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ON TREATMENT OF SOME PHYSICAL PROPERTIES OF GAS IN SIMULATION OF HIGH-VOLTAGE SF_6 CIRCUIT BREAKERS

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Abstract: Simulation of unsteady flow of SF_6 gas in a simplified high-voltage circuit breaker model describing the nozzle, contacts and their nearest surrounding is presented. SF_6 is considered as viscous, compressible, real gas described by Redlich-Kwong model. Heat transfer is taken into account due to the gas compressibility. The heat source, triggered by the electric arc between the contacts, was out of the scope of the current research, thus it was not included in the simulations presented. Turbulence, caused by the gas viscosity, is described using realizable k-ε model. In the simulation model, one of the contact sides – electrodes, is considered as moving at prescribed velocity. The part of the space 'swept' by the moving electrode is considered as the gas with imposed artificially increased viscosity in order to imitate the rigid body behaviour. Thus, no moving parts of the computational mesh are used in the model. The conservation equations of mass, momentum and energy, given in integral form, are solved using a finite-volume method on unstructured computational grids.

Keywords: high-voltage circuit breaker (HVCB), gas dynamics, SF_6, numerical simulation, computational fluid dynamics (CFD)

INTRODUCTION

Conventional high-voltage circuit breakers (HVCBs) employ a gas to quench and extinguish the electric arc during the separation of contacts [1]-[3]. Proper operation of HVCB and successful current interruption depend strongly on the physical properties and flow characteristics of the gas.

Usually, sulphur-hexafluoride (SF_6) is used. Some of its advantages over other gases are high thermal conductivity and dielectric strength, it is chemically stable, non-inflammable, highly electronegative, inert and not toxic.

Calculation of gas-flow structure as well as spatial distribution and temporal variation of the typical quantities, such as pressure, temperature and density, local velocity or flow rates through relevant sections, supports assessment of considered design solutions and operating conditions.

Therefore, the use of computational fluid dynamics (CFD) methods for detailed analysis of gas flow in complex geometric domains becomes common practice also in analysis and development of HVCBs.

1. MATHEMATICAL MODEL OF FLUID FLOW

The fluid flow is governed by laws of continuum mechanics, and can be described by the balance equations of mass, momentum and energy, respectively:

$$\frac{\partial}{\partial t}\int_V \rho dV + \oint_S \rho \boldsymbol{u}\cdot\boldsymbol{n}\, dS = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\int_V \rho \boldsymbol{u}\, dV + \oint_S \rho \boldsymbol{u}\otimes\boldsymbol{u}\cdot\boldsymbol{n}\, dS = \oint_S \boldsymbol{\sigma}\cdot\boldsymbol{n}\, dS + \int_V \boldsymbol{f}_V dV \tag{2}$$

$$\frac{\partial}{\partial t}\int_V \rho h\, dV + \oint_S \rho h\,\boldsymbol{u}\cdot\boldsymbol{n}\, dS = \oint_S \boldsymbol{q}\cdot\boldsymbol{n}\, dS + \int_V q_V dV + \int_V \left(\boldsymbol{u}\cdot\nabla p + \boldsymbol{\sigma}:\nabla\boldsymbol{u}\right) dV + \frac{\partial}{\partial t}\int_V p\, dV \tag{3}$$

where t is the time, ρ is the fluid density, V is the volume of the considered part of the space, enclosed by the

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surface S, $\boldsymbol{u}$ is the flow velocity vector, $\boldsymbol{n}$ is the unit normal vector of the surface S, σ is the stress tensor, $\boldsymbol{f}_V$ is the body force, h is the enthalpy, $\boldsymbol{q}$ is the heat flux, q_V is the volumetric heat source or sink, and p is the static pressure.

For the constant values of the specific heat capacities the enthalpy is equal to:

$$h = c_p T \tag{4}$$

where c_p is the specific heat capacity at constant pressure, and T is the temperature.

In order to close the system of the governing equations (1)-(3), the constitutive relations are used. In the momentum equation, stress-strain rate relation is used:

$$\boldsymbol{\sigma} = 2\mu\boldsymbol{\varepsilon} - \left(p + \frac{2}{3}\mu \mathrm{tr}\boldsymbol{\varepsilon} \right) \boldsymbol{I} \tag{5}$$

where μ is the dynamic viscosity of the fluid, ε is the deformation rate defined as:

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u} \right) \tag{6}$$

and $\boldsymbol{I}$ is the identity tensor. In the energy equation, the Fourier's law of heat conductivity is used:

$$\boldsymbol{q} = \lambda \nabla \boldsymbol{T} \tag{7}$$

Treatment of the static pressure p in equation (2) depends on the assumption of the fluid compressibility.

2. GAS FLOW PROPERTIES

The two most important physical properties of a fluid, governing its (mechanical-) transport characteristics, are compressibility and viscosity.

In a number of engineering applications, for sake of simplicity, gases can be regarded as incompressible (if Mach number is sufficiently low, approximately Ma<0.3). In that case, the density is constant, and one of the solution methods is to use the continuity equation (1) in combination with the momentum equation (2) to adjust the pressure and the velocity vector through an iterative procedure (such as in the SIMPLE and other similar algorithms) [4]. However, if the Mach number of local flow conditions is higher (approximately Ma>0.3), or if the part of space occupied by the gas is completely enclosed but its volume changes due to moving walls, or if the temperature-induced density variation is relatively large (which in most cases indeed happens), the local and/or temporal density change has to be taken into account and that means the gas has to be regarded as compressible. The simplest approach to describe compressibility effects is based on ideal-gas equation of state, which relates the static pressure p, the density ρ, and the temperature T, completely closing the system of equations (1)-(7):

$$p = \rho R T \tag{8}$$

where R is the individual gas constant. This is however applicable to conditions of high temperatures and low pressures only.

Otherwise, real-gas assumptions have to be taken into account. Depending on the gas characteristics, a number of real-gas models have been used in practice to attempt to account for real-gas effects: from the van der Waals equation [5], [6] over widely used Redlich-Kwong model [7] to models based on expansions into power series with virial coefficients first proposed by Kamerlingh Onnes [8]. Accuracy of the models with virial coefficients can be controlled by the number of terms in the series used. On the other hand, high-order terms may negatively affect the solution procedure (the model becomes more complex and may be prone to instability). In this paper, the most results are obtained using the Redlich-Kwong model, which is a relatively simple extension of the ideal-gas equation and van der Waals equation, still yielding plausible and acceptable results in real-gas conditions:

$$p = \frac{R_0 T}{V_m - b} - \frac{a}{V_m (V_m + b)} \frac{1}{\sqrt{T}} \tag{9}$$

where R_0 is the universal gas constant, V_m is the molar volume of gas, and a and b are auxiliary coefficients:

$$a = 0.42728 \frac{R_0^2 T_c^{\frac{5}{2}}}{p_c} \quad , \qquad b = 0.08664 \frac{R_0 T_c}{p_c} \tag{10}$$

with T_c and p_c as the critical temperature and the critical pressure, respectively. Validity of the Redlich-Kwong model is found in the range:

$$\frac{p}{p_c} < \frac{1}{2} \frac{T}{T_c} \tag{11}$$

Treatment of the other important transport property – dynamic viscosity, may require attention. Its neglecting is allowed in a limited range of applications, when inner resistance to relative tangential motion of adjacent fluid layers is negligible as compared to other forces acting on the fluid element under observation. However, such an idealized fluid may in certain occasions respond completely differently from the real fluid (e.g., significantly failing at prediction of separations and consequent calculated values, such as drag force, in flows around bluff bodies). Hence, in a vast number of cases, viscosity is not neglected. If viscosity would be relatively high, flow stability would increase leading to laminar flow regime, which is in case of gases quite seldom (typically, the dynamic viscosity of gases is relatively low). Turbulence, which is a consequence

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of the existing viscous effects in fluid flow and arises very frequently, may affect transport processes in the fluid flow considerably. Direct simulation of turbulence requires very fine resolution in space and time, such an approach implies very high demands on the required computational resources. Hence, modelling of turbulence is employed. One of the earliest practically used model in industrial applications is the k-ε model (where k describes turbulent kinetic energy, and ε denotes the specific dissipation rate of the turbulent kinetic energy) [9]. So far, a large number of models have been developed based on its or other concepts. Nowadays, the models such as realizable k-ε model [10] or k-ω SST [11] model, and those derived from these, are very frequently used in industrial applications. Neither of these models is perfect and can be universally used in all applications. Bosović et al. analysed the flow in a HVCB with fixed contacts, [12]. It was shown that the realizable k-ε model, the standard k-ω model, and the solution of Navier-Stokes equations without a turbulence model deliver very similar distributions of the density along the specific monitoring line. The calculated density values and their trends of variation are very similar, with some relatively small differences in the regions of the trend change and in the outflow region. In this work, the realizable k-ε model, with adaptive treatment of all y^+-values (non-dimensional wall distance), is used due to its expected smoothing and stabilizing behaviour.

3. COMPUTATIONAL MODEL

Due to two-dimensional, axisymmetric shape of the observed part of space, the geometric model is created as a longitudinal slice comprising of a quarter of the cylindrical domain (90º wide) with axisymmetric conditions imposed in circumferential direction.

The solution domain represents the parts of space occupied by SF_6, and it focuses on the region around the electrodes and the nozzle, see Figure 1. The domain consists of a finite number of adjoining, non-overlapping cells closed by a number of flat faces (mostly, hexahedral and tetrahedral cells). Each cell in such a mesh is observed as a control volume, for which equations (1)-(3) are discretized and solved using the methods given in [13].

The operation of the circuit breaker is very dynamic, the contact and nozzle are moving to the drive side causing compression of gas, which results in gas flow through the nozzle. For simulation purposes, it is easier to attach the frame of reference to the nozzle, so the movable parts become fixed and vice versa. In this model, the gas flow from the chamber toward the nozzle, driven by a moving piston (not present in the model), is described by the time-dependent velocity within the first 50 ms of the simulated time at the open inlet boundary (boundary 1 in Figure 1). Immediately before the nozzle, the gas flow separates into two streams, being directed toward the outflow boundaries (boundaries 2 and 3), where the absolute pressure of 8 bar is specified.

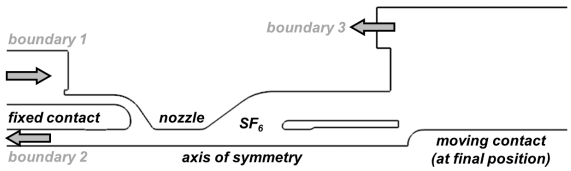

Figure 1: A part of the solution domain around the contacts and the nozzle

In the asymptotic limit of infinite viscosity, the fluid would become solid, thereby completely changing its behaviour. This idea is used to describe the motion of the contact. Moving electrode is modelled as the time-dependent region with imposed artificial, relatively high viscosity, as illustrated in Figure 2. During the simulation this region is continuously changed (moving from left to right) representing the velocity of electrode-motion of 5.5 m/s. The artificial viscosity value of 1000 Pas in this region was found to be acceptable. Larger values cause instabilities of computations.

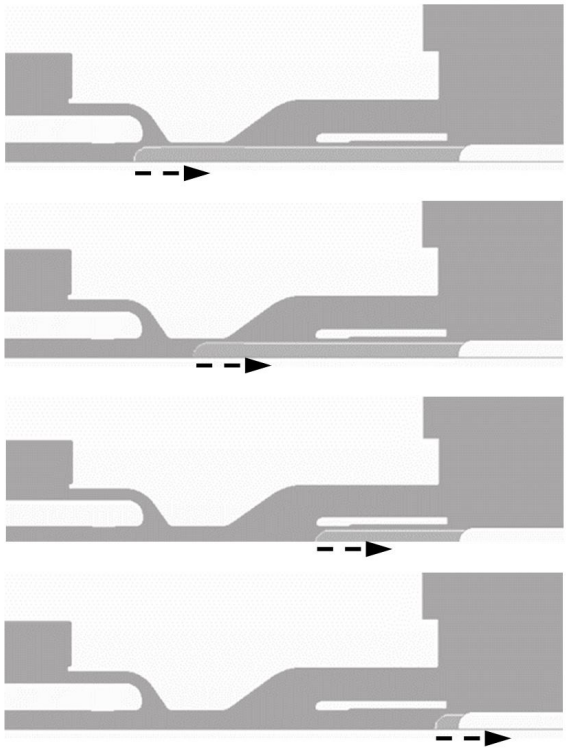

Figure 2: Region with artificial viscosity representing moving electrode 0 ms, 10 ms, 30 ms and 50 ms after current zero (from top to bottom, respectively).The electrode tip motion is indicated by the arrows.

4. RESULTS

Figure 3 shows the spatial distribution of the gas density 50 ms after the current zero calculated with the time step size of 0.1 ms on three different mesh resolutions: the coarse one with 310000 cells, the medium one with 455000 cells, and the fine one with 950000 cells (in one quarter of the full-cylindrical domain, i.e. in the 90º slice). Obviously, the coarse mesh and the medium one result in a smearing of the results in the nozzle region, where the density reduction is not detected well. On the fine mesh, strong density gradients around the nozzle are captured, which is essential for the estimation of possible electric-arc restrike after the contact separation. In Figure 4, where the results calculated using the fine mesh and three different time steps are shown, even stronger smearing of the density field is seen in case of the coarse and the medium time step size. Due to strong dynamics of the circuit breaker operation, and relatively large speeds of its moving parts, time steps have to be sufficiently small in order to achieve a proper flow structure. Here, the time step size of 0.1 ms or lower seems to be acceptable, yielding a required time scale of $T/\Delta t \geq 500$, where T=50 ms is the previously imposed overall period of the contact motion. By further refining the mesh and/or decreasing the time step the results do not change significantly.

For the purpose of assessment of real-gas model choice, a comparison of the use of Redlich-Kwong model, given by equations (9)-(10), and Peng-Robinson model [14] is shown in Figures 5 and 6 for different instants of time during the contact separation. In the early stage of the separation up to 30 ms, both models show very similar results. When the separation is almost finished, 50 ms after current zero, some differences can be observed – in the outflow region toward the boundary 2 (left outflow) and in the region "swept" by the moving electrode the density is obviously higher. In the critical region inside the nozzle, the density values are however approximately the same.

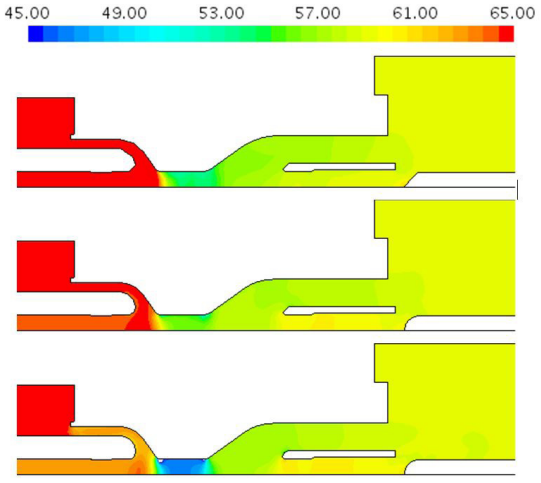

Figure 3: Density distribution calculated 50 ms after current zero: coarse (top), medium (middle) and fine (bottom) computational mesh.

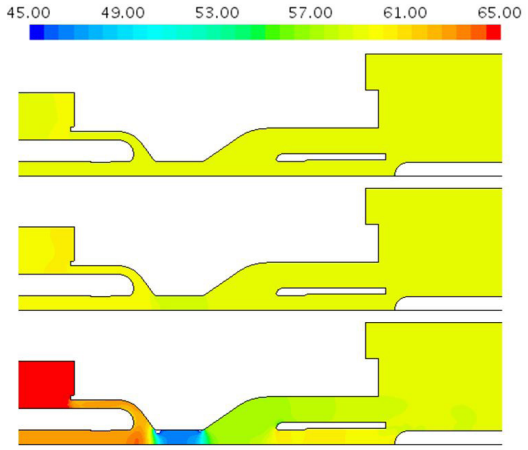

Figure 4: Density distribution calculated 50 ms after current zero using time step size: 1 ms (top), 0.5 ms (middle) and 0.1 ms (bottom).

5. CONCLUSION

The computer simulations, based on numerical methods of fluid mechanics, are used to calculate the unsteady flow of SF_6 gas in a HVCB with a moving electrode.

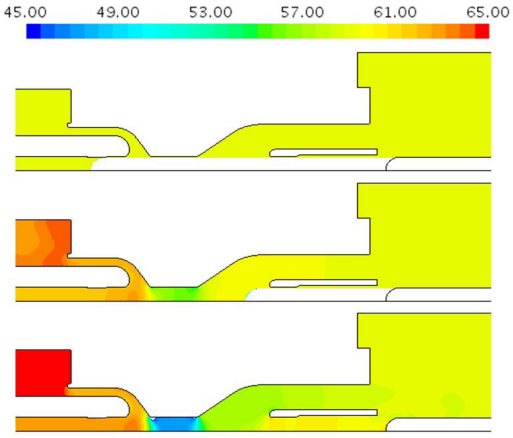

Figure 5: Density distribution calculated using Redlich-Kwong real-gas model during the contact separation: 10 ms (top), 30 ms (middle) and 50 ms (bottom) after current zero.

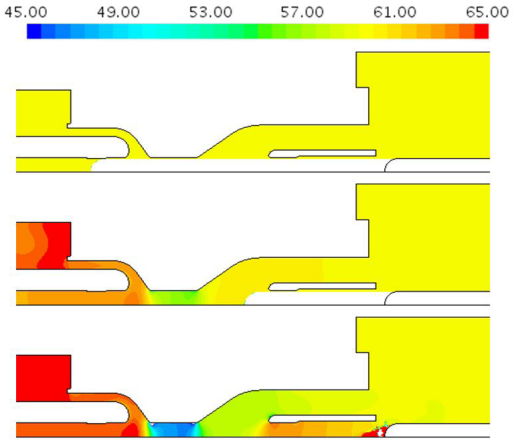

Figure 6: Density distribution calculated using Peng-Robinson real-gas model during the contact separation: 10 ms (top), 30 ms (middle) and 50 ms (bottom) after current zero.

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The Redlich-Kwong real gas model is applied to describe compressibility of the gas. In addition to that, also the gas viscosity is taken into account aiming at two effects: (a) to describe turbulence in gas flow, and (b) to describe a part of the gas-occupied region as moving electrode, by imposing an artificial, high value of viscosity. Use of the increased viscosity is a very simple approach to imitate rigid body motion (much simpler than the methods with moving grids), which turned out to be acceptable for this purpose. Simulations are done with different spatial and temporal resolutions showing that strong smearing of the results may be expected if the level of discretization in space and time is not sufficient. The differences in the results between the different meshes or between the different time steps are much stronger, than the differences between the real-gas models used for testing, indicating that simulation is more sensible to the spatial and temporal discretization (obviously due to highly dynamic phenomena) than to real-gas behaviour.

Future research is needed in order to investigate the heat transfer processes (including radiation) caused by realistic heat sources, electric-arc and surrounding plasma modelling, as well as computation of the electrostatic field in order to analyse conditions of electric-arc extinction.

REFERENCES

[1] M. Kapetanović, Visokonaponski prekidači, Elektrotehnički fakultet u Sarajevu, 2002
[2] M. Kapetanović, High Voltage Circuit Breakers, Faculty of Electrical Engineering, Sarajevo, 2011
[3] R. Smeets, L. van der Sluis, M. Kapetanovic, D. F. Peelo and A. Janssen, “Switching in Electrical Transmission and Distribution Systems”, Wiley, 2014
[4] S.V. Patankar and D.B. Spalding, “A calculation procedure for heat mass and momentum transfer in three dimensional parabolic flows”, Int. J. Heat Mass Transfer, Vol. 15, p. 1787, 1972
[5] J. D Van der Waals, “Over de Continuiteit van den Gas- en Vloeistoftoestand” [About the Continuity of the Gas and Fluid States] (in Dutch). University of Leiden, 1873
[6] J.D. Van der Waals, “The equation of state for gases and liquids”, Nobel Lecture, December 12, 1910 [https://www.nobelprize.org/uploads/2018/06/waals-lecture.pdf, last access 02.09.2022.]
[7] O. Redlich, J. N. S. Kwong, “On The Thermodynamics of Solutions”. Chem. Rev. 44 (1): 233–244, 1949
[8] H. Kamerlingh Onnes, Expression of state of gases and liquids by means of series, KNAW Proceedings, 4, 1901-1902, Amsterdam, 125-147,1902
[9] K. Hanjalić, “Two-dimensional Asymmetric Turbulent Flow in Ducts, University of London”, PhD thesis, 1970
[10] H. Shih, W.W.Liou, A.Shabbir, Z.Yang,Z. and J.Zhu, “A New k-ε Eddy-Viscosity Model for High Reynolds Number Turbulent Flows - Model Development and Validation. Computers Fluids, 24(3):227-238, 1995
[11] F. R. Menter, “Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications”, AIAA Journal, vol. 32, no 8. pp. 1598-1605, 1994
[12] B. Bosović, D. Bešlija, M. H. Kim, M. Torlak, E. Džaferović and M. Kapetanovic, “A real gas model for numerical flow analysis in a high-voltage SF_6 circuit breaker”, Turbulence, Heat and Mass Transfer 8, Begell House, Inc, 2015
[13] J. Ferziger, M. Perić and R.L. Street, “Computational Methods for Fluid Dynamics”, 4th ed., Springer, 2020
[14] D. Y. Peng and D. B. Robinson, “A New Two-Constant Equation of State”. Industrial and Engineering Chemistry: Fundamentals. 15: 59–64, 1976

BIOGRAPHY

Muris Torlak graduated from Mechanical Engineering Faculty, University of Sarajevo in 1998. After the studies, he spent one year as visiting researcher at Fraunhofer Institute of Production Engineering and Automation in Stuttgart, and in 2006 he obtained his doctoral degree at Technical University of Hamburg-Harburg with a thesis on computational methods for fluid and structural mechanics. Since 2004 he worked with CD-adapco Group, Nuremberg (nowadays a part of Siemens PLM) and later moved to Siemens Corporate Technology, Erlangen. From 2009 to 2013 he was also a guest lecturer at University of Applied Sciences Esslingen. In 2011 he started as assistant professor at International University of Sarajevo, and since 2012 he is with University of Sarajevo, Mechanical Engineering Faculty, where he works now as professor at Department of Energy, Process Technology and Environmental Engineering.

Samir Čaluk graduated from Mechanical Engineering Faculty, University of Sarajevo, in 2019 with a master’s degree in energy, process and environmental engineering. Since 2021 he works with Delta Petrol d.o.o. Kakanj as lead engineer at Department of Mechanical Construction and Installation with focus on petroleum and oil mechanical installations.

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Amer Smajkić obtained his bachelor's, master's, and doctoral degree at the Faculty of Electrical Engineering Sarajevo, University of Sarajevo, in 2011, 2013, and 2020 respectively. His first employment experience was as R&D engineer at EnergoBos ILJIN where he worked at development of new HV circuit breakers up to 420 kV and development of simulation software for HV circuit breakers. Currently he works as Assistant professor at Faculty of Electrical Engineering, University of Sarajevo. His fields of interests are design and modelling of HV circuit breakers. Amer Smajkić is member of national CIGRE committee of Bosnia and Herzegovina since 2013.