J. PIEPRZYCA, T. MERDER

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MODIFIED FROUDE CRITERION IN MODELING TWO-PHASE FLOWS IN A STEEL LADLE

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The dominant dynamic similarity criterion in the modelling of two-phase flows in steel metallurgy is the modified Froude (Fr) criterion. Modifications of this criterion, depending on the purpose of the research, may take various forms. The article presents the results of experiments carried out with the application of the steel ladle water model, with the use of various modifications of Froude criterion. The results obtained allow for the classification of the tested modifications from the perspective of the research objectives.

Key words: steel, steel ladle, two-phase flows, physical modelling, modified Froude criterion

INTRODUCTION

The mechanism of the inert gas flow in liquid steel has been a subject of many studies. For fundamental reasons, they are generally implemented using modelling methods. Water models are often used for this purpose [1-10]. The condition for the effectiveness of this research is the determination of the required conditions for the similarity of the dynamic and kinematic model to the real object. A commonly used criterion for gas flow in liquid steel is the Froude criterion [2, 3, 4, 10]. This criterion is understood as a measure of the ratio of the force of inertia to the force of gravity, and it characterizes the influence of the force of gravity on the phenomena of fluid flow. However, the use of this criterion in two-phase flows in a steel ladle requires some modification. Several solutions have been proposed in recent years; for example, taking into account the difference in the density of the studied phases [5], the buoyancy force [6], or the momentum of the blown gas [7].

The article presents a summary of the experimental results carried out with the application of the steel ladle water model, with the use of various modifications of Froude criterion. The experiments were conducted in two aspects: qualitative and quantitative. The qualitative results refer to the marker flow visualisation results in the ladle workspace, whereas the results of empirical and quantitative research concern the mixing time of the marker in the ladle workspace.

PROBLEM DESCRIPTION

The Navier Stokes equations and the stream continuity equations were used for the dimensional analysis of the flow and steel mixing. Based on these equations as well as by applying the Buckingham's theorem, similarity criteria are determined in the form of criterion numbers. The assumption that the steel flow is isothermal allows for adopting the criterion equation in the form [8]:

$$\varphi\ (Eu; Str; Fr; Re) = 0 \qquad (1)$$

where: Eu – Euler number; Str – Strouhal number; Fe – Froude number; Re – Reynolds number.

The dominant criterion determining the similarity of the model under consideration to the real object is the Froude criterion. Therefore, the equation (1) simplifies and takes the following form:

$$\varphi\ (Fr) = 0 \qquad (2)$$

Based on the Froude criterion, the kinetic similarity of the model to the industrial conditions can be determined. For this purpose, the scale method is used to determine the flow rate scale of the model fluid S_Q in accordance with the equation (3):

$$S_Q = S_V \cdot S_L^2 = S_L^{5/2} \qquad (3)$$

where: S_Q – flow rate scale, S_V – velocity scale, S_L – assumed linear scale.

This approach is appropriate for model studies of single-phase phenomena. In the case of multi-phase flows, the similarity of the properties of individual phases should be taken into account when determining the criteria. Both in the method of blowing steel with inert gases and in the circulating method of vacuum degassing the steel, there occur a liquid phase and a gas phase. In such circumstance the classic Froude similarity criterion requires modification. The method of introducing these modifications depends on the purpose of the research. In the case of research on the process of blowing inert gas into liquid steel through the bottom of a steel ladle, the

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J. Pieprzyca, T. Merder: Silesian University of Technology, Faculty of Material Science, Katowice, Poland, e-mail: jacek.pieprzyca@polsl.pl, tomasz.merder@polsl.pl

modifications may relate to a parameter such as the phase density, which is related to buoyancy forces. The Froude criterion then takes the form [5]:

$$Fr_N = \rho_g \cdot V^2 / \rho_l \cdot g \cdot L = C \cdot Q^2 / L \cdot d^4 \qquad (4)$$

where:

$$C = 9{,}159 \cdot 10^{-10} \, (M^2 / \rho_g \cdot \rho_l) \qquad (5)$$

where: ρ_g – gas density / kg/m^3; ρ_l – liquid density / kg/m^3; g – acceleration due to gravity / m/s^2; L – liquid height in the model / m; Q – volume flow of gas / m^3/s; V – gas injection velocity / m/s; M – molar mass of the gas / kg/mol; d – inside diameter of the nozzle / m; C – constant.

After comparing the modified Froude number for the water model and the real reactor, respectively, and applying equation (3), the following dependence is obtained:

$$Q_m = (C_m / C_p)^{-1/2} \cdot S_L^{5/2} \cdot Q_p \qquad (6)$$

After calculating the constant, the relationship is obtained:

$$Q_p = 0{,}488 \cdot S_L^{5/2} \cdot Q_m \qquad (7)$$

where: Q_m – volumetric gas flow rate for the water model / m^3/s; Q_p – volumetric gas flow rate for an industrial reactor / m^3/s; C_m – constant for the water model, C_p – constant for an industrial reactor.

Similarly, the Froude number is modified due to the difference in gas expansion under the influence of temperature in industrial conditions and in the model. This expansion is described by the expression [6]:

$$Q_g = Q\grave{}_g / (\beta T + 1) \qquad (8)$$

where: Q_g – gas volumetric flow rate at 25 °C, $Q\grave{}_g$ – gas volumetric flow rate at 1 600 / °C, T – temperature / °C; β – constant = 1/273.

Assuming all this into account, the gas flow rate in the physical model can be expressed by the relationship:

$$Q_p = \frac{1}{\beta T + 1} \sqrt{\frac{\rho_{air}\left(\rho_{st} - \rho_{Ar}\right)}{\rho_{Ar}\left(\rho_w - \rho_{air}\right)}} \cdot \left(\frac{1}{S_L}\right)^{\frac{5}{2}} \cdot Q_{air} \qquad (9)$$

where: ρ_{air} – air density / kg/m^3; ρ_{Ar} – argon density / kg/m^3; ρ_{st} – steel density / kg/m^3; ρ_w – water density / kg/m^3; Q_{air} – volume flow of air / m^3/s.

After calculating the constant, the following relationship is obtained:

$$Q_p = 0{,}817 \cdot S_L^{5/2} \cdot Q_m \qquad (10)$$

Another parameter for modifying the Froude criterion may be the properties of the porous material or the diameter of the nozzles through which the inert gas is blown. Then a similar procedure is used as in the case of using the buoyancy force as a criterion. However, the constants C are determined taking into account the radii of capillaries (nozzles) according to the formula [5]:

$$\frac{Q_m^2}{Q_p^2} = \left(\frac{C_p}{C_m}\right)\left(\frac{L_m \cdot d_m^4}{L_p \cdot d_p^4}\right) \qquad (11)$$

After converting to the conditions of the experiment, the following equation is obtained:

$$Q_p = 1{,}295 \cdot S_L^{5/2} \cdot Q_m \qquad (12)$$

The relations presented above enable to determine the value of the air flow in the water model, however the value of the gas flow in the industrial reactor has to be taken into account.

RESEARCH METHODOLOGY

The experiments were carried out with the use of the steel ladle model (S_L= 0,2), representing an industrial ladle with a capacity of 50 Mg of liquid steel. The ladle model is equipped with one porous plug. It is built in accordance with the requirements of the similarity theory described above. The geometry and view of the model are shown in Figure 1, and the dimensions in Table 1.

The modelling research stand is equipped with control and measurement apparatus enabling precise control of the gas flow rate and recording of the obtained results. The course of the experiments is recorded using a video camera. An aqueous solution of $KMnO_4$ and NaCl were used as a tracer in the experiments. This model is described in detail in [9,10].

The aim of the research was to determine the influence of the assumed methods of modifying the Froude number on the obtained results of model tests, and to attempt to classify these methods based on identification of the specific phenomena occurring during the process of inert gas blowing through liquid steel. The evaluation criteria include the experience from work of a real steel ladle in industrial conditions. Therefore, a research program adequate for this purpose was devel-

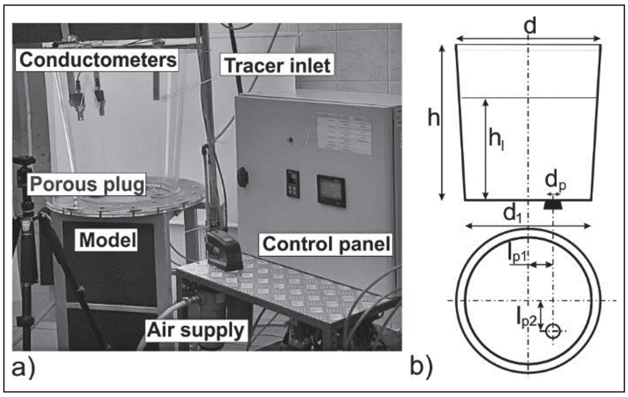

Figure 1 a) Scheme of model, b) view of the test model

Table 1 **Design parameters of the ladle model (scale 1:5)**

Parameter / Unit	Symbol	Value
Volume / m^3	V	0,057
Diameter / m	d	0,511
	d_1	0,386
Height / m	h	0,648
Height (liquid steel level) / m	h_l	~0,44
Diameter – porous plug / m	d_p	0,023
Position – porous plug / m	l_{p1}	0,094

Table 2 **Assumed parameters of the bath blowing process in industrial conditions and their values calculated for the conditions of model tests**

Experiment variant	Scale 1:1	Scale 1:5	
	The intensity of gas		
	/ m^3/h	/ m^3/h	/ l/min
A	10,8	0,19	3,10
B	10,8	0,09	1,43
C	10,8	0,16	2,67
D	10,8	0,25	4,17

oped, divided into four variants of the experiment. This plan is presented in Table 2. Modification variant A according to the equation (3), modification variant B according to the equation (7), modification variant C according to the equation (10), and modification variant D according to the equation (12).

RESULTS AND DISCUSSION

The analysis of the research results was divided into two groups: qualitative and quantitative.

The qualitative tests were aimed at determining the effect of the blown gas stream on the nature of the gas column being formed and the growth of gas bubbles. The analysis was carried out on the basis of the video obtained during the experiments. Figure 2 shows exemplary frames of the film.

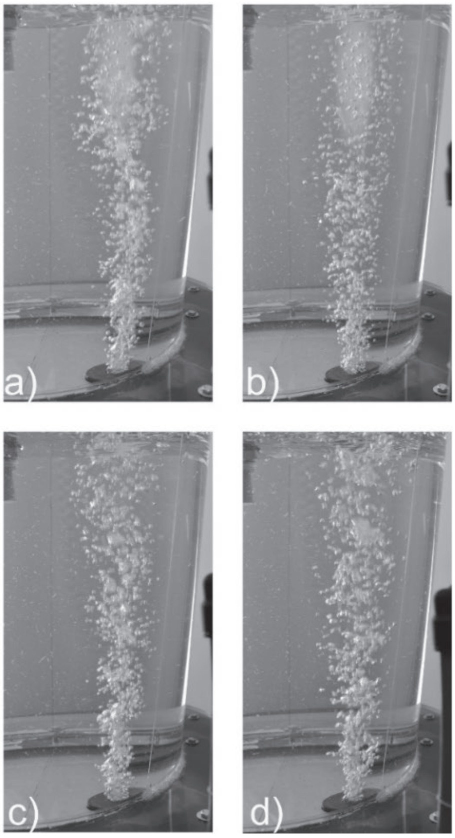

Figure 2 Results of visualization for the variant: a) A, b) B, c) C d) D

For the study of the gas column formation mechanism, the most frequently used modification of the Froude number, is variant B. Based on the visualization, it can be concluded that in this variant the experiment is performed correctly. The obtained results are representative as evidenced by the size of the eye formed on the surface of the model liquid. It can also be stated that variants A and C should be excluded from the analysis of the gas column forming.

The use of the Froude number modification variant C to evaluate the expansion of inert gas in the gas column is similarly positive. The studied phenomena are clearly visible and allow sufficiently accurate measurements of the bubble diameter. In variant B they are too fragmented, and in the other variants A and C the column is too unstable.

The visualisation studies also confirmed the usefulness of the variant C of the Froude number modification for the evaluation of the suitability of the porous material for the process of blowing inert gas into liquid steel. In this case, the test area is a zone on the surface of the material, and the stability of the gas column is of less importance.

Quantitative research is the analysis of the marker mixing curves in the ladle working space (minimum mixing time). In order to determine the mixing curves, the change in the electrical conductivity of the model liquid was recorded at two measurement points. The measured values were converted to the form of dimensionless concentration in accordance with the relationships described in [9,10].

Figure 3 shows an exemplary mixing curve (changes in the dimensionless concentration of the tracer during gas injection into the model liquid).

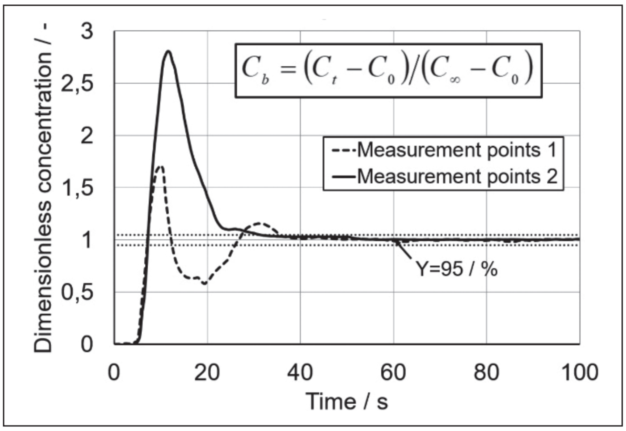

Figure 3 Exemplary changes of dimensionless concentration of the tracer
Where: C_t, C_0, C_∞ – tracer concentration at time t, at the beginning and end of the process.

The presented mixing curves describe the hydrodynamic conditions prevailing in the ladle model during the experiment. The obtained data were processed to determine the minimum mixing time. The procedures are described in [9,10].

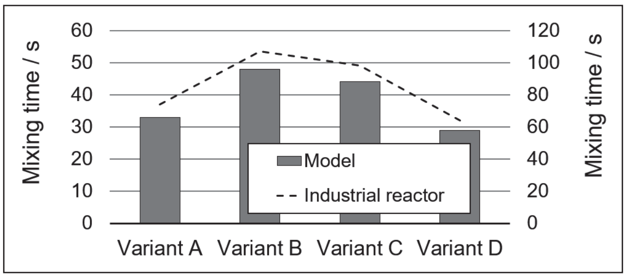

Figure 4 Mixing times for variant experiment

Figure 4 shows the values of the minimum mixing times for individual variants of the experiment. The presented values relate to the time measured during the experiment and converted into the real time of the industrial process. The analysis of Figure 4 shows the expected differences in the value of the minimum mixing time for individual variants of the experiment. As the value of the blown gas stream increases, the minimum mixing time is shortened. In conclusion, there is an inversely proportional relationship. However, this differentiation is so minor that from the perspective of the practice of the conducted process, in which inert gas is blown into the ladle throughout the entire duration of the secondary metallurgy, the expected process efficiency is comparable.

SUMMARY AND CONCLUSIONS

One of the basic goals of modelling industrial processes is to obtain a technique of forecasting the behaviour of the system under certain conditions. The process of blowing gases into liquid steel is very complex. Its hydrodynamic effectiveness depends on many influencing factors. The basic ones are the value of the gas blown stream, the gas column formation mechanism, the expansion of the gas by flowing towards the liquid steel mirror, the properties of the porous material or nozzles, etc. Identifying each of these factors requires an individual approach. In this case, it concerns the method of modifying the Froude criterion number, adopted as the main criterion for the similarity of a dynamic model to an industrial object.

Therefore, it can be concluded that effective modelling of complex industrial processes requires:

- isolation of the main factors influencing their course,
- individual identification of each of them using their respective similarity criteria,
- sensible synthesis of the results obtained.

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Note: The responsible for the translation to English is Paulina Pieprzyca, Katowice, Poland