The role of radiation losses in high-pressure blasted electrical arcs

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Abstract. The paper deals with experiments carried out on an arc heater where the electric arc is stabilised by flowing working gas. Measured quantities (especially arc current, voltage drop, gas flow rate, and energy loss) serve as input data for a mathematical model of the arc inside a cylindrical anode channel. Previously, the losses of cathode and anode spots were assumed to be negligible in comparison with the total loss. In the new sets of experiments, a modular structure of the arc heater has made it possible to separate the losses of anode and cathode from the energy losses of the arc itself. Furthermore, the losses caused by radial conduction have been introduced into the model. The most significant change of the model concerns the computation of radiation losses of the arc. In the original model, radiation losses were taken as a portion $\varepsilon$ of the total input power. In the modified model, the radiation loss is expressed using a theoretically calculated net emission coefficient of argon (by V. Aubrecht and M. Bartlova). This approach is possible due to a more precise determination of the arc net energy loss which results in flatter radial temperature profiles. Axial distribution of energy loss for the original and modified model is given in figures.

1. Introduction

Transport and thermodynamic properties of the working gas and the mechanisms of energy exchange between electric arc and its surroundings play a substantial role in the design and operation of various devices with intensively blasted electric arcs, such as arc heaters and circuit breakers. External integral quantities characterising the device, especially the current, voltage, gas flow rate etc., can be sometimes measured but the internal processes often remain hidden. Mathematical models can exploit measured data for discovering and describing the phenomena running inside.

Many contributions have dealt with switching electrical arcs. With a different stage of simplification the behaviour of the electric arc burning in flowing gas has been analysed. For instance...
Frost and Liebermann [1] presented computed properties of hexafluoride and a simplified model of enthalpy flow in high-current interval. Ragaller [2] used data obtained from experiments with a quasi-stationary, high-pressure axially blasted electrical arc of cylindrical shape for modelling. Approximation of radial temperature dependencies with a generalized parabola in the arc and with a Gaussian function outside the arc recommended by Ragaller seems to be suitable also for our experiments and modelling. Lowke, Ludwig and Tuma [3], [4] dealt with a simple model of stabilised electric arcs. Lowke, Stokes and Ramakrishnan [5] designed one-dimensional models of free high-current electric arc with the influence of turbulence included by means of Prandtl mixing length. Their relations between the arc cross-section and current were used in the presented model with the exponent \( n \) as one of the computational parameters.

The authors try to design a simple model of electric arcs stabilized by a flowing gas in a cylindrical arc heater channel. The model should exhibit no special requests for software and hardware but it should clearly describe especially the energy exchange between the arc and its surroundings. As mentioned above, some relations of older work can be utilized. Previous computations with an older version of the model indicated a prevailing role of the arc radiation in the total power loss of the arc. This fact turns attention to a more adequate expression of the radiation term in the energy balance. For this purpose, the net emission coefficient of argon [6], [7], [8] has been used with a necessary modification caused by the non-ideal real experimental situation.

This paper is organised as follows: Section 2 describes the mathematical model with special attention to the newly introduced modifications. Section 3 deals with the experimental device that served as a source of the input experimental data. Section 4 compares the results of three comparable experiments and computations and demonstrates the influence of the designed modifications of the model. Section 5 concludes the paper.

2. Mathematical model of an electric arc: Basics and advanced modifications

The basics of the model of the electric arc designed by the authors are explained in detail in [9], [10]. Here, only necessary basic relations are mentioned while attention is focussed on advanced modifications. The aim is to get a more precise description of the physical phenomena inside the anode channel.

The model is based on the mass and energy conservation equations and Ohm’s law. The arc plasma is supposed to be in local thermodynamic equilibrium. It is assumed the kinetic energy is small compared to the enthalpy. Presumed cylindrical symmetry of the arc follows from the shape of the anode channel. A further simplifying presumption is that the Mach number \( M \) is constant over the channel cross-section. In the energy balance of individual elementary cylinders \( \Delta V_A \) and cylindrical rings \( \Delta V_C \) of the channel (see figure 1), conductive and radiation energy flow in the radial direction and enthalpy flow in the axial direction are considered as highly prevailing components.

![Figure 1. A schematic view of the electric arc in the anode channel of an arc heater.](image)
A schematic view of the electric arc in the anode channel of an arc heater is given in figure 1. The anode channel of the radius $r_C$ and the length $z_L$ is divided into a cylindrical arc zone and a remaining ring volume. The arc zone is characterized by high plasma conductivity. On the arc zone boundary, plasma conductivity sharply falls nearly to zero. The corresponding temperature $T_{AA}$ at the arc boundary depends on the used working gas ($T_{AA} = 6000$ K for argon). The quantities in the arc zone are indicated with subscript A. In the remaining ring volume between the arc zone and the channel wall the temperature is below $T_{AA}$ and can be as low as the temperature of the cold working gas at the input $T_0$. In the region of relatively low temperatures $T < T_{AA}$ some temperature dependencies of transport and thermodynamic properties of the working gas can be expressed in simple forms, which makes the computation simpler and faster. Subscript C is used to indicate quantities and functions in this zone.

The axial development of the arc is described by the dependency of the arc boundary radius $r_A(z)$

$$r_A(z) = r_0 \left[ 1 + \left( \frac{z}{r_0} \right)^{1/n_r} \right]$$  \hspace{1cm} (1)

where $r_0$ is the radius of the arc at the cathode, defined by the arc current and by the cathode current density ($10^8$ Am$^{-2}$ for currents up to 2.16 kA), while $n_r$ is a calculated parameter.

Another calculated parameter is the exponent $n$ in the relation describing the radial dependency of temperature in the arc zone

$$T_A(r, z) = T_0 + (T_{AA} - T_0) \left[ \left( \frac{T_A(0, z) - T_0}{T_{AA} - T_0} \right)^{1/n} - 1 \right] \left[ 1 - \frac{r^2}{r_A^2(z)} \right]^{1/n}$$  \hspace{1cm} (2)

where $T_{AA}$ is the temperature for which the conductivity of the working gas sharply falls to zero (6000 K for argon) while $T_0$ is the temperature of cold gas at the input. Outside the arc zone, the radial temperature dependency is approximated by a Gaussian function as follows

$$T_C(r, z) = T_0 + (T_{AA} - T_0) \exp \left( \frac{r^2(z) - r^2}{b_C^2(z)} \right).$$  \hspace{1cm} (3)

Both function values and derivatives of (2), (3) at the arc boundary must be equal to ensure a smooth radial temperature dependency together with equal conductive heat flows at both sides. This demand gives the following expression for $b_C(z)$

$$b_C(z) = r_A(z) \left[ n \left[ \frac{T_A(0, z) - T_0}{T_{AA} - T_0} \right]^{1/n} - 1 \right]^{-1}. \hspace{1cm} (4)$$

With the above mentioned presumptions, continuity and energy conservation equations can be written for the arc zone (subscript A) and the rest (heated and cold zone, subscript C) as follows

$$M(z) \int_{r_A(z)}^{r_C(z)} \rho \chi A \phi A \chi A \phi A \chi A \frac{1}{2} \pi r \, dr + \int_{r_A(z)}^{r_C(z)} \rho \chi C \phi C \chi C \phi C \chi C \frac{1}{2} \pi r \, dr = G, \hspace{1cm} (5)$$

$$M(z) \left\{ \int_{0}^{r_A(z)} \rho A \chi A \phi A \chi A \phi A \chi A \frac{1}{2} \pi r \, dr + \int_{r_A(z)}^{r_C(z)} \rho A \chi A \phi A \chi A \phi A \chi A \frac{1}{2} \pi r \, dr \right\} = U(z)I - P_L(z) \hspace{1cm} (6)$$

Here, $M$ is Mach number, $\rho$ the specific mass, $a$ the sound velocity, $h$ the enthalpy, $G$ the gas flow rate, $U(z)$ the voltage at the axial position, $I$ the arc current, and $P_L(z)$ the power loss. The left-hand side of the equation (6) expresses the enthalpy flow $P_h(z)$ at the axial position $z$. 


Having approximated the radial temperature dependency (2), integration over the arc radius can be converted into integration over temperature. Generally expressed for integrating a function \( \{T_A(r,z)\} \) } in the arc zone, the transform is the following

\[
\int_0^{r_A(z)} \left[ T_A(r,z) \right] 2\pi r dr = \pi r^2(z) F \left[ T_A(0,z), n \right],
\]

(7)

\[
F \left[ T_A(0,z), n \right] = \left\{ n \left[ T_A(0,z) - T_0 \right]^{\frac{1}{n}} - \left( T_{AA} - T_0 \right)^{\frac{1}{n}} \right\} \int_{T_{AA}}^{T_A(0,z)} \left( T - T_0 \right)^{\frac{1}{n}} dT.
\]

(8)

Using (7), (8) and suitable approximations of the temperature dependencies of the specific mass \( \rho \), sound velocity \( a \), enthalpy \( h \) and electric \( \sigma \) and thermal \( \lambda \) conductivity, the necessary functions can be computed beforehand which makes the solution much easier. In the following text, \( RA \left[ T_A(0,z) \right] \) stands for integration (8) with \( f(T-T_0) \) equal to the product of the specific mass \( \rho(T-T_0) \) and sound velocity \( a(T-T_0) \), thus

\[
RA \left[ T_A(0,z), n \right] = \left\{ n \left[ T_A(0,z) - T_0 \right]^{\frac{1}{n}} - \left( T_{AA} - T_0 \right)^{\frac{1}{n}} \right\} \int_{T_{AA}}^{T_A(0,z)} \rho(T-T_0) a(T-T_0) (T-T_0)^{\frac{1}{n}} dT.
\]

Similarly \( RAH \left[ T_A(0,z) \right] \) stands for integration (8) with \( f(T-T_0) = \rho(T-T_0) a(T-T_0) h(T-T_0) \), thus

\[
RAH \left[ T_A(0,z), n \right] = \left\{ n \left[ T_A(0,z) - T_0 \right]^{\frac{1}{n}} - \left( T_{AA} - T_0 \right)^{\frac{1}{n}} \right\} \int_{T_{AA}}^{T_A(0,z)} \rho(T-T_0) a(T-T_0) h(T-T_0) (T-T_0)^{\frac{1}{n}} dT
\]

and

\[
for f(T-T_0) = \sigma(T-T_0) \int_{T_{AA}}^{T_A(0,z)} \frac{n \left[ T_A(0,z) - T_0 \right]^{\frac{1}{n}} - \left( T_{AA} - T_0 \right)^{\frac{1}{n}} \right\} \sigma(T-T_0) (T-T_0)^{\frac{1}{n}} dT.
\]

With temperatures lower than \( T_{AA} \), the temperature dependencies of \( \rho, a, h \) and their products can be expressed in very simple forms [10].

The axial dependency of centreline temperature \( T_A(0,z) \) is calculated in individual elements of the channel volume. The total length \( z_l \) is divided into \( m \) elements \( \Delta z \). The energy equation for each segment states that the increment of the input electric power \( \Delta U_{ch} \) is equal to the sum of the increments of the enthalpy flow \( \Delta P_h \), conductive \( \Delta P_{con} \) and radiation power loss \( \Delta P_r \),

\[
\Delta U_{ch}(z) = \Delta P_h(z) - \Delta P_{con}(z) - \Delta P_r(z) = 0.
\]

(9)

The value of the Mach number in the \( i \)th element can be derived from the continuity equation and reads

\[
M(z_i) = G \pi r^2(z_i) RA \left[ T_A \right] + p \left\{ \frac{\kappa M_p^2}{R} \right\} \frac{1}{2} \int_{T_{AA}^{\frac{1}{n}}}^{T_{AA}^{\frac{1}{n}}} (T-T_0)^{\frac{1}{n}} dT.
\]

(10)

where \( G \) is the gas flow rate, \( p \) the pressure, \( \kappa \) Poisson constant, \( M_p \) the molar mass, \( R \) the universal gas constant, \( r_i \) the channel radius, \( T_C \) the temperature outside the arc zone. The individual terms of (9) can be expressed as follows:

- The increment of the input power of the \( i \)th element

\[
\Delta U_{ch}(z) = E(z) \Delta z = 1^2 \Delta z \left[ \pi r^2(z_i) \int_{T_{AA}^{\frac{1}{n}}}^{T_{AA}^{\frac{1}{n}}} (T-T_0)^{\frac{1}{n}} dT \right]^{-1}
\]

(11)

- The increment of the enthalpy flow of the \( i \)th element

\[
\Delta P_h(z) = \pi \left\{ M(z_i) r^2(z_i) RAH \left[ T_A \right] - M(z_{i-1}) r^2(z_{i-1}) RAH \left[ T_A \right] \right\} + 2 \pi p C_p \left\{ \frac{\kappa M_p^2}{R} \right\} \frac{1}{2} \left[ M(z_i) r^2(z_i) \left[ \sqrt{T_{AA}^{\frac{1}{n}}} - \sqrt{T_C(0,z_i)} \right] - M(z_{i-1}) r^2(z_{i-1}) \left[ \sqrt{T_{AA}^{\frac{1}{n}}} - \sqrt{T_C(0,z_{i-1})} \right] \right]^{-1}
\]

(12)

where \( C_p \) is the thermal capacity of the working gas at \( T<T_{AA} \).

- The increment of the conductivity loss of the \( i \)th element

\[
\Delta P_{con}(z) = \pi \left\{ M(z_i) r^2(z_i) RAH \left[ T_A \right] - M(z_{i-1}) r^2(z_{i-1}) RAH \left[ T_A \right] \right\}
\]

\[
+ 2 \pi p C_p \left\{ \frac{\kappa M_p^2}{R} \right\} \frac{1}{2} \left[ M(z_i) r^2(z_i) \left[ \sqrt{T_{AA}^{\frac{1}{n}}} - \sqrt{T_C(0,z_i)} \right] - M(z_{i-1}) r^2(z_{i-1}) \left[ \sqrt{T_{AA}^{\frac{1}{n}}} - \sqrt{T_C(0,z_{i-1})} \right] \right]
\]

where \( C_p \) is the thermal capacity of the working gas at \( T<T_{AA} \).
\[ \Delta P_{\text{con}} = 4\pi \Delta z \left[ r_c^2 \frac{\lambda T_c(r_c,z_i)}{b_c(z_i)} \right] \left[ T_c(r_c,z_i) - T_0 \right] \]  

(13)

where \( \lambda \) is the thermal conductivity. If temperature \( T_c \) is nearly as low as \( T_0 \), this term can be neglected.

- The increment of the radiation loss of the \( i \)th element

\[ \Delta P_r(z_i) = 4\pi^2 \Delta z k_r^2 r_A^2(z_i) \varepsilon_N \left[ T_A(0,z_i) \right] k_r r_A(z_i) \]  

(14)

where \( \varepsilon_N \) is the net emission coefficient of gas which depends on the centreline temperature \( T_A(0,z) \) and the effective arc radius \( k_r r_A(z) \) [6], [7], [8]. In the previous model [9], [10] the radiation loss of the arc segment was computed as a fixed portion of the input power \( \Delta P_L(z_i) = (1 - \varepsilon) \Delta U(z_i) I \). The parameter \( \varepsilon = P_L/U I \) was determined as a ratio of the measured total loss of the channel and the total input power. Thus the same value was taken for all segments with no respect to their temperature and radius. The net emission coefficient is defined by the power irradiated from a homogeneous gas cylinder of the radius \( R \) and the constant temperature \( T \). In real experiments, this condition is hardly fulfilled. That is the reason for introducing the calculation parameter \( k_r \). The radiation of the arc slice is computed using the net emission coefficient of the gas cylinder of the effective radius \( k_r r_A \) and temperature \( T_A(0,z) \). In comparison with the previously applied relation, the approximate description of the radiation loss using the net emission coefficient \( \varepsilon_N \) and the effective arc radius \( k_r r_A \) at least partly respects the connection of the irradiated power and the temperature and radius of arc segments.

During the computation, a set of parameters \( n, n_r \) and \( k_r \) is searched for with which measured and computed integral values of voltage drop, total power loss and output enthalpy flow differ mutually less than by accepted differences (several percent). For a chosen set of parameters \( n, n_r \) and \( k_r \), the energy equation of individual segments is solved and the centreline temperature is determined. Finally, the increments of the voltage and the radiated power loss of the segments are summed along the whole channel length and the output enthalpy flow is computed. The computed and measured values are compared and the computation is either finished or repeated with a modified set of parameters until a satisfying agreement is reached.

3. Experimental set-up

Experimental input data for the designed model of the electric arc burning in the working gas flowing through a cylindrical channel have been collected during numerous experiments. The arc heater used has been designed by the authors as a modular device for a laboratory purpose. Both the cylindrical anode channel and other possible parts (anode, expanding chamber etc.) can be compact or built of several segments. The lengths, radii, electric and cooling circuits’ connections can be changed according to the aims and demands of an experiment. The dimensions of the core part of the device are in order of centimetres (e.g. the channel radius between 4 and 8 mm, the channel length up to 125 mm). The input electric power is up to 30 kW and the working gas flow rate up to a few tens of grams per second depending on the medium used (argon, nitrogen, methane, or their mixtures).

The set of measured data includes mainly basic electrical parameters (the arc current \( I \), the voltage drop \( U \)), the flow rate of working gas \( G \), and flow rates and input and output temperatures of cooling water going through individual segments of the arc heater.

Originally, the entire measured voltage drop \( U \) was taken as arising in the arc column and the power losses of the cathode and anode spots were supposed to be negligible. More precise measurements on the reconfigured arc heater with separated input and output segments showed that this presumption is too rough. The arc column voltage drop \( U_{ch} \) can be obtained from the total measured voltage \( U \)

\[ U_{ch} = U - 2 \frac{P_{\text{cat}}}{I} \]  

(15)
$P_{\text{cat}}$ is the measured power loss of the cathode. The measured power loss of the output part of the anode channel includes not only the power loss of the anode spot, but also of the arc burning in this output segment. To separate them, the loss of the anode spot is taken to be equal to that of the cathode spot. Similarly, the loss of the arc $P_L$ can be determined from the total measured loss $P_{\text{tot}}$ of all segments

$$P_L = P_{\text{tot}} - 2P_{\text{cat}}. \quad (16)$$

4. Results and discussion

Three experiments discussed here as examples have been carried out under similar conditions: with the same channel radius of 8 mm, the same argon flow rate of 22.5 g/s, and the same arc current of 122 A.

The first case is referred to as the “original” experiment and evaluation. In this experiment the loss of the cathode and of the anode part of the channel were neglected and the entire voltage $U=111.8$ V was taken as the voltage drop over the arc column. As explained above, the radiation of the arc column was computed as the certain portion (1-$\varepsilon$) of the input power with no relation to the radius and temperature of the arc. The resulting exponents were found $n_r=3.2$ and $n=1.0$.

In the second and third case, the arc heater was reconfigured in order to measure the power loss of individual parts of the arc heater. The power losses of the cathode and of the output part of the channel (including the anode part of the arc and the anode spot) were measured separately. In the second experiment (“corrected”) the measured voltage after correction was lowered (15) to $U_{\text{ch}}=81$ V. The computation of the radiation loss was the same as in the first experiment. While the exponent $n_r=3.2$ remained the same as that found in the first case, the exponent $n=0.1$ was substantially different.

In the third case the correction of the voltage was applied as well but a longer channel was tested ($z_L=108$ mm instead of 80 mm). In the third case (referred to as “modified”) the radiation loss was computed using the net emission coefficient of argon and the effective radius $k_r A$ (14). Although both exponents $n_r=3.2$ and $n=0.1$ were the same as those found in the second case, some differences between the computed dependencies can be found.

In figure 2 substantial differences between radial dependencies of temperature between the “original” case on one side and both other cases on the other side can be seen. If the losses of the cathode and anode spots are not extracted from the measured values the resulting dependencies are strongly influenced. The radial dependencies for $z=78$ mm are given as an example. In the first case, the computed exponent $n=1.0$ leads to a rather sharp maximum of the radial temperature dependency.

![Radial temperature profile (z = 0.078 m)](image)

**Figure 2.** The radial temperature profiles for the “modified”, “corrected” and “original” case.
in the arc zone. A zone of heated gas can be seen near the arc boundary. In the second (“corrected”) and third (“modified”) cases, the substantially lower exponent $n=0.1$ results in the flat radial dependency of the temperature in the arc zone. The gas outside the arc zone remains cold due to a very high derivative of the radial temperature dependency at the arc boundary (2), (3), (4).

Figure 3 shows the development of the centreline temperature along the channel axis computed for the three discussed cases. Because of non-corrected voltage the temperature in the “original” case is too high. The axial dependencies of the centreline temperatures obtained for the “corrected” and “modified” case are similar mutually, the slope of the latter being slightly lower.

**Figure 3.** Comparison of the dependency of the centreline temperature $T_A(0,z)$ on the longitudinal coordinate $z$ for the “modified”, “corrected” and “original” case.

**Figure 4.** The dependencies of the arc radius $r_A$, the centreline temperature $T_A(0,z)$ and the arc specific radiated power $w_e$ on the longitudinal coordinate for the “modified” case.
Figure 4 illustrates the connection among the specific radiated power \( w_e(T_A(0,z)) = 4\pi\varepsilon_N[T_A(0,z)] \), the corresponding temperature and the arc radius. The curve \( w_e(z) \) is rather flat, with the small maximum near the channel input and the slight decrease towards the channel output. This tendency corresponds to the course of both other dependencies in figure 4: the net emission coefficient \( \varepsilon_N \) decreases with the decreasing temperature and with the increasing radius.

**Figure 5.** The dependency of the electric field strength \( E \) on the longitudinal coordinate \( z \) for the “modified”, “corrected” and “original” case.

**Figure 6.** The axial development of the arc radiation losses \( \Delta P \) of the cylindrical segments \( \Delta z = 2 \text{ mm} \) for the “original” and “modified” cases, and the specific radiated power \( w_e \) of the arc for the “modified” case.

The dependencies of the electric field strength \( E \) vs. longitudinal (axial) coordinate \( z \) in figure 5 are similar for all cases. In the “corrected” and “modified” case they are almost the same. The axial
dependencies of the radiation loss $\Delta P$ of individual segments in the “original” and “corrected” case copy the course of $E(z)$. This fact is due to the computation used in these cases $\Delta P(z) = (1-\varepsilon) \Delta U(z)I$ as explained above.

In figure 6 the axial development of the arc radiation losses $\Delta P$ of the cylindrical segments $\Delta z = 2\text{ mm}$ for the “original” and “modified” cases are given, together with the specific radiated power $w_e$ of the arc for the “modified” case again. For the “original” case, the arc radiation losses $\Delta P$ exhibit the sharp maximum at the beginning of the channel, the rapid decrease in the middle part and almost constant value near the end. In the “modified” case, when the modified computation of the radiation loss using the net emission coefficient and the effective arc radius has been applied, the resulting dependency of the radiation losses of individual segments along the axis is different: excepting the area near the cathode, the radiation losses are distributed almost uniformly along the channel.

5. Conclusions
The paper presents the modified model of the electric arc burning in argon flowing through the arc heater’s cylindrical channel and demonstrates the computed results obtained for real input data. An older version of the model was updated. The comparison of the results computed from rough and carefully corrected new measured data clearly shows that the previous presumption of negligible power loss of cathode and anode spots is not valid. A proper segmentation of the channel and mathematical correction of input data is necessary. The obtained very flat corrected radial temperature profile indicates that the sometimes used two-zone models are probably not far from reality [1], [2], [3].

The minor modification concerns relations describing radial temperature dependencies. The terms of the input gas temperature $T_0$ have been inserted into approximations of $T_A(r,z)$ and $T_C(r,z)$ which is more correct but the actual influence on the results is weak. The substantial modification focuses on the radiation loss term in the energy conservation equation. The net emission coefficient of argon was used for the expression of the radiation loss. Because the real situation does not comply with the theoretical presumption of a homogeneous gas cylinder of constant temperature and infinite length, an effective radius $k_{rA}$ of the radiating gas cylinder was introduced as another computational parameter. Naturally, the designed modification is not exact but its advantage consists in preserving the connection of the computed radiation loss to the temperature and geometry of the radiating element. Due to this modification, the resulting dependency of the computed radiation loss of individual segments on the longitudinal coordinate $z$ exhibits no significant extremes.

The computations using the measured integral quantities show the dominant role of radiation in the total power loss of the arc inside the arc heater’s anode channel. The character of the obtained dependencies of the centreline temperature $T_A(0,z)$ and electric field strength $E(z)$ on the longitudinal coordinate $z$ is very similar to the corresponding curves given in [2], [3], [4], [11].

From a practical point of view, also some modifications making the computation faster and easier have been prepared and found advantageous. Preliminary computations of integrals $F[T_A(0,z),n]$ (8) have been replaced by analytical computation with suitable approximations of temperature dependencies of argon properties and/or their products $\rho a h, \rho a, \sigma$. The total duration of the calculation can be reduced using pre-estimated computational parameters $n_0, n$ based on previous experience. From the energy balance at the input and output cross-sections of the arc column approximate values of centreline temperatures can be simply estimated.

Acknowledgement
The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 230126. The research was also financially supported by the Ministry of Education of the Czech Republic under the projects no.
MSM0021630513 and MSM0021630516. The authors would like to express their gratitude to the anonymous reviewers for their time and effort spent during careful inspections as well as their helpful comments and suggestions for the improvement of the paper.

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