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PHYSICAL MODELLING OF THE STEEL FLOW IN RH APPARATUS

MODELOWANIE FIZYCZNE PRZEPŁYWU STALI W URZĄDZENIU RH

The efficiency of vacuum steel degassing using RH methods depends on many factors. One of the most important are hydrodynamic processes occurring in the ladle and vacuum chamber. It is always hard and expensive to determine the flow character and the way of steel mixing in industrial unit; thus in this case, methods of physical modelling are applied. The article presents the results of research carried out on the water physical model of RH apparatus concerning the influence of the flux value of inert gas introduced through the suck legs on hydrodynamic conditions of the process. Results of the research have visualization character and are presented graphically as a RTD curves. The main aim of such research is to optimize the industrial vacuum steel degassing process by means of RH method.

Keywords: steel, vacuum degassing, RH apparatus, physical modelling.

Skuteczność procesu próżniowego odgazowania stali metodą RH zależy od wielu czynników. Jednym z ważniejszych są procesy hydrodynamiczne zachodzące w kadzi stalowniczej i komorze próżniowej. Określenie sposobu przepływu i mieszania się stali w urządzeniu przemysłowym jest bardzo trudne i kosztowne. W związku z tym do tego celu wykorzystuje się m. in. metody modelowania fizycznego. W artykule przedstawiono rezultaty badań przeprowadzonych na wodnym modelu fizycznym urządzenia RH, dotyczące wpływu wartości strumienia gazu obojętnego wprowadzanego przez dysze króćca ssącego na warunki hydrodynamiczne procesu. Wyniki badań mają charakter wizualizacji oraz przedstawione zostały w postaci krzywych retencji RTD. Cel tego typu badań związany jest z optymalizacją przemysłowego procesu próżniowego odgazowania stali metodą RH.

1. Introduction

Secondary metallurgy is a part and parcel of steel production. The efficiency of processes occurring during secondary metallurgy influences the quality of obtained product – to achieve that aim many different techniques and technologies are applied depending on the specificity of the particular steel plant production. Vacuum steel degassing process is one of such methods and depends on sucking the liquid steel from the ladle to the vacuum chamber equipped with two legs (suck leg and outlet leg). When the inert gas is blown to the liquid steel, then the circulation movement of steel between vacuum chamber and ladle is forced. The efficiency and duration time of the process depends on the value of the flow rate of inert gas (see Fig. 1), which determines the circulation speed – see equation (1) and Fig. 2 – and the value of subatmospheric pressure created in the vacuum chamber. Such values are the main parameters of the process, and their optimal choice depends on the chemical composition of the out-gassed steel [1-3].

$$R = 3.8 \cdot 10^{-3} \cdot d_s^{0.3} \cdot d_w^{1.1} \cdot G_n^{0.31} \cdot h_g^{0.5}, \ Mg \cdot min^{-1} \tag{1}$$

where: d_s and d_w – diameter of suck leg and outlet leg, mm; G_n – flow rate of inert gas (argon), $Nm^3 \cdot h^{-1}$; h_g – height of that part of leg, on which the gas is delivered, m.

Determining the optimal parameters of the liquid steel degassing process in RH apparatus in industrial conditions is difficult and expensive [3-5]. Thus, the convenient solution is to carry out research with the use of water models and computational simulation (applied commonly in metallurgy of steel and non-ferrous metals) [6-13].
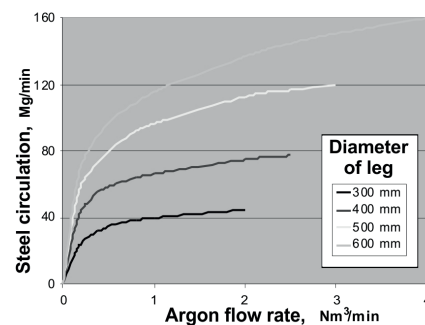

Fig. 1. Steel circulation speed in RH method depending on flow rate of gas [14]

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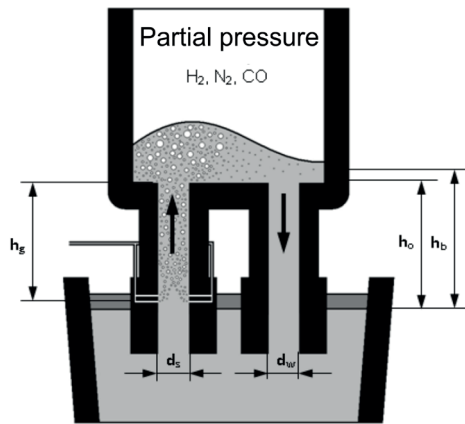
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Fig. 2. Scheme of the reaction area of the process

TABLE 1

Basic geometrical and technological parameters of industrial RH apparatus

Parameter	Value
Nominal capacity of the ladle	320 Mg
Nominal diameter of the vaccum chamber	2080 mm
Nominal diameter of the sucking leg	600 mm
Nominal diameter of the outlet leg	500 mm
The height of the legs	1625 mm
Number of injection nozzles in the sucking leg	12 in two lines
Diameter of pipes introducing the inert gas (Ar)	6 mm
The level of liquid steel in vacuum chamber	about 1000 mm
Duration time of the process	8 – 12 min
Time of liquid steel circulation	6 – 9 s
Flow rate of the inert gas (Ar)	1.2 Nm3·min-1

2. Physical model of RH apparatus

Built physical model of the apparatus for steel vacuum degassing is destined for research of hydrodynamic phenomena occurring during RH process. The main aim of such research is getting to know better mechanisms of liquid steel flow in the apparatus and also the optimization of its working parameters. The model is the pattern on RH apparatus working in one of polish steel plants. Table 1 presents the basic geometrical and technological parameters of the real RH apparatus.

Physical model is made from the transparent materials analyzing visualization of the process. Water is used as a modelling agent. Linear scale of the model is $S_L = 1:10$. Dynamic similarity of the model to the real apparatus was realized basing on the criterial numbers determined by means of dimensional analysis [15]. Fulfilling the conditions for all criterial numbers (Fr, Re, Eu, Sl) [16] in physical model is really difficult, and in some define cases even impossible. Therefore, the dominant criterion is often determined by considering the character of the hydrodynamic phenomenon occurring during the modelling research. Froude`s criterion was determined as a dominant criterion in the carried out case. This criterion, however, concerns one-phase flows. In case of multi-phase flows the properties of particular phases should be considered when similarity criteria are determined. In steel degassing process (by means of RH apparatus) two phases can be

found: liquid and gaseous. Then, the classic Froude`s criterion of similarity need to be modified:

$$Fr_n = \frac{\rho_g \cdot v_T^2}{\rho_l \cdot g \cdot L} = C \cdot \frac{Q^2}{L \cdot d^4} \qquad (2)$$

where:

$$C = 9.159 \cdot 10^{-10} \left(\frac{M^2}{\rho_g \cdot \rho_l} \right) \qquad (3)$$

where: ρ_g – gas density, kg·m^{-3}; ρ_l – liquid density, kg·m^{-3}; g – gravitational acceleration, m·s^{-2}; L – liquid height, m; Q – volumetric flow rate of gas, m^3·s^{-1}; v_T – velocity of gas introduction, m·s^{-1}; M – molar mass of gas, kg·mol^{-1}; d – inert diameter of nozzle, m; C - constant.

Modified Froude`s criterion for the water model has the following form [17,18]:

$$Fr_n' = C' \cdot \frac{Q'^2}{L' \cdot d'^4} \qquad (4)$$

To obtain similarity of the flows in water model to the ones in industrial unit the following equation can be fulfilled:

$$Fr_n' = Fr_n \qquad (5)$$

which, after transformation can be written:

$$Q' = \left(\frac{c'}{c} \right)^{-\frac{1}{2}} \cdot S_L^{\frac{5}{2}} \cdot Q \qquad (6)$$

where: Q' – volumetric flow rate of gas for the water model, m3/s; C' – constant for the water model, SL – linear scale.

Using equation (3) constants C` for water model and C for industrial reactor can be determined. When replacing the obtained results to equation (6) the following relationship is obtained:

$$Q = 0.448 \cdot S_L^{-\frac{5}{2}} \cdot Q' \qquad (7)$$

Such relationship gives the possibility to determine the value of fair flow in water model, however the knowledge about the value of gas flow in industrial reactor is also required.

3. Modelling research

The aim of conducted modelling research was to determine the optimal hydrodynamic conditions of the steel degassing process using RH apparatus, taking into account the flow rate of ascending gas. Additionally, the characteristics of efficiency of steel homogeneity in the tundish after circulation in RH apparatus was assigned in the wide range of flow rate of ascending gas. Such characteristics were determined basing on graphically obtained resident curves (Residence Time Distribution, RTD [19] - they inform about the time which the given volume fraction spent in the reactor and could be obtained experimentally from industry or water models or numerically [20,21]). Therefore, to obtain such characteristics the flow rate of gas was wider than that applied in case of industrial conditions. Fig. 3 presents the scheme and view of the test stand.
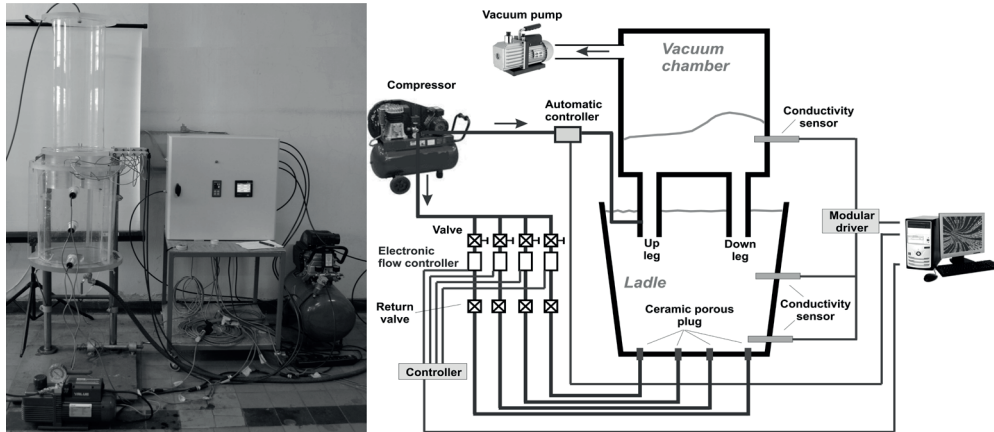
Fig. 3. The view and scheme of test stand

Special control-measuring panel was designed to enable the precise control of the flow rate of liquids and to archive the obtained experimental data. It consists of: microprocessor controller AR642, precise automatic valves, electronic control equipments of particular flow channels and MultiCon CMC-99/141 data recorder.

To determine RTD curves NaCl water solution was used as a tracer. Such solution was introduced injectively by one of the nozzles installed in the sucking leg. Additionally, the water model was equipped with conductometers which measure the changes of modelling liquid conductivity.

In the visualization research KMnO4 water solution was applied as a tracer. It was introduced in the same way as NaCl in the amount of 15 cm³.

To fulfill the rules of dynamic similarity the flow rate of gas in the sucking leg was determined basing on the modified Froude`s number. Consequently, the values of flow rate were calculated basing on the real values applied in industry. They were broaden to obtain wide range of characteristics of the examined phenomenon.

To realize the research the following procedure was used:
- Introducing the modelling liquid (water) to the ladle model.
- Putting the vaccum chamber model down to the ladle model.
- Starting the vaccum pump and obtaining the sucking of modelling liquid to the vacuum chamber model of RH apparatus. The volume of sucking modelling liquid is 10% of the volume of liquid in the ladle model.
- Regulating the value of subatmospheric pressure in the vacuum chamber model by means of precise valve. It allows to fix constant and unchangeable level of modelling liquid surface in the vacuum chamber model.
- Introducing to the sucking leg the flux of air (determined on the basis of dynamic condition of similarity) to force the modelling liquid circulation. Such operation is realized by means of precise setting equipment.
- Regulating the value of subatmospheric pressure in the vacuum chamber model (compensation of incoming air) and fixing the constant and unchangeable level of modelling liquid surface.
- Stabilizing the system.
- Entering the measuring apparatus.

- Introducing the tracer to the sucking leg (tracer in the form of water solution of NaCl for RTD curves and KMnO4 for visualization).
- Registering and archiving the measuring data.
- Finishing the experiment.

Research was conducted for six variants (Table 2) varying in flow rate of gas in the sucking leg of RH apparatus.

TABLE 2

Flow rate of gas in the model and industrial apparatus

Variant	Q [m³·min⁻¹]	Q` [dm³·min⁻¹]
A	2.8	3.80
B	3.0	4.10
C	3.3	4.45
D	3.5	4.80
E	3.8	5.15
F	4.0	5.50

Research concerning determination of RTD curves relies on measuring the changes of modelling fluid conductivity when the tracer was introduced to the model. Fig. 4 presents the exemplary results of such measuring.
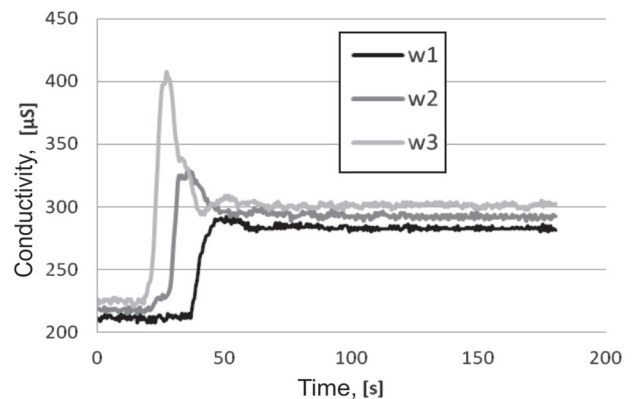

Fig. 4. Curves characterizing the change of conductivity in time

To compare the results of conducted experiment objectively in all variants, the dimensionless concentration of tracer was determined according to the following equations:

$$C = \frac{C_{pom}}{C_{max}} \qquad (8)$$

and

$$C_b = \frac{C - C_0}{C_\infty - C_0} \qquad (9)$$

where: C_{pom} – tracer concentration in time, C_b – dimensionless tracer concentration, C_0 – initial tracer concentration, C_{max} – maximal tracer concentration, C_∞ - final tracer concentration.

Fig. 5 shows the determined resident time curves (RTD) for the exemplary values of flow rate of ascending gas in the sucking leg, which are applied in industry; whereas Fig. 6 presents the time of steel homogenization depending on gas flow rate in the suck leg. Exemplary results of visualization research for F variants are shown in Fig. 7

4. Conclusions

Basing on the conducted modelling research the following conclusions were drawn:

1. the higher flow rate of inert gas in the sucking leg of vacuum chamber, the shorter time of total intermixing,
2. the higher flow rate of inert gas in the sucking leg of vacuum chamber, the higher velocity of modelling fluid circulation in RH apparatus model,
3. the increase of velocity of modelling fluid circulation is not linear, its character is exponential,
4. the increase of circulation is seen only to certain point, then it stops on the constant level (critical point of inert gas flow rate),
5. the mechanism of creating the inert gas bubbles in the sucking leg has the essential influence on the circulation velocity – the smaller gas bubbles, the better circulation,
6. optimal parameters of the conducted process determined on the model correspond to the parameters applied in the industrial conditions.
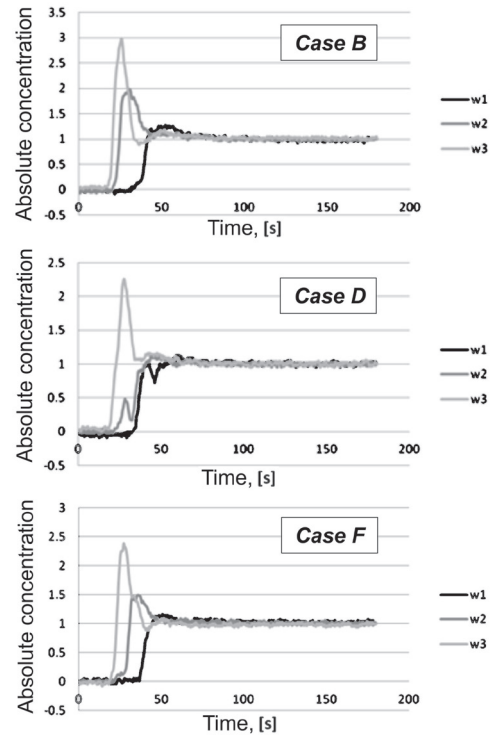

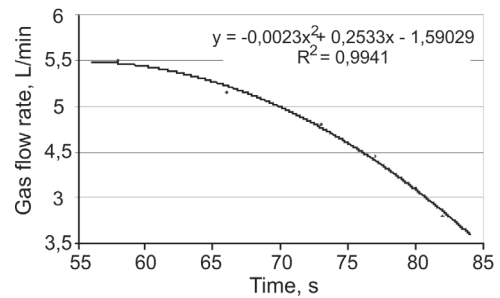Fig. 5. RTD curves for B, D and F variants of conducted research

Fig. 6. Time of steel homogenization depending on gas flow rate in the sucking leg
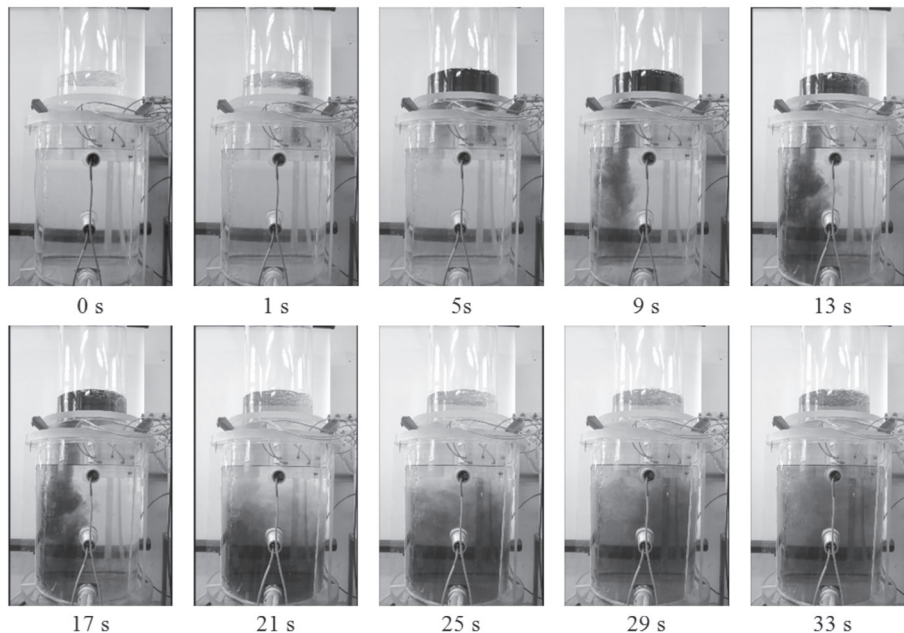

Fig. 7. Examples of visualization results of RH process for F variant

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