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MODELING THE TAPPING OF SILICON MELT FROM THE SUBMERGED ARC FURNACES

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ABSTRACT

In this paper we investigate flow phenomena related to tapping of silicon melt from a submerged arc furnace. The multiphase flow model predicts how the gas pressure variations inside the furnace crater zone may effect phenomena like the gas flow pattern inside different zones of the charge materials inside the furnace, the metal tapping flow rate, and the gas blow out from the furnace tap hole.

The full 3D multiphase flow model of the furnace is based on the real geometry and the most probable physical properties of different zones in the furnace, such as density, charge material particles size, porosity and permeability of the packed beds on the furnace bottom. In addition different spatial arrangements of charge material zones have been investigated.

The results of the model show that existence of the mentioned high pressure crater zone in the furnace has a considerable effect on the metal tapping and the gas flow rate from the tap hole. The predicted tapping rate compares well to industrial tapping trials, using crater pressure levels that has been measured previously on a ferrosilicon furnace.

The model also shows that gas blow out from the tap hole can change the gas flow pattern inside the charge materials all the way to the furnace top.

NOMENCLATURE

ρ^k	density of phase k
$\vec{v}^k$	velocity of phase k
ε	void fraction (porosity)
g	gravity acceleration
μ^k	viscosity of phase k
L	depth of the packed bed
P	pressure
d_p	mean particle diameter
α	permeability
C_2	inertial resistance
T	temperature

INTRODUCTION

Silicon commercially is produced through carbothermic reduction of quartz (SiO_2) in the submerged arc furnaces. The furnace consists of a body with the shape of a shallow crucible, made of a steel shell and a lining that can withstand extremely high temperatures and attack by chemicals. The furnace is filled up to its rim with raw materials charged by gravity through a system of silos and tubes. As they are consumed by reactions (smelting) in the inner zones of the furnace the raw materials are transported downwards in the furnace. The energy required for the chemical reactions is delivered as 3-phase alternating current through three carbon electrodes positioned vertically and submerged deep into the charged materials. The supplied energy is by large dissipated as heat through the electric arcs in the gas-filled cavities surrounding the tips of the electrodes inside the furnace (Schei (1998)). Silicon producing chemical reactions mainly happen in the high temperature zone of the furnace near by the electrode tips (the crater zone).

The molten silicon, as the main product, is produced through the net chemical reaction below (1) and is accumulated on the furnace bottom. The metal is tapped from the tap hole designed in the furnace bottom.

$$SiO_2(s) + 2C(s) = Si(l) + 2CO(g) \tag{1}$$

The tapping is a critical operation in the silicon production process. The tapping process is simply how to bring molten silicon from the furnace into the ladle. The tapping process has a direct impact on the total process performance. If the tapping of produced silicon from the furnace heart fails, the production must be stopped until silicon can be tapped in a proper way. Good draining of the molten metal in the furnace is essential to obtain an optimum silicon yield.

The tapping process and hence the metal flow rate from the tap hole is influenced by the furnace internal conditions. Depending on the different operating parameters of the furnace, such as temperature distribution, chemical reactions rate inside the crater zone, flow of charge materials into the crater zone and flow of reactive gases through charge materials in the upper part of the furnace, different zones are formed inside the furnace. Each of these zones therefore has its own physical properties such as density, particles size, porosity and permeability. The existence of these regions inside the furnace can affect the tapping process in many different ways.

The silicon metal accumulated over the furnace bottom is removed from the furnace by opening of the tap hole during the tapping process. However the silicon metal is not the only material on the furnace bottom. The results of furnace excavations have shown that beside silicon metal there are layers of solid and porous material mainly composed of silicon carbide (SiC) and to a lesser extent unreacted and high viscosity molten silica (SiO_2) over the entire furnace bottom. Existence of this porous region around the tap hole is the main reason for reduced metal flow rate from the tap hole. In fact the produced silicon metal must drain through this porous region and existence of high viscosity molten silica in the porous region around the tap hole causes the phenomenon which is well known as tap hole clogging.

The second issue related to the tapping process is the existence of high gas pressure condition inside the crater zone of the furnace. In fact due to the existence of chemical reactions inside the charge materials, there is always a high gas pressure situation in the furnace heart. Because of reduced permeability of charge materials due to these reactions and melting of charge materials in the region near by the electrode tips (the crater walls), the gas pressure in the crater zone increases to higher levels than what could be predicted by the operation. Existence of this high pressure gas zone some times leads to blowing out of high velocity hot gasses from the taphole during tapping. Investigations and measurements of the gas pressure inside the crater zone of the submerged arc furnace for silicon and ferrosilicon production have been done in previous studies (Johansen (1998), Tveit (2002)). A 2D inside view of a submerged arc furnace used for silicon production together with the previously mentioned issues is presented in figure 1.

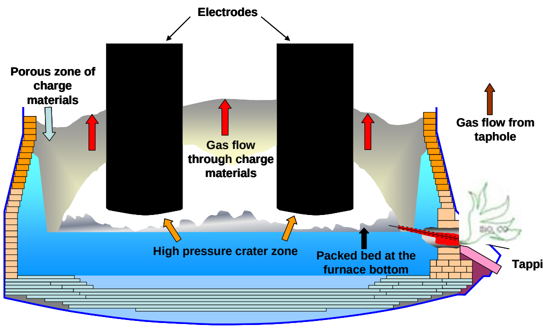

Figure 1: Schematic of submerged arc furnace used for Silicon production.

In this paper a 3D CFD multiphase model for the tapping process of silicon melt from the submerged arc furnace is proposed. Our goal is to investigate how different parameters such as high gas pressure in the crater zone and a low permeability situation on the furnace bottom and near the tap hole can affect the silicon melt tapping flow rate. Moreover the flow pattern of reactive gases through the charge materials in the different zones inside the furnace and the off gases from the furnace top is studied. The geometrical and operational data are from the real operating furnace and the inside condition and physical properties of different zones in the furnace has been selected based on the most probable conditions inside of the furnace based on literature and previous scientific works (Shei (1998, 1967), Otani (1968), Myrhaug (2003)).

The results are in good agreement with real data from industry which itself shows the validity of the developed model.

MODEL DESCRIPTION

In order to simulate the tapping process of silicon melt from the submerged arc furnaces, a full 3D multiphase model of the furnace was developed. The multiphase system is composed of charge materials, molten metal and reaction gases inside the furnace. The bulk of charge materials inside the furnace were divided into different zones and each zone has its own physical properties. The particles size and the porosity of the packed bed of charge materials in each zone is the crucial parameter which determines the permeability and hence resistance of the zone against the flow of process gas through charge materials up to the furnace top. The permeability distribution further controls the drainage of produced molten metal through the packed bed on the furnace bottom towards the taphole. In order to model the high gas pressure inside the furnace a gas source was applied inside the crater zone. The electrodes, made of carbon materials, were defined as solid parts in the model. The permeability of the packed bed of solid particles in the bottom layer of the furnace, where the molten silicon has been accumulated, was considered to decrease as the distance from the furnace centre increases. The taphole and the furnace top were considered as pressure outlets at atmospheric pressure.

MODEL EQUATIONS

The physical model used in this study is based on the unsteady turbulent multiphase flow of process gasses and molten silicon. The fluids are treated as immiscible but are interacting with porous media of charge materials for the gas phase and packed bed of solid SiC and slag for the liquid and gas phases in the furnace. Therefore the governing equations for each phase in the system are continuity equation:

$$\frac{\partial}{\partial t}\rho^k + \vec{\nabla}\cdot\left(\rho^k \vec{v}^k\right) = 0 \tag{2}$$

And the momentum equation:

$$\frac{\partial}{\partial t}\left(\rho^k \vec{v}^k\right) + \vec{\nabla}\cdot\left(\rho^k \vec{v}^k \vec{v}^k\right) = -\varepsilon\vec{\nabla}P^k + \varepsilon\rho^k \vec{g}^k + \vec{\nabla}\cdot\left(\mu^k \vec{\nabla}\vec{v}^k\right) - \vec{S}^k \tag{3}$$

Where the porous media viscous resistance to the flow is based on the Ergun's equation for porous media as follows (Ergun 1952):

$$-\frac{\Delta P}{\Delta L} = \frac{150\mu}{d_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3}\vec{v} + \frac{1.75\rho(1-\varepsilon)}{d_p\varepsilon^3}\vec{v}^2 \tag{4}$$

$$\vec{S}^k = -\left(\frac{\mu}{\alpha}\vec{v}^k + C_2\frac{1}{2}\rho|v|\vec{v}^k\right) \tag{5}$$

$$\alpha = \frac{d_p^2}{150}\frac{\varepsilon^2}{(1-\varepsilon)^3} \tag{6}$$

$$C_2 = \frac{3.5}{d_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{7}$$

The turbulence model used in this work is the standard k-ε model using the transport equations for the turbulent kinetic energy (k) and its dissipation rate (ε).

NUMERICAL METHOD

In order to perform the numerical solution of the model equations, the FLUENT software version 6.3.21 was used. To construct the interphase between liquid and gas phases in the furnace, the volume of fluid (VOF) method together with the CICSAM scheme, suitable for fluids with big viscosity difference, was chosen. In order to model the effect of the packed bed on the fluid flow the porous media boundary conditions available in the software was applied to the model. The volume of fluid (VOF) method is itself able to include the effects of interfacial tensions and wall adhesion whenever these effects are considerable.

SIMULATION SETUP

Geometry

The real data for the geometry of the submerged arc furnace was used in this study. The effective furnace diameter and its effective height are 10.5m and 3.2m respectively. The taphole diameter and the taphole length were 0.12m and 0.3m. Electrodes were represented as solid mediums and the diameter of each electrode is 1.8m. The real geometry of the furnace which has been used in this study is presented in figure 2.

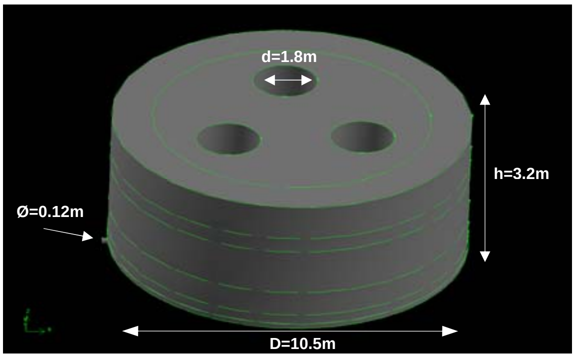

Figure 2: Pressure patterns inside the submerged arc furnace.

Due to the complexity of the furnace geometry and the required accuracy in order to represent the fluid flow in the region near by the taphole, non-conformal grid meshes were used.

Material Properties

The properties of the silicon melt and reaction gasses inside the furnace were selected based on the operating temperature and fluid compositions. For the gas phase we considered a mixture of SiO and CO gas. The density of the gas mixture in the operating temperature is 0.23 kg/m3. In the silicon melt the density and viscosity were represented as follows (Lida (1998), Rhim (2000)):

$$\rho_m = 2350 - 0.35(T - 1687)kg/m^3 \quad (8)$$

$$\mu_m = 0.75\times10^{-3} - 1.22\times10^{-6}(T - 1687)kg/m.s \quad (9)$$

The working temperature of the furnace was constant at 1700 ^{0}C. The properties of the porous zone of charge materials and the packed bed layer at the furnace bottom were based on the data found in the literature and the results of furnace excavations. Depending on the position of the zone in the furnace, the porosity ranges from 15% up to 60%. A 2D view of the packed bed of charge materials, consisting of different zones inside the furnace is presented in figure 3.

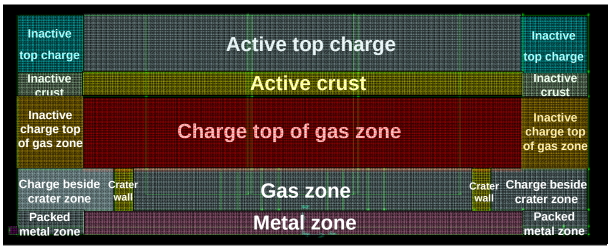

Figure 3: 2D view of different zones inside the silicon production furnace.

RESULTS AND DISCUSSIONS

In order to show the effect of high pressure in the crater zone on the silicon metal flow rate during the tapping process, different cases studies were developed. In the first case there was no excess gas pressure in the crater zone and only the effect of gravity drainage of the silicon melt from the packed bed layer on the furnace bottom was investigated. The flow rate of silicon melt from the furnace taphole vs. time is presented in figure 4.

It should be noted that in all case studies the initial metal height in the furnace was considered to be the same as the taphole level which is 0.112m.

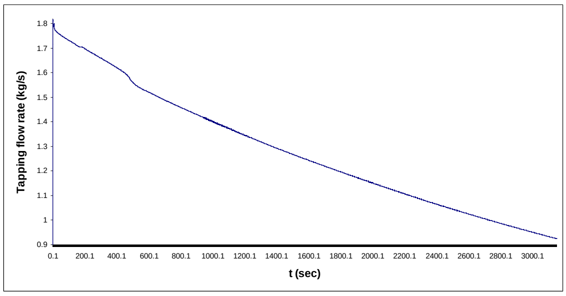

Figure 4: Tapping flow rate of silicon melt from the furnace taphole without excess gas pressure.

In the next five cases we investigate the high pressure in the crater zone and its effect on the molten silicon flow rate and the starting time for the gas blowing out from the taphole. This phenomenon is known as taphole gassing. The range for the gas pressures in the crater zone of the furnace was varied in the range between 30-41mbar. The considered range is based on the measurements reported in [2]. The pressure pattern inside the crater zone of the furnace is presented in figure 5.

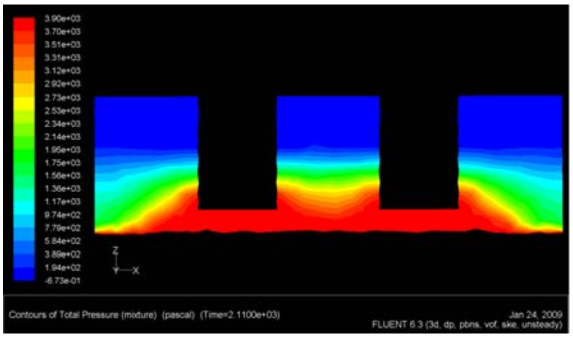

Figure 5: Pressure patterns inside the submerged arc furnace.

A comparison between the above mentioned case studies for different gas pressure inside the crater zone of the furnace is shown in figure 6. As it is observed from this figure the pressure increase in the crater zone will lead to increased metal flow rate and hence decreases the tapping time before gas blowing out from the furnace taphole is initiated.

By comparing with the case of zero excess gas pressure, figure 4, it is clear that in the existence of high pressure crater zone can increase the metal flow rate up to 2 times. The reason for selecting the considered range for crater gas pressures is the measurements reported in [2, 3].

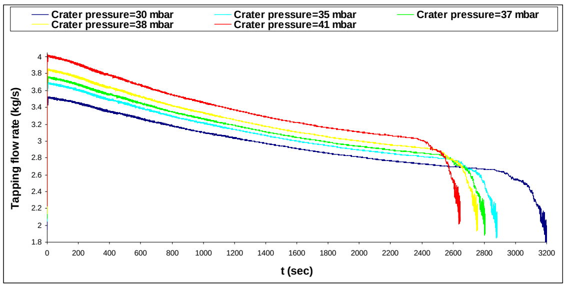

Figure 6: The effect of crater gas pressure on both the tapping flow rate and starting time of gassing taphole phenomenon.

The results of the CFD model show that there is a direct relation between maximum tapping flow rate and crater pressure. The increasing maximum metal flow rate with crater pressure is seen clearly from figure 7.

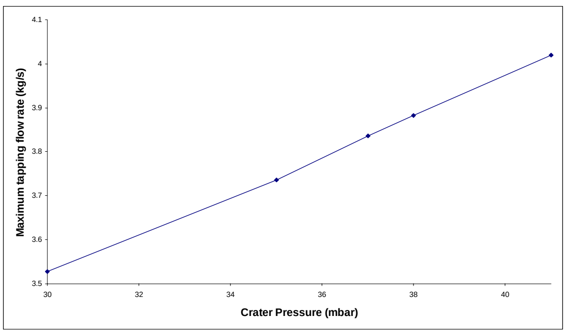

Figure 7: Maximum tapping flow rate increases with increase of crater pressure.

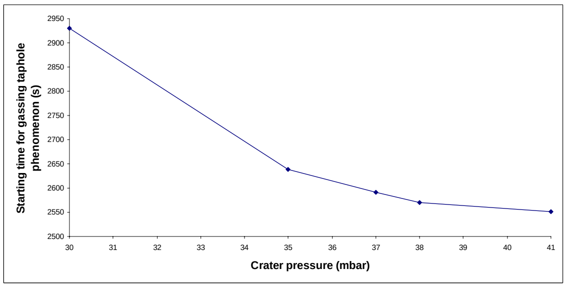

Figure 8: Relation between crater pressure and starting time of gassing taphole phenomenon.

As it can be seen from figure 8 the crater pressure also plays an important role in determining when the gassing taphole phenomenon starts.

Further more the results of the model show that the crater pressure affects on the total amount of metal tapped from the furnace. As seen from figure 9, an increase in crater pressure will lead to increased drainage of metal from the furnace. At high crater pressure tapping is faster, but a smaller fraction of metal can be drained before severe gas blowing starts.

The velocity pattern of reaction gasses inside the porous bulk of charge materials inside the furnace is shown in figure 10.

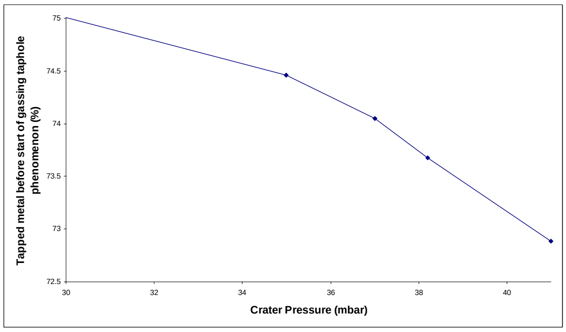

Figure 9: Percentage of total metal in the furnace before gassing taphole phenomenon starts.

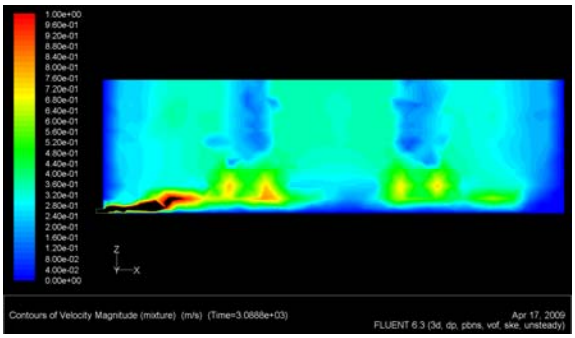

Figure 10: Velocity contours of reaction gasses in the charge materials during the tapping process

From the figures 10, 11 we see that the gas flow pattern through the furnace top depends on the tapping situation. During normal operation the gas flow is symmetric through the charge surface, while during tapping together with gassing phenomenon, more gas exits the charge surface close to the taphole area.

During tapping with gassing more reactive furnace gasses flow closer to the taphole and may increase the local metal producing reaction in an intermittent manner (gassing-tapping cycle).

In order to validate the model data from tapping of metal from an industrial ferrosilicon furnace is used. In the industrial campaign weight of tapped metal versus tapping time was recorded. The parameters of the CFD model were tunned based on the industrial furnace design. Because the actual ferrosilicon furnace was smaller than in the previous calculations, the crater pressure was set to 29 mbar. With these modifications (furnace size and crater pressure) almost perfect agreement with the industrial data was obtained. The overall results are shown in table 1.

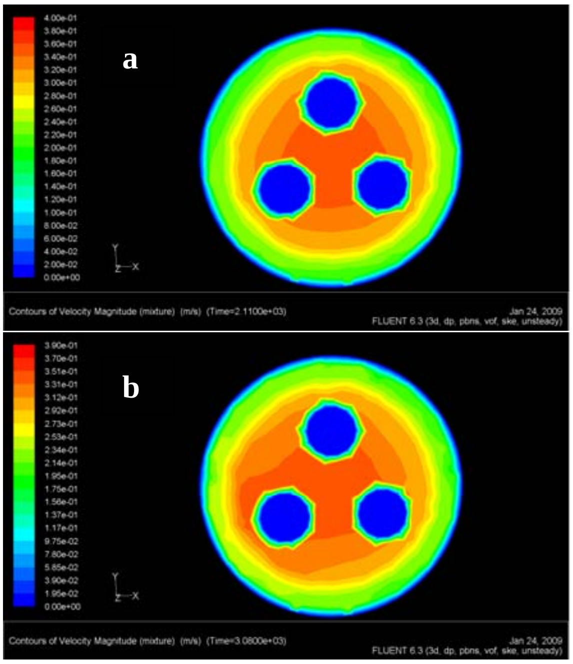

Figure 11: Gas velocity pattern on the furnace top (a)during normal tapping and (b) during the taphole gassing situation

Parameter	Industrial Data	Model Result
Average metal flow rate (kg/s)	2.054	2.09
Average tapping time (s)	2000	2000
Total metal tapped (kg)	4108	4180
Starting time of gassing taphole phenomenon (s)	Variable	1817

Table 1: Model results in comparison with industrial data

CONCLUSION

A full 3D multiphase model of tapping of metal from the submerged arc furnace has been developed. The effects of high gas pressure inside the crater zone and at the permeability of the packed bed in the furnace bottom layer, on the tapping flow rate of metal from furnace into the ladle was studied. Moreover the flow of reaction gasses through the porous media of the charge materials inside the furnace and also the off-gasses from the furnace top was investigated.

Existence of a high gas pressure inside the crater zone increases the tapping flow rate and it is a major reason for the taphole gassing phenomenon. Increased gas pressure in the crater zone due to reduced permeability of charge materials above the crater zone can lead to higher metal flow rate and earlier break through of gas from taphole. The results of the model are in good agreement with real data from the tapping process and the model is able to generate the industrial data with reasonable degree of accuracy.

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