ELECTROMAGNETIC FUNNEL FOR STIRRING UP SOLID REAGENTS INTO MOLTEN METALS

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Introduction of tiny solid particles into molten metals to alloy them, to prepare specific melts, to re-melt scrap and so on is an acute problem for metallurgy. Its solution by the presently known methods and devices [1, 2, 3] is difficult enough due to large difference in densities of particles and the melt, high values of surface tension in molten metals, strong oxidation of particles on the melt surface and so on.

To intensify the stirring up of disperse particles into molten metals, among others, various magnetohydrodynamic (MHD) devices for electromagnetic stirring of the melt have been proposed [4, 5]. Yet, they have not been widely used due to their low efficiency and problems for practical implementation.

The present paper describes a new method for stirring up disperse particles into molten metals [6] and reports on the results of conducted investigations by a MHD device called "an electromagnetic funnel" (EMF). The idea of the method rests upon the known method for introducing solid and gas particles into the liquid by a funnel-like (vortical) flow [7].

With reference to the above said method [7], by a special device solid particles are introduced into an arbitrary hydraulic (vortical) funnel, formed at liquid pouring out through a hole in the bottom (or side wall) of a vessel. The particles are caught by the liquid, rotating in the funnel, and transported by a transit flow into a reservoir.

Yet, the funnel-like (vortex) flow arbitrary forms only at certain ratios between the size of the drain hole and the value of hydrostatic pressure in the vessel. Moreover, the higher is the density of the liquid, the smaller is the value of hydrostatic pressure, at which the formation of a funnel takes place. When work with molten metals and practically available sizes of drain holes, the value of metal-static pressure, needed for the funnel formation, turns out so small that the melt could solidify in the vessel due to its strong cooling. Minding the above said and the danger of air penetration into the melt (at small values of metal-static pressure), the phenomenon of arbitrary formation of vortical flows cannot be applied in metallurgical aggregates.

For the method under discussion, the vortex flow is force-driven (artificially) in the vessel by imposing rotating magnetic fields (RMF) on the melt. Being exposed to the RMF, the electrically conducting liquid (molten metal) starts rotating, so initiating the formation of a vortex funnel in the vessel at any values of metal-static pressure independent on the diameter of the drain hole (Fig. 1*a*).

Visual observations of the funnel flow formation and evolution during the experiments have demonstrated that as the strength of the RMF influence on molten metal increases, three successive flow modes appear in the formed vortex funnel.

Mode 1. At small rates of melt rotation the vortex funnel forms at a small depth from the melt surface and its solid particle catching efficiency is low.

Mode 2. If the melt rotation rate increases, the vortex funnel penetrates deeper into the melt, but the rotation of the molten metal is not yet accompanied by the appearance of an air core (gap) in the middle of the funnel. This flow mode is characterized by a high efficiency of catching and transporting of any solid particles, occurring inside the vortex funnel zone, into the melt bulk.

Mode 3 appears in the vortex funnel at the further increase of the RMF induction and, relatively melt rotation rate. This mode is characterized by the air core in the vortex funnel, which penetrates down to the drain hole, and by an intensive catching of the air by the liquid jet.

From the point of view of metallurgical technologies, mode 2 is obviously the most preferable mode.

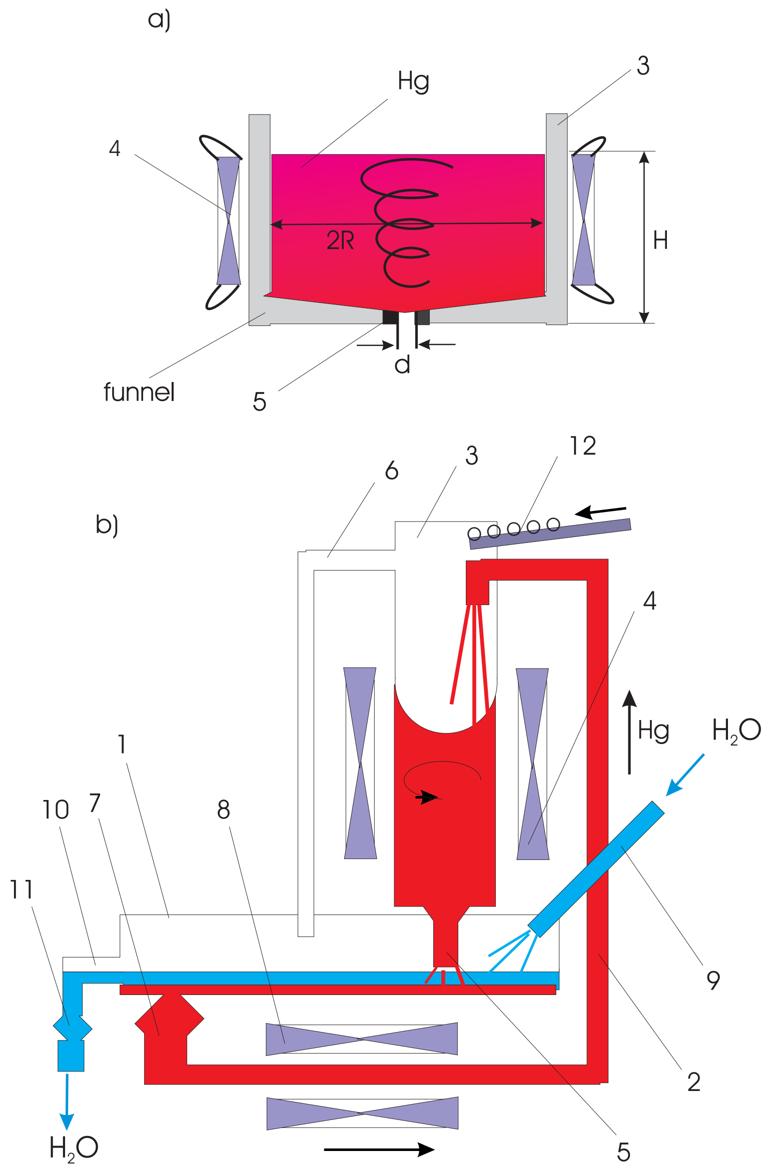

Fig. 1. (*a*) Formation of the funnel flow by the RMF; (*b*) schematic of the experimental setup.

To evaluate and study the qualitative and quantitative characteristics of conditions of formation and features of mixing up for the EMF, an experimental setup (see the schematic in Fig. 1*b*) was used. The experimental setup is a closed mercury loop, consisting of a rectangular reservoir 1, filled with mercury and connected by a pipeline 2 to the body. The EMF is a cylindrical vessel, embraced from the outside by the RMF inductor 4, with a drain branch 5 in its bottom. The top of the vessel 3 has a hole 6 for mercury draining from the EMF into the reservoir 1 in case of mercury excess in the funnel.

Mercury is supplied from the reservoir 1 into the EMF 3 through a filter 7 by an electromagnetic pump 8, connected to a controlled transformer, in such a way that its flowrate could be controlled within a wide range. When the setup is in operation, water through a pipeline 9 is continuously supplied onto the mercury surface in the reservoir 1 (water excess through a hole 10 and a filter 11 pours out into the waste-water disposal system). Solid particles are supplied into the EMF by a vibro-chute 12, whose regime of operation determines the rate and amount of particle load into the molten metal.

The experimental procedure was the following. When the electromagnetic pump 8 was turned on, mercury from the reservoir 1 was supplied into the body 3 of the EMF and poured out from there through the drain branch 5 back to the reservoir 1. The regime of operation for the pump 8 was such that the molten metal level in the EMF was kept constant at settled diameters of the branch 8. Then the RMF inductor 4 was switched on and mode 2 of the funnel-like flow was driven by varying the current in inductor's windings. Solid disperse particles were supplied through the vibro-chute 12 onto the metal surface in the EMF and, being caught by the funnel-like flow, entered the reservoir 1. There they either came to the mercury surface (at $\rho < \rho_{\mathrm{Hg}}$) and were taken away by the water stream, being filtered by the filter 11, or were caught (at $\rho > \rho_{\mathrm{Hg}}$) by the flow of mercury and sedimented on the filter 7.

The first series of experiments investigated the conditions for the funnel flow formation at different ratios of the diameter D of the EMF body 3 to the diameter d of the pouring out branch 8 and to the value of metal-static pressure H in the EMF body. During experiments the ratio D/d varied within $15 \leq D/d \leq 25$, and the ratio H/D within $1 \leq H/D \leq 2$. The formation of mode 2 of the funnel flow and a corresponding angular velocity of molten metal rotation were registered in every experiment. Processing of the obtained experimental data for the condition of stable mode 2 setting up in the EMF allowed the following empiric formula:

$$\omega_0 \approx 1.8d/\left(d^2 + D^2\right)\sqrt{gH} \quad (1/\mathrm{s}),$$

where ω_0 is the angular velocity of liquid rotation, g is the free fall acceleration. Moreover, with a possible change of the funnel flow to mode 3 with air capture into the funnel, it is considered necessary that the operation mode of the EMF would be implemented at $\omega_p \leq \omega_0$.

Apparently, the rate of molten metal rotation ω_0 needed for the EMF formation is determined by the induction value B of the rotating magnetic field (RMF) and depends on the molten metal level H in the vessel. Since the RMF induction value is controlled by varying the electric current value in the RMF inductor, the above value of ω_0 is easily kept practically even if the value of H varies during the EMF operation. The conducted investigations have revealed that when the melt level H in the vessel varies, the stability of the funnel operation mode can be kept by varying the RMF induction from

$$B_p = B_0\sqrt{H} \quad (\mathrm{T}),$$

where B_p (T) is the operating (required) value of the RMF induction, and B_0 (T) is the RMF induction value at stationary mode 2 of the funnel-like flow, H(m) is the value of metal-static pressure.

Another series of experiments examined the dependence of mixing up of solid disperse particles of different sizes l and densities ρ into the liquid metal (mercury with $\rho = 13.6$ g/cm^3). The following solid particles were used: polystyrene granules ($l = 100$ μm $\div$ 2 mm, $\rho = 1.06$ g/cm^3); graphite powder ($l = 50$ μm $\div$ 1 mm, $\rho = 2.3$ g/cm^3); glass balls ($l = 1 \div 6$ mm, $\rho = 2.65$ g/cm^3); filings of non-magnetic stainless steel ($l = 200$ μm $\div$2 mm, $\rho = 8.4$ g/cm^3); powder of tungsten carbide ($l = 100$ μm $\div$1 mm, $\rho = 15$ g/cm^3); tungsten particles ($l = 1 \div 3$ mm, $\rho = 19.3$ g/cm^3); poppy seeds ($l = 0.2 \div 0.5$ mm, $\rho = 0.6$ g/cm^3) birch sawdust ($l = 1 \div 3$ mm, $\rho = 0.7$ g/cm^3). So the particle sizes varies within 50 μm $\div$6 mm, and the ratio of the particles densities to the density of mercury varied within $\rho/\rho_{\rm Hg} = 0.044 \div 1.419$.

In every experiment, definite particles were supplied into the EMF, quickly caught by the funnel-like flow, and a mixture of the molten metal with the particles entered the reservoir 1 with mercury and water streaming over it. As said above, the particles with $\rho < \rho_{\rm Hg}$ came to the surface and were taken away by the water stream, precipitating on the filter 11, and the particles with $\rho > \rho_{\rm Hg}$ were caught by the mercury flow and precipitated on the filter 7. Comparing the mass of particles supplied into the EMF with the mass of particles caught by the filters reveals that almost 98–100% of the particles supplied into the EMF are captured by the funnel-like flow and transported into the reservoir 1. Note that when the RMF inductor is switched off, the funnel-like flow does not form and the particles with $\rho < \rho_{\rm Hg}$ move on the mercury surface independent on the continuous metal flow in the loop. A similar situation is observed at $\rho > \rho_{\rm Hg}$ if particles are tiny and not wetted with mercury.

Conclusion. The conducted experiments allow to conclude that (i) the above method for creation of a forced funnel-like flow is rather effective and can be used at any values of metal-static pressure, any sizes of vessels and diameters of drain holes; (ii) the efficiency of solid particles mixing up into the molten metal by the electromagnetic funnel almost does not depend on their sizes and the ratios of particle densities to the density of molten metal; (iii) to avoid air capture and its transfer into the molten metal, the mode of EMF operation should correspond to the above discussed dependencies.

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