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# Analysis of radiation models of high-current phase of AC arc

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Numerical modelling is widely used in the study of energy exchange between the arc and gas flow in arc-quenching devices of gas-operated high-voltage circuit breakers. In the high-current phase, the main factor influencing the energy exchange is radiation. In this paper a study of different radiation models and their analysis is carried out. The description of the considered radiation models and their implementation in COMSOL Multiphysics are given. The comparison of calculated results obtained using different models with experimental data is carried out. Recommendations on the use of the models are formulated.

**Keywords:** switching arc, high-current phase, numerical modeling, radiation.

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One of the main characteristics of HV gas-blast circuit breakers is its breaking capacity, which is determined by the rate of recovery of strength of the intercontact gap. The strength recovery process is affected by the flow history: arc discharge characteristics in the high-current phase when the arc current values are near-amplitude (e.g., critical heat flux, which is typical high-current interruption); changes in the nozzle geometry rated current commutation; and an increase in temperature of arc-quenching flow in the high-current phase when auto-puffer arc quenching device with heating volume are used. However, the high density of plasma makes it difficult to examine arc parameters in the high-current phase experimentally, since optical methods probe primarily the peripheral discharge regions [1].

Modeling of an arc-quenching device of high-voltage gas-filled switching equipment is a complex interdisciplinary task. Radiation is the main mechanism of energy exchange between the arc and the gas medium in the high-current phase [1,2]. Radiation calculation is a multiparameter problem. Numerical modeling is a versatile tool for investigation of the influence of radiation on the high-current arc phase.

The main objective of the present study is to examine radiation models. Modeling is performed in COMSOL Multiphysics based on a system of magnetohydrodynamic equations without account for the influence of the magnetic field.

Two approaches to radiation modeling are used. The first one relies on the model of radiative heat conduction developed in [3]. The model is essentially as follows: under the assumption of isotropy of radiation and local thermodynamic equilibrium of radiation with matter (the plasma is optically thick, which is typical for breaking arcs [3]), an additional quantity characterizing the flow of radiative energy ($\mathbf{q}_{rad}$) is added to the energy balance equation. This quantity is defined as

$$\mathbf{q}_{rad} = -\lambda_\psi \nabla T, \tag{1}$$

where $\lambda_\psi$ is the radiative heat conduction coefficient, which is defined in accordance with [4] as

$$\lambda_\psi = k_\psi c_p,\, k_\psi = C_\psi \begin{cases} 0, & \text{if } T \leqslant T_s, \\ \left(\frac{T_{av}}{T_s} - 1\right)^3, & \text{if } T > T_s, \end{cases} \tag{2}$$

where $C_\psi = 2 \cdot 10^{-4}$ is an empirical coefficient, $T_{av}$ is the average gas temperature on the axis, and $T_s$ is the temperature below which gas becomes non-radiating.

The second approach relies on the radiative transfer equation implemented in the Radiation in Participating Media (rpm) module in COMSOL Multiphysics. Model P1 was chosen out of all the models available in this module. Radiative transfer is characterized in it by equation

$$\nabla\left[-D_{p_1}\nabla G\right] = -\kappa\left[G - 4\pi I_b(T)\right],$$

$$D_{p_1} = \frac{1}{3(\kappa + \sigma_s)}, \quad I_b(T) = \frac{n_r^2 \sigma T^4}{\pi}, \tag{3}$$

where $G$ is the radiation intensity, $I_b$ is the spectral intensity of blackbody radiation, $\kappa$ is the absorption coefficient, $\sigma_s$ is the scattering coefficient, and $n_r$ is the refraction index.

The source term in the energy equation, which incorporates the effect of radiation, is written as

$$Q_r = \kappa\left[G - 4\pi I_b(T)\right]. \tag{4}$$

The following values of coefficients included in the model were adopted in the present study. Coefficient $n_r$ was set to unity. The absorption coefficient depended on the values of temperature, pressure, and arc radius. The absorption coefficient for nitrogen was calculated in Fluid Workbench v3.1 within the temperature range from 300 to 30,000 K and the pressure range from 1 to 30 atm. Thermodynamic calculations were carried out for the following components: $e$, N, $N_2$, $N_3$, $N^{2+}$, $N^{3+}$, $N^{4+}$, $N^{5+}$, $N^{6+}$, and $N_2^+$. The absorption coefficient was calculated for arc radii of 1, 5, 10, 20, and 40 mm.

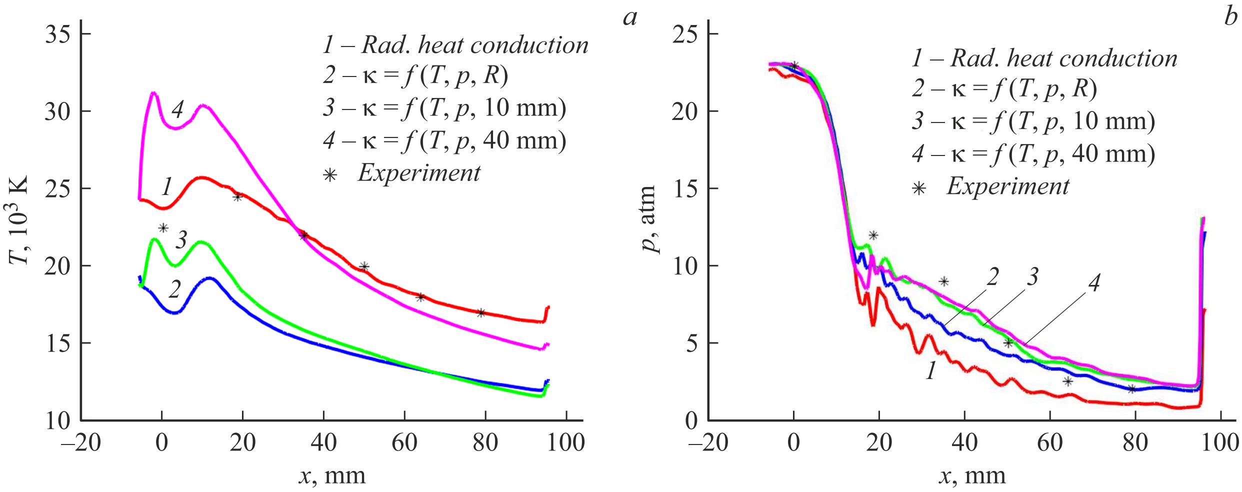


**Figure 1.** Distribution of temperature (*a*) and pressure (*b*) along the axis.

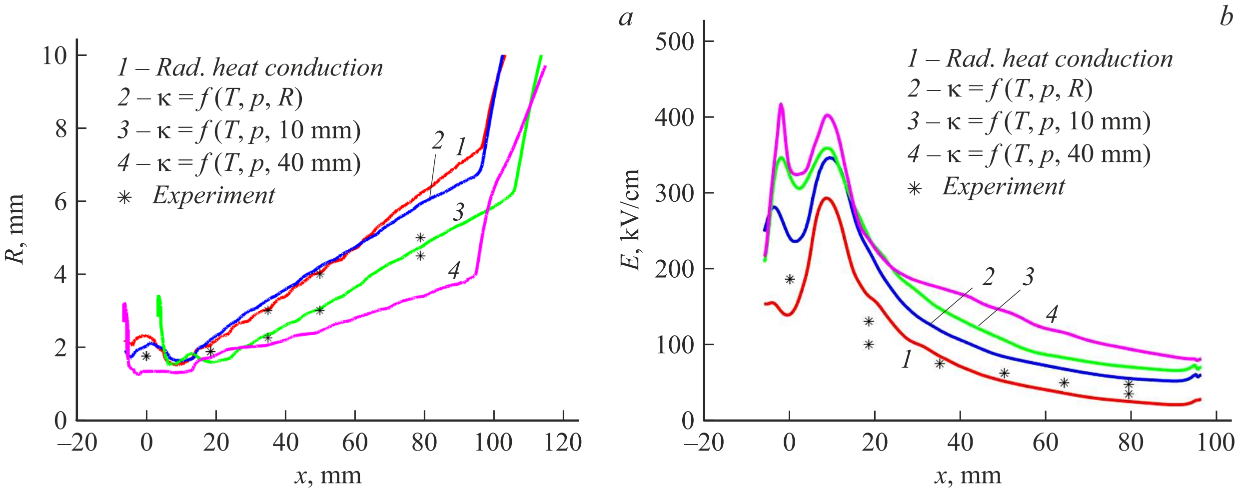


**Figure 2.** Distribution of arc radius (*a*) and electric field strength (*b*) along the axis.

Calculations were performed for a single-flow arc-quenching device with two pressure stages. The geometry of a Laval nozzle-type channel was set according to the data from [4,5]. The Laval nozzle is axisymmetric, the entrance radius of the channel is 6 mm, the half-angle of the diffuser is 4°, the total nozzle length is 110 mm, and the confuser part length is 10 mm. The working gas is nitrogen ($T_s = 8000$ K in accordance with [6]), and a $p_1 : p_2 = 23 : 1$ pressure drop ensures nozzle operation in the design mode. A stationary arc with current $I = 2$ kA was considered, and the calculation results were compared with experimental data [5].

Since the dependence of the absorption coefficient is multiparametric, calculations were carried out for various combinations of parameters: $\kappa = f(T, p, R)$ — the absorption coefficient depends on three parameters; $\kappa = f(T, p, 10\,\text{mm})$ — the absorption coefficient depends on two parameters at a fixed arc radius of 10 mm; and $\kappa = f(T, p, 40\,\text{mm})$ — the absorption coefficient depends on two parameters at a fixed arc radius of 40 mm. The arc radius was determined from the 4000 K isotherm and calculated as the radius value averaged along the length of the channel.

The distributions of thermodynamic parameters along the channel axis for different models are compared with experimental data in Fig. 1. The data presented in Fig. 1, *a* demonstrate that the calculation based on the radiative heat conduction model with the chosen semi-empirical coefficient provides a fine agreement between the calculated and experimental data. At the same time, none of the curves calculated with the rpm module agreed with the experimental data.

The value of coefficient $\kappa$ calculated with $\kappa = f(T, p, 40\,\text{mm})$ lower than the one for $\kappa = f(T, p, 10\,\text{mm})$. Specifically, its value at a temperature of 10 000 K and a radius of 10 mm (40 mm) is 866 $\text{m}^{-1}$ (217 $\text{m}^{-1}$), and at a temperature of 30 000 K and a radius of 10 mm (40 mm), it is equal to 470 $\text{m}^{-1}$ (117 $\text{m}^{-1}$).

A four-fold reduction in the value of coefficient $\kappa$ leads to an underestimation of the radiation magnitude in the confuser. When the $\kappa$ value for a larger radius is used, the temperature curve lies above the experimental values.

The results of calculations for $\kappa = f(T, p, R)$ and $\kappa = f(T, p, 10\,\mathrm{mm})$ are close in the diffuser. This is attributable to the fact that the arc radius value in the diffuser averaged along the channel length in the stationary mode is close to a fixed radius of 10 mm. However, the arc radius varies along the channel (Fig. 2, $a$), which must be taken into account in the calculation, since the absorption coefficient has a significant dependence on radius.

The pressure curves obtained using the rpm module agree better with the experimental data than those provided by the radiative heat conduction model, which yields erroneously low results (Fig. 1, $b$).

Compared to the experimental data, the rpm module yields higher values in the distribution of field strength (Fig. 2, $b$). The field strength in the cross section may be estimated as the ratio of current to conductivity averaged over the cross section [4]. At a constant current value for $\kappa = f(T, p, R)$ and $\kappa = f(T, p, 10\,\mathrm{mm})$, the discrepancy between the calculated and experimental data is then attributable to the underestimated calculated temperature. A reduction in temperature translates into a lower conductivity in the arc. With $\kappa = f(T, p, 40\,\mathrm{mm})$, underestimation of the arc radius (Fig. 2, $a$) entails a reduction in the integral value of conductivity in the cross section.

Thus, it was demonstrated that the radiative heat conduction model provides calculated data consistent with the experimental ones, does not require longer calculation times, and does not make the used arc model more complex. If used to solve the additional radiation transfer equation, the rpm module makes the model more complex, since it requires solving an additional partial differential equation with coefficients that depend on the arc parameters (temperature, pressure, and arc radius).

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### Conflict of interest

The authors declare that they have no conflict of interest.

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