CFD Arc Simulation of a Switching-off Process in a Model Chamber

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This paper deals with the investigation of the switching arc process in a model chamber by CFD arc simulation. A transient axisymmetric model based on the @Fluent software is used. The applied arc model considers electromagnetic phenomena, radiative transfer, ablation of PTFE parts and pin motion as well. The influence of the boundary conditions for the solution of the current continuity equation is highlighted. The obtained results are validated by measurements on the model chamber [1].

Keywords: CFD arc simulation, model chamber, switching-off process

1 INTRODUCTION

CFD simulation of a switching-off process simplifies and facilitates the development of high voltage circuit-breakers. Still, in order to obtain reliable simulation results a variety of sub-models for physical phenomena like radiation transport [3], PTFE ablation [4] etc. must be integrated in the CFD arc simulation tool. The significant amount of sub-models requires enormous numerical costs thus making only 2D axisymmetric CFD simulation possible to perform during reasonable calculation time. In order to prove the total accuracy of the utilized physical sub-models and the usability of the axisymmetric flow assumption a model chamber has been assembled [1]. The model chamber is designed in the way that almost all 3D construction elements in the region of hot gas flow can be directly transferred in 2D axisymmetric geometry. Besides, the model chamber contains the main features typical for high voltage circuit-breaker.

In the present study the developed 2D axisymmetric CFD arc simulation tool based on the @Fluent software is validated by spectroscopic measurements on the model chamber [1]. Additionally, pressure build-up in the heating volume (see Fig. 1) has been measured and arc power has been evaluated. Also, it has been demonstrated the necessity of the adjustment of the porous electrode boundary conditions for the current continuity equation [2] in case of axisymmetric geometry and small current. The obtained simulation results are in good agreement to the measurements.

2 MODEL CHAMBER

The detailed description of the model chamber is given in [1]. The arc quenching area of the model chamber is presented in Fig. 1. The experimental set-up enables the spectral spatial optical emission spectroscopy (OES) measurement which can be evaluated in radial temperature distribution. Besides the spectroscopic measurements, arc power and pressure build-up in the heating volume have been measured.

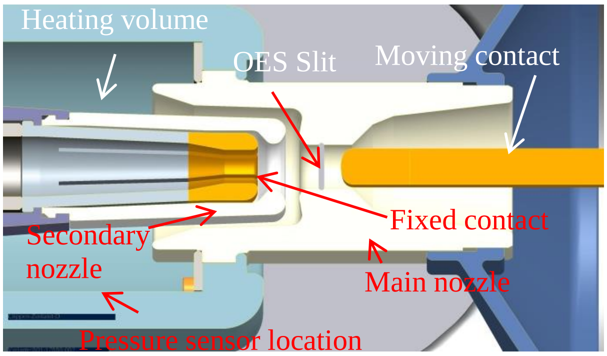

Fig. 1: The arc quenching area of the model chamber

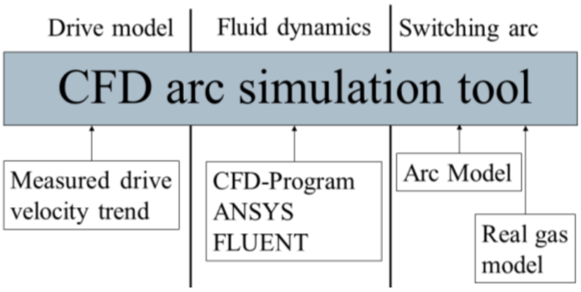

Fig. 2: CFD arc simulation tool

3 NUMERICAL MODEL

The set-up of the CFD arc simulation tool is presented in Fig. 2. The motion of the moving contact (see Fig. 1) is controlled by pre-set velocity trend which is evaluated from experimentally measured stroke.

The hot gas flow inside the model chamber is simulated by Navier-Stokes equations which are solved by means of ANSYS Fluent software. The Navier-Stokes equation can be written in generalized form including the additional source terms describing various effects of plasma flow:

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

In equation (1), ϕ is a variable to solve, ρ is the mass density, Γ_ϕ is the associated diffusion coefficient and S_ϕ is the source term of the equation. By means of source terms S_ϕ the Joule heating, Ampere force and PTFE ablation are modelled. In order to simulate properly the ablation of PTFE nozzles a two components SF_6-C_2F_4 gas mixture is considered. The transport properties of gas mixture are interpolated from the tabulated values [5]. Radiation transport is simulated by multiband hybrid P1-DO radiation model [3]: the radiation transport of the optically thin bands is calculated by means of DO model and the radiation transport of optically thick bands is calculated by means of P1 model. The ablation process takes into account pre-heating, pyrolysis and evaporation phases of PTFE [4].

The electrical current effects are modelled by the current continuity equation:

$$\vec{\nabla}\cdot(\sigma\vec{\nabla}\varphi)=0 \qquad (2)$$

In equation (2), φ is scalar electrical potential, σ is electrical conductivity. The boundary conditions for the equation (2) are presented in Fig. 3. The moving contact is considered as a solid body of W-Cu alloy with electrical conductivity σ depending on temperature. At the right side of the moving contact the uniform current density profile is given. The value of the current density is evaluated from the value of electrical current. The electrode model (Coupled BC, see Fig. 3) provides the boundary coupling between the solid phase of the moving contact and plasma and takes into account heat and electrical current transfer continuity at the surface between the gas and solid phases. At all other surfaces the boundary conditions are kept to $\frac{\partial\varphi}{\partial n}=0$.

Due to two dimensional flow geometry the fixed contact surface cannot be considered as arc attachment surface. For this purpose the “porous” electrode approximation is applied [2]: setting the electrical potential to zero in the flow region left from the dashed line, see Fig. 3. The detailed description of “porous” electrode approximation is presented in [2]. Still, the provided in [2] “porous” electrode formulation is suitable for simulation of wall stabilized arc. In the experimental study [1] the conditions of wall stabilized arc have been not fulfilled. Therefore, as it is demonstrated by the obtained results below, the “porous” electrode formulation must be improved.

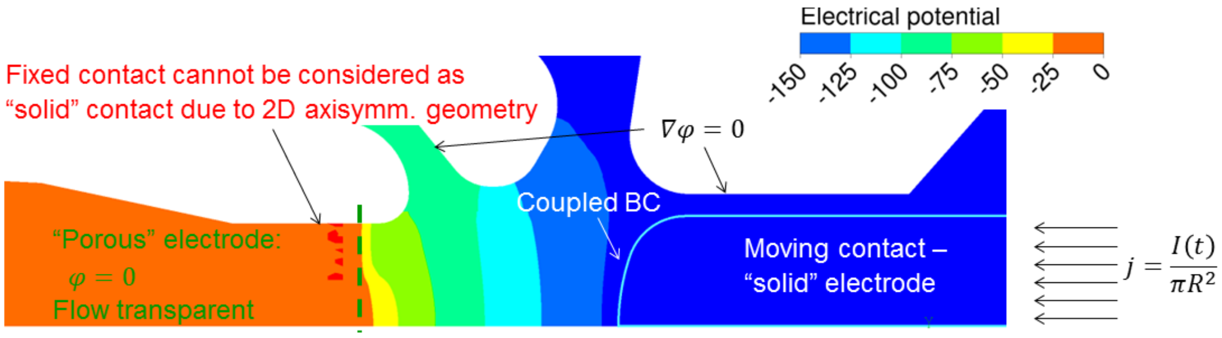

Fig. 3: The boundary conditions for the current continuity equation (2)

In the present study “porous” axisymmetric attachment with variable radius is supposed. The main parameter of such approximation is minimal current density j_{min} at the “porous” electrode boundary. The value j_{min} is the same order of magnitude as the current density at the tip of the moving contact. The radius of the “porous” attachment is evaluated as $R_{por}=\sqrt{I/\pi j_{min}}$. In order to avoid numerical problems at small current (near current zero points) the “porous” attachment radius has been kept constant. Effective heat removal from the “porous” attachment is not considered in the present study.

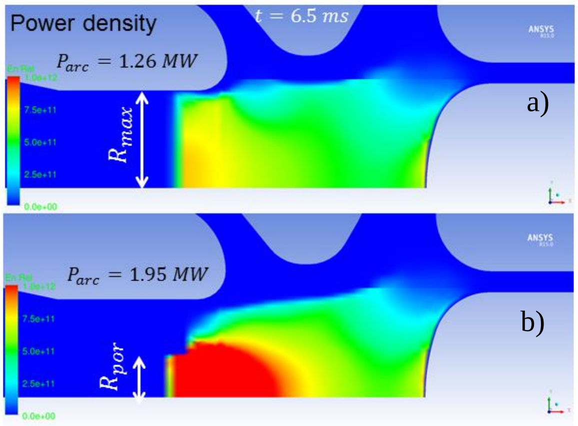

Fig. 4: “Porous” electrode approximations

The Fig. 4 demonstrates the comparison of distribution of volumetric power density for a) standard “porous” electrode approximation and b) variable “porous” attachment radius. It is clearly seen that the volumetric power density near the moving contact is nearly the same for the both “porous” approximations. Whereas the power distribution near the “porous” electrode boundary changes drastically.

The evaluated total arc power P_{arc} at time instant t=6.5 ms is equalled to P_{arc}=1.26 MW in the case of standard “porous” electrode approximation (SPA – standard “porous” attachment) and P_{arc}=1.95 MW in the case of variable “porous” attachment (VPA). In the results below it will be shown that the results obtained under assumption of the variable “porous” attachment demonstrate the best agreement to the experimental results.

4 RESULTS

In the present study the switching arc process in the model chamber (see Fig. 1) by means of CFD arc simulation tool (see Fig. 2) has been simulated. The considered interruption current has arcing time t_{arc}=10 ms and rms-value I_{rms}=10 kA. Both “porous” electrode approximations have been considered and compared.

The comparison of arc power obtained under assumption of the standard “porous” electrode approximation (SPA) and variable “porous” attachment (VPA) with the experimentally obtained trend is presented in Fig. 5. The best agreement to the measurements demonstrates the arc power calculated under assumption of variable “porous” attachment. In case of standard “porous” electrode approximation the difference between the simulation results and the measurement is considerable. The reason is the assumption of wall stabilized arc which results in the attachment area all over the cross section of the fixed contact at the location of “porous” electrode condition (see Fig. 4). Such assumption causes artificial expansion of arc thus decreasing the arc resistance what results in decreasing of the arc power.

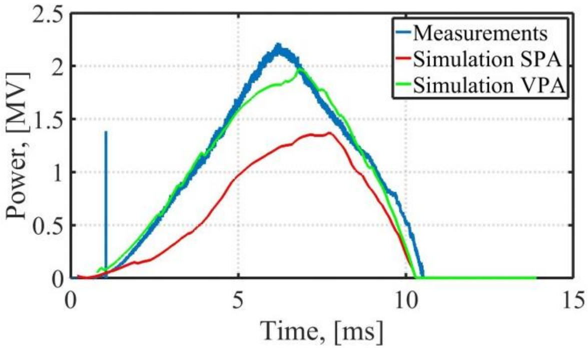

Fig. 5: Arc power

Still, the simulated arc power obtained under assumption of variable “porous” attachment within the time range from 5 ms until 7ms is approximately 15% smaller as the measured one. This effect can be explained by missing of heat transfer to the fixed contact what takes place in reality and hardly can be taken into account in case of 2D flow geometry. In reality the heat transfer to the wall of the attachment surface decreases the temperature near the electrode resulting in decreasing of electrical conductivity of plasma thus increasing the arc resistance.

The comparison of pressure build-up in the heating volume is presented in Fig. 6. The Pressure build-up obtained under assumption of standard “porous” electrode approximation demonstrates the worst agreement to the measurement. The simulated pressure build-up is almost twice lower as the measured one. The reason is smaller arc power obtained in simulation in comparison to the real one. The smaller arc power results in smaller production of C_2F_4 which plays essential role in pressure build-up in the heating volume [4]. On the opposite, the pressure build-up obtained under assumption of variable “porous” attachment demonstrated very good agreement to the measurements. More exactly simulated arc power under assumption of variable “porous” attachment causes higher production of C_2F_4 thus yielding in higher pressure build-up.

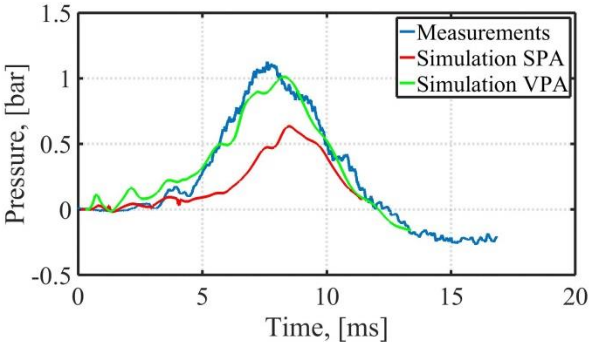

Fig. 6: Pressure build-up in the heating volume

In Fig. 7 the simulated temperature profile is compared with the temperature profile evaluated from the OES measurements [1]. The temperature profiles (the simulated and the measured one) are compared at the time instant corresponding to electrical current $I=1.7$ kA. The simulated temperature profile width is in good agreement to measurements too. Small deviation in the profile width can be explained by influence of OES slit in the main nozzle (see Fig. 1) which violates axial symmetry of flow.

The presented in Fig. 7 simulated temperature profile demonstrates also that there is no wall stabilization of arc during the most of arcing time. Indeed, the temperature profile width is about 3 mm. The main nozzle radius is 9 mm. Assuming the square root dependence of arc core radius from electrical current, the wall arc stabilization occurs at current higher than 15 kA. This fact emphasizes the necessity of assumption of variable “porous” attachment.

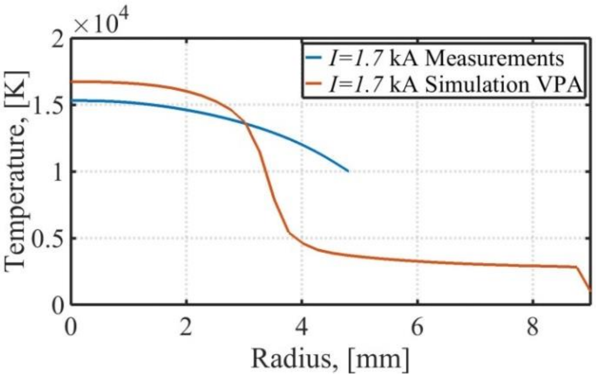

Fig. 7: Comparison of radial temperature profiles

5 CONCLUSIONS

The CFD simulation of switching arc in the model chamber with design similar to design of high voltage circuit-breaker has been performed. The validity of the applied physical sub-models has been confirmed. The “porous” electrode boundary condition for current continuity equation has been extended on the case of arc without wall stabilization. The obtained simulation results demonstrate good agreement to the measurements.

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