Model Experiment Validating the Feasibility of a Permanent-Magnet Stirrer for Large-Scale Metal Melting Furnaces

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Abstract: Model experimental set-up was built aiming to ensure achievable similitude to large scale metal melting furnaces, where electromagnetic stirring is required to reduce the melting time and to achieve thermal and compositional uniformity. The widely used three-phase AC current linear travelling magnetic field inductor is substituted by a new energy-saving concept of a Permanent-Magnet (PM) inductor, consisting of a multitude of cylindrical dipoles, which form a Halbach array and are rotated synchronously. The stirrer creates very unstable time-dependent flow pattern in the liquid metal pool. The turbulent local velocity has been measured, delivering experimental data about time-averaged flow and turbulence intensity as well. Spatial components of velocity were measured by ultrasound Doppler anemometry and by potential difference probe with an incorporated permanent magnet, delivering mutually verifying and complementary data with higher reliability. The experimental data would be used to validate the full three dimensional numerical simulations of the stirring produced in actual large scale metal melting furnaces.

1. Introduction

Electromagnetic stirrers EMS of the molten metals are widely used during light metal alloy remelting and conditioning to achieve uniform temperature and composition of the melt in large furnaces up to 70 m^3 in capacity. Most of the EMS available today are AC current travelling magnetic field inductors. Since safety, energy economy and durability of the furnaces requires the stirring to be achieved through thick refractory walls, usually enclosed in additional steel jacket up to 50 mm thick, the travelling magnetic field stirring is realized by a large size Copper coils carrying high ampere-windings of a 3-phase current. In order to deliver high integral stirring in large pools of the melt, the frequency of the AC current is kept as low as 0.2 to 1 Hz allowing to deliver electromagnetic impact with considerable penetration depth, limited by the skineffect [1,2]. Most widely used are the AC current EMS by several companies. All the AC current stirrers consume quite high electrical power and require intense water or air cooling of the inductor coils. Alternative to AC current travelling magnetic field stirring has been implemented using permanent magnet stirrers PMS, which as a rule have a multitude of alternating polarity permanent magnets in an axially symmetric array, which during rotation deliver travelling magnetic field impact in the liquid metal. In order to deliver the EM-forcing through thick walls, the magnet size should be large and usually require local reduction of the wall thickness and/or modification of the wall configuration [3,4,5]. Here we report a novel design of the PMS [6,7,8] and the model experiment validation of the efficiency of this design for stirring in a large scale Aluminium furnaces through thick walls of the bottom of the furnace.

2. Experimental model and similitude criteria

The reported PM EMS, delivering linear travelling magnetic field, consists of a multitude of the cylindrical permanent magnet dipoles with magnetization of each cylinder in direction normal to the axis. The magnet cylinders are mechanically conjugated allowing synchronous rotation of the whole array, sustaining unchanging phase shift of the magnetization directions between them. The PM assembly forms a Halbach array delivering increased magnetic field magnitude to the side of the liquid metal pool.

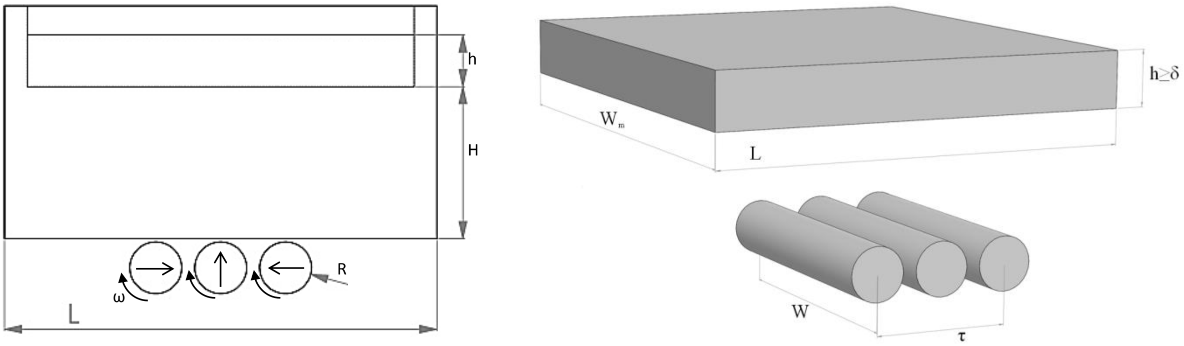

Figure 1. Experimental setup.

During synchronous rotation of the cylinders a magnetic field travelling parallel to tangent of the magnet rotation is delivered in the liquid metal region [6]. A schematic of the experimental model is shown on Fig. 1. The geometrical similarity of the experimental model to the proposed large scale Aluminium stirrer is given by a set of a dimensionless aspect ratios: $h/\tau = 0.25$; $H/\tau = 0.6$; $W/\tau = 0.93$; $L/\tau = 2.7$; $W_m/\tau = 1.9$, H – the distance from the magnets to the bottom of the liquid metal pool, W – length of the magnet cylinders, R – the radius of the magnets, and $\delta = \sqrt{\frac{2}{\sigma\omega\mu}}$ is the skin-depth in the liquid metal at angular frequency ω of the magnet rotation. The physical similitude of the model and the actual furnace requires identity of following dimensionless criteria:

$$\Omega_d = \left(\frac{\tau}{\delta}\right)^2 \text{ and } N = \frac{B}{\omega\tau\sqrt{\mu\rho}}$$

where ρ is the density of the melt, μ – magnetic permeability, B – the magnitude of magnetic field induction in the liquid metal region, Ω_d – dimensionless frequency, and N – electromagnetic interaction parameter. The model experiment was built aiming to similitude to 7.5 times larger scale liquid Aluminium pool. Since both physical similitude criteria identity could not be met on a single model, the dimensionless frequency identity was set as a priority – the skin-depth were required not to exceed the liquid metal pool depth. The unconventional electromagnetic interaction parameter both during the model experiment, and for the proposed large scale Aluminium pool would be much smaller than unity $N << 1$, but during the model experiment was for an order of magnitude smaller than for the large scale Aluminium pool. The N = idem (simultaneous to Ω_d = idem) could not be achieved, because of physical limitations set by achievable remanence of the permanent magnet material. A second model experiment to achieve similitude of N, but not satisfying Ω_d = idem, is considered as a next step. During experiment the liquid metal was In-Ga-Sn eutectic with density 6400 kg/m^3, electrical conductivity $3.3 \cdot 10^6$ S/m and kinematic viscosity $3.1 \cdot 10^7$ m^2/s. Reference liquid Aluminium properties were taken as for pure liquid Al.

The liquid metal velocity measurements were done by two methods, permitting to verify each other. One was the potential difference local velocity probe with an incorporated miniature permanent magnet, the other – ultrasound Doppler anemometry.

3. Experimental results

The local velocity of the flow was measured in two vertical cross-sections, normal to the travelling magnetic field direction. At a large relative distance from the PM cylinders to the liquid metal layer $H/\tau = 0.6$ or 2.5 diameters of the magnet cylinders, the amplitude of the travelling magnetic field induction did not exceed 10 mT. At 50 rev/s of the cylinder rotation the velocity magnitude above the stirrer exceeded 10 cm/s. Since the main purpose of the stirrer is too achieve high integral flow rate, the surface plot shown on Fig. 2 and 3, are most informative – at the vertical cross-section above the longitudinal midpoint of the stirrer the flow-rate was 0.47 l/s, at the cross-section downstream at 0.2 L from the end wall – 0.14 l/s. For the 7.5 times larger Aluminium pool that would be equivalent to 26 l/s or mass stirring rate 220 tons per hour at 0.3 rev/s of permanent magnet cylinders.

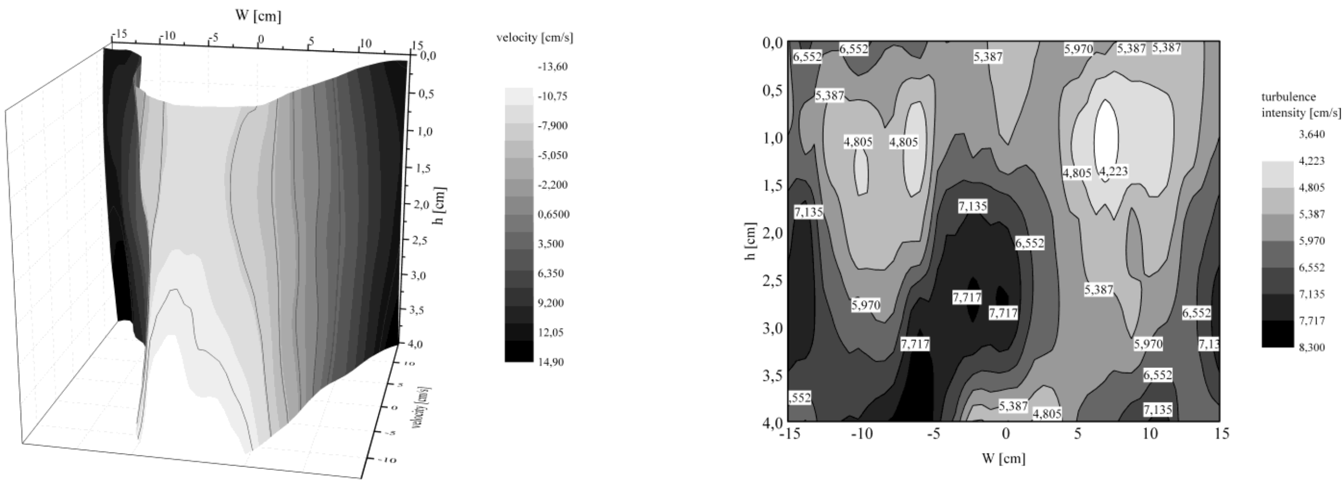

Figure 2. Velocity field above the middle magnet (left) and turbulent velocity pulsations (right).

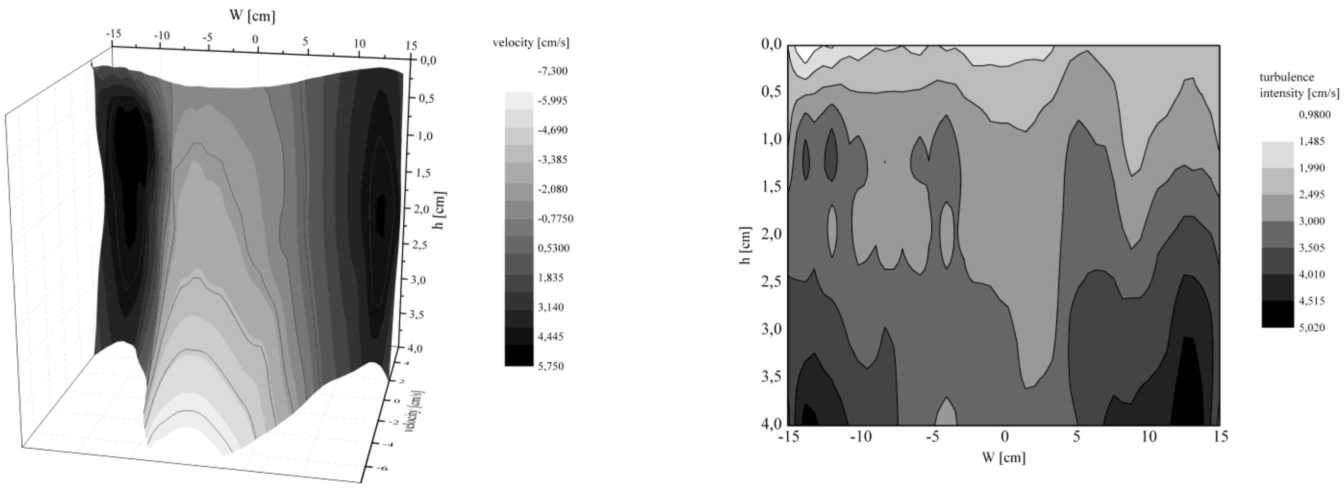

Figure 3. Velocity field between the last magnet and wall (left) and turbulent velocity pulsations (right).

The second major task of the model experiment was to demonstrate if the stirring is efficient all over the pool region. Fig. 2 and 3 show also the information on turbulence intensity, standard deviation distribution is depicted in both above mentioned cross-sections.

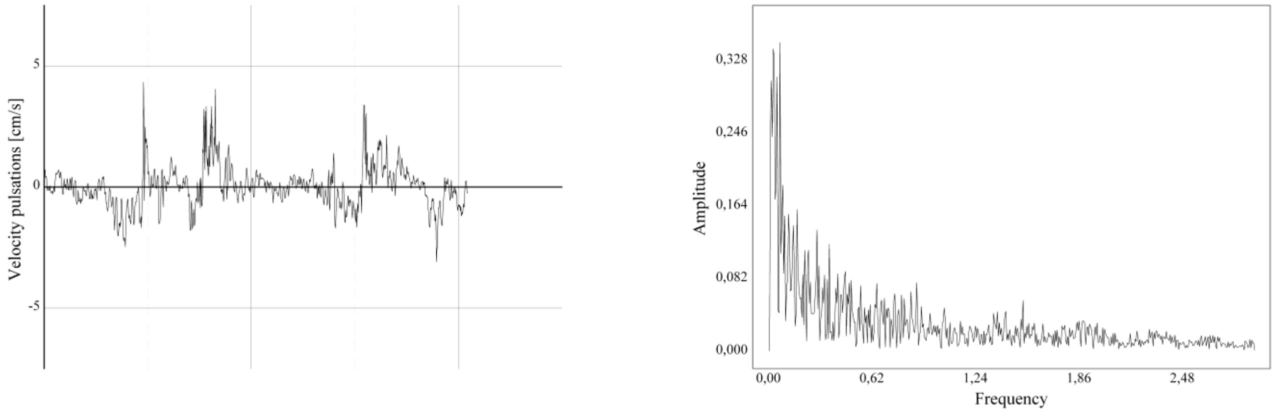

Figure 4. Time dependent velocity signal (left) and Fourier spectrum in the corner of the pool (1 cm from both walls and under liquid metal surface) (right). Average velocity is 0.9 cm/s. Peak-to-peak is 7.41 cm/s.

Besides that the most questionable region regarding the stirring – in the corner of the pool – was investigated. From general considerations the time averaged velocity in the corner region should be small, tending to zero. Fig. 4 confirm very efficient stirring even in the corner of the pool due to very unstable character of induced flow, the turbulence intensity is quite high all over the melt pool. Peak-to-peak velocity oscillations in the corner region are nearly the same as the maximum of the time-averaged velocity of the jet on the bottom of the pool just above the center of the stirrer. The turbulence spectra shown on the right side of Fig.4 confirm that the large scale vortices, corresponding to very low frequencies, are dominant in this flow. The extreme instability of the flow is shown on Fig. 5, where a photo of the momentous free surface deformations of the melt is shown.

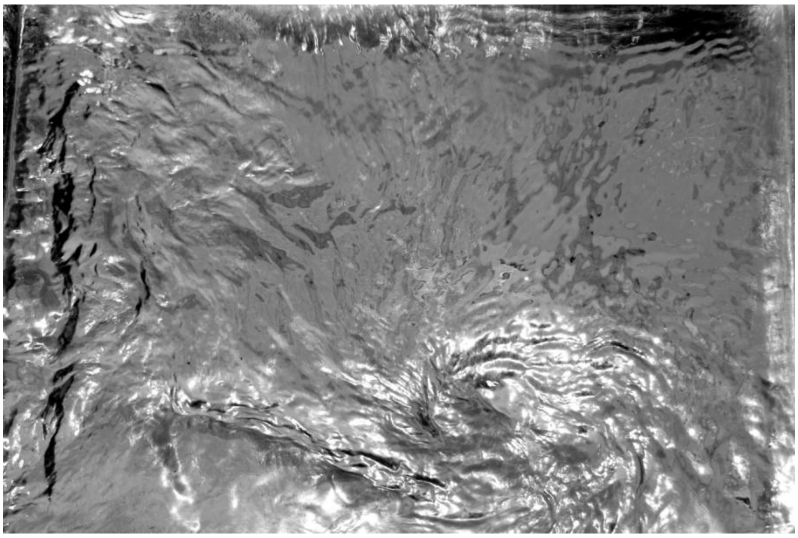

Figure 5. Snapshot of vortex in Ga-In-Sn when mixing is done with high angular frequency.

4. Conclusions

Experimental model did not achieved the full similitude with the industrial scale of stirring in a large Aluminium remelting furnace, since simultaneous identity of relevant physical dimensionless criteria could not be achieved. Nevertheless since both of the compared phenomena involve electromagnetic interaction parameter $N << 1$, the results may be considered sufficient to prove feasibility of the proposed linear permanent magnet inductor for the task of stirring the Aluminium pools in furnaces with bottom thickness up to 50 cm and capacity up to 50 tons. The power consumption of such a stirrer does not exceed 10 kW, there is no requirement for water cooling or intense air cooling. The results of model experiment will be used also to validate the three-dimensional numerical model, currently being developed.

Acknowledgments

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