Physical Modelling of 3D Melts Mixing for Electrometallurgical Aggregates

A. Chudnovsky

Abstract

We study the melt mixing in the bath of electro-aggregates and the mixing control system. For this we use physical modelling of electro-vortex flows in conductive, viscous, incompressible liquid. In the article we describe: the task of the modelling; toroidal vortex as a base electro-vortex flow; the interaction of vortexes under two (and more) top electrodes; the mixing in the 3-phases EAF (electrical arc furnace) in comparison to the next generation DC EAF with built-in bottom electrodes; the flow structure in the bath with thin liquid layer and submerged electrodes; some other tasks. In many cases the flow structure can be estimated by approximating the electromagnetic forces field. For some nonlinear, nonstationary effects, like the localization of flow or large-scale 3D auto-oscillations, the physical modelling is the only research method. The results of modelling were confirmed and applied in real technologies.

Introduction

There are a lot of effective industrial technologies where electrical current is passed through the bath with liquid melt: electro-slag welding and remelting, multi-electrodes facing, 3-phases EAF, next generation DC EAF, flux and salt melting furnaces and others.

The spatial distributed electrical current $\vec{J}$ in liquid media interacts with own magnetic field $\vec{B}$ and generates electromagnetic forces field $\vec{J} \times \vec{B}$. When this force field is non-potential than all fluid elements get elementary rotation around a local axis of force vorticity vector $\nabla \times (\vec{J} \times \vec{B})$. Under small current the process is continuing, while tension of friction and force vorticity will be balanced in each points of the flow. As a result an electro-vortex flow appears, (named also “Electrically induced vortical flows” – EIVF). With further growing of velocity field, the flow structure becomes depending on nonlinear transfer $\vec{W} \times \vec{V}$ of fluid vorticity $\vec{W} = \nabla \times \vec{V}$.

The technical components of electro-aggregates, - like form and relative position of electrodes, built-in and external current leads, bath geometry, ferromagnetic masses and others,- define the current distribution in the melt and EIVF there. From another hand, the EIVF defines heat-mass-transfer in a melt bath and, as a result, metal quality, energy efficiency, ecology and safety. So, the understanding of EIVF is a key factor for building an effective technology.

The physical modelling is very exclusive and power method for EIVF investigation. Some 3D nonlinear effects, gotten by this way, can’t be predicted otherwise, for example, large-scale non-stationary vortexes, 3D auto-oscillations, spatial localization of flow and others. The EIVF physical modelling was intensively provided in 70-th [1], 80-th and till the middle of 90-th years. Later on, gotten results were implemented in real technologies. Perhaps, the most effective result was gotten in the next generation DC EAF with built-in control system of electromagnetic melt mixing.
1. The task of modelling

We use the equation of vorticity transfer: \( \nabla \times (\vec{W} \times \vec{V}) = \nabla^2 \vec{W} + S \nabla \times (\vec{J} \times \vec{B}) \) in dimensionless form with five basic assumptions. 1) A liquid has constant values of density \( \rho \), viscosity \( \nu \) and electrical conductivity \( \sigma \). 2) The electro-dynamic approximation: \( \nabla \times \vec{B} \ll \vec{J}/\sigma \), \( (\vec{J} = \sigma \vec{E}) \) allows calculating electromagnetic fields independently on fluid motion. 3) Current density doesn’t depend on time; - we use DC (direct current) or quasi-stationary AC (alternative one) with time-averaged \( \nabla \times (\vec{J} \times \vec{B}) \) and neglecting by skin-effect. 4) The thermo-convection is neglected. 5) The free surface deformation is small and has no affect to electromagnetic fields.

The transfer equation has single dimensionless parameter: \( S = \mu_0 I^2 / 4\pi^2 \rho \nu \), \( (I \text{- common current}) \). The task of modelling includes: the investigation of flow structure evaluation with increasing value of \( S \); getting of velocity estimations; checking possible violation of mentioned assumptions. There are three requirements for a physical model: the geometrical similarity; the similarity of electrical boundary conditions; developed nonlinear regime of flow, \([2]\), \([3]\).

2. The EIVF in a form of axisymmetric toroidal vortex

An axisymmetric toroidal vortex is a base EIVF structure that appears under conical current discharge, \([4]\). The typical example is a flow in a cylindrical model of slag bath for electro-slag welding. Here (Fig.1) current \( I \) discharges from the top electrode (radius \( R1 \) ) through the liquid to the bottom electrode (radius \( R2 \), \( k = R1/R2 \leq 1 \)); the bath depth \( H \) is equal to bath radius \( R2 \); the side wall is not electrically conductive. The flow has a structure of toroidal vortex, where the axis jet moves from top to bottom (with current density decreasing); than fluid moves to the side wall along the bottom, than up to free surface near the wall and is converging to the axis on the free surface.

The fluid velocity \( V_0 \) on the axis is described by formula: \( V_0 = 1.26 \times (\nu/H) \times \sqrt{S} \times M \), \([3]\). Here \( M = \sqrt{1-k^2}/k \) is the dimensionless integral of vorticity of electromagnetic force field. For an axisymmetric task this integral is equal to the flow of \( \nabla \times (\vec{J} \times \vec{B}) \) through the meridional plane, or, what is the same, the circulation of \( \vec{J} \times \vec{B} \) along the contour around this plane. ( -The integral \( M \) plays the same role for EIVF like integral of impulse for a jet from point hole on a plane, or integral of impulse momentum for a rotating needle). So, in Fig. 1a, when \( R1 \rightarrow R2 \), \( (k \rightarrow 1) \) than \( M \rightarrow 0 \) and there will be no liquid motion under any value of \( S \) (of common current). Otherwise, if \( k \rightarrow 0 \), (and when \( R1 \) decreases to point source), - than \( V_0 \) increases like \( 1/k \) under any \( S \).

It was shown experimentally in \([5]\) and recently confirmed in \([6]\), that a toroidal vortex under large \( S \) (in nonlinear regime) with converging to axis flow on a free surface is rotating around the bath axis of symmetry. It is recognised that azimuthal force appears due to an interaction of horizontal component of discharging current with small vertical component of Earth magnetic field. The other possible source of small azimuthal forces is non-symmetry of electric or magnetic fields.

One more experimental result relates to effective sizes of toroidal vortex under large values of \( S \): the depth \( H \) of the vortex becomes equal to it radius \( R \). When \( H > R \) up to about 40%, or \( R > H \) up to 40% than liquid around the core becomes involving into common vortex flow. But when \( H = 2R \)
or \( R = 2H \), than the secondary toroidal vortexes appears around or under area \( H = R \) due to friction tensions with central vortex boundary.

The next effect is shown on Fig. 2. There are two separate zones in a bath with conical current discharges and separate toroidal vortexes. On the left side the EIVF appears due to half-spherical boundary of electrical conductivity; on the right - near a small electrode. In both vortexes the fluid in near-axis area is moving in the same direction – from the right to the left. But between these vortexes there is a fluid zone without any moving. This is the fundamental result. In the area between vortexes there are an electrical current \( \vec{J} \), own magnetic field \( \vec{B} \) of the current and electromagnetic force field \( \vec{J} \times \vec{B} \). But this force field is potential. There is no vorticity of electromagnetic force:

\[
\nabla \times (\vec{J} \times \vec{B}) = 0
\]

so, the fluid is not moving.

One more effect is an appearing of vortexes street under electrode of small diameter \( d \) and under large \( S \). Intensive vortexes (of \( d \) scale) are breaking from the electrode and taking out the electromagnetic vorticity.

Details of velocity and pressure fields for toroidal vortex where investigated in [7], [6], [1]. The condition for thermo-convection neglecting is described in [3].

3. EIVF under two or several top electrodes

In a bath with two or more top electrodes a conical current discharge takes place under each electrode. Correspondently, current jets and toroidal vortexes (or liquid metal jets) are inducing under each electrode and interact upon each other. Backward flows become organized as 3D circuit trajectories (recirculation contours). The physical modelling of base flows under two and three top electrodes where provided in [8], [9], [10].

3.1. The bifilar power supply schemes

The bifilar scheme means that the current discharges through a liquid between two electrodes. On Fig.3,a, there is a photo of EIVF that exists on electrodes plane between partly submerged electrodes of small diameters, [11]. Here current jets from under electrodes have opposite directions and liquid metal jets are pushing from electrodes to side wall. On a real free surface liquid is converging to each electrode, (Fig.3, b). The flow circuits are discussed below.

3.1.1. Flow circuits under not submerged electrodes

Here the electromagnetic force field can be estimated by using superposition of two point sources (with “plus” and “minus” potentials), placed on a plane. As it was shown in [12], in this model a vorticity of electromagnetic forces has all three components; so, fluid trajectories circuit in all three
coordinate planes. Looking to a flow structure from the bottom side (Fig. 3, c), we see four horizontal contours, developed due to z-component of vector of electromagnetic vorticity.

3.1.2. Flow circuits under fully submerged electrodes

In this case both functions of electrical current and electrical potential do not depend on vertical coordinate. The current discharge picture corresponds to a classical one between two point sources, (+/-, like in bipolar cylindrical coordinates). It can be shown, that the vector of electromagnetic vorticity here has only horizontal components.

The flow (see Fig. 4) circuits in 4-contours structure too, but with backward direction (relatively to Fig.3, c). And these contours represent a secondary flow, because there is no z-component of electromagnetic vorticity.

![Fig. 4. EIVF near 2 submerged electrodes: a - top photo, b - top scheme](image)

The main flows (jets) are developing in the electrodes plane between electrodes. Liquid is moving up along the cylindrical surface of electrodes, than moving to the bath axis along a free surface, than the flow is divided into two parts. The first part is moving down along the bath axis to a bottom and then back to electrodes along the bottom. The second part is moving to the side wall in orthogonal (to electrodes plane) direction. These orthogonal jets, when reaching the side wall, are divided too. A flow partly is moving along the side wall, making two circuit contours in horizontal plane – left and right. The second part of this flow circuit in a vertical plane (orthogonal to electrodes plane), moving backward to a bath axis along the bottom.

3.1.3. Slightly submerged electrodes in a large cylindrical bath

Such a flow was investigated in [10] both visually (by free surface observation) and by exact velocity measurement, using fibre-optical sensor, (in a physical model of flux melting furnace).

When \( H = R \) (bath depth is equal to it radius) the flow is like quasi-axisymmetric toroidal vortex with periodical velocity changing by azimuthal coordinate. The flow near the side wall is moving down in electrodes plane and is moving up in the orthogonal one. It means, that in near-wall area (inside the toroidal vortex) there is large scale slow rotation of fluid along a cylindrical surface \( R = \text{const} \). There are four separate sectors of such rotation, - one quadrant for each along-side-wall vortex, (90 degrees by azimuthal coordinate for each one). Flow at the bath axis is moving up. When \( H \) increases up to 1.4*R, the flow still has the same structure.

But, when \( H = 2*R \) then the structure includes two toroidal vortexes – lower and upper, with common axis of symmetry, and with vortex depth equal to vortex radius for each vortex. The upper vortex is the same, like when \( H = R \). The lower vortex is an axisymmetric - the flow is moving up in the axis and moving down along whole side wall.

Note, there was the first detailed investigation of toroidal vortex velocity structure under bifilar current leads. The effect of second vortex appearing for \( H=2*R \), (or \( R = 2*H \),) was fixed also under axisymmetric current discharge, (see p.2 above and p.4.2 below).
3.1.4. **Large electrodes in electro-slag remelting process**

The electro-slag remelting process requires the bath and electrodes of large diameters: bath – up to 2 meters and electrode – up to 1 meter. In these cases the form of electrode stump becomes essential for current discharging. On Fig. 5 there is an example of such a flow in a meridional plane. There are a quasi-axisymmetric vortex in a main bath area (near the bottom) and two intensive small-sized vortices in interelectrodes area.

In a real free surface liquid is converged to each electrodes (like on Fig.3, b). Electrodes are melting in a process and are submerged into slag by stumps only. So, we can expect 3D flow circuits here like on Fig. 3,c)

Whit this, on Fig.6 there is a photo of two huge electrodes (diameter 0.7 m for each), gotten after real electro-slag remelting process with bifilar scheme [13]. It’s looking like a main and intensive EIVF structure (near-stumps vortex) appears in the interelectrodes area. These local vortices retain the hot slag here. And there were no nor heating enough nor hot convective flows outside of interelectrodes area. The effect demonstrates the heat-transfer localization, induced by non-linear flow localization under large common current.

![Fig. 5. Meridional EIVF scheme between two electrodes of large diameters](image1)

![Fig. 6. Photo of two real electrodes after electro slag remelting process](image2)

![Fig. 7. 3-phases not-submerged electrodes: a - meridional, b - bottom flows](image3)

3.2. **Three-phases AC power supply scheme under three top electrodes**

Such schemes are used in furnaces for electro-slag remelting and flux-melting. A fluid flow under 3-electrodes can be estimated like a superposition of three bifilar pairs with three planes of melt bath symmetry; (- every plane passes through axes of a bath and one of electrode).

When electrodes are not submerged, the flow on a plane of symmetry AB is shown on Fig.7,a. There is a fluid jet from under electrode that downward to side wall and rounded by 3D contours. Vertical flows circuit is seen on Fig.7,a. Looking from the bottom we’ll see 3 pairs of horizontal vortexes, that appeared due to z-component of electromagnetic rotor (Fig.7,b). Note that the skin-effect was fixed in [10] for not submerged electrodes. Then electromagnetic fields and flow velocity were urged up a little to electrode stumps, but common flow structure was not changed.

When electrodes are fully submerged, the flow on a symmetry plane is shown on Fig.8,a. Like under bifilar, the main flow contours are developing in each of three planes of symmetry between an electrode and bath axis. This flows also circuit in horizontal plane in a three pairs of horizontal vortexes (Fig.8, b). But these six contours are a secondary flow due to a zero value of z-component of electromagnetic vorticity.

On a free surface a flow is converging to each electrode, (Fig.8, c) in all cases.
3.3. **Six electrodes scheme with three-phases AC in T-crystallizer**

Such a scheme was used for getting of ingots with very large diameter during electro-slag remelting process. Six electrodes are placed symmetrically around the bath axis, (Fig. 9,a). There are several ways for turning each pair of various electrodes to single phase of 3-phases scheme. The flow structure will not depend on this.

Common flow structure will be again a superposition of three bifilar pairs with EIVF jet under each of six electrodes (Fig. 9, b) in vertical plane of symmetry. Each jet will move from the electrode stump to down and to the side wall, over a flange of T-crystallizer. Liquid jets will be circuit by 3D trajectories. Due to electrodes are slightly submerged, we can expect the existing of pair of horizontal vortexes under each of six electrodes. All these 12 contours are forced by \( \nabla \times (\vec{J} \times \vec{B}) \). – Four contours are shown in Fig. 9, b. On a free surface liquid will convergent to each of six electrodes. In means, the flow will move up in the area of bath axis.

The skin-effect urges up all effects (to electrode stumps).

4. **Melt mixing in electrical arc furnaces (EAF)**

The EAF is world–wide modern technology of getting qualitative metal from a previously used metal scrub. This task sometimes bring a problem, when instead of a metal, gotten by classical metallurgical technology, we can get some “mixture of various material components”. Such a problem affects a quality of liquid metal and depends on a metal mixing during a final stage of steel-making. Below we’ll discuss the systems of liquid metal mixing, when a scrub is fully melted, (but will not discuss technologies itself).

4.1. **Three-phases EAF**

The flow structure is the same, like described in p.3.2 above for not-submerged electrodes. There are three hot melt jets from under each arc-melt contact to a furnace bottom. Also, there are six sectors with horizontally-closed circuits inside. The skin-effect urges all a little to a free surface.

Such mixing scheme can’t be accepted as an effective one, because: 1) Sectioned circuit trajectories are not good enough for common heat-mass-transfer. 2) Hot metal from a free surface can’t moves down to all deep layers of melt bath. 3) More heating power is required to be sure that all
4.2. The flow structures in next generation DCAF

In the small DCAF (0.5 to 6 tons) there is a bottom electrode with effective diameter some more than diameter of arc-melt contact. The flow structure is a toroidal vortex, rotating around bath axis. Hot metal from a free surface is effectively transferred into the depth of melt. The velocity formula from p.2 above was confirmed in a real aluminium melting process. The secondary vortex existing around the core in a bath with $R = 2*H$ was confirmed too for a 0.5 tons furnace.

It was fixed in real furnaces the bottom electrode is melting in its upper part. This is a result of the local vortex formation here with backward meridional rotation.

The middle size DCAF (up to 25 tons) it has up to 5 meters diameter and two bottom electrodes, [14]. The physical model of 25t DCAF was built in 1:10 scale. The model had two bottom electrodes at the plane of symmetry and the top electrode (instead of real arc), displaced a little from the bath axis. The system demonstrates a huge number of possible 3D mixing structures.

So, on Fig. 10 there is a stable horizontal structure of dipole type with two vortexes, each over a bottom electrode. In the front of dipole axis the flow fragment is looking like “ergodic mixing”. When common current increases, this dipole begins a horizontal auto-oscillation. On Fig. 11 there are two photos (from 11), made during one period of oscillation every 1 sec.

Note that in all photos on Fig. 10-11 the electromagnetic force field, both meridional and azimuthal components, do not depend on time. It means that if in the first half of oscillation period a fluid is moving along the force direction, than in the second half-period – opposite to it. This is an effect of non-linear transfer of fluid vorticity.

On Fig.12 one can see the localized vortex with strong azimuthal and meridional velocities inside and with no any fluid motion around. The vortex is located over one of bottom electrode. There is also the strong deformation of free surface, that violent one of our assumption regarding physical modelling. The surface deformation changes the space of current discharge. As a result, electromagnetic force field and force vorticity field are changed too.

All these exotic flows can’t be accepted as a system of mixing for DCAF. The realized system is based on two regular experimental results. 1) For given conditions, the electromagnetic force field has stable azimuthal component, so the melt is always rotating around the bath axis. 2) With this, there is an intensive heat mass transfer between azimuthally-rotating fluid layers due to three internal toroidal vortexes. One of them exists under the arc-melt contact. It draws hot metal from the free surface into a depth of the melt. Two other vortexes are formed each over own bottom electrode. All
three vortexes interact one to another, so a flow in the plane of symmetry is looking like it shown on Fig. 13.

Note, that the common current through a bottom electrode, as well as, fluid velocities here are twice less than current and velocity under the arc. With this, all vortexes over the bottom electrodes are carrying away by the azimuthal rotating. The melting of bottom electrodes is decreases.

Additionally, there are some specific measures for preserving a mixing from localization, like on Fig. 12.

![Fig. 12. DC EAF model: localized vortex, a - no moving around, b - vortex near](image1)

![Fig. 13. DC EAF model: scheme of melt mixing in meridional flow](image2)

**Conclusion**

The DCAF is a next generation EAF due to a number of real improvements. No any additional processing (lading refinance) required. Metal quality can be estimated directly by taking probes from a melt bath. Here we can add activators or other specific materials. Metal quality is outstanding for any steel grade. Dust-gas emission from over furnace top is two orders less than in 3-phase EAF processes. The ecology around the DCAF is absolutely better. The noise level is much less. Required electrical power is less. The work place around the furnace is safely for workers. These all became possible due to a correct melt mixing system, (and, of course, related tech environment – arcs regimes, power supply source, transformer and other). The mixing effects and variants for this technology where studied by physical modelling.

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**Author**

Dr. Phys., Chudnovsky, Alexander
Privat research company BIS Global SIA,
Kr.Valdemara Str., 79/81-15, LV-1013 Riga, Latvia
E-mail: alexchud@inbox.lv