# Investigation of mass transfer processes between metal and slag at film stage of ESR process

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## Abstract

In this work the results of theoretical and experimental studies the mechanism of refining the metal under ESR are presented, in particular, the role of the different stages of droplet transfer in removing of the harmful impurities and the ways of intensification the most slow phase of the process. The physics and chemical processes of refining are complicated by fluid-flow phenomena, which are connected with capillary formation and gravity waves on the stage of forming the film on butt end of the electrode. This is practically excludes the possibility of the analytical description of hydrodynamics as a single physics and chemical process.

By the method of physical modeling, particularities of the mechanism of droplet transfer during ESR are established. Using of the method of integral analogue has allowed obtaining the criteria, which allows to evaluate quantitatively the simulation criterion of the process on physical model. By means of these criterions (Fourier, Fraud, Weber and phase transformation) the physical model is calculated and the scale factors are determined, which are allowed to transfer the results of modeling on real process. It is installed that under melting the consumable electrode yet before the moment of the droplet forming, the break of the film of electrode metal occurs and quick ascent of it‘s part upwards on surface of the electrode that provides intensive liquids mixing in film. It is shown that duration of the metallic film forming on butt end of the steel electrode and direct generations and detachment of droplet consists accordingly 80% and 20% from the time of general cycle of droplet formation.

For conditions of ESR by analytical way with use of the Highby diffusion renovation model the equations for determination factors of mass transfer component in system "film of electrode metal-slag" are received, dependence of intensities of mass transfer on velocity of electrode melting is found, part of separate stages in general refining process is determined and the recommendations upon their speedup are given.

On the base of the theoretical researches method is designed and equations are received for determination of apparent activation energy of physics and chemical process, which are running in diffusion mode in two-phase system that allows to elaborate the mechanism of passing the refining processes, define the limiting stages and develop scientifically motivated actions upon their speedup.

## Introduction

During the chamber electroslag remelting (ChESR) the main physical and chemical reactions of refining are run on the border of the two phases - the metal and the refining slag. Their intensity depend on many factors: chemical composition and temperature of the slag, the reaction time of the melted metal with slag, the velocity

of the reagent delivery from the metal volume to the interfacial surface and rejection of the reaction products to the slag volume.
Among the researchers there always has been the big theoretical and practical interest to estimation of the separate stage influence on the general process of refining and to development of the possible ways of the speeding up the limiting links of the whole process [1-6] for the reason of metal quality management.
If you take into account the fact that at the high temperatures of the chamber electroslag remelting realization the chemical reactions are run with the high velocity, it is possible to suppose that the intensity of the metal refining, mainly, is connected with the heat and mass-transfer processes.
The intensity of the mass-transfer processes, which are accompanied with the heterogeneous chemical reactions, is determined by the specific interphase and coefficients of the mass transfer of components in the corresponding phases, in other words, the conditions of the hydrodynamic processes at each stage of the electroslag process [1,2].
In the given work the results of the theoretical and experimental investigations of the mechanism of the metal refining during ChESR, in particular, the role of the separate stages of the drop transfer in removing the harmful admixtures and the ways of the intensification of the slowest stage of the process are described [7-9].
The physical and chemical processes of remelting are complicated by the hydrodynamic phenomena which are connected with the formation of the capillary and gravitational waves at the stage of the film formation on the butt end of the electrode. This practically excludes the possibility of the analytical description of hydrodynamics and the physical and chemical process as a whole.
In this connection the attempt of studying of these processes was undertaken with the help of the physical modeling. For this purpose the heat model of melting the electrode was designed and it was founded on transfer of the heat in a moving film of the metal, taking into account the heat balances on the boundary of "slag-film", "film-electrode" and the energy phase conversions. Mathematically the heat problem is set up. Using the method of the integral analogue has allowed to get the criteria which are enabling quantitatively to value the similarity of the process on the physical model. With the help of criteria of Pekle, Fourier, Fraud, Weber and the phase conversion, the physical model has been calculated and the scale coefficients have been determined, which have allowed transferring the results of modeling on the real process.
As the simulated agents there ice (the electrode) and vegetable oil (the slag) with addition of kerosene for regulating the density and viscosity were used. Drop carrying was fixed with a web-camera and all data were sent to a computer. For fixing the parameters of drop carrying in the icy "electrodes" of different diameter, the graphite powder was introduced.
On this model there was studied the nature of shaping a fluid film and draining it on the surface of the electrode, forming the drops (fig.1). The conducted researches have revealed the set of the features which in a considerable extent reveal the mechanism of the drop metal transfer under ESR.

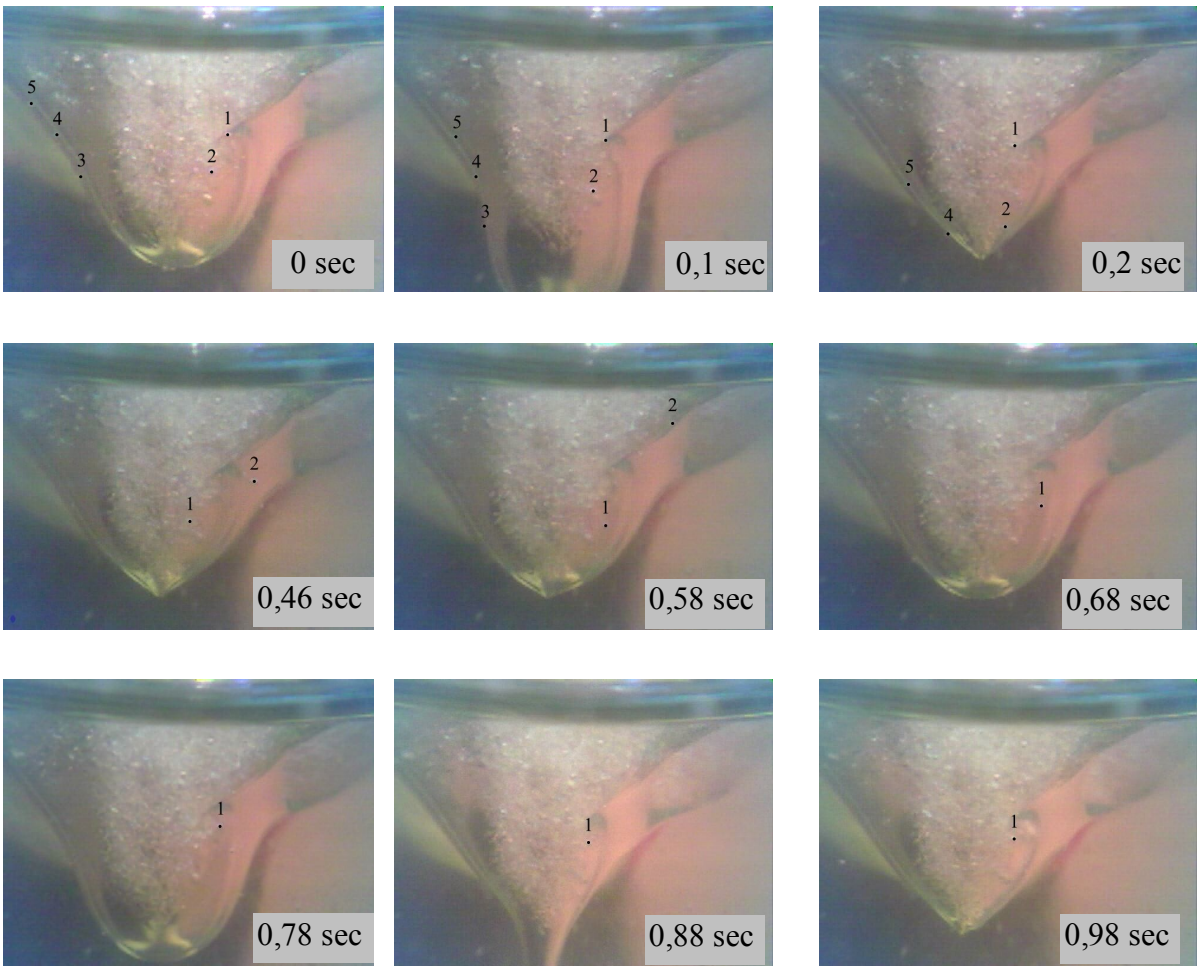


*Figure 1 – The behavior of the flowing down films on the different stages of the process of drop formation*

It is determined that in the process of draining a film on the surface of a cone-shaped butt end of an electrode in the lower part liquid is accumulated and the bulge of the film occurs. When the determined critical thickness of the film is reached it tears into two parts. The lower part under the action of gravity quickly flows down to the top of the cone of the electrode and is formed into a drop with its following take-off. The upper part of the film under the action of the power of the surface tension quickly rises upwards on the surface of the electrode. Moreover, the rise of the film is accompanied by the intensive stirring of the liquid volume, concluded in it. The similar phenomenon of the film rise was fixed earlier by V. V. Panin and I. S. Ivahnenko while studying of the drop formation under ESR with the use of the x-ray survey. As a result of coming in the film the new portion of the melted metal its fluent "climbing down" downwards with continuous increase of the thickness occurs. When the critical thickness of a film is reached, the film tears and the cycle is repeated. Simultaneously it is determined that formation of the following drop takes place not immediately after tearing of the previous one. It is fixed by the filming that not the whole mass of metal in the film is used for shaping of the tearing of drop, but time of shaping and tearing of drop is short in comparison with the general cycle of the drop formation. Processing the results of the video filming has shown that the process of the destruction of a flowing down metallic film takes place in the time

which is approximately equal to 80% of the general time of the cycle of the drop formation. The time of shaping of a drop is about 20% of the time between tearing the two adjacent drops. The determined fact is important for the estimation of the deleted admixture on the stage of shaping a drop.

The results of the physical modeling give the basis to consider the mechanism of the behavior of the film and drop formation as an intermittent process and use the model of the renovation of Highby for analytical description of the mass transfer under ESR. Really, the quick rise of a part of the film at the moment of its destruction (begining of a cycle) promotes the intensive stirring of metal and slag adjoining to it and making concentrations of the diffusing component more homogenious in the corresponding phases. The condition of its balance on the interphase border is violated. This brings about the unsteady-state diffusion of the component in metallic and slag phases during the time, which is equal to the cycle of the formation and tearing the drop. As a result these appear the gradients of concentrations of the carried component in the corresponding phases, which are destroyed at the beginning of the initially new cycle.

The mathematical statement of the problem with the use the Highby model was considered on the basis of an example of removing sulphur from metal into slag. The following indications are accepted:

$C_S^M$ and $C_S^{III}$ – - the current concentrations of sulphur in metallic and slag phases, kg/m$^3$;

$\bar{C}_S^M$ and $\bar{C}_S^{III}$ – an average weight concentration of sulphur in metallic and slag phases, kg/m$^3$;

$L_S = \dfrac{C_S^{III}}{C_S^M}$ – a distribution coefficient of sulphur between slag and metallic phases;

$D_S^M$ and $D_S^{III}$ – the coefficients of molecular diffusion of sulphur in metal and slag accordingly, m$^2$/s;

$\tau$ and $\tau_к$ – the current time of the diffusion process and the time between tearing the two adjacent drops, s;

$j_S^{III}$ – the diffusive flows of sulphur in metal and slag, kg/(m$^2$ s).

According to the accepted physical model the one-dimensional problem of the unsteady-state diffusion of sulphur in metal and slag is described by the system of differential equations:

$$\frac{\partial C_S^м}{\partial \tau} = D_S^M \frac{\partial^2 C_S^M}{\partial x^2}; \qquad (1) \qquad \frac{\partial C_S^ш}{\partial \tau} = D_S^ш \frac{\partial^2 C_S^ш}{\partial x^2}; \qquad (2)$$

Having taken the boundary of metal-slag as the origin of coordinates it is possible to write the boundary conditions of the problem:

$$C_S^M\Big|_{\tau=0} = \bar{C}_S^M; \qquad (3) \qquad C_S^ш\Big|_{\tau=0} = \bar{C}_S^ш; \qquad (4)$$

$$D_S^M \cdot \left.\frac{\partial C_S^M}{\partial x}\right|_{x=0} = D_S^{ш} \cdot \frac{\partial C_S^{ш}}{\partial x}; \qquad (5) \qquad C_S^{ш} = L_S C_S^M; \qquad (6)$$

$$\left.\frac{\partial C_S^M}{\partial x}\right|_{x=+\infty} = 0; \qquad (7) \qquad \left.\frac{\partial C_S^{ш}}{\partial x}\right|_{x=-\infty} = 0. \qquad (8)$$

The conditions (7) and (8) are accepted for small period of the cycle of drop formation, when the diffusion flows penetrate to the small depth in the corresponding phases.

The system of the equations (1) and (2) together with boundary conditions is solved with the help of the operating method.

As a result we received the expressions, which describe the time distribution of concentrations of sulphur in volumes of the metallic film and slag:

$$C_S^{м} = \bar{C}_S^{м} + \frac{1}{1+L_S \cdot k} \cdot \left(1 - erf\left(\frac{x}{2 \cdot \sqrt{D_S^{м} \cdot \tau}}\right)\right) \cdot \left(\bar{C}_S^{м} \cdot L_S - \bar{C}_S^{ш}\right); \qquad (9)$$

$$C_S^{ш} = \bar{C}_S^{ш} + \frac{k}{1+L_S \cdot k} \cdot \left(1 - erf\left(-\frac{x}{2 \cdot \sqrt{D_S^{ш} \cdot \tau}}\right)\right) \cdot \left(\bar{C}_S^{м} \cdot L_S - \bar{C}_S^{ш}\right). \qquad (10)$$

In the equations (9) and (10): $k = \sqrt{\frac{D_S^{м}}{D_S^{ш}}}$; $erf$ – the error function of Gauss defined with the help of the following correlation: $erf\left(\Phi\right) = \frac{2}{\sqrt{\pi}} \cdot \int_0^{\Phi} e^{-\Phi^2} d\Phi$, where

$$\Phi = -\frac{x}{2 \cdot \sqrt{D_S^i \cdot \tau}}.$$

With the use of equations (9) and (10) we found the average integral diffusion flows of sulphur in metallic and slag phases for the time of the cycle of the drop formation ($\tau = \tau_к$):

$$\bar{j}_S^{м} = \frac{1}{\tau_к} \cdot \int_0^{\tau_к} j_S^{м} d\tau = \frac{2 \cdot \sqrt{D_S^{м}}}{\sqrt{\pi \cdot \tau_к} \cdot \left(1 + \sqrt{\frac{D_S^{ш}}{D_S^{м}}} \cdot L_S\right)} \cdot \left(\bar{C}_S^{м} \cdot L_S - \bar{C}_S^{ш}\right); \qquad (11)$$

$$\bar{j}_S^{ш} = \frac{2 \cdot \sqrt{D_S^{ш}}}{\sqrt{\pi \cdot \tau_к} \cdot \left(1 + \sqrt{\frac{D_S^{ш}}{D_S^{м}}} \cdot L_S\right)} \cdot \left(\bar{C}_S^{м} \cdot L_S - \bar{C}_S^{ш}\right). \qquad (12)$$

From the equations (11) and (12) we received the expressions for determination the coefficient of mass transfer of sulphur in metallic and slag phases and the coefficient of mass transfer it from metal into slag:

$$\beta_S^M = \frac{2}{\sqrt{\pi\tau_k}} \cdot \frac{\sqrt{D_S^M}}{L_S}; \qquad (13) \qquad \beta_S^{ш} = \frac{2}{\sqrt{\pi\tau_к}} \sqrt{D_S^{ш}}; \qquad (14)$$

$$\beta_S^{M-Ш} = \frac{2 \cdot \sqrt{D_S^{ш}}}{\sqrt{\pi \cdot \tau_к} \cdot \left(1 + \sqrt{\frac{D_S^{ш}}{D_S^{м}}} \cdot L_S\right)}. \qquad (15)$$

The obtained equations show that the intensity of mass transfer of sulphur for the film stage of the drop formation depends on coefficients of the diffusion of the component in the phases, chemical composition of the slag ($L_S$) and frequencies of tearing the drop of the metal ($\tau_к$). The mass transfer of sulphur is defined by the process of diffusion in metallic and slag phases.

The calculations on the equation (15) have shown that the metallic phase can limit the mass transfer of sulphur in ESR process when slag is used, for which the value $L_S$ is high, for instance it is more than 30.

With the help of the analytical studies of mass transfer on the base of the obtained equations and with the use of the literature facts the role of a separate stage of the drop transfer in general refining the metal under ESR has been evaluated. On the basis of the metal desulphuration it was shown that the prevailling refining (more than 90%) occurs at the stage of the film formation.

## Conclusions.

1. The method of physical modeling has clarified the particularities of the mechanism of the drop transfer under ESR, which means in that under melting the consumable electrode even before the moment of shaping a drop the breakup of the film of the electrode metal occurs and the quick rise of a part it upwards on the surface of the electrode occur, that brings about the intensive stirring of liquid in the film. It is shown that duration of shaping the metallic film on butt end of the steel electrode and directly generations and tearing of drop make up correspondently 80% and 20% of the time of the general cycle of drop formation.
2. For the first time by the analytical way with the use of the diffusion models of the renovation Highby the equations have been received for determination of coefficients of mass transfer of the component in the system " electrode metal film - slag", its dependency of intensity of mass transfer on the velocity of the electrode melting, share of the separate stages in the general refining process has been determined.

## References

1. Электрошлаковый переплав / Ю.В. Латаш, Б.И. Медовар. – М.: Металлургия. – 1969. – 240 с.
2. Металлургия электрошлакового переплава / М.М. Клюев, А.Ф. Каблуковский. – М.: Металлургия. – 1969. – 256 с.

3. Жмойдин Г. И. Кинематика рафинирования электродного металла шлаком // Восстановление и рафинирование железа. М.: Наука. – 1968. – С. 105-107.
4. Панин В.В., Ивахненко И.С. К вопросу о каплеобразовании металла при плавлении его в шлаке. – Изв. Вузов. Чер. металлургия, сер. Металлы. – 1971. – №2. – С. 36-38.
5. Иваненко О. Г., Рощин В. Е., Поволоцкий Д. Д. Гидродинамика формирования капли при сплавлении заготовки в шлаке. – Изв. Вузов. Чер. Металлургия. – 1984. – №4. С. 15-18.
6. О месте протекания физико-химических процессов при ЭШП / Г.М. Григоренко, В.В. Лакомский, Ю.М. Помарин // Проблемы специальной электрометаллургии. – 1988. – №2. – С. 70-75.
7. Дымнич А. Х., Троянский А. А., Разинов А. Н. Массоперенос кислорода в системе шлак-металл // Металлургическая и горнорудная промышленность.– 2004. – №8. – С. 232-235.;
8. Троянский А. А. К оценке лимитирующей стадии массопередачи в системе жидкий металл-шлак // Теория и практика металлургии. – 2005. – №1-2. – С. 54-57.
9. Троянский А. А., Дымнич А. Х., Медовар Л. Б., Рябцев А. Д. Особенности процессов массообмена в пленочной стадии процесса ЭШП // Современная электрометаллургия. – 2005. – №4. – С. 6-9.