DETERMINATING THE POWER OF MIXING OF A METAL BATH DURING PROCESSING IN A LADLE FURNACE

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Abstract

In modern metallurgical processes, the mixing of a metal bath is a basic operation that allows achieving a state of close chemical and thermal homogenization of liquid steel after the insertion of the alloy addition. Mixing also increases the efficiency of removing non-metallic inclusions. Research into metal bath mixing processes contributes to the optimization of steelmaking processes.

The article presents the calculations made at the conditions prevailing in a ladle furnace with a volume of 145 Mg liquid steel. The effect of mixing power of argon on chemical homogenization bath was determined. The mixing power values for the argon flow rates in the ladle Q_{Ar} = 100-500 [dm^3/min] were calculated.

Keywords: Steelmaking, ladle furnace, mixing power

1. INTRODUCTION

The modern steel industry uses metal bathing in almost all stages of production of liquid metal. It uses various metallurgical aggregates for this purpose. During the smelting of steel in the oxygen converter there is obvious mixing with oxygen introduced through the lance or additional nozzles mounted in the bottom of the converter. In addition, the metal movement is often intensified by inert gas blown in with the fittings embedded in the bottom or side walls of the converter. Also in modern electric furnaces there are oxygen lances and gas-permeable fittings whose task is to mix the charge in order to melt it faster. Nevertheless, the mixing of baths is most widely carried out at the post-furnace work stations, including the most common ladle furnace (LF) [1-4].

Argon is blown into metal baths through the porous shaped body proceeds with the intensity necessary to induce a turbulent flow able to excite the circulation of liquid steel. This movement, in turn, is necessary to achieve a state close to complete chemical and thermal homogenization of the liquid steel after the introduction of the alloy addition and before leaving the ladle for the continuous casting of steel. Depending on the current needs, the operator of the ladle process has full control of the mixing of the bath by regulating the gas flow rate. Another positive effect of gas injection is the adhesion of non-metallic inclusions to floating gas bubbles, and thus their capture from liquid metal and removal from the metal bath to the slag [2,4].

All these positive aspects of the metal bath mixing process through inert gas are widely used in practice and researched by scientists to further optimize steelmaking processes. Research is necessary to identify specific parameters of technological processes. They can be partially carried out directly on industrial equipment working with the use of control and measurement equipment mounted on them. The results of such so-called industrial tests have a very high practical significance, because they allow the direct application in real conditions. Unfortunately, due to the specificity of the conducted processes in metallurgical devices, the industrial research is limited in scope and usually concerns individual measurements. These restrictions also apply to the study of phenomena occurring in the steel ladle at the LF stand. In situations where it is not possible to obtain the required information directly on the working device, model tests using physical or numerical modeling techniques are carried out [4-6]. Such studies have - due to the simplifications used.

The paper presents the effect of certain assumptions regarding the initial conditions of the numerical model of the argon injection into the steel bath, in particular the liquid steel parameters, on the parameters of the entire LF process, in particular on the calculated mixing power.

2. MIXING ALLOY ADDITION IN THE INDUSTRIAL LADLE FURNACE

As mentioned, the injection of argon into the bath is a commonly used secondary metallurgy treatment, including refining at the LF station [2]. Despite the simplicity of the design of the device itself, mixing the metal bath for chemical and thermal homogenisation in the ladle furnace is a complex phenomenon. It is attempted to describe it by means of a characteristic sequence of physical partial processes while using data from model experiments. Despite the variety of attempts, the mixing description always uses the characteristic behaviors and characteristics of such elements of the system as the gas bubble, its motion and the structure and properties of the gas-liquid column.

Transmission of gas energy to the liquid takes place as a result of interphase interaction at the contact surface of the two-phase column and liquid. It depends to a large extent on the quantity, size and shape of gas bubbles generated during injection. This energy causes a turbulent movement of the liquid steel, turning into a circulating flow. In the majority of studies presented in literature, no analysis of the impact of individual gas bubbles is undertaken, devoting more attention to the global aspects of the steel mixing process after introducing the alloy addition to the metal bath.

MIXING TIME

Monitoring changes in marker concentration by determining the chemical composition of metal samples taken from the same place at several second intervals would reveal the existence of mixing characteristics. **Figure 1** presents an example of the characteristics obtained from industrial measurements, changes in the concentration of the alloy addition during the argon process at the ladle furnace station.

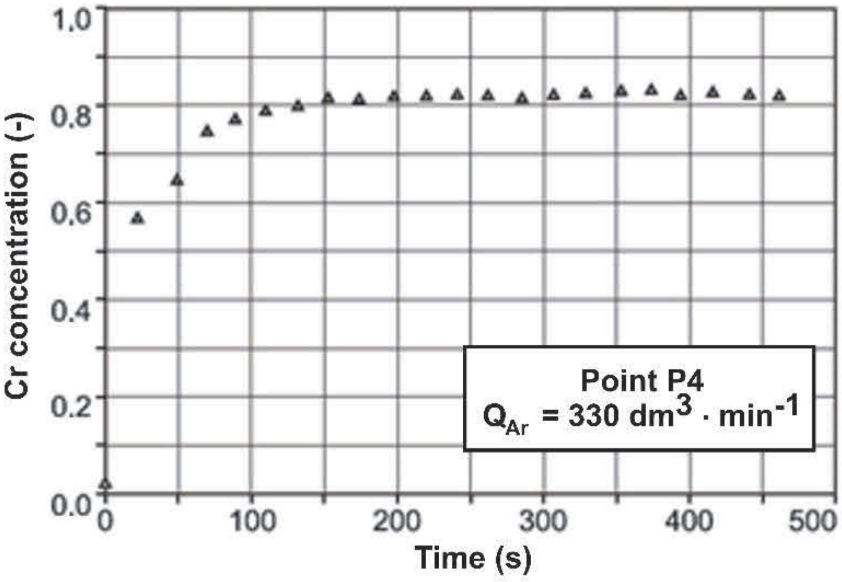

Figure 1 Cr concentration in the metal bath during agitation with argon [6]

CHARACTERISTICS OF TIME OF MIXING

The potential inherent in modern mathematical modeling and numerical simulation techniques allows such a range of substantive penetration of phenomena that we find sufficient argumentation to disprove the contradictions and show their sources. It was decided to use this route to find out the probable mechanism of chemical homogenization and thermal metal bath in a ladle and propose a formula for determining the time necessary to achieve the required state of homogenization.

According to literature [7-10], mixing is considered to be pre-filled when 95 % homogenisation of the bath is reached, which corresponds to $C_b \in \langle 0.95; 1.05 \rangle$ or as satisfied when the degree of bath homogenisation reaches 99.5 %, which corresponds to $C_b \in \langle 0.995; 1.005 \rangle$. An exemplary characteristic illustrating the change of the dimensionless marker concentration during the argon injection into the metal bath is shown in **Figure 2**. Additionally, the upper and lower limits of the 95 % chemical homogenization band of liquid steel defined as $Y = C_b \cdot 100$ % were applied thereon.

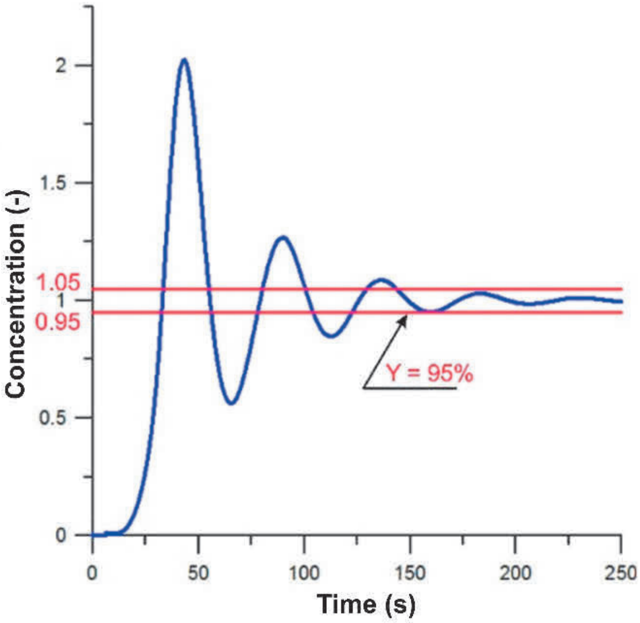

Figure 2 Exemple of changes of dimensionless marker concentration during argon injections into a metal bath

Own research and literature data [11] show beyond any doubt that the determined mixing time depends on the location of the monitoring point (in the zone of so-called stagnation flows, called the dead zone, it is much longer). Since the characteristics as well as time needed to reach the expected homogenization level differs from each other; it is usually assumed that the longest of them should be taken as the total mixing time.

3. THE POWER OF ARGON MIXING

More universal than the gas flow rate, the characteristic feature of mixing is the amount of energy that, through the buoyancy of bubbles and their thermal expansion, disperses when blowing argon into a metal bath. The parameter used for this purpose is suitable for the so-called mixing power (ε_m), expressed in W/t or in W/kg steel.

In the available literature there are a number of dependencies determining the effective mixing power transferred to liquid steel by the injected gas [1,7-10], two dependencies deserve attention:

$$\varepsilon_m = \frac{6.18 \cdot Q \cdot T}{M} \ln\left((1 + \frac{\rho \cdot g \cdot H}{P_0} \right) \tag{1}$$

$$\varepsilon_m = \frac{340 \cdot Q \cdot T}{M} \ln\left((1 + 0{,}707) \frac{H}{P_0} \right) \tag{2}$$

legend:

ε_m - power of mixing, W/t (1) or W/kg (2),

Q - gas flow rate, m^3/min (1), m^3/s (2),

T - temperature, K,

M - steel mass, t (1) or kg (2),

H - height of the metal column, m

g - acceleration of the earth = 9,81 m/s,

ρ - liquid steel density, kg/m^3

Po - gas pressure over the metal mirror, atm (1) or Pa (2).

The presented relationships between (1) and (2) cover the kinetic energy of the gas flowing out of the nozzles and the energy transmitted to the liquid during the isothermal expansion of rising bubbles in the gas-liquid column.

In dependence (1) there is a density of liquid steel for which the calculation also has a number of dependencies, taking into account only the C content, e.g. [12]:

$$\rho_{st} = (8319{,}49 - 0{,}835 \cdot T)/(1 - 0{,}01 \cdot C) \tag{3}$$

legend:

ρ_{st} - density of liquid steel, kg/m^3,

T - temperature, °C,

C - carbon content in steel, wt%

In order to analyze the formulas used to represent the proper mixing power of a steel bath, it was decided to carry out exemplary calculations.

The calculations were performed for a 145 Mg steel ladle furnace, in which the height of the metal column is 2.9 m. To study the effect of the total proper argon mixing power for chemical bath homogenization, the values of this power were calculated for the gas flow rates used in the vessel $Q_{Ar} \in \langle 100; 500 \rangle$.

Alloyed steels with a C content of 0.20 to 0.29 % by mass were analyzed. The calculated values of liquid steel density using the dependence (3) are shown in **Table 1**.

Table 1 Calculated steel density at different C content (wt%)

C (wt%)	Temperature (K)	Density (kg/m^3)
0.20	1853	7,014.2
0.22		7,015.6
0.29		7,020.5

As can be seen from the data in **Table 1**, the calculated values of liquid steel density do not differ too much from each other. On the basis of the liquid steel density value (**Table 1**), the mixing power (**Table 2**) was calculated from the dependence (1) for four gas intensities and different densities, assuming a steel temperature of T = 1,853 K.

Table 2 The calculated mixing power for different steel densities

Q_{Ar}, (dm^3/min)	Density of liquid steel accepted for calculation (kg/m^3)			Difference (W/t)
	7,014.2	7,015.6	7,020.5	
	Power of mixing, $\square_m$ (W/t)			
100	8.595	8.596	8.600	*0.005*
150	12.893	12.895	12.900	*0.007*
200	17.191	17.193	17.200	*0.009*
250	21.488	21.491	21.500	*0.012*
300	25.786	25.789	25.800	*0.014*
350	30.084	30.087	30.100	*0.016*
400	34.382	34.386	34.400	*0.019*
450	38.679	38.684	38.700	*0.021*
500	42.977	42.982	43.000	*0.024*

As can be seen from the calculations presented in **Table 2**, the density of liquid steel used in calculations does not have a large impact on the calculated mixing power.

The calculated values of the mixing power according to the dependence (1) for = 7,020.5 kg/m^3 and (2) for the gas flow rates in the ladle $Q_{Ar} \in \langle 100; 500 \rangle$ are included in **Table 3**.

Table 3 Mixing power (W / t) determined from the presented equations for different argon flow rates

Q_{Ar}, (dm^3/min)	Mixing power, $\sum_m$ (W/t)		Difference (W/t)
	eq. (1)	eq. (2)	
100	8.600	11.583	2.982
150	12.900	17.374	4.474
200	17.200	23.165	5.965
250	21.500	28.956	7.456
300	25.800	34.748	8.947
350	30.100	40.539	10.439
400	34.400	46.330	11.930
450	38.700	52.122	13.421
500	43.000	57.913	14.912

Table 3 clearly shows that the correct mixing power of a metal bath is higher for calculations using the dependence (2) in which it does not take into account the liquid density of the steel.

4. CONCLUSION

Valid data for numerical calculations is necessary to carry out the simulation, whose results will be the basis for proper inference. From the calculations it follows that if various formulas are used to determine the liquid steel density is of little importance, there are different formulas for determining the mixing power in the ladle furnace they are already important (reaching even several dozen percent). Therefore, the goal the next tests should be to carry out numerical simulations for different process input parameters.

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