Mathematical simulation of non-equilibrium plasma processes of a pulsed arc discharge in a chamber of a multi-chamber arrester

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Abstract: The paper is devoted to mathematical simulation of non-equilibrium plasma processes of a pulsed arc discharge of complex chemical composition. The calculation of the composition, thermodynamic and transport properties of the plasma was carried out taking into account vapors of the chamber material and electrodes. Plasma processes were calculated using the two-temperature model both in the chamber of the arrester and in a plasma jet at an ambient pressure of 1 atm and 0.3 atm. A comparison of the results is presented.

Keywords: 2T model, simulation, pulse arc discharge, multi-chamber arrester.

1. Introduction

Protection of important energy facilities from direct lightning impact requires the creation of special devices for lightning protection.

Currently, a new promising way to protect overhead power lines from lightning impact is the use of multi-chamber arresters [1–3]. The multi-chamber arrester consists of a large number of series-connected chambers (Fig. 1) in which an arc discharge occurs during breakdown. Such a discharge is accompanied by erosion of the electrodes material and ablation of the material of the discharge chamber. During that process an increased pressure occurs in the chamber leading to the formation of a plasma jet from the discharge chamber and to the extinction of the electric arc (Fig. 2).

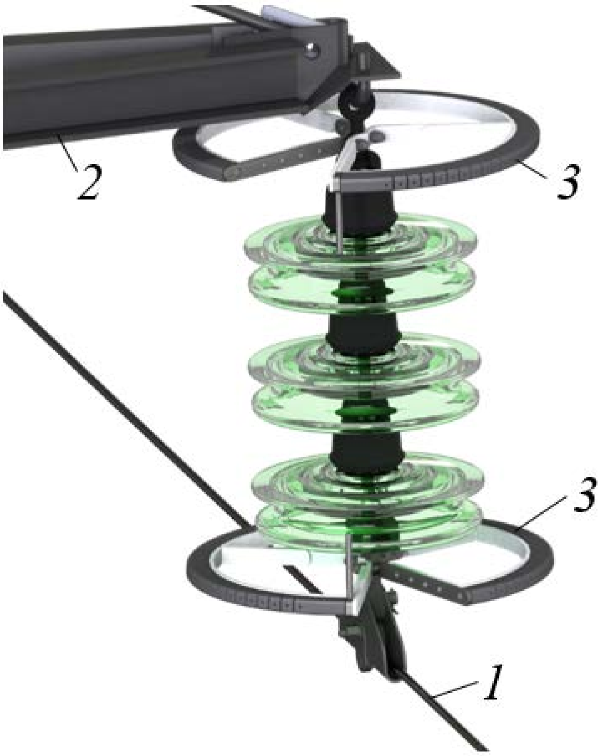

Fig. 1. Arrester RMK-E-35: 1 – high-voltage wire, 2 – transmission tower part, 3 – multi-chamber systems

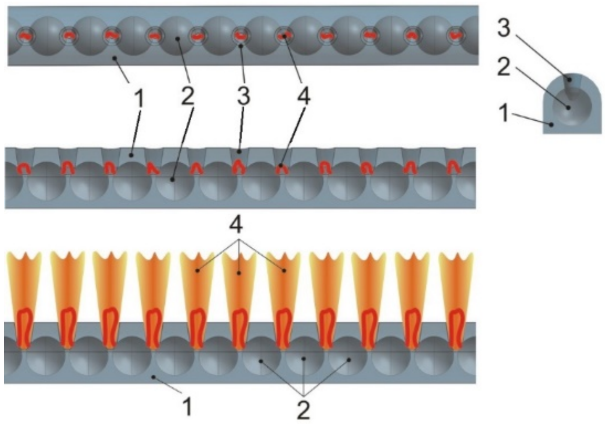

Fig. 2. Arc discharges in a multi-chamber system: 1 – silicone rubber; 2 – electrodes; 3 – air gaps; 4 – discharge channels

Investigations of the physical processes that take place inside such devices have been carried out over the years to improve the efficiency of multi-chamber arrester operation. Along with experimental methods [4], theoretical studies using mathematical modeling become widespread [5–10]. The data obtained during experiments are used in the mathematical model as initial data as well as for the purpose of correcting the model.

Currently, there is the problem of application of arresters for power lines located in mountainous areas where in some cases the pressure may be 0.3-0.8 of the atmospheric pressure. The extinction of an electric arc in the arresters under such conditions becomes difficult, which is caused by the stable maintenance of the arc under reduced pressure. Therefore, the creation of lightning arresters requires significant adjustments.

At reduced pressure plasma in the presence of an electric field is characterized by a disturbance of thermal equilibrium. Therefore, plasma in such conditions is more adequately described by the two-temperature model [11].

The purpose of this article is to develop a mathematical model of non-equilibrium plasma processes of a pulsed arc discharge of complex chemical composition using the example of processes in a discharge chamber of a multi-chamber arrester operating in mountainous areas.

2. Methods

2.1. Calculation of plasma properties

To develop a non-equilibrium mathematical model of a pulsed arc discharge it is necessary to know the thermodynamic and transport properties of a plasma as a function of electron temperature, heavy particle temperature, and pressure.

A method of calculation of the composition, thermodynamic and transport properties of both equilibrium and two-temperature plasma is described in sufficient detail in the references [11–15].

Silicone rubber has the following chemical formula:

$$(\mathrm{C2H6SiO})_n$$

Using this information and considering possible cases of the electrode material (Cu, W, Fe) the 85 components were taken into calculation.

The equilibrium constants for the equations of the mass action law were taken from [16, 17], and the partition functions of atoms and ions were calculated based on NIST data [18]. Enthalpies of individual components were taken from [16, 17] to calculate the thermodynamic properties.

To calculate the transport properties, it is necessary to find data on collision cross sections for each pair of species. The book [19] was used as the main source for specifying collisions between two neutral species and between neutral and charged components. If the required cross section was not found in the book [19] then we acted as follows.

When considering collisions between two neutral components it was assumed that the cross section can be described by the Lennard-Jones interaction potential [20], the main interaction parameters were taken from [21, 22] using rules given in [22].

When considering collisions between neutral and charged components it was assumed that the cross section can be described by the polarization potential, the parameters of which were taken from [21, 22].

The collision of two charged components was described by a screened Coulomb potential [23].

A series of calculations were carried out for a pressure range of 0.3–1.0 atm and a temperature range of 1000–30 000 K with the following proportions of basic chemical elements included into the system:

Si:O:C:H=1:1:2:6; Fe:O=1:10.

These ratios were determined using a condition that the walls of the discharge chamber are made of silicone rubber and the electrodes are made of steel.

The ratio Fe:O=1:10 was made on the basis of experimental studies of the plasma composition at a discharge in the chamber of the multi-chamber arrester.

The obtained dependences [24] of plasma properties on the electron temperature and the heavy particles temperature were used in the further mathematical model.

2.2. Mathematical model

A mathematical model of non-equilibrium plasma processes of a pulsed arc discharge in a discharge chamber of a multi-chamber arrester was developed using the package ANSYS Fluent.

In this paper, a two-temperature plasma model was used. This model was described in detail in [25], a chemical equilibrium was assumed.

In addition to the equations of gas dynamics and the energy equation of heavy particles, which are standardly solved in ANSYS Fluent, the following equations were included into the mathematical model using the UDF (user-defined functions) interface: the energy equation for electrons, the equation for scalar electric potential and the equation for vector magnetic potential [25].

A calculation domain including both the space inside the discharge chamber and the plasma jet region is shown in Fig. 3. The task was solved in a two-dimensional formulation.

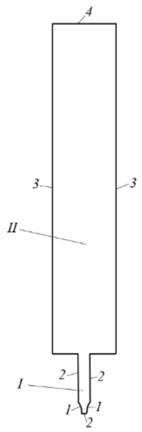

Fig. 3. Calculation domain: I – the space inside the discharge chamber; II – the plasma jet region; 1 – electrodes; 2 – walls of the discharge chamber; 3 – symmetry boundary; 4 – outlet (ambient pressure)

The computational mesh consisted of 55 000 triangular control volumes.

The boundary conditions were defined as follows. A value of scalar potential difference was set at the electrodes (Fig. 3, boundaries 1) so that to provide the necessary discharge current (see below). The ablation of the walls of the discharge chamber was taken into account (Fig. 3, boundaries 2), i.e. a source of mass was considered on the wall. Its value was calculated from the condition that all power transferred to the wall was spent on the evaporation of the wall material. Borders 3 (see Fig. 3) were considered as symmetry boundaries since the arrester has a multi-chamber design (it means that the same chambers are located to the left and right of the considered discharge chamber). The ambient pressure was set at the boundary 4 (Fig. 3).

3. Results

Simulation was carried out for the time range from 0 to 250 μs for two cases: ambient pressure was 1 atm and 0.3 atm. Examples of the obtained results i.e. temperature distributions for time t = 150 μs are shown in Figs. 4, 5.

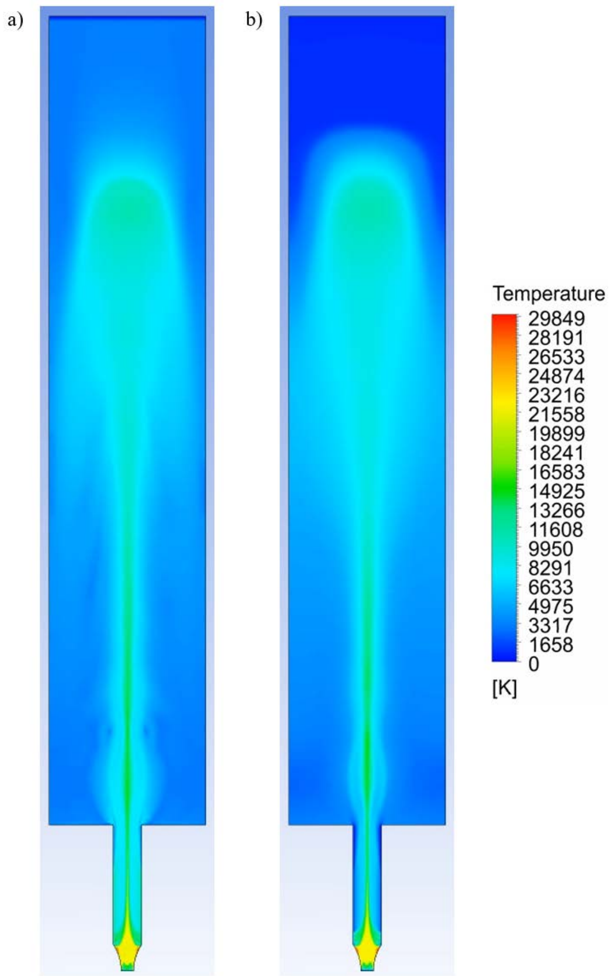

Fig. 4. Distributions of electron temperature (a) and temperature of heavy particles (b) at time t = 150 μs (p = 1 atm)

Comparison of the electron temperature and heavy particle temperature distributions in Figs. 4 and 5 shows that the plasma in considered model is close to thermal equilibrium which is explained by the presence of molecular components in the plasma [26] and the assumption of chemical equilibrium.

In both cases the experimental dependence of the discharge current on time was used. To reduce the computation time, only the first 250 μs and 150 μs before current zero were used. The graph of the used dependence of the discharge current on time is shown in Fig. 6.

The time dependences of the voltage providing the given current for pressure of 1 atm and 0.3 atm are shown in Fig. 7. It is seen that at the end of the time dependences the voltage on the discharge chamber is greater in the case of a pressure of 1 atm than in the case of a pressure of 0.3 atm. This suggests that with decreasing pressure the breaking capacity of multi-chamber arresters decreases.

A conductivity of the discharge gap was calculated on the base of the obtained data (see Fig. 8).

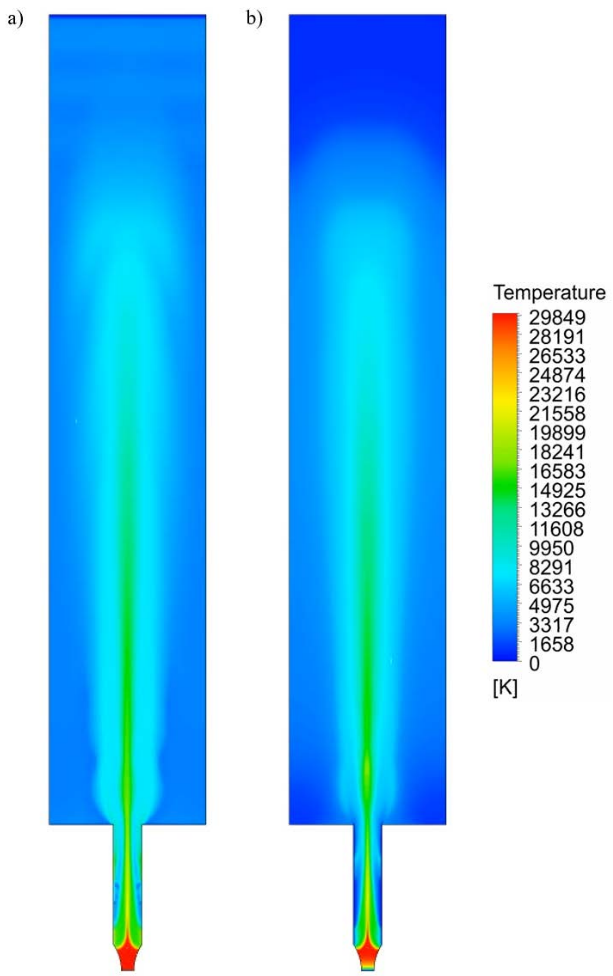

Fig. 5. Distributions of electron temperature (a) and temperature of heavy particles (b) at time t = 150 μs (p = 0.3 atm)

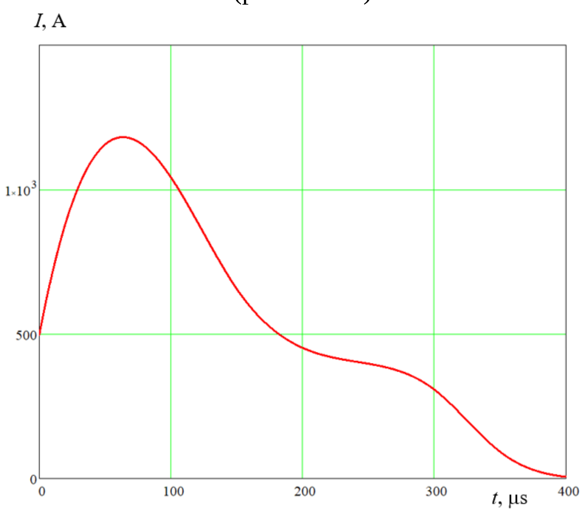

Fig. 6. A dependence of the discharge current on time

It can be seen (Fig. 8) that at the end of the time dependences the conductivity of the discharge gap at a pressure of 0.3 atm is 20% higher than the conductivity at a pressure of 1 atm.

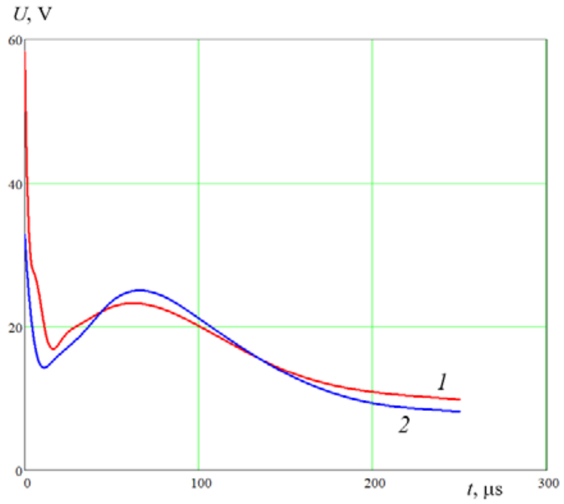

Fig. 7. The dependence of the discharge voltage on time for operation at different pressures: 1 – 1 atm, 2 – 0.3 atm

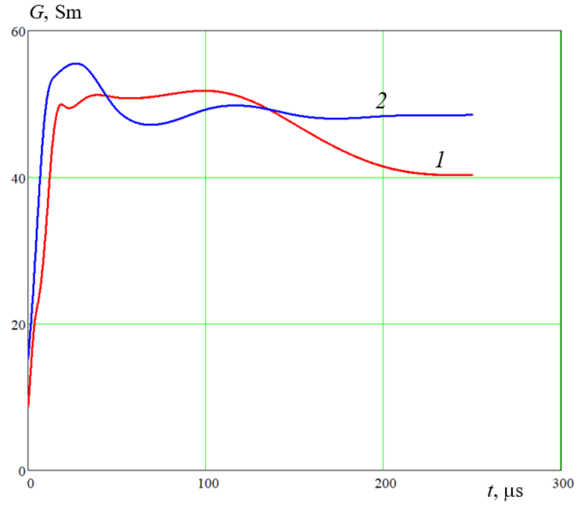

Fig. 8. The dependence of the discharge conductivity on time for operation at different pressures: 1 – 1 atm, 2 – 0.3 atm

4. Conclusions

To clarify the characteristics of the breaking capacity of multi-chamber arresters it is necessary to improve the mathematical model, namely, to take into account the disturbance of chemical equilibrium.

5. References

[1] G.V. Podporkin, E.Yu. Enkin, E.S. Kalakutsky, V.E. Pilshikov, A.D. Sivaev, X Int. Symp. on Lightning Protection, 569 (2010).

[2] R. Kozakov, A. Khakpour, S. Gorchakov, D. Uhrlandt, D. Ivanov, I. Murashov, G. Podporkin, V. Frolov, Plasma Phys. Technology, **2(2)**, 150 (2015).

[3] G.V. Podporkin, Plasma Phys. Technology, **2(3)**, 241 (2015).

[4] M.E. Pinchuk, A.V. Budin, I.I. Kumkova, (...), A.N. Chusov, R.I. Zaynalov, J. Phys.: Conf. Series **774(1)**, 012187 (2016).

[5] V.Y. Frolov, D.V. Ivanov, Y.V. Murashov, A.D. Sivaev, Technical Physics Letters, **41(4)**, 310 (2015).

[6] V. Frolov, D. Ivanov, I. Murashov, A. Sivaev, Proc. 2016 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conf., ElConRusNW 2016, 562 (2016).

[7] A.N. Chusov, G.V. Podporkin, M.E. Pinchuk, D.V. Ivanov, I. Murashov, V.Ya. Frolov, Proc. 33rd Int. Conf. on Lightning Protection (2016).

[8] Zhiwei Guo, Xinping Long, Zhongdong Qian, Ning Qiu, AIP Advances, **6**, 045117 (2016).

[9] V.Y. Frolov, D.V. Ivanov, R.A. Belsky, Proc. 2017 IEEE Russia Section Young Researchers in Electrical and Electronic Engineering Conf., ElConRus 2017, 1520 (2017).

[10] V.Y. Frolov, D.V. Ivanov, G.V. Podporkin, A.D. Sivaev, 2017 Int. Symp. Lightning Protection, XIV SIPDA 2017, 240 (2017).

[11] M.I. Boulos, P. Fauchais, E. Pfender, Thermal Plasmas: Fundamentals and Applications, Vol. 1. (1994).

[12] M. Capitelli, G. Colonna, A. D'Angola, Fundamental Aspects of Plasma Chemical Physics: Thermodynamics (2011).

[13] Thermodynamic and Thermophysical Properties of Combustion Products, Ed. by V. P. Glushko, Vols. 1 (1971) [in Russian].

[14] A.L. Suris, Thermodynamics of High-Temperature Processes (1985) [in Russian].

[15] V.Ya. Frolov, D.V. Ivanov, J. Phys.: Conf. Ser., **1058(1)**, 012040 (2018).

[16] NIST Atomic Spectra Database: http://physics.nist.gov/PhysRefData/ASD/index.html

[17] Thermodynamic Properties of Individual Substances: Reference Book, Ed. by V. P. Glushko et al., 3rd ed. (1978–1982), Vols. 1–4 [in Russian].

[18] M.W. Chase, Jr., Editor. NIST-JANAF Thermochemical Tables, J. Phys. Chem. Ref. Data. Monograph No. 9 (Part I and II) (1998).

[19] M. Capitelli, D. Bruno, A. Laricchiuta, Fundamental Aspects of Plasma Chemical Physics: Transport (2013).

[20] J.O. Hirschfelder, C.F. Curtiss, R.B. Bird, Molecular theory of gases and Liquids (1966).

[21] Y. Cressault, R. Hannachi, Ph. Teulet, A. Gleizes, J.-P. Gonnet, J.-Y. Battandier, Plasma Sources Sci. Technol., **17**, 035016 (2008).

[22] P. Andre, J. Aubreton, S. Clain, M. Dudeck, E. Duffour, M.F. Elchinger, B. Izrar, D. Rochette, R. Touzani, D. Vacher, Eur. Phys. J. D, **57**, 227 (2010).

[23] E.A. Mason, R.J. Munn, F.J. Smith, Phys. Fluids, **10(8)**, 1827 (1967).

[24] D. Ivanov, V. Skornyakov, I. Savelieva, M. Korotkikh, V. Shestakov, D. Uhrlandt, G. Podporkin, MATEC Web of Conferences, **245**, 07003 (2018).

[25] P. Freton, J.J. Gonzalez, Z. Ranarijaona, J. Mougenot, J. Phys. D: Appl. Phys. **45**, 465206 (2012).

[26] S.V. Dresvin, ed. Physics and technology of low-temperature plasmas, 1977.