

COMPUTATIONAL INVESTIGATION OF EFFECTS OF SF₆, CO₂ AND N₂ ON ARC INTERRUPTION IN A SUPERSONIC NOZZLE

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ABSTRACT

Supersonic nozzles are commonly used in modern high voltage circuit breakers. The thermodynamic and electrical behaviour of arcs burning in such nozzles is closely related to the nozzle geometry, the quenching and insulating medium, and the parameters of the medium at the nozzle inlet and exit.

Computational investigation has been carried out on the thermal interruption capability of a supersonic nozzle with different quenching and insulating mediums. The critical rate of rise of recovery voltage (RRRV), which is the most important parameter determining the thermal interruption capability of a circuit breaker, was predicted for three gases of SF₆, CO₂ and N₂ under typical practical operation conditions.

1. INTRODUCTION

A key element in a high voltage circuit breaker is the arcing chamber where current interruption is carried out. A supersonic nozzle is commonly used as the arcing chamber. Gases or their mixtures are used as a working medium to flow through the nozzles to provide the desired characteristics. For high-voltage circuit breakers, SF₆ is currently used as its excellent insulating and switching capabilities. However SF₆ is a strong greenhouse gas with a life time of 3200 years and a global warming potential (GWP) of 22800 in comparison with CO₂ which has a GWP of 1.0 [1]. The replacement of SF₆ with a more environmentally friendly gas is becoming an increasingly interesting research topic [2] and practically important issue for power equipment manufacturers and network operators [3].

The thermal interruption capability of the supersonic nozzle with SF₆ has been computationally investigated by Zhang et al [4]. The predicted results of RRRVs have been compared with the test values of Campbell et al [5] in a wide range of inlet stagnation pressure and exit—inlet stagnation pressure ratios. The work reported here is an extension of the work in [4]. It focuses on the effects of the material properties (thermodynamic and transport properties) of the different mediums on arc extinction. The supersonic nozzle of Campbell et al [5] used in [4] is also used in the present work for the comparison's sake. Three gases of SF₆, CO₂ and N₂ have been investigated. The thermal recovery and dielectric recovery processes following the extinction of an arc in the supersonic nozzle have been simulated. The RRRVs have been predicted for the three different quenching and insulating mediums under typical practical operation conditions. The causes for the different interruption capability of the three gases were analysed in detail and particularly the roles of material properties played in such processes were considered.

2. ARC MODEL

Since the flow in a supersonic nozzle is axis-symmetric, the governing equations that describe the arc behaviours in the nozzle can be written in cylindrical polar coordinates (r, z) system:

$$\frac{\partial \rho \varphi}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left[r \rho v \varphi - r \Gamma \frac{\partial \varphi}{\partial r} \right] + \frac{\partial}{\partial z} \left[\rho w \varphi - r \Gamma \frac{\partial \varphi}{\partial z} \right] = S_{\varphi} \quad (1)$$

Where φ , Γ and S_{φ} are, respectively, the dependent variable, the diffusion coefficient, and the source terms, which are listed in Table 1 for the mass, momentum, and energy equations.

Table 1 Source terms and diffusion coefficients for governing equations

Equation	Dependent variable	Diffusion coefficient	Source term
Continuity	ρ	0	0
Momentum in z direction	w	$\mu_l + \mu_t$	$-\partial P/\partial z + \text{viscous terms}$
Momentum in r direction	v	$\mu_l + \mu_t$	$-\partial P/\partial r + \text{viscous terms}$
Energy (Enthalpy)	h	$(k_l + k_t)/c_p$	$\sigma E^2 - q + dP/dt + \text{viscous dissipation}$

Since the arcing current investigated is relatively low, the Lorentz force generated by the current interacting with its own magnetic field is neglected in comparison with the imposed pressure gradient [4].

In equation (1) and Table 1, all notations have their conventional meaning. The subscript l denotes the laminar part of the transport coefficient and t stands for the turbulent component. q in the enthalpy equation represents the net radiation loss per unit volume and time. It is calculated with the approximate model of Zhang et al [6]. Equation (1) assumes local thermodynamic equilibrium. Thus, the thermal and transport properties are functions of pressure and temperature, which are tabulated and put into the program. The properties of SF₆ from Murphy [7], CO₂ from Yokomizu [8], and N₂ from Yos [9] are used. The gases are assumed to be ideal at temperatures below 500 K. The electric power input σE^2 in the energy source is calculated by a simplified Ohm's law:

$$i = E \int_0^\infty \sigma 2\pi r dr \quad (2)$$

where i is the current.

The mass, momentum, and energy fluxes at the inlet of the nozzle are calculated by isentropic relationships. Wall friction and energy loss by heat conduction at the nozzle and electrode surfaces are not taken into account because of their negligible effects on the arc behaviour. The stagnation pressure and the temperature at the nozzle inlet are fixed to 7.14 bar absolute and 300 K respectively. The exit-to-inlet stagnation pressure ratio is given to 0.2 to insure without the reverse flow generated for all of the cases simulated [4].

The nozzle and the two electrodes are arranged as shown in Fig. 1. A 1,000 Hz sinusoidal current with a peak value of 1,700 A, which gives a di/dt of 10.68 A/ μ s before current zero, will be used. As the peak current is far less than the current limitation of the nozzle clogging,

which is about 3.5 kA, nozzle ablation by arc radiation is negligible. For all the cases investigated the transient arc is initiated from the steady state solution of a 200 A DC arc under the corresponding pressure conditions since the solution of the conservation equations is virtually independent of the initial conditions as long as the initial DC current is below 200 A [4].

Turbulence-enhanced momentum and energy transport are modelled by the Prandtl mixing length model. The turbulent viscosity is calculated by:

$$\mu_t = \rho l_m^2 \left| \frac{\partial w}{\partial r} \right| \quad (3)$$

where the length scale, l_m , in the arc region is taken as a fraction of the arc thermal radius defined as the radial distance from the axis to the position of 4,000 K isotherm.

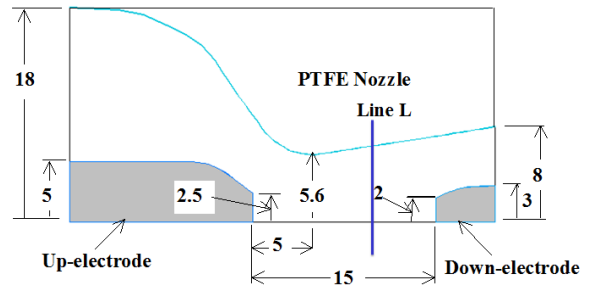


Fig. 1 Schematic Diagram of the Supersonic Nozzle with Dimension Indicated. Units: mm

3. RESULTS AND DISCUSSION

The conservation equations and the current continuity equation are solved by a commercial CFD package called PHOENICS [10]. Body fitted coordinates (BFC) are used to model the curved geometry of the nozzle and the electrodes. There are altogether 132 cells in the radial direction and 80 cells in the axial direction. To resolve the thin arc column under conditions of the small or zero arcing currents, 80 cells are used in the first 1.0 mm in the radial direction. The time step used before current zero

is 1.8×10^{-7} s and 1.0×10^{-8} s is used for the calculation of RRRV.

The plasma column and velocity vector in front of the downstream electrode for SF₆ case, which is taken as an example, are shown in Fig. 2. The flow circulation is formed in front of the electrode as a result of the adverse pressure gradient associated with the surrounding cold flow forms a hot stagnant patch there. The similar flow patterns in the front of the electrode appear in the cases of CO₂ and N₂.

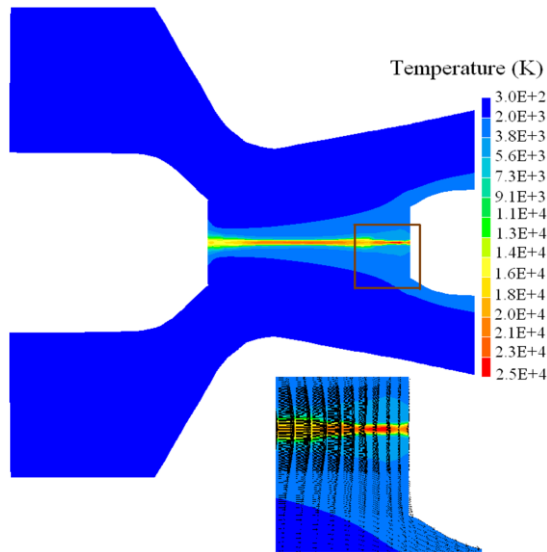


Fig. 2 SF₆ Residual plasma column and velocity vector in front of the downstream electrode at current 40 A before the current approaching its zero.

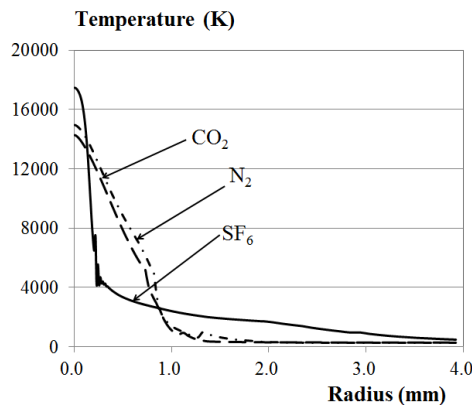


Fig.3 Radial temperature profiles on the line L (Fig. 1) at current 40 A before its zero for the three quenching mediums.

The radial temperature distributions on the line L (Fig. 1) at an instantaneous current of 40 A before current zero are shown in Fig. 3. The axis temperatures of SF₆ arc are highest between the three gases. However the SF₆ arc column is thinnest. The axis temperatures and the arc columns in CO₂ and N₂ cases are quite close with each other. The characteristic of the temperature distribution at the current of 40 A continues to

current zero. The radial temperature distributions on the line L at current zero are shown in Fig. 4.

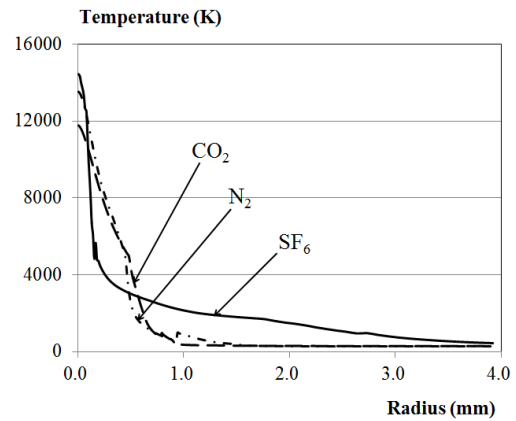


Fig.4 Radial temperature profiles on the line L (Fig. 1) at current zero for the three quenching mediums.

In fact the temperature profiles in the most of the arc region between the two electrodes are similar with those on the line L. Fig. 5 shows that the temperature distributions of the three arcs on the axis and on the radius of 0.3 mm between the two electrodes. SF₆ arc has still highest axial temperature and thinnest arc column in the most of the arc region. The temperatures of SF₆ arc are obviously lower than those of CO₂ and N₂ arcs in the majority region.

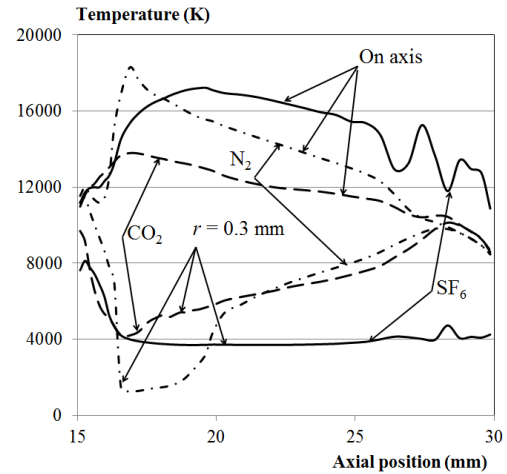


Fig. 5 Arc temperature distributions at current zero on the axis and on $r = 0.3$ mm. The different quenching mediums are indicated.

The thermodynamic state of the residual plasma at current zero determines the thermal recovery performance of the arc--nozzle system. The RRRV of the nozzle system is determined by applying a linearly increasing recovery voltage after current zero. The dv/dt of the recovery voltage is increased in small steps until it reaches a critical value at which the discharge current starts to increase rapidly after current zero, as shown in Fig. 6.

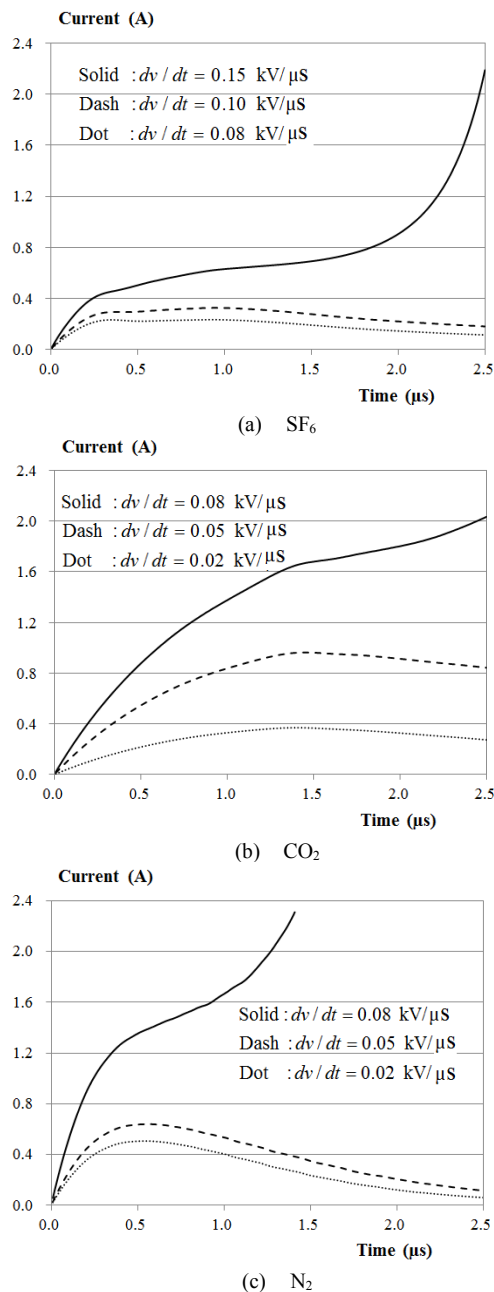


Fig. 6 Post-zero-current for different values of dv/dt . (a) SF₆ arc; (b) CO₂ arc; (c) N₂ arc.

4. CONCLUSION

Computational investigations have been made on the thermal recovery of a linear voltage ramp after current zero for the supersonic nozzle with a arcing current sinusoidally increasing to its peak of 1.7 kA before decreasing towards current zero at a frequency of 1,000 Hz. The influence of thermodynamic and transport properties has been studied for the three different quenching and insulating mediums of SF₆, CO₂ and N₂.

For the cases investigated, it is found that under the conditions of small or zero arcing current, the

temperature profiles of CO₂ and N₂ arcs are close to each other; the axial temperature of SF₆ arc are higher than those of CO₂ and N₂ arcs; while the SF₆ arc column is much thinner in the most of the arc regions. The thinner arc column dominates the critical rate of rise of recovery voltage (Fig. 6). The thermal interruption capability of SF₆ is about twice higher than those of CO₂ and N₂.

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