MHD instability at the cathode spot as the origin of the vortex formation in high-intensity plasma arcs

Hadi Barati\textsuperscript{1}, Abdellah Kharicha\textsuperscript{1}, Mohamad Al-Nasser\textsuperscript{1}, Daniel Kreuzer\textsuperscript{2}, Gernot Hackl\textsuperscript{2}, Markus Gruber\textsuperscript{3}, Anton Ishmurzin\textsuperscript{4}, Christian Redl\textsuperscript{5}, Igor O Teplyakov\textsuperscript{6} and Andreas Ludwig\textsuperscript{6}

\textsuperscript{1} Christian Doppler Laboratory for Metallurgical Applications of Magnetohydrodynamics, Franz-Josef Street 18, 8700 Leoben, Austria
\textsuperscript{2} RHI Magnesita, Kranichberggasse 6, 1120 Vienna, Austria
\textsuperscript{3} RHI Magnesita, Department of Modelling and Simulation, Magnezitstrasse 2, 8700 Leoben, Austria
\textsuperscript{4} INTECO melting and casting technologies GmbH, Wienerstrasse 25, 8600 Bruck a.d. Mur, Austria
\textsuperscript{5} Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
\textsuperscript{6} Chair for Modeling and Simulation of Metallurgical Processes, Department of Metallurgy, Montanuniversitaet Leoben, Franz-Josef Street 18, 8700 Leoben, Austria

E-mail: abdellah.kharicha@unileoben.ac.at

Keywords: sausage pinch, Z-pinch instability, cathode spot, electric arc furnace, magnetohydrodynamics, plasma arc, CFD

Abstract

Magnetohydrodynamic instability in a high-intensity arc, similar to typical arcs in DC electric arc furnaces, is simulated using an induction based model under 2D axisymmetric conditions. Time-averaged results show a good agreement with steady-state calculated results expected for a stable arc. The transient results declare that z-pinch close to the cathode, occurring due to the high electrical current density, is responsible for arc instability in this region. The unstable behavior of the arc can be evaluated in a periodic procedure. Moreover, correlations between the fluctuations in total voltage drop curve and the arc shape are investigated: when the arc is in form of column (or bell) the total voltage drop is on a minimum peak; if there is an irregular expansion of the arc in form of arms, the total voltage drop shows a maximum peak.

1. Introduction

Plasma arcs are widely used in various metallurgical applications like cutting\cite{1}, welding\cite{2}, and melting\cite{3} materials. In welding, the applied current is up to few hundred amperes and the flow is usually laminar (typically few hundred meters per second). In melting technologies, electric current in the arc is in the range of a few kA up to 200 kA. Correspondingly, the flow velocity would be larger than thousand meters per second\cite{4}. In an electric arc furnace (EAF), an electric arc is used to melt various raw and scrap materials. Generally, there are two types of EAF according to the type of electric current: AC-EAF and DC-EAF. In AC-EAF, the electric current is applied between the electrodes; in DC-EAF, the electrical current flows through the bulk of slag and metal to reach the bottom boundary.

Experimental measurements on free-burning argon arc has been conducted\cite{5}, this enabled accurate modeling of the arc (up to hundreds of amperes) in addition cathode and anode regions\cite{6,7}. However, the experimental study of the arc in a real EAF is too difficult due to the high temperature and fast nature of the arc. Therefore, numerical modeling provides a helpful tool to study the behavior of the arc during the process. Two types of methods are available to simulate the arc in EAF: averaged and detailed. In an averaged method, also called Channel Arc Model (CAM), the arc is considered as a fixed cylindrical channel with constant boundary conditions including inlet and outlet for gas and heat transfer on the circumferential area\cite{8}. In this method, details of the arc motion are missing but a large computational domain can be considered in the simulation. In a detailed method, the arc is simulated in terms of space and time\cite{9-15}. Hence, the detailed dynamic behavior of the arc can be studied. However, it applies to a small domain around the arc. In the current paper, we focus on the detailed simulation of a DC arc in an EAF.
In general, the presence of the magnetic field in the turbulent flow of an electrically conducting fluid leads to damping of turbulence, like an applied magnetic field in steel continuous casting [14, 16]. However, in the arc of EAF, arc’s own magnetic field is too weak to influence the turbulence of the high-speed fluid [15, 17].

High-intensity arcs are usually unstable in direction and form. The source of the arc instabilities can be external (e.g. magnetic field due to the external electrical circuit outside of the arc) or internal. Arc instabilities can be also categorized into magnetic or hydrodynamic. Magnetic instabilities appear due to the interactions of electromagnetic and flow fields. An example of magnetic instabilities is kink instability which forms by bending the plasma column due to the local Lorentz force [16, 18]. A schematic illustration of link instability is shown in figure 1(a). Another magnetic instability is sausage instability which happens when radial Lorentz force leads to a local contraction of the arc column [16, 18], as shown in figure 1(b). Kelvin–Helmholz instability, shown in figure 1(c), is a kind of hydrodynamic instabilities [17–20]. This instability is a consequence of high-velocity shear on the interface of the arc column and surrounding gas. Helical instability is another hydrodynamic instability leading to a 3D spring form of the arc [19, 21], shown in figure 1(d). Reynolds [12] observed the mentioned instabilities by a high-speed photographing of a pilot-scale DC arc (3 kA). Bowman [17] concluded that helical instability is a spontaneous once the current exceeds 400 A which may emerge from cathode vapor or and aerodynamic instability similar to nozzle jet.

In the current paper, a new transient induction based equation set is developed to calculate electromagnetic variables based on the axisymmetric assumption. Moreover, z-pinch instability of a high-intensity arc, similar to that in a real size DC-EAF, is simulated and investigated. The objective of this paper is to find the origin of the arc instabilities especially close to the cathode.

Figure 1. Schematics of arc magnetic instabilities: (a) kink and (b) sausage, and hydrodynamic instabilities: (c) Kelvin–Helmholtz and (d) helical.
2. Modeling

To model the dynamic behavior of the arc, the arc is treated as a gas. The temperature of the gas defines the presence of the arc. If the gas temperature is high enough, the electric current can pass through it. The main assumptions of the current 2D model are listed below.

- The arc is axisymmetric.
- The gas is only made of air.
- The arc is in local thermal equilibrium (LTE), i.e. the electron and heavy-particle temperatures are very similar.
- The physical properties of the gas depend only on temperature.
- The cathode and anode surfaces are supposed to be flat.
- Compressibility effects are neglected.
- There is no absorption inside the arc.

2.1. Governing equations

Conservation equations of mass and momentum, in 2D cylindrical coordinates, describe the flow of the gas.

\[
\frac{1}{r} \frac{\partial (\rho u_r)}{\partial r} + \frac{\partial (\rho u_z)}{\partial z} = 0,
\]

\[
\frac{\partial (\rho u_r)}{\partial t} + \frac{\partial (\rho u_r u_r)}{\partial r} + \frac{\partial (\rho u_r u_z)}{\partial z} = -\frac{\partial P}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{2\partial u_r}{\partial r} - \frac{2}{3} (\nabla \cdot \vec{u}) \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{2\partial u_z}{\partial z} \right) + E_z,
\]

\[
\frac{\partial (\rho u_z)}{\partial t} + \frac{\partial (\rho u_r u_z)}{\partial r} + \frac{\partial (\rho u_z u_z)}{\partial z} = -\frac{\partial P}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{2\partial u_z}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{2\partial u_r}{\partial r} \right) + E_r,
\]

where \( \rho \) is the density of fluid; \( \vec{u} \) is the fluid velocity; \( t \) is the time; \( p \) is the static pressure; \( \mu_{eff} \) is effective viscosity. In equations (2) and (3), the last term on the right-hand side represents Lorentz force which is the driving force of the arc motion: \( E_r = j_r B_0 \) and \( E_z = j_z B_0 \).

To model the turbulent flow, the standard k-\( \varepsilon \) model is adopted to calculate the turbulence kinetic energy and its dissipation rate.

\[
\rho \frac{\partial k}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_{eff} \frac{\partial k}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\mu_{eff} \partial k}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{\partial \varepsilon}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\mu_{eff} \partial \varepsilon}{\partial z} \right) + G - \rho \varepsilon,
\]

\[
\rho \frac{\partial \varepsilon}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_{eff} \varepsilon \right) + \frac{\partial}{\partial z} \left( \frac{\mu_{eff} \varepsilon}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left( \mu_{eff} \frac{\varepsilon}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\mu_{eff} \varepsilon}{\partial z} \right) + \frac{G}{k} (C_k - C_{2\varepsilon}) \varepsilon.
\]

Conservation equation of thermal energy may be expressed as

\[
\frac{\partial h}{\partial t} + \frac{1}{r} \frac{\partial (\rho h u_r)}{\partial r} + \frac{\partial (\rho h u_z)}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left( \Gamma_h \frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z} \left( \Gamma_h \frac{\partial h}{\partial z} \right) + \frac{J_r^2 + J_z^2}{\sigma_{\varepsilon}} - S_R
\]

\[
+ \frac{\partial}{\partial r} \left( \frac{J_r}{C_p} \frac{\partial h}{\partial r} + \frac{J_z}{C_p} \frac{\partial h}{\partial z} \right)
\]

where the last three terms on the right-hand side are source terms representing Joule heating, radiation heat loss, and the transport source term of enthalpy due to electron drift (Thompson effect), respectively.

To calculate electromagnetic variables, i.e. magnetic field \( B \) and electric current density \( j \), instead of using potential method, induction method is employed. In potential method, electrical potential \( \phi \) is solved as the main variable. Then, \( J \) and \( \vec{B} \) are achieved according to the generalized Ohm’s law \( \vec{j} = \sigma (-\nabla \varphi - \vec{u} \times \vec{B}) \) and Ampere’s law \( B_0 = \frac{\mu_0}{r} \int_0^r j_r rdr \), respectively. This method is more accurate than the induction method but it is much slower due to the numerical integration to find \( B_0 \).
In induction method, based on 2D axisymmetric assumption, $q_B$ is calculated directly using the following equation:

$$
q_B = \frac{k_{mag}}{2\pi r}, \text{ if } r < R_{\text{cathode}} \\
q_B = \frac{k_{mag}}{2\pi r}, \text{ if } r > R_{\text{cathode}}.
$$

Then, $J$ is obtained by

$$
J = -\frac{1}{\mu_0} \frac{\partial q_B}{\partial z}, \quad J_z = \frac{1}{\mu_0 r} \frac{\partial (r q_B)}{\partial r}.
$$

### 2.2. Simulation settings

Figure 2 shows the computational domain and its dimensions. It is assumed that cathode spot radius, $R_{\text{cathode}} = \sqrt{\frac{I_0}{\pi}}$, is fixed during the process. $J_c$ is the average current density in the cathode spot supposed to be $4.4 \times 10^7$ A m$^{-2}$ and $I_0$ is the imposed current which is equal to 40 kA.

The boundary conditions are listed in Table 1. Electrode and melt bath surfaces work as walls with constant temperatures. The temperature of the electrode is set to 4000 K based on the evaporation temperature of the graphite (material of the electrode) and the temperature of the melt bath surface is 1800 K, the typical temperature of steel melts in EAF. Open air means boundaries are exposed to atmospheric pressure. Boundary conditions of $q_B$ are determined based on equation (8) explaining Ampere’s Law. Accordingly, at cathode spot $J_z = \frac{k_{mag}}{2\pi r}$, at anode $J_z = 0$, and at open air $J_z = \frac{k_{mag}}{2\pi r}$. It is assumed that cathode or anode material has much more electrical conductivity than the plasma at immediate vicinity of the electrodes.

Arc is treated as a gas with temperature-dependent properties; the gas is air. These properties including density, specific heat, thermal conductivity, viscosity, and electrical conductivity are plotted as functions of temperature in figure 3(a). The values for temperature larger than 30000 K are extrapolated. The radiation heat loss, defined as a source term in equation (6), is taken from experimental measurements [20, 22] for air at 1 atm pressure. The heat loss value as a function of temperature is also shown in figure 3(b).

| Boundary       | $B_{th}$                        | Thermal energy Flow |
|----------------|---------------------------------|---------------------|
| Electrode      | $B_{th} = \frac{k_{mag}}{2\pi r}$, if $r < R_{\text{cathode}}$ | $T = 4000$ K $u_r = u_0 = 0$ |
|                | $B_{th} = \frac{k_{mag}}{2\pi r}$, if $r > R_{\text{cathode}}$ |                     |
| Open air       | $B_{th} = \frac{h_0}{2\pi r}$   | $\frac{\partial h}{\partial r} = 0$ $p = 1$ atm |
| Melt bath surface | $\frac{\partial h}{\partial r} = 0$ | $T = 1800$ K $u_r = u_0 = 0$ |
| Symmetry axis  | $B_{th} = \frac{h_0}{2\pi r}$   | $\frac{\partial h}{\partial r} = 0$ $\frac{\partial h_0}{\partial z} = 0$ |

Figure 2. Computational domain and its dimensions with a schematic presentation of the arc.

Table 1. List of boundary conditions.
The governing equations are solved using commercial CFD code ANSYS-FLUENT 14.5 with extended user-defined functions (UDFs) to calculate electromagnetic variables. Due to the high speed of gas inside the arc, a very small time step ($10^{-7}$ s) is considered in the simulation.

3. Results and discussion

In figure 4(a), the transient behavior of the arc is shown by several snapshots of the simulation results. The time-averaged data over 6 ms is plotted in figure 4(b). The time-averaged results show a stable arc with column shape; the column diameter expands a little close to the anode; the flow is a downward jet; the gas enters the arc column through a small area close to the cathode and exits at the bottom when it hits the anode. This is similar to the classically defined picture of an arc in EAF [9]. However, transient results in figure 4(a) indicate that the arc is very unstable during the time. The temperature distribution and flow patterns change frequently. A small vortex forms close to the cathode and disappears quickly ($t = 0.21–0.51$ ms). The small vortex may also survive and expands, then goes downwards and disappears when it reaches the anode ($t = 0.57–0.90$ ms). This procedure repeats frequently during the process.

Time-averaged temperature and magnetic field are compared with those of steady state simulation by Alexis et al [9], shown in figure 5. It should be mentioned that in their work potential method is used while induction method is employed here. Figure 5 shows that the time-averaged results of the current simulation match those of steady-state potential method. Therefore, one can conclude that the developed induction method can reproduce the results of the potential method properly.
The results in a zoomed view of the area close to the cathode with short time intervals (0.02 ms) are illustrated in figures 6 and 7 to have a better understanding of how instabilities initiate and extend. In figure 6, temperature and velocity vectors are plotted and in figure 7, vectors of current density and Lorentz force are shown.

It shows that in a stable condition (like \(t = 0.39\) ms), within the arc, there are a small vortex below the electrode and a long vertical jet in the center of the arc column towards the anode. Electric current density vectors come from the anode and go with the largest magnitude into the cathode spot. Since current density vectors are mostly vertical and magnetic field is only in \(\theta\) direction, the Lorentz force should be horizontal towards the axis. The pinch effect results in the formation of a neck close to the cathode. The pinch effect appears because of the very high current density at the cathode spot. The Lorentz force wants to pinch the arc column.
more and more. Hence, the small vortex is shot downward \((t = 0.43)\). The narrower neck results in the larger Lorentz force since both the current density and magnetic field increase. However, the plasma pressure is against the pinching. Therefore the neck expands and returns to a stable condition \((t = 0.45)\). This procedure leads to the periodic formation and disappearing of vortices in the region close to the cathode. As can be seen in \(t = 0.45–0.49\) ms, the small vortex is pinched and pushed downwards again. It should be mentioned that all main variables (i.e. temperature, velocity, magnetic field, current density, Lorentz force) are highly coupled with each other. Therefore, when a small instability initiates, it propagates very quickly. One can conclude that the periodic pinching is the origin of the arc instabilities at the cathode. However, Kelvin–Helmholtz instabilities may be observed in the lower region of the arc because of the velocity shear on the cathode interface.

The periodic instabilities of the arc can be demonstrated by measuring the total voltage drop between cathode and anode during the process. Fluctuations in the total voltage drop represent the instabilities of the arc. The total voltage drop is calculated by

\[
\Delta \varphi = \frac{1}{I_0} \sum \frac{J_x^2 + J_y^2}{\sigma} \Delta V.
\]  

In this equation, it is assumed that the total voltage drop is completely converted to Joule heating. In figure 8, the fluctuation in the total voltage drop during 6 ms of the process is plotted. In this figure, some peaks in the curve are selected; the related detailed information of the arc at the selected peaks is shown on the right-hand side. The solid line on the right-hand side represents \(T = 10000\) K, which is supposed to be the border of the arc.
comparison of the curve and arc shapes shows that when the arc has a column shape (or bell shape), the total voltage drop is on a minimum peak. In other words, the electrical conductivity of the arc is very high. When the arc expands locally and forms arms, electrical current can go through these arms. Therefore, the total electrical conductivity of the arc decreases to a minimum level and a maximum peak is observed in the total voltage drop curve.

In figure 9, the radius of arc cross section at the half distance between cathode and anode ($z = 0.125$ m) during the process is plotted. The arc border is assumed to be $T = 10000$ K. The fluctuations of the arc cross section are very similar to those of the total voltage drop, shown in figure 8, but in opposite way. A maximum peak in voltage drop graph is correlated to a minimum peak of cross section graph. Figures 8 and 9 explain the unstable arc regime in high-intensity plasma arc like what happens in DC-EAF.

The results demonstrate that the developed model can predict the instabilities of the arc in detail properly; the origin of arc instability close to the cathode is discussed; the role of the arc shape on total voltage drop can be explained; the effects of various operating parameters (e.g. arc length, imposed current, etc) on the arc instabilities may be studied using the current model. However, the model is built on some assumptions and settings which need to be refined in the future. The most important ones are explained as follows:

- The assumption of LTE simplifies modeling of the arc. This assumption is reasonable in the arc column in EAF, but in the vicinity of cathode and anode, the conditions could deviate from LTE [5, 21, 23]. As instabilities of the arc initiate in the area close to the cathode, a study of non-equilibrium conditions in the vicinity of the cathode would improve the knowledge of transient behavior of the arc.
Although some empirical formulas have been suggested to estimate the cathode spot size, like what is shown in figure 2, the cathode spot size and its position vary during the process. Under 2D axisymmetric conditions, only size of the cathode spot can change. If the temperature of the cathode boundary layer changes due to the instabilities of the arc, the electrical conductivity in this area varies. In other words, the electrical current can go into the electrode where is hot enough to be conductive. Therefore, a variable size of the cathode spot would be observed.

In this paper, standard k-ε model is employed to treat turbulence of the flow. This model is fast but it may damp the vortex structures and the velocity. Use of more advanced turbulence models, like SAS or LES, can improve predicting details of transient arc behavior. Further study is needed to find the most appropriate turbulence model with optimum parameters.

Due to the fact that the flow velocity exceeds the sonic velocity, compressibility has to be taken into account. In this case thermos-physical properties should be considered as functions of both temperature and pressure.

- Although some empirical formulas have been suggested to estimate the cathode spot size, like what is shown in figure 2, the cathode spot size and its position vary during the process. Under 2D axisymmetric conditions, only size of the cathode spot can change. If the temperature of the cathode boundary layer changes due to the instabilities of the arc, the electrical conductivity in this area varies. In other words, the electrical current can go into the electrode where is hot enough to be conductive. Therefore, a variable size of the cathode spot would be observed.

- In this paper, standard k-ε model is employed to treat turbulence of the flow. This model is fast but it may damp the vortex structures and the velocity. Use of more advanced turbulence models, like SAS or LES, can improve predicting details of transient arc behavior. Further study is needed to find the most appropriate turbulence model with optimum parameters.

- Due to the fact that the flow velocity exceeds the sonic velocity, compressibility has to be taken into account. In this case thermos-physical properties should be considered as functions of both temperature and pressure.
Since the aim of this work is to study the arc instabilities, the effect of compressibility is studied in another work.

4. Summary

An induction-based model is developed for 2D axisymmetric conditions to study the instability of high-intensity plasma arc. The model can predict the transient behavior of the arc in details properly. Time-averaged results of the current induction based model are in good agreement with those of steady-state potential method.

A study on the transient behavior of the arc shows that 2-pinches close to the cathode, occurring due to the high electrical current density, is responsible for arc instability in this region. The role of the arc shape on the total voltage drop in the arc is investigated: when the arc is in form of column (or bell) the total voltage drop is on a minimum peak; if there is an irregular expansion of the arc in form of arms, the total voltage drop shows a maximum peak.

The current model needs further improvements. The missing points to achieve a robust model to reproduce detailed transient behavior of a high-intensity arc are discussed. Considering non-equilibrium conditions, variable cathode spot size, more advanced turbulence model, and compressibility of the plasma arc can improve the model capability and accuracy.

Acknowledgments

The authors acknowledge financial support from the Austrian Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development within the framework of the Christian-Doppler Laboratory for Metallurgical Applications of Magnetohydrodynamics.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Hadi Barati  https://orcid.org/0000-0002-1888-2668
Abdellah Kharicha  https://orcid.org/0000-0001-8636-2368

References

[1] Nemchinsky V A and Severance W S 2006 What we know and what we do not know about plasma arc cutting J. Phys. D: Appl. Phys. 39 R423–38
[2] Liu Z, Cui S, Luo Z, Zhang C, Wang Z and Zhang Y 2016 Plasma arc welding: process variants and its recent developments of sensing, controlling and modeling J. Manuf. Processes 23 315–27
[3] Odenthal H-J, Kemminger A, Krause F, Sankowski L, Uebber N and Vogl N 2018 Review on modeling and simulation of the electric arc furnace (EAF) Steel Res. Int. 89 1700098
[4] Murphy A B and Uhrlandt D 2018 Foundations of high-pressure thermal plasmas Plasma Sources Sci. Technol. 27 63001
[5] Hsu K C, Etemadi K and Pfender E 1983 Study of the free-burning high-intensity argon arc J. Appl. Phys. 54 1293–301
[6] Loweke J I and Tanaka M 2006 LTE-diffusion approximation for arc calculations J. Phys. D: Appl. Phys. 39 3634–43
[7] Tanaka M, Terasaki H, Ushio M and Lowke J I 2003 Numerical study of a free-burning argon arc with anode melting Plasma Chem. Plasma Process. 23 585–606
[8] Gruber J C, Echterhof T and Pfeifer H 2016 Investigation on the influence of the arc region on heat and mass transport in an EAF freeboard using numerical modeling Steel Res. Int. 87 15–28
[9] Alexis J, Ramirez M, Trapaga G and Jonsson P 2000 Modeling of a DC electric arc furnace. Heat transfer from the arc ISIJ Int. 40 1089–97
[10] Wang F, Jin Z and Zhu Z 2006 Numerical study of dc arc plasma and molten bath in dc electric arc furnace Ironmaking & Steelmaking 33 39–44
[11] Reynolds Q G 2017 Computational modeling of arc–slag interaction in DC furnaces JOM 69 351–7
[12] Reynolds Q G 2014 Computational modelling of shear–layer instabilities and vortex formation in DC plasma arcs Miner. Eng. 65 35–44
[13] Wang Y 2019 Numerical modeling of the metal melting utilizing a dc electric arc plasma for electric arc furnace MS thesis Purdue University Graduate School 10.25394/PGS.11356460.v1
[14] Almeida N A, Benilov M S and Naidis G V 2008 Unified modelling of near-cathode plasma layers in high-pressure arc discharges J. Phys. D: Appl. Phys. 41 245201
[15] Baeva M, Benilov M S, Almeida N A and Uhrlandt D 2016 Novel non-equilibrium modelling of a DC electric arc in argon J. Phys. D: Appl. Phys. 49 245205
[16] Vakhrushev A, Kharicha A, Liu Z, Wu M, Ludwig A, Nitzel G, Tang Y, Hackl G and Watzinger J 2020 Electric current distribution during electromagnetic braking in continuous casting Metallurgical and Materials Transactions B 51 2811–28
[17] Bowman B and Krüger K 2009 Arc Furnace Physics (Düsseldorf: Verlag Stahleisen GmbH)
[18] Haines M G, Lebedev S V, Chittenden J P, Beg F N, Bland S N and Dangor A E 2000 The past, present, and future of Z pinches Phys. Plasmas 7 1672–80
[19] Min K W 1997 Simulation of the Kelvin–Helmholtz instability in the magnetized slab jet Astrophys. J. 482 733–46
[20] Bodo G, Massaglia S, Ferrari A and Trussoni E 1994 Kelvin–Helmholtz instability of hydrodynamic supersonic jets aap 283 655–76
[21] Plaschko P 1979 Helical instabilities of slowly divergent jets J. Fluid Mech. 92 209–15
[22] Morris J C, Bach G R, Krey R U, Liebermann R W and Yos J M 1966 Continuum radiated power for high-temperature air and its components AIAA J. 4 1223–6
[23] Hsu K C and Pfender E 1983 Two-temperature modeling of the free-burning, high-intensity arc J. Appl. Phys. 54 4359–66