Temperature field at the tap-hole in a manganese furnace – a computational modelling study

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The extraction of slag and metal through smelting furnace tap-holes during the tapping process is a complex procedure involving many coupled thermophysical effects. Insight into the fluid flow and heat transfer in such systems can be gained by using computational mechanics tools to build high-fidelity models of the fluid flow, heat transfer, and other relevant physical phenomena.

A CFD-based model accounting for conservation of mass, momentum, and energy has been applied to study the temperature field and flow of metal and slag in the tap-hole region in a typical manganese furnace. The temperature field is important for slag/metal-flow since it determines material properties. It is also important for wear of furnace refractories. A sensitivity study on which parameters affect the temperature field has been carried out

Keywords: fluid flow, heat transfer, modelling, taphole, ferromanganese.

INTRODUCTION

During production of ferroalloys and other metals in electric furnaces, the metal and slag are tapped through a tap-hole. The tapping process involves movement of materials and heat to the next process unit (normally a ladle) in the metal production flow sheet. The flow of molten materials through the tap-hole affects the temperature field in the tapping block and the neighbouring refractories and ramming paste. Flow and wear behaviour in the tap-hole are temperature-dependent since the mechanical and physical properties of the materials involved vary with temperature. Thus, understanding heat transfer will improve the knowledge base for tap-hole design decisions and materials choice.

Heat transfer during furnace tapping can be studied by computational modelling using a sound mathematical description of the physics of the problem. Modelling of various aspects of furnace tapping has been carried out elsewhere (*e.g.* Kadkhodabeigi, Tveit, and Johansen, 2011, Reynolds and Erwee, 2017). Although heat transfer through tap-blocks has been studied extensively, the coupling to the furnace physics has not been properly established. Often an assumed temperature on the inside of the tap block is applied. Here we try to remedy that by presenting a mathematical model for studying the coupled fluid flow and heat transfer behaviour in a submerged arc furnace. Note that this is work in progress.

MODEL DESCRIPTION

The numerical model is based on conservation of mass, momentum, and energy, allowing for calculation of material flow and temperature. The burden and coke bed in the furnace form porous layers and are not modelled directly, but are accounted for by a pressure drop in the gas flow according to Ergun's equation (see *e.g*. Kadkhodabeigi, 2011). Full modelling of energy sources and sinks due to chemical reactions occurring between the materials fed to the furnace is not considered at present. The thermochemistry of the manganese smelting process is very complex, and a pragmatic approach has therefore been adopted to estimate the temperature in the reaction zones at the centre of the furnace. This is discussed further in the following section on model geometry and material zones.

Numerical meshes and solutions of the governing equations were obtained using the commercial software ANSYS Fluent v16.1[1].

Model Geometry and Boundary Conditions

The objective of the model is to study the heat transfer and temperature field in the tapping block and the region around it during tapping. The model assumes that the furnace can be divided into three symmetrical zones, one around each electrode. A drawback to this approach is that it implies that the furnace is tapped from three tap-holes simultaneously, which is not realistic – however, this assumption is expected to have only a minor impact on the gross fluid flow and heat transfer behaviour, which is the focus of the present study.

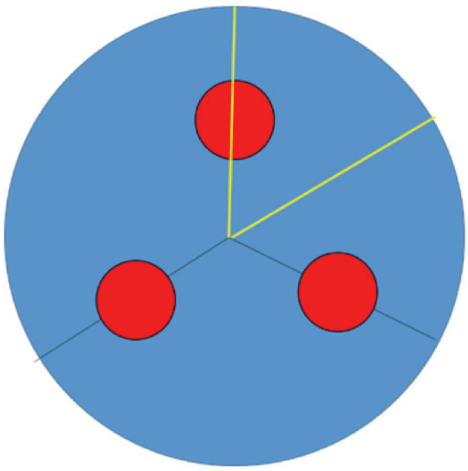

Figure 1. Symmetry planes in furnace. The section applied for modelling is indicated by the yellow lines (the tap-hole is placed along one or the other of these lines).

Material zones used in the model are illustrated in Figure 2. This arrangement is representative of typical ferroalloy submerged arc furnaces, with the specific model used here being based on a ferromanganese furnace. The furnace core represents the coke bed where the majority of energy is input and consumed by the furnace and metal, slag, and gas are produced. Excess furnace power not consumed by thermochemical reactions (actually 1/6 of the total power input due to the symmetry assumption) can be introduced as an Ohmic heat source in this zone, or alternatively an expected temperature can be specified as a fixed value. In the present modelling work, a specified temperature of 1600°C was applied, which might serve a conservative (high temperature) estimate (Olsen, Tangstad, and Lindstad, 2007).

[1] www.ansys.com

Most materials have physical properties which vary with temperature; however, accurate quantification of these variations is challenging, especially at pyrometallurgical temperatures, and may introduce additional sources of uncertainty into the model. We therefore apply constant material properties as given in Table I. The tapping block in the present example consists of bricks with a fairly high thermal conductivity, which is comparable to other furnaces (*e.g.* Steenkamp, Pistorius, and Tangstad, 2015).

As indicated earlier, in the zone containing gas, coke, and ore the energy balance does not take into account specific chemical reactions – these are instead lumped together into a single energy sink value representing the combined thermochemical changes in the burden layer. This heat sink is a constant source term (W/m^3) which is calibrated to provide a gas temperature of 350-400°C at the furnace top (Olsen, Tangstad, and Lindstad, 2007).

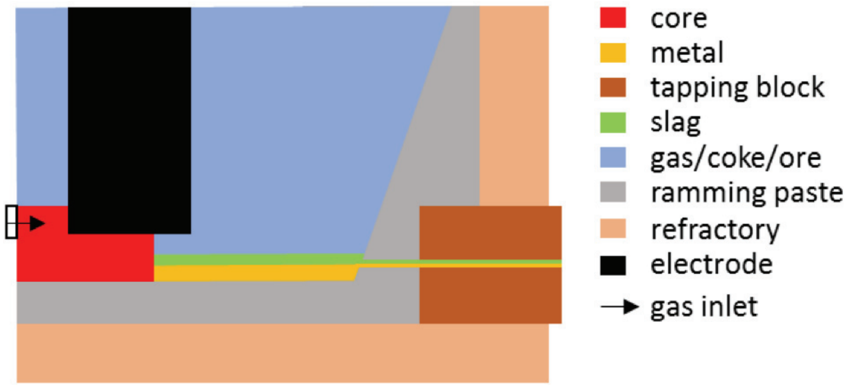

Figure 2. Material zones in the ferroalloy furnace model.

It is challenging to provide realistic boundary conditions to the furnace model in a pragmatic approach since a number of complex phenomena must be considered. At the top of the furnace burden, gas generated by the process is flowing out while coke and ore are flowing in. The implementation of accurate boundary conditions accounting for simultaneous inflow and outflow of different phases is complex, and such detailed modelling has not been attempted here. We apply a gas inlet in the core zone, which creates an overpressure at the centre of the furnace underneath the electrodes (see Figure 2). This overpressure drives the slag and metal towards the tap-hole (like a storm surge) while the gas moves outwards and upwards through the porous burden. An outlet condition is applied for the gas phase at the upper boundary. Since only the flow resistance of the porous coke and ore mixture in the burden is accounted for (see above), any hydrostatic pressure provided by the weight of the burden is lumped together with the gas inlet pressure. This is of course a simplification and assumption, but it permits a degree of empirical adjustment in the model – in this case, the pressure is calibrated to provide a velocity of 1.5 m/s in the tap-hole, which is quite typical (Kadghodabeigi, 2011).

At the outer walls water cooling is assumed to be present, with a water temperature of 75°C and an effective heat transfer coefficient of 500 W/m^2K (typical for forced-convection water cooling in closed channels). In reality the water temperature will vary throughout the cooling loops, but it is not expected that the model results will be particularly sensitive to this parameter.

Table I. Material properties.

	Density (kg/m³)	Thermal conductivity (W/m K)	Heat capacity (J/kg K)	Viscosity (Pa s)
Refractory	2300	1.5	1000	Solid
Tapping block	2650	13	1000	Solid
Ramming paste	2000	5	1500	Solid
Gas / burden	Ideal gas law	0.5	1000	10^{-5}
Metal	6100	40	800	0.005
Slag	3000	3	1800	0.1

RESULTS AND DISCUSSION

The simplified and pragmatic model described above has been applied in a series of simulations to assess the sensitivity of the heat transfer behaviour to changes in chosen parameters. The reference case assumes a core temperature of 1600°C, metal/slag velocity of 1.5 m/s in the tap-hole, a temperature of 338°C at the top of the furnace burden, water-cooled surfaces, and material properties as given in Table I. In order to assess sensitivity, temperature was monitored in four different locations: three in the refractory lining of the furnace as indicated in Figure 3, together with the outflow temperature of metal/slag. The refractory locations indicate temperature in the ramming paste near the tap-hole (1), in the tapping block (2), and close to the base of the furnace hearth (3). The simulations were performed by running a transient simulation with very small time steps (typically 10^{-5} s) until a quasi-steady-state flow field was obtained. The flow field was then fixed and used as input for a steady-state heat transfer simulation to converge the temperature field. The converged temperature results are reported in the following subsections.

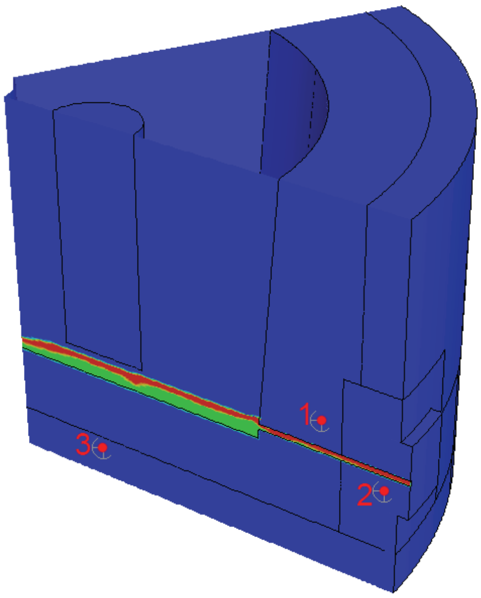

Figure 3. Slag (red) and metal (green) in furnace with indicated monitoring points for temperature.

Heat Convection vs Conduction

The reference simulation was compared against a case in which the metal and slag velocity were set to zero. This is almost similar to a situation of no tapping, although with metal instead of clay in the tap-hole. The resulting temperature profiles in the furnace are shown in Figure 4. It can be seen that there is a significant difference in temperature distribution in these two cases, indicating that heat transfer by thermal convection is significant, particularly in the regions in and around the tap-hole channel. This is largely to be expected, given the relatively low thermal conductivities and high densities and heat capacities of the molten metal and slag.

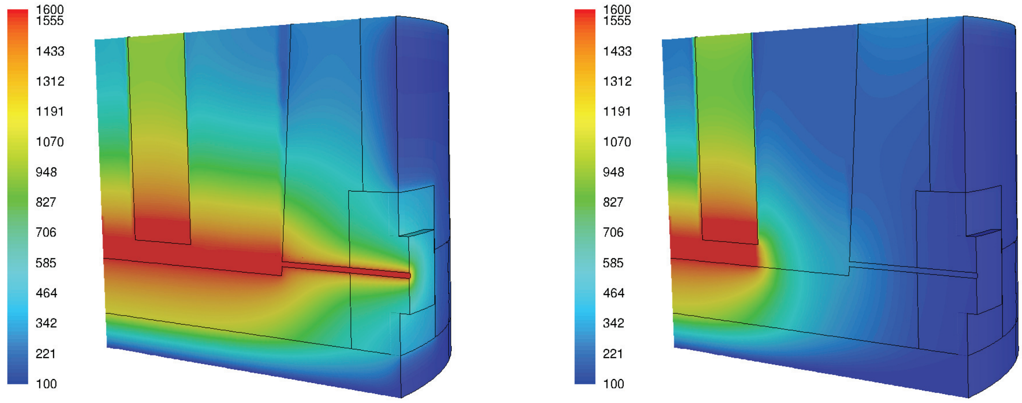

Figure 4. Temperature distribution (°C) in furnace, with (left) and without (right) thermal convection.

Water Cooling vs Natural Convection

In general, water cooling will provide better sidewall protection than natural convection, but the effect is mitigated somewhat due to the fact that the thermal energy must pass through a significant thickness of refractory material before it can be removed. A case was run using a heat transfer coefficient typical for natural convection (10 W/mK and T_{inf} = 50°C) and compared against the reference case with water cooling (500 W/mK and T_{inf} = 75°C) to quantitatively assess differences between cooling strategies. The temperature fields comparing the two cases are shown in Figure 5. Visually, there are no appreciable differences in the furnace interior; however, the water-cooled furnace is colder than the naturally cooled furnace near to the boundaries, as seen in Table II. The effectiveness of different cooling designs must also be balanced against operational and safety requirements, which often mandate a particular cooling philosophy on different parts of the furnace vessel.

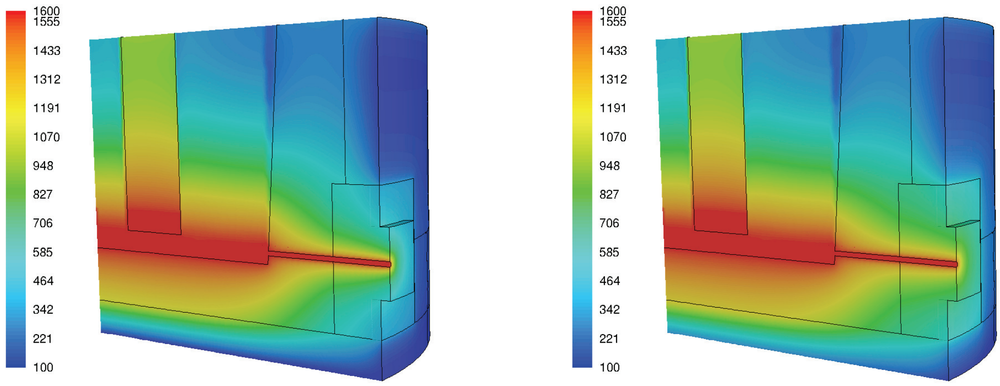

Figure 5. Temperature distribution (°C) in a water-cooled furnace (left) and naturally cooled furnace (right).

Thermal Conductivity

Thermal conductivity affects heat transfer in regions where convection is limited or absent. The sensitivity of the temperature field in the model to variations in thermal conductivity was assessed by varying the conductivity of different parts of the furnace while keeping all other values fixed per the reference case. The results are shown in

Figure 6, where the effect of a doubling in conductivity has been studied. The temperature fields appear quite similar visually, but if we study them more closely we see that there are small differences – for example the green contours move somewhat between each case. This is documented quantitatively in Table II which shows that in general the temperature at a monitoring point increases if thermal conductivity increases in the tapping block and ramming paste, and decreases if the conductivity in the refractory bricks is decreased. The impact on the monitoring points is strongest from the material in which the monitoring point is located. The material with the overall highest impact is the ramming paste, but it should be noted that the overall difference in impact as the conductivities are changed is not large. Extreme changes in material conductivities, such as those resulting from moving to a copper-cooled tap-hole design or switching between conductive and non-conductive refractories, would however be expected to alter the temperature profiles significantly, particularly in the tap-hole region.

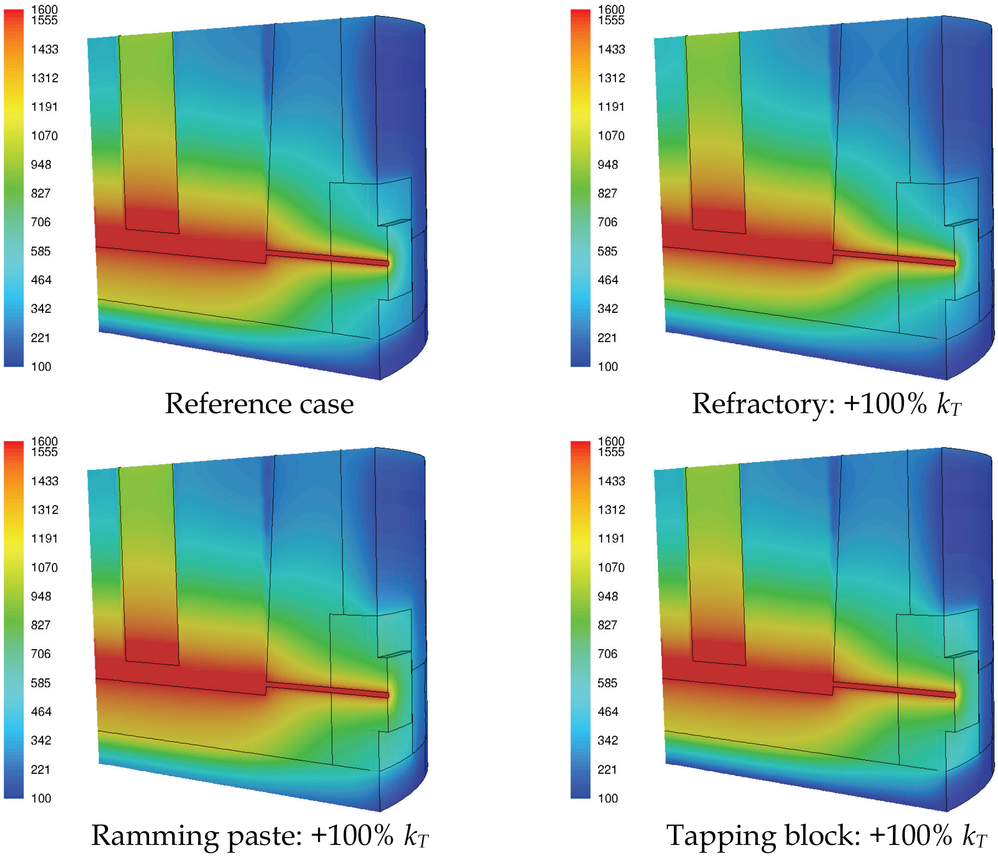

Figure 6. Temperature distribution (°C) in furnace for cases with increased values of thermal conductivity in different furnace materials.

Table II. Monitored temperature (°C) for various locations and cases. Change relative to the reference case is given in parenthesis.

	Ramming paste (1)	Tap block (2)	Hearth (3)	Outlet
Reference case	920.5	901.4	837.1	1597.9
No convection	185.3 (-80.0 %)	124.7 (-86.2 %)	696.3 (-16.8 %)	1597.1
Natural cooling	1002.2 (+8.9 %)	1034.8 (+14.8 %)	937.8 (+12.0 %)	1598.3
Refractory	888.9 (-3.5 %)	874.8 (-3.0 %)	665.1 (-20.5 %)	1597.4
Ramming paste	994.5 (+8.1 %)	950.3 (+5.4 %)	978.6 (+16.9 %)	1597.5
Tapping block	963.1 (+4.6 %)	989.7 (+9.8 %)	837.3 (+0.0 %)	1597.1

CONCLUSIONS

A simplified and pragmatic computational model of a submerged arc ferroalloy furnace has been developed to study fluid flow and heat transfer behaviour in the furnace. The dimensions of the current model are based on an industrial ferromanganese furnace design. Although the model does not perfectly reproduce the many complex coupled heat-transfer effects occurring inside an operating furnace, the temperature field is sufficiently representative to act as the basis for a sensitivity analysis.

A set of cases was compared by running a series of simulations with changes in individual parameters. It was found that convection of the slag and metal phases in the furnace plays an important part in determining the overall heat transfer through the tapping channel and surrounding refractories. As expected, water cooling is more efficient than natural cooling and this is confirmed by the model, but the strength of the effect is significant only in parts of the furnace sidewall close to the cooled surfaces. Changes in refractory material properties do influence the heat transfer behaviour, although a significant change in thermal conductivity is required before appreciable changes in local temperatures inside the furnace become obvious.

This work is intended as a starting point for future research, and as such, further work on developing such three-dimensional heat transfer and fluid flow models for sensitivity analysis of ferroalloy furnaces is highly recommended. A more realistic description of the energy sources and sinks related to the thermochemical reactions occurring in the furnace would help to reduce uncertainties related to these phenomena and their impact on the model results. Comparison of the model against temperature measurements from operating furnaces would be of great value in validating its behaviour and the quality of the approximations made during its development. Finally, measured wear profiles from tap-holes and sidewall refractories in industrial furnaces should be assessed in light of model results such as these, with the aim of determining how much of the wear pattern can be assigned to purely thermal effects as opposed to chemical and mechanical attack.

ACKNOWLEDGEMENTS

The work presented in this paper was conducted in the project Controlled Tapping, which is funded by Norwegian Research Council and FFF. The authors would like to acknowledge valuable input and discussion with Joalet Steenkamp, Stein Tore Johansen, and Eli Ringdalen.

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