



# SOLUTOCAPILLARY EFFECTS OF SULPHUR IN CAO-AL<sub>2</sub>O<sub>3</sub> SLAGS, IN MARANGONI INSTABILITY AND CONVECTION ONSET, RELATED TO THE DESULPHURIZATION OF LOW CARBON, ALUMINIUM KILLED STEELS

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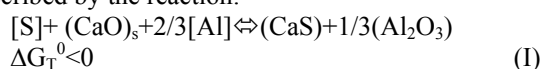
## ABSTRACT

*Based on the "one layer model" applied to desulphurization slag layer with boundary conditions, imposed due to the sulphur transfer through the interface steel-slag during desulphurization process, the threshold conditions of instability for Marangoni convection in the desulphurization slag at 1873K are evaluated in the CaO-Al<sub>2</sub>O<sub>3</sub> system at ratios CaO/Al<sub>2</sub>O<sub>3</sub>=1.5 and 1.0, for sulphur concentration lower than the solubility limit and in conditions of fully liquid slag. Threshold critical values  $\Delta\sigma_c=(51-79.62)10^{-6}$  N/m, for the surface tension in slag and interfacial tension slag-steel, closed to the value  $\Delta\sigma_{crit}=30.748\cdot10^{-6}$  N/m obtained in steel and  $\Delta(S)_{crit}=(20-44.73)10^{-4}$  mass%, for the local fluctuations of sulphur concentration, were found for onset instability and Marangoni convection in slag, at the minimal value of the critical dimensionless solutal number  $Ma_s^c=80$ . There are small differences between numerical values of the quantities for threshold conditions obtained on the base of the surface tension of the slag and on the base of the interfacial tension steel-slag. The instability with onset of the turbulent convection is predicted to take place starting from values  $\Delta\sigma>(312.36-501.61)\cdot10^{-6}$  N/m, corresponding of  $\Delta(S)=(126-228.82)\cdot10^{-4}$  mass%. An enhancement coefficient of the mass transfer of sulphur at interface on the slag side is established in the conditions of the onset Marangoni flow and convection. The solutal parameter  $\Delta(S)$  is the most sensitive in contributing to instability conditions and in producing mixing effects in slag in a thickness layer  $\delta_{eff}$  at interface, by energy dissipation of Marangoni flow and helps to make important differences between conditions in slags C/A=1.5 and C/A=1.*

KEYWORDS: solutocapillary, desulphurization process, Marangoni effect

## 1. Introduction

During steel refining under slags, surface active elements such as oxygen and sulfur, induce additional interfacial convection flow, which is able to promote an enhancement of the mass transfer in certain conditions. The sulphur removal from a low carbon, aluminium killed steel, in a CaO-Al<sub>2</sub>O<sub>3</sub> base slag is described by the reaction:



The usual desulphurization slags belong to the system CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> in the range of mass% contents corresponding to ratios CaO/ Al<sub>2</sub>O<sub>3</sub>≈1-1.5 and low contents of SiO<sub>2</sub> and MgO (less than 5-10mass%).

Treatments under such slags are applied also to obtain clean steel, by the advanced removal of the non-metallic inclusions, especially of alumina. In the present paper, the contributions of the sulphur presence in slag during such treatments, to some aspects of the interfacial dynamics the process, are evaluated. Experimental data regarding the surface tension in slags and the interfacial tension in systems steel-slag reflect the influence of the chemical composition of the CaO-Al<sub>2</sub>O<sub>3</sub> slags, in the presence of sulphur<sup>1)</sup> or in absence of it<sup>2)</sup>. The analysis of the influence exerted by the chemical composition variations of the slag will be evaluated from the point of view of producing flow and convection, based on the Marangoni dimensionless number, in the form proposed in ref.<sup>3)</sup>, adapted for solutocapillary effect,



produced by the sulphur content, under the form of the rel.(1):

$$Ma_s = |\partial\sigma/\partial(S)| \cdot \Delta(S) \cdot L / \rho \cdot \nu \cdot D = |\partial\sigma/\partial(S)| \cdot \Delta(S) \cdot L / \eta \cdot D \quad (1)$$

Where:

$|\partial\sigma/\partial(S)|$  - absolute value of the concentration coefficient of the surface tension or of the interfacial tension, related to the sulphur as surface active component, in  $N \cdot m^{-1} \cdot (\text{mass}\%)^{-1}$  or in  $N \cdot m^{-1} \cdot (\text{mole fraction})^{-1}$ ;  $\Delta(S)$ -is a characteristic concentration difference across the liquid layer of slag or along its surface, expressed in terms of sulphur content, in mass % or mole fraction, or a characteristic concentration of the sulphur in slag ( $S_0$ );  $L$ - is a characteristic length, in m;  $\rho$ - density of the slag, in  $kg/m^3$ ;  $\nu$ -kinematic viscosity of slag,  $m^2/s$ ;  $D$ -diffusion coefficient of sulphur,  $m^2/s$ ;  $\eta = \rho \cdot \nu$ -dynamic viscosity of the slag, Pa·s.

Further, any reference to the content of any component will be taken as mass %. In the rel. (1) the absolute value for  $\partial\sigma/\partial(S)$  is an alternative method to the use of the (-) sign, to make positive the concentration coefficient of the surface tension or of the interfacial tension, whose values are negative when sulphur content increases in CaO/ Al<sub>2</sub>O<sub>3</sub> slags. The surface tension gradient upon the concentration of the sulphur acts as a share stress exerted by the interface on the adjoining bulk liquid (Marangoni stress) and will generate flow or it will alter an already existing one (Marangoni effect). In the solutal case, the variation of surface tension along an interface may be due to the appearance of a concentration gradient of a surface active solute, along the interface or perpendicular to it. In the first situation an instantaneous convection occurs, but in the second situation the flow occurs when an instability threshold is overcome.<sup>4)</sup> As it was mentioned,<sup>4)</sup> when a transfer of a superficial active solute between two immiscible fluid phases (liquid-liquid or liquid- gas), accompanied by a chemical reaction takes place, the interface becomes instable, even at low amplitudes of the local fluctuations of the solute concentration resulting long-waves length waves which represent a deformational monotonic mode. The diffusion of sulphur in slag is recognized, under certain conditions, as a limiting step of the global rate of sulphur transfer through the interface slag-steel. An additional mass transfer superimposed on the normal mass transfer, due to the confirmed interfacial convection was evaluated at 1873K, in the case of the sulphur transfer through the interface between liquid iron-slag (CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>).<sup>5)</sup> Also it was directly observed the inhibition of interfacial convection as consequence of the precipitation of calcium sulfide crystals in slag at the slag/metal interface.<sup>5)</sup> Although the increasing of sulphur content, in a similar slag, reduces the values of the surface and interfacial tension steel-slag, it was

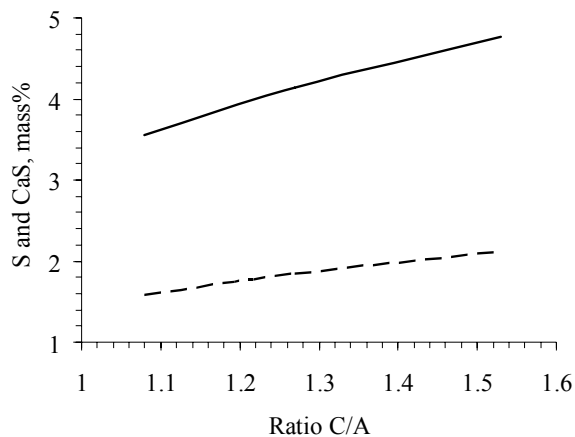
not reported an adverse effect on removal of CaS from the iron-melt in the presence in slag of 3-5% CaS, in the equilibrium conditions.<sup>1)</sup> An adequate knowledge of the dynamic processes at interfaces requires a deeper analysis of the specific possible contributions to the enhancement of mass transfer coefficient.<sup>6,7)</sup> The aim of the paper is to simulate the behaviour of the slag in the conditions of local instability and further, during the desulphurizing process, especially as occurrence of short-scale Marangoni convection. Also, it is intended to find the corresponding thresholds of sulphur concentration as inhomogeneity, the corresponding thresholds of the surface and interfacial tension and also to reveal aspects of dynamics of the slag. On this base, at least at a local scale, an evaluation of the Marangoni convection and the possible enhancement of the mass transfer coefficient will be made.

## 2. Relevant properties in the CaO-Al<sub>2</sub>O<sub>3</sub>-CaS system related to solutal Marangoni number

The existing experimental data are summarized in the **Table 1** where are presented also points derived from curves mentioned in references and statistical relations derived in the present paper. The abbreviations used in this paper are slag A, or (C/A=1,5), for slags containing 60%CaO-40% Al<sub>2</sub>O<sub>3</sub> and slag B, or (C/A=1), for slags containing 50%CaO-50%Al<sub>2</sub>O<sub>3</sub>. There are only few data on the density values in CaO-Al<sub>2</sub>O<sub>3</sub> slags at the two considered compositions (Tab.1) and they exhibit a relative dispersion.<sup>8-14)</sup> There are not any data regarding the influence of the sulphur content on the density and on the viscosity in slags based on the simple CaO-Al<sub>2</sub>O<sub>3</sub> system. Some trends of influence could be evaluated only by similitude, based on data in the system CaO-CaS-SiO<sub>2</sub>, at 1873K<sup>9,15)</sup> and in the system CaO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>-MgO-MnO-CaS at 1773K<sup>15,16)</sup>. On these bases, a negligible influence of the sulphur content on the viscosity in the system CaO-Al<sub>2</sub>O<sub>3</sub>-CaS at 1873K, is presumed for concentrations below the saturation limit. Values of the dynamic viscosity  $\eta$  for CaO-Al<sub>2</sub>O<sub>3</sub> slags, at C/A=1,5 and C/A=1, are given in tab.1<sup>(a-d)</sup>, mainly according to ref.<sup>15-18)</sup>. The adopted diffusion coefficient of sulphur in the slag was  $D_s = 2,9 \cdot 10^{-10} m^2/s$  (**Table1**), recomputed from data at 1773K,<sup>9)</sup> compared with another value  $D_s = 2,48 \cdot 10^{-10} m^2/s$  used in the ref.<sup>20)</sup>. The largely accepted experimental data on the sulphur solubility in CaO-Al<sub>2</sub>O<sub>3</sub> slags at 1873K are given in the ref.<sup>21)</sup>. Based on them, statistical regression relations have been obtained in this paper and they are given in the **Table 1** and represented in the **Figure 1**.

**Table 1.** Relevant quantities and parameters for CaO-Al<sub>2</sub>O<sub>3</sub> slags at 1873

Quantity, symbol, units	Value, reference
Density, $\rho$ , kg·m <sup>-3</sup> : 1)slagA, (C/A=1.5) 2)slagB, (C/A=1.0)	1) 2685 <sup>8,9)</sup> 2) 2710 <sup>10,11)</sup> , 2750 <sup>12,13)</sup> , 2870 <sup>14)</sup>
Dynamic viscosity, $\eta$ , Pa·s: 1)slagA 2)slag B	1) <sup>a)</sup> 0.1184 <sup>17)</sup> , <sup>b)</sup> 0.162 <sup>18)</sup> , <sup>c)</sup> 0.2735* 2) <sup>d)</sup> 0.197 <sup>18)</sup> , <sup>e)</sup> 0.23 <sup>17)</sup> . *Urbain model
Diffusion coefficient of sulphur $D_S$ , m <sup>2</sup> ·s <sup>-1</sup>	<sup>g)</sup> 2.9·10 <sup>-10,19)</sup> <sup>h)</sup> 2.48·10 <sup>-10, 20)</sup>
Solubility of sulphur in CaO-Al <sub>2</sub> O <sub>3</sub> slags as function of the ratio (C/A)	(%S)= 1,5492Ln(C/A)+1,4639 (%CaS)= 3,4717Ln(C/A)+3,2989
Surface tension( $\sigma$ ) dependence on sulphur content (S, mass%), in 10 <sup>-3</sup> N·m <sup>-1</sup>	$\sigma_A = 2.1217(\%S)^2 - 22.922(\%S) + 563$ $\sigma_B = 1.4781(\%S)^2 - 22.159(\%S) + 546$
Interfacial tension ( $\sigma_i$ ) dependence on sulphur content (mass%), in 10 <sup>-3</sup> N·m <sup>-1</sup>	$\sigma_{i,A} = 0.7353(\%S)^2 - 25.504(\%S) + 1284.8$ $\sigma_{i,B} = 0.7928(\%S)^2 - 31.548(\%S) + 1316.5$
Ratio $R = \sigma_i/\sigma$ between the interfacial tension ( $\sigma_i$ ) and the surface tension ( $\sigma$ ).	$R_A = -0.0076(\%S)^2 + 0.0489(\%S) + 2.282$ $R_B = -0.0051(\%S)^2 + 0.0425(\%S) + 2.412$
Ratio $M = [\partial\sigma_i/\partial(S)]/[\partial\sigma/\partial(S)]$ , between the sulphur concentration coefficient of the interfacial tension and of the surface tension.	$M_A = 0.0613(\%S)^2 + 0.1056(\%S) + 1.1179$ $M_B = 0.0221(\%S)^2 + 0.1148(\%S) + 1.4247$

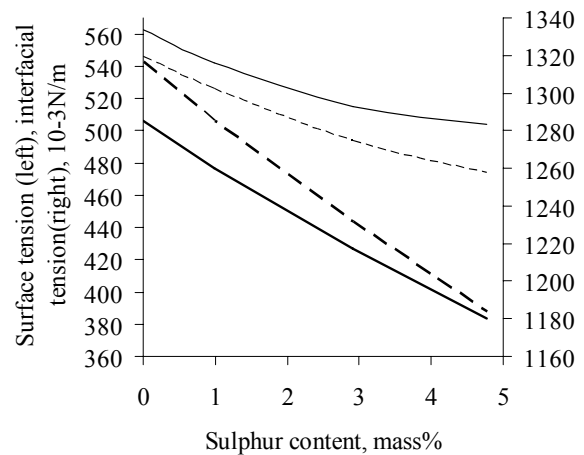


**Fig. 1.** Solubility limit of sulphur (—) and of CaS(---) in slags CaO- Al<sub>2</sub>O<sub>3</sub> at 1873K, as function of the ratio C/A, based on data from ref.[21].

The maximal solubilities at the temperature 1873K, obtained from the regression relation are S=2,092% in slag C/A=1,5 and S=1,464% in slag C/A=1, identical with experimental values<sup>21)</sup>.

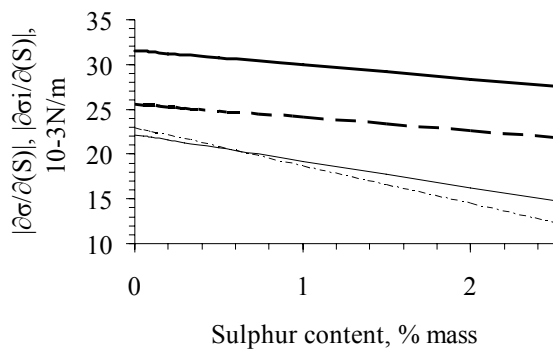
Data regarding the influence of the sulphur content in terms of mass content on the surface tension of slags in the system CaO-Al<sub>2</sub>O<sub>3</sub> and on the interfacial tension steel-slag were found only in the ref.<sup>1,2)</sup> at temperature 1873K, for slag A and B.

Based on them, using points derived from curves, statistical relations were derived (Table 1) for the dependence upon sulphur content, of the surface tension in slags and of the interfacial tension steel-slag (Figure 2).



**Fig. 2.** Influence of the sulphur content in slag CaO-Al<sub>2</sub>O<sub>3</sub>-CaS at 1873K, on the surface tension of the slag and on the interfacial tension slag-steel. Surface tension (---) C/A=1.5; (---) C/A=1. Interfacial tension (—) C/A=1.5; (---) C/A=1.

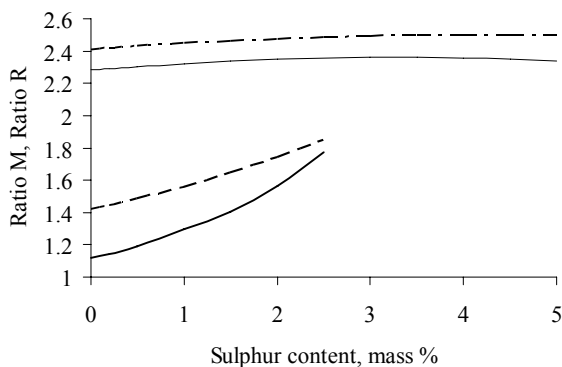
In the Figure 3 it is shown the variation of the concentration coefficients of the surface tension  $|\partial\sigma/\partial(S)|$ , and of the interfacial tension  $|\partial\sigma_i/\partial(S)|$  upon the sulphur content in slag for slags C/A=1.5 and C/A=1. In the reported experiments<sup>1,2)</sup> a low carbon steel (0.11%C; 0.44%Si; 1.32%Mn; 0.022%P; 0.035%S; 0.0045%O; 0.0115%N) and ARMCO<sup>®</sup> iron have been used. According to the Figure 2, there is a closed relation between the interfacial tension in the system steel-slag (CaO-Al<sub>2</sub>O<sub>3</sub>-CaS) and the surface tension in the slag CaO-Al<sub>2</sub>O<sub>3</sub>-CaS, at 1873K.



**Fig. 3.** Variation of the concentration coefficients of the surface tension  $|\partial\sigma/\partial(S)|$ , and of the interfacial tension  $|\partial\sigma_i/\partial(S)|$  upon the sulphur content in slag.

$|\partial\sigma/\partial(S)|$  ———  $C/A=1.5$ ; - - -  $C/A=1$ ;  
 $|\partial\sigma_i/\partial(S)|$  — · - ·  $C/A=1.5$ ; · · ·  $C/A=1$ ;

This is expressed using a coefficient  $R$ , representing the ratio between the two quantities, computed for each value of the ratio  $C/A$  (Figure 4). Values of  $R_A$  and  $R_B$  show a similar evolution up to contents of 1.5-2.0%S, which are frequent at the end of desulphurization process at a plant scale, applied to low carbon steels under slags, based on  $\text{CaO-Al}_2\text{O}_3$  system. Respecting the ratios  $R_A$  and  $R_B$ , it would be possible a treatment of some aspects regarding the interfacial tension slag-steel on the basis of the surface tension in the slag.



**Fig. 4.** Evolution of the ratio  $R=\sigma_i/\sigma$  and of the ratio  $M=\partial\sigma_i/\partial(S)/\partial\sigma/\partial(S)$  upon the sulphur content in slag  $\text{CaO-Al}_2\text{O}_3\text{-CaS}$  at 1873K;  $\sigma$ - surface tension in slag,  $\sigma_i$ -interfacial tension steel- slag,  $\partial\sigma_i/\partial(S)$ -concentration coefficient of the interfacial tension,  $\partial\sigma/\partial(S)$ - concentration coefficient of the surface tension.

Ratio  $R$  (---)  $C/A=1.5$ ; (- · - · -)  $C/A=1$ .  
Ratio  $M$  (——)  $C/A=1.5$ ; (- - -)  $C/A=1$ .

In general terms this would suggest that in order to study the solutal effects in the desulphurization slag, due to sulphur content, besides the classical treatment according to the two layers model (slag-steel) with an interface between them, the "one layer" model would be applicable in the conditions of introducing factors representing the essential aspects of the connection with the real system. In this sense it is to be taken into account the variation of the concentration coefficients of the surface tension  $|\partial\sigma/\partial(S)|$ , and of the interfacial tension  $|\partial\sigma_i/\partial(S)|$  upon the sulphur content in slag, shown in Figure 3 and the evolution of the ratio  $M = \partial\sigma_i/\partial(S)/\partial\sigma/\partial(S)$ , between the concentration coefficient of the interfacial tension and the concentration coefficient of surface tension. In Figure 4, both relations are shown, being derived in this paper from initial relations given in Table 1 and represented in the Figure 1. The quantity viscosity is sensitive to the local precipitation of  $\text{CaS}$  and exerts an influence on the local dynamics induced by solutal effects of the sulphur content. Therefore, in this paper the slag will be considered at concentrations of sulphur in slag, far from saturation, being fully liquid.

### 3. Parameters for the onset of solutal Marangoni instability in slag due to sulphur

If the thermal equilibrium in the system steel-slag is considered and the electrical phenomena at interface are neglected, the instability/stability at the interface on the slag side is determinate by the competition between the actions of gravity, diffusion/viscosity and capillarity due to the solutal effects, further called as solutocapillary effects or solutocapillarity. In this paper the slag will be considered according to the concept of one layer model. The slag is taken as a separate fully liquid phase, connected to the desulphurization process by the effective transfer coefficient of sulphur ( $k_{\text{eff}}$ ), also by the evolution of the surface tension and of the interfacial tension steel- slag. The Marangoni solutal effect acts at macroscale, by imposing gradients of concentration through external actions<sup>22)</sup>, or at microscale when local gradients of concentration appear due to local inhomogeneities of different origins, along the interface or across it. The actions of gravity, diffusion/viscosity (called also viscous diffusion) and solutocapillarity are competing according to their time scales:

- the gravitational time scale,  $t_{\text{grav}}^2 = L/g$  (2)

- the diffusive-viscosity time scale,  
 $t_{\text{diff}}^2 = t_{\text{diff}} \cdot t_{\text{visc}} = (L^2/D)(L^2/\nu) = L^4/\nu \cdot D$  (3)

- the solutocapillary time scale,  
 $t_{\text{solutocap}}^2 = \rho \cdot L^3 / |\partial\sigma/\partial(S)| \cdot \Delta S$  (4)



The solutocapillarity is a factor of instability while the viscosity/diffusion and gravity act as stabilizing factors by damping the effects of this instability. Viscous diffusion acts to dampen the concentration fluctuations and the associated fluid flow. The gravity acts physically to flatten the interface and thus to stabilize the deformational perturbations. All these actions are competing and the dominating action in this competition is the one having the shortest time scale. When solutocapillary effects are analysed in local dynamics, the conditions when solutocapillarity time scale is the shortest, among the others, must be evaluated. The overcoming of the neutral stability conditions, mainly of a threshold, leads to the hydrodynamic instability of the interface on short scale and on long-scale, caused by the surface tension gradients (the Marangoni effect). This instability presents different convective patterns as regular convective structures (rolls, hexagons), interfacial waves and chaotic convective motions in the vicinity of the interface, called also interfacial turbulence. In this paper only the short scale of solutal capillary effects are considered, in the form of local Marangoni flow and adjacent convection, because the most part of observed waves at steel-slag interface are short-wavelength waves<sup>23)</sup> and there are not satisfactory explanations for this. Taking into consideration values of the characteristic difference  $\Delta(S)$ , representing a moderate fraction from the limit of sulphur solubility, possible to appear by normal local fluctuation of factors, it remains to consider the value of the coefficient  $|\partial\sigma/\partial(S)|$  of interfacial tension variation with concentration and the magnitude of the characteristic length (L). The characteristic length scale(L) is very important when the characteristic time scales of different actions, involved in the appearance of instability, are computed. The characteristic length can be scaled using the dimensionless number Galilei, used in fluid dynamics and defined by the following equivalent relations:

$$Ga = \text{gravity force/viscosity force} = Bo/C \quad (5)$$

$$Ga = t_{diff}^2/t_{grav}^2 = g \cdot L^3/\nu \cdot D \quad (6)$$

The dimensionless number Bond (Bo) is the most common comparison of gravity and surface tension effects, usually used to find the characteristic length scale in complex scaling problems. The dimensionless Bo number allows a comparison of the effect of surface tension in making a spherical meniscus with the effect of gravity in keeping the surface flat over length scales of order L. A value  $Bo < 1$  indicates that surface tension dominates. The crispation dimensionless number (C) represents the relative effect of viscous/ diffusion forces versus surface tension acting across an interface between a liquid and a gas, or between two immiscible liquids, on a certain thickness. At values  $C < 10^{-5}$ , flow is strongly dominated by surface tension forces. This is the case

of the system steel- slag ( $CaO-Al_2O_3$ ) which presents high value of the interfacial tension, also of the desulphurization slag  $CaO-Al_2O_3$ , containing sulphur in the limits of solubility. The characteristic length scale is frequently understood as depth, considered from the free surface or from an interfacial surface towards inside of a liquid. It can be equally considered also as a non-oriented distance from a point on interface along it, because of the radial aspect of the diffusion. The neutral stability boundary, for monotonic instability mode, giving values of the  $Ma(k)$ -Marangoni number is a function of the wave number k. The neutral curve has only one minimum  $Ma_s^c$  for critical values  $k_c \neq 0$ , at around around  $k_c = 1.993$ , for the dimensionless numbers Biot solutal  $Bi_s = 0$  and adsorption  $N_a = 0$  which correspond to the moments just before the onset of the convection due to solutal effect. By linear analysis, a minimal value for  $Ma_s^c = 79.6 \approx 80^{(3)}$  was computed. For convenience a round value  $Ga = 3/2Ma_s^c = 120$  is adopted, considering that it is large sufficiently, so that the response time of gravity is short enough that deformational perturbations are quickly stabilized, and the short scale convection, due to solutal perturbations, is the primary instability. Scaling the characteristic length (L) using the value of  $Ga = 120$  at  $Ma_s^c = 80$  and taking the normal gravity acceleration  $g = 9,81 m^2/s$ , the following relations are obtained for the threshold of stability/instability and for convection onset:

$$L = (Ga \cdot \nu \cdot D \cdot g^{-1})^{1/3} = (3/2Ma_s^c \cdot \nu \cdot D \cdot g^{-1})^{1/3} = 2.30411(\nu \cdot D)^{1/3}, \text{ m} \quad (7)$$

$$Ma_s^c = 2/3Ga = 2/3g \cdot L^3 \cdot \nu \cdot D \quad (8)$$

Based on the rel. (1)(7)(8), the resulting critical thresholds of concentration  $\Delta(\%S)^c$  and of the surface tension  $\Delta\sigma_c$  for the value of  $Ma_s^c = 80$  are given by the following relations:

$$\Delta(S)^c = Ma_s^c \cdot \rho \cdot \nu \cdot D \cdot L^{-1} |\partial\sigma/\partial(S)|^{-1} = 34.721 \rho \cdot (\nu \cdot D)^{2/3} \cdot |\partial\sigma/\partial(S)|^{-1} \quad (9)$$

$$\Delta\sigma_c = |\partial\sigma/\partial(S)| \cdot \Delta(S)^c = Ma_s^c \cdot \rho \cdot \nu \cdot D \cdot L^{-1} = 34.721 \rho \cdot (\nu \cdot D)^{2/3} \quad (10)$$

The parameters of the onset solutal instability depend on the physical data  $\rho$ ,  $\nu$ ,  $D$  and on the coefficient of surface/ interfacial tension variation with concentration of sulphur. The values of the characteristic length scale L and of the parameters  $\Delta\sigma_c$ ,  $\Delta(S)^c$  are given in **Table 2** for available values of density  $\rho$  and dynamic viscosity  $\eta$  of  $CaO-Al_2O_3$  slags at 1873K and the established dependences for  $\partial\sigma/\partial(S)$  and  $\partial\sigma_i/\partial(S)$ , given in **Table 1**.

#### 4. Parameters of solutal Marangoni effect acting in the local mass transfer enhancement

The Marangoni flow, at a velocity scaled by Marangoni velocity ( $V_M = |\partial\sigma/\partial(S)|/\nu$ ) will affect the



movement of the layers beneath the interface, on the side of the slag, up to a certain depth considered from the flat surface.

The characteristic thickness of the layer, within which the velocity changes significantly, due to the dissipation of the movement energy is given in the relation (11), according to the ref.<sup>24</sup>:

$$\delta_v \cong (v_0 \tau)^{1/2}, \text{ m} \quad (11)$$

where  $v_0$ -kinematic viscosity;  $\tau$ -time scale of the tangential motion, here this being the solutocapillary time scale taken only as the dominant action.

The significant velocity changes must be understood as a decrease with one order of magnitude. Inserting the time scale of Marangoni motion, given by the relation (3) the following relation is obtained:

$$\delta_v \cong \{v_0[\rho \cdot L^3 / \partial\sigma / \partial(S)] \cdot \Delta(S)\}^{1/2} = v_0^{1/2}[\rho \cdot L^3 / \partial\sigma / \partial(S)]^{1/4} \cdot \Delta(S)^{1/4}, \text{ m} \quad (12)$$

The characteristic thickness, corresponding to critical conditions is the following:

$$\delta_v^c \cong v^{1/2}(\rho \cdot L^3 / Ma_s^c \cdot \rho \cdot v \cdot D \cdot L^{-1})^{1/4} = 0.53474(Ma_s^c)^{1/12}(v^7 \cdot D)^{1/12} = 0.7704v^{0.58(3)} \cdot D^{0.08(3)}, \text{ m} \quad (13)$$

**Table 2.** Values of relevant parameters in characterization of the influence of the sulphur content in instability threshold and onset of Marangoni convection in desulphurization slags CaO-Al<sub>2</sub>O<sub>3</sub> at 1873K.

Slags data Characteristic Quantities, parameters	C/A=1.5; ρ=2685kg·m <sup>-3</sup>		C/A=1.0; ρ=2710kg·m <sup>-3</sup>	
	Surface tension	Interfacial tension	Surface tension	Interfacial tension
Characteristic length scale L, 10 <sup>-6</sup> m	a) 53.881; b) 59.882; c) 71.227		d) 63.651; e) 67.529	
$\Delta\sigma_{crit}=[(\partial\sigma/\partial(S))\Delta(S)]_{crit}$ , 10 <sup>-6</sup> N·m <sup>-1</sup>	a) 51.01; b) 62.83; c) 89.09		d) 71.81; e) 79.62	
Characteristic thickness $\delta_v^c$ , 10 <sup>-6</sup> m	a) 355.76; b) 427.15; c) 579.77		d) 476.20; e) 521.23	
Concentration coefficients $\partial\sigma/\partial(S)$ , $\partial\sigma/\partial(S)$ , 10 <sup>-3</sup> N·m <sup>-1</sup> ·(mass% S) <sup>-1</sup>	4.2434(S)- -22.922	1.4706(S)- -25.504	2.9562(S)- - 22.159	1.5856(S)- -31.548
Critical concentration of sulphur $\Delta(S)_{crit}$ , 10 <sup>-4</sup> mass % C/A=1.5: 0-2.092(%S) C/A=1.0: 0- 1.464(%S)	a) 22.25-36.32 b) 27.41-44.73 c) 38.86-63.43	a) 20.0-22.74 b) 24.63-28.0 c) 34.93-39.72	d) 32.41-40.27 e) 35.93-42.41	d) 22.76-24.57 e) 25.24-27.24
Minimal concentration of sulphur $\Delta(S)$ , (10 <sup>-4</sup> %) for onset instability with turbulent convection ( $\varepsilon=6.3$ )	a) 140.18-228.82 b) 172.68-281.8 c) 244.82-399.61	a) 126-143.26 b) 155.17-176.46 c) 220.06-250.24	d) 204.18-253.70 e) 226.36-267.18	d) 143.4-154.8 e) 159-171.6

Quantities and parameters in **Table 2**, noted <sup>a),b),c), d),e)</sup>, followed by computed values corresponding to the same noted dynamic viscosities in **Table 1**.

According to rel. (12), the increasing of the value of  $\Delta\sigma = |\partial\sigma/\partial(S)| \cdot \Delta(S) > \Delta\sigma_c$  will lead to a local and temporary decreasing of the value of  $\delta_v$ . On Earth ( $g=9.81\text{m/s}^2$ ), the critical values of the quantities involved in the threshold conditions for onset of instability at  $Ma_s^c=80$ , that means L,  $\Delta\sigma_c$ ,  $\delta_v^c$ , at an established temperature, depend only upon the physico-chemical values of the slag,  $v$ -kinematic viscosity of slag and D- mass diffusion coefficient of sulphur in slag. These values are presented in **Table 2**, together with other important parameters in the evaluation of the Marangoni convection, also in other conditions than those critical. The magnitude of  $\delta_v$  is the same with the diffusion layer thickness and decreases when the time scale of the tangential motion( $\tau$ ) decreases. The obtained values of  $\delta_v^c$  (**Table 2**) sustain that the Marangoni convection by natural gradients of surface/interface tension, including those solutal of different origins as interfacial reactions or the transport of a surface active solute through interface, acts at microscale, in interface layers of thickness below 10<sup>-3</sup>m. A comparison with data obtained for a low carbon steel, aluminium killed, similar as composition to the steel

in ref.<sup>1,2)</sup>, at 1873K leads to interesting results. In this case taking the for the kinematic viscosity a value  $v=5.425 \cdot 10^{-7}\text{m}^2/\text{s}$ ,<sup>25)</sup>  $\rho= 6970\text{kg}/\text{m}^3$  and the sulphur coefficient in steel  $D=4.4 \cdot 10^{-9}\text{m}^2/\text{s}$ ,<sup>26)</sup> the similar critical values for an unperturbed flat steel layer of infinite depth are  $L=25.972 \cdot 10^{-6}\text{m}$ ,  $\Delta\sigma_{crit}=30.748 \cdot 10^{-6}\text{N}\cdot\text{m}^{-1}$ ,  $\delta_v^c=32.911 \cdot 10^{-6}\text{m}$ . It is obvious the nearness of the critical value for the instability threshold of the quantity  $\Delta\sigma_{crit}$  for slag and steel, and the values of the characteristic length L in steel are half from the values in slag. The major differences are observed when the values of  $\delta_v^c$  are compared. In both phases, the interfacial instability of solutocapillary origin, could arise almost simultaneously and further, this could be a source of self-sustained capillary effects, including the appearance of the strong turbulent, up to violent aspects at interface, with favourable consequences for desulphurization of steels under adequate slags. A mass transfer coefficient of sulphur through the interface between slag and steel  $k_{eff}=5.52 \cdot 10^{-5}\text{m}\cdot\text{s}^{-1}$  is reported,<sup>5)</sup> at 1873K in systems containing lime saturated slag (CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>), under definite and very moderate flow conditions of liquid aluminium-deoxidized iron, induced by argon

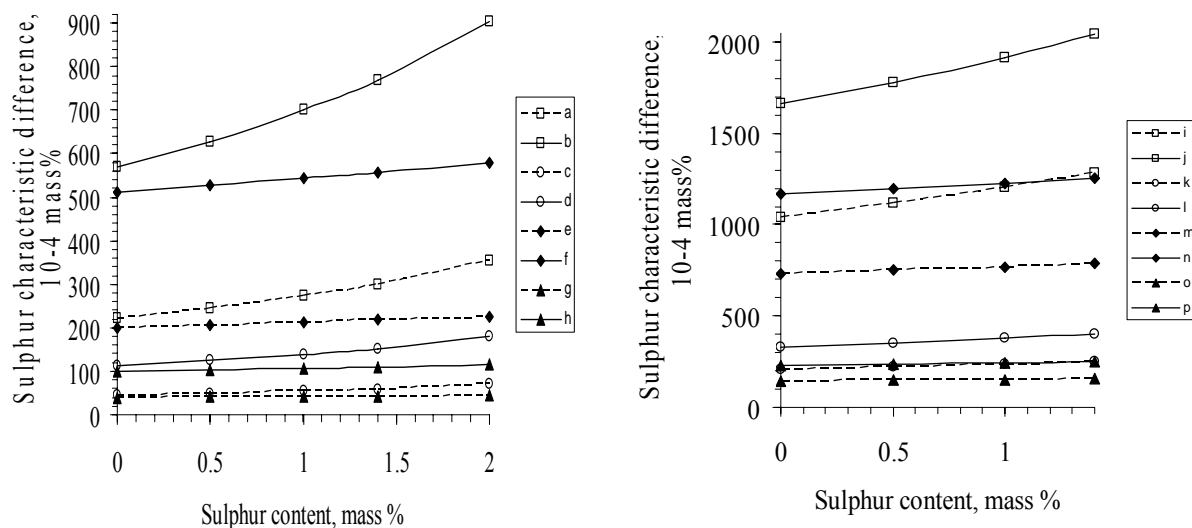
bubbling. This value could be obtained by the boundary-layer theory applied to the metal/slag interface. <sup>5)</sup>Taking a thickness of the liquid film at interface in steel  $\delta=(100-200)\cdot 10^{-6}\text{m}$ , in conditions of local interfacial turbulence and the mass diffusion coefficient of sulphur in liquid steel  $D_{[S]}=4.4\cdot 10^{-9}\text{m}^2/\text{s}$ , it results a mass transfer coefficient in the liquid steel  $k_{\text{steel}}=(2.2-4.4)\cdot 10^{-5}\text{m}^2/\text{s}$ , confirming by comparison with the value of  $k_{\text{eff}}$  that the limiting step of the sulphur transfer is the sulphur transport in slag, which opposes the main resistance to this transfer. According to the film layer theory, taking into account the diffusion of sulphur through the limit layer in slag as transport mechanism in quasi-static conditions, the mass transfer coefficient is  $k_D = D/\delta$ . A value  $D_{[S]}=2.9\cdot 10^{-10}\text{m}^2\text{s}^{-1}$  at 1873K is computed from data at 1718K<sup>19)</sup> and a thickness of the liquid film in the slag  $\delta=200\cdot 10^{-6}\text{m}$  is obtained in dynamic conditions.

It results a mass transfer coefficient, by the simple mass diffusion in slag for sulphur,  $k_D=1.45\cdot 10^{-6}$

$\text{ms}^{-1}$ . in quasi-static conditions and an enhancement factor of the mass transfer  $\phi=k_{\text{eff}}/k_D \cong 38$ . This leads to the necessity to consider also another type of mass transfer which assumes that mass transfer is a nonsteady-plate process, in this case due to the Marangoni flow and convection by solutocapillary effects. This could be the boundary diffusion layer theory but in a modified vision.

The main modification consists in considering the mass transfer in a boundary layer at interface on the slag side where the surface tangential stress due to sulphur solutal Marangoni effect, scaled by Marangoni speed, increases the mass transfer of sulphur. This takes place by energy dissipation of the slag flow, towards the bulk, in a boundary layer of thickness  $\delta_{\text{eff}} = \delta_v$ , this last being given by the rel. (12).

In **Figure 5 a** and **5b** are established the conditions of sulphur characteristic concentration,  $\Delta(S)$  leading to the obtaining of values  $\delta_{\text{eff}}=200\cdot 10^{-6}\text{m}$  and  $\delta_{\text{eff}}=300\cdot 10^{-6}\text{m}$ . Values  $\delta_{\text{eff}}=200\cdot 10^{-6}\text{m}$  are obtained in a restricted area of accessible conditions.



**Fig. 5. a, b.** Computed values of the sulphur characteristic difference  $\Delta(S)$  for obtaining imposed values of effective layer thickness ( $\delta_{\text{eff}}$ ), in  $\text{CaO-Al}_2\text{O}_3$  slags at 1873, as function of sulphur concentration in slag, at  $C/A=1.5$  (fig. 5a) and  $C/A=1.0$  (fig. 5b), for quantities and parameters from tab.1 and tab.2. 1)  $\delta_{\text{eff}}=200\cdot 10^{-6}\text{m}$  (a,b,e,f-fig. 5a) (i,j,m,n-fig. 5b); 2)  $\delta_{\text{eff}}=300\cdot 10^{-6}\text{m}$  (c,d,g,h-fig. 5a) (k,l,o,p-fig. 5b); 3) considering the sulphur concentration coefficient of surface tension(a,b,c,d-fig. 5a)(i,j,k,l-fig. 5b); 4) considering the sulphur concentration coefficient of interfacial tension(e,f,g,h-fig. 5a) (m,n,o,p-fig. 5b); 5)  $\eta=0.1184\text{Pa}\cdot\text{s}$ (a,c,e,g-fig. 5a); for  $\eta=0.162\text{Pa}\cdot\text{s}$ (b,d,f,h-fig. 5a);  $\eta=0.197\text{Pa}\cdot\text{s}$  (i,k,m,o-fig. 5b);  $\eta=0.23\text{Pa}\cdot\text{s}$  (j,l,n,p-fig. 5b).

Boundary layers  $\delta$ , also the scales of phenomena and instabilities are different for different species and processes and co-exist many in the same time. Therefore it must be mentioned once again that in this paper only the influence of sulphur is analysed, as solute in the mentioned slag. In these conditions, the mass is transferred through the interface not only by

molecular diffusion but also by turbulent diffusion, determining a kinetic characteristic under the form of an effective diffusion coefficient  $D_{\text{eff}}$ , taken into account as the sum of the molecular diffusion ( $D$ ) and the turbulent diffusion ( $D_t$ ):

$$D_{\text{eff}}=D+D_t=D(1+D_t/D) \quad (14)$$



In fully turbulent conditions, considered at local scale, due to high values of Marangoni speed, the transfer by turbulent diffusion is dominant and at weak tangential surface stress, the main mass transfer mechanism is the molecular diffusion. In intermediary conditions both two mechanisms participate at the mass transfer, in a sensitive manner.

Dividing the rel (14) at the effective thickness  $\delta_{eff}$  it is obtained:

$$D_{eff}/\delta_{eff} = D/\delta_{eff} + D_t/\delta_{eff} \quad (15)$$

$$\text{Noting } k_{eff} = D_{eff}/\delta_{eff}; k_D = D/\delta_{eff}; k_t = D_t/\delta_{eff}, \quad (16)$$

$$\text{the relation (15) becomes:} \quad (17)$$

$$k_{eff} = k_D + k_t = k_D(1 + k_t/k_D)$$

An adequate effective thickness of the boundary layer  $\delta_{eff}$  will be convenient simultaneously for molecular and the turbulent diffusion and could be the thickness  $\delta_v$  (rel 12.) for the dynamic case by Marangoni effect. In this paper the ratio  $\Delta\sigma/\Delta\sigma_c$  is proposed as a measure for the ratio  $k_t/k_D$ . Besides the known significance of  $\Delta\sigma_c$ ,  $\Delta\sigma$  is variation of the surface tension of the slag at a value  $\Delta(S) > \Delta(S)^c$  at the considered sulphur concentration of slag in bulk. A relation, giving the effective mass transfer coefficient  $k_{eff}$ , as a function of the mass transfer coefficient by diffusion  $k_D$  and of the variation of the interfacial tension  $\Delta\sigma$ , exceeding a certain critical value  $\Delta\sigma_{crit}$ , was proposed<sup>28)</sup>, in the following form:

$$k_{eff} = k_D[1 + \alpha(\Delta\sigma - \Delta\sigma_{crit})] \quad (18)$$

Taking into consideration the the proposal made in the present paper and identifying here  $\Delta\sigma_{crit}$  from rel. (18), by  $\Delta\sigma_c$  from the rel (10), the relation (18) can be written under other useful forms:

$$k_{eff} = k_D[1 + \alpha(\Delta\sigma - \Delta\sigma_c)] = k_D[1 + \alpha\Delta\sigma_c(\Delta\sigma/\Delta\sigma_c - 1)] = k_D[1 + \alpha\Delta\sigma_c(Ma/Ma_c - 1)] \quad (19)$$

$$k_{eff}/k_D = 1 + k_t/k_D = 1 + \alpha\Delta\sigma_c(Ma/Ma_c - 1) \quad (20)$$

The proportionality constant  $\alpha$  has the dimension [m/N] and in the present case it has very high values because of the very small values of  $\Delta\sigma_c$  (Tab2). It was established that in the above mentioned condition, the distance from the threshold of the instability is given by a parameter  $\varepsilon$ .<sup>29)</sup>

$$\varepsilon = (Ma_s - Ma_s^c)/Ma_s^c \quad (21)$$

At values  $2.1 < \varepsilon < 6.3$ , convection consists in rolls and hexagonal cells. The turbulent convection is installed at values  $\varepsilon > 6.3$ <sup>29)</sup> and consists in mixed rolling cells and hexagonal cells, becoming directly turbulent, even chaotic at higher values of  $Ma_s$  and respective of  $\varepsilon$ . The analysis of instability threshold and convection at high and very high Marangoni numbers needs a specific treatment. It results from rel. (18)–(21):

$$k_{eff} = k_D(1 + \alpha \cdot \varepsilon \cdot \Delta\sigma_{crit}) = k_D(1 + \beta\varepsilon) \quad (22)$$

The rel.22 makes a reunion of the specific and critical conditions by the product between  $\beta = \alpha \cdot \Delta\sigma_{crit}$  and the distance from the threshold of instability  $\varepsilon$ , in the local enhancement of the mass transfer coefficient.

The rel.(22) contains factors which can be computed, including the proportionality constant  $\alpha$ . For  $\varepsilon = 6.3$ ,  $k_{eff} = 5.52 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1.5} \Delta\sigma_{crit}$  (Table1),

$D_{(S)} = 2,9 \cdot 10^{-10} \text{ m}^2/\text{s}$  (tab1),  $\delta_{eff} = 200 \cdot 10^{-6} \text{ m}$ , it results  $\alpha = 115349 \text{ m/N}$  and  $\beta = 5.88$  for slags  $C/A = 1.5$ . The use of coefficient  $\beta$  is more convenient for magnitude and missing of dimension reasons.

The contribution of the surface and interfacial tension, by their individual sulphur concentration coefficients to the development of surface driven instability and convection, depends upon the magnitude of the sulphur characteristic concentration  $\Delta(S)$ . It is remarkable the great sensitivity of the parameter  $\Delta(S)$  to the cumulated action of the involved factors giving its value. Separately, each of these factors does not differ too much from one set of conditions to another (Table 1 and Table 2).

The effective influence of the solutal effect of sulphur, exerted by the threshold of the characteristic difference of concentration of sulphur in slag  $\Delta(S)$  and of the influence exerted by the slag characteristics results more clearly, in from Figure 5a and 5b which were built to obtain imposed values of effective layer thickness- $\delta_{eff}$  ( $200 \cdot 10^{-6} \text{ m}$  and  $300 \cdot 10^{-6} \text{ m}$ ) in CaO-Al<sub>2</sub>O<sub>3</sub> slags at 1873K, as function of sulphur concentration in slag, at  $C/A = 1.5$  and  $C/A = 1$ .

The values of  $\delta_{eff}$  were selected because of their large acceptance as limits of magnitude of the boundary layers thickness, included in diffusive problems, in many metallurgical liquid systems strongly stirred. The local dissipative flow, due to the short scale and short wave-length waves Marangoni convection, at the mentioned characteristic length scales  $L_c$  (Table 2) and  $\delta_{eff}$  (including also other values than the two considered) represents an important stirring factor, intensifying the mass transfer. As it is shown in Figure 5a, b the range of the required values of  $\Delta(S)$ , for the same set of values of factors, varies within a maximal range up to 12-15 times considering the sulphur concentration coefficient of surface tension and the sulphur concentration coefficient of interfacial tension in the case of slag  $C/A = 1.5$ . This parameter, involved in the threshold conditions of instability, represents in fact a threshold value of local fluctuation of the concentration of sulphur, taking into consideration its possible origins and the mechanisms which average these fluctuations. The magnitude of the local effective fluctuations, which cannot be however high, leading to an effective influence, could be considered statistically in the range up to about 3- 4% from the maximal solubility of sulphur in slag and these are taken into account as reference values in the present paper. At higher contents of sulphur in slag, closed to the maximal solubility in slag, a higher level of the sulphur fluctuation of concentration could overcome locally this solubility and the amount of sulphur





exceeding its precipitates as CaS, thus modifying the local dynamic viscosity of slags. Such a situation must be evaluated separately as consequences in instability and mass transfer enhancement. An important reason for which only local and small amplitude of sulphur concentration fluctuations are taken into account in this paper is that, at higher values of these, local gradients of other quantities become of a significant magnitude for the instability conditions and deviate from the conditions of the present analysis. The computed data show an increased sensitivity of  $\Delta(S)$  values upon the sulphur content in slags when sulphur concentration coefficient of surface tension is taken into account according to curves (a,b,c,d-**Figure 5a**) and (i,j,k,l-**Figure 5b**) and a less important sensitivity when the sulphur concentration coefficient of interfacial tension is considered, according to curves (e,f,g,h-**Figure 5a**) and (m,n,o,p-**Figure 5b**), mainly determined by the regression relations established statistically (**Table 1**).

The considered values of the dynamic viscosities of slags exert a major influence in the obtained values of  $\Delta(S)$  at the same value of  $\delta_{\text{eff}}$  for the considered slags. In slag  $C/A=1.5$ , considering the case  $\delta_{\text{eff}}=200 \cdot 10^{-6}\text{m}$  and the sulphur concentration coefficient of surface tension, a value  $\Delta(S)=215-320 \cdot 10^{-4}$  mass % is obtained for the dynamic viscosity  $\eta=0.1184\text{Pa}\cdot\text{s}$  and a value  $\Delta(S)=570-900 \cdot 10^{-4}$  mass % is obtained for the dynamic viscosity  $\eta=0.162\text{Pa}\cdot\text{s}$ . Both values of  $\Delta(S)$  seem to be acceptable according to the before mentioned aspects regarding the possible magnitude of the sulphur concentration fluctuations considered. In slags  $C/A=1$ , mainly because of the higher values of the dynamic viscosities, the required values of  $\Delta(S)$  to produce mixing effects in the diffusion of boundary layers at interface are too high to be accepted when sulphur concentration coefficient of surface tension is taken into account (**Figure 5b-i,j**) also for considering the sulphur concentration coefficient of interfacial tension (**Figure 5b-n,m**). To all these aspects it must be added the lower value of the sulphur solubility limit  $S=1.464\text{mass}\%$  (**Table 1**), which acts as a prohibitive factor in the range of higher values of sulphur contents in slag  $C/A=1$ .

## 5. Conclusions and commentaries

Using the one layer model of slag, it was simulated the local possible dynamic behaviour of the interface slag-steel on the slag side, when the sulphur content in slag increases during desulphurization of steel under slag. For the considered data, it was found that despite the major differences in magnitude between the surface tension of the slag  $\text{CaO-Al}_2\text{O}_3$  and of the interfacial tension steel –slag the dependences upon the sulphur content at both two considered compositions, the two quantities present a

quasi-parallel evolution up to 1.5-2mass% sulphur contents in slag, also their concentration coefficients for more than this, the sulphur concentration of the surface tension of the slag  $\text{CaO-Al}_2\text{O}_3$  and the interfacial tension steel –slag are very closed as values. Therefore only them alone can not contribute to clarify major aspects of solutocapillarity effect and its possible contributions to local interfacial dynamics of slag and further to mass transfer aspects, especially of sulphur. In established conditions where the solutocapillary Marangoni effect has the smallest time of action, the instability threshold consisting in values for the critical differences  $\Delta\sigma_c$  and  $\Delta(S)^c$  were established for onset solutal Marangoni convection in slag, for critical value of the solutal Marangoni number  $Ma_s^c=80$  and wave number  $k_c=1.993$ . Despite their differences, the threshold found values in slags  $C/A=1.5$  and  $C/A=1$ ; they are very closed and depends only on the physico-chemical data of the slag, density  $\rho$ , kinematic viscosity  $\nu$  and mass diffusion coefficient of sulphur in slag  $D_s$ , at the considered temperature. Values of the local sulphur content differences taken as local possible fluctuations of sulphur content in the threshold of instability for onset the Marangoni flow and convection by in minimal conditions of monotonic neutral stability, are of order of tens of ppm sulphur, being below the usual contents of sulphur in slags and of the precision of usual analyse is methods. The threshold of sulphur concentration and of the variation of surface tension/interfacial tension for onset the turbulent flow and further for the chaotic flow are functions of a parameter  $\varepsilon$  describing the distance from the threshold of the instability. An enhancement coefficient of the mass transfer of sulphur at interface on the slag side is established in the conditions of the onset Marangoni flow and convection. A parameter  $\beta$  was introduced to makes a reunion of the specific and critical conditions in the local enhancement of the mass transfer coefficient, besides the existing parameter  $\varepsilon$  for the distance from the threshold of instability. The parameter  $\Delta(S)$  was found to express better the instability conditions and the conditions of mixing effects in layers near the interface, by energy dissipation of Marangoni flow and seems to be able to take account of important differences between conditions in slags  $C/A=1.5$  and  $C/A=1$ . Due to the cumulated actions of  $\text{CaO-Al}_2\text{O}_3$  slag parameters, it was established that in the case of slag  $C/A=1.5$  the magnitude of the parameter  $\Delta(S)$  is sensible lower than in slag  $C/A=1$  that means in the slag  $C/A=1.5$ .

Small fluctuations of sulphur concentrations, higher enough than the critical values  $\Delta(S)^c$ , up to values representing 3-4% from limit of sulphur solubility in  $\text{CaO-Al}_2\text{O}_3$  slags can excite and sustain Marangoni instability at interface, determining the corresponding Marangoni flow of turbulent character



and energy dissipation in an effective layer of thickness  $\delta_{\text{eff}}$  of the same magnitude with thickness of the diffusion boundary layer. In slags  $C/A=1.5$  compared to slag  $C/A=1$  there are better conditions that desulphurization contributes to its self-sustaining of surface dynamics and sulphur mass transfer enhancement by solutal effect of sulphur. An important uncertainty of computed values is introduced by the differences between the reported values of slags parameters in different published papers, mainly of the kinematic viscosity, dynamic viscosity, also of the density, but in a lower measure and of the isothermal mass diffusion coefficient of sulphur, determined experimentally or established using models. The approach of the presented problem and the quantitative results obtained on the mentioned basis contributes to an improved vision on the efficiency of  $\text{CaO-Al}_2\text{O}_3$  slag contribution, in the dynamic aspects of desulphurization of aluminium killed steels, under slag. The results plead for a self-sustained dynamics of desulphurization of steels under  $\text{CaO-Al}_2\text{O}_3$  slag, in determine conditions.

The revealed dynamic aspects can contribute also to evaluating the role of  $\text{CaO-Al}_2\text{O}_3$  slag in the assimilation of  $\text{Al}_2\text{O}_3$  inclusions and possible of other inclusions in the slag, regarding of steel reoxidation and slag dispersion in steel. It is given a quantitative evaluation of the variation of the interfacial tension between  $\text{CaO-Al}_2\text{O}_3$  slag and steel, during the mentioned desulphurization process, which can contribute quantitatively in more realistically establishing the conditions of occurring the interfacial instability Kelvin-Helmholtz and its specific wavelength.

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