IMPROVED MODELING OF ABLATION PROCESS IN HIGH-VOLTAGE CIRCUIT BREAKERS FOR SWITCHING ARC SIMULATION

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ABSTRACT

The paper deals with the utilization of an improved model for the ablation process in the simulation of on-load switching-off processes in high-voltage circuit breakers (HVCBs). In order to describe the plasma arc behaviour, a transient axisymmetric model is used which is based on the @Fluent software. The presented arc model uses mixed formulations for the calculation of the self-induced magnetic field and the radiative transfer. The proposed ablation model is validated by the comparison of the measured and simulated ablated mass and pressure build-up in the heating volume. It is shown that the consideration of PTFE evaporation enthalpy in dependence on pressure yields to best agreement between experiment and simulation. Nevertheless, the approximation of the constant enthalpy stays in a satisfactory agreement with the measurements at the interruption current 25 kA.

1. INTRODUCTION

Nowadays CFD simulation improves the understanding of gas flow inside HVCBs and thus provides significant support in the development of new HVCBs. In order to perform a correct simulation of hot gas flow inside the interrupter unit (IU), a lot of physical sub models must be considered.

The evaporation of PTFE has a strong influence on the pressure distribution. In most of studies the PTFE evaporation is modelled under the assumption of a constant evaporation enthalpy [1]. In the present study we have improved the PTFE ablation model which considers variable evaporation enthalpy. The both approaches are proved experimentally. The simulation results are in a good agreement with the measurements.

2. NUMERICAL MODELS

A SF_6 self-blast circuit breaker is considered. The schematic diagram of the solution domain is presented in Fig. 1. The simulated interruption current is $I_{rms} = 25$ kA. In order to describe the plasma behavior in the HVCB, a system of coupled equations is solved. Due to the ablation of PTFE, a two species SF_6-C_2F_4 gas mixture is considered and the SF_6 mass fraction equation is solved. The Navier-Stokes equations describe the hot gas flow:

$$\frac{\partial \rho\phi}{\partial t} + \vec{\nabla} \cdot (\rho\phi\vec{v}) = \vec{\nabla} \cdot \left(\Gamma_\phi \vec{\nabla}\phi\right) + S_\phi. \quad (1)$$

In Equation (1) ϕ – is a variable to solve, ρ – is the mass density, $\vec{V}$ – is the velocity vector, Γ_ϕ – is the associated diffusion coefficient, S_ϕ – is the source term.

The electrical current distribution is calculated with the aid of Laplace equation:

$$\nabla \cdot (\sigma \nabla \varphi) = 0, \quad (2)$$

where φ – is scalar potential, σ – is electrical conductivity. In order to save computational cost, the magnetic field and the radiation transport are calculated by using the mixed formulation described in [2] and in [3]. For radiation, this formulation uses both P1 and DO models, depending on the thickness of the spectral bands.

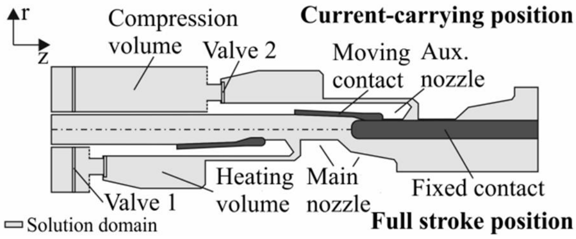

Fig. 1 Schematic diagram of a part of the solution domain

Inside the computation domain the calculation of magnetic field is based on the vector potential equations:

$$\nabla^2 \vec{A} - \frac{1}{c^2}\frac{\partial^2 \vec{A}}{\partial t^2} = -\mu_0 \vec{J}, \qquad (3)$$

where $\vec{A}$ – is magnetic vector potential, $\vec{J} = \sigma\, \nabla\varphi$ is the electrical current density. The boundary values of the vector potential $\vec{A}$ are calculated with the aid of Biot-Savart Law [2].

The improved PTFE ablation model is based on a 1D balance between the energy flux coming from the plasma (sum of the radiation and convection-conduction fluxes) and conduction within the PTFE nozzle. The ablation model takes into account pre-heating of PTFE walls, pyrolysis and evaporation. These effects are modelled by additional source terms in species, mass and energy transport equations and by specific boundary conditions. In this model, the PTFE walls are considered as non-deformable.

Two cases of evaluation of evaporation enthalpy are considered: constant value H_{vap} = 12 MJ/kg [4] and pressure dependent $H_{vap} = H_{vap}(P)$. The PTFE evaporation enthalpy H_{vap} = 11 MJ/kg obtained in the study [5] differs very slightly from [4] and it is to expect that the using of the enthalpy value [5] instead of [4] will have negligible influence to the solution of the gas dynamic equations (1).

The calculation of $H_{vap} = H_{vap}(P)$ is based on the Maximum Entropy Principle (MEP) which is used in [5]. In the ablation process the MEP principle is applied on the thin layer between the solid PTFE wall and the PTFE vapor in LTE (Local Thermal Equilibrium) state. The PTFE vapor mass production per unit area is:

$$\dot{M} = \rho v. \qquad (4)$$

Energy balance implies that

$$Q_{rad} = \dot{M}\left(h(T) - h(T_p) + H_{vap} + \frac{v^2}{2}\right), \quad (5)$$

where Q_{rad} is the radiation flux, $h(T)$ is the specific enthalpy of the ablated material and T_p is the pyrolysis temperature. The entropy production rate per unit area is:

$$\dot{S} = \dot{M}\left(s(T) - s(T_p)\right). \qquad (6)$$

If the PTFE vapor velocity near the wall is neglected mass flow from the Equation (5) can be substituted in the Equation (6):

$$\dot{S} = \frac{Q_{rad}\left(s(T) - s(T_p)\right)}{\left(h(T) - h(T_p) + H_{vap}\right)}. \qquad (7)$$

The PTFE evaporation enthalpy $H_{vap} = H_{vap}(P)$ is obtained by maximization of the Equation (7). The results are presented in Fig. 2.

In case of a small pressure the enthalpy value differs slightly from the values obtained in the study [4] and [5]. Still with increase of pressure the evaporation enthalpy decreases. It is to note that PTFE ablation from the main and auxiliary nozzles takes place in the arc chamber (see Fig. 1) where absolute pressure can rich the value of tens bars. According to the Fig. 2, such high pressure causes a remarkable difference of evaporation enthalpy compared to the studies [4] and [5].

The dynamic mesh is used to describe properly the motion of the valves and of the IU. The scaled drive velocity (solid line) and the interruption current I_{rms} = 25 kA (dashed line) are presented in Fig. 3. The simulated current trend is the same as in the experiment. The contact separation takes place at t = 12 ms. The current remains equaled to zero after t = 32 ms.

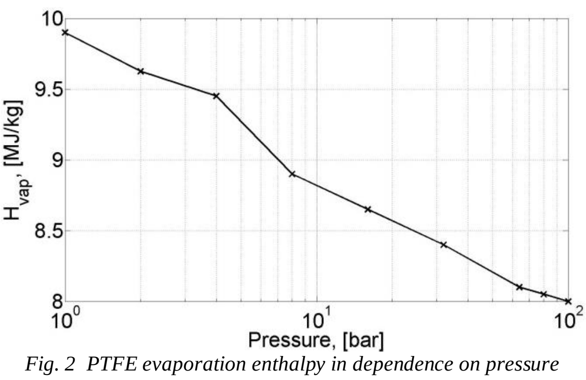

Fig. 2 PTFE evaporation enthalpy in dependence on pressure

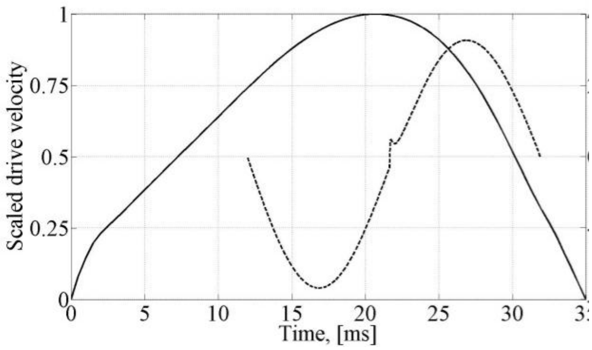

Fig. 3 Drive velocity and the interruption current

The motion of valves is controlled by the Second Newton's Law. The resulting force acting on the valve is computed from pressure distribution [6].

3. RESULTS AND DISCUSSION

The comparison of the pressure build-up for the interruption at I_{rms} = 25 kA is presented in Fig. 4. The abbreviation "Meas." means experimentally measured. It can be clearly seen, that the assumption of the constant PTFE evaporation enthalpy results in a lower pressure build-up in comparison to the measurements. On the contrary, the pressure build-up obtained under the assumption of the pressure dependent enthalpy is higher than pressure build-up obtained under assumption of H_{vap} = 12 MJ/kg and is in better agreement to the measurements. The reason of the higher build-up behavior is the larger amount of the ablated material. The amount of the ablated PTFE in case of $H_{vap} = H_{vap}(P)$ is approximately 44% higher for the main nozzle and approximately 53% higher for the auxiliary nozzle than in case of H_{vap} = 12 MJ/kg. The pressure build-up obtained under assumption of $H_{vap} = H_{vap}(P)$ is slightly higher than the measured one in its maximum but demonstrates very good agreement during decay phase.

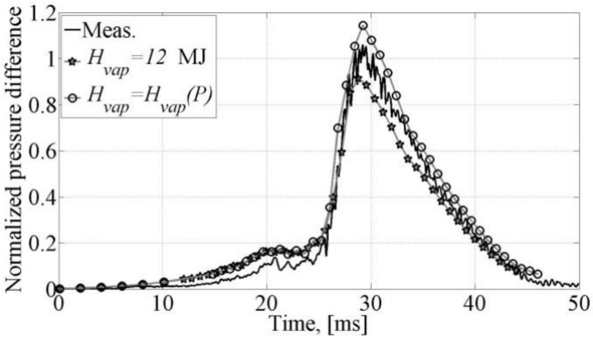

Fig. 4 Pressure build-up in the heating volume, I_{rms} = 25 kA

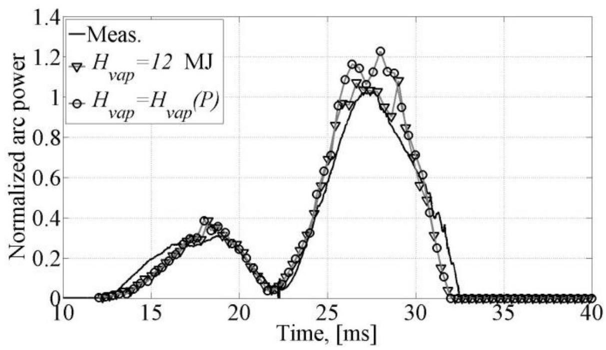

Fig. 5 Arc power, I_{rms} = 25 kA

The comparison of arc power according to Fig. 5 demonstrates a good agreement to the measurements for both approximation of the PTFE evaporation enthalpy.

It is also interesting to compare the specific ablation (ablated PTFE mass per energy ratio). In case of $H_{vap} = H_{vap}(P)$ the value of specific ablation is 12 mg/kJ for the auxiliary nozzle and 18 mg/kJ for the main nozzle. These values are in a good agreement to the experimental results obtained from estimation of geometry change in the study [7].). In case of H_{vap} = 12 MJ/kg the value of specific ablation is 8 mg/kJ for the auxiliary nozzle and 13 mg/kJ for the main nozzle which is in a worth agreement to [7].

4. CONCLUSIONS

- A new approach to simulate the wall ablation is presented.
- The comparison of pressure build-up in the heating volume shows that the utilization of the constant PTFE evaporation values obtained in [4] leads to the satisfactory agreement to the measurements. The utilization of the constant PTFE evaporation values obtained in [5] can slightly decrease the deviation between the measurements and the simulation results. Still, the best agreement to the measurements is achieved under assumption of $H_{vap} = H_{vap}(P)$.
- The simulated arc power is nearly the same in both cases of H_{vap} = 12 MJ/kg and $H_{vap} = H_{vap}(P)$.
- The approximation $H_{vap} = H_{vap}(P)$ demonstrates better agreement of the specific ablation to the experiment [7].

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