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M. SATERNUS*, J. BOTOR*

REFINING PROCESS OF ALUMINIUM CONDUCTED IN CONTINUOUS REACTOR – PHYSICAL MODEL

RAFINACJA ALUMINIUM W REAKTORZE CIĄGŁYM – MODEL FIZYCZNY

Primary and secondary aluminium after receiving process contains many impurities. The most effective way to remove them, especially hydrogen, is the barbotage process. It can be carried out in the bath and continuous reactors. Such reactors become more and more popular. Phenomenon taking place during the barbotage process are very complex, however they should be familiar if the best results of refining process are to be obtained. Physical modelling is an appropriate method to learn something about barbotage process. If the kinetic, dynamic, heat and geometrical similarities of the model and real object are kept, physical modelling gives opportunity to observe what happens during the process.

For the purpose of the research the test stand for physical modelling of aluminium refining process in URC-7000 continuous reactor was built. The examination of oxygen removal from modelling agent was carried out as an analogy of hydrogen desorption from liquid aluminium. Water was used as a modelling agent. The flow rate of water was steady whereas the flow rate of refining gas was changing from 2 to 30 dm^3/min. The obtained results (pictures taken by the digital camera) were juxtaposed in the tables. Four different patterns of gas dispersion in the liquid aluimnium (minimum, intimate, uniform and overdispersion) are known. The obtained results were divided into the adequate dispersion type according to their characteristics and as a consequence, the range of the flow rate of refining gas was selected to this dispersion type.

Carried out research allowed to choose the optimal parameters of the aluminium refining process by means of URC-7000 reactor. This choice let to control this process in the most effective way.

Keywords: aluminium, refining process, continuous reactor, physical model

Zarówno aluminium pierwotne, jak i wtórne zawiera po procesie otrzymywania wiele zanieczyszczeń takich jak wodór, tlenki, węgliki, sód, wapń itd. Proces barbotażu jest w chwili obecnej jedną z najlepszych metod usuwania tych zanieczyszczeń, zwłaszcza wodoru. Proces ten można prowadzić w reaktorach cyklicznych, bądź ciągłych, przy czym te ostatnie stają się coraz bardziej popularne.

W trakcie procesu barbotażu zachodzi szereg skomplikowanych zjawisk. Wiedza o tych zjawiskach pozwala osiągać dobre wyniki odgazowania ciekłego aluminium i jego stopów. Jedną z powszechnie stosowanych metod do poznania zjawisk zachodzących w ciekłym metalu w trakcie przedmuchiwania pęcherzykami gazowymi jest metoda modelowania fizycznego. Aby rezultaty uzyskiwane z tego typu badań były reprezentatywne i mogły zostać przeniesione na warunki rzeczywiste, modele fizyczne budowane są według ściśle określonych zasad wynikających z teorii podobieństwa (zachowanie kryteriów podobieństwa zarówno geometrycznego, jak i dynamicznego dla czynnika modelującego).

Badania modelowe zostały przeprowadzone w laboratorium Katedry Metalurgii Politechniki Śląskiej. Zbudowane urządzenie do badań modelowych pozwala na symulowanie warunków panujących w ciekłym metalu podczas rafinacji metodą barbotażu w reaktorze URC-7000. Jako czynnik modelujący stosowano wodę. W urządzeniu usuwano tlen rozpuszczony w wodzie jako analogię procesu desorpcji wodoru z aluminium. Badania modelowe wykonano zmieniając natężenie przepływu gazu rafinującego w zakresie od 2 dm^3/min do 30 dm^3/min. Prędkość przepływu wody w reaktorze była ustalona i wynosiła 11 dm^3/min. Wyniki prób (rejestrowane fotograficznym aparatem cyfrowym) zestawiono w odpowiednich tabelach. Znane są cztery schematy przepływu gazu w ciekłym metalu i ich stopień dyspersji w przypadku reaktorów, w których gaz jest wprowadzany do metalu poprzez kształtkę gazoprzepuszczalną (dyspersja minimalna, dokładna, równomierna i nadmierna). Otrzymane wyniki przypisano do odpowiedniego rodzaju dyspersji i dobrano zakres natężenia przepływu gazu rafinującego.

Przeprowadzone badania pozwoliły na dobór optymalnych parametrów procesu rafinacji aluminium i jego stopów przy pomocy reaktora URC-7000, umożliwiając w ten sposób sterowanie tym procesem.

* SILESIAN UNIVERSITY OF TECHNOLOGY, 40-019 KATOWICE, 8 KRASIŃSKIEGO STR., POLAND

1. Introduction

Both, primary and secondary, aluminium contain impurities such as: hydrogen, oxides, nitrides, carbonates, sodium and calcium [1,2]. The hydrogen level in aluminium and its alloys ranges from 0.10 to 0.60 cm^3/100g Al [3,4]. The low level of hydrogen prevents from creating bubbles in alloys, which undergo heat treatment. Generally in the production process of aluminium goods, there is a need to have a stable hydrogen concentration below 0.10 cm^3/100g Al. Such level can be obtained when the optimal refining parameters are applied. This optimization is desirable even if the requirements concerning the metal quality are low. This is why the cost and time of the process can be saved.

The essential aim of the aluminium industry nowadays is to improve the quality of liquid metal. In industrial conditions it is impossible to obtain the liquid metal and casts without any inclusions. However, the choice of appropriate refining methods can decide upon the number of inclusions. So the refining process by means of barbotage is the one of the most effective methods in removing hydrogen and other metallic inclusions from aluminium.

2. The refining process by means of barbotage method

The refining process using barbotage methods is based on introducing to the metal many tiny gas bubbles of the refining gas (there can be no hydrogen in this gas), which absorb hydrogen from liquid metal and remove it. These tiny gas bubbles also cause the flotation process, and this is why the nonmetallic inclusions such as oxides or carbonates can be removed from the metal [5,6].

During the last years the refining process has been modified. Many batch reactors have been replaced by the continuous ones. As a refining gas argon or argon with small amount of chlorine is used – chlorine alone is rarely used due to its harmfulness. There are also changes in the way of introducing gas to the metal. In the batch reactors the lances were replaced by the rotary impellers which can cause the uniform gas dispersion in the whole liquid metal. In the continuous reactors on the other hand there are fixed ceramic porous plugs in such way that the best mixing of the refining gas bubbles with the liquid metal can be obtained. Currently applied reactors can also combine the refining process with filtration process - in such reactors there are different kinds of filters or two chambers are used: one for refining, second for filtration.

Typical examples of continuous reactors are [7]: MINT® Consolidated Aluminium, DMC Degassing Multicast™, DUFI Alusuisse, AFD Alcan Filter Degasser, GIFS Gas Injection Fluxing System Noranda Technology Centre, IMN reactor for continuous refining, Jetcleaner Pechiney Aluminium Engineering, Alcoa 622, URC-7000. Table 1 presents the basic processing parameters (the flow rate of refining gas and metal) of these reactors. The effectiveness of these reactors - the level of hydrogen and nonmetallic inclusions removal from liquid metal are also shown.

TABLE 1

Processing parameters and the effectiveness of continuous reactors used for refining process of aluminium and its alloys [7-13]

Process	Flow rate of gas, dm^3/min	Flow rate of metal, kg/h	Hydrogen removal, cm^3/100g Al	Nonmetallic inclusions removal
MINT	300	5000-15000	0.25-0.05	+
DMC	60-100	5000	0.11-0.06	+
DUFI	75-100	2500-20000	0.19-0.08	> 80 %
Alcoa 622	93-140	43200	0.22-0.15	+
AFD	66	19800	0.14-0.10	90 %
IMN	10-23	5000	0.25-0.09	70 %
URC – 7000	30-50	5000	to 0.10	+

In Poland URC-7000 reactor is used among other places in Metallurgical Plants in Skawina and in Nicromet in Oświęcim. This reactor was designed by the Nonferrous Metals Institute – Light Metal Division in Skawina in 2003. The reactor (see Fig. 1a) consists of two chambers: refining one (see Fig. 1b,c) and filtrating one (see Fig. 1d). The refining chamber is assembled with the steel shell which is isolated by the fire-resistant materials. The concrete furnace lining with fixed ceramic porous plugs is placed in this steel shell. In the refining chamber the hydrogen and also the non-wettable nonmetallic particles are removed from the liquid metal. This is why many tiny refining gas bubbles are introduced to the chamber. In the filtrating chamber the filter (see Fig. 1d) is installed. Above the filter in the upper part of the cover there is also a gas burner which is used for warming up the filter and chambers. The processing parameters and the effectiveness of the URC-7000 reactor are shown in Table 1.

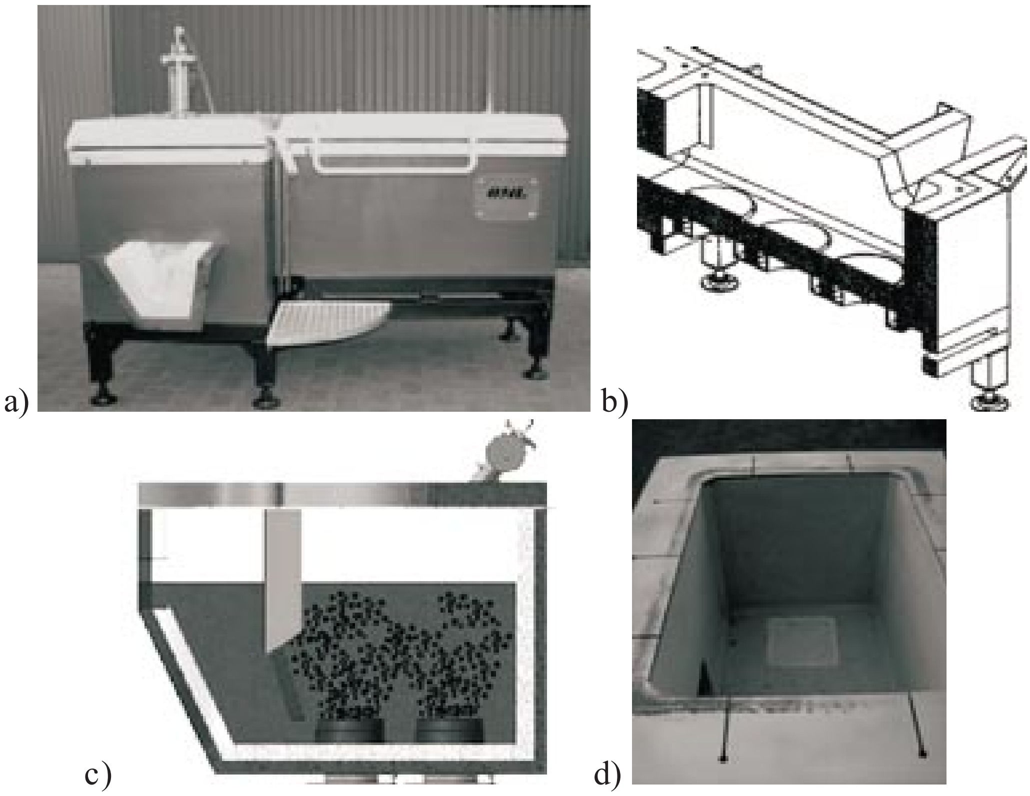


Fig. 1. URC-7000 reactor: a) real view, b) section through the refining chamber with the ceramic porous plugs, c) simulation of gas dispersion in the chamber, d) filter and the filtration chamber [14,15]

3. Physical modelling

Methods of physical modelling are usually applied in modelling process of aluminium barbotage [16-19]. This method allows to obtain information concerning the phenomenon that take place in the liquid metal during the blowing process of the refining gas. Water is used as a modelling agent because of its availability, low costs, but mainly the fact that some physical features of water (e.g. dynamic viscosity) are similar to the physical features of aluminium (see Table 2). The physical model allows to choose the optimal processing parameters such as a flow rate of the refining gas or the rotary impeller speed. Physical models are built according to the precisely defined rules resulting from the theory of similarity [20,21]. Therefore the results obtained from physical modelling can be representative and can be transferred to industrial conditions. This similarity concerns the characteristic features of the real object because of their important influence on the phenomenon occurring in the studied process. The similarity of physical models for reactors used in aluminium refining requires keeping the criteria of geometrical and dynamic similarity for the modelling agent. In such models it is achieved by means of the suitable criterial number. These numbers should have the same value in the model as well as in the real object. Industrial experience is the final verification of results obtained during the physical modelling research.

TABLE 2
Comparison of the basic features of aluminium and water

Liquid	Water	Aluminium
Temperature T, K	293	973
Dynamic viscosity η, Ns/m^2	0.00101	0.00100
Surface tension σ, N/m	0.072	0.680
Density ρ_c, kg/m^3	1000	2400

The effect of modelling research concerning aluminium refining is the identification of the phenomenon occurring when blowing the refining gas through the liquid metal and stirring gas with metal. Therefore, for the purpose of this research it is absolutely essential to fulfill the rules of hydraulic similarity [22,23], that is:

– geometrical similarity of the model and the object,
– hydrodynamic similarity for the liquid flow in the model and in the object such as:
▷ kinetic similarity,
▷ dynamic similarity,
▷ heat similarity.

Table 3 presents characteristics of these similarities. If the mentioned rules of similarity are to be kept, it is sufficient to fulfill the equality rule of adequate criterial number for the model and the studied object. As a consequence, the obtained results from the modelling research can be transferred to the industrial conditions.

When choosing the criteria of similarity, particularly useful are the methods of dimensional analysis [21]. This is a field of applied mathematics and its role is to determine the form of physical formulas, so that their dimensions are correct. In the modelling research this analysis is commonly used for defining:
– conditions of the similarity of the model with the real object,
– scales of particular physical quantities important for conducted research.

One of the main theorem applied in the dimensional analysis is the Buckingham theorem [21,22]: every physical regularity can be presented as a relationship between the dimensional characteristic numbers.

TABLE 3

Characteristics of mentioned similarities [20-23]

Similarity	Characteristics	Scheme	Formula
geometrical	size similarity of the model and real object i.e. ratio of the adequate linear quantities is constant; when the dimensional scale S_L is 1 it is the most favorable, there can be two more cases: scaled-up: $S_L > 1$ and scaled-down: $S_L < 1$	Fig. 2a	$S_L = \frac{L'}{L} = const$ $S_L = \frac{a'}{a} = \frac{b'}{b}$
kinetic	there is the constant ratio of the agent velocity (acceleration) in geometrically similar points of model and the real object	Fig. 2b	$S_v = \frac{v_1'}{v_1} = \frac{v_2'}{v_2} = \frac{v_3'}{v_3}$
dynamic	concerning the forces that influence the system, for physical modelling research these forces influence the dynamics of flow and are closely related	Fig. 2c	$S_F = \frac{F_1'}{F_1} = \frac{F_2'}{F_2} = \frac{F_3'}{F_3}$
heat	the ratio of heat parameters occurring in a model to heat phenomenon occurring in a real object; it is important in modelling processes with no isothermal course	Fig. 2d	$S_T = \frac{T_1'}{T_1} = \frac{T_2'}{T_2} = \frac{T_3'}{T_3}$

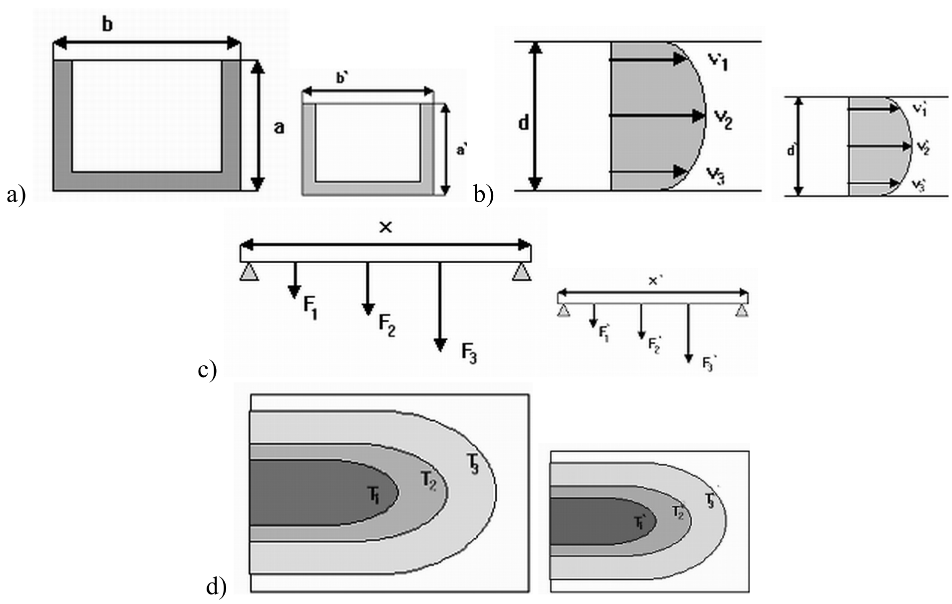


Fig. 2. The example of similarities: a) geometrical, b) kinetic, c) dynamic, d) heat one [22,23]

Dimensionless characteristic numbers are mainly the quotient from the physical quantities (important for a given problem) with the equal dimensions, e.g. forces. These forces can be graphically presented as points which are connected with suitable segments. Quotient of two forces connected in such a way always gives dimensionless characteristic number called criterial number or similarity number. Fig. 3 shows the distribution of forces which are very important in the modelling process of aluminium barbotage. From relations that can be observed in Fig. 3 the following dimensionless criterial numbers result:

$$\text{Euler's number}: \frac{K_p}{K_\rho} = \frac{\Delta p}{\rho \cdot u^2} = \text{Eu} \tag{1}$$

$$\text{Reynolds's number}: \frac{K_\rho}{K_\eta} = \frac{\rho \cdot u \cdot L}{\eta} = \text{Re} \tag{2}$$

$$\text{Froud's number}: \frac{K_\rho}{K_g} = \frac{U^2}{g \cdot L} = \text{Fr} \tag{3}$$

$$\text{Weber's number}: \frac{K_\rho}{K_\sigma} = \frac{\rho \cdot u^2 \cdot L}{\sigma} = \text{We} \tag{4}$$

where: g – acceleration of gravity, m/s^2; L – characteristic dimension, m; p – pressure, Pa; u – velocity of flow, m/s; η – dynamic viscosity coefficient, Pa·s; σ – surface tension, kg/s^2; ρ – density; kg/m^3.

Euler‘s number is a ratio of pressure difference in defined two points of model to the dynamic pressure. Generally the value of Euler‘s number is searched for, so it is considered as a dependent variable and shown as a relationship of other criterial numbers [21], for example:

$$Eu = F(\text{Re},\ Fr) \tag{5}$$

Euler‘s criterion has to be taken into consideration when there is a case of flow under pressure, for the case of flow in the open channels or reactors this influence can be neglected.

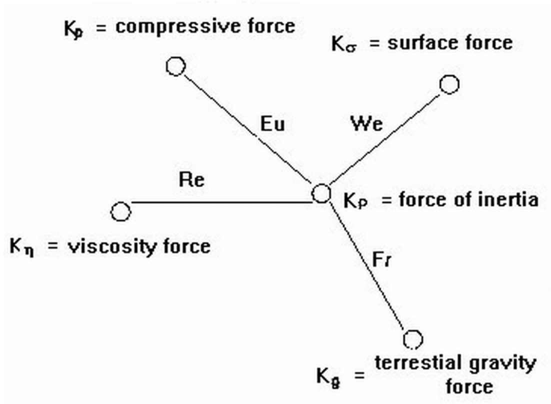


Fig. 3. The graphical presentation of forces creating dimensionless criterial numbers [22]

Reynold‘s number is interpreted as a ratio of the dynamic forces to the friction force which are present during the liquid flow. When the values of Reynold‘s number are small the laminar flow is observed, when these values are big the turbulent flow is quoted. Very often transfer from the laminar flow to the turbulent one is rather violent and then the limiting value of Reynold‘s number is defined as a critical value of Re. In this range of flows the value of Reynold‘s number changes slightly (if the character of the flow is not changing). This range is known as a selfmodelling region that means region in which the studied phenomenon is practically independent of the similarity numbers, so in that case there is no necessity to obtain the equality of criterial numbers.

Froud‘s number is a ratio of the dynamic forces to the terrestrial gravity forces. Froud‘s number has to be taken into consideration when the modelling process takes place in the reactor in which the gravitational forces are important. Usually the same acceleration of gravity acts on the model and on the studied object. Then Froud‘s similarity can be written in the following form:

$$Fr = \frac{u^2}{L} = \frac{u'^2}{L'} = Fr' \tag{6}$$

which means that in the scaled-down model suitably smaller velocity of liquid flow should be applied and scales are fulfilled according the proportion:

$$S_u = S_L^{0.5} \tag{7}$$

It means that for the scaled-down model (S_L=1:4) it should be remembered that the flow rate has to be decreased 5 times.

Weber‘s number is a ratio of the force of inertia to the force of surface tension. Table 4 presents values of Reynold‘s, Weber‘s and Froud‘s numbers for water and aluminium

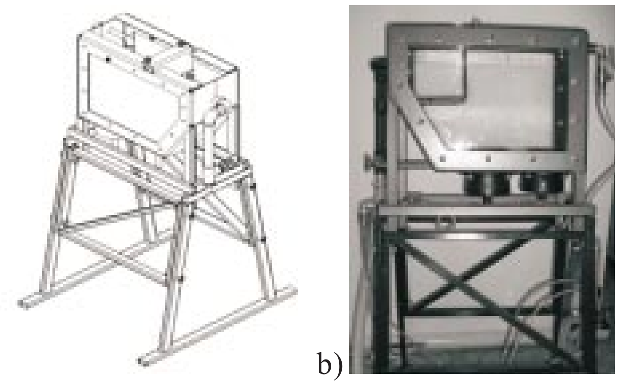
TABLE 4
Comparison of criterial numbers for water and aluminium

Criterial number	Water T = 293 K	Aluminium T = 973 K
Reynolds's number, Re	1905.9	4620.0
Weber's number, We	0.467	0.118
Froud's number, Fr	$2.8\cdot10^{-4}$	$2.8\cdot10^{-4}$
u – velocity of outflow = 0,0175 m/s		
L – diameter of nozzle = 0,11 m		

4. Measuring apparatus

Apparatus for modelling research was built in the scale of 1:4 by the IMN-OML in Skawina. It is possible to simulate conditions that can be met in liquid metal during the aluminium refining process by means of barbotage (removal process of oxygen soluble in water and this is an analogy to the hydrogen desorption process from aluminium). Fig. 4 presents the scheme and actual view of this test stand.

Table 5 presents setting-up of the equipment used for building the test stand (rotameters, ceramic porous plugs, filter, tank, compressor, filler and outflow of liquid) and their parameters and short characteristics. System of introducing the refining gas to the plugs was provided with the ball valve which allows independent control of gas flow rate to every plug.



a) b)

Fig. 4. Scheme a) and real view b) of the test stand [24]

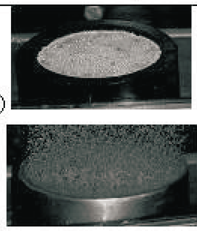
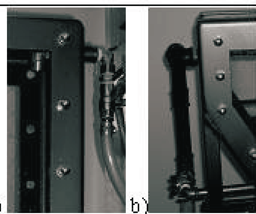
5. Experimental procedure

Modelling research was carried out at the laboratory of Metallurgy Department, Silesian University of Technology in Katowice. The influence of refining gas flow rate on the level of gas dispersion in the liquid was examined. The flow rate of refining gas was changing from 2 to 30 dm^3/min. The flow rate of water was steady and equaled 11 dm^3/min. Results of test were registered by the digital camera. Experimental procedure was the following:

- ▷ preparing of test stand (filling the tank with water, setting the steady flow rate of water, putting the compressor in motion),
- ▷ carrying out the preliminary test (checking if everything is working well),
- ▷ taking the photographs of the dispersion of refining gas in water at the flow rate of the refining gas equal 2 dm^3/min,
- ▷ registering every tests several times,
- ▷ taking the photographs of the dispersion for the flow rate of refining gas ranging from 2 to 30 dm^3/min, there were two rotameters: one which range was 2-15 dm^3/min and the second which range was 15-30 dm^3/min, if the first one was installed the photographs were taken every 1 dm^3/min and when the second one was installed the photographs were taken every 5 dm^3/min,
- ▷ photographs of dispersion were taken for the whole reactor working with two plugs and also when only one plug was working – it was possible to obtain better zoom.

TABLE 5

Equipments used for building the test stand for physical modelling process of aluminium barbotage in URC-7000 reactor

Equipment	Characteristics	Picture
Rotameters and water flowmeter	Description: two rotameters (a) RIn-06 from the ZACH „Metalchem" with the range 0-15 and 0-30 dm^3/min, one water flowmeter (b) from ZMP Ormontowice with the range 0-40 dm^3/min Fixing point: plate installed on the metal construction holding up the tank Aim: for measuring the flow rate of refining gas and the modelling agent	a) b) 
Plugs	Description: two ceramic porous plugs made of the Polish (a) and English (b) material, the same material was used in industry, dimension was suitably chosen for the model scale Fixing point: the bottom of the refining reactor Aim: for generating the small tiny gas bubbles of refining gas	a) b) 
Compressor	Description : air compressor from Genius Fini Oilless Compressors Aim: for blowing the refining gas (here air) to the modelling agent through the plugs	
Filler and outflow of liquid	Description: reactor is provided with the water system which supplies (a) water to the tank and then carries this water from it, flow rate of water can be regulated by the ball valve, after ending the test it is possible to empty the tank completely	a) b) 
Filter	Description: ceramic foam filter Aim: fixed inside the chamber for the whole simulation of industrial conditions	
Tank and the framework	Description: reactor was designed as a steel frame construction, walls were made from the plexiglass Aim: for giving possibility to observe the refining gas dispersion in the whole volume of liquid	

6. Results of research

Table 6 presents the results of refining gas dispersion in water. Column 1 shows the value of refining gas flow rate. Column 2 shows the photographs of the dispersion when only one plug was working. Column 3 presents the influence of the flow rate of the refining gas on the liquid surface. Column 4 illustrates the dispersion of refining gas in the whole reactor for two working porous plugs.

TABLE 6

Results of research presenting the level of refining gas dispersion in modelling agent

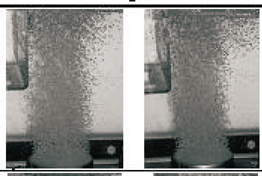
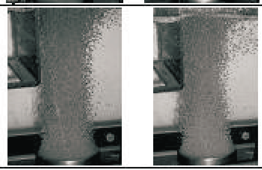
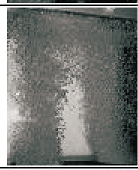
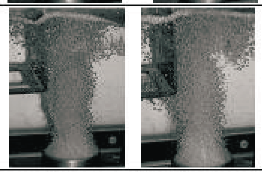
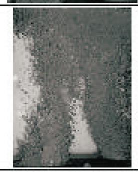
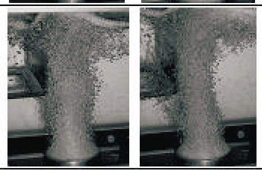
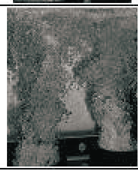
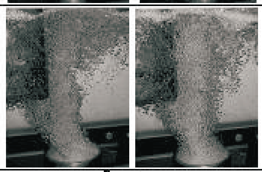
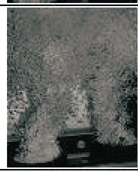
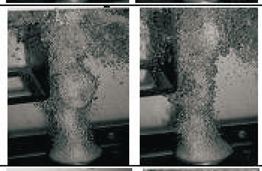
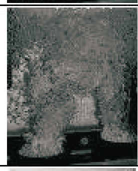
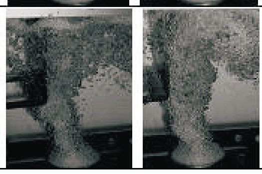
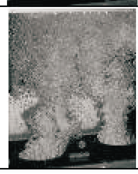
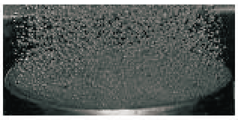
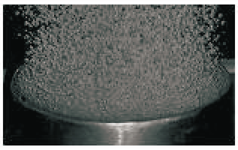
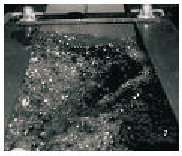
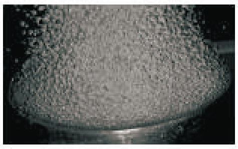
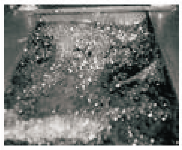
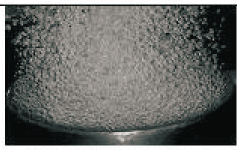
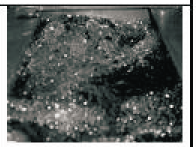
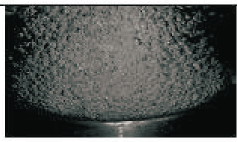
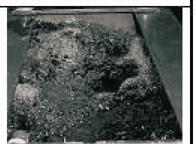
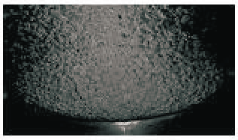
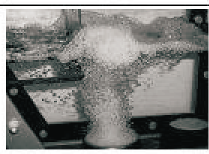
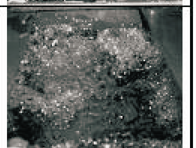
Gas flow rate	One plug	Surface	Two plugs
1	2	3	4
2 dm^3/min			
5 dm^3/min			
10 dm^3/min			
15 dm^3/min			
20 dm^3/min			
25 dm^3/min			
30 dm^3/min			

Table 7 shows the influence of flow rate of the refining gas on the generation of gas bubbles and on the liquid surface. Column 1 illustrates plugs generating gas bubbles and behavior of these bubbles. Column 2 presents the surface of the modelling agent and its change with the flow rate of refining gas, whereas in column 3 there are the views of modelling agent surface seen from the top of the reactor.

TABLE 7
The influence of refining gas flow rate on generation of gas bubbles and on the surface of the modelling agent

Gas flow rate	Zooming of plugs	Surface of modelling agent	View of the reactor from the top
1	2	3	4
2 dm^3/min			
5 dm^3/min			
10 dm^3/min			
15 dm^3/min			
20 dm^3/min			
25 dm^3/min			
30 dm^3/min			

7. Discussion of results and conclusions

The built test stand for modelling research (Fig. 4, Table 5) allowed to simulate the conditions which take place in liquid metal during the industrial barbotage process of aluminium. The dispersion level of refining gas in the modelling agent was observed and registered by the digital camera especially taking into account its changes with the flow rate of refining gas. Results of carried out research were presented in Tables 6 and 7. It is known that the flow rate of refining gas has a great impact on the shape of created gas bubbles. The following shapes can be found taking into consideration the gas bubbles diameter [6,25]:

a) d = 0.5 – 0.7 cm → spherical,

b) d = 0.8 – 1.0 cm → ellipsoidal,

c) d > 1 cm → spherical cap,

d) if bubbles diameter is still increasing → wobbling.

Analysis of the presented bubble shapes allows to state that it is necessary to introduce the equivalent diameter d_e, that means it is diameter which the bubble would have if it was a spherical one [6]. For the moderate flow rate of refining gas and for the gas bubbles with diameter range between 0.3 to 1.5 cm the equivalent gas bubble diameter dependents only on the flow rate of the refining gas. The mathematical model describing aluminium refining process in the continuous reactor was presented in the earlier works [7,26]. If we use this model and the relationship for calculating the kinetic and thermodynamic parameters occurring in the model, it is possible to calculate the equivalent bubble diameter for the industrial refining process of alloys: AlSi9 and AlSi9Cu3(Fe). Such calculations were done and the equivalent gas bubble diameter was the following for the alloy:

- ▷ AlSi9 – 0.0038 m (flow rate of refining gas = 40 dm^3/min, temperature = 998 K),
- ▷ AlSi9Cu3(Fe) – 0.0061 m (flow rate of refining gas = 60 dm^3/min, temperature = 1009 K).

The obtained results confirmed the earlier assumptions. Fig. 5 presents the influence of the gas flow rate on the shape of gas bubbles. Three basic ranges can be mentioned:

- ▷ range I – bubbles moved freely, they have a spherical or ellipsoidal shape,
- ▷ range II – spaces between gas bubbles begin to disappear, films between bubbles are broken, in consequence their deformation is observed, the chain flow of gas bubble is also seen,
- ▷ range III – gas bubbles hit each other (see Fig. 5 – bubble 2 hit bubble 1), as a result their disintegration takes place and the cloud of gas bubbles with different diameters can be observed.

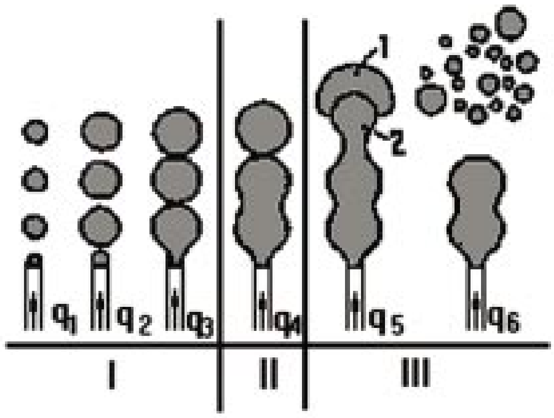


Fig. 5. The influence of the gas flow rate on the shape of gas bubbles [27]

The flow rate of refining gas does not only influence the shape of gas bubbles, but also the way of their dispersion in the liquid metal. Works [6] and [28] presented the five patterns of gas flow in the liquid metal and their level of dispersion in reactors with rotary impellers. There are the following dispersions: no dispersion, minimum, intimate, uniform and overdispersion. These patterns are adapted to the rectors with ceramic porous plugs – all apart from the first one, because if there is more than one plug, the minimum dispersion is observed, even if the flow rate of the refining gas is very small. Table 8 presents the characteristics of the mentioned types of dispersion and their patterns in the reactor with the ceramic porous plugs. Apart from patterns there are also shown photographs taken during the modelling research and presenting the determined types of dispersion. The behavior of gas bubbles and the kind of flow are also presented. For example, when there is overdispersion the bubbles join in groups and as a consequence the chain flow of gas bubbles can be observed. Basing on the carried out modelling test every type of dispersion is assigned to the adequate range of the flow rate of refining gas – Table 9 presents results of this operation.

TABLE 8

Types of dispersion of gas bubbles in liquid metal in the reactor with ceramic porous plugs

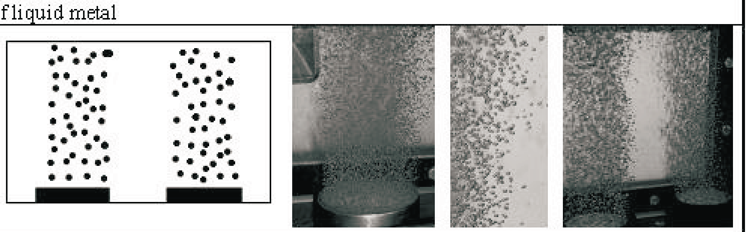
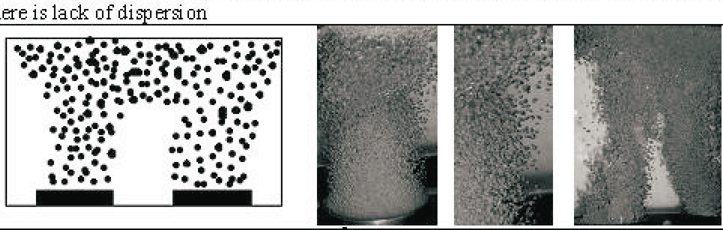
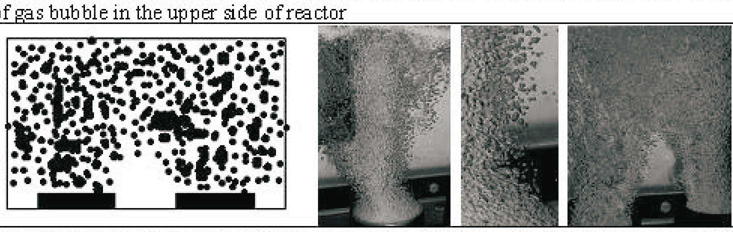
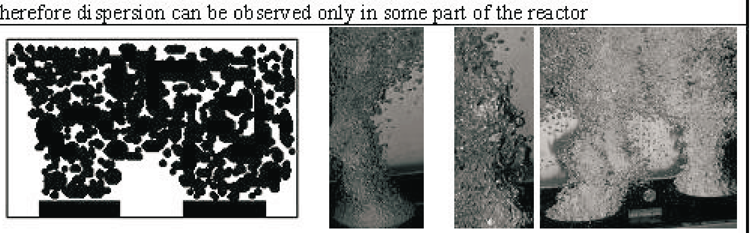
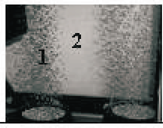
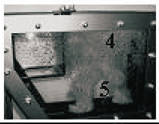
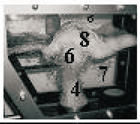
	Types of dispersion, examples and characteristics
MINIMUM	single gas bubble rise up to the top of the reactor, dispersion is observed only in the region of gas bubble creation – there is no mixing of gas bubble in the whole volume of liquid metal 
INTIMATE	single gas bubbles rise up to the top of reactor, there is good mixing of the gas bubble with the liquid metal, however near the side walls and in the bottom of the reactor there is lack of dispersion 
UNIFORM	single gas bubbles rise up to the top of reactor, the chain of gas bubbles starts to create, the gas bubbles are very well mixed with the liquid metal, lack of dispersion can be observed only in the bottom of the reactor, swirls at the surface cause mixing of gas bubble in the upper side of reactor 
OVERDISPERSION	mixing of gas bubbles with the liquid metal is very good, probability of creating the chain of gas bubbles is very high, the chain flow causes the appearance of swirls, and therefore dispersion can be observed only in some part of the reactor 

TABLE 9

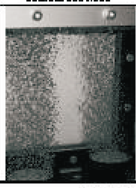
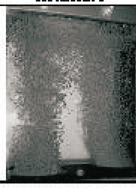
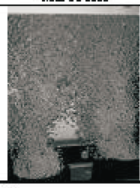
Description of dispersion types and the range selection of the flow rate of refining gas

Dispersion	minimum	intimate	uniform	overdispersion
Flow rate of refining gas	2-6 dm^3/min	7 – 10 dm^3/min	11 – 25 dm^3/min	> 25 dm^3/min
Scheme				
Description	1 – single gas bubbles rising up to the top of reactor 2 – dispersion occurs only in the area of bubbles introduction to the metal – there is no mixing in the whole volume of liquid 3 – good level of mixing gas bubble with liquid, the lack of dispersion is observed only by the side walls and in the bottom of the reactor 4 – gas bubbles are very well mixed with the liquid 5 – the lack of dispersion is observed only in the bottom part of reactor (near the plugs) 6 – bubbles create chains and the existence of chain flow of refining gas is seen, which causes creation of swirls 7 – swirls are created and therefore dispersion is observed only in some parts of reactors 8 – swirls existing near the surface cause that the impurities removed from metal to surface comes back inside the metal			

Carried out research and calculations allow to choose the optimal parameters of the aluminium refining process by means of URC-7000 reactor. This choice allows to control this process in most effective way. Table 10 presents these optimal technical (capacity, time of process, way of gas introduction) and processing parameters (temperature of process, type of refining gas, the range of flow rate of refining gas and the optimal values of this flow). Table 10 also presents mathematical equation which let to control the aluminium refining process in the URC-7000 reactor.

TABLE 10

Optimal technical and processing parameters for aluminium refining process in the URC-7000 reactor

Technical parameters				
Gas introduction	2 ceramic porous plugs in the bottom of reactor			
Filtration	ceramic foam filter, dimensions: 200x200x40 mm			
Capacity	to 5 Mg/h			
Refining time	Dependable on the emptying of furnace			
Processing parameters				
Process temperature	690 – 730 °C			
Refining gas	argon			
Flow rate of refining gas	Range: 10-60 dm^3/min, Optimal: 15-25 dm^3/min			
	2-6 dm^3/min	7 – 10 dm^3/min	11–25 dm^3/min	> 25 dm^3/min
Dispersion type	minimum	intimate	uniform	overdispersion
Scheme				
Equation for process control				
Equation	$\left(\frac{c_i}{c_t}-1\right)=\frac{k\cdot\rho\cdot A}{Q_m}$			
List of symbols	A – area of mass exchange surface, c_i/c_t – initial/final hydrogen concentration, k – mass transfer coefficient, Q_m – flow rate of metal, ρ – density of liquid aluminium			

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