

Modeling of Industrial Electric Arcs Using Different Plasma Gas Compositions



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Electric arcs are an important heat source in submerged arc furnaces that are used in the pyrometallurgical production of silicon. They are therefore of great interest to study so that the production process can be improved and made more efficient. Modeling of industrial arcs is a multiphysics problem that involves simultaneously solving several coupled physical phenomena, such as electromagnetics, fluid dynamics, and heat transfer, including radiative heat transfer from the plasma arc. Coupling fluid dynamics and electromagnetics is known as Magnetohydrodynamics (MHD). Two MHD model implementations developed by the authors are used to simulate alternating current arcs with different plasma gas compositions. The thermophysical properties of each composition are calculated using specialized code as well as gathered from literature. We investigate the dependence of the results on both the MHD model used and the input plasma data for three argon data sets and compare the results to data obtained from laboratory experiments. Finally, we investigate furnace conditions using different ratios of SiO to CO gases.

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I. INTRODUCTION

SILICON metal is typically produced in a large electric smelting vessel called a submerged arc furnace (SAF). In simple terms, the furnace converts electricity and internal energy of carbon-based materials into heat which drives chemical reactions between the raw materials, thus producing Si metal. The electrodes that carry the electric current are submerged in a deep bed of raw material used in the furnace, and heat is released via plasma arcs and resistive heating at the electrode tips. In silicon and ferrosilicon production, the electric arc is essential to provide heat at high enough temperature to separate the silicon from the oxides. In these processes,

much of the current will pass through the arc, which burns in a gas-filled volume, surrounded by a solid silicon carbide (SiC) crust. The extremely hostile environment inside SAFs makes any direct observation of the arc impossible. Therefore an accurate numerical simulation model of the electric arc can be a helpful tool for enhanced understanding and improved furnace operation. Liquid silicon forms in a pool below the arcs and is tapped into ladles via tapping holes located in the furnace sidewalls. High temperatures of over 10000°C in and around the arc provide the required energy to drive the chemical reactions of liquid SiO₂ with SiC to form Si metal in liquid form and CO gas.^[1]

SAFs are large pieces of industrial equipment and usually span a few floors of the buildings they are situated in. The furnace itself is circular, with diameters ranging from approximately 5 to 11 m and heights from 3 to 5 m. Raw materials are added through feed chutes located in the roof of the vessel and gradually descend as they are consumed by heating and reactions occurring around the electrode tips. A diagram of a SAF can be seen in Figure 1 below.

The construction and operation of the SAF makes it almost impossible to observe or measure anything from the interior of the furnace. Simulation models that attempt to estimate the internal parameters of the SAF are therefore of great value to researchers and plant operators. The simplest models in use for industrial arcs are probably the Cassie-Mayr models (which are fully numerical) used in for example in References 2 and 3

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and in Reference 4. They are easy to implement and have a low computational cost but are not very accurate. Slightly more complex and accurate are channel arc models described in Reference 5, where the arc is implemented as a cylindrical conductor and the arc

characteristics are calculated based on power balances between electric input and various output losses. The most complete and complex are the magnetohydrodynamics (MHD) models. These models provide highly detailed and accurate results but are computationally formidable—some examples for direct current (DC) arcs are References 6 and 7, and for alternating current (AC) arcs.^[5,8,9]

In this paper, we will investigate the effect of the composition of the plasma gas present in the crater at the center of a silicon smelting furnace, Figure 2, on the transient electrical behavior of the arc. We start by verifying two independently developed MHD models by comparing them using three different plasma property data sets for Argon, in a geometry that corresponds to a known laboratory furnace for which experimental measurements are available. This allows us to assess the effect that different plasma property data sets have on the final results, and how well they fit the experimental data. We also simulate an industrial case using high current and two plasma property data sets for a 50/50 mixture of SiO and CO gas, again investigating the effect that different property data sets will have on large-scale arcs with the gas that is expected to be present in the crater region. Finally we simulate industrial arcs in plasmas generated from different mixtures of SiO and CO gas, and investigate how the arc conditions change as the crater gas becomes more CO- or SiO-rich.

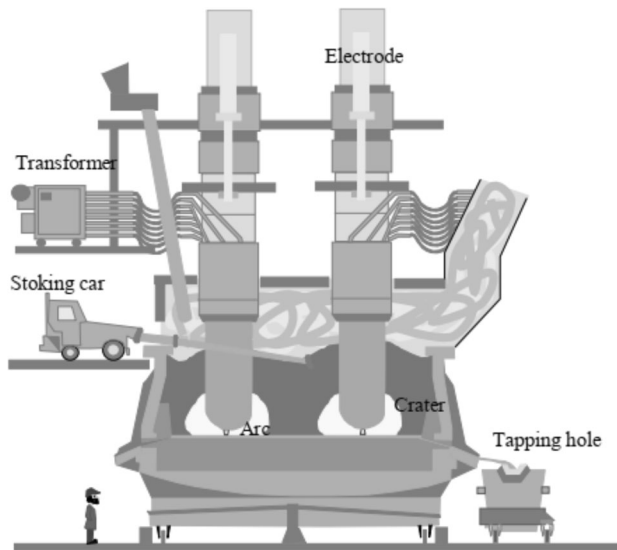


Fig. 1—A schematic drawing of a SAF in operation.

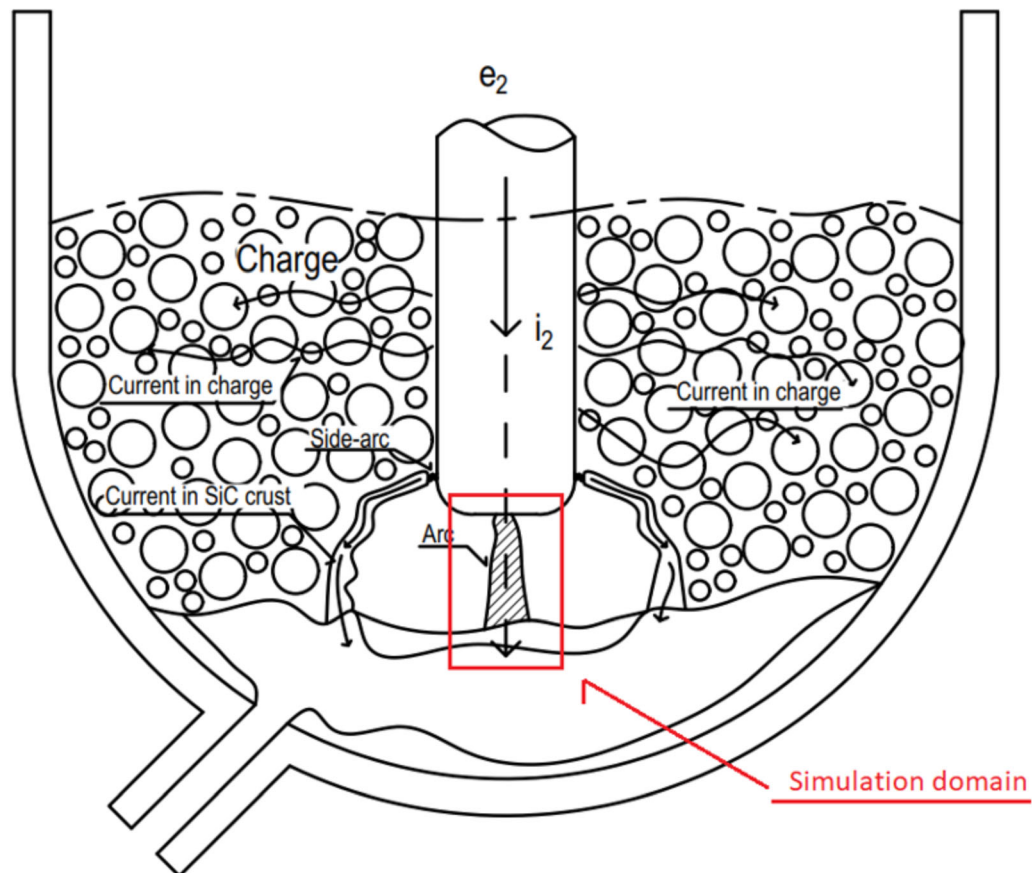


Fig. 2—The simulation domain for our MHD models is directly below the electrode in SAF.

II. PLASMA GAS COMPOSITION

One of the major challenges in simulation of arc furnaces is the lack of precise data on the compositions of the arc plasma gas. Additionally, there is a lack of thermodynamic and transport property data for this plasma gas, which is known to exist in the high-temperature regions of the arc. Argon is used as the plasma gas in many simulations and experiments due to its ease of use and comprehensive knowledge of its thermophysical properties. The main gases present inside an industrial furnace are SiO(g) and CO(g), and these can be in different ratios depending on conditions in the furnace interior.

For this paper, we have used different methods to estimate the plasma gas properties, and we will be studying the effect of different data sets on the overall simulation results. The plasma property data used as input for the simulations are the enthalpy h , density ρ , electric conductivity σ , thermal conductivity κ , and Specific heat C_p . First we compare three different data sets for Argon, and then we move to comparing two different sets for SiO + CO gas in half and half ratios. In the end we vary the ratios of SiO to CO from 0 to 100 pct in order to give an overview of how the properties change with different gas compositions.

A. Argon Properties

Here we have used two different calculation procedures to estimate the parameters for Argon, as well as previously tabulated data from calculations by Boulos *et al.*^[10] The benefit of using Argon for verification is

that its properties are well understood even at the temperatures present in an arc, and it is often used as a plasma gas in arc experiments which provide measured data for model validation. The three above mention data sets for Argon are surprisingly different but follow a similar trend, see Figure 3:

B. Industrial Furnace Gas Properties—50/50 Mixture

For the industrial case studies, a SiO + CO gas with an equimolar mixture ratio was chosen. This is the most likely composition of the gases present in the crater at optimal furnace operating conditions. The data sets conform for density, enthalpy, and electric conductivity but are fairly divergent for the rest except for specific heat at lower temperatures, see Figure 4:

C. Industrial Furnace Gas Properties—All Mixtures

Thermophysical property data for a range of plasma compositions from 0 to 100 pct SiO (the rest being made up of CO) were calculated to further investigate the effects of changing plasma composition on the industrial scale. In Figure 5, we can see how the enthalpy-temperature curves change as the SiO fraction is increased. The corresponding variation in the specific heat capacity curves is quite extreme, particularly at low to moderate temperatures, and this can be expected to have an appreciable impact on the thermal behavior of the arc. This discrepancy is likely due to how the two data sets are calculated, since atomic interaction is handled in a slightly different manner.

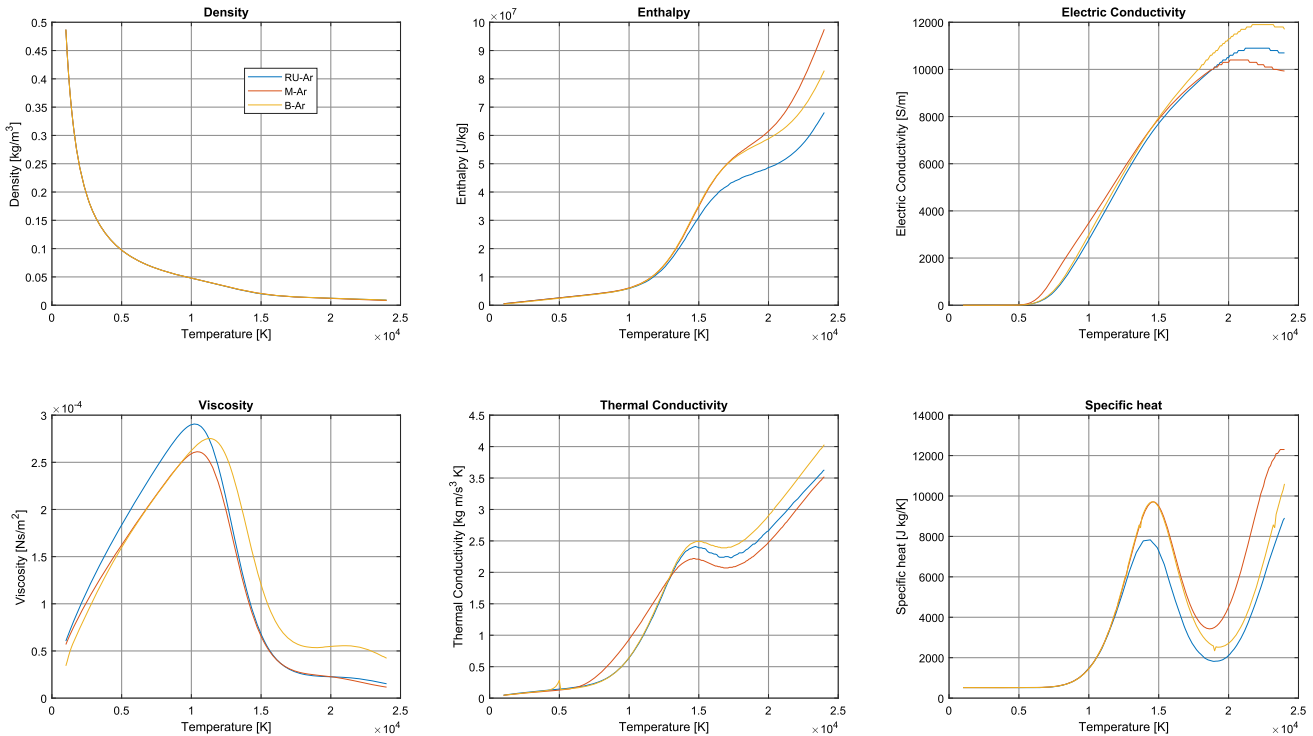


Fig. 3—Plasma properties for different argon plasma compositions. Blue is RU data, red is Mintek, and yellow is the Boulos (Color figure online).

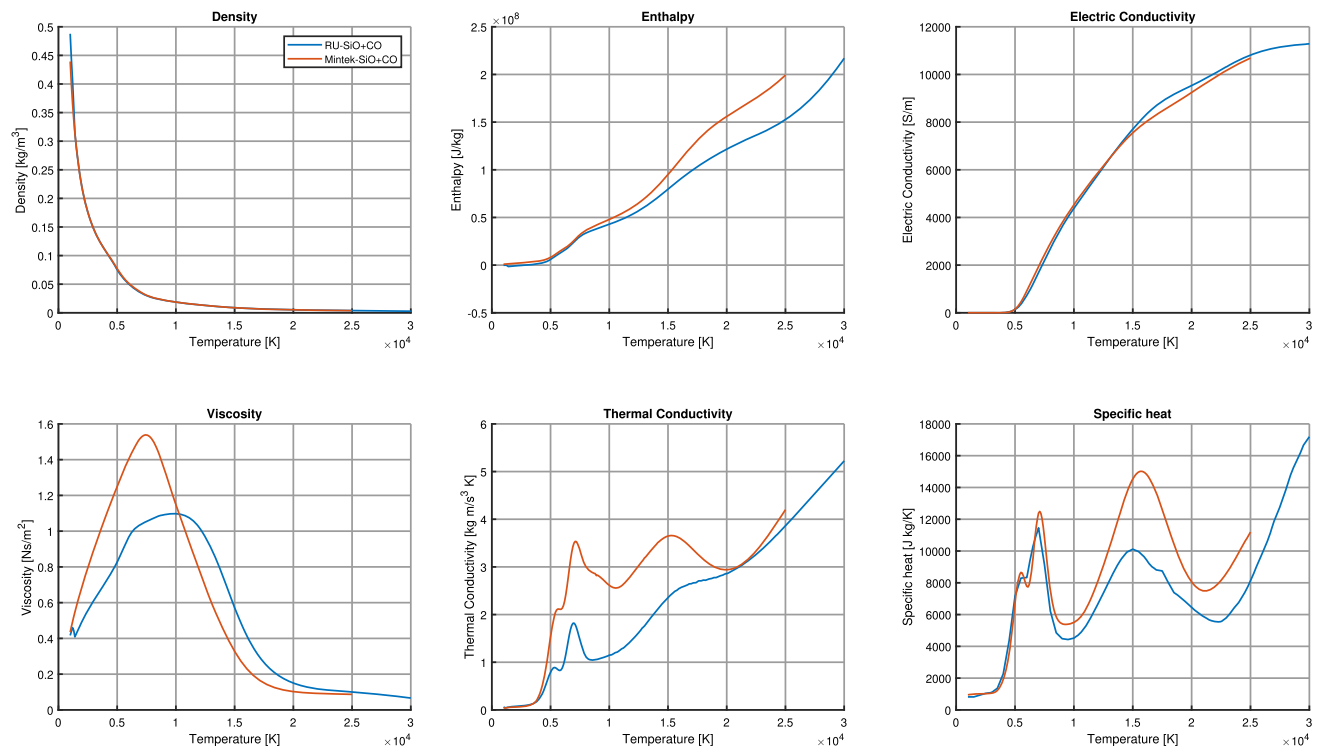


Fig. 4—Plasma properties for the industrial plasma compositions. Blue is RU data, red is Mintek (Color figure online).

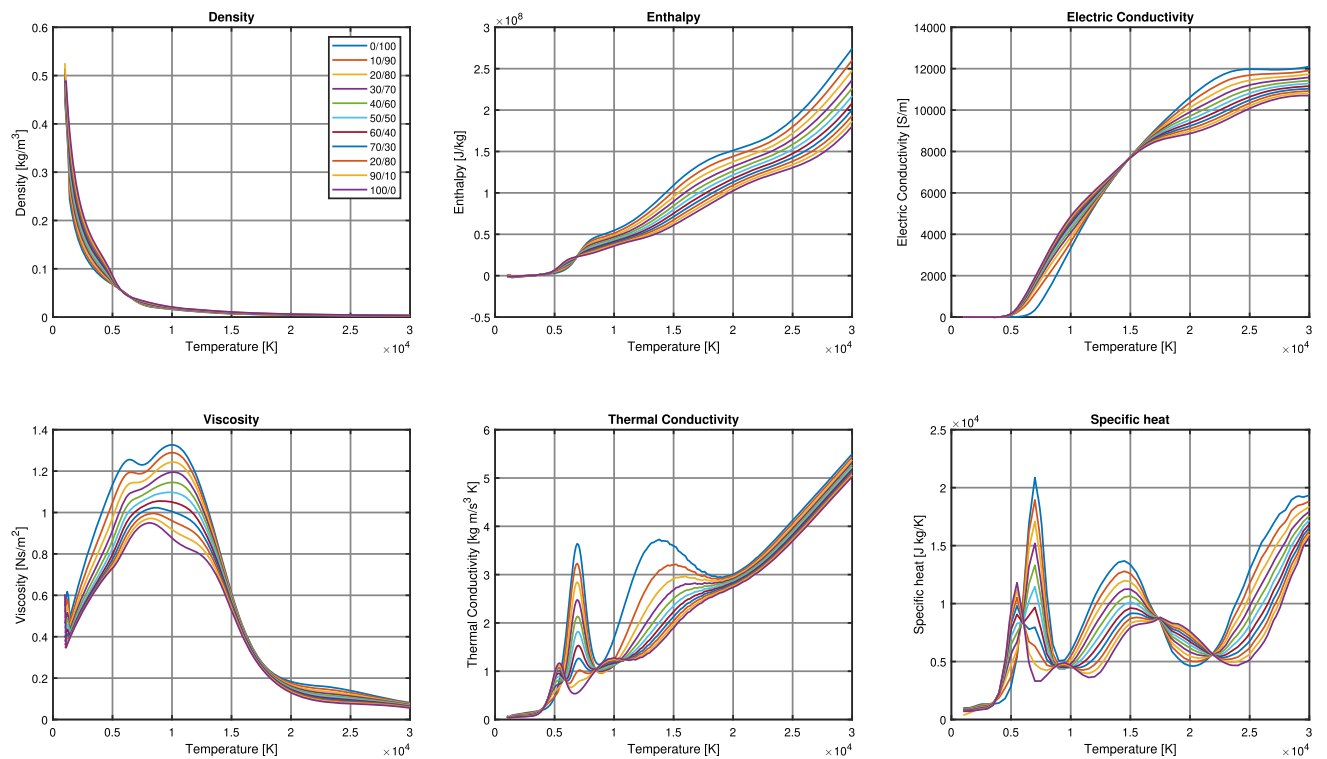


Fig. 5—Plasma properties for the different industrial plasma compositions from RU, here the ratio of SiO to CO varies from 0 to 100 pct.

III. MODEL DESCRIPTION

Detailed electric arc models are generally based on MHD, as this approach incorporates most of the relevant physics. To capture the momentum and heat transfer as well as the effect of the electromagnetic fields, Maxwell's equations are solved together with Navier-Stokes and energy conservation equations. This results in a total of seven coupled partial differential equations.

The electromagnetic fields are governed by Maxwell's equations:

$$\nabla \cdot D = q \quad [1]$$

$$\nabla \times H - \frac{dD}{dt} = j \quad [2]$$

$$\nabla \cdot B = 0 \quad [3]$$

$$\nabla \times E + \frac{dB}{dt} = 0 \quad [4]$$

where $D = \epsilon_0 E$ is the flux density, $H = B/\mu_0$ is the magnetic field density, ϵ_0 is the electric permittivity, q is the electric charge, j is the current density, and μ_0 is the vacuum magnetic permeability.

Fluid flow is described using the Navier-Stokes equations for momentum conservation, and the continuity equation for mass conservation:

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u \otimes u) + \nabla P = \mu \nabla^2 u + j \times B \quad [5]$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad [6]$$

Here ρ is the plasma density, u is the velocity field, P is the pressure field, μ is the viscosity, j is the electric current density, and B is the magnetic field.

Heat transfer is described by the energy conservation equation. We have added extra terms on the right hand side to include the effects of electric current on the energy. The second term on the right is the electron energy transport term and the third is the ohmic heating. As most of the thermophysical properties of plasmas are strongly temperature dependent, this couples the energy equation tightly to the other components in the model. The general equation is:

$$\begin{aligned} \frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho u h) = & \nabla \cdot \kappa \nabla T + \nabla \cdot \left(\frac{5k_B T j}{2q} \right) \\ & + \frac{j \cdot j}{\sigma} + Q_m - Q_R \end{aligned} \quad [7]$$

Here h is the enthalpy field, κ is the plasma thermal conductivity, σ is the plasma electrical conductivity, k_B is the Boltzmann constant, and Q_R is the radiation

energy loss term. Q_m includes all additional terms related to the mechanical contribution to the energy from compressibility effects.

Both models used in this paper aim to solve all of these equations, however, this is done in slightly different ways. In particular the model made by Reynolds^[11] solves Eqs. [1] through [4] using a semi-explicit approach based on current conservation, and also uses simplified boundary conditions for the electric potential which define a fixed arc orientation between the electrode and work surfaces.

A. New model implementation

In the present work, we have developed a new MHD model implementation in the OpenFOAM-v2012[®]^[12] open-source computational mechanics framework. We used a modified version of the standard rhoPimpleFoam solver as a base for our solver, given its existing capabilities for transient turbulent flow and heat transfer. A new MHD solver loop was added to the base code of the standard solver. For the implementation in OpenFOAM[®] simplifications for Eqs. [1] through [4] can be made by using the electric scalar potential ϕ and magnetic vector potential A :

$$\nabla \cdot j = 0 \quad \text{with} \quad j = -\sigma \left(\nabla \phi + \frac{\partial A}{\partial t} - u \times B \right) \quad [8]$$

$$\nabla^2 A = -\mu_0 j \quad \text{with} \quad B = \nabla \times A \quad [9]$$

With B and j , it is then possible to calculate the Lorentz force and the Ohmic heating source terms for the Navier-Stokes equation and the energy conservation equation. For each time step the electromagnetic calculation loop is iterated multiple times to increase the accuracy of the solution.

To account for the radiation heat transfer term we currently use OpenFOAM[®]'s built-in P1 radiation model. The main assumption of this model is that the directional dependence in the radiative transfer equation is integrated out, resulting in a diffusion equation for incident radiation. The model is described by:

$$\nabla^2(\Gamma, G) - aG = -4(e\sigma_{SB}T^4 + E) \quad [10]$$

where Γ is the diffusivity, G is the incident radiation intensity, a is the absorption coefficient, e is the emission coefficient, T is the temperature, σ_{SB} is the Stefan-Boltzmann constant, and E is the emission contribution. The emission and absorption coefficients have been tabulated for different temperatures and pressure which are then input into the radiation model.

This model could, however, be changed out due to the modular nature of the solver it is possible to implement more detailed radiation models in the future. With the modifications above, we have a new MHD solver for OpenFOAM[®] called mhdRhoPimpleFoam.

B. Boundary Conditions

In order to compare the two MHD solvers, we use the same conditions as described in Reference 11 with the exception of the electric potential ϕ . For this, we have created a new boundary condition for the MHD solvers which correctly identifies the surface that electrons are emitted from at any point in the AC cycle. As in previous work the electric potential boundary condition is based on the current density field on the emitting surface, which is set to the thermionic emission current j_k in computational cells where the temperature is the highest such that a specified total current is obtained. So, in cells where emission occurs, we have:

$$\frac{d\phi}{dn} = -\frac{j_k}{\sigma} \quad [11]$$

In the new boundary condition, the arc is reversed by switching the emitting surface between the electrode and the work surface in order to simulate the change in voltage polarity at different points in the AC cycle. Figure 6 shows the boundary conditions for ϕ :

C. Modeling Domain

In order to compare the solvers and plasma data sets, simulations are run on two different geometries. The first replicates the Argon pilot furnace used for the experiments described in Reference 13 (Figure 7).

The second case is a representative geometry for an industrial-scale arc, and is constructed in such a way that it simulates part of the arc cavity in a submerged arc furnace. The upper boundary is the electrode material, the lower boundary is the work surface representing the silicon metal bath, and the sides are pressure boundaries open to inflow and outflow. Figure 2 shows which part of the cavity is being simulated.

The industrial case geometry is a cylinder with a height of 7 cm and a total radius of 30 cm. The domain height was chosen to represent a typical arc length for an operating furnace.^[5,14] A 5×5 cm central area has a smaller mesh size to increase simulation accuracy in the arc area. In this region the dimensions of the boundary elements are $1.43 \times 1.43 \times 0.35$ mm, with the element height gradually increasing closer to the middle of the domain. This is important due to the rapid spatial and temporal changes in the temperature field in and around the arc column during the simulation. The mesh inflation layers near the upper and lower boundaries permit better evaluation of local variations in the magnetic vector potential A in the electromagnetic field solution (Figure 8).

IV. MODELING RESULTS

A. Verification and Validation Between Solvers for Argon Experiments

As discussed earlier, experimental data from laboratory furnace experiments were used to verify and cross-validate our models. We compared measurement data from Reference 5 obtained from the pilot furnace experiment described in Reference 13 to simulations conducted with the two MHD models and the three Argon plasma property data sets. We observed minimal differences between the two solvers, but there was some significant variance between the different data sets. The results are shown in Figure 9 below. The measurements from the actual furnace show somewhat more chaotic behavior than all the simulations, but a similar trend can easily be observed. We can therefore say that the solvers are working as desired and conform acceptably well to measurements and to each other for this known case.

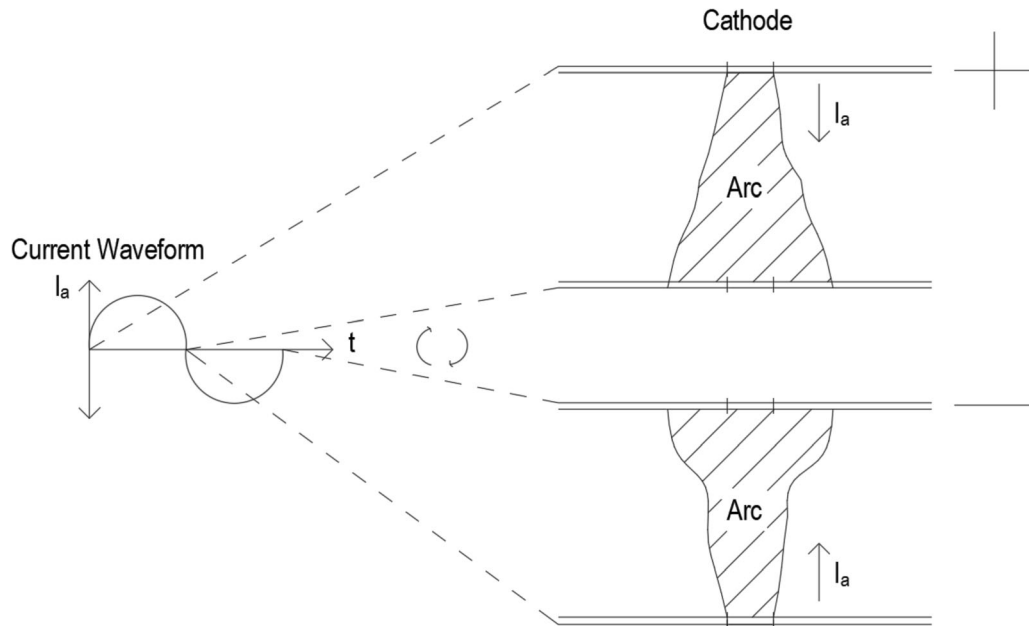


Fig. 6—The arc changes direction using the new boundary conditions for the voltage potential Φ .

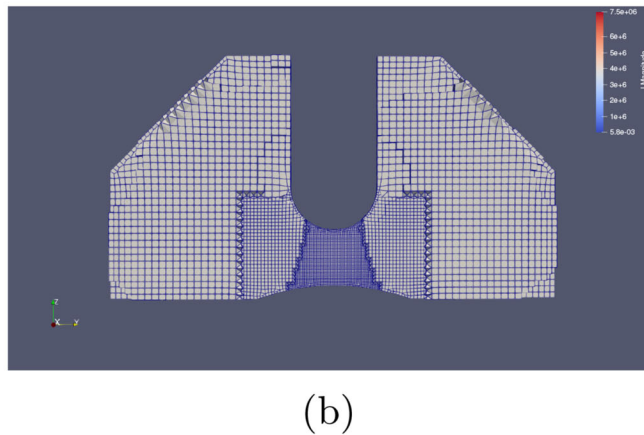
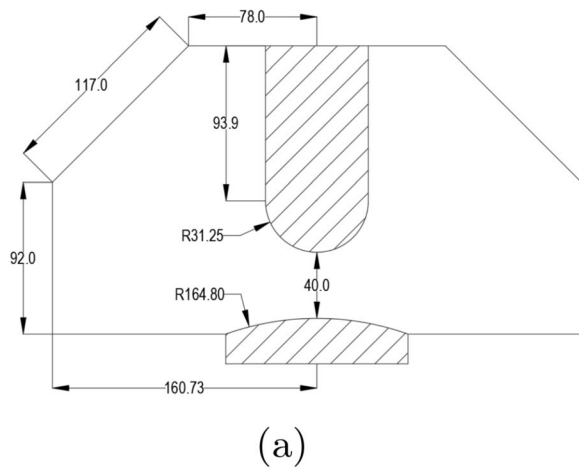


Fig. 7—(a) The argon furnace geometry in mm, (b) The mesh of the argon furnace.

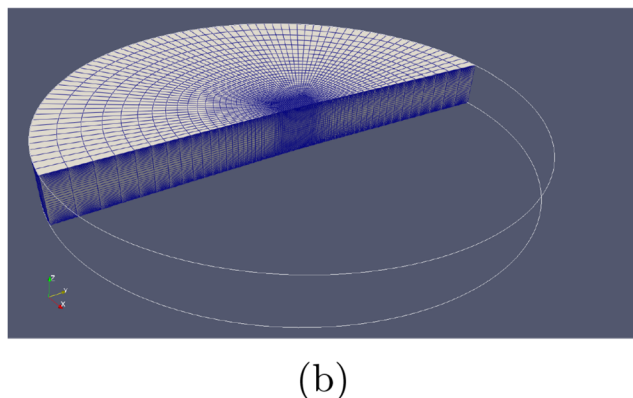
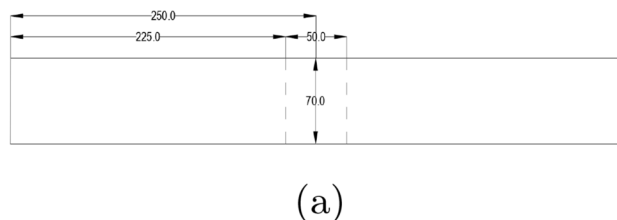


Fig. 8—(a) The Industrial furnace geometry in mm, (b) A visual representation of the mesh used in the simulation of the industrial case.

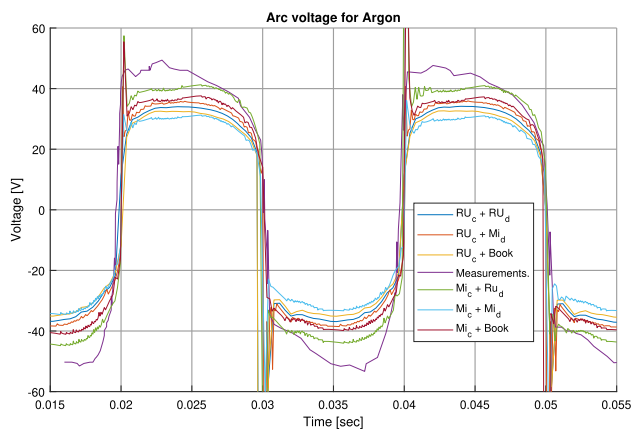


Fig. 9—Arc voltage of the three different argon plasma data sets, run with both solvers. Measurements data is plotted in purple (Color figure online).

We can, however, see that the different data sets give slightly differing results. The voltage varies from around 40 to 30 V for different data sets, or approximately 25 pct.

This difference can be attributed in part to the substantial deviations in calculated electrical conductivity of Argon plasma between 5000 and 10000 K which can be seen in Reference 3. This temperature range is very significant for the bulk of the conducting volume of the arc, and changes in plasma properties here can have a disproportionate effect on the macroscopic electrical behavior.

B. Mesh Dependence for the Industrial Case

The simulations for the industrial case were observed to have a large amount of noise during the transition from zero to top current. A simple mesh dependence study was performed to check if this was due to numerical or physical issues. We both reduced and increased the mesh element size from 2 to 1.1 mm, respectively, to see if that would be a noticeable change in the behavior of the noise as well as the final result. Figure 10 show the results for the mesh study and we can see that the noise appears to be dependent on mesh resolution, but the final values of the arc voltage vary only a little.

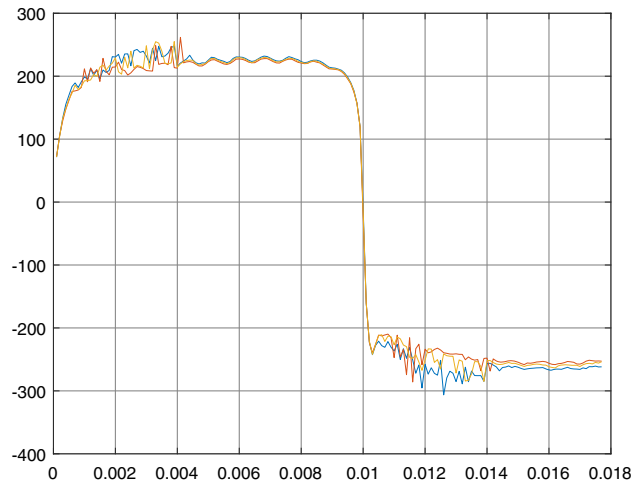


Fig. 10—Arc voltage of the three different mesh densities. The noise seems to be dependent on the mesh not the physical parameters and the final result changes little between meshes.

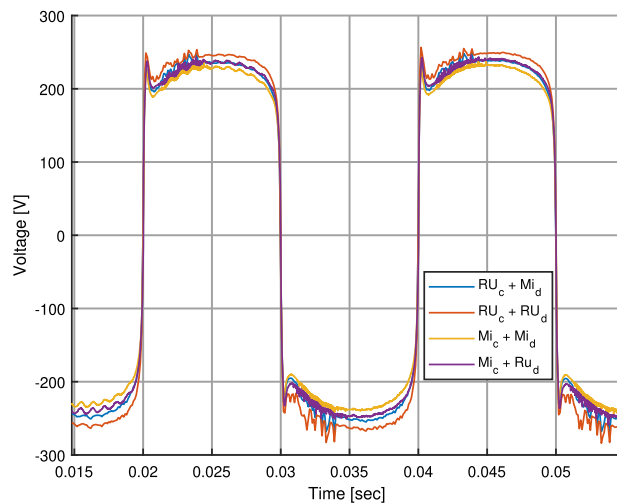
C. Verification Between Solvers for Industrial Case

With this set of cases, the aim was to test if the different solvers produce similar results at higher currents representative of industrial-scale operation. The most likely plasma composition, a 50 pct mix of SiO and CO, was used. The current has an amplitude of 50 kA, and for the boundary condition of ϕ we use the current density $j_k = 2.0 \times 10^7 \text{ A/m}^2$. We can see on Figure 11 the arc voltage for both solvers and both data sets. We observed a good fit between the solvers and the data but with small differences, somewhat less than for the previous argon case. The Mintek plasma property data gives a slightly lower voltage than the RU one, and

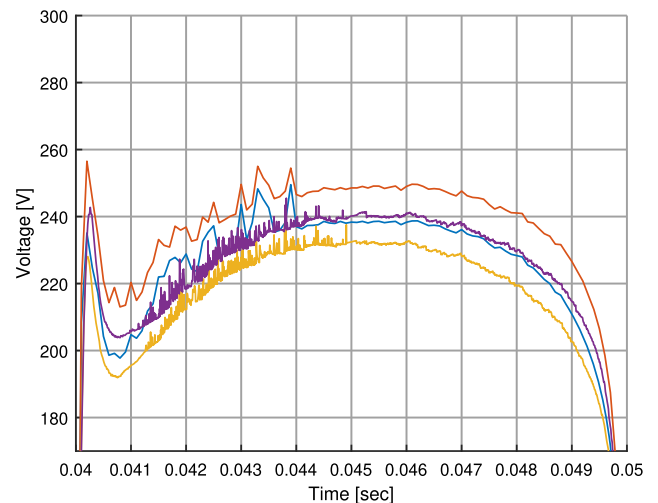
similarly for the solvers. When the RU solver is running on Mintek data and vice versa, the models produce similar results. The voltage is higher than expected from industrial silicon smelting operations, but it is likely that this is due to the oversimplified cathode boundary condition being used here; implementation of a physically realistic cathode model as seen in Reference 15 may improve matters. The simplicity of the radiation model used is also likely to be a contributing factor, as this may be exaggerating energy losses from the arc column resulting in a cooler and less conductive plasma.

D. Effect of Plasma Composition in Industrial Case

In this set of tests the aim was to investigate how the arc voltage in the industrial case would change with different plasma compositions. As mentioned above we varied the composition from 0 to 100 pct SiO in the SiO–CO mixture to get an indication of how the corresponding arc voltage would change; this could then be used to estimate changes in furnace conditions in a real furnace. The resulting arc voltages are shown in Figure 12. We can see that the voltage changes from approximately 263 to 240 V. This is a small variation of only roughly 8 pct—we can therefore say that changes in the composition of the arc plasma will not significantly impact the voltage in a operating silicon SAF unless the furnace transformer is constrained at or near its current or voltage limits. It is also interesting to observe that the voltage increases only when relatively low fractions of SiO are present in the arc plasma. These composition ranges are, however, not likely to occur in a live furnace. This suggests that increased furnace resistance may be more strongly correlated with upsets in the metallurgical process rather than normal operation.

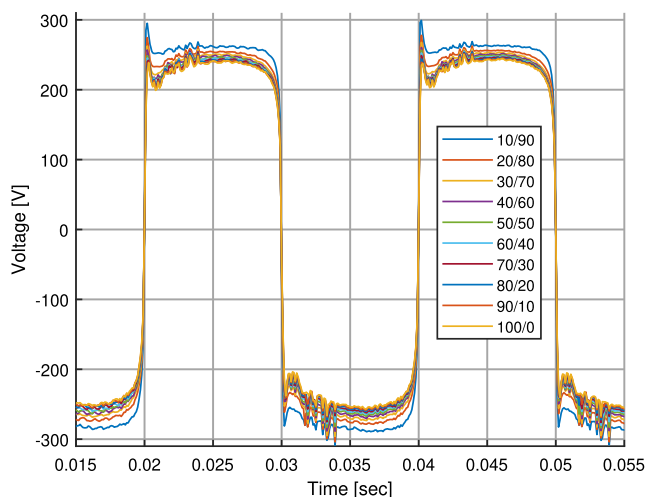


(a)

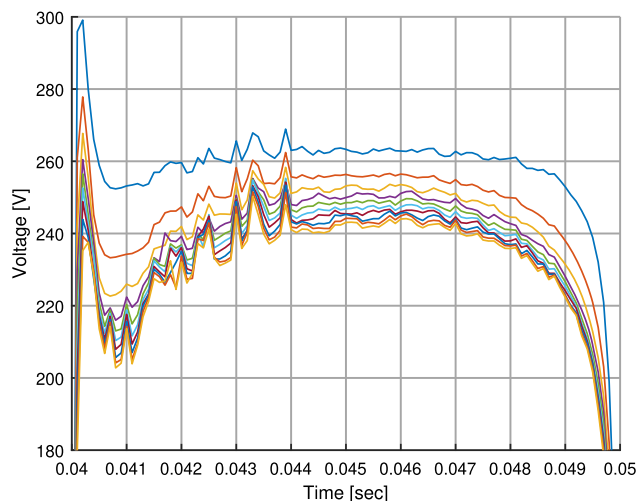


(b)

Fig. 11—Arc voltage for the industrial case where the SiO to CO ratio is 50/50. Here both solvers are used and both data sets for the plasma. (a) shows the larger waveform and (b) Zooms in on one of the tops.



(a)



(b)

Fig. 12—Arc voltage of the ten different SiO / CO ratios of plasma data sets, run with the RU solver. (a) shows the larger waveform and (b) zooms in on one of the tops.

V. CONCLUSION

We investigated the effect of changing compositions on the plasma gas present in a silicon submerged arc furnace using a selection of different plasma property data sets and MHD models. We have validated the models using a known geometry of an Argon furnace for which measurement data was available, we use three different data sets for argon gas for this purpose. All model and data set combinations gave qualitatively acceptable results for the argon furnace geometry, although some differences in predicted voltage were observed. This is most likely due to discrepancies in the Argon plasma electrical conductivity between data sets.

To test the models at industrial current levels we used a 50/50 mixtures of SiO and CO plasma gas, and compared the results obtained from various combinations of MHD models and plasma property data sets. The results were found to be acceptably close to each other, although we did observe the voltages to be somewhat high compared to what we would expect from real furnace operations. This is likely due to lack of detail in the modeling used, in particular the simplified thermal radiation sub-model or the arc might be too long.

Finally, the models were used to study how different mixtures of the two gases in the furnace can impact the electrical behavior of the arc. A variation of 8 pct in the peak voltage was observed, with CO-rich compositions producing more resistive arcs with higher voltages.

Some problems were encountered with the models, especially related to the formulation of the cathode boundary conditions and the radiation sub-models. Inconsistencies in the plasma data sets were also observed, and can produce significant differences in the end results. These issues will need to be given attention in future work, but overall the two MHD

models tested were seen to be acceptably consistent and accurate for simulating arcs in industrial processes. We also have an improved understanding of the importance of input parameters when simulating electric arcs, and that care is needed when choosing plasma property data sets for such high temperatures.

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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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REFERENCES

1. M. Tangstad, L. Kolbeinsen: Metal Production in Norway. Akademika Publishing. OCLC: 866576889, 2013.
2. A. Alzate, J. Durango, A. Mejia: in: 2010 IEEE ANDESCON, pp. 1–6, 2010. <https://doi.org/10.1109/ANDESCON.2010.5629655>.
3. S. Golestani, H. Samet: *IET Gener. Trans. Distrib.* vol. 10 (13), pp. 3364–73, 2016. <https://doi.org/10.1049/iet-gtd.2016.0405>.
4. H. Haraldsson, Y.A. Tesfahunegn, M. Tangstad, G. Sævarsdottir: *SSRN J.*, 2021. <https://doi.org/10.2139/ssrn.3927158>.
5. G. Sævarsdottir, H. Larsen, J. Bakken: *Int. Quart. High-Technol. Plasma Processes*, 1999, vol. 3, pp. 1–15. <https://doi.org/10.1615/HighTempMatProc.v3.i1.10>.
6. Q.G. Reynolds: *JOM: J. Miner. Metals Mater. Soc.*, 2017, vol. 69 (2), pp. 351–57. <https://doi.org/10.1007/s11837-016-2166-9>.
7. A.D. Rocca, Q.G. Reynolds: large-eddy simulations of electric arcs at industrial scale, 2019. <https://doi.org/10.13140/RG.2.2.24803.71209>.
8. J.A. Bakken, L. Gu, H.L. Larsen, V.G. Sevastyanenko: *J. Eng. Phys. Thermophys.*, 1997, vol. 70 (4), pp. 530–43. <https://doi.org/10.1007/BF02663569>.
9. G. Sævarsdottir, J. Bakken, V.G. Sevastyanenko, L. Gu: *High Temp. Mater. Processes*, 2011, vol. 15, pp. 205–25. <https://doi.org/10.1615/HighTempMatProc.v15.i3.40>.
10. S. Documentation: MathWorks, 2020. <https://www.mathworks.com/products/simulink.html>.
11. Q.G. Reynolds: in: *Proceedings of the 14th International Conference on CFD in Oil & Gas, Metallurgical and Process Industries*, pp. 99–106, 2007.
12. OpenFOAM. <https://www.openfoam.com/> Accessed 22 April 2024.
13. H.L. Larsen, G. Liping, J.A. Bakken, J.K. Tuset, I.G. Page, H. Tveit: in *International Ferroalloys Congress: 7th, Norwegian Ferroalloy Research Organization*. Backup Publisher: Norwegian Ferroalloy Industry, pp. 517–528, 1995. <https://www.tib.eu/de/suchen/id/BLCP>.
14. G. Sævarsdottir, T. Magnusson, J.A. Bakken: Electric arc on a coke bed in a submerged arc furnace, 2007. <https://api.semanticscholar.org/CorpusID:224792531>.
15. G. Sævarsdottir, M.T. Jonsson, J. Bakken: in: *16th International Symposium on Plasma Chemistry*, 2003.

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