4-th European Academic Symposium on EAF Steelmaking, Aachen, 2021

Dr. Phys. Alexander Chudnovsky,
JSC LATVO, Riga, Latvia, 2021,
eivf19@gmail.com

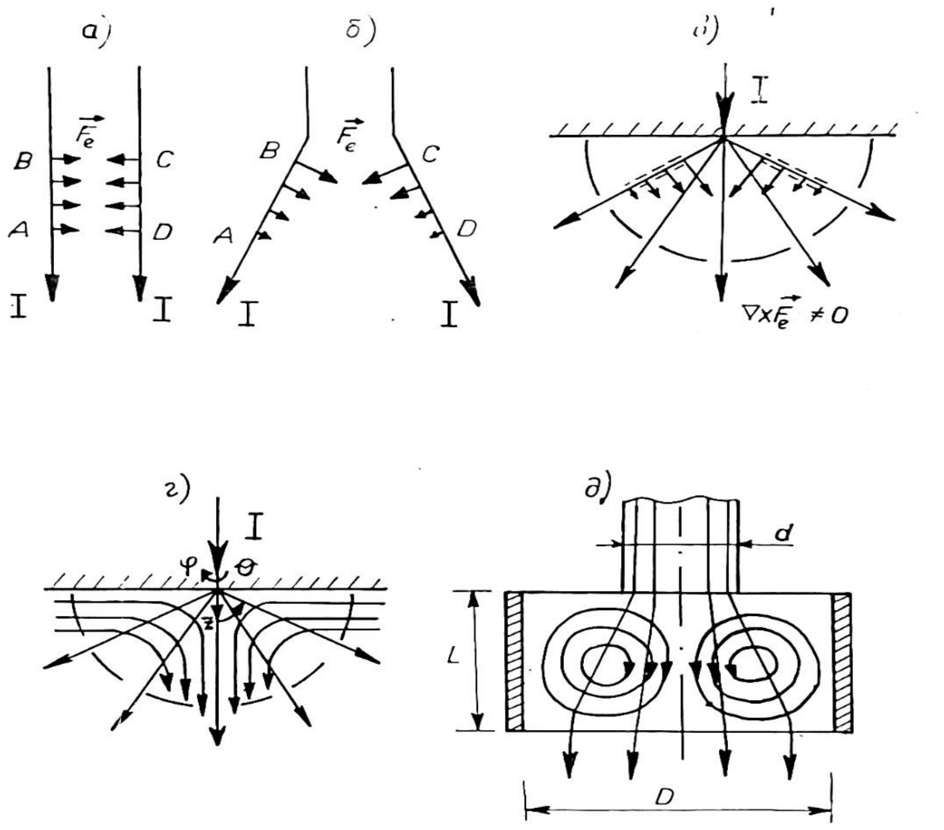
The stirring of melts in EAF

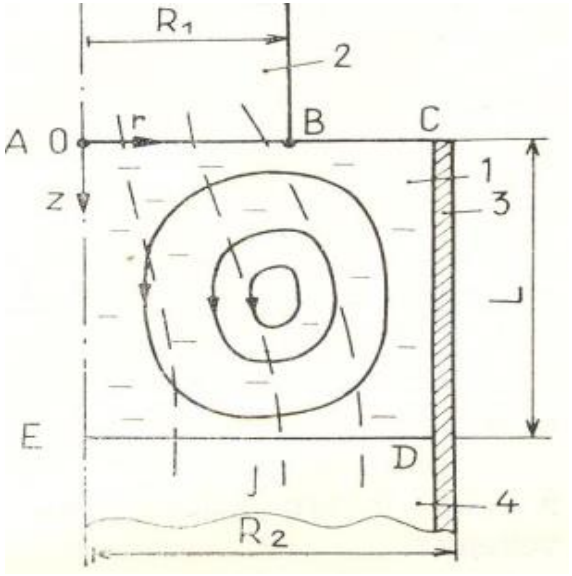
With support of Latvian University and ERDF grant No.1.1.1.1/18/A/108

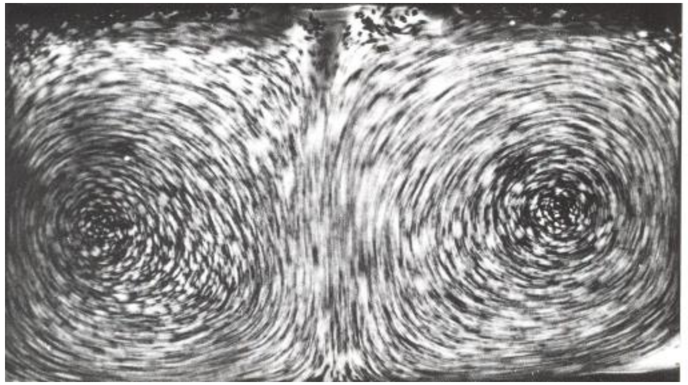
Content

1. Introduction
2. DC EAF with axisymmetric current supply
3. Twin – electrodes EAF
4. 3-phases EAF
5. The stirring in DC EAF UNG (Universal, Next Generation)
6. Conclusion

1.1. What is EIVF? - (Electrically induced vortical flows, or Electrovortex flows, EVF): a-e was published in [1]







1.2. Industrial technologies with EIVF stirring

1. Various types of EAF: 3-phases, DC (European), DC UNG (Russia)
2. Electroslag remelting: 1 to 6 melting electrodes, DC / AC / 3-phases
3. Various types of electrical welding
4. Electric ore smelting furnaces, flux- and salt-melting furnaces

EIVF take place in melt bathes in all this equipment.

The question is – can we use the EIVF for technology improvement?

1.3. EIVF equations for physical modelling

EIVF equations are gotten from common MHD equations with some basic assumptions, that includes, [1]:

- Thermo-convection can be neglected relatively to electromagnetic one
- No strong deformation of free surface
- Electrodynamics approximation $\boldsymbol{V} \times \boldsymbol{B} << \boldsymbol{J}/\sigma$

Then EIVF equations includes:

1) Vorticity transfer ($\boldsymbol{W} = \boldsymbol{\nabla} \times \boldsymbol{V}$)

$$\frac{\partial \boldsymbol{W}}{\partial t} + \boldsymbol{\nabla} \times (\boldsymbol{W} \times \boldsymbol{V}) + \nu \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times \boldsymbol{W}) = \frac{1}{\rho} \boldsymbol{\nabla} \times (\boldsymbol{J} \times \boldsymbol{B});$$

2) Incompressibility

$$\nabla \cdot \boldsymbol{V} = 0;$$

3) Maxwell's equations

$$\boldsymbol{\nabla} \times \boldsymbol{B} = \mu_0 \boldsymbol{J}; \quad \nabla \cdot \boldsymbol{B} = 0; \quad \boldsymbol{\nabla} \times \boldsymbol{E} = 0; \quad \nabla \cdot \boldsymbol{E} = 0;$$

4) Ohm's law in electrodynamics approximation

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

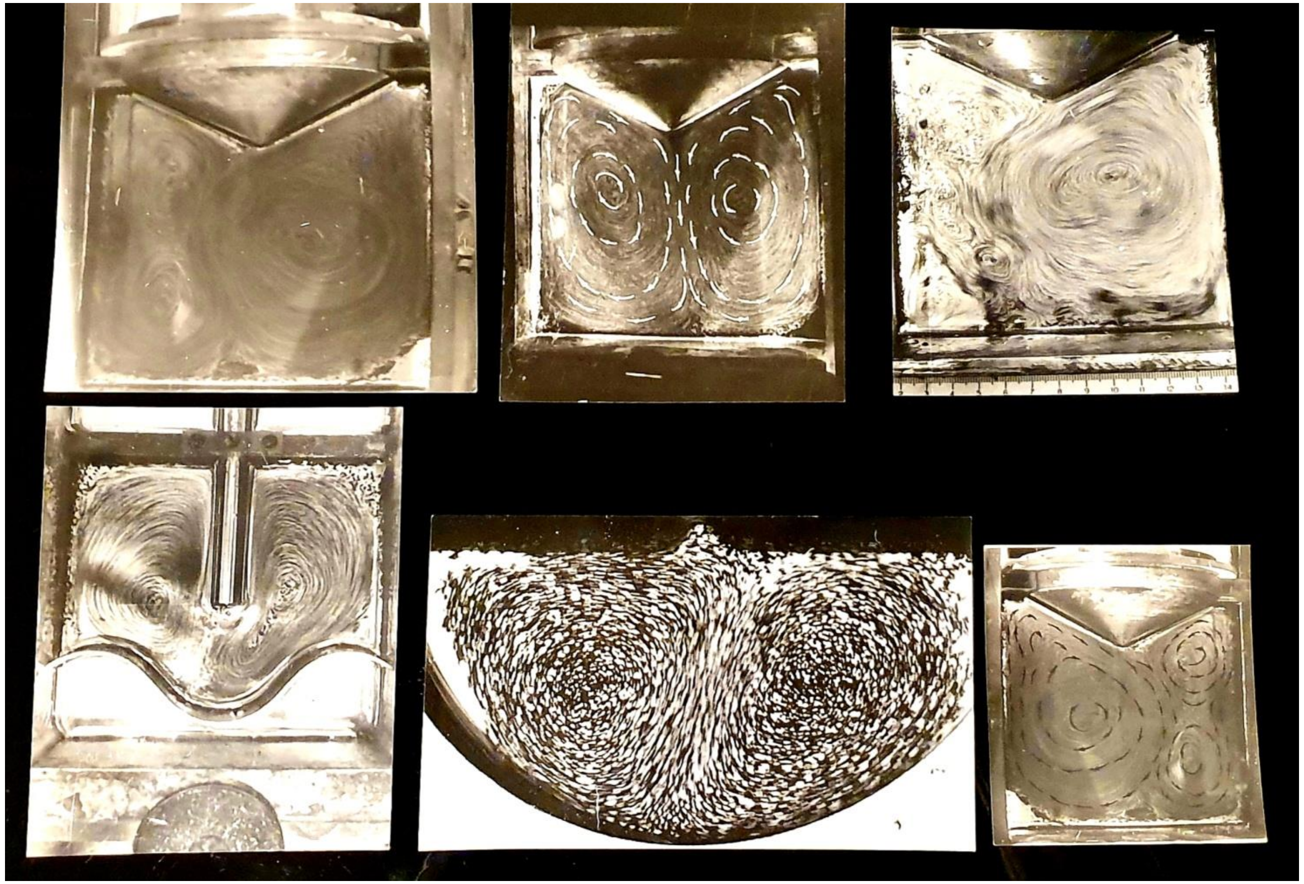
2.1. Examples of EIVF in form of axisymmetric toroidal vortex

(Photos 4, 7-10, 12 where gotten together with A. Chaikovsky and S. Andrienko, [2])

1-2

3-4

5-6



7-8-9

10-11-
12

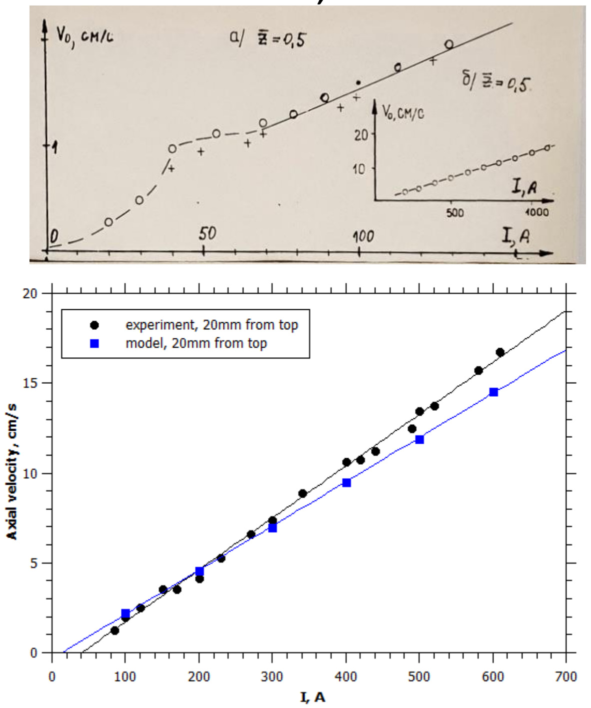
2.2. Properties of toroidal vortex

1. Electrovortex flow parameter $S = \mu_0 I^2 / \rho\nu^2$
2. Dimensionless integral M of electromagnetics vorticity flux through the meridional plane:
   $M = (1 - k^2) / k^2$, where $k = R_{arc} / R_{electrode} < 1$
3. Maximum velocity: $V_0 \sim I \sim \sqrt{SM} \sim \sqrt{S_M}$ = const $\frac{I}{kL}\sqrt{(1-k^2)\mu_0/\rho}$, const ≈ 0.9
4. Axial velocity approximation $V_z/V_0 =$ - $(\frac{2z}{z_0} - 1)^4$, $(r = o, z_0$ - bath depth), where *k = R arc / R electrode < 1*
5. Estimations of turbulence (using *k* -ε model) :
   1. The density of kinetic energy of pulsations $k \sim u'^2 \sim {V_0}^2 \sim I^2 \sim S_M$
   2. The energy dissipation $\varepsilon \sim {V_0}^3 \sim I^3$
   3. The turbulent viscosity $\nu_{\text{турб}} \sim k^2/\varepsilon \sim I \sim V_0 \sim \sqrt{S_M}$
   4. The turbulent thermo-conductivity: $\chi_{\text{турб}} = {Pr_{\text{т}}}^{-1} \rho_0 C_p \nu_{\text{турб}} \sim \sqrt{S_M}$, where $Pr_{\text{т}} \approx 0.9$ – Prandtl turbulent number
   5. Axial pulsation $\sqrt{< u'^2 >} \sim I \sim \sqrt{S_M}$

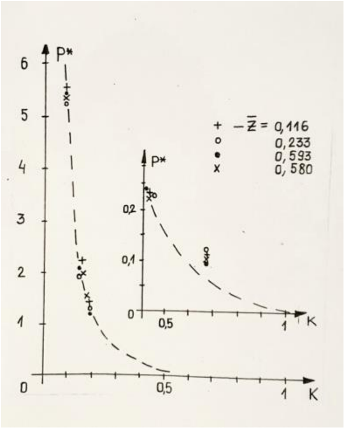
5. The condition of small thermo convection $\Delta T \ll \frac{1}{2\pi^2}\frac{\mu_0 I^2}{\rho_0 g\beta L^3}\frac{1-k^2}{k^2}$, *ΔT is averaged by bath depth temperature difference between the bath axis and side wall ; .[2] , [3]*

2.3. Measurements in a toroidal vortex, [3], [4]:

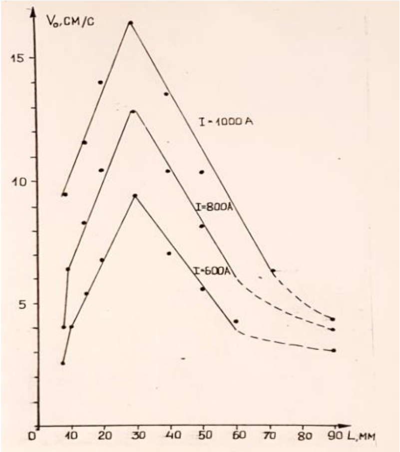
1 – a, b



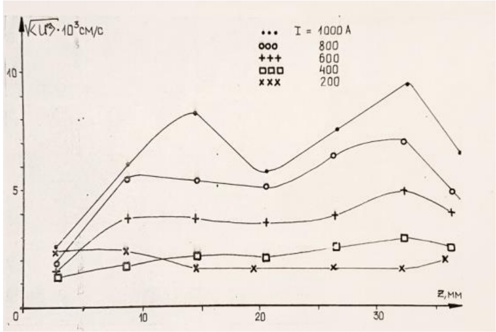
2



3



4



1) *A)* $V = c\, I^2$ *S < 40 A;* $V = c\, I$ when *S > 70 A ;* b) a comparison with calculation *I = 100A to* 700A, [4]

2) $P \sim V^2 \sim [(1-k^2)/k^2]^2$, *k = R1/R2, 0 < k < 1*

3) *Vo = Vo (L), Vo* –maximum velocity on the axis, *L* – bath depth, *R2 = 30 mm = const*

4) $\sqrt{<u'^2>} \sim I \sim \sqrt{S_M}$ for various Δz = *const*

3. Twin –electrodes EAF

3.1. Divided cathode scheme and bifilar scheme

Meridional EIVF (photos 1-5 was gotten by V. Sharamkin and V. Moshnjaga, [2])

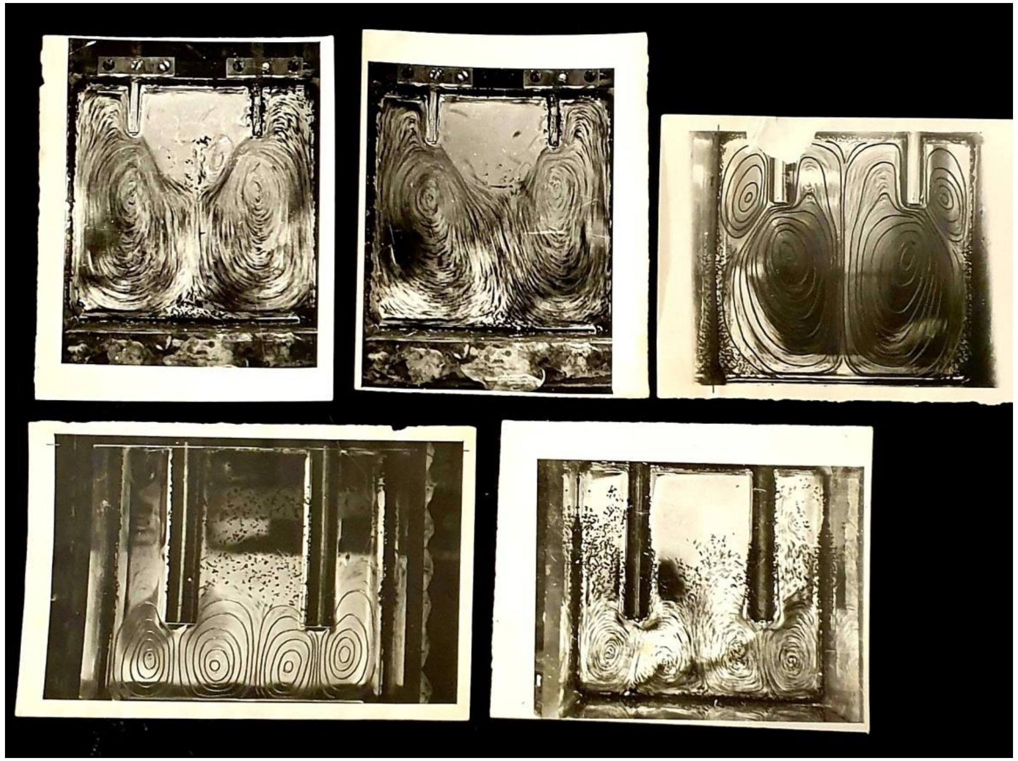
1-2 – Divided electrode;

3 – bifilar;

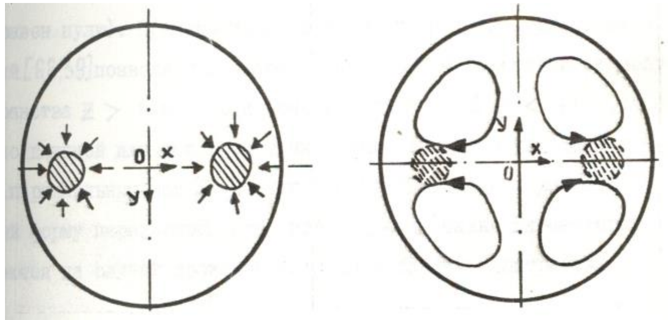
4-5 – bifilar with non conductive side-walls of electrodes;

6-7 – Scheme of flow circuit for bifilar current supply.

1-2-3



4-5



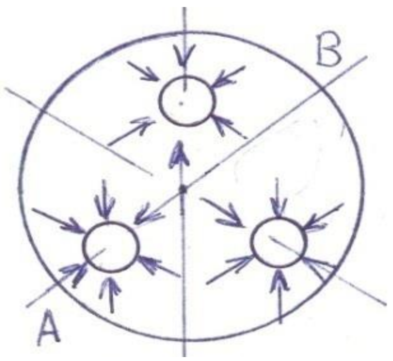
In bifilar scheme a flow on a free surface is converged to each electrode.

Near the bottom there are two pairs of plane vortexes with stable jets from under each electrode to side wall and two zones without stirring in orthogonal plane

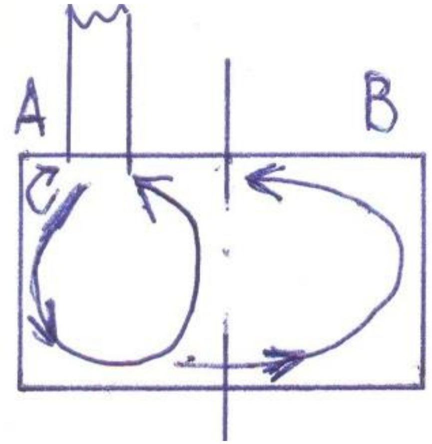
4.1. The schemes of flow patterns under 3-phases current supply

Flow patterns here is looking like a superposition of 3 bifilar pairs, [4]:

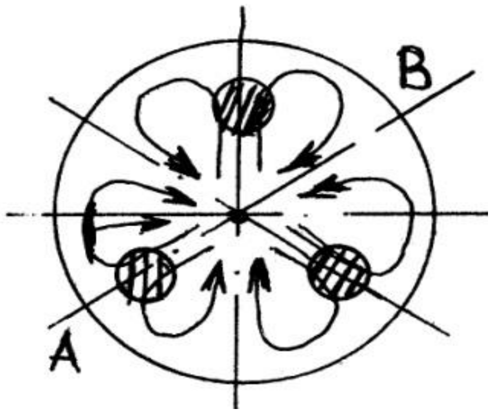
on a free surface



on each of 3 meridional planes AB



Near the bottom (view from-under the bottom



Flows are converging
to each arc

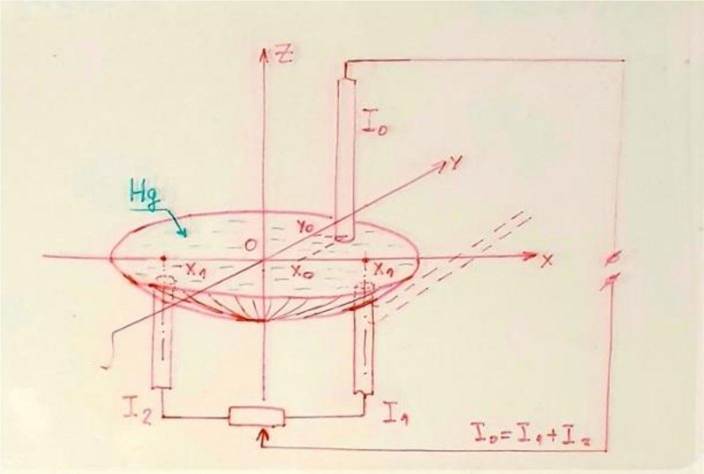
On 3 points A there are stable hottest jets to each from under related arc.

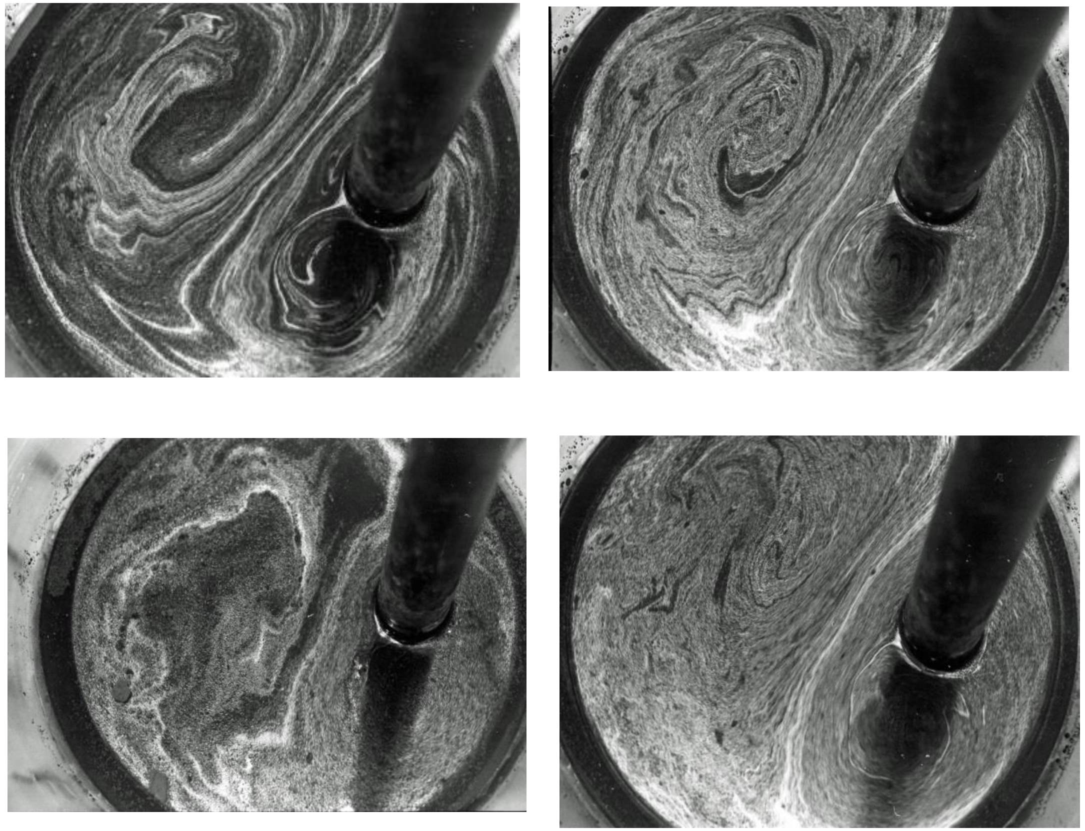
On 3 points B there are zones with relatively slow stirring due to counter-moving side jets

5.1. Dipole type of stirring in a free surface

Nonlinear quasi-stationary flow, [1] – a dipole on a free surface, $I = I_1$

Scheme of a model





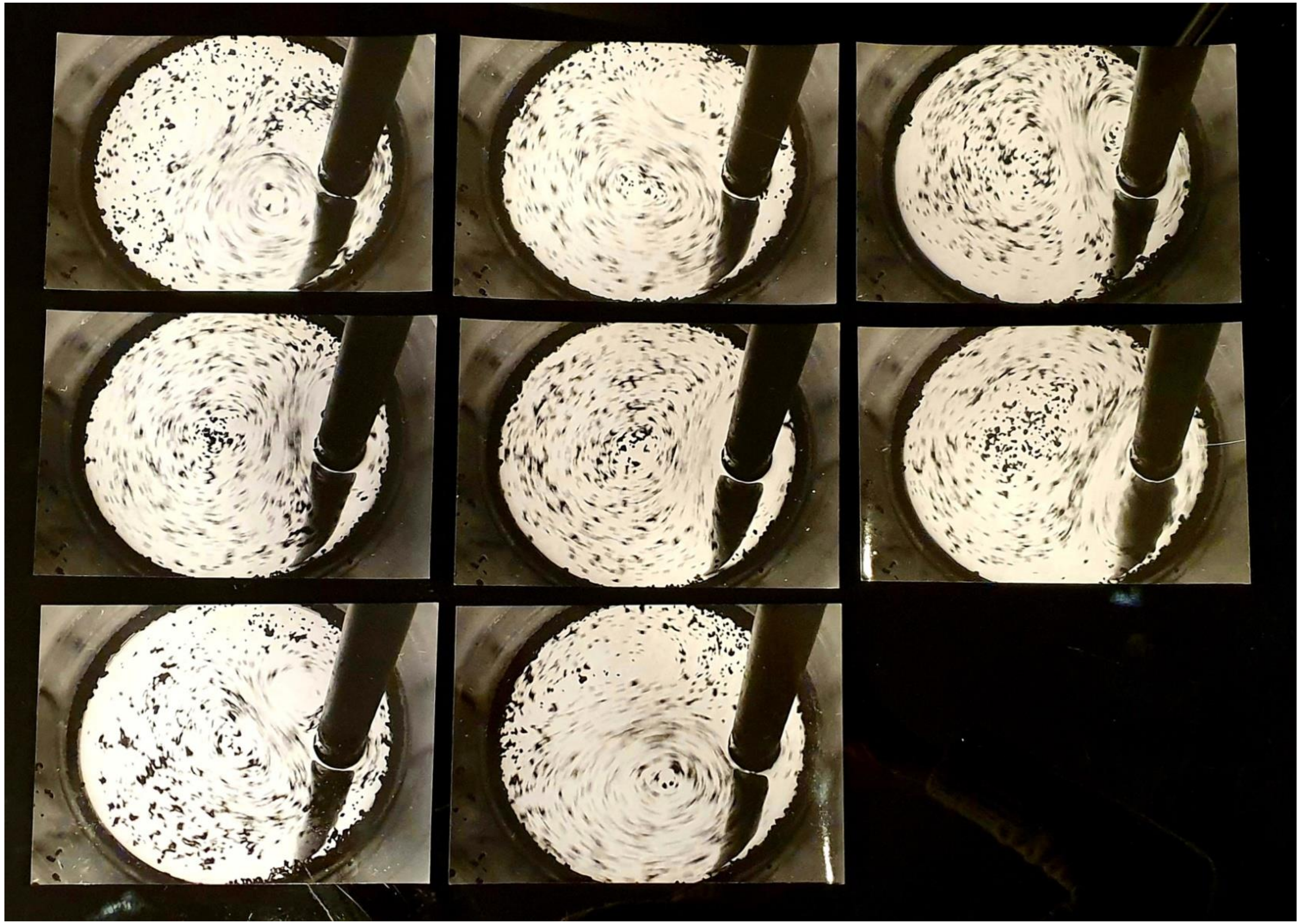
5.2. Nonlinear 3D self oscillations of dipole with total current $I = I_2 > I_1$

Electromagnetic force field does note relate on a time and there is no a deformation of free surface.

1-2-3

4-5-6

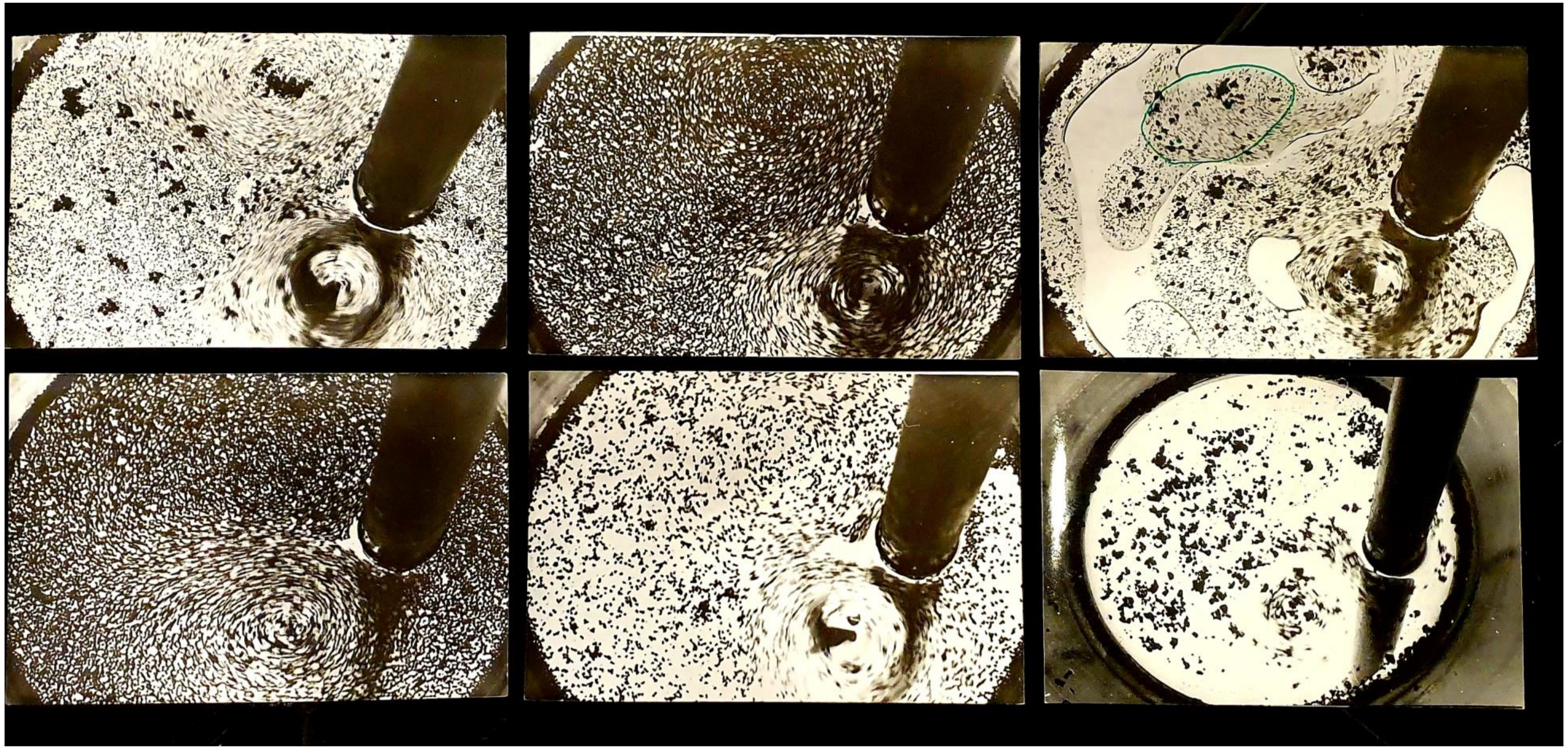
7-8

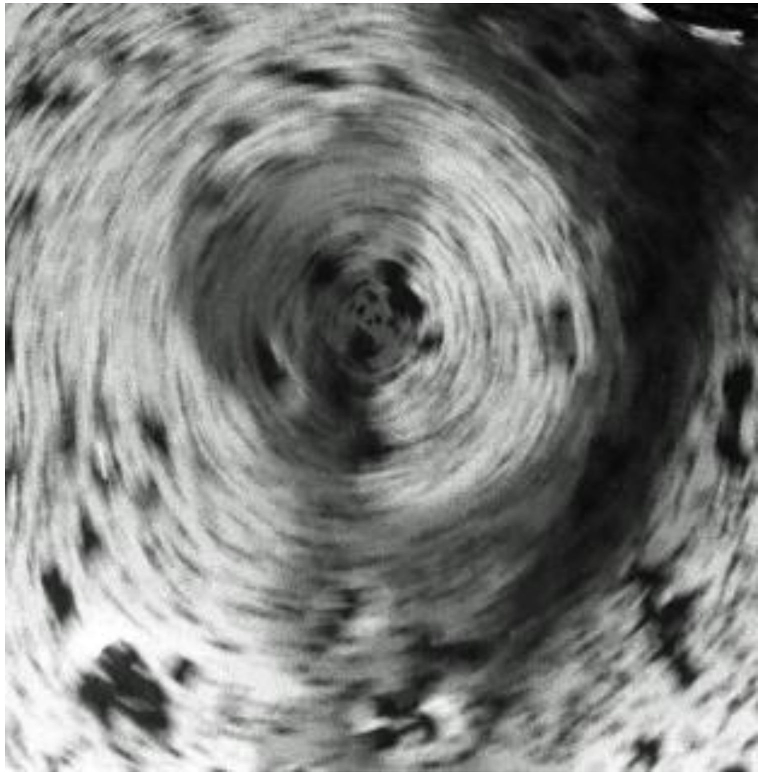


The dipole structure oscillates in a clockwise direction (1-6) and back (7-8). This result was published partly in [1]

5. The stirring in DC EAF UNG

5.3. Localized vortex without any moving around (total current $I = I_3 > I_2$).





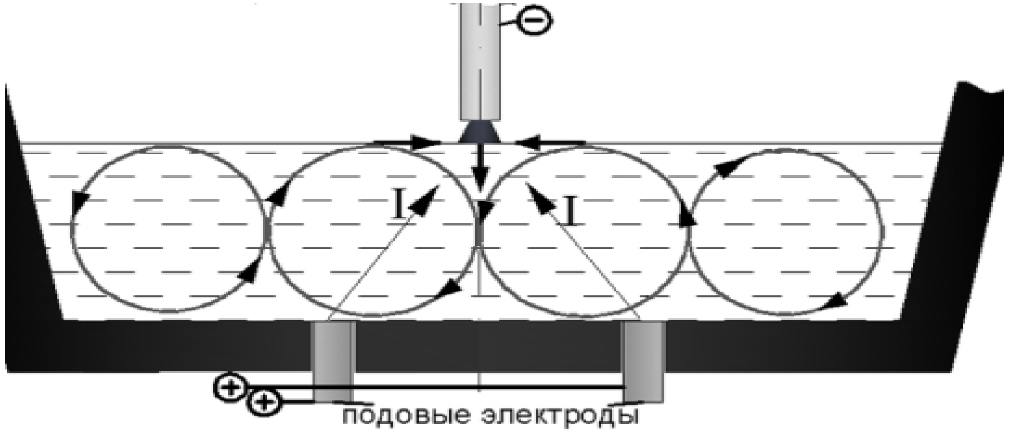
Photos 1-6, made in various photo-technics, demonstrate a repeatability of the physical effect.
The last photo shows a large scaled localized vortex

6. The conception of EAF stirring:

1. EAF with 2 or 3 arcs, including 3-phases AC EAF, do not produced an effective stirring in a melt bath.
2. The conception of good stirring can be formulated as full azimuthal rotation with a stirring between rotated layers by EIVF, that are formed under an arc (most powerful) and over each of bottom electrodes, [5]. For today, this stirring scheme is realized in DC EAF UNG, [1], [6].

With this:

- Hot melt and chemical additions from a free surface is drawing into a depth of metal bath
- No overheating zones (no stable oriented jets)
- No zones without stirring
- Comprehensive stirring provides homogenous temperature and chemical composition of molted metal. (Some not needed elements are burned then under furnace-roof and burn out in the special column)



7. References

[1] A. CHUDNOVSKY. Physical modelling of 3D melt mixing for electrometallurgical aggregates. *Magnetohydrodynamics*, vol. 53 (2017), pp. 747–758

[2] V. BOJAREVICH, J. FREIBERG, E. SILOVA AND E. SCHERBININ. *Electrically induced vortical flows* (Cluwer Academic Press, Springer Netherlands), 1989.

[3] A. CHUDNOVSKY. Modelling electrovortex flows. *Magnetohydrodynamics*, vol. 25 (1989), pp. 503–507.

[4] S. DEMENT'EV, V. ZILIN, YU. IVOCHKIN, A. OKSMAN AND A. CHUDNOVSKY. The question of forming electrovortex flows with multielectrode current supply. *Magnetohydrodynamics*, vol. 24 (1988), pp. 503–507.

[5] A. CHUDNOVSKY, YU. IVOCHKIN, A. JAKOVICS, S. PAVLOV, I. TEPLYAKOV, D. VINOGRADOV. Investigations of electrovortex flows with multi electrodes power supply. *Magnetohydrodynamics*, 2020, Nr 4.

[6] V. MALINOVSKY. Universal next generation direct current arc furnaces. Industria, 2005, №1/39, (in Russian)

Thank you for attention