**Improvement of In-mold Electromagnetic Stirrer by Feeding of Magnetic System with Polyharmonic Current**

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The elaboration relates to a method of electromagnetic stirring in continuous casting of carbon steels, when the surface quality and entrapping of nonmetallic inclusions still remain as the major problems concerning of ingot quality and success on the steel market.

The improvement of surface quality of ingot means a decreasing or elimination of oscillating mark, corner cracking, and pinholes. Intensity of nonmetallic particles entrapping depends on meniscus disturbance: inclusions do not penetrate into liquid portion of ingot through quiet meniscus. Based on the phenomenon of electromagnetic edge effect, which exists in each of asynchronous stirrer, by condition of feeding of magnetic system by polyharmonic currents the new method of in-mold electromagnetic stirring has been developed. Thanks to that the depth of oscillating marks decreases, the flow on the meniscus is suppressed, and the meniscus disturbance and inclusions entrapping is prevented.

KEY WORDS: electromagnetic stirring; edge effect of asynchronous motor; polyharmonic magnetic fields; stirring intensity; meniscus disturbance; inclusions entrapping; oscillating mark; corner cracking.

1. **Introduction**

   Nevertheless diversity and multiplicity of electromagnetic systems for stirring by continuous casting of steels that appeared during 50-years of previous century thanks to S. Junghans and O. Shaaber, the conventional stirring systems for billet/bloom casting that are in operation by numerous users, are uniform, extreme simple, reliable metallurgical installation that should based on the next scientific-technical principles:
   1. In-mold stirrer does not make the obstacles for workability of mold;
   2. The copper mold has to be simple and cheap, like mono-block, easy changeable;
   3. For decreasing of magnetic flux leakage the magnetic system of stirrer has to be submerged into cooling water, being located as close to copper mold as possible;
   4. The main intention of in-mold stirrer is taking away of melt superheat and the stirrer has to provide efficient heat transfer through interface solidus–liquidus;
   5. The revolving magneto-hydrodynamic flow in the mold is a preferable for reaching of high heat transfer on the interface and uniform freezing of ingot on the mold surface.

   The aim of this publication is to show the new manner of electromagnetic in-mold stirring that allows to satisfy the above-mentioned requirements, following the principle of minimum changes in conventional, very rational caster. As example of the in-mold electromagnetic asynchronous stirrer in-mold stirrer for bloom caster 300×400 mm was taken in consideration. The mathematical two- and three-dimensional models of turbulent magneto-hydrodynamic flows (ANSYS software) and experimental data were used for analysis of methods of electromagnetic stirrer improvement. The schematic view of in-mold electromagnetic stirrer model is shown in the Fig. 1.

2. **Meniscus Disturbance**

   Analyzing the situation with meniscus disturbance, which causes the lowering of surface quality and nonmetallic inclusions entrapping, let’s take in consideration only methods and equipment, which have found a place in wide casting practice: rotational asynchronous low frequency stirrer that is fed from multi-phase inverter. We avoid a numerous suggestions of electromagnetic molds such as mag-

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Fig. 1. Schematic view of in-mold electromagnetic stirrer for bloom.
neto-impulse mold for fast billet casting, meniscus free molds, providing a high meniscus position and electromagnetic pushing of liquid steel from "triple" point, and others. Let’s assume also that the perfect control of molten steel feeding and steady position of meniscus are provided.

It is well-known that the liquid steel, coming into mold from tundish, under the action of in-mold electromagnetic stirrer creates a complete three-dimensional magneto-hydrodynamics flow at the top of mold. The hydrodynamic perturbation leads to appearing of surface defects in the ingot. The rotating flow on the meniscus creates the hills in mold corners that usually surpass above mold powder and therefore, prevents the penetration of mold powder into gap between mold and ingot near mold corners. At the same time the rotating flow on the meniscus on the walls of submerged nozzle has the depression that is caused of non-metallic inclusions entrapping through disturbed meniscus into ingot. The dual electromagnetic stirrer that consists of two asynchronous stators—main and brake—with different direction of electromagnetic torques, involved for braking of rotation on meniscus, could not solve this problem because another mechanism of meniscus disturbance adds to the above mentioned one. The currents, which induce in the ingot by both stators, joined in the common loop. The one of horizontal part of this current loop locates directly below meniscus. The magnetic flux of both stators tries to avoid the copper mold and ingot above and concentrates directly at the meniscus, where interacts with above-mentioned radial component of common induced current, gives a strong vertical (upward) component of oscillating electromagnetic force. This electromagnetic force, having a frequency that is close to intrinsic frequency of gravity oscillation of free surface, on the contrary to suppress the disturbance, swings it and creates the strong vertical irregular and progressive waves that "shakes" the meniscus. The conditions for creation soliton waves appear here.

On the other hand, the braking torque, applying at the sufficient portion of ingot below meniscus, reduces the common stirring intensity and partially deprived the stirrer of its main quality—taking away of the melt superheat. Therefore, the dual EMS for billet/bloom casters—that was first time very popular solution—has been canceled after-ward in many casters, having submerged nozzles and using the mold powder.

Another solution regarding suppression of meniscus spinning provides the lowering of regular asynchronous stator on the 150 mm and more below meniscus. This solution that was implemented in the row of in-mold stirers did not allow the full elimination of the vortex around submerged nozzle. This vortex showed the decreasing of meniscus motion intensity but the cooling function of stirrer decreased sufficiently because hot incoming metal does not remain in the upper part of the mold and penetrates to the lager depth.

An imposition of direct vertical magnetic field into the top part of ingot—like in case of electromagnetic brake for slab caster—was not effective when the in-mold electromagnetic stirring was provided. The combination of two kinds of magnetic field—alternate and direct—leads to interaction of imposed direct magnetic flux with induced alternating current from main coil near meniscus. It causes the meniscus oscillation with frequency, which was close to intrinsic frequency of gravity waves. This phenomenon existed with common suppression of stirring intensity.

The method, which is suggested here especially for prevention of turbulence at the meniscus, is similar to but based on the two phenomena. The first is the edge effect that develops differently by different frequencies of imposed magnetic flux. The second is the simultaneous imposition of two alternate magnetic fields that creates in the same regular inductor but by feeding of it with poly-frequency current.

The design of in-mold electromagnetic stirrer is typical for conventional industrial continuous bloom 300×400 mm casting machines, is shown on Fig. 1:

- six or four poles asynchronous stator that provides the rotate motion of molten steel around mold axis,
- low frequency current feeding,
- tubular or assembled copper mold with or without supported stainless steel plates on the external sides of copper mold, water submerged coils, forced convection water-cooling of mold, and coils.

The two- or three-phase magnetic system feeds from low frequency inverter that generates the multiphase polyharmonic currents with controlled phase sequence, amplitudes and harmonic structure.

Low frequency (0.8–3.0 Hz) current-component has direct phase sequence, and amplitude 100%, high frequency (13–20 Hz) component has the reverse phases sequence, and current amplitude equals to 50–75% depending on cast ingot sizes, mold geometry, steel grade and casting speed.

The principal electric scheme of polyharmonic current source (power supply) for in-mold stirrer is shown on Fig. 2. The logical programmable electronic block that forms the managing signals for power thyristors transforms the direct current from rectifier in complete alternate polyharmonic current, having above-mentioned or any harmonic consistence, amplitudes, and phase sequence. The polyharmonic current applies to coils of inductor as in ordinary two- or three-phase asynchronous stirrer.

Above-mentioned current structure is determined from standpoint of using of edge effect for:

- applying the reverse electromagnetic torque on the meniscus to suppress the vortex at the meniscus, reducing the vertical components of steel velocity for prevention of inclusions entrapping into ingot, saving the stirring intensity inside mold, nevertheless, the opposite torque applied to meniscus of molten steel, oscillation with amplitude 2 mm of meniscus edges for increasing of molten mold powder flow into gap between mold and ingot walls, Joule heating of solidified shell edges, and melting of it for lowering of point of initial solidification on 2–3 mm and prevention of touching and bending of shell edges.

Fig. 2. Structure of polyharmonic power supply for in-mold stirrer. 1 – rectifier, 2 – block of polyharmonic current adjusting, 3 – block of power thyristors, 4 – EM Stirrer.
when mold oscillates.

The explanation what is the edge effect of asynchronous stirrer is given in Fig. 3. A magnetic flux, generating in the coils of stator, unfortunately, can flow only partially through copper mold and steel ingot because it meets the electromagnetic resistance in the high conductive mold and ingot as result of inducing of eddy currents. These currents create the own magnetic flux that prevents the penetration of primary flux into mold and ingot. Resulting, the primary magnetic flux tries to avoid the high conductive mold above and below. At the mold top, above meniscus, the magnetic flux does not meet the obstacles and try to penetrate downward, into steel ingot trough meniscus. The higher a magnetic field frequency component the more magnetic flux avoids the mold and ingot and the higher is the concentration of magnetic flux at the meniscus and especially at the meniscus edges. If a mold design provides the installation of steel ferromagnetic insert above in-mold stirrer, this insert absorb part of magnetic flux and the concentration of magnetic flux on the meniscus decreases, and, as result, decrease the edge effect intensity. The magnetic flux, which concentrates on the meniscus edges, interacts with eddy currents inside ingot, and creates the electromagnetic forces and Joule heat sources.

The edge effect develops differently by different frequencies. The higher magnetic field frequency, the stronger an edge effect develops on the ingot surface (Fig. 4(a)), the stronger torque is applied to meniscus and the further the force frequency from intrinsic frequency of meniscus “shaking”. Contrary, the low frequency rotating magnetic flux easy penetrates into ingot and creates sufficient electromagnetic torque in the middle of stirrer. At the same time by low frequency the rotating torque on meniscus is small and by decreasing of frequency lower than 2 Hz the rotating torque on meniscus can even have an opposite direction (Fig. 4(b)).

Therefore, the main idea of suppression of meniscus rotation and saving of high common stirring intensity is based on the combination of frequencies components of feeding current, which provides the using of positive properties of different frequency edge effect: strong low frequency rotating torque inside stirrer, but suppression of this frequency component torque only at the meniscus, at the same time, applying of the high frequency breaking reverse torque on the meniscus. The example of distribution of helical component of Lorenz force on the meniscus and inside stirrer by polyharmonic magnetic field, which has created with this principle, is shown in the Fig. 5.

Before determination of consistency of polyharmonic current that has to feed the magnetic system of stirrer need to determine the influence of current frequency on the level of liquid steel stirring velocities. As follows from Figs. 6 and 7, the higher common stirring intensity presents by current frequency $f = 5$ Hz. Notable, that practically all in-mold stirrers are working by current frequency that is very close to this value.

Installation of ferromagnetic insert above in-mold stirrer makes a correction of edge effect and allows to suppress of all velocity components at the meniscus that can be seen on the Figs. 6(a) and 6(b). The same decreasing of velocity

![Fig. 3. Magnetic field of in-mold stirrer by frequency $f = 5$ Hz: a – regular EM stirrer, b – EM stirrer with ferromagnetic insert (thickness 30 mm), which decreases the concentration of magnetic field above meniscus.](image)

![Fig. 4. The distribution of rotating component Lorenz force density on meniscus (between points A and B) and in the middle of stirrer (between points C and D) for different frequencies: a) for higher frequency 9 Hz, b) for lower frequency 1 Hz.](image)
in the middle section of magnetic core occurs too, but in lower measure that follows from comparison of Figs. 7(a) and 7(b).

The behavior of the meniscus is determined by level of velocity components, especially axial downward directed velocity component that response for entrapment of non-metallic particles into ingot. These velocities distinguish by feeding of inductor with currents of different frequencies. Axial component of velocity at the meniscus for frequency \( f = 1 \text{ Hz} \) and \( f = 5 \text{ Hz} \) equals to 0.017 m/s, for \( f = 9 \text{ Hz} \) this velocity equals to 0.008 m/s and for \( f = 13 \text{ Hz} \) 0.004 m/s. Near submerged nozzle the axial component of meniscus velocity directed downward (inside ingot), but along mold walls and particularly in mold corners—upward. The radial components of velocities at the meniscus equals to 0.05 m/s by frequencies \( f = 1 \text{ Hz} \) and \( f = 5 \text{ Hz} \), 0.03 m/s for \( f = 9 \text{ Hz} \) and 0.02 m/s by \( f = 13 \text{ Hz} \). The electromagnetic forces have a direction from submerged nozzle to the mold walls and
contribute to creation of cavity and entrapping of nonmetallic inclusions into ingot through meniscus near submerging nozzle.

The intensity of edge effect can be changed sufficiently if the concentration of magnetic flux above meniscus will be changed. If the top of in-mold stirrer is covered by ferromagnetic insert the part of magnetic flux that try to avoid the copper mold and ingot will be absorbed and put back into magnetic core of inductor. The level of all components of electromagnetic forces decrease:

– vertical component decreases 3.5···5 times for current frequency 5, 9, and 13 Hz, and for frequency $f = 1$ Hz decreases 9 times,
– radial force component that pushes the molten steel from submerged nozzle to mold walls and so helps to entrap the non metallic inclusions into ingot—decreases 3–3.5 times for all frequencies,
– radial force component on mold walls, which responses for good contact with mold walls and level of oscillating mark, decreases 4···6 times.

Velocities in meniscus decrease sufficiently when the ferromagnetic insert was installed above in-mold stirrer: axial velocity decreases in average on 15%. So, installation of ferromagnetic insert above in-mold stirrer allows decreasing of meniscus disturbance.

But cardinal suppression of the flow on the meniscus occurs when the polyharmonic two-frequency current used for feeding of stirrer coils. As mentioned above, the main principle of adjusting of current frequency-consistence based on the combination of high frequency breaking torque for suppression of meniscus motion and applying of low frequency torque for main mass of molten steel confined in mold. The feeding current has two—one low, and second high frequency components. Each of current components has own amplitude. The phase sequences of three- or two phases high and low frequency components are opposite. Current amplitudes changes in the range $1.3 \leq f_{\text{low}}/f_{\text{high}} \leq 2$. Installation of ferromagnetic plate above mold decreases the right (main) torque at the meniscus. The twelve different combination of frequency and current amplitude of low and high components, which had allowed finding the variant, when the maximum suppression of meniscus motion takes place, were considered (see Table 1). The analysis of all simulated electromagnetic parameters and kinematic structures of MHD flow in mold with variation of frequency and amplitude components of polyharmonic currents allowed to choose the combination of these parameters that provides the suppression of meniscus disturbance, decreasing of oscillation mark.

Two current combinations have shown the best situation on the meniscus.

Combination 1: low frequency component $f = 3$ Hz, $I = 275$ A, high frequency component $f = 13$ Hz, $I = 200$ A.

Combination 2: low frequency component $f = 2$ Hz, $I = 275$ A, high frequency component $f = 20$ Hz, $I = 200$ A.

These current combinations have allowed to get the sufficient decreasing of all velocity components on the meniscus comparatively with base regime for current of monofrequency 5 Hz and current level $I = 275$ A:

– the helical velocity component on the meniscus decreased from 0.22 to 0.16 m/s, as result of appearing of reverse breaking torque thanks to the current of high (17···20 Hz) frequency component and reverse phases sequence comparatively with current of low (0.8···1.0 Hz) frequency component. In spite of dual stirrer, where the horizontal induced current along meniscus is stronger and holds a large space below meniscus, the high frequency breaking torque concentrates much close to the free surface and did not suppress the common stirring intensity;
– frequency of axial forces exceed sufficiently the intrinsic frequency of meniscus vertical waves;
– the ascending velocity on the corners of meniscus decreased from 0.09 to 0.06 m/s;
– the vertical downward component velocity on the submerged nozzle decreased from 0.16 to 0.08 m/s.

Figures 8 and 9 demonstrates the comparison of velocity components on the meniscus and in the middle horizon of stirrer by mono- and poly-frequency current in the coils of in-mold stirrer.

### Table 1. Combination of frequency and current amplitude of low and high components, which were considered in calculation.

<table>
<thead>
<tr>
<th>#</th>
<th>1-st component of polyharmonic current</th>
<th>2-nd component of polyharmonic current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency, Hz</td>
<td>Current in turn, A</td>
</tr>
<tr>
<td>1</td>
<td>1 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>2</td>
<td>1 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>3</td>
<td>1 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>4</td>
<td>1 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>5</td>
<td>2 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>6</td>
<td>2 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>7</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>8</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>9</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>10</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>11</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
<tr>
<td>12</td>
<td>3 Hz</td>
<td>275 A</td>
</tr>
</tbody>
</table>
zle, with electromagnetic rotation of steel. The molten slag and the mold powder, which exists on the meniscus can be instable. The appearing of interface instability is determined by critical Reynolds Number.\(^3\),\(^8\)

\[
\text{Re} = \frac{D_v}{H_1} \left( \frac{d_{\text{slag}}}{n_{\text{slag}} n_{\text{steel}}} \right)^{0.5} \]

where \(D_v\) – velocity difference between molten steel and molten slag, \(d_{\text{slag}}\) – the thickness of liquid slag layer on the meniscus, \(v_{\text{slag}}\) and \(v_{\text{steel}}\) – respectively kinetic viscosity of liquid slag and molten steel, \(R\) – the radial distance from lateral internal wall of mold. When \(\text{Re} > 500\) \(\ldots\) 700, the waves develop at the interface, and apexes of them are as centers of dispersion of both liquids and creation of slag or steel droplets. The higher the velocity difference and the lower the viscosity of liquid slag and steel, the easier instability of interface and droplets of both liquids—steel and slag is obtained. Droplets of molten slag can be involved into liquid portion of billet; nevertheless the difference of steel and slag densities is sufficient. If the mold powder is used as lubricant, usually the solid crust or layer of baked together granules appears on the meniscus, and difference of velocities \(\Delta v\) increases. Let’s estimate this velocity difference. If the kinetic viscosities of molten slag and steel by typical conditions of middle carbon steel are respectively \(n_{\text{slag}} = 68.75 \cdot 10^{-6} \text{ m}^2/\text{s}\) and \(n_{\text{steel}} = 0.865 \cdot 10^{-6} \text{ m}^2/\text{s}\), the distance from mold walls \(R = 50\) mm, and the thickness of liquid slag layer \(d_{\text{slag}} = 3\) mm, then velocity difference will be \(\Delta v = 0.314 \ldots 0.44\) m/s.

Other kinematics parameters: vortex on the meniscus and axial components of involving velocity of mold powder particles of being initially hard on meniscus is stipulated by existence of strong vertical velocity component that is caused because the steel flow through submerged nozzle joins with vortex on meniscus from stirring action. The vortex has a strong vertical velocity component directed downward, near submerged nozzle into ingot, and this velocity is enough for involving of particles having size 200 and less microns. The dependence of particle size from velocity difference can be described by Stockes formula:

\[
\Delta v = \frac{d^2}{18} \left( 1 - \frac{\rho_{\text{slag}}}{\rho_{\text{steel}}} \right) \frac{g}{v_{\text{steel}}} \]

where \(d\) – particle size, \(\rho_{\text{slag}}\) and \(\rho_{\text{steel}}\) – respectively density of liquid slag and molten steel, \(v_{\text{steel}}\) – kinetic vis-
cosity of molten steel, $g$ – gravitational acceleration.

As follow from graph in Fig. 10, which is built according to the Stockes formula, the level of velocity differences is enough for involving of particles that are presented on the meniscus.

4. Surface Quality

Long time exploitation of in-mold electromagnetic stirrers has showed that revolving of liquid metal on the meniscus can decrease the surface quality of ingot. By intensive stirring together with filling of steel through submerged nozzle the revolving liquid steel on the meniscus has the hillocks in the corners of mold and hollows between corners. Both, hillocks and hollows, are not stable, however, average vertical sizes of hillocks and hollows are in proportional to second power of circular velocity. The mold powder slips down from hillocks and collects in the hollows. Mold oscillations together with action of hillocks on the corners leads to non-uniform distribution of mold powder, coming into gap between mold and ingot. Resulting, the heat contact between ingot and cold copper mold is different by different current flowed through submerged nozzle, and the mold powder increased the falling and the flow rate of moving powder was different by different current flowed through nozzle 6. When the magnetic field appeared the easy access into gap between mold and ingot and increasing of heat resistance of mold powder increased the falling and the flow rate of moving powder was different by different current flowed through nozzle 6. When the magnetic field appeared the easy access into gap between mold and ingot and increasing of heat resistance of mold powder.

**Fig. 10.** The difference of velocities liquid steel and slag that are enough for involving particles into ingot.

**Table 2.** The values of estimated meniscus edge replacement under the action of MEMS.

<table>
<thead>
<tr>
<th>Frequency components, Hz</th>
<th>Axial component of EM force $F_z$, N/m²</th>
<th>Edge amplitude, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Hz</td>
<td>140</td>
<td>0.048</td>
</tr>
<tr>
<td>3 Hz – low</td>
<td>180</td>
<td>0.1736</td>
</tr>
<tr>
<td>13 Hz – high</td>
<td>85</td>
<td>1.3 $\times 10^3$</td>
</tr>
<tr>
<td>20 Hz – low</td>
<td>200</td>
<td>0.434</td>
</tr>
<tr>
<td>20 Hz – high</td>
<td>75</td>
<td>1.62 $\times 10^3$</td>
</tr>
</tbody>
</table>

magnetic field provides the pushing of meniscus edge to the ingot center and leads to simultaneous induction heating here, and to local suppression of solidification intensity. Resulting, the curvature of meniscus surface here decreases, the mold powder obtains the easier access into gap between mold and ingot and increasing of heat resistance of gap with simultaneous Joule heating replace down the initial solidification point. Similar mechanism is present when the stirrer is fed with above-mentioned polyharmonic current: nevertheless the intensity of electromagnetic force is less and radial pushing of edges is much smaller than in case of electromagnetic mold. The short-wave vibration of meniscus near edges can make as better the access of mold powder into gap.

The amplitudes of meniscus edges oscillation can be estimated with equation:

$$\frac{du}{d\tau} = \frac{F_z}{\rho}$$

where $\rho$ – liquid density, $\tau$ – time, $F_z$ – axial component of electromagnetic force, $u$ – vertical component of velocity at the meniscus edge. After double integration of this equation for half period of oscillation, the edge amplitude:

$$\Delta z = \frac{F_z}{16 \cdot \rho \cdot f^2}$$

where $f$ – frequency of magnetic field. The values of estimated edge replacement is shown in Table 2.

Nevertheless amplitudes of edge oscillation were small, the effect of improvement of powder access into gap was observed by test on the simple physical unit. **Figure 11** demonstrates the device that consists of immovable stainless steel vessel 2 with low melting metal Sn–Bi that had convex meniscus on the level a little bit above vessel edges. The vessel was surrounded by oscillating ceramic cylinder 1 that created the gape around vessel edges 1.6 mm. Both stainless steel vessel with low melting Sn–Bi alloy and ceramic cylinder were installed into magnetic field of model inductor of single-pole 3-phase stator that generated the magnetic field similar to bloom mold electromagnetic stirrer (MEMS). The magnetomotive forces of 6 coils were 5 times lower comparatively with real bloom MEMS, but field of forces was similar to original. The inductor was fed by polyharmonic current. The base regime for comparison had the monogamous frequency 5 Hz. The weight of mold powder that fell down through gap between ceramic cylinder and stainless steel vessel was measured periodically by weighing machine 6. When the magnetic field appeared the mold powder increased the falling and the flow rate of moving down powder was different by different current flowed through inductor. So, see **Table 3**, by combination of regimes.
Table 3. Experimental data of low melting metal test.

<table>
<thead>
<tr>
<th>Current in each coil of experimental unit inductor, A turns (current in each coil of natural MEMS, A)</th>
<th>Frequency components, Hz</th>
<th>Frequency of cylinder oscillation, Hz</th>
<th>Average gap between ceramic cylinder and vessel with low melting metal, mm</th>
<th>Powder flow rate, kg s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>4950 A turns (275 A)</td>
<td>5</td>
<td>0.8</td>
<td>1.6</td>
<td>1.1·10⁻²</td>
</tr>
<tr>
<td>4950 A turns (275 A)</td>
<td>3 – low freq.</td>
<td>13 – high freq.</td>
<td>0.8</td>
<td>1.67·10⁻²</td>
</tr>
<tr>
<td>3600 A turns (200 A)</td>
<td>3 – low freq.</td>
<td>13 – high freq.</td>
<td>2.1</td>
<td>1.71·10⁻²</td>
</tr>
<tr>
<td>4950 A turns (275 A)</td>
<td>2 – low freq.</td>
<td>20 – high freq.</td>
<td>0.8</td>
<td>1.7·10⁻²</td>
</tr>
<tr>
<td>3600 A turns (200 A)</td>
<td>2 – low freq.</td>
<td>20 – high freq.</td>
<td>2.1</td>
<td>1.73·10⁻²</td>
</tr>
</tbody>
</table>

Fig. 11. Unit for estimation of influence of melt edges vibration on the mold powder flow rate: 1 – ceramic cylinder, 2 – stainless steel vessel with low melting alloy, 3 – EMS inductor, 4 – mold powder, 5 – oscillating drive, 6 – weighing machine.

\[
\frac{f_{\text{low}}}{f_{\text{high}}} = \frac{3}{13} \text{ Hz}, \quad \frac{I_{\text{s,low}}}{I_{\text{s,high}}} = \frac{3600}{4950} \text{ A·trans} \quad \text{and} \quad \frac{I_{\text{l,low}}}{I_{\text{l,high}}} = \frac{3600}{4950} \text{ A·trans}
\]

(here \(f_{\text{low}}\) and \(f_{\text{high}}\) – frequencies of polyharmonic current components, \(I_{\text{s,low}}\) – amplitude value of magnetomotive force of low frequency component, \(I_{\text{s,high}}\) – amplitude value of magnetomotive force of high frequency component) the first regime has shown increasing of powder fall down on 1.67/1.1 = 1.52 times by oscillating frequency 0.8 Hz and on 1.71/1.1 = 1.55 times when oscillation frequency was increased to 2.1 Hz. So, influence of “mold” oscillation on the power flow rate was lower, then current composition.

5. Conclusions.

(1) Sufficient improvement of conventional in-mold stirrer with the same low frequency inverter can be obtained when the inverter generates the polyharmonics currents, having low frequency 2–3 Hz and high frequency component 13–20 Hz depending on ingot and mold size and grade of cast steel. The inverter has to be equipped with logistic adjuster of such current contents.

(2) The feeding of magnetic system of EMS by polyharmonic three- or two-phase current allows to get the reverse electromagnetic torque on the meniscus and suppress the disturbance that in turn decreases the entrapping of particles into ingot through meniscus.

(3) At the same time the feeding of magnetic system of EMS by polyharmonic three- or two-phase current allows to suppress on the meniscus the hillocks in the mold corners, and, resulting, increase the mold powder incoming around billet (bloom) corners, and allows to avoid the cracking of this corners during solidification.

(4) The feeding of magnetic system of EMS by polyharmonic three- or two-phase current leads to oscillation of meniscus edges, and to increasing of mold powder entering. Resulting, the suppressing of the heat flux at the point of initial solidification that allows decreasing the oscillating mark.

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