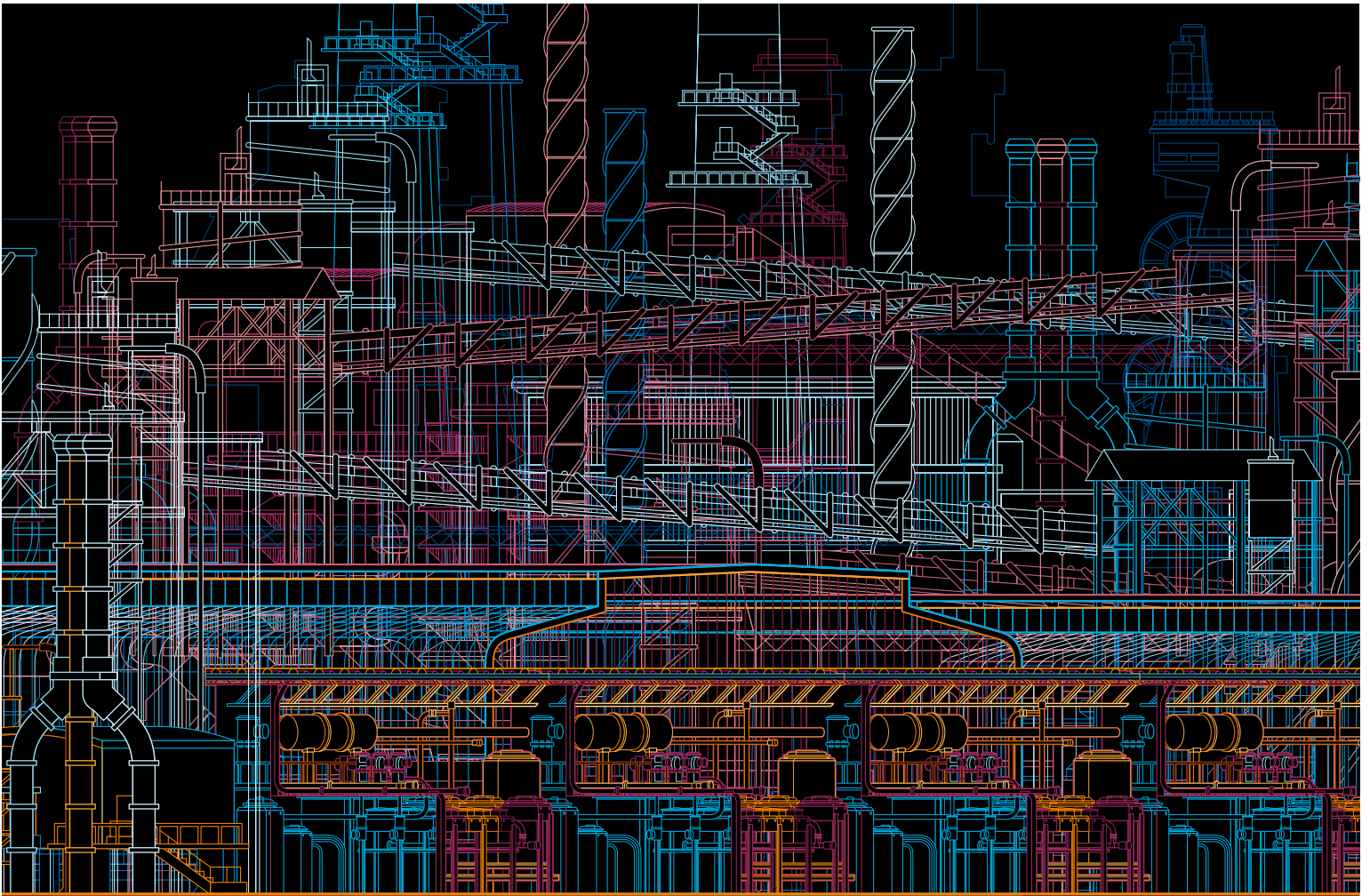




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Electromagnetic stirring in aluminum ladles

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Electromagnetic stirring in aluminum ladles

Abstract

Electromagnetic stirring (AL-EMS) in aluminium melting and holding furnaces is now a well-established technology to enhance chemical and thermal homogeneity and to reduce cycle time, energy consumption and dross formation. This paper will discuss the benefits of using AL-EMS for ladle stirring of liquid aluminium.

To become more cost efficient some foundries are purchasing liquid aluminium. By doing so, a reduction of material losses together with savings in energy and logistic costs, as well as current assets, can be achieved. The molten aluminium is stored in ladles which can be put on hold for as long as 24 hours before being delivered to the foundry. Heating and therefore stirring will be needed to assure correct temperature during this waiting time.

Experiences from industrial plant trials have shown that electromagnetic stirring can generate total thermal homogenization in aluminium ladles. Reduction of melt surface temperature by AL-EMS and how this can suppress surface oxidation and improve heat transfer to the melt is discussed in this paper. This further demonstrates the potential of AL-EMS to reduce burner running cost. AL-EMS also assures a high melt quality resulting from the minimization of thermal gradients.

History

Since 1947, ABB has been supplying various kinds of electromagnetic stirring systems for the aluminum and steel industries. More than 1,400 systems have been delivered for aluminum furnaces, continuous casting machines and for ladle furnaces. The first installation of an electromagnetic stirrer (AL-EMS) for a single-chamber aluminum furnace was made by ABB in 1969. Since then, the number of installations has steadily increased, even though AL-EMS has been considered an exclusive technology requiring a high initial investment. Electromagnetic stirring systems have consequently been installed mainly on larger furnaces above 70 tons. The EMS technology, however, has continuously evolved and is now highly competitive with other stirring methods, also for smaller furnaces. Today, there are more than 400 systems operating worldwide. The majority can be found in Japan and China where electromagnetic stirring is considered a standard technology for aluminum furnace operations.

Introduction

Efficient stirring of the aluminium melt is important when it comes to improving the kinetics of reactions as well as heat and mass transfer, which are essential factors to increase productivity, to improve the quality of the aluminium and to achieve a cost-efficient operation. Electromagnetic stirring in aluminium furnaces (AL-EMS) is today a proven and accepted technology for stirring molten aluminium in both melting and holding furnaces. By ensuring improved heat and mass transfer and faster reaction kinetics, the cycle time and dross formation can be reduced, thus giving a more cost-efficient operation. With the growing demand from the industry to increase furnace productivity and reduce operational cost with minimum investments, a growing interest in AL-EMS has become evident. The objective of this paper is to briefly describe the technology of electromagnetic stirring (EMS) in order to demonstrate what EMS can accomplish in terms of ladle stirring.

AL-EMS system

The main component of an AL-EMS system is the electromagnetic stirrer, which is water-cooled and mounted outside the ladle side wall or underneath the ladle, see figure 1. There is no physical contact between the stirrer and the ladle. A normal refractory lining can be used, but in order to allow the magnetic field to penetrate into the ladle, a "window" of non-magnetic stainless austenitic steel must be made just in front of the stirrer. The stirrer operates using a low frequency travelling magnetic field, penetrating through the ladle plate and refractory lining and moving the melt in an analogous way to a linear electric motor. AL-EMS can be installed on all new ladle stands and retrofitting is possible on most existing ladles stands.

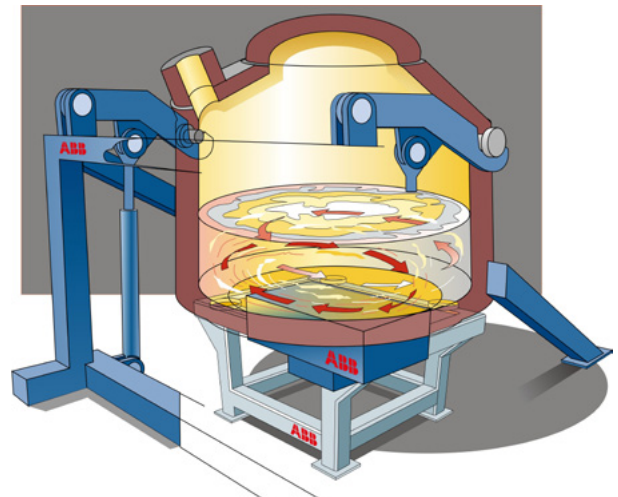


Figure 1. Schematic picture of a bottom mounted ladle stirrer (AL-EMS) in a ladle stand.

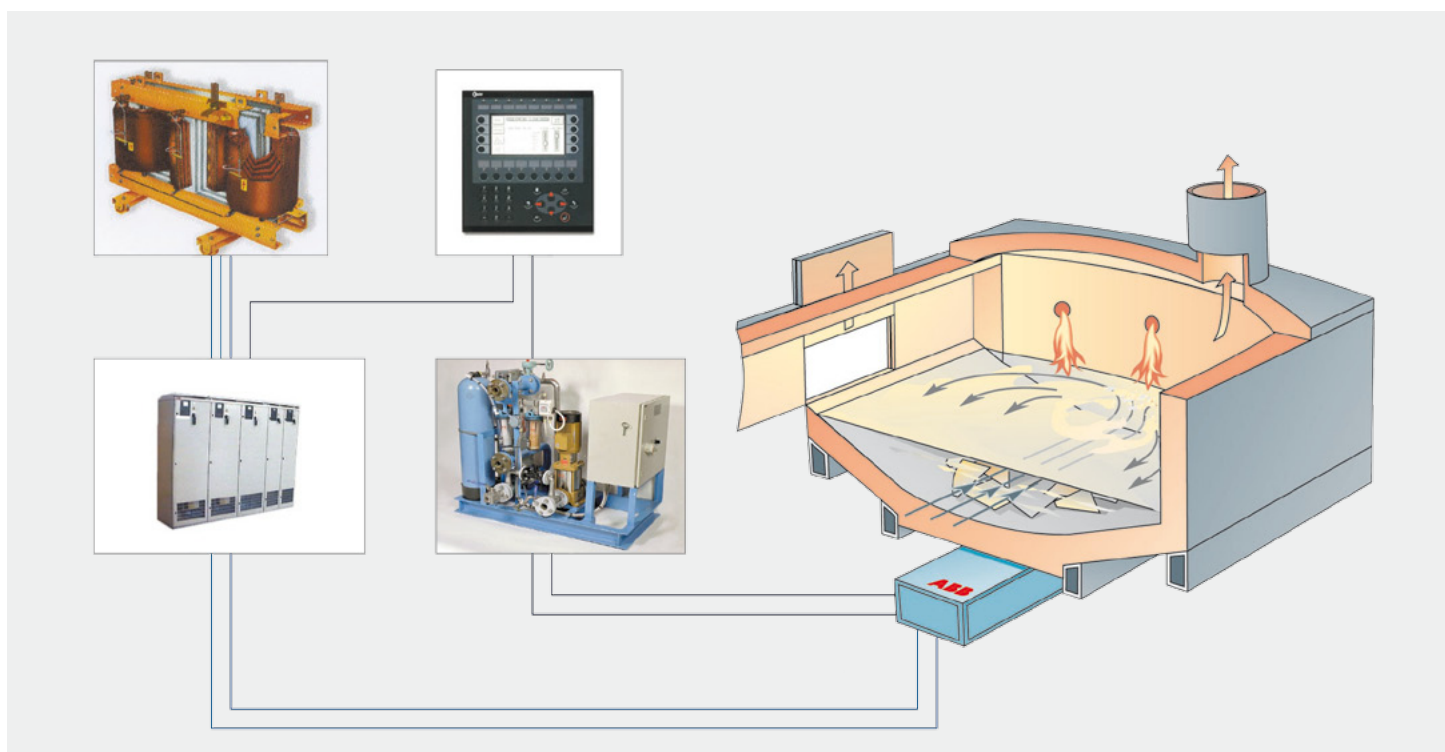


Figure 2. Overview of the AL-EMS system with the included items; transformer, frequency converter, water station, control panel and the stirrer coil.

The AL-EMS system can consist of one or more stirring coils, a frequency converter, a transformer, a cooling water station and control system, see figure 2. The stirrer can be operated from either the stirrer control system or from the customer's HMI system. In cases where more than one ladle is equipped with AL-EMS, a common supply and water unit is generally used to minimize the necessary space and cost.

Plant trials

During waiting time, the ladles need to be heated to maintain correct temperature. This waiting time could be as long as 24 hours and in some cases even more. The heating is normally done by a burner located at the top of the ladle and by doing so, heating the surface of the molten aluminium.

To ensure that the stirring force is efficient and that the thermal homogeneity is reached, temperature measurements have been performed at an existing plant installation. The test was carried out by measuring the bottom and surface temperature in an 8 ton capacity ladle that has been held for 1 hour without stirring. See figure 3 for the measurement setup.

During the 1 hour holding time, the burner was running and the set point temperature was 750 °C. As mentioned before, the surface and bottom temperature was continuously measured and after approximately 1.5 minutes the stirrer was turned on, see Figure 4. The thermocouples were placed five centimeters from both the bottom and the top surface. The thermocouples used were of K-type with a maximum operating temperature of 1200 °C. The temperature data was recorded every 2 seconds

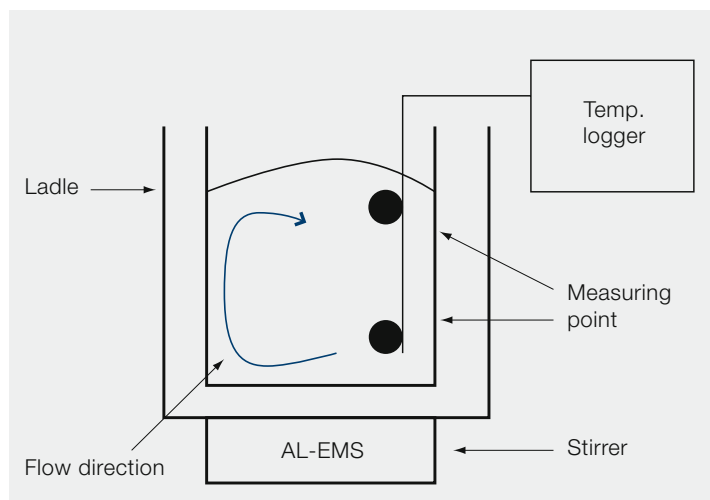


Figure 3. Test setup and placement of thermocouples.

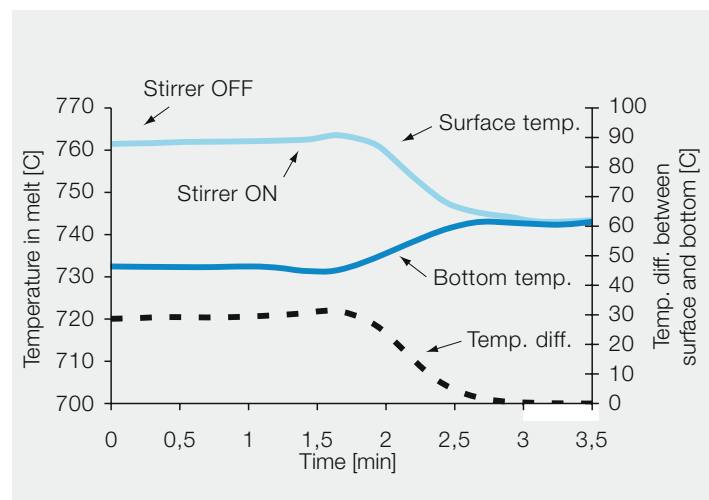


Figure 4. Temperature measurements at bottom and surface of a ladle and temperature homogenisation due to stirring by AL-EMS.

with a temperature logger named GL 200 manufactured by Graphtec.

According to the measurements shown in figure 4, there is a temperature difference between the surface and bottom of approximately 30 °C after 1 hour holding time, at time zero in the figure above. The stirrer is then turned on after 1.5 minutes and after an additional 1.5 minutes the temperature difference is reduced to almost zero. This indicates effective stirring and that the thermal homogeneity is complete as the AL-EMS is running. The benefits of thermal homogeneity in general and reduced surface temperature in particular are discussed in the following chapters.

Thermodynamics and heat transfer

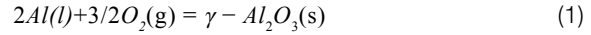
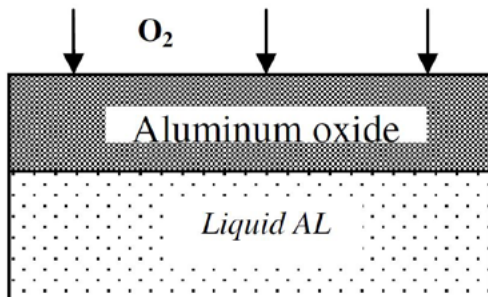
Due to the low heat conductivity and poor mass transfer caused by natural convection of molten aluminium, forced convection, i.e. stirring, is required to achieve a homogenous temperature as shown in Figure 4. There are two reasons, as well as homogenous temperature and homogenous chemical analysis, why continuous stirring should be applied during heating:

- Dross minimisation for decrease in metal loss and to preserve high melt quality
- Enhanced heat transfer for improved burner efficiency for reduced running cost

Both these issues are discussed below starting with dross formation in relation to surface temperature.

Dross formation and surface temperature

Dross consists of aluminium oxide, aluminium metal trapped in aluminium oxide and melt reaction products, e.g. aluminium nitrides and magnesium oxides. The formation of aluminium oxide is correlated to the oxidation of liquid aluminium. The formation of aluminium oxide as a reaction between liquid aluminium and oxygen is presented below in equations 1 & 2.



$$K = \frac{a_{Al_2O_3}}{a_{Al}^2 \cdot P_{O_2}^{3/2}} \quad (2)$$

Where K is the equilibrium constant, $a_{Al_2O_3}$ is the activity for aluminium oxide,

a_{Al} is the activity for aluminium in the melt and P_{O_2} is the partial pressure of oxygen in the ladle atmosphere. The density of the formed oxide is higher than the molten aluminium. But due to the high surface tension of the molten aluminium the dross remains on top. Assuming that the reaction takes place between pure liquid aluminium and that the reaction product is pure solid aluminium oxide, then the expression for the equilibrium constant K can be written as follows:

$$K = \frac{a_{Al_2O_3}}{a_{Al}^2 \cdot P_{O_2}^{3/2}} = \left\{ \begin{matrix} a_{Al_2O_3} = 1 \\ a_{Al} = 1 \end{matrix} \right\} = \frac{1}{P_{O_2}^{3/2}}$$

$$K = \frac{1}{P_{O_2}^{3/2}}$$

$$\Delta G = \Delta G^0 + RT \ln K = 0, \quad \text{Assuming equilibrium}$$

$$\ln K = \frac{-\Delta G^0}{RT}$$

$$\Delta G^0 = -1682927 + 323,239 \cdot T \quad [J/mol] \quad (1)$$

$$\ln K = \frac{202420.865}{T} - 38.897$$

$$K = \exp \left(\frac{202420.865}{T} - 38.897 \right) \quad (3)$$

Where R is the ideal gas constant, T is the temperature in Kelvin, ΔG is the change in Gibbs free energy and ΔG^0 is the change in Gibbs free energy for pure substances. As aluminium oxidation is an exothermic reaction a higher surface temperature would suppress the dross formation from a thermodynamic perspective, given by equation 3. However, in this case the kinetic point of view is of much greater importance. As shown in figure 5, the surface temperature should be kept below 775 °C to avoid dross formation and therefore the temperature can't be adjusted upwards for dross reduction according to thermodynamic reasons. Minimizing the partial pressure of oxygen in the surrounding atmosphere would also thermodynamically suppress aluminium oxidation. However, thermodynamic considerations have shown that a partial pressure of oxygen as low as 10^{-50} atmospheres would be required to eliminate oxidation. As this is not possible in practice, the focus should be on dross minimisation rather than dross elimination. Neither of these two thermodynamic

considerations, temperature or partial oxygen pressure, can be of any practical help to avoid surface oxidation. But they can be used as guidelines when discussing dross formation.

As can be seen in figure 5, the temperature needs to be lower than 775 °C to avoid a drastic change in the formation rate. Therefore, it's important that the melt surface, which is in contact with the oxygen in the ladle atmosphere, does not exceed a temperature of approximately 770 °C. And by stirring with ABB AL-EMS the excess temperature at the metal surface will be reduced, as shown in figure 4, and by so reducing aluminium oxidation.

Heat transfer and surface temperature

Almost all materials processing is carried out above room temperature (25 °C). This calls for the knowledge of both thermodynamics and heat transfer for process control and optimizing. In this section, the theory of heat transfer is discussed. The second law of thermodynamics tells us that energy can not spontaneous be transferred from a substance with low temperature to a substance with high temperature, known as the Clausius statement. If we transfer this to the heating of aluminum, kept in ladles, it means that to effectively transfer energy from the burners "hot" to the metal "cold" we need as large temperature difference as possible. This is where stirring comes into the picture and how stirring can improve this will be discussed later in this chapter after a short introduction of the three mechanisms of heat transfer.

Conduction. Conduction is the transfer of thermal energy (heat) from a higher temperature zone to a lower temperature zone. As mentioned above, for fluids with low electrical conductivity heat conduction takes place at the molecular level where atoms of high energy content are passing energy to their low temperature neighbors. However, in molten metals, aluminum in this case, heat conduction occurs mostly by the motion of free electrons, as molten metals are relatively good conductors. Except for some natural convection, conduction is the determining heat transfer mechanism in an unstirred aluminum bath.

Convection. In case of convection, thermal energy is moved from one part to another part of the system by means of fluid bulk flow. Broadly, there are two types of convection, natural convection and forced convection. Natural convection can for example be described by movement in a fluid due to density variations caused by thermal or chemical gradients in the system. The colder parts of the liquid normally have a higher density compared to warmer parts and that will give rise to motion. The colder parts, with higher density, will move downwards in the system whereas the warmer parts, with lower density, will move upwards towards the surface. Forced convection, on the other hand, can be described by the example when pouring cold milk in hot coffee and wanting to

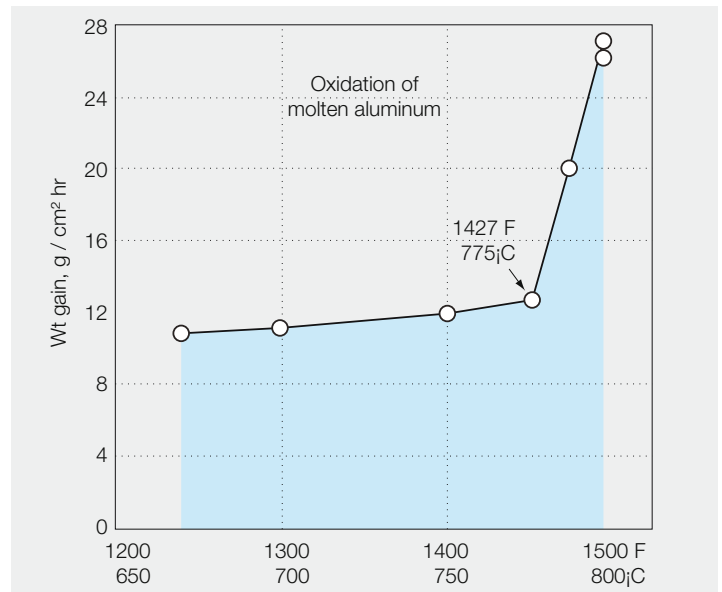


Figure 5. Oxidation rate of liquid aluminium at different temperatures. [2]

mix it with a spoon. The spoon is then forcing the liquid to move and will by doing so evoke forced convection. When stirring a ladle with AL-EMS this is of course the same case as of the coffee-milk example, i.e. forced convection.

Radiation. All forms of matter can emit or absorb thermal energy in the form of radiation. Both conductive and convective heat transfer requires the presence of a conducting medium. However, radiation between two surfaces occurs by the transmission of photons or electromagnetic waves and does not require any transportation medium. One important factor is that radiation will play a significant role at higher temperatures as the energy emitted from a body is proportional to the fourth power of its temperature.

Summary of heat transfer

All types of heat transfer are more or less influenced by thermal gradients in the system. In ladles, the surface of the molten aluminium is the receiving area of energy transferred from the burners and therefore, surface temperature is important for optimizing burner efficiency. By using electromagnetic stirring, the molten aluminium is efficiently mixed and by so the surface temperature is kept at as low value as possible, as shown in figure 4.

Calculations of mass transfer

By using Computer Fluid Dynamic-calculations, the needed stirring force for suitable mass flow can be pre-determined, see figure 6. For that reason there is no need of risking too strong or too weak stirring and the stirring force can be optimized and the energy consumption minimized.

The calculations also show the surface velocity which needs to be taken into account as to how surface turbulence might cause oxidation. There is a risk of producing dross if the surface turbulence gets violent, due to the fact that surface turbulence enhances surface renewal and thereby promotes surface oxidation. However, there has not been established how great impact the surface turbulence has on dross formation [3].

Discussion and conclusions

Plant trials have shown that by stirring with ABB AL-EMS, a total thermal homogenisation can be rapidly achieved. By doing so, the surface excess temperature is lowered when being mixed with the colder parts of the aluminium bath. This indicates that heating combined with electromagnetic stirring can effectively be used for temperature control during very long holding times, 24 hours and even more.

The lower surface temperature both suppresses aluminium oxidation, due to kinetic reasons, and also enhances heat transfer due to larger temperature gradients between emitting and receiving areas.

ABB AL-EMS gives an effective stirring system that provides effective temperature control. AL-EMS also reduces melt loss because of minimized oxidation and improves heat transfer and thereby burner efficiency, which is important for minimizing operational costs. The chemical homogeneity is also assured by stirring the melt and achieving total homogenisation. So by introducing stirring, the loss of metal due to oxidation is reduced, thermal and chemical homogenisations are greatly improved and the burner efficiency is enhanced, which assures melt quality and lowering burners running cost.

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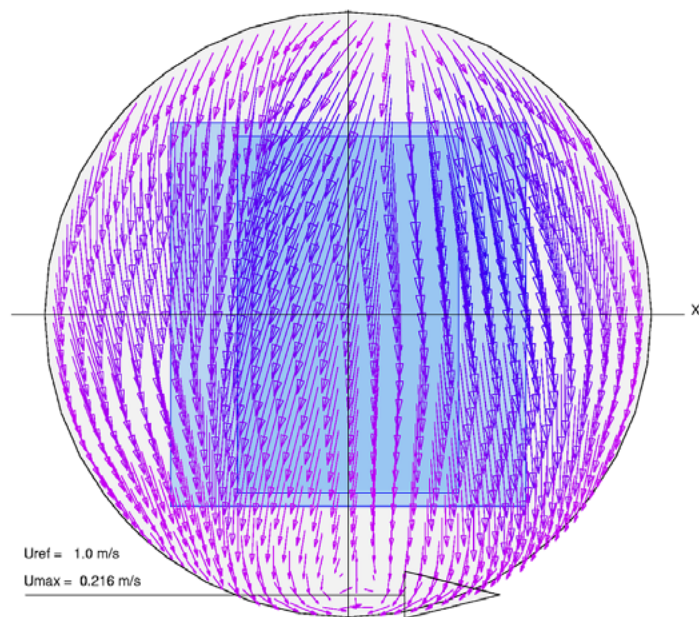


Figure 6. Surface velocity in a ladle stirred by a bottom mounted AL-EMS.

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