ABSTRACT

The computer simulation that is presented here is the response of an industrial challenge about how the electric arc furnace, where the smelting process of magnesium oxide (MgO) is taking place, should be charged for avoiding shell overheating. If solid MgO is charged at a very high rate, the processing time becomes very long; on the other hand, if the feed rate is too slow, external shell made of steel reaches temperatures above its melting point. Thus, it is necessary to reduce the electrode current or to charge more material for avoiding shell overheat. With the aid of this model, a charge scheme for the furnace could be proposed, in order to have the maximum production without shell overheat. Validation of the model has been made with temperature
measurements along the external shell while the process was being conducted; the size and shape of the smelted zone after the fusion were also compared with information obtained from the graphic results predicted by the model. Results from the model are in good agreement with the measurements done. Calculation of the specific energy consumption can be provided with the input energy rate and the mass of the smelted MgO.

1. INTRODUCTION

At the present time one way for producing smelted magnesium oxide is by using an electric arc furnace [1,2]. Production of this kind of materials is carried out by smelting high purity briquettes of sinterized magnesium oxide. The electric arc furnace is used for conducting the smelting process that takes place with the radiant energy that comes from an electric arc. While the charged material is being smelted, more briquettes are being fed to cover the arc. The wall of the furnace is naked (it does not have any refractory material), but the briquettes that have not been smelted insulates the wall from the heat that is being produced in the arc. As the material is charged the electrodes must vary their position. The solid material conducts the heat to the wall giving hot spots, and the process has to be stopped in order to avoid shell perforation. The aim of this work was the development and validation of a computer model that describes the thermal profile of the shell of
the furnace at different charge rates, in order to give an advise about which should be the best charge procedure for avoiding shell overheating. The results obtained with this model were applied to an industrial furnace with very good results.

2. GENERAL DESCRIPTION OF THE MgO PRODUCTION PROCESS

In a general way, the MgO production process consists in an electric arc furnace that is being charged with briquettes of sinterized MgO. The furnace has a circular base ring (2 meters of diameter) filled with recycled briquettes and covered with a cylindrical shell made of steel (2 meters height, 1.80 m top diameter, 2.10 m bottom diameter and 2.54 cm wall thickness). There are three electrodes at 120° each one connected to its own phase. Due to the MgO has a very high electrical resistance at room temperature, approximately $10^{15}$ ohm-cm [3], it is necessary to set graphite bars (2.54 cm x 2.54 cm x 12.25 cm) between the electrodes, this arrangement has the shape of a delta. An scheme of the shell and the electrodes arrangement is presented in Figure 1. When the electric power is connected, the graphite bars start to heat by Joule effect until the MgO that is surrounding the bars is smelted, in this conditions the MgO becomes a good electricity conductor ($10^{13}$ times better), thus the graphite bars become unnecessary. When the fusion starts, the arc becomes submerged in the semisolid MgO, the process continues by charging more
briquettes and lifting the electrodes at the same time. Due to that new charge is cold its conductivity is not good enough to sustain a good electric arc until it gets hot. Normally the current decreases until the charge is smelted, adding more charge and continuing the cycle until the furnace is full. Generally, the electrode current is the measured variable that permits the control of the electrodes movement and the charge rate, high currents means semisolid MgO, so more charge is added and the electrodes are raised. In this furnace, the raise speed of the electrodes could be 10 cm/hr through 20 cm/hr, while the charge rate vary from 100 Kg/min through 280 Kg/min of MgO briquettes. Normally the operator tries to keep the raise speed constant, maintaining under control the current with the charge rate. The main purpose of these controls is to prevent overheating of the shell. The zone where temperature is high enough to smelt the MgO starts from the end of the electrode down to the bottom of the furnace. When the furnace is full the fusion ends, even when not all of the material is smelted; at this point the electrodes could be lifted without the addition of more briquettes. After the end of the fusion the whole system is allowed to cool, the part that was smelted becomes a solid stone of MgO, this stone is the most important part of the process, because it is the product. In order to avoid the shell overheat it could be convenient to (a) insulate the steel wall; (b) use and external water jacket for cooling the steel shell; and (c) manipulate the feeding rate of MgO.
The first alternative is applied practically during normal operation because the solid MgO fed acts such as insulating layer between the shell and the heat source; indeed thermal conductivity of MgO is about the same (taking both pure dense and powdered MgO) than insulating firebricks [3] and the distance between the electrode and the shell is about 80 cm, but the overheat problem persists.

It is important to note that plant facilities do not permit the use of water as coolant avoiding the second alternative. Thus for overcome the shell overheat problem the only alternative is to manipulate the MgO feeding rate.

3. DEVELOPMENT

3.1 Process simplifications

The assumptions accepted in this model are listed below, some of them are justified here and the rest in the experimental details section.

- There is angular symmetry respective to the heat source, thus the system could be reduced to two dimensions scheme, radial (r) and height (z). Even when the shell is not a perfect cylinder, taking this shape simplifies the solution. The most important part is the zone where the fusion is taking place, and this part includes just the zone between the bottom and the tip of the electrode. Thus it is valid to take the furnace as a cylinder
because the final position of the electrodes (that defines the melting zone) is about 40 cm from the base ring.

- The external heat losses are due to convection, free convection is accepted with a constant value of 30 w/m² K. It is accepted that the convection coefficient is a function of the temperature of the shell, but we found that this constant coefficient gives a good approximation of the temperature profile on the shell. Even when the base of the furnace is not perfectly insulated, heat transfer to the material in the base ring was considered constant as the heat transfer to the ground below the furnace base because this part reaches the highest temperature almost at the beginning of the process remaining at this value during all the test. Besides the overheat shell (hot spots), when they appear, are present at the middle of the height. In this case we found that thermal profile of the external shell predicted by the model is in good agreement with the actual profile, while the size and shape of the MgO stone obtained by the isothermal graphic results provided by the model were also in good agreement with the real stone. The description of the MgO stone and the measurement procedure are presented below in the results and discussion section. -The initial temperature of the charge is constant (room temperature).

- The heat source has a narrow variance of power along the process.

- The power source of the arc is being raised vertically at constant speed.
- The charged material is distributed uniformly inside the furnace, so it can be considered as a continuous material with [4]:

\[ k_e = k_{MgO} (1 - \text{porosity of the bed}) \]  

Once that the material is charged it remains as a packed fixed bed until it is smelted.

3.2 Numerical method
With the above conditions and simplifications for the model, a heat balance or control volume technique gives a description of the system. There are several ways for obtaining the basic equations for any geometry [5]. The general discretization equations for cylindrical coordinates can be procured from the extension of one dimension \( r \) (radial) in the transitory state [6];

\[ \rho C \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r k \frac{\partial T}{\partial r} \right) \]  

It is true that most of the heat is being produced by Joule effect from the graphite bars, but this stage is too short compared with the total time required for completing the process.

3.3 Adaptation of the numerical method
For building the model it is necessary to analyze the fusion process, taking into account the points given above and the
general discretization equation in two dimensions. The furnace is considered a hollow cylinder with the energy source inside, the energy distribution is uniform and concentric. This consideration is correct at the end (tip) of the electrode that is the place where the arc is. Even when the rest of the electrode develops a thermal profile, it is considered that energy comes from a single source.

Thermal characterization of the furnace proves that the temperature profile depends on the vertical position ($z$) and the radius ($r$), but it does not depend on the angular position in a significative manner, thus the previous assumption of angular symmetry is right.

In summary, the system consist in a cylinder that is being fed with MgO, the external shell is loosing heat by convection to the air, while there is an energy input at the tip of the electrode. The proposed model considers that MgO bed is conductive (regardless the graphite bar) and that the heat input is coming from the arc that is supplying certain amount of energy (the boundary condition is the heat flux at the tip instead of the temperature). In other words we accepted that the heat source is the tip of the electrode and not the dissipation of electrical energy within the charge itself. Due to symmetry conditions, two-dimensional discretization is performed in just half of the furnace, along the cylinder and following one of the electrodes axle. The discretization consists then in placing elements following a cartesian distribution. In this particular case the
elements over the r axle are spaced at $\Delta r$ equal over all the MgO charge.

In the z axle the discretization is uniform from the top through the bottom of the furnace. With all the nodes placed, the lines that conforms the mesh pass right at the middle of the distance between two adjacent nodes.

Implicit scheme was taken for two dimensions with a heat source $Q$, the discretization equations for each node are:

$$a_P T_P = a_E T_E + a_o T_o + a_N T_N + a_s T_s + b$$  \hspace{1cm} (3)

where:

$$a_E = \frac{k_E \Delta z}{(\delta r)_E} (1 + \ln(\frac{r_e}{r_0}))$$  \hspace{1cm} (4)

$$a_o = \frac{k_o \Delta z}{(\delta r)_o} (1 + \ln(\frac{r_e}{r_0}))$$  \hspace{1cm} (5)

$$a_T = \frac{k_t \Delta r}{(\delta z)_t}$$  \hspace{1cm} (6)

$$a_s = \frac{k_s \Delta r}{(\delta z)_s}$$  \hspace{1cm} (7)
The amount of elements and equations are the same in order to have a system that can be solved at certain time. The solution of this system is part of the program that was developed for simulating the MgO smelting process.

3.4 Equation resolution presented as a simulation program.

The program has some sections of routines for performing the solution of the system explained above.

In the main program the Gauss-Seidel iteration technique was applied to get the implicit values of the temperatures in the algebraic equations in an indirect mode [7]. Inside each iteration the properties of the materials are calculated in a special subroutine. For having an efficient program, regarding with the accuracy and running time, we tried to maximize the size of the elements and maximize the time increment. After several runs and comparisons with the actual profile we found that the optimum

\[ a_r^0 = \frac{\rho C \Delta r \Delta z}{\Delta t} \]  

\[ b = Q \Delta r \Delta z + a_r^0 T_r^0 \]  

\[ a_r = a_E + a_o + a_t + a_s + a_r^0 \]
amount of elements that gives mesh insensitivity are 80 elements along the height and 42 along the radius. Measurement devices at the plant give information each 5 minutes, so we decided to use half of this time as the increment value.

4. Experimental details

4.1 Electrodes and power supply
The three electrodes are connected to a three phases power supply, through a transformer of 6 MW 13700/180 V. The electrodes size is 31.2 cm diameter and 3 meters long.

4.2 The charge
The briquettes have a hazelnut shape of about 2 cm large and they were obtained from pure MgO compacted and sinterized at more than 2000°C. MgO is a ceramic and it is considered one of the best electric insulator, its melting point is 2800°C and it is also a good thermal insulator. Heat conductivity and heat capacity are given by equations (11) and (12) according to Kingery [3].

\[ k_{MgO} = 2180 - 2.7T + \frac{0.001}{T} \frac{J}{\text{min} \, m \, K} \]

\[ C_{pMgO} = 1127.78 + 0.1243T - 21672915.36T^2 \frac{J}{\text{Kg} \, K} \]
4.3 Temperature measurements
After a review of the techniques for taking the temperature measurements it was decided to use thermocouples inserted in the steel wall at 40 cm height (the place were the hot spots usually appear), one in front of the electrode (following the radial coordinate), another 60° at the right of the electrode and a third one 60° at the left of the same electrode for each electrode (total of 6 positions over the shell).

4.4 Test description
The tests consists in, firstly fill the base ring with recycled material (MgO briquettes that where unmelted in other previous melting processes) and then starts the charge procedure with an initial charge of 280 Kg, after that the charge rate is controlled in accordance with the electrodes current, as was explained above. Each test was 180 minutes long, taking one data each 5 minutes in each thermocouple to get a table of temperature against time.

4.5 Test conditions for model validation
The program wrote needs the following information:
Maximum time of test (180 minutes).
Electric Power (3000 watts).
Raising speed of the electrodes (12 cm/hr).
Fraction of volume occupied by the briquettes in the bed (0.5).
Feeding rate (variable).
In order to give make more important the charge procedure the raise speed was fixed at a constant value along the test. The fraction of volume occupied by the briquettes was the value employed in the calculation of the thermal conductivity of the MgO, separate packing tests gives a value of 0.5 for this parameter. As explained above, the feeding rate depends on the electrode current, therefore, the current was controlled with the feeding rate, in the model this amount variation was taken into account.

5. Results and discussion

5.1 Simulation adjustment
Experimental data was compared with the information given by the model. A summary of the experimental results are presented in the Figure 2. The curve A represents the temperatures of a thermocouple placed at 40 cm height, in front of the electrode (following the radial coordinate), curve B is at the same height, but at the right of the electrode (60°), and the curve C is 60° at the left of the same electrode. Note how close the curves are, meaning that the two-dimension analysis was appropriate. One important thing is the maximum temperature at the begin of the test, where the arc is being stabilized and there are very few material, so practically the current is passing through the
graphite bars. This aspect was observed during the model validation.

5.2 Validation of the computer model

Temperatures calculated with the model are shown in Figure 3. Curve titled "Measured" corresponds to the average of the values shown in Figure 2, while curve titled "Calculated" is plotted with the data given by the model. It is important to notice that temperature rises very fast at the starting of the process decreasing when the smelting process is being conducted with the electric arc covered by the MgO briquettes. The calculated temperature decreases more than the measured, despite this situation, the error is very small, maximum 13% when the furnace is almost empty and much lower when the process has been stabilized following the charge procedure. This error magnitude shows that the equations and relations used in this work are appropriate, even from an industrial point of view. Trials for minimizing the error, supported by the operation of an empty furnace (just with the initial charge and the electrode partially covered by the MgO) gives a more complex model that does not have necessarily more reliability because the arc is covered by MgO most of the time. Other possible error source is that in the actual process the energy is supplied at the beginning with the help of the graphite bars that could produce higher temperatures that the ones obtained from conduction of MgO.

One aspect taken to validate this computer program was the size
and shape of the smelted zone that after cooling forms a solid stone of MgO. The Figure 4 shows a scheme of the furnace, specially the smelted zone that gives the stone product. Temperature in the smelted zone is around melting point of MgO because the heat of transformation and the quality of the insulator. At the end of the fusion, the electrode is removed in such a way that the top of the MgO stone gets plane, after few days of cooling the steel shell is removed and the briquettes that were not smelted are collected for a new charge. The MgO stones are removed (there are three, one for each electrode) and they are the product. The shape, size (about 0.2 cubic meters) and weight (about 800 Kg) of the stone are in good agreement with those predicted by the model. The good agreement on the temperature profile of the shell and the shape and size of the smelted stone provide a good degree of confidence about MgO temperature profile predictions. The product has the shape of a cone, following the illustration of Figure 4. Its base is about 1 meter diameter and 0.90 meters height. General information is provided by the program while it is running. Figure 5 is the screen that the computer shows, in this case it is just an example of the thermal profile of the furnace after 45 minutes of processing. This figure is also used for calculating the size of the stone, the portion that is presented with a temperature over the MgO melting point is the zone that at the end of the process will be the stone. Whit this revolution body it could be deduced the size of the stone and the weight from the MgO density. The purpose of this work was to find
an appropriate charge scheme without hot spots over the shell, the measurement of the stone is just an extra data for validation of the model and thus the thermal profile. One way for calculating the mass of the product inside the computer program is by counting the elements that reaches temperatures above the melting point of the MgO, these will be very useful at the moment of include the production rate in the program. Graphic on the bottom right corner of Figure 5 shows the temperature evolution at two different places on the shell.

6. Conclusions

The model describes the thermal profile of the furnace, and running different conditions allows selecting the best charge procedure. In other words, results of the model gives the charge procedure that permits high production rate without hot spots on the external shell. The procedure that ensures maximum productivity without the melting of the shell was with the following steps:

Initial charge of 110 Kg; 110 Kg/min for 5 minutes; 220 Kg/min for 10 minutes; 160 Kg/min for 10 minutes; 50 Kg/min for 135 minutes, and 20 minutes without feeding. These procedures were tested at the plant and it was confirmed that it is one of the best procedures. This procedure also maintains the raise speed practically constant at 12 cm/hr. It was confirmed also that
heating of the shell is due to conduction through the briquettes of MgO bed, temperature in the smelted part is not high enough to permit that MgO liquid of low viscosity travels through the bed and touches the wall. This late condition is not responsible of the hot spots on the shell. This model shows a balance between phenomena description and observed behavior, without unnecessary elements that makes the problem artificially more complex. Different heat transfer coefficients on the external shell at free convection did no change the results. Conduction to the ground from the material in the base ring alters the results in an amount smaller than the experimental error.

This development simplifies the description of the process and gives a straight answer to a straight question with the capacity for conducting a wide range of conditions, given a good advice before the real process is conducted. Calculation of specific energy consumption is very easy to obtain for the different charge schemes.

7. Nomenclature

$k_e$ Equivalent thermal conductivity of the bed
$k_{\text{MgO}}$ thermal conductivity of the MgO solid
$\rho$ density
$C_{\text{heat}}$ capacity at constant pressure
$T$ temperature
time coordinate
r-coordinate \( r \) in cylindrical coordinates
\( \varepsilon_1 \) emissivity factor of the electric arc
\( \varepsilon_2 \) emissivity factor of the steel shell
\( \sigma \) Stefan-Boltzmann constant
\( A_1 \) area of the theoretical energy source (electric arc)
\( A_2 \) area of the steel shell

References

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Figure 1. Scheme of the shell of the furnace, and the electrodes arrangement and graphite bars for starting the process.
Figure 2. Temperature of the shell (at 40 cm height from the furnace bottom) against time in three different places around the furnace.
Figure 3. Comparison between average temperature on the external shell (at 40 cm height from the bottom of the furnace) and the calculated temperature.
Figure 4. Scheme of the furnace showing the smelted zone after 160 minutes, the left side in the bottom is the center of the furnace (the part that is between the three electrodes).
Figure 5. Status of the process and thermal profile shown on the computer's screen (black line is the charge level).