made based on **Figure 4** and **Figure 5**. Using **Figure 4** and **Figure 5** and determining the difference between the replacement surface and the original data, **Figure 6** is produced.

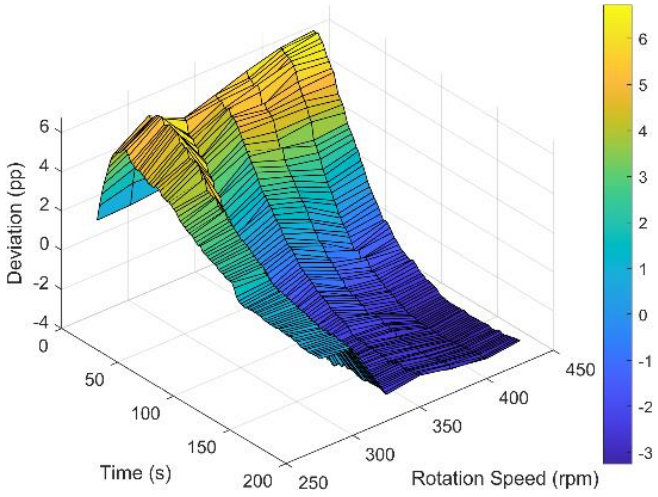


Figure 6 Deviation of the original and interpolated data for a gas flow rate of 17 Nl·min^{-1}

Figure 6 is again determined for a single rotor and a single gas flow (17 Nl·min^{-1}), but a total of 70 datasets were evaluated in this way. All the processed data and deviations showed a similar character. In **Figure 6** we see an initial area with a maximum of deviations between 10-40 s, where the replacement surface lies below the values of the original experimental data (see **Figure 4**). Subsequently, the surfaces get closer together and their absolute distance decreases. From the principle of fitting the data with the replacement surface, it is clear that part of the data will always lie below the replacement surface and part above. A total of 70 groups of degassing curves were processed using the method described; in none of the cases did the deviation exceed 10% and, in all cases, the maximum deviation was in the region of 10-40 s.

4. CONCLUSIONS

A data processing method has been described where a whole group of degassing curves is replaced by a single numerical parameter that can be used to characterize the ability of the rotor to perform degassing. During the analysis of a large amount of data, it became apparent that the nature of the replacement function captures the later stages of degassing well but is unable to capture the initial character of the degassing curves, where the degassing process is initiated in the first few tens of seconds and the curves are initially flatter in character. Assuming a standard degassing time between 60 and 180 s, this inaccuracy is negligible. This character is common to all the data analysed, which is important for the usability of the parameter and for the comparison of different rotors or e.g. different gas flow rates for the same rotor. The parameter a can be used to predict the degassing time, which gives a good opportunity to compare different rotors in terms of parameters commonly used in industrial practice, e.g. how much gas could be saved by changing the rotor to a more efficient one, or how much degassing time would be reduced while maintaining the operating parameters.

Possible errors in this data processing method and their impact on the applicability of the method were discussed.

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REFERENCES

[1] MICHALEK, K. *Využití fyzikálního a numerického modelování pro optimalizaci metalurgických procesů*. Ostrava: VŠB-Technická univerzita, 2001. ISBN 80-707-8861-5

[2] BUL'KO, B., MOLNÁR, M., DEMETER, P. Physical Modeling of Different Configurations of a Tundish for Casting Grades of Steel that Must Satisfy Stringent Requirements on Quality. *Metallurgist*. 2014, vol. 57, iss. 11-12, pp. 976-980. Available from: https://doi.org/10.1007/s11015-014-9832-3.

[3] BUL'KO, B., MOLNÁR, M., DEMETER, P., BARICOVÁ, D., PRIBULOVÁ, A., FUTÁŠ, P. Study of the Influence of Intermix Conditions on Steel Cleanliness. *Metals*. 2018, vol. 8, iss. 10. Available from: https://doi.org/10.3390/met8100852.

[4] BUĽKO, B., DEMETER, P., PARILÁK, Ľ., BUČEK, P., PETRÍK, J., BLAŠKO, P., BARICOVÁ, D., CHOMIČ, V., VESELOVSKÝ, P. The influence of ladle shroud misalignment on steel flow in three strand T-shape tundish. In: *METAL 2019: 28th International Conference on Metallurgy and Materials*, Ostrava: TANGER, pp. 35-41. Available from: https://doi.org/10.37904/metal.2019.679.

[5] SATERNUS, M., MERDER, T. Physical Modeling of the Impeller Construction Impact on the Aluminum Refining Process. *Materials*. 2022, vol. 15, iss. 2. Available from: https://doi.org/10.3390/ma15020575.

[6] HERNÁNDEZ-HERNÁNDEZ, M., CAMACHO-MARTÍNEZ, J.L., GONZÁLEZ-RIVERA, C., RAMÍREZ-ARGÁEZ, M.A. Impeller design assisted by physical modeling and pilot plant trials. *Journal of Materials Processing Technology*. 2016, vol. 236, iss. 2, pp. 1-8. Available from: https://doi.org/10.1016/j.jmatprotec.2016.04.031.

[7] SATERNUS, M., MERDER, T. Physical Modelling of Aluminum Refining Process Conducted in Batch Reactor with Rotary Impeller. *Metals*. 2018, vol. 8, iss. 9, pp. 1-8. Available from: https://doi.org/10.3390/met8090726.

[8] CAMACHO-MARTÍNEZ, J. L., RAMÍREZ-ARGÁEZ, M. A., ZENIT-CAMACHO, R., JUÁREZ-HERNÁNDEZ, A., BARCEINAS-SÁNCHEZ, J. D. O., TRÁPAGA-MARTÍNEZ, G. Physical Modelling of an Aluminium Degassing Operation with Rotating Impellers - A Comparative Hydrodynamic Analysis. *Materials and Manufacturing Processes*. 2010, vol. 25, iss. 7, pp. 581-591. Available from: https://doi.org/10.1080/10426910903367386.

[9] GÓMEZ, E. R., ZENIT, R., RIVERA, C. G., JUÁREZ-HERNÁNDEZ, G., RAMÍREZ-ARGÁEZ, J. D. O., TRÁPAGA-MARTÍNEZ, G. Physical Modeling of Fluid Flow in Ladles of Aluminum Equipped with Impeller and Gas Purging For Degassing. *Metallurgical and Materials Transactions B*. 2013, vol. 44, iss. 4, pp. 581-591. Available from: https://doi.org/10.1007/s11663-013-9845-5.

[10] KUGLIN, K., SZUCKI, M., PIEPRZYCA, J., GENTHE, S, MERDER, T., KALISZ, D. Physical and Numerical Modeling of the Impeller Construction Impact on the Aluminum Degassing Process. *Materials*. 2022, vol. 15, iss. 15, pp. 974-983. Available from: https://doi.org/10.3390/ma15155273.

[11] WALEK, J., MICHALEK, K., TKADLEČKOVÁ, M., SATERNUS, M. Modelling of Technological Parameters of Aluminium Melt Refining in the Ladle by Blowing of Inert Gas through the Rotating Impeller. *Metals*. 2021, vol. 11, iss. 2. Available from: https://doi.org/10.3390/met11020284.

[12] CAMACHO-MARTÍNEZ, J., RAMÍREZ-ARGÁEZ, M., JUÁREZ-HERNÁNDEZ, A., GONZÁLEZ-RIVERA, C., TRÁPAGA-MARTÍNEZ, G. Novel Degasification Design for Aluminum Using an Impeller Degasification Water Physical Model. *Materials and Manufacturing Processes*. 2011, vol. 27, iss. 5, pp. 556-560. Available from: https://doi.org/10.1080/10426914.2011.593234.

[13] SATERNUS, M., MERDER, T., PIEPRZYCA, J. The Influence of Impeller Geometry on the Gas Bubbles Dispersion in Uro-200 Reactor – RTD Curves. *Archives of Metallurgy and Materials*. 2015, vol. 60, iss. 4, pp. 2887-2894. Available from: https://doi.org/10.1515/amm-2015-0461.

[14] PRÁŠIL, T., SOCHA, I., GRYC, K., SVIŽELOVÁ, J., SATERNUS, M., MERDER, T., PIEPRZYCA, J., GRÁF, M. Using Physical Modeling to Optimize the Aluminium Refining Process. *Materials*. 2022, vol. 15, iss. 20, pp. 974-983. Available from: https://doi.org/10.3390/ma15207385.

[15] SATERNUS M. *Modelowanie fizyczne zjawisk zachodzących podczas rafinacji roztworów Fe i Al za pomocą gazów obojętnych*. Gliwice: Wydawnictwo Politechniki Śląskiej, 2020. ISBN 978-83-7880-706-3

[16] PRÁŠIL, T., SOCHA, I., GRYC, K., SVIŽELOVÁ, J., SATERNUS, M., MERDER, T., PIEPRZYCA, J., GRÁF, M. Impact of Rotor Material Wear on the Aluminum Refining Process. *Materials*. 2022, vol. 15, iss. 13, pp. 556-560. Available from: https://doi.org/10.3390/ma15134425.

[17] PRÁŠIL, T., SOCHA, I., GRYC, K., SVIŽELOVÁ, J., SATERNUS, M., MERDER, T., PIEPRZYCA, J., GRÁF, M. Impact of Rotor Design on Its Wear and Work Efficiency of the Aluminum Refining Process. *Metals*. 2022, vol. 12, iss. 11, pp. 556-560. Available from: https://doi.org/10.3390/met12111803.