THE APPLICATION OF NUMERICAL MODELLING TO THE DESIGN OF ELECTRIC FURNACES

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ABSTRACT

Electric furnace smelting is one of the principal unit operations for ferroalloy production, and increased process intensity, improved availability, minimal maintenance and a longer campaign life are common objectives for electric furnace operation in order to obtain favourable economics of production. Furnace designers have continued to develop innovative solutions that have allowed these objectives to be realised, e.g., furnace cooling systems, and numerical modelling plays a key role in the design process. Enhanced understanding of the energy transfer process in the furnace and the ability to develop, evaluate and optimise components of the crucible design to match process requirements are the key motivators for modelling.

This paper provides an overview of recent applications of numerical modelling to the design of electric furnaces. The aim is to illustrate what can be done, and identify areas where further work is needed in this field. Examples include furnace bath modelling, crucible cooling system design, taphole design, baking of Soderberg electrodes, off-gas systems, and fume control and building ventilation. It is argued that the trend is for numerical models to become more encompassing while at the same time more accessible, and therefore further improvements in furnace design will be realised with continued and well validated modelling efforts.

1. INTRODUCTION

One of the main processing steps in the production of ferroalloy units is the smelting of ore in electric furnaces. The three electrode, AC submerged arc furnace dominates the industry, with shielded-arc and DC plasma arc furnaces achieving limited application [1,2]. Commercial furnaces range in size from a few megawatts to more than eighty megawatts of power supplied and all operate with the common objective of maximising the return on capital invested. Maximising productivity and energy efficiency are two direct mechanisms for achieving this objective and this takes the form of process intensification, improved availability, minimal maintenance, and increased campaign life for the furnace and associated equipment. At the same time, the need to minimise the environmental impact of metal production through the reduction of particulate emissions, greenhouse gases, and other harmful by-products must also be met.

Furnace designers have responded to these needs, and innovations in furnace cooling and binding systems have been developed to maintain a tight, leak free furnace with high power-on time [3,4]. Similar innovations in the design of water-cooled tapholes, post-combustion off-gas systems, electrode columns, and other furnace components and control systems have been made that have contributed to the success of the electric furnace as a processing unit [5,6,7,8,9]. Experience and empiricism provides the vision for the development of innovations, but the actual development and design requires a comprehensive understanding of energy and material flows in the furnace. Numerical modelling based on computational methods, such as computational fluid dynamics (CFD) and finite element analysis (FEA), has come to play key role in achieving this understanding, as well as providing the opportunity to rationalise and optimise designs prior to implementation [10,11,12,13,14].

The acceptance of computational modelling as an engineering tool has not come quickly to the minerals and metals processing industry and this is in part due to the complexities of the different processes. That is, real problems within the context of electric furnace smelting are multi-dimensional, multi-phase, multi-physics, and multi-species flows that are reacting, undergo phase change, and are inherently transient. The advantage of computational modelling over simpler mathematical methods is the ability to simulate many more aspects of a real process. Limitations of scaling associated with pilot plants are eliminated, as are isothermal, non-reacting flow conditions generally required for physical modelling at reduced scales. Therefore, the accuracy and value of the computational solution is significant. However, it is important to emphasise that the trustworthiness of the computational modelling result depends on many factors, most importantly, the need to understand the process and operating conditions being modelled, the need to accurately characterise material properties, and the requirement for the modeller to concisely define the real conditions pertinent to the numerical model. Because there is no easy way to ensure that these fundamental requirements are met in all cases, validation of the modelling effort is essential, and this requires data that are applicable to the process being modelled.

This paper provides an overview of recent applications of computational modelling to the design of electric furnaces. The aim is to illustrate the exploitation of computational modelling as an engineering analysis and design tool, and to show the trend for such models to more comprehensively represent the component physics, chemistry, and kinetics of the processes being evaluated. Examples include furnace bath modelling, taphole design, furnace crucible cooling, baking of Soderberg electrodes, post-combustion off-gas system design, fume control, and building ventilation. These examples have been chosen as they are representative of common applications of computational modelling to the challenges of furnace design and illustrate what can be learned when computational modelling is used to its best advantage.

2. FURNACE BATH MODELLING

Experience has shown us that alloys and metals can be produced by melting and reducing various ores in a crucible. While the smelting process is understood in general terms, a fundamental and detailed understanding does not exist. Scientists and engineers have developed numerous mathematical models to analyse different aspects of the electric furnace smelting process [10,11], but the number of comprehensive computational models developed and published is limited [12,13,14,16]. However, much is to be gained through computational modelling that provides a better understanding of the details of mass and energy transfer in the furnace bath. Energy efficiency can be improved, cooling systems can be optimised, and operability can be made more stable.

One example of furnace bath modelling is shown in Figure 1 below. The model represents one-third of the slag bath for a 3-electrode circular furnace. The objective for this work was to evaluate the effects of scale-up, with the scale-up encompassing both the intensity of the process and the size of the furnace. Specific issues that were addressed were the intensity and distribution of heat transfer to the sidewall, the stirring intensity in the bath, the ability to keep high melting point phases in suspension, and identifying optimal locations for feeding. The effects of numerous operating and design parameters were evaluated within this context, including operating power, current level, and electrode immersion.

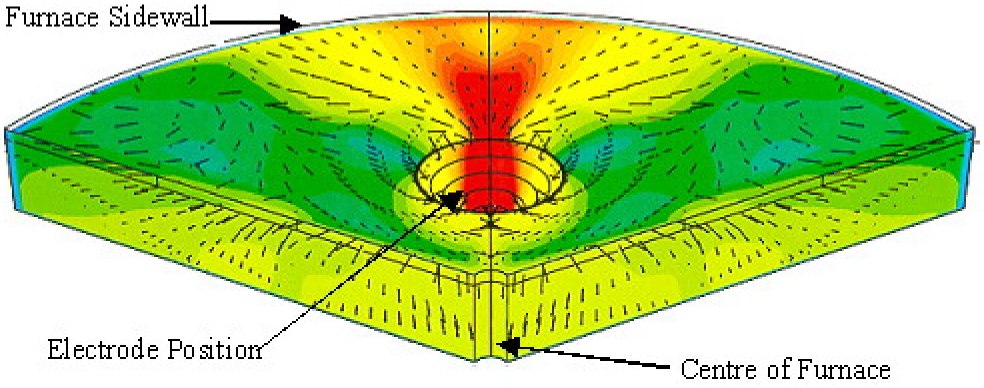

Figure 1. Sample simulation showing the temperature and flow conditions in the slag bath of an electric furnace. The model represents one third of the bath.

A furnace bath is a tremendously challenging system to describe mathematically, and great care must be taken when doing so to ensure the usefulness of the model. The example shown in Figure 1 included the effects of buoyancy, gas bubbles, and electromagnetics as driving forces, and Joule heating, melting, and reduction to account for the thermal energy supplied to and consumed in the bath. It is noted that the model is not a “virtual” furnace, and the understanding and data required to develop this model was based on extensive physical measurements made in an existing, smaller commercial furnace for the same process. These measurements included, most notably, bath temperature and tracer measurements, electrical measurements, and heat loss measurements. The computational model was developed and validated for the smaller commercial furnace before being applied to evaluate the larger furnace design.

While the furnace model described here included many aspects of this multi-physics, multi-phase system, and was used to successfully design a new furnace, simplifications and assumptions were required, and some aspects of the component physics and chemistry could only be represented implicitly rather than explicitly, and were developed outside of the model. Continued development of mathematical algorithms and models to account for micro-scale phenomena occurring in the bath will make the modelling of this type of system more representative in the future, and therefore more valuable. Until this development work is completed, furnace bath modelling and its application to the design of electric furnaces must only be done after validation with comprehensive experimental testing and the inputs of experienced furnace designers and operators.

3. TAPHOLE MODELLING

The tapping of alloy or metal from an electric furnace is a critical operation, and the taphole is often considered to be the weakest point of the furnace in terms of safely containing the melt in the crucible. Failure of the taphole can be serious, endangering the safety of the employees and causing damage to the furnace. Operating time lost while repairs are made and the cost of repairs, has a significant impact on the financial performance of the smelter. Much work has been done to design robust and reliable tapholes, and simple refractory designs have been gradually replaced with water-cooled copper tapblocks, especially with increases in the operating intensity of furnaces.

Computational modelling has played a significant role in the development of high performance water-cooled copper tapblocks, and continues to be an important analysis tool as tapblocks are designed to handle every increasing thermal loads. The designer must have a detailed understanding of the transient thermal loads the block must handle during tapping if the operating requirements are to be achieved. The furnace operator must also acquire this understanding so that the safe operating conditions are not exceeded and maintenance needs specific to the taphole are executed as required. For example, the operator will monitor block temperatures, and determine from these temperatures if the tapblock is operating within its design envelope and estimate the relative “health” of the block, i.e., is there a need for refractory repairs to be made, or is replacement of the block required.

Figure 2 shows a computational model of a water-cooled copper tapblock, and the resulting temperature distribution in the block for a specified operating condition. The view has been sectioned to show the copper on the left side, and the cast-in water piping on the right side. The generation of such a model requires a high degree of dimensional accuracy, so in this case the computational model is created from the same CAD model that is used to design and manufacture the tapblock. Once generated, operating conditions for the tapblock are simulated as accurately as possible by including metal tapping, and the flow of water through the cooling water passage. Data obtained from tapblocks in operating furnaces are used to validate the models.

Very detailed thermal data is obtained from the model for a variety of operating conditions, and this information is used in a number of ways. First, the designer will optimise and refine the design of the tapblock so that the anticipated range of operating conditions will be achieved, including optimising the placement and density of cooling water passages to avoid localised boiling. Second, the location of the thermocouples cast into the block will be specified for effective monitoring, and finally, the temperature signatures associated with different operating and wear conditions are used as fundamental input data for advanced monitoring and control systems.

The advanced control system provides the operator with "intelligent" guidance for safe tapping and estimates the "health" of the tapblock. This eliminates the operator's requirement to interpret temperature measurements, which can vary from operator to operator. An advanced control system is a must for the safe operation of a high intensity, high productivity furnace, and would not be possible without the comprehensive computational model that has been described here.

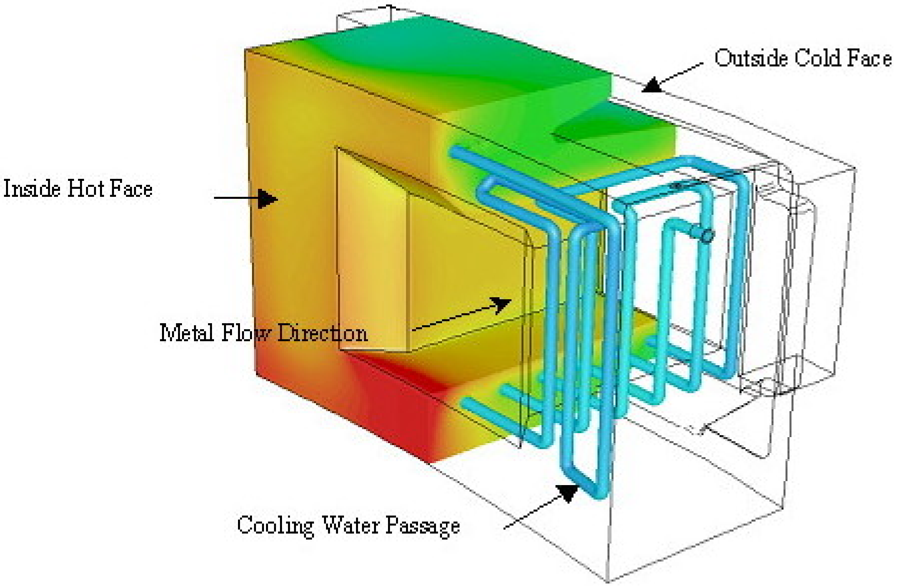

Figure 2. Computational model showing the temperature distribution in a water cooled copper tapblock. The left side of the model shows the copper tapblock, and the right side shows the water piping that is cast into the tapblock. Refractory is not shown for clarity.

4. FURNACE COOLING SYSTEM DESIGN

There are a wide variety of cooling systems used on electric furnaces, ranging from simple air cooling for low rates of heat removal, to sophisticated water-cooled "waffle" type copper coolers for high rates of heat removal. Cooling of the hearth, upper and lower sidewalls, and furnace roof is common for a high-intensity, high-productivity furnace. With any cooling system, the objective is to remove a sufficient amount of the process heat to protect the furnace crucible from risk of run-out and increase its campaign life. The process heat load on the crucible has increased with the trend towards high power, high productivity furnaces, and water cooling has become a common practice because of its capacity for high heat removal and relatively low implementation and operating cost. The use of copper coolers has proven itself to be a safe and reliable method of using water [3,6].

Computational modelling is used extensively in the design of furnace cooling systems, for both air-cooled and water-cooled systems. The purpose is to guide the designer in establishing the configuration and intensity of the cooling system required for a given process. The procedures and methods used for the modelling are well established, and process heat loads applied to the models are determined through measurement. In the event of a significant scale-up in process intensity, process heat loads can be obtained from a comprehensive bath modelling exercise, as discussed in Section 3.

Figure 3 shows a comparison between the actual thermal equilibrium profile, defined as the slag freezing isotherm, measured in a furnace and that predicted by the computational model. Water-cooled copper plate coolers are installed in this instance. The close correlation between the measured and predicted results is evidence of the effectiveness of computational modelling for this type of work. This effectiveness has helped make water-cooled copper cooling systems the cooling technology of choice for high intensity furnaces.

Figure 3. Comparison showing the thermal equilibrium erosion profile in a furnace (left) and that predicted by the computational model (right).

Models used to evaluate the performance of furnace cooling systems have continued to evolve to be more comprehensive in a continuous effort to increase cooling performance. Efforts are currently directed at increasing the level of modelling detail in copper coolers so that the potential for localised boiling in the water passages can be investigated, and the effect of direct contact between the molten phase in the furnace and the copper cooler, as can occur when refractory spalls, can be evaluated. This requires full scale three dimensional models that include the flow of water through the passages, and include the transient melting and solidification of the bath and/or copper. Models with this level of complexity will be computationally intensive and require fast, parallel computing machines to obtain solutions within an engineering time frame. Similar efforts are also being directed at enhanced forced air cooling systems.

5. SODERBERG ELECTRODE MODELLING

Soderberg electrodes find extensive use in ferroalloy production, and electrode breaks must be avoided to maximise furnace availability. This is achieved with good electrode management practice, which covers casing design and addition, paste quality and filling practices, and furnace operating practices (e.g., power on, power off, idling, slipping, etc.) that don't compromise the integrity of the electrode. One of the keys to avoiding electrode breaks is to ensure that the electrode is baked properly and that the thermal stress does not exceed safe limits. Computational modelling provides a means to evaluate both the baking behaviour of the electrode for different operating modes and the thermal stress in the electrode during transitional operating periods when stress in the electrodes is high.

Figure 4 shows the location of the baking zone (400 to 500^{o}C) for three different operating conditions in a non-ferrous smelting furnace. The electrode configuration for this furnace has the electrode clamps positioned above the roof, with the electrode extending down through the furnace freeboard and a thin layer of floating charge, before being immersed into the slag bath. Current levels and thermal conditions in the freeboard dictate the baking of the electrode, as is shown in this result.

The computational model used to simulate the baking of electrodes is a coupled thermal-electromagnetic model that accounts for slipping of the electrode and the skin effect associated with AC current. All material properties are defined to include their temperature dependency. Confidence in the numerical model has been established through validation work that compares the results of the model with electrode temperature measurements made in operating furnaces. Figure 5 shows the results of temperature measurements taken in a Soderberg electrode and these indicate the baking zone is located in the upper freeboard and roof area for the operating conditions of the furnace.

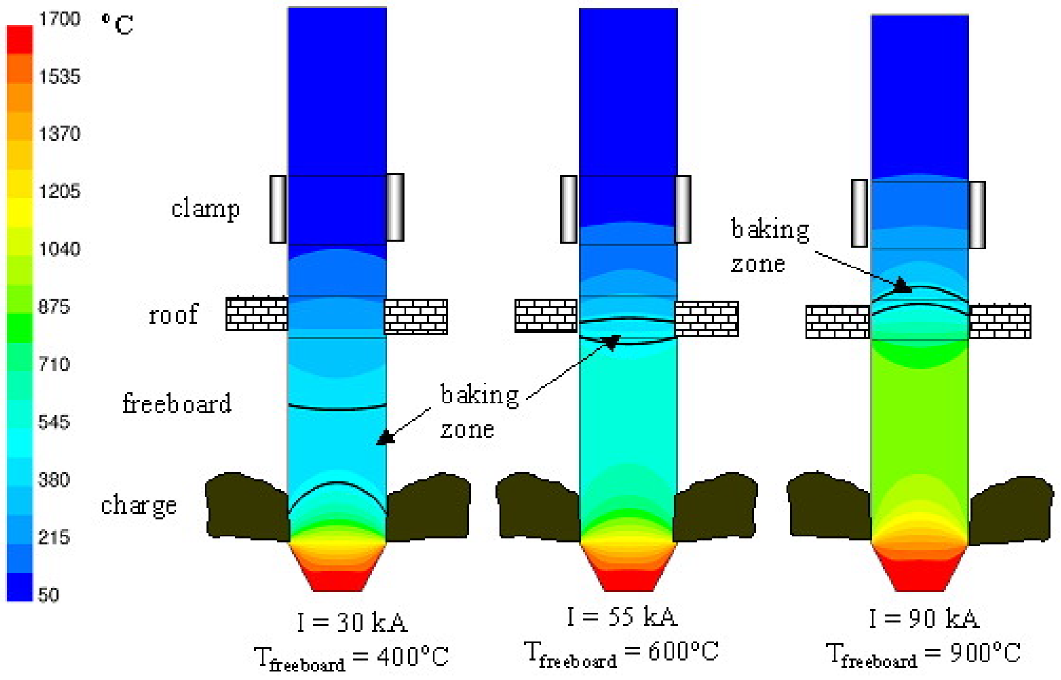

Figure 4. Predicted temperature distribution and baking zone location in a Soderberg electrode for three different operating conditions.

In addition to predicting the thermal condition of the electrode for normal furnace operation, transient conditions, such as during power-off, idling, and power-on periods, can also be modelled and the resulting thermal stress can be determined from the computed thermal gradients. Effective electrode management practices can be developed once this fundamental information is available and understood.

This type of modelling has traditionally been completed as a stand-alone exercise, with engineers and operators taking the results, interpreting them, and then applying it to their operation as best they can. For this to be successful requires that the operators extrapolate between or beyond the conditions modelled. This transfer of knowledge and extrapolation can be eliminated by running the models in real time, with model inputs coming directly from furnace operating conditions. This is feasible because of the continued development of numerical algorithms and the availability of low cost computing power. With an electrode model running in real time, good electrode management will be easier to accomplish.

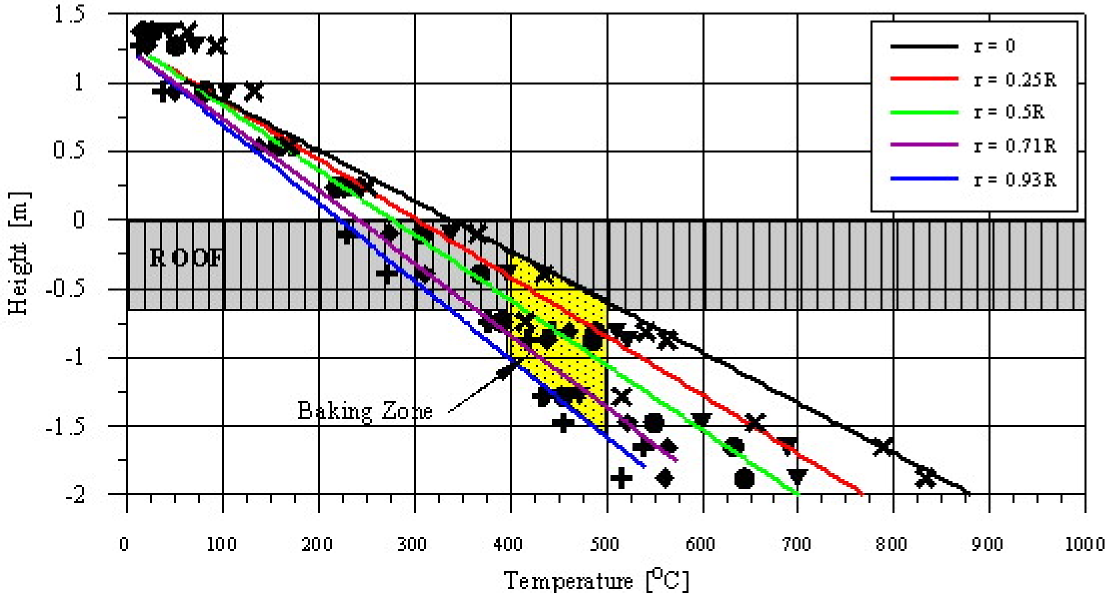

Figure 5. Measured temperature distribution in a 1400 mm Soderberg electrode (R = 700 mm) for a non-ferrous smelting furnace operating at an average current of 30 kA and a freeboard temperature of 600°C.

6. POST-COMBUSTION OFF-GAS SYSTEM DESIGN

The off-gas system is a critical component of an electric furnace and represents approximately 50% of the total installed smelter cost, depending on the requirements of the operation. Poor performance of the off-gas system will have a strong negative impact on the productivity of the furnace, prevent environmental emission targets from being achieved, increase maintenance and operating costs, and compromise the safety of employees. The design of an off-gas system that provides the performance and reliability required for a modern electric smelting furnace is a complex task, and computational modelling plays an important role in the success of the design [9,15].

One example of computational modelling for a component of an off-gas system is shown in Figure 6. CO rich gas leaving the furnace is burned in a water-cooled chamber before being cooled in an evaporative spray cooler and cleaned in a baghouse. The destruction of CO gas is required to prevent explosions, and with the combustion chamber also acting as a duct to transport the gas to the spray cooler, the cost and footprint for the system is minimised. Air is introduced in a staged arrangement along the length of the combustion chamber in order to minimise peak gas temperatures and ensure complete combustion of the CO gas. Because the combustion of CO gas is mixing rate limited and radiation is an important component of the heat transfer analysis, computational modelling is well suited to the analysis and design optimisation of the equipment. For the computational analysis, the three-dimensional transport of the combustion gases is solved along with the chemical reactions, with the heat transfer to the walls predicted. Once the model is developed, the effect on the combustion chamber performance of different design and operating conditions is evaluated, allowing the designer to customise the system to meet operating criteria. Operational data of gas temperature and CO concentration has validated the accuracy of the design for this equipment.

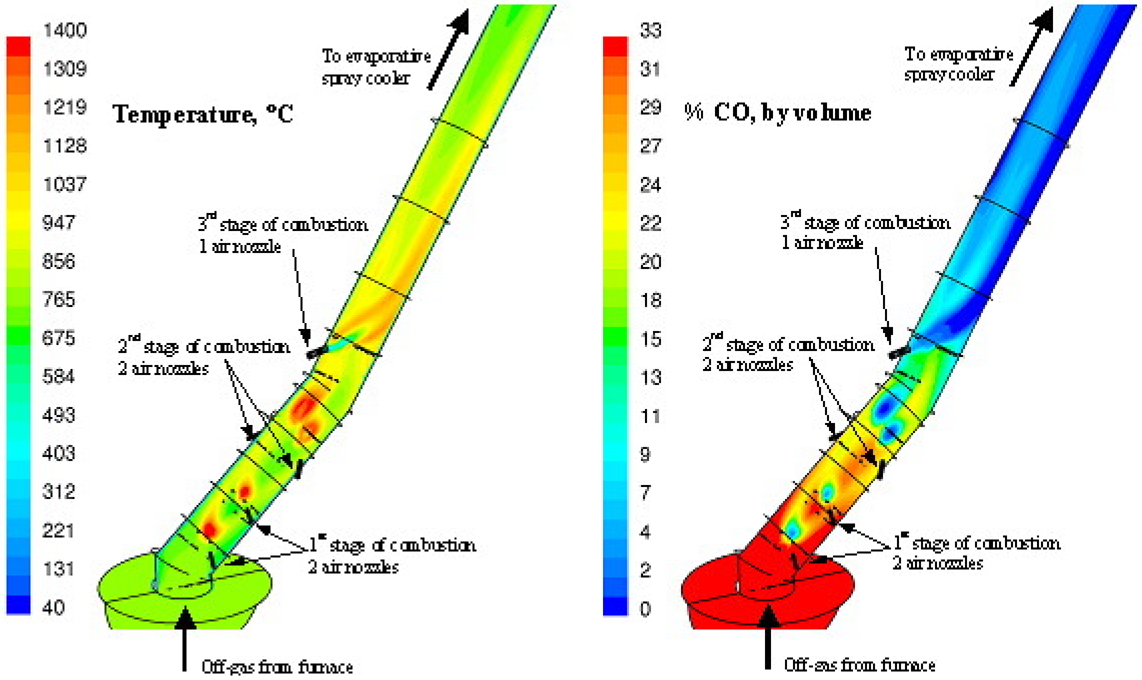

Figure 6. Simulation results showing the temperature profile (left) and CO gas concentration (right) in a water cooled combustion chamber. Air is injected into the chamber at strategic locations to control the maximum gas temperature and ensure effective destruction of the CO gas.

7. FUME CONTROL AND BUILDING VENTILATION

Controlling emissions and providing a safe, clean, and comfortable work environment is a requirement of the modern smelter. Successful operators recognise that a large part of their success is in the hands of employees. Employees distracted by poor or dangerous working conditions will not be inclined to maximise smelter productivity regardless of how well the equipment operates. Therefore, effective control of fugitive emissions and a good building ventilation system are required for a high productivity, high efficiency smelter operation.

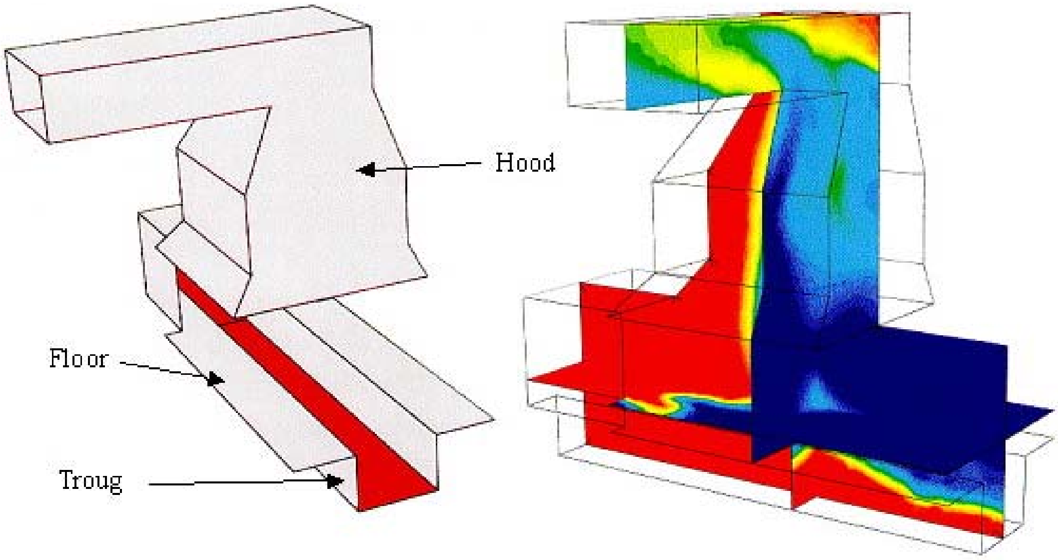

Figure 7. Computational model used to evaluate the fume capture performance of a tapping hood. The left figure shows the domain and components of the model, and the figure on the right shows the hood in operation.

Computational modelling is routinely used by designers to develop low cost, effective systems for fume control and building ventilation. Quantification of capture performance of collection hoods, evaluating the local concentration of toxic gases such as carbon monoxide within a smelter building, and calculating the heat stress workers will experience are all possible with the computation models available today.

Figure 7 shows a model used to optimise a hood design for a taphole and launder. The model is generated to scale, includes the effects of buoyancy and radiation heat transfer, and considers the fume as a species separate from air so that the capture performance of the hood can be quantified. Optimisation of the hood size and exhaust flow rate is readily accomplished at a very reasonable cost.

Figure 8 illustrates computational modelling used to evaluate building ventilation conditions in a smelter. Like the example in Figure 7, the building is modelled in full scale, with emissions from the two electric furnaces modelled as a species separate from air. Cross-drafts through the building were limiting the effectiveness of the two canopy hoods in the emissions, and different building modifications were evaluated to reduce the effect of the cross drafts. With this demonstrated capability of computational modelling, achieving good control of fugitive emissions and an effective building ventilation system is possible. This will help ensure that productivity, environmental, and safety goals for the smelter are achieved.

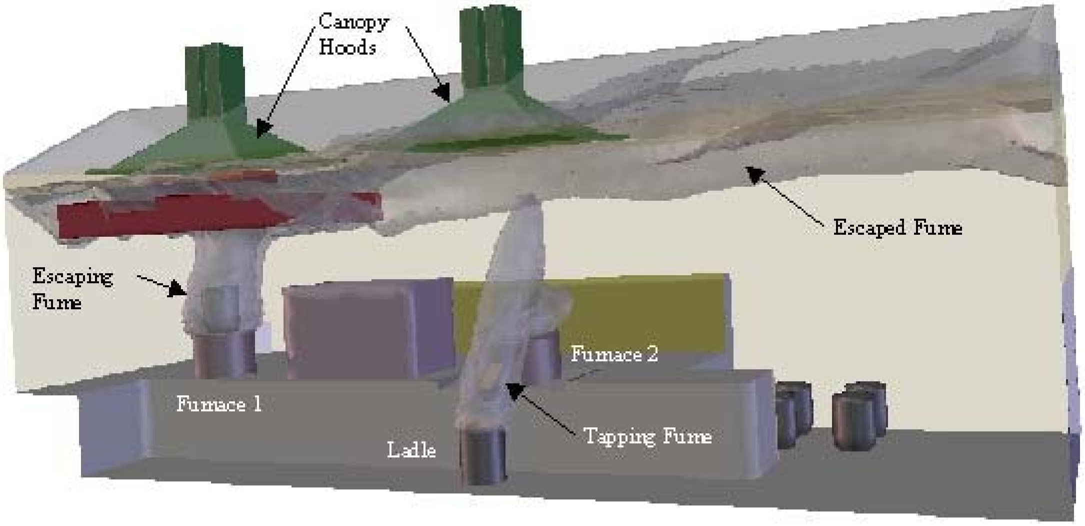

Figure 8. Simulation result showing the effect of fume released into a smelter building and fume that is not captured by the canopy hoods installed for this purpose.

8. CONCLUSION

This paper has highlighted the application of numerical modelling to the design of electric furnaces. The examples presented demonstrate the capability of numerical modelling based on computational methods and their role in achieving the understanding of material and energy flows required to develop, rationalise and optimise innovations in furnace design. This is providing the opportunity to maximise the productivity and energy efficiency of the electric furnace, with advances being made in process intensity, improved availability, reduced maintenance, reduced environmental impact, and increased campaign life. The electric furnace continues to be a viable processing unit for the production of alloys and metals because of the innovations that have been made in its design and operation.

The acceptance of computational modelling as an engineering tool in the minerals and metals processing industry has not come quickly. Rule-of-thumb designing and ad-hoc plant experimentation are still routinely practised. However, the inherent capability of computational modelling to simulate many aspects of real systems makes it a valuable engineering and analysis tool, a tool to be used in complement with traditional methods, such as, scale modelling, piloting, and carefully planned and controlled plant experimentation. Although much work has been done in the area of algorithm development and physical model development, there is still work yet to be done, especially for multi-phase, multi-physics problems. Therefore, it is important to recognise the need for rigorous validation of the computational model, as well as the application of experience and a sound process understanding. Subject to these conditions, future innovations in electric furnace design will be realised.

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