Melt Flow Measurement in Aluminium Alloys in Electromagnetic Stirred Industrial Furnace

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Abstract

The present paper describes a cooperative research project between the Institute for Electrothermal Processes, University of Hannover and the Scientific and Manufacturing Centre of Magnetic Hydrodynamics, Krasnoyarsk State Technical University. For the first time melt flow measurements in aluminium alloys have been carried out in industrial conditions to investigate the effectiveness of electromagnetic stirring of the melt in 40 tons furnace. The results show the quantitative distribution of the melt flow velocity and the dynamics of the stirring process for different operating parameters.

Introduction

Non-contact force electromagnetic field influence on the liquid metal is known to be a component part of modern technological processes both in ferrous and non-ferrous metallurgy. With the help of electromagnetic field it is possible to stir metal in the melting machines, and during the non-furnace treatment – in the forehearth, ladles, mixers, etc. At that, the processes of alloy obtaining become much simpler and accelerated, energy consumption per unit of metal mass is reduced, the working conditions in the metallurgical shops become better, metal quality increases, the degree of process automation increases as well.

When optimizing the system for electromagnetic stirring (Fig. 1), consisting of Magneto Hydrodynamic (MHD) stirrer 1, thermal insulation 2 and melt 3, and predicting the technology of melt stirring with the aim of increasing the effectiveness of alloys preparation, it is very important to investigate the velocity distribution pattern in the furnace bath during different operation modes. In particular, the important tasks of research in the field of stirring technology are: to study the velocity distribution in horizontal plane of the furnace bath and along the melt depth, to determine a maximum velocity of the melt motion depending on frequency of stirrer current, etc.
1. Method and Device to Measure the Liquid Metal Flow Velocity

When choosing a method for measuring the flow of the metal melt it is necessary to take into consideration the following criteria:
- heat-resistance of the active element;
- chemical resistance of the active element;
- mechanical durability of the active element;
- ageing, life cycle;
- influence of the electromagnetic fields;
- measuring sensitivity;
- possibility of measuring signal processing;
- dynamic behaviour;
- influence on the object of measuring;
- maintenance characteristics;
- cost.

The principle of electromagnetic sensor operation is based on the electromagnetic law of Faraday $\mathbf{E} = -(\mathbf{V} \times \mathbf{B})$.

In one electrical conductor moving with velocity $\mathbf{V}$ in magnetic field $\mathbf{B}$, electric field $\mathbf{E}$ is created that is perpendicular to the direction of the conductor motion and to the magnetic field direction.

The metal melt works as moving with velocity $\mathbf{V}$ conductor, which flows perpendicular across magnetic field $\mathbf{B}$ of the magnet. At that the electric field is created directed perpendicular to both vectors. This field is proportional to the velocity of the flowing metal and is measured as the voltage across the pair of electrodes.

For complete defining of the three-dimensional turbulent distribution of flow all three spatial components of velocity should be determined. Because it is impossible to measure all three components simultaneously, first, using 90° chamfered holder of the probe rod the radial and axial components of the flow velocity are measured, then with the help of the direct holder – radial and azimuth ones.

With the melt temperature higher than the maximum working temperature of the sensors with the permanent magnet (about 450°C) there appears distinct, partially irreversible, not reproducible weakening of magnetization. That is why the sensors with the permanent magnet, measuring the flux, have very limited application in liquid aluminium [1]. No induction methods for measuring local flow velocity in liquid metals within the temperature range between 600°C and 700°C are known from the literature. That is why for the application in the aluminium melt the electromagnetic velocity sensor shown in Fig. 2 was developed and made [2].
Unlike the probe rod with the permanent magnet, the magnetic field of the electromagnetic sensor is created by the excitation coil along which the direct current is flowing. The case of the sensor, magnetic core and the coil case are made of ferromagnetic steel to provide better magnetic conductivity and higher induction of the field. During the measurements the coil current was kept on the level of 10 A. The indicated level of the current was chosen taking into consideration the provision possibly high strength of the field with the limited density of current in the coil wire.

Low corrosion durability of the flow velocity measuring sensor in the aluminium melt appeared to be the greatest problem in the measurements performed. After 10-20 minutes of operation the magnetic steel core and the steel case were so greatly corroded that the sensor became unfit for the further operation. To prolong the lifetime of the sensor at the expense of other materials application such as platinum or tungsten, is impossible as they do not have long durability against the aluminium melt [1]. The attempts to prolong the operation period of the sensor protecting it with the ceramic cover did not bring the desired results as well.

The device for measuring velocity of aluminium alloys in the industrial furnace with MHD stirrer consists of electromagnetic sensor, source of direct current of the sensor coil, system of the sensor fixation in the specified point of the melt, data acquisition system and connecting wires and cables.

Designed and specially manufactured for the installation described (Fig. 3), the sensors have some specific features. Taking into consideration the melt bath dimensions, it appeared possible to manufacture the sensors of relatively larger size. This allowed to increase the number of coil layers up to three and to increase the sensitivity of the sensor. Besides to protect the sensor from corrosion the thickness of its case was increased, that allowed to increase the time of its operation up to one hour. Both the signal conductors and the coil of the sensor are made of special wire in the protective cover made of stainless steel with the isolation made of magnesium oxide which provides working capacity of the sensor at the melt temperature up to 800-900°C.

The sensors can be attached to the vertical pipe made of stainless steel 850 mm long both vertically or horizontally (with the 90° turn) with the help of special reducing bushings. Inside the pipe there are four signal conductors and two power supply conductors of sensor coil.

To fix the sensor in the specified point of the furnace a specially designed for this purpose rod made of titanium alloy and cooled with the compressed air was used. Inside the rod the necessary conductors are provided that at one end of the rod are connected with the special conductors of the sensor in the high temperature connecting box and at the other end – with the cable of the system and the source of direct current.

The data acquisition system is based on Top Message device from Delphin firm and portable computer Pentium III 700 MHz, connected into network TCP/IP Ethernet (Fig. 7). The Top Message device has a 24 bit analog-digital converter and provides the processing of signals from 15 analogue inputs. The high precision of the converter allowed to refuse of using DC preamplifiers and connected with this zero drift and additional disturbances. Finally to solve the problem of zero drift appeared to be possible at the expense of periodical changing of the direct current power supply source polarity in the process of measurement.
The measuring system possibilities allowed to refuse of using physical filters for suppression the alternating current disturbances and to change them for mathematical filtration of the signal. This is especially important during the measurements under the condition of low frequency disturbances, which is typical for MHD stirring [3]. In the process of preparatory work the best result was attained while averaging the signal from the sensor during 10 seconds. Such processing of a signal allows to estimate both the average level of velocity, as well as the level of turbulence of its motion at the acceptable measurement time of 2-3-min.

2. Methodology of the Measurements

The methodology of industrial experiments to measure flow velocity of aluminium alloy melt is based on the following statements and assumptions:

1. The measurements can be carried out simultaneously only in one point of the melt for two spatial components of melt flow velocity.
2. Only average in time melt flow velocity can be estimated quantitatively.
3. The dynamic characteristics of the process can be estimated only qualitatively.
4. The durability of sensor operation in the melt is strongly limited by the chemical activity of the aluminium alloys.
5. For reliable estimation of the velocity value in each selected point the record of stable signal should be done during several minutes.

All the experiments have been conducted for 41 points in the melt bath of the furnace with fixing three coordinates and operating frequency.

3. Analysis of the Results

The results of measurements have been analyzed and organized in the following groups:

- Distribution of the melt flow velocity in horizontal plane of the furnace.
- Distribution of the horizontal velocity components according to the depth of the melt.
- Dependence of the horizontal velocity components in the point of intensive motion on the frequency of MHD stirrer.
- Investigation of the MHD stirrer reverse mode in the point of intensive motion of the melt.

The distribution of melt velocity in the horizontal plane of the furnace was built on the basis of 25 points where both x and y horizontal components of the velocity were successfully measured. The distribution of the melt flow velocity with the arrow length proportional to the value of velocity is shown in Fig. 4a. For better
visualization of melt motion contours the same velocity field with the constant arrow length is shown in Fig. 4b.

The distribution of horizontal components of velocity on the melt depth was performed in the point of intensive stirring which is located nearby the stirrer. It was possible to measure only $x$ component of the stirring velocity, because of the signal from the sensor about its $y$ component was lost in that experiment. However, in the indicated zone the $x$ velocity component that is two orders of magnitude higher than $y$ component, fully characterizes the melt motion. The distribution of $x$ component of velocity over the depth of the melt is shown in Fig. 5. In the undersurface layer (at the depth of 0.1 m) the velocity of melt motion is maximal and comprises 0.61 m/sec. With the increase of the distance from the surface the velocity monotonously drops down to 0.37 m/sec in the near bottom layer (at the depth of 0.7 m).

The dependence of the horizontal velocity components on the frequency of MHD stirrer has been investigated in the same point of intensive melt motion. Unfortunately, as in the previous case, it was possible to measure only $x$ component of the stirring velocity. The dependence of $x$ component of the melt flow velocity on the MHD stirrer frequency is shown in Fig. 6. The maximum of the melt velocity with the MHD stirrer frequency of 0.6 Hz has been detected.

Investigation of MHD stirrer reverse mode was made at the depth of 0.54 m in the point of intensive melt motion with the coordinates in the horizontal plane $x=0$, $y=-0.25$ m. At the time of 19:26:00 the MHD stirrer was switched on. In Fig. 7 a part of the time diagram of the melt speeding-up in the $x$ direction between 19:26:00 and 19:28:00 is clearly seen. The speeding-up is accompanied with relatively small level of fluctuation components of the motion. After speeding-up in 19:28:00 a section with the steady-state average level of velocity and increased turbulent fluctuation of the motion is seen. Thus, in the indicated point of the furnace the time of the transfer process when switching on the MHD stirrer can be estimated as 2 min.

**Conclusions**

Experimental measurements of aluminium melt flow velocity in large capacity melting-casting industrial furnace have been carried out for the first time. It allowed to get to
know the quantitative distribution of the melt flow in the furnace bath and to determine the optimal frequency of MHD stirring. Dynamics of the stirring process and the turbulent fluctuation components of the melt flow have been estimated qualitatively. Results of the measurements are used for verification of mathematical models and improvement of stirring equipment.

References

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Fig. 7. Time diagram of the melt flow velocity signal in the data acquisition system