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A. SMIRNOV*, V. SAFONOV*, A. TSUPRUN **, A. KOVALEV ***, V. TIUNOV****

UPGRADING OF EAF SHOP AT KRAMATORSK ENGINEERING PLANT ENERGOMASHSPECSTAL (UKRAINE)

MODERNIZACJA STALOWNI EAF W ZAKŁADZIE „ENERGOMASHSPECSTAL” W KRAMATORSKU (UKRAINA)

Competitive and high quality steelmaking is unthinkable today without ladle treatment stations and vacuum degassing systems in which secondary metallurgical operations are carried out. Emphasis in ladle metallurgy operations was placed on rational molten steel mixing in gas stirred ladles. On the basis of physical modeling results of bath stirring with two porous plugs the H/D ratio and gas flow rate were found to exert most influence on mixing time. To substantiate the adequacy and appropriateness of simulation results the operational trials were carried out in a 75 t commercial ladle-furnace facility using varied values of gas flow rates. The results of plant experiments revealed the relationships between average desulphurization rate as well as arc heating rate and mixing efficiency. A new method of steel stirring was proposed as one of the means for stirring optimization under concurrent processing steps of desulphurization and heating in the ladle. A flow chart of high quality steel production at EAF shop of ENERGOMASHSPECSTAL JSC, based on process module principle, was developed to meet modern quality requirements for large ingots and to assure resource- and energy saving.

Keywords: Ladle furnace, ladle treatment facility, gas stirring, desulphurization, mixing time, electric arc heating, homogenization time

Konkurencyjne i jakościowe wytwarzanie stali jest dzisiaj niewyobrażalne bez stanowiska do obróbki kadziowej i systemu odgazowania próżniowego, w których przeprowadzane są operacje metalurgii pozapiecowej. Nacisk w operacjach metalurgii kadziowej został położony na racjonalne mieszanie ciekłej stali w kadziach z dmuchem gazowym. Na podstawie wyników modelowych mieszania kąpieli w kadzi z dwoma porowatymi zatyczkami stwierdzono, że wskaźnik H/D i szybkość przepływu gazu wywierają największy wpływ na czas mieszania. Aby udowodnić adekwatność wyników symulacji próby zostały przeprowadzone w 75 t piecokadzi przemysłowej umożliwiającej użycie różnych wartości szybkości przepływu gazu. Wyniki doświadczeń przemysłowych pokazały zależność między średnim stopniem odsiarczania, jak również szybkością nagrzewania łuku, a sprawnością mieszania. Nowa metoda mieszania stali została przedstawiona jako jedna z możliwości optymalizacji mieszania przy równoczesnym odsiarczaniu i nagrzewaniu w kadzi. Schemat technologiczny produkcji stali wysokiej jakości w stalowni EAF przedsiębiorstwa ENERGOMASHSPECSTAL JSC, bazujący na zasadzie modułu, został opracowany, aby sprostać współczesnym wymaganiom jakościowym dużych wlewków i aby zapewnić oszczędność zasobów i energii.

1. Introduction

Kramatorsk Engineering plant ENERGOMASHSPECSTAL was established in 1964 as a base power engineering plant to produce large forged ingots. Production facilities at EAF shop were put into operation by mid 80s comprising arc-furnaces (capacities of 12, 50 and 2×100 tons), RH vacuum degasser and vacuum cameras for ingot casting of up to 220 tons.

To raise its competitive capacity EAF shop requires modern upgrading which has started gradually to keep its production volume at present-day level, amounting to 110–120 thousand tons of large ingots per annum. The upgrading program provides for the replacement of three obsolete arc furnaces by a high-capacity electric arc furnace and a ladle treatment station (LF – VOD).

While selecting the optimum EAF capacity meant to replace the equipment in service the following conditions were taken into account:

- space shortage: site limitations for location and working area of EAF;

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* DONETSK NATIONAL TECHNICAL UNIVERSITY, DONETSK, UKRAINE
** DONIX LTD., DONETSK, UKRAINE
*** ENERGOMASHSPECSTAL JSC, KRAMATORSK, UKRAINE
**** NKMZ JSC, KRAMATORSK, UKRAINE

- performances of handling machinery and casting ladles running in the shop;
- interrelationship between furnace capacity characteristics and maximum permissible ingot weight;
- matching the productivity of ladle treatment plant with that of the steel-making unit.

Target output of EAF shop (approximately 220–230 thousand tons of liquid steel per year) is most likely to be ensured by heat weight of about 35–40 tons. However, the rated EAF capacity can bring the following disadvantages:

- institutional and processing complexity arising from casting of ingots exceeding 40 tons; present-day share of the ingots in question averages 40% and is believed to increase;
- EAF shop would miss the unique opportunity of casting large (150 t and over) forged ingots.

The increase in heat weight up to 60–65 tons was accepted as one of the means to advance EAF shop development. Adopted capacity would allow casting of ingots ranging up to 360 tons.

Consequently, conditions and arguments stated above call for the availability of two dimension-type casting ladles in the shop:

- 130 t to contain 2 heats and large-sized ingot casting;
- 75 t to contain one heat and casting of small and mid-sized ingots.

Before development of technology procedures for ladle-degassing treatment, the production characteristics and features of EAF shop were analyzed, particularly they are:

- exact adjustment of the steel composition, i.e. close tolerances on alloy additives content, low content of hydrogen (<1.5 ppm), total oxygen and non-metallic inclusions, improved overall steel cleanliness;
- space shortage, i.e. site limitations for location and working area of EAF and ladle-degassing treatment;
- target design and two dimension-type casting ladles;
- completion of vacuum degasser with power-driven pumps to comply with the VOD operational cycling.

In recent years, studies of ladle metallurgy operations in steelmaking have been widespread. Emphasis was placed on rational molten steel mixing in gas stirred ladles. This is to be expected because of the variety of gas injection configurations in the ladle. Inert gas purging is done through one or two (rarely three) nozzles, their locations are affected by the following [1, 2]:

- the eye of the exposed metal is not be agitated by injected air in the electric arc operation zone;
- one of the nozzles is to be located in the ferroalloy delivery zone, thus improving mixing;
- the nozzles are not to be located in the region of steel free jet under ladle filling;
- nozzles location in the vicinity of ladle walls is inappropriate, as long as this can result in high refractory erosion in the region of upwelling plume distribution;
- particular process steps of typical ladle refining operations specify the rate of argon injection;
- location of a nozzle at a certain distance from the outlet is a must.

Moreover, casting ladles of EAF shop vary in molten steel depth, which leads to different interrelationship between bath depth and ladle diameter.

Each engineering step of secondary metallurgy, either designing, constructing and putting facilities into operation, was accompanied by extensive research and analysis aimed at optimization of molten steel stirring by inert gas injection. The results achieved are reported below.

The equipment specifications are presented in Tables 1 and 2.

TABLE 1

Equipment Specification of Ladle Furnace

Parameter	Values
Ladle capacity (t)	130/75
Furnace transformer (MVA)	18
Electrode diameter (mm)	400
Maximum heating rate (°C/min)	5.7
Electrode consumption (g/kW*hour)	9
Energy consumption (kW*hour/t*°C)	0.28
Processing time (min) total/heating	50–60/20–30
Startup date	2007

TABLE 2

Equipment Specification of VOD

Parameter	Values
Ladle capacity (t)	130/75
Operation mode	VD/VOD
Pump type	Mechanical type
Minimum pressure (kPa)	0.67
Pumping capacity in dry air (kg/hour)	300
Vacuum rate (min)	5–8
N content (ppm)	<60
H content (ppm)	<1.5
Startup date	2007

The purpose of the present work is to examine thoroughly the process of steel stirring by inert gas injection through two porous plugs in steelmaking ladles with different D/H interrelationships and to offer advanced secondary metallurgy solutions for optimization of liquid steel stirring at ladle furnace station installed at Kramatorsk Engineering plant ENERGOMASHSPECSTAL.

2. Physical model description

For this study, a transparent model of a steelmaking ladle has been developed to follow the hydrodynamic, temporal and geometrical similarity parameters. It is applied in this work to simulate and to visualize the process dynamics and associated efficiencies of molten metal processing operations resulting from liquid agitation. It has been shown from experiments that in gas stirred ladles gravitational force determines the behaviour of floating gas bubbles while inertia force specifies the circulating flows behaviour in the molten steel bath. Considering these circumstances, Froude criterion and homochronous criterion were adopted as principal similarity criteria [3–5]. A cylindrical vessel, having an inner diameter of 24 cm and a height of 36 cm was used to represent a 1/8-scale and a 1/12-scale steel ladles of 75 tons and 130 tons respectively.

In this study, we used water at 18–25°C as the model for liquid steel. The reason can be explained by the fact that the viscosity of water at ladle treatment temperatures approximates the actual viscosity of molten steel. Compressed air was injected into the bath through a plug on the bottom of the vessel. a schematic diagram of the apparatus is shown in Fig. 1. The dynamics of the liquid stirring were snapshot with a digital video recorder.

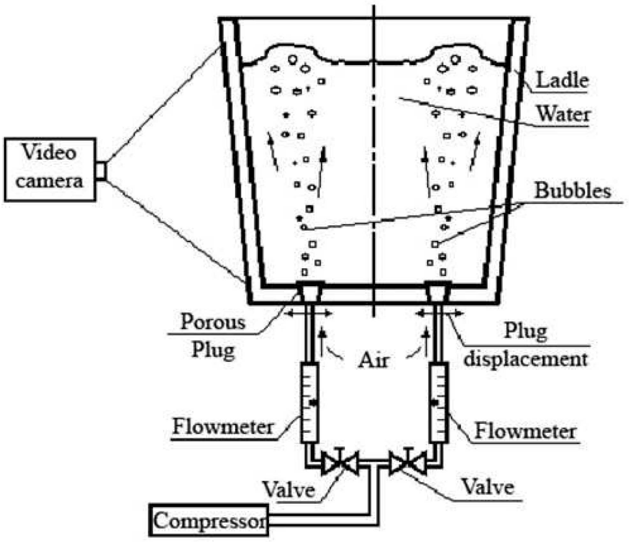

Fig. 1. A schematic diagram of a model ladle

Homogenization time of agitated water was measured by adding 5 ml concentrated solution of sodium chloride to the bath. The changes in the electrical conductivity of the water were measured in two monitoring points of the bath. Two sensors, made from a pair of platinum electrodes, were employed to record changes in local conductivity. They were immersed in diametrally opposite locations at 0.2 m and 0.8 m of the bath depth and were connected in bridge circuit. The advantage of this connection can be explained subsequently. Since the output signal is the difference between sensors values, therefore, it holds good for deducing the state of homogeneously mixed electrolyte.

Oscilloscope pictures obtained in this way were processed by specific software, while the homogenization time was defined in the present context as the picture segment at which parameter modification would exceed 2% of the maximum value corresponding to the start time of electrolyte addition on an immersed sensor.

Homogenization times were measured in room temperature modelling over a wide range of conditions including salt solution feeding in the centre of the model bath and in the vicinity of a sensor. Comparisons of measurement results confirm that the homogenization times are not affected by the feeding point change. To ease the subsequent measurements we added the electrolyte directly to the sensor region as long as deviation value in these circumstances is somewhat greater than that of central feeding. A minimum of three measurements were made for each operating condition, if maximum variation of these measurements exceeded 10%, a series of measurements were repeated, and an average mixing time was thereby determined.

The experiments were carried out in the gas stirred model water bath with two porous plugs at the bottom, plugs location being varied (see Fig. 2).

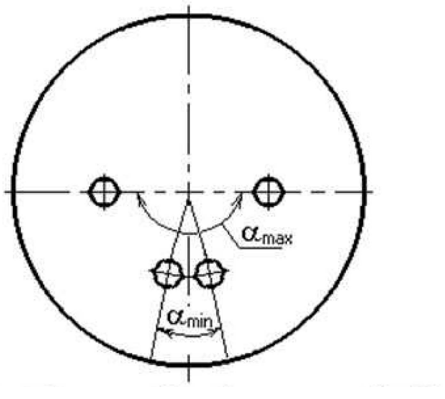

Fig. 2. Variation of porous plugs location at the bath bottom

Equal gas flow rate was adjusted for each porous plug. Homogenization times were measured for porous plugs location reaching half radius in relation to the bath central axis. Angle α, which outlines the porous plug location at the bottom, injected gas flow rates and water depth in the model bath were varied as process parameters. The angle variation ranged from 20–180°C, as indicated in Fig. 2, gas flow rate ranged from 0.2–1.0 l/min, H/D = 1.0–1.5.

Experimental mixing times (over 150 values) were compared to their theoretical estimates, while simultaneously analyzing the adequacy and accuracy of the obtained results.

3. Plant experiment

To investigate desulphurization rate and heating rate, operational trials were carried out in a commercial ladle-furnace facility using varied values of gas flow rates. However, other treatment conditions remained invariable, namely heating and mixing parameters, as well as the amount of refining slag. Moreover, no alloying agents were added to the ladle in the trials.

The steps in the plant experiments are summarized as follows:

- the furnace transformer goes off before the test start, the operation window opens in order to visualize the homogeneity degree of refining slag (the slag is to be boiled) and to assess the porous plugs operation;
- on adjusting and averaging metal temperature in the ladle (1.0–1.5 min) steel temperature was measured (T_1, °C) with an immersed thermocouple followed by steel sampling ($\%S_1$);
- when the furnace transformer was on again, its operation was monitored by instruments readings (heating period must be prevented from the stages shift and from the current strength jumps);
- on heating termination (τ = 10–15 min) and averaging metal temperature in the ladle (1.0–1.5 min) steel temperature was measured again (T_2, °C) with an immersed thermocouple followed by the second steel sampling ($\%S_2$);
- steel heating rate (V_T, °C/min) was calculated with the following ratio:

$$V_T = \frac{T_2 - T_1}{\tau}, \quad ^\circ\text{C/min} \qquad (1)$$

- while for estimation of desulphurization rate (V_S, ppm/min) the following correlation was proposed:

$$V_S = \frac{S_2 - S_1}{\tau}, \quad \text{ppm/min} \qquad (2)$$

4. Results

Observation results obtained in this study show that irrespective of gas flow rate and bath depth at a relatively small angle between the porous plugs (less 30°-35°) one trend was detected, being the process of interflow of two upwelling jets into one. At larger angles between porous plugs, the upwelling flows tend to rise independently of one another. When moving horizontally, rising flows collide partially with each other at the ladle upper part. Measured homogenization times are plotted in Fig. 3.

Summarizing the data presented so far, it is reasonable to draw the following conclusions: increasing of the angle between porous plugs leads to the increase of homogenization times, running up to its maximum value at diametrally opposite plugs. However, the correlation of homogenization time and angle increase holds good largely for ladles with high H/D ratio. Minimum homogenization time was obtained at porous plugs location at angles ranging 40°–60°. On the basis of observations, it might be anticipated that the above-mentioned location of porous plugs induces the generation of two recirculation flows, contacting with each other in the bath upper part.

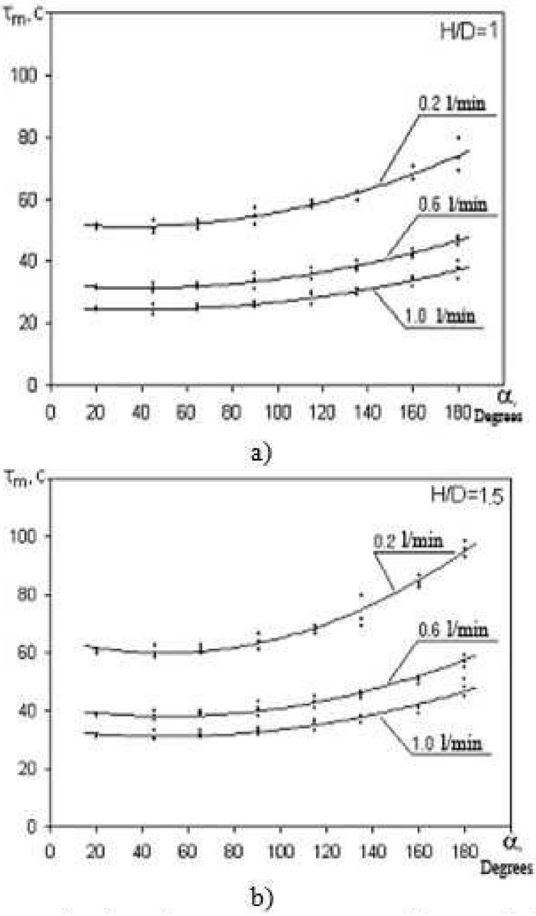

Fig. 3. Variation in homogenization time versus corresponding angle between porous plugs and corresponding gas flow rates under different liquid depth: a) H/D = 1.0, b) H/D = 1.5

Consequently, it might therefore be suggested that the collision of circulating flows generated by porous plugs contributes to the increase in homogenization time, provided that the angle between the porous plugs exceeded 120°. As a result, the contribution of the energy to causing homogenization is reduced, thus increasing the homogenization time. On the other hand, the dynamic collisions of circulating flows would promote the intensification of liquid mixing with regard to the extraction procedures acceleration, e.g. desulphurization and diffusive deoxidization. Hence, a definite conclusion on the efficient liquid mixing in the bath with two porous plugs cannot be reached at present. A final conclusion should be made after accumulating modeling results on metal-refining slag interaction.

On the basis of extensive experimental measurements and theoretical findings presented above the porous plugs were located at 120° at the bottom of 75 t and 130 t commercial ladle-furnaces.

The task of the next experiment step was to elucidate mixing efficiency in 75 t vessel. The operational trial included heating and desulphurization of steel in the ladle-furnace facility.

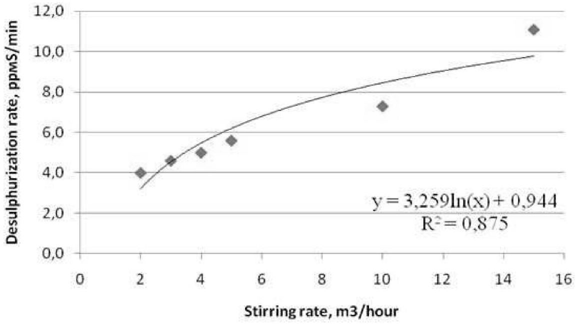

Fig. 4. Effect if argon flow rate on desulphurization rate

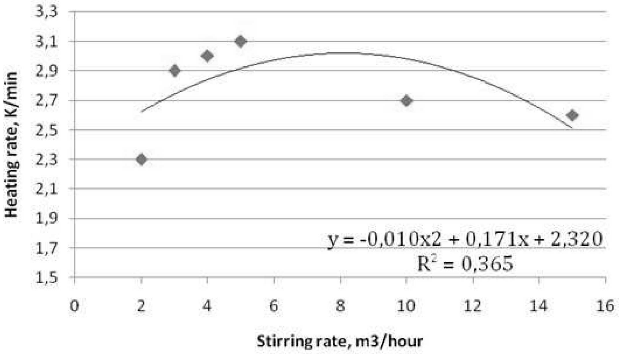

Fig. 5. Effect of argon flow rate on steel

Results on steel desulphurization and heating rate are presented in Figs. 4 and 5. It is deduced that the average desulphurization rate ranges from 4 to 11 ppm/min under initial sulphur content of 0.055–0.034% and is greatly dependent on gas flow rate. To prevent the formation of the metal exposed region produced by upwelling plume, the gas flow rate was limited to 15 m^3/hour.

It is evident that the average desulphurization rate increases with mixing efficiency. In contrast to this, the dependence of steel heating rate on mixing efficiency is not unambiguous one. The rise in mixing efficiency while simultaneously enhancing heat conduction from up to bottom leads to advanced heat transfer to cold ladle walls. Hence, within the range of conditions investigated in this study at given heating stage capacity with an electric arc the optimum (extreme) values of function affected by stirring rate can be obtained. It is redily apparent that the optimum gas flow rate ensuring steel melt heating ranges from 3 to 6 m^3/hour, while the optimum gas flow rate providing steel melt desulphurization averages 15 m^3/hour. Curves patterns are determined by general relationships, and it is legitimate to assume, that the same conclusions can be derived within the range of heating stage capacity, slag composition and amount.

5. Discussion

Typical metallurgical fine-tuning at LF often employs concurrent processing steps in the ladle furnace facility, e.g. steel melt heating and desulphurization. Consequently, stirring rate aimed at both steel compositional and temperature adjustments at a given time, as well as reducing inert gas and energy consumption, has to be estimated.

Thus, actual ladle refining operations at Kramatorsk Engineering plant ENERGOMASHSPECSTAL called for the following tasks to be resolved concurrently:

- steel heating before vacuum degassing treatment by 60°C;
- sulphur content reducing by 150 ppm.

The following relationship is expected to calculate the appropriate stirring rate.

Desulphurization rate and heating rate can be represented via the following correlations:

$$V_S = \frac{\Delta S}{\tau} \tag{3}$$

$$V_T = \frac{\Delta T}{\tau} \tag{4}$$

Considering that

$$V_S = f_S(Q) = 3.259 \cdot \ln Q + 0.944 \tag{5}$$

and

$$V_T = f_T(Q) = -0.010 \cdot Q^2 + 0.171 \cdot Q + 2.320 \tag{6}$$

Sulphur content change and steel temperature rise can be manipulated in the alternative form:

$$\Delta S = f_S(Q) \times \tau \tag{7}$$

$$\Delta T = f_T(Q) \times \tau \tag{8}$$

Expressing specified processing step characteristics via ΔS_0 and ΔT_0, the relationship is easily modified into the factorial

$$\varphi = [(f_S(Q) \times \tau - \Delta S_0) \times m_S + \\ +(f_T(Q) \times \tau - \Delta T_0) \times m_T] \rightarrow \min \tag{9}$$

where m_S and $m_T$are significance coefficients.

Calculation results are summarized below. The factorial minimum value (version #2) corresponds to stirring rate of 7.3 m^3/hour, being the optimum value for anticipated processing results.

TABLE 3

Rated values

#	Time (min)	ΔSo (ppm)	ΔTo (°C)	Estimated values			
				Q (m^3/hour)	ΔS (ppm)	ΔT (°C)	ϕ
1	25	150	60	4.1	138.7	71.2	9.97E-05
2	**20**	**150**	**60**	**7.3**	**149.3**	**60.7**	**9.92E-05**
3	15	150	60	17.7	144.8	40.9	−21.40

A relatively large deviation of the experimental data is obvious in Version #1. It resulted in steel superheating and incomplete desulphurisation. The increase in processing time up to 25 min under given operating conditions claims the furnace transformer redirection to a lower heating stage effecting an enhance in stirring rate, which would promote desulphurisation rate.

The solution for Version #3 conditions has not been worked out. There appeared an apparent discrepancy between predicted values and corresponding experimental results. Meeting the operating conditions would require the furnace transformer redirection to a higher heating stage and adjusting the refining slag composition (amount). Calculation of optimum gas flow rate in concurrent steel heating and desulphurisation must be preceded by the estimation of function values of heating $f_T(Q)$ and desulpharization$f_S(Q)$ for modified stirring conditions.

6. Conclusion

Physical modeling results of bath stirring with two porous plugs confirm that the mixing time is most sensitive to H/D ratio and gas flow rate. The mixing time was however twice less affected by the angle, α, between the porous plugs location. The mixing time in gas stirred ladles appeared to be hardly dependent on the location of porous plugs, $\rho = r_{\Pi}$/R. The increase in gas flow rate brings shortening of mixing time, while an enlargement in ladle depth and plugs distancing from the ladle vertical axis results in increase of mixing time.

The results of commercial trials carried out in 75 t steel ladle revealed the relationships between average desulphurization rate as well as arc heating rate and mixing efficiency. Within the range of conditions investigated in this study the optimum (extreme) values of function affected by stirring rate can be deduced. The optimum gas flow rate ensuring steel melt heating ranges from 3 to 6 m^3/hour, while that providing steel melt desulphurization averages 15 m^3/hour.

A new method of steel stirring, which estimates the required stirring rate assuring both steel compositional and temperature adjustments at a given time, as well as reducing inert gas and energy consumption, was proposed as one of the means for stirring optimization under concurrent processing steps of desulphurization and heating in the ladle.

Competitive and high quality steelmaking is unthinkable today without ladle treatment stations and vacuum degassing systems in which secondary metallurgical operations are carried out. The facilities are vital to assure quality and productivity improvement, minimum power intensity and low operating costs.

A flow chart of high quality steel production at EAF shop of ENERGOMASHSPECSTAL JSC, based on process module principle, was developed to meet modern quality requirements for large ingots and to assure resource- and energy saving.

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