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Modelling steel's homogenization during argon purging

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Analysis and modelling

ABSTRACT

Purpose: One of the primary tasks that put the steel producers to the test is to reduce production costs while maintaining high quality. This objective is achieved among others through the optimization of conducted technological processes. Commonly used technology of steel homogenization with inert gases is an important stage in the production of steel in which that objective can be accomplished.
Design/methodology/approach: Tests of hydrodynamic processes occurring during the steel blowing with inert gases process directly in industrial conditions is very difficult or impossible. Therefore, as the primary research method physical modelling was used. In order to carry out the tests described in the article a physical model of the station for the argon purging was used that is working at the VSB-TU, Department of Metallurgy and Foundry in Ostrava.
Findings: As a result the study provided values for the investigated process and determined the appropriate location of the gas-permeable fittings in steelmaking ladle's bottom plug. This allows to obtain the required conditions for the steel mixing in the entire volume of ladle's workspace.
Research limitations/implications: Tests presented in the article were carried out in the VSB-TU in Ostrava. Due to this fact some research limitations occurs that applies to localization and physical model's specific construction. Therefore, as a result of cooperation between VSB-TU in Ostrava and the Silesian University of Technology will be carried out the construction of the new research station in Katowice.
Practical implications: The results of the research constitute the basis to make changes that will allow the optimization to so far used purge of steel technology.
Originality/value: The results presented in the article are addressed to the steel producers and it allows to optimize on-going steel homogenization process that takes place in the ladle
Keywords: Liquid steel; Secondary metallurgy; Argon blowing; Physical modelling

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1. Introduction

During metallurgical operations connected with secondary refining of steel (alloying, heating, chemical composition correction, etc.) it is necessary to get the melt into the homogenized state so quickly as possible. The blowing of inert gas (usually argon) into the ladle (mostly by the porous stir elements - SE - positioned on the ladle bottom) is generally used method for temperature and chemical homogenization of such refined steel melt.

Homogenisation processes during argon bubbling into steel in a ladle was investigated by many authors [1-7] and it brought numerous partial pieces of knowledge. Some of them are already generally accepted and are used in daily practice almost in every steelmaking shop. With some simplification it can be summarised that for the given geometry of pouring ladle there exists certain optimum axle offset of the stir element, which ensures the best results from the viewpoint of homogenisation time and rate, and last but not least it makes also possible to optimise the influence of secondary metallurgy processes on final liquid steel quality.

Usually, it is recommended to place the stirring element in the mid to two-thirds of the radius of the ladle bottom (from the centre of the ladle). This position, however, may not be optimal according to the previous data obtained from physical modelling in terms of intensification of transmission phenomena between the slag and metal, such as in case of refining by synthetic slag.

2. Theoretical basics

Commonly used liquid steel mixing method is blowing with inert gases. The gas is introduced mostly by gas-permeable fittings placed in the bottom of the ton or through the lance.

Gas-permeable fittings are made of granular refractory materials by using modern technologies. The basic raw materials for their production are corundum characterized by fire resistance under load of 1860-1900°C, or mullite corundum ($MgO \cdot Al_2O_3$) with a fire resistance under load 1900-1920°C. The porosity of materials for gas-permeable fittings (called open porosity) varies in the range of 25-40%. The radius of capillaries (pores) in this type of material depends on granular refractory material fraction used for the production and is expressed as dependence:

$$r = 0.22 \cdot R \tag{1}$$

where: R -average dimension of loose fraction of the material for fittings production.

Example values of the parameters for gas-permeable fittings' material shows the Table 1.

Table 1.
Parameters for gas-permeable fittings' material

Fractions of material dimension, mm	Open porosity, %
0.0-0.5	28.2
0.5-1.0	27.6
1.0-3.0	25.0

From a technological point of view, it is important to obtain an optimal diameter of gas bubbles, their number and flow out speed. These parameters are essential in terms of on-going purge process efficiency.

The diameter of gas bubble in the flow out process increases from the critical value (when out from the capillary) to the final value (once it leaves the metal bath). The reason for the increase of bubble's diameter is on the one hand the thermal expansion of gas in the metal bath, on the other hand the changing of ferro-static pressure along the steel column. Bubble dimension while exiting from gas-permeable material capillary is determined by formula [8]:

$$d = \left(\frac{108 \cdot \eta_m \cdot \vartheta_g}{\pi \cdot g \cdot \rho_m} \right)^{0,25} \tag{2}$$

where:
η_m - dynamic viscosity, Pa · s
ϑ_g - spread out of gas through the capillary, $cm^3 \cdot s^{-1}$
g - gravitational acceleration, $cm \cdot s^{-2}$
ρ_m - metal's density, $g \cdot cm^{-3}$

The above relation indicates that the diameter of the gas bubble once it leaves gas-permeable material's capillary does not depend on its diameter. Empirical studies, however, helped to formulate a binding dependence of the bubble critical diameter and the capillary diameter. It can be presented as [9]:

$$\frac{d}{D} = 1.82 - 200 \left(\frac{\rho_g}{\rho_m - \rho_g} \right)^{0.96} \cdot We^{0.36} \tag{3}$$

where:
d - bubble's diameter, m
D - capillary diameter, m
ρ_g - density of gas, $kg \cdot m^{-3}$
ρ_m - metal's density, $kg \cdot m^{-3}$
We - Weber's criterion

According to Ciborowski argon bubble's radius can be described by the relationship:

$$r_g = \frac{1}{2} \sqrt{\frac{6 \cdot d_p \cdot \sigma_{cs}}{\rho_{cs} - \rho_{Ar}}} \tag{4}$$

where:
d_p - diameter of the capillary in gas-permeable fitting, m
σ_{cs} - liquid steel's surface tension, $N \cdot m^{-1}$
ρ_{cs} - liquid steel density, $kg \cdot m^{-3}$
ρ_{Ar} - argon's density = 1.784 $kg \cdot m^{-3}$

Another parameter determining the efficiency of metal bath purging with inert gases is mentioned earlier, speed of flow out of gas bubble. That speed describes the relationship:

$$\omega = \sqrt[6]{\frac{h \cdot g^2 \cdot \sigma_{m-g}}{a^2 \cdot (\rho_m - \rho_g)}} \tag{5}$$

where:
h - steel column height, m
$\sigma_{m\text{-}g}$ - metal-gas interfacial tension, $N \cdot m^{-1}$
a - environmental resistance factor, ≈ 1.3

It was stated that bubble flow out time in liquid iron (steel) with a column height h = 2 m, while blowing through the capillary of diameter D = 0.0005 m is 6 s and an order of magnitude is smaller than would appear from the Stokes equation.

In industrial conditions, in order to achieve the above-mentioned technological parameters and to ensure safe operation of blowing steel with argon process, gas is fed at a specific pressure.

The general form of the formula for the minimum argon's pressure in the metal bath blowing is written as [10]:

$$P = P_{atm} + \Delta p_1 + \Delta p_2 + \Delta p_3 + \rho_m \cdot h_m + \rho_z \cdot h_z + \frac{2\sigma}{r} \quad (6)$$

where:
Δp_1 - constant resistance of the argon's supply system,
Δp_2 - constant pressure of porous fitting,
Δp_3 - excess of pressure to maintain continuous and steady blowing,
$\rho_m \cdot h_m$ - ferrostatic pressure,
$\rho_z \cdot h_z$ - slag's pressure.

The results of calculations of minimum argon's pressure while blowing steel with argon are presented in Table 2.

Table 2.
The results of calculations of minimum argon's pressure while blowing steel with argon [10]

Bubble's diameter, mm	Argon's minimal pressure, $kg \cdot s / cm^2$ h				Fittings' porosity, %
	0.4 m	1.52 m	2.6 m	4.0 m	
0.1	0.50	1.62	2.52	3.80	38
0.015	0.76	1.86	2.78	4.03	38
0.005	1.04	2.52	3.40	4.67	38
0.1	0.62	1.72	2.76	3.90	25

3. Investigated variants and used experimental methodology

Physical modelling experiments were realised for conditions of 180 tons steel ladles. The aim was to obtain data about influence of argon volumetric flow rate and position of the stir element (SE) in the ladle bottom on progress of homogenisation in the ladle.

Figure 1 shows investigated positions of the stir elements. There was studied only positions St, A, F, E in this paper. Determination of physical similarity conditions was based on verified and used procedure published in our own previous works, e.g. in [11,12].

While studying homogenisation processes occurring in the steel ladles blowing by argon is the chemical inhomogeneity degree of homogenized compound content in any place "A" and the time τ expressed by the dimensionless quantity:

$$\bar{C}_{E,A,\tau} = \frac{c_{E,A,\tau} - c_{E,H}}{c_{E,H}} \quad (7)$$

where:
$c_{E,A,\tau}$ - mass concentration of the compound E in the bath at poin A in time τ,
$c_{E,H}$ - mass concentration of the compound E corresponding to fully homogenised bath.

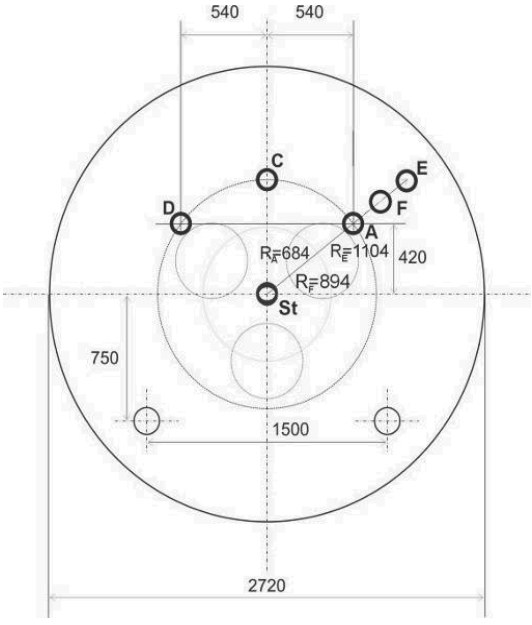


Fig. 1. Positions of stir plugs in ladle bottom used for modelling study

The value of $\bar{C}_{E,A,\tau}$ quantity is a function of the set of $K_{i,j}$ determining criteria and the parameters X_A, Y_A, Z_A determining the position of the "A" point in the bath:

$$\bar{C}_{E,A,\tau} = \varphi\left(K_{i,j}; X_A; X_B; X_C\right) \quad (8)$$

This paper does not describe the detailed method to derive $K_{i,j}$ criteria and their survey, however, this is already contained in the previously cited works [7,8].

Ladle model in length scale $M_L = 1:9$ was used for experimental model research.

Argon flow rate measurement was realised by precise mass flow meter with automatic regulation. Scale factor of volumetric flow rate:

$$M_{Q_V} = \frac{Q'_V}{Q_V} = 0.007552 \quad (9)$$

was determined from the modified Froude's criterion, which respects also influence of blown argon expansion due to increase of its temperature caused by passage through a liquid phase. Volumetric flow rate of argon in the model $Q_v' = 1{,}835$ l.min^{-1} then corresponds to the argon flow rate of basic operational case $Q_v = 243$ l.min^{-1} (see Table 3). Time scale factor was calculated to be

$$M_\tau = \frac{Q'_\tau}{Q_\tau} = 0.333 \tag{10}$$

Table 3.
The volumetric values of gas flow in the model and the ladle

Volumetric flow in the model, Q'_v (l ·min^{-1})	Volumetric flow in the ladle, Q_v (l · min^{-1})
0.378	50
0.884	117
1.835	243
3.021	400
4.252	563

Argon bubbling in the model was realised by stir element design, which was a model equivalent of the real element for industrial conditions.

Development of homogenisation processes after start of bubbling was evaluated on the basis of electrical conductivity and temperature change, which were measured at three points of the ladle volume by conductivity and temperature sensors.

Figure 2 shows typical record of homogenisation process and the record of the tracer change measured in three areas of the bath in the ladle model.

The visualisation method was based on injection of violet contrast substance ($KMnO_4$) - Figure 3 presents the obtained results.

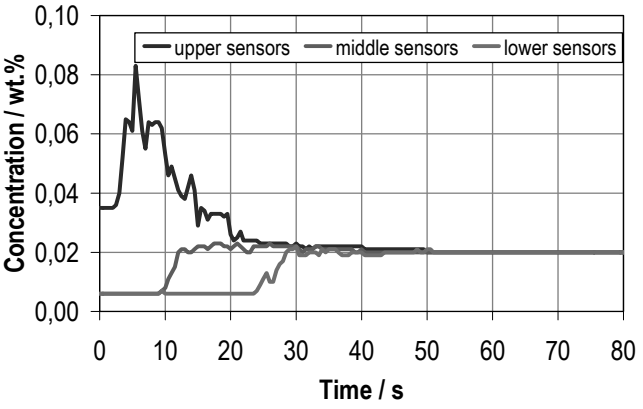


Fig. 2. Typical record of tracer concentration change in three measured places of the bath in the ladle model after start of argon blowing through stir plugs

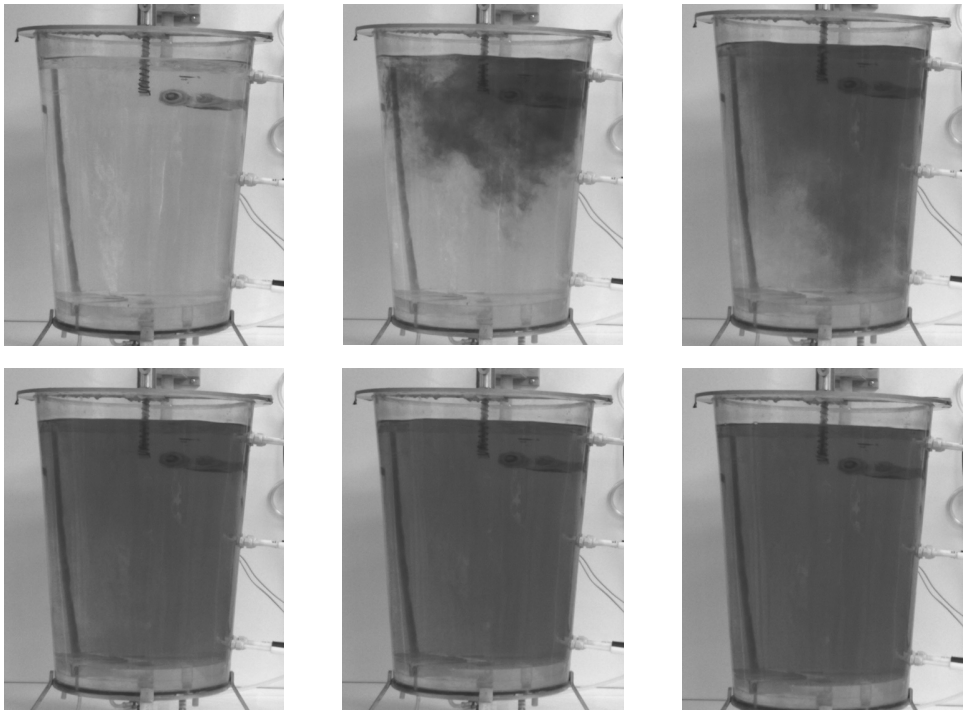
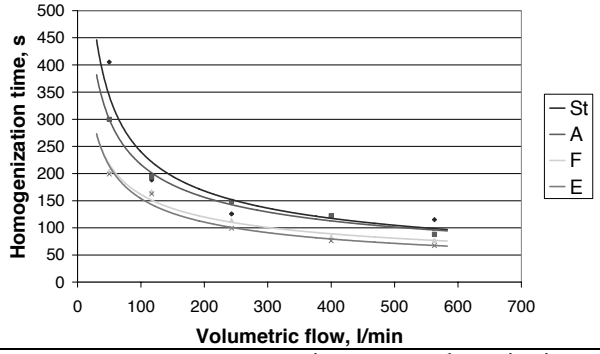


Fig. 3. Violet tracer visualisation ($KMnO_4$) of homogenisation process

4. Obtained results

For purposes of industrial interpretation, the homogeneity times measured on the model were re-calculated with use of already determined volumetric flow rate and time scale factors (M_{Qv}, M_τ) to industrial conditions of the above mentioned 180 tons steel ladles. These values were processed graphically and interlaid by regression function of the type $\tau_H = a \cdot Q_v^{\ b}$ - see the Fig. 4.

The graph shows visible decrease of homogenisation time values τ_H with increase of argon volumetric flow rate. This decrease is not too significant and homogenisation time values vary between 75 to 125 s in the area above 400 l·min^{-1}. Contrary to that, the homogenisation time values steeply increase and they achieve up to 405 s in dependence on position of the SE if the flow rate is only 50 l·min^{-1}.



positions	regression functions	determination coefficients
St	$y = 4381.4\ x^{-0.5971}$	$R^2 = 0.9666$
A	$y = 4966.9\ x^{-0.6245}$	$R^2 = 0.989$
F	$y = 7223.5\ x^{-0.6437}$	$R^2 = 0.9284$
E	$y = 5251.6\ x^{-0.6115}$	$R^2 = 0.9857$

Fig. 4. Influence of argon volumetric flow rate Q_v on the achieved homogenisation times τ_H for three positions of stir elements in the ladle bottom marked St, A, F and E; and obtained regression functions and their determination coefficients for individually modelled variants

From the viewpoint of homogenisation times, the course of curves also indicates that there are distinct differences between bubbling through SE at their positions. Positions St and A are the worst, and for positions F and E can be seen relatively the same and lower homogenisation times. The position E can be regarded as the most favourable position of the SE, because it had shortest homogenisation times in comparison with another positions.

5. Conclusions

Physical modelling method was used for model investigation of influence of argon bubbling through a stir element situated in the ladle bottom in the course of homogenisation processes in a bath. The best results were obtained in variants with simultaneous bubbling through the SE in positions E (Figure 4). On the other hand, the longest homogenisation time was obtained during bubbling variant with location of the SE in position St (centre of ladle bottom).

The results of research presented in this article are the result of collaboration between VSB-TU in Ostrava and the Silesian University of Technology in Katowice. This cooperation has an evolving nature. The next phase is the build of laboratory stand (physical model) in Katowice to study the hydrodynamic processes occurring during purging steel with inert gases. Research carried out here will be addressed to the Polish steel producers to optimize the process of steel in the steelmaking ladle homogenization and improving the efficiency of steel refining from nonmetallic inclusions.

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