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SIMULATIVE COMPARISON OF RADIATION MODEL PARAMETERIZATIONS FOR DIRECT CURRENT ARCS IN A BUSBAR SETUP

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Abstract. The influence of different methods for calculating mean absorption coefficients on the mean arc voltage and velocity of an arc moving in air along parallel busbars is investigated in a numerical arc simulation. The radiation model used is the discrete ordinate method. Planck, hybrid and Rosseland mean calculations for a three- and six-band selection are discussed. Compared with the experimental results from a published paper, the Planck mean for six bands shows the most promising results.

Keywords: direct current arcs, numerical arc simulation, radiation modelling, mean absorption coefficient calculation.

1. Introduction

Low-voltage direct current (DC) systems are increasingly in the focus of research and development. Exemplary applications include electric vehicles, DC microgrids and photovoltaic systems. One key challenge in designing these systems is the capability of interrupting nominal and fault currents, with mechanical switching devices providing a cost-effective solution. During the switching operation in these devices, an electric arc is created when opening the current-carrying contacts. This arc has to be extinguished for a successful current interruption. Hence, a fundamental understanding of DC arcs is essential for the design of efficient and reliable DC switches [1].

Due to arc core temperatures of typically more than 10 000 K, high local pressure gradients and arc dynamics, experimental measurements of relevant parameters on electric arcs are challenging. Therefore, spatially and temporally resolved numerical DC arc models offer a promising addition to experimental investigations and could potentially reduce time and expenses involved in the development of DC switching devices. Due to the occurring temperatures in arcs, radiation is the dominant heat transfer mechanism [2].

There are several methods of modelling radiation in numerical arc models, among them the common approach of solving the spatial and spectral parts of the radiation independently. Models such as the discrete ordinate method (DOM) or the P1 approximation are used for solving the spatial part. However, both methods work only with a single value of the absorption coefficient that is independent of the frequency. Therefore, the spectral part is simplified by dividing the absorption spectrum into so-called bands and calculating the mean absorption coefficient (MAC) for each band. The choice of the band limits and the averaging method is dependent on the medium and is critical for the accuracy of the solution [3].

Several band selections have been proposed in the literature, with the six bands from [4] being the most frequently used selection for the medium air in numerical arc simulations. However, radiation modelling in numerical arc models requires significant computational effort, which scales linearly with the number of bands. Hence, reducing the number of bands saves computation time, with [3] suggesting a band selection of only three bands. The first band of the three-band selection approximately covers the first four bands of the six-band selection, with the last two bands roughly having the same limits.

The preference for an averaging method depends on the application and the pressures present. The Planck mean tends to overestimate the importance of the atomic lines, which leads to overestimated values of divergence of the radiation flux, while the Rosseland mean tends to underestimate it. The hybrid mean attempts to compensate this by combining the Planck and Rosseland mean [5]. Other methods use the Planck mean, but apply an escape factor or line limiting factor to the line spectrum in order to limit its influence [6]. However, the disadvantage of those methods is that a characteristic length, often associated with the plasma radius, must be known beforehand in order to obtain improved results [5].

The influence of the Planck, hybrid and Rosseland mean on the mean arc voltage and velocity of an arc moving in air along parallel busbars is investigated in a numerical arc simulation in this paper. The simulation model presented in [7] is optimized in order to better match the results from an experimental study [8]. The results are discussed for the two aforementioned band selections with three and six bands and are compared

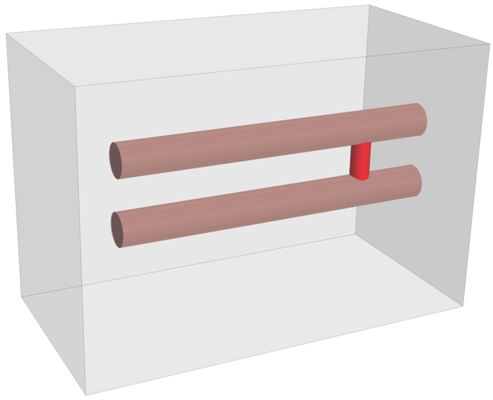

Figure 1. Simulation geometry with initial arc channel.

to the results from the experimental study.

2. Simulation model

2.1. Geometry and mesh

The model consists of two cylindrical copper busbars in atmospheric air (cf. Figure 1). The busbars have a diameter of $d_{\mathrm{busbar}} = 10\,\mathrm{mm}$ with a distance to each other of $d_{\mathrm{gap}} = 5\,\mathrm{mm}$. Their length $l_{\mathrm{run}} = 14.9\,\mathrm{cm}$ ensures the arc roots do not reach the end of the busbars during the simulation time. The dimensions of the airbox are $60 \times 75 \times 159\,\mathrm{mm}$. The domain is discretized with polyhedral cells with a base size of $d_{\mathrm{cellSize}} = 0.375\,\mathrm{mm}$. The cell size increases towards the boundary of the air box. Three prism layers with a total thickness of $d_{\mathrm{prism}} = 0.25\,\mathrm{mm}$ provide the transition between solids and fluid.

2.2. Governing equations

Assuming local thermodynamic equilibrium, a magnetohydrodynamic low-frequency approach is used to model the thermal plasma. The Reynolds-averaged Navier–Stokes equations are solved with the k-ϵ turbulence model. The equations are solved in finite volumes, including the magnetic vector potential as no ferromagnetic materials are considered. Ohmic heating and Lorentz forces are calculated by the electromagnetic equations and included as source terms in the CFD governing equations. Eddy currents are suppressed in all domains. To model the arc fall voltages, the electric current density dependent voltage curve from [4] is implemented at the interfaces between the electrodes and the air with asymptotic voltage drops of $V_{\mathrm{Anode}} = 5\,\mathrm{V}$ and $V_{\mathrm{Cathode}} = 10\,\mathrm{V}$ for the anode and cathode, respectively.

Spatial and spectral parts of radiation are solved independently. The spatial part is solved with the DOM, while the spectral part is solved using MACs. The MACs are calculated from the frequency-dependent spectrum of atmospheric air [9] by dividing it into bands. A selection of three [3] and six [4] bands is used. The MACs are calculated for each band selection using the formulae for the Planck and Rosseland

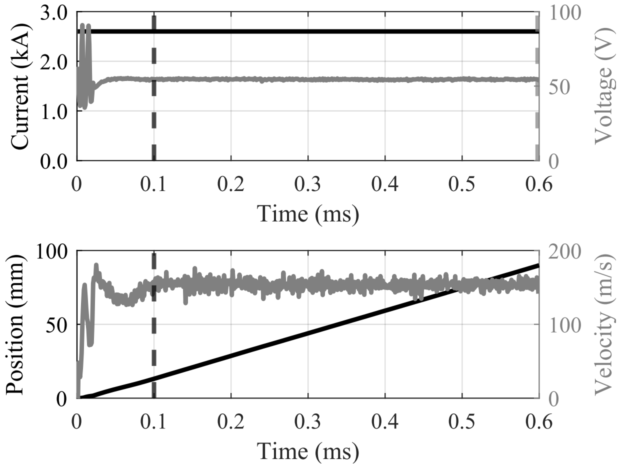

Figure 2. Simulation results of arc current, voltage, position, and velocity of exemplary simulation with six-band hybrid MAC.

mean as follows [10]:

$$\kappa_{\mathrm{Planck}} = \frac{\int_{\nu_1}^{\nu_2} \kappa_\nu B_\nu(T)\, d\nu}{\int_{\nu_1}^{\nu_2} B_\nu(T)\, d\nu} \tag{1}$$

$$\kappa_{\mathrm{Ross}}^{-1} = \frac{\int_{\nu_1}^{\nu_2} \kappa_\nu^{-1} \frac{dB_\nu(T)}{dT}\, d\nu}{\int_{\nu_1}^{\nu_2} \frac{dB_\nu(T)}{dT}\, d\nu} \tag{2}$$

The hybrid MAC is calculated from the Planck and Rosseland MAC using the following formula:

$$\kappa_{\mathrm{hyb}} = \kappa_{\mathrm{Ross}} \left(2 - \frac{\kappa_{\mathrm{Ross}}}{\kappa_{\mathrm{Planck}}}\right) \tag{3}$$

It is to be noted, that under certain conditions, the formulation results in negative values for the hybrid MAC [5].

2.3. Boundary and initial conditions

Contact ablation is neglected. Therefore copper vapor is not included in the simulation model, and the material data used for the plasma is based on pure atmospheric air. The material data is temperature dependent [9]. The relative permeability for both air and copper is assumed to be $\mu_{\mathrm{r}} = 1$. The electrical conductivity of copper is set to $\sigma_{\mathrm{Cu}} = 59.6\,\mathrm{MS/m}$.

The boundary of the air box is defined as pressure outlet with atmospheric pressure. At one boundary face Γ of the busbars, the total electric current is defined as $I_{\Gamma 1} = 2.6\,\mathrm{kA}$, with a constant current spatial distribution, while the electric potential is set to $\Phi_{\Gamma 2} = 0\,\mathrm{V}$ at the other boundary of the busbars. The arc is initialized with a temperature profile [3] that is applied to a channel between the electrodes. The temperature profile has a core temperature of $15\,000\,\mathrm{K}$, with the temperature decreasing in the radial direction to the ambient temperature of $300\,\mathrm{K}$. The location of the initial arc channel is depicted in Figure 1. The time step size is $1\,\mathrm{\mu s}$, with 32 inner iterations per time step and an overall simulation time of 0.6 ms. Simcenter STAR-CCM+ is used as software framework.

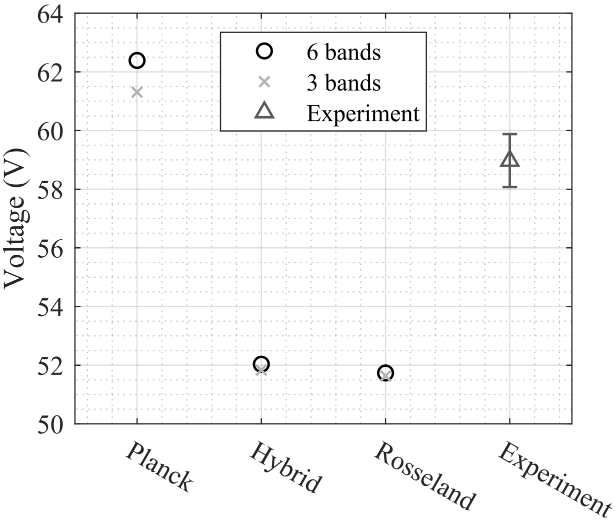

Figure 3. Mean arc voltage of three- and six-band selection for different averaging methods. The experimental mean, as well as the minimum and maximum value of the test series from [8] are shown for comparison.

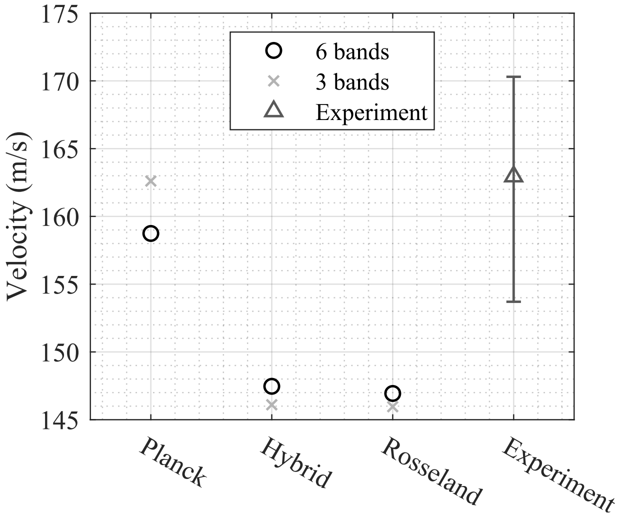

Figure 4. Mean arc velocity of three- and six-band selection for different averaging methods. The experimental mean, as well as the minimum and maximum value of the test series from [8] are shown for comparison.

3. Evaluation method

In this chapter, the evaluation method is explained by means of an example (6 bands hybrid mean). The arc current, voltage, position, and velocity of the simulation are presented in Figure 2. The electric current is determined by integrating the current density in a plane in the center of the gap, while the arc voltage is determined by the maximum voltage of the air. The arc position is calculated as the average position of every cell with a temperature above 10 000 K weighted by temperature. The velocity is obtained as the derivative of the position over time. Transient processes in the arc voltage and velocity are observed in the first timesteps due to the injection of current into the initial arc channel. The resulting oscillations of the numerical equations reach steady state by $t_1 = 0.1\,\mathrm{ms}$. The values remain constant in good approximation until the end of the simulation at $t_2 = 0.6\,\mathrm{ms}$. To facilitate comparison with the experimental results, the mean arc voltage and velocity are calculated in the time interval $[t_1, t_2]$.

4. Results and discussion

The mean arc voltages and velocities are presented in Figure 3 and 4 respectively, illustrating their dependence on band selection and averaging method. Experimental data for the mean arc voltage and velocity, obtained from [8], are also included in the figures for comparison. The mean value for the experimental results is calculated from a test series of five tests with the whiskers marking the minimum and maximum value of the test series.

For the Planck mean, the three- and six-band selection show an absolute difference of about $V = 1\,\mathrm{V}$ and $v = 4\,\mathrm{m/s}$ which means a relative difference of about 1.6 % and 2.4 % respectively. As the last two bands between the three- and six-band selections are roughly the same, the difference must be attributed to the first band of the selections. In contrast, the difference between the band selections is lower than 1 % for the hybrid and Rosseland mean. So the Planck mean shows a higher sensitivity to the band selection compared to the other averaging methods.

When comparing the results of the averaging methods, the Planck mean shows higher values compared to the hybrid and Rosseland mean. The relative differences is about 15 % (three bands) and 16.5 % (six bands) for the mean voltage compared to the hybrid and Rosseland mean. For the mean velocity the relative difference is about 10 % (three bands) and 7 % (six bands) compared to the hybrid and Rosseland mean. This can be explained by the higher radiation emission of the arc core for the Planck mean. On the one hand, the higher emission leads to lower temperatures and therefore lower electrical conductivity in the core. As the arc core conducts most of the current through the arc, this results in an overall higher arc voltage. On the other hand, the radiation emitted from the core is absorbed in the arc fringes, preheating the path of the arc and resulting in an overall higher arc velocity. Interestingly, the differences between hybrid and Rosseland mean are negligible, despite the fact that the hybrid mean emits slightly more radiation from the arc core than the Rosseland mean. A fact that should be looked at more closely in future.

Compared to the experimental results, the hybrid and Rosseland mean have a relative difference of about 13.5 % for the mean voltage for three and six bands compared to the experimental results. The Planck mean has a relative difference of 3.8 % for three bands and 5.3 % for six bands. None of the simulation results is within the minimum and maximum value of the experimental results for the mean arc voltage. However, the results for the Planck mean are closer with the three-band selection being the closest compared to the hybrid and Rosseland mean. The hybrid and Rosseland have a relative difference of 11.6 % (three bands) and 10.8 % (six bands) for the mean arc velocity while the Planck mean has a relative difference of 0.2 % (three bands) and 2.7 % (six bands). While the hybrid and Rosseland mean are below the experimental minimum, the Planck mean is within the minimum and maximum value with the three-band selection being the closest to the mean value. Overall, the Planck mean shows the highest agreement with the experimental results for the specified boundary conditions with the three-band selection being the closest to the experimental mean arc voltage and velocity. However, it also shows the highest sensitivity in the band selection, which should be investigated in the future. All in all, the results are in good agreement with theoretical investigations, which show that, at atmospheric pressure, the Planck mean is superior to the hybrid and Rosseland mean [5].

5. Conclusion

In this paper, the influence of different methods for calculating mean absorption coefficients for modelling radiation with the DOM is investigated in numerical arc simulations. The influence of the Planck, hybrid and Rosseland mean on the arc voltage and velocity is investigated by simulation of an arc moving in air between two parallel busbars. The results are discussed for two band selections of three and six bands and compared with results from an experimental study. The Planck mean shows a higher sensitivity to band selection with respect to other averaging methods. Compared to the experimental results and for the specified boundary conditions, the Planck mean shows the highest agreement with the experimental results, with the three-band selection being closest to the experimental mean arc voltage and velocity. This is consistent with theoretical studies, which show that the Planck mean is more suitable for modelling radiation at atmospheric pressure than the hybrid or Rosseland mean.

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