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Thermal Radiation Effect on the Extinction Properties of Electric Arcs in HV Circuit Breakers

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Abstract: During the formation of the electric arc at the opening of a high voltage circuit breaker, the generated plasma will be the seat of a very important thermal exchange. Models founded only on conduction and convection thermal transfers don't reproduce the whole thermal exchanges that are governing the extinction process. This paper is devoted to the development of a model of the electric arc extinction in a high voltage circuit breaker taking in account the thermal radiation of the plasma, in addition to the conduction and convection phenomena. The Stefan-Boltzman equation is coupled with the heat equation, and both equations are solved simultaneously in order to follow the evolution of the arc voltage and the conductance of the thermal plasma. The obtained results are found in good agreement with experimental recordings.

Keywords: Electric arc modeling, Circuit breaker, Thermal radiation

1 Introduction

The interruption of a short circuit current in circuit breakers passes by the creation of an electric arc constituted by a thermal plasma which is composed by ions and electrons coming from the dielectric (air, SF6) and from metallic vapours issuing from the electrodes. The arc thus produced has a very elevated temperature, of the order of 15000K [1], and is going to exchange heat with the surrounding medium by three modes: thermal conduction, convection and radiation. Most of the existing arc models [2,3] consider the modes of heat transfer to be due to conduction and convection. A summary on the different types of arc models and their applications can be found in [4]. Usually, they do not consider the physical processes in detail.

A thermal exchange by radiation will be introduced in our computations in order to improve these classical models. On the other hand, the Boltzman's equation [5] is added to the system in order to introduce the conductance of the electric arc. Finally, we will realise a coupling between the two equations of the

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system and the expression of the dissipated energy in order to follow the evolution with time of this latter.

2 Power Radiated by a Thermal Plasma

The transfer of the heat by thermal radiation is fundamentally different from the two other modes of transfer, because plasma is going to exchange heat with the surrounding medium by electromagnetic wave emission.
Boltzman's equation [5, 6] enables to calculate the power emitted per surface unit by a thermal plasma heated at a temperature T.

$$P_R = \varepsilon \cdot \sigma \left(T^4 - T_0^4 \right),$$

where ε is the plasma emissivity,

T - the temperature in Kelvin,

T_0 - the external temperature,

σ - Boltzman's cœfficient, $\sigma = 5.67 \cdot 10^{-8}$ Wm^{-2}K^{-4}.

3 Electric Arc Model [2]

Generally, to describe the behaviour of the arc, one uses the equation of the total energy conservation in the stationary regime coupled with Ohm's law, for a constant electric field E and a constant current I, that leads to the equation of Elenbaas-Heller [7]:

$$I = 2\pi E \int_0^R \sigma \, \mathrm{d}r, \tag{1}$$

$$\sigma E^2 + \frac{1}{r} \frac{\mathrm{d}}{\mathrm{d}r} \left(r K_T \frac{\mathrm{d}T}{\mathrm{d}r} \right) = 0, \tag{2}$$

where σ, T, K_T and r are respectively the electric conductivity, the temperature, the thermal conductivity and the distance between the cylindrical plasma and the considered point. This equation will be solved through a cylinder of radius R.

4 Proposed New Formulation for Arc Model Before Current Zero

4.1 Conductance model by thermal radiation

The arc will be considered as a resistive column of constant section S and resistivity ρ. Cassy's assumption that the arc extinction will be due to its section increasing, will be assumed.

From the fact that the arc is created within the plasma and heated at a very high temperature (10000 to 100000 K) [7], a certain thermal energy will be emitted by electromagnetic radiation at the time of its formation. So, the total electric power provided to the arc can be written:

$$P = ui = P_p + \frac{\mathrm{d}Q}{\mathrm{d}t} + P_R\,, \tag{3}$$

where P is the total electric power provided to the arc, $u(t)$ the arc voltage and $i(t)$ the current.

P_p : The power lost by thermal convection.

P_R : The power lost by radiation.

$\frac{\mathrm{d}Q}{\mathrm{d}t}$: The necessary power to the arc creation.

The conductance is considered to be the best parameter that permits to prejudge on the ability of a gas to recover its dielectric rigidity in a given lapse of time. In order to establish an electric equation governing the formation of the arc, we must assume that the conductance of the arc is only a function of its heat content Q.

The following differential equation describes the rate of change of the arc conductance.

$$g = g(Q)\,. \tag{4}$$

From equation (3), we deduce $\frac{\mathrm{d}Q}{\mathrm{d}t}$

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = P - P_P - P_R\,,$$

or

$$\mathrm{d}Q = \left(P - P_P - P_R\right)\mathrm{d}t\,.$$

By differentiating eq. (4) with regard to time, and by multiplying and dividing by $\mathrm{d}Q$:

$$\begin{gathered}\frac{\mathrm{d}g}{\mathrm{d}t} = \frac{\mathrm{d}g}{\mathrm{d}Q} \times \frac{\mathrm{d}Q}{\mathrm{d}t}\,,\\ \frac{\mathrm{d}g}{\mathrm{d}t} \times \frac{1}{g} = \frac{\mathrm{d}g}{\mathrm{d}Q} \cdot \frac{1}{g}\left(P - P_P - P_R\right) = \frac{\mathrm{d}g}{\mathrm{d}Q \cdot g}\left(P - P_P\right) - \frac{\mathrm{d}g}{\mathrm{d}Q \cdot g} \times P_R.\end{gathered} \tag{5}$$

The conductance per length unit of the arc can be expressed by:

$g = \frac{S}{\rho}$, where ρ and S are respectively the resistivity and the surface of the arc column, then we can deduce the arc section: $S = g \cdot \rho$.

By using the arc surface in Cassie's hypothesis [2], relative to the energy Q necessary to the creation of the arc and to the power P_p spent by thermal convection:

$Q = SC$ and $P_P = S\lambda$ where C and λ are constants of proportionality.

One find:

$$Q = g\rho C \text{, with } \frac{\mathrm{d}g}{\mathrm{d}Q} = \frac{1}{\rho C}.$$

By substituting this relation in equation (5), we find:

$$= \frac{\mathrm{d}g}{\mathrm{d}t \cdot g} = \frac{1}{\rho C g}\left(P - P_P\right) - \frac{1}{\rho C} \cdot \frac{P_R}{g}. \tag{6}$$

And, since the power provided to the arc is $P = ui(t)$, the current trough this arc is $i(t) = gu$ and the power lost by thermal convection is $P_P = gu_a^2$ [2], where u_a is the arc voltage.

Equation (3) becomes:

$$\frac{\mathrm{d}g}{\mathrm{d}t \cdot g} = \frac{1}{\rho C}\left(u^2 - u_a^2 - \frac{P_R}{g}\right), \tag{7}$$

leading to:

$$\frac{\mathrm{d}g}{\mathrm{d}t \cdot g} = \frac{u_a^2}{\rho C}\left(\frac{u^2}{u_a^2} - 1 - \frac{P_R}{g u_a^2}\right). \tag{8}$$

On the other hand,

$$P_P = S\lambda = gu_a^2$$

and

$$u_a^2 = \frac{S\lambda}{g} = \rho\lambda.$$

By replacing this expression in equation (7), we obtain:

$$\frac{\mathrm{d}g}{\mathrm{d}t \cdot g} = \frac{\rho\lambda}{\rho C}\left(\frac{u^2}{u_a^2} - 1 - \frac{P_R}{g u_a^2}\right).$$

After simplification and setting $\frac{\lambda}{C}=\tau$ and $gu_a^2 = P_P$, where τ represents the deionisation time of the dielectric.

One obtains finally:

$$\frac{\mathrm{d}g}{\mathrm{d}t\cdot g}=\frac{1}{\tau}\left(\frac{u^2}{u_a^2}-1-\frac{P_R}{P_P}\right),$$

that can be written:

$$\frac{\mathrm{d}\ln g}{\mathrm{d}t}=\frac{1}{\tau}\left(\frac{u^2}{u_a^2}-1-\frac{P_R}{P_P}\right). \tag{9}$$

This equation expresses the variation of the conductance g as a function of the arc voltage $u(t)$.

τ is the time constant of the electric arc.

The Transient Recovery Voltage (TRV) which depends on the characteristics of the circuit where the breaker is placed has been supposed to evolve more slowly than the arc voltage in order to eliminate the hypothesis of dielectric breakdown.

Thus, by expressing the thermal power radiated by the plasma by Boltzman's equation, we finally obtain:

$$\frac{\mathrm{d}\ln g}{\mathrm{d}t}=\frac{1}{\tau}\left(\frac{u^2}{u_a^2}-1-\frac{\sigma\varepsilon_R\left(T^4-T^4{}_0\right)}{gu_a^2}\right).$$

This new equation introduces an important parameter which is the temperature of the plasma.

If we neglect the term of radiation in this equation, one finds Cassie's equation [2].

$$\frac{\mathrm{d}\ln g}{\mathrm{d}t}=\frac{1}{\tau}\left(\frac{u^2}{u_a^2}-1\right)$$

In the first step of the study, we set $f=\frac{P_R}{P_P}$ in order to estimate the contribution of the exchanged thermal power by radiation in relation with the power lost by thermal convection. The obtained equation can be finally written:

$$\frac{\mathrm{d}\ln g}{\mathrm{d}t}=\frac{1}{\tau}\left(\frac{u^2}{u_a^2}-1-f\right). \tag{10}$$

4.2 Coupling of the arc model with the heat equation:

In the second step, the obtained equation (10) will be coupled with Boltzman's equation and the heat equation. Then, we obtain a system of two differential equations.

$$\frac{\mathrm{d}\ln g}{\mathrm{d}t} = \frac{1}{\tau}\left(\frac{u^2}{u_a^2} - 1 - \frac{\sigma\varepsilon_R(\nu)}{g u_a^2}\right), \tag{11}$$

$$\rho c \frac{\partial T}{\partial t} - \vec{\nabla}\left(K_T \cdot \vec{\nabla}(T)\right) = h(T_0 - T), \tag{12}$$

where T is the plasma temperature in Kelvin,

T_0 is the external temperature,

ρ - The density of the gas (SF6 or air) in kg/m^3,

c - the specific heat of the gas in J/kg/K,

K_T - the thermal conductivity of the gas in W/m/K,

h - the thermal exchange factor in W/K.m^2.

The arc that is created between the circuit breaker poles corresponds to discharges in gases at temperatures situated between 10000 and 100000K [1]. The thermal transfer by conduction can be neglected with regard to the thermal exchange created by forced convection [6]. In the present simulation, only the cooling by forced convection is considered.

5 Arc Breaking Simulation and Results

The mechanism of current breaking is based on the separation of contacts that involves an arc formation in order to limit the electric current. In practice, the breaking of short circuit currents takes place at the passage of a sinusoidal current by zero. The considered current in this simulation, set to 100% of the breaking capacity, is assumed to be: $i(t) = 50000\sqrt{2}\sin(314t)$ [A] in a circuit breaker of characteristics 245kV/50kA/50Hz, which has been experimentally investigated by Shavemeker and Van der Sluis [1].

This work is focused on the influence of the thermal radiation on the arc voltage and the conductance of the plasma. The computations are performed for two breaking mediums: SF6 and air. In order to be able to compare our results and to be closer with the real conditions, the initial conductance of the plasma is taken equal to 10^4 Sm^{-1} for SF6 and 3600 Sm^{-1} for air [1]. The 4-th order of Runge Kutta method is used to solve the system of equations. It permitted us to draw the variations of the current for times varying between 0 and 90s (Fig. 1) and the evolution of the arc voltage for several values of f (Figs. 2 and 3). The constant of time has been taken equal to 1.2μs and $u_c = 3.8\,\mathrm{kV}$.

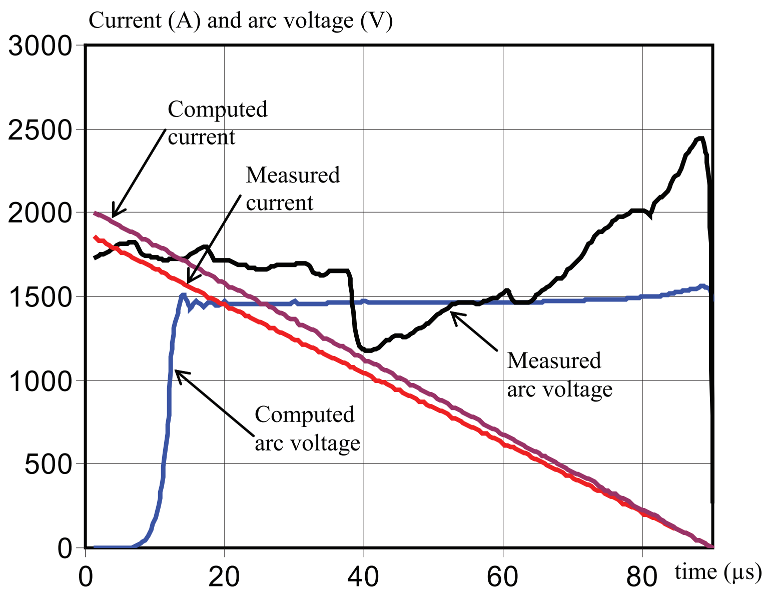

Fig. 1 – *Computed and measured* [1] *current and arc voltage variations in* SF6.

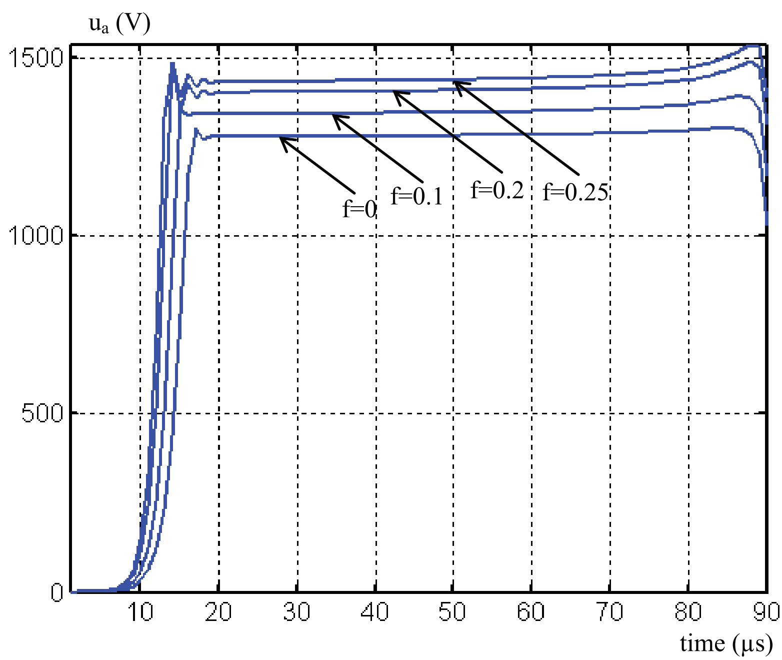

Fig. 2 – *Evolution of the arc voltage u_a in* SF6 *for different radiation factors*.

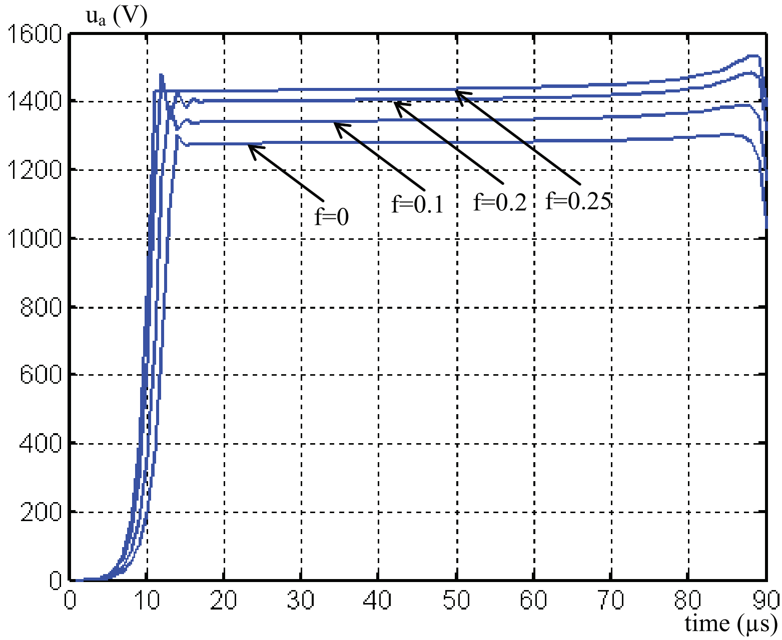

Fig. 3 – *Evolution of arc voltage u_a in air for different radiation factors.*

Fig. 2 represents the variations of the arc voltage when a circuit beaker is opened in SF6 for different factors *f* of energy radiation. One sees that the arc voltage increases in time, which has for consequence to limit the growth of the short circuit current. The increase of thermal radiation is enough significant so that the maximal value of the arc voltage passes from 1280V for $f = 0$ to 1420V for $f = 0.25$.

The same shape of curve is obtained for plasma in air, except that the growth of the arc voltage begins with a greater slope.

6 System Solving for SF6

We assume that plasma is a perfect gas in local thermodynamic equilibrium. The radiating surface of the plasma was set constant for three temperatures 10000K, 15000K and 20000K. The emissivity ε_r, and the values of ρ, *c* and *h* have been deducted from [5,8].

The system of equations was solved by Runge-Kutta method for the three initial temperatures (10000K, 15000K and 20000K), and with an initial conductance of 10^4 Sm^{-1} for SF6.

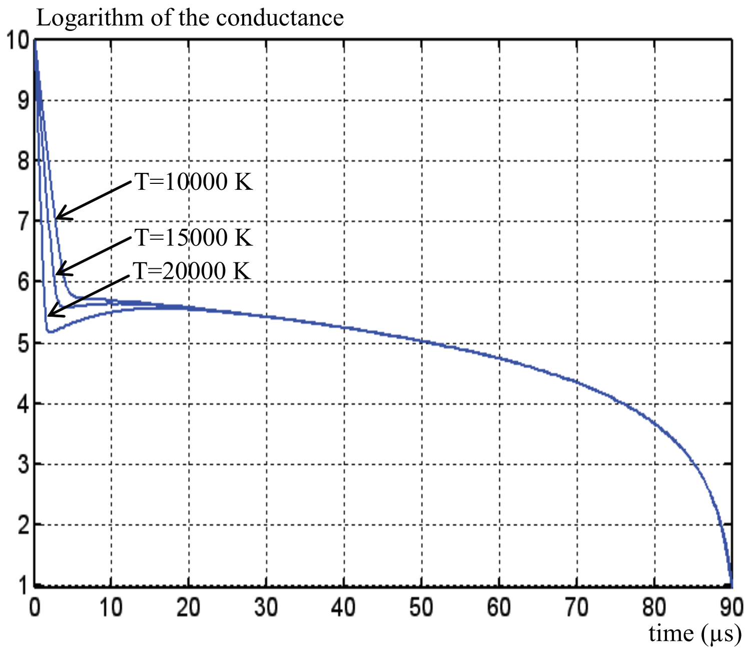

Fig. 4 – *Evolution of the logarithm of the conductance in* SF6 *for different initial temperatures.*

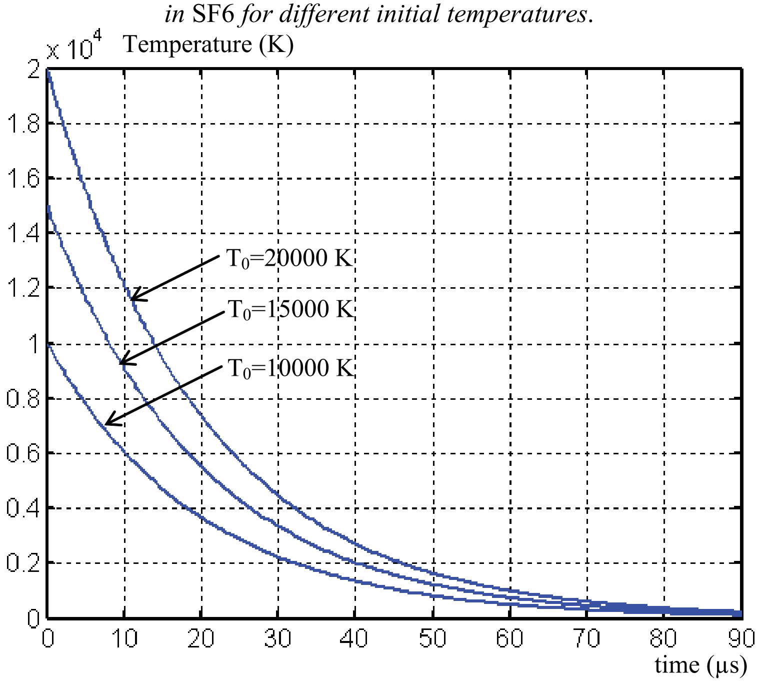

Fig. 5 – *Temperature evolution in* SF6 *for different initial temperatures.*

The variations of the logarithm of the conductance (Fig. 4) show the effect of the thermal radiation at the first instants of breaking, which are lower than 20µs. We note through these curves that the decrease of the conductance is faster for the most radiating plasmas at these instants. This phenomenon can be interpreted by the fact that the thermal power of radiation that propagates by electromagnetic waves is not extended in time but it is rather localized and instantaneous. One also notices on Fig. 5 that the evolution of plasma temperatures for the three initial temperatures, allows the current breaking because the dielectric recovers its properties after a time $t = 90\mu s$, knowing that SF6 begins to be decomposed and loses its insulating properties at temperatures greater than 2100K.

7 Dissipated Energy at the Circuit Breaker Opening

The total energy dissipated at the breaking time of the circuit is given by:

$$W = \int_0^{T_f} u(t)i(t)\,\mathrm{d}t\,, \tag{13}$$

where T_f is the overall breaking time.

This equation can be written as:

$$\mathrm{d}W = u(t)i(t)\,\mathrm{d}t\,,$$

or finally:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{i^2}{g}\,. \tag{14}$$

In order to be able to assess this energy, equation (14) was coupled with the differential equations (11) and (12) for finally obtaining a system of 3 equations with 3 unknowns.

The numerical method of Runge Kutta is used in order to solve this equation system as a function of time, where g, T and W are the variables. The same initial conditions as follows are considered for the conductance and temperature. For the dissipated energy, we consider $W = 0$ at $t = 0\,\mathrm{s}$. A typical result is reported on Fig. 6. We can note that the energy dissipated by the circuit breaker is higher in the case where thermal radiation is taken in account. The energy value overtakes 0.25kJ at the end of the breaking, improving thus the breaking performances of the apparatus.

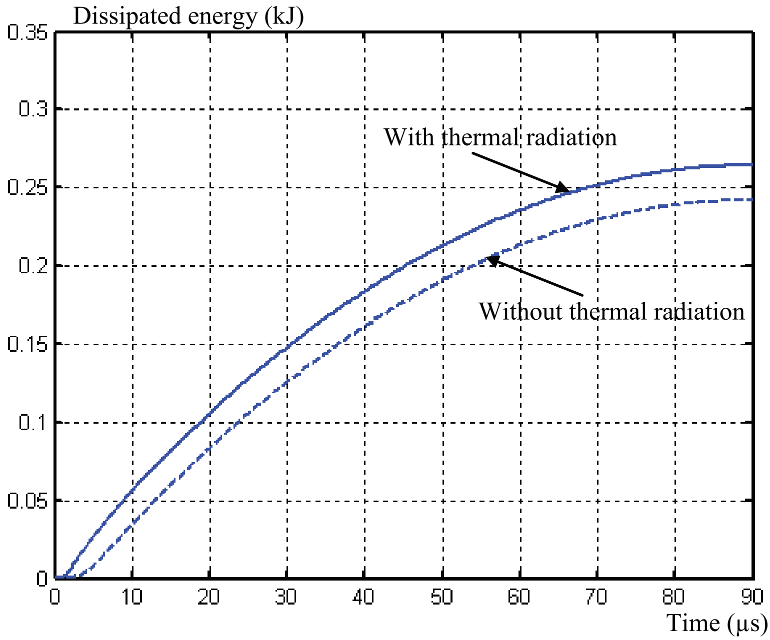

Fig. 6 – *Energy dissipated by the arc as a function of time.*

8 Field of Temperature

Temperature is the best parameter that describes the extinction of plasma. By the use of the software Matlab-PDEtool, the heat equation (12) has been solved numerically by finite elements. This method is well adapted to perfect gases in two dimensions domain. Limit conditions as of Dirichlet type ($hT = r$) have been applied to contours on a rectangular domain. Cooling of air plasma by forced convection is simulated for a final position of tungsten electrodes and for an initial temperature of 10000K. The cathode temperature has been estimated by the use of Richardson-Dushmann formula:

$$J(T,\phi) = \frac{4\pi e m_e}{h^3}(K_B T)^2\, \mathrm{e}^{-\phi/K_B T},$$

where, e is the electron charge, m_e its mass, h the Planck constant and φ the energy of electrons extraction (2.67eV).

For a current of 50kA crossing a cathodic surface of 10mm^2, an electronic density of 5.10^9A/mm^2 was found, corresponding to a temperature of 3800K. This temperature is then used to fix the limit values at the electrodes.

Figs. 7a, 7b and 7c relative to 1, 30 and $90\,\mu\text{s}$, show chronologically the evolution of the field of temperature inside the plasma, through which one notes a cooling of the gas that will enable it to recover its dielectric properties.

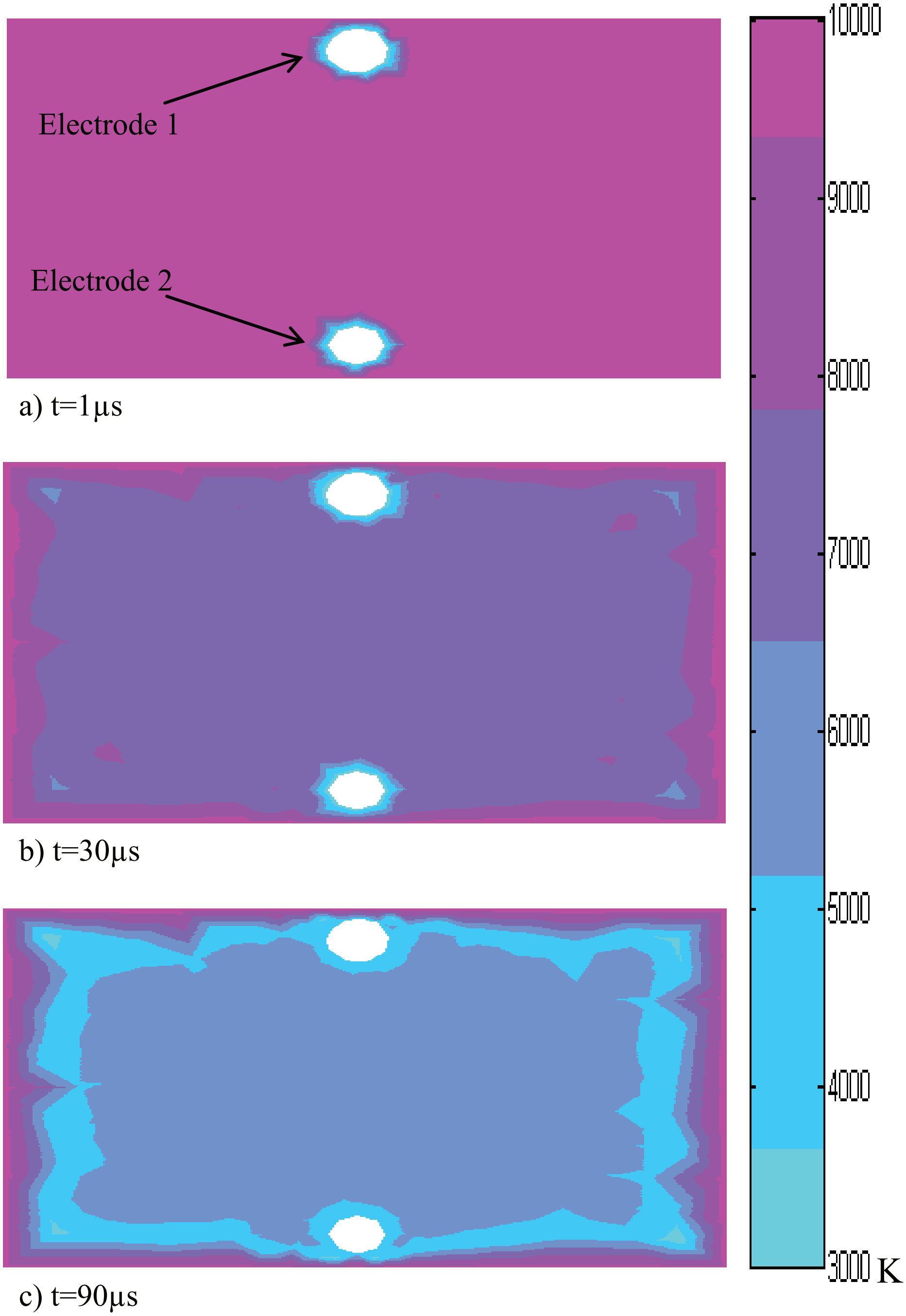

Fig. 7 – *Plasma field of temperature at*: a) $t = 1\mu s$; b) $t = 30\mu s$; c) $t = 90\mu s$.

9 Conclusion

The effect of the radiated heat represents a significant part of the whole injected energy. It appears at the first breaking instants corresponding to high currents which are greater than 15000A (concentric arc regime). The developed arc model enables to take in account the thermal exchange by electromagnetic radiation. It ensues from a more realist energy balance.

The system of equations proposed in this paper enables to yield a mathematical representation of the extinction of gaseous plasma in circuit breakers. The whole of the obtained results shows well that the arc voltage values are influenced by this thermal exchange, and increase with the latter. Actually, since the considered temperatures are greater than the temperatures of metal electrodes fusion, their evaporation during the formation of the arc will modify the radiation properties of the plasma, notably the coefficient of emission. The dissipated power in the circuit breaker $\int ui(t)\,\mathrm{d}t$ is thus improved. Moreover, the coupling of the basic equation with Boltzman's equation and the heat equation enabled us to evaluate and enlighten the influence of the initial temperature on the conductance.

10 References

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