[O2.18]

Numerical simulation of overhead power line cooling in natural convection regime

G. Kosec*, J. Slak

Jozef Stefan Institute, Slovenia

Introduction (300 words)

The complexity of the electrical power systems and increasing demands for electrical power constantly pressure the transmission system operators to utilize existing power lines more effectively and safely. The transfer capability of the power transmission lines, i.e. the maximal allowed current, is often limited by the maximal temperature of the overhead line that should not be exceeded in order to avoid excessive sags. There has been substantial work done on Dynamic Thermal Rating (DTR) of overhead lines [1-4] in last few decades, which is summarized in leading standards, namely IEC [5], IEEE [6] and CIGRE [7]. All three standards model the convection as an empirical relation that agree well in wind regimes above 0.6 m/s, however, their predictions in low wind regimes differ considerably, which casts doubt on model reliability and consequently diminishes its usability in operative use. Besides, the transmission capacity is often still determined for worst case weather conditions, e.g. ambient temperature of 40 C, with no rain and no wind.

In this paper we tackle the modelling of the convective cooling based on continuum description of heat and momentum transport. The model considers Joule heat generation and transport within the power line and its vicinity, fluid flow driven by buoyancy force, solar heating, and radiation in order to appropriately model the phenomena, with a goal to improve state-of-the-art prediction of the overhead power line skin temperature, especially in the low wind regimes.

The problem is solved with a Meshless Local Strong Form Method (MLSM) [8] with explicit Euler stepping and Artificial Compressibility Method (ACM) for addressing the pressure velocity coupling [9].

Methods (300 words)

The power line is made of two domains, namely the steel core and the aluminium conductor. The electrical conductivity of steel core is negligible in comparison to the aluminium conductor, consequently there are no Joule losses and only heat conduction take place there

$$c_p^{st}\rho^{st}\frac{\partial T^{st}}{\partial t}=\lambda^{st}\nabla^2 T^{st}\ , \tag{1}$$

while in aluminium domain heat generation is present as well

$$c_p^{al}\rho^{al}\frac{\partial T^{al}}{\partial t}=\lambda^{al}\nabla^2 T^{al}+q_J\ , \tag{2}$$

with Joule heating modelled as

$$q_j=\frac{4}{\pi D^2}I^2R\ \left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]. \tag{3}$$

Both domains are coupled through

$$T^{al}\left(r_1\right)=T^{st}\left(r_1\right), \tag{4}$$

$$\lambda^{al}\left.\frac{\partial T^{al}}{\partial \mathbf{n}}\right|_{r_1} = \lambda^{st}\left.\frac{\partial T^{st}}{\partial \mathbf{n}}\right|_{r_1} . \tag{5}$$

The $T^{st,al}$ stand for temperature, $c_p^{st,al}$ stand for specific heat capacity, $\lambda^{st,al}$ stand for thermal conductivity, $\rho^{st,al}$ stand for density, with superscripts al and st denoting aluminium and steel domains, D stands for line diameter, I stands for electric current, R stands for electric resistance, $\mathbf{n}$ for normal vector, and r_1 represents the radius of aluminium domain.

The heat transfer in surrounding air is modelled as

$$\rho^a c_p^a \frac{\partial T}{\partial t} + \rho^a c_p^a \nabla \cdot (T\mathbf{v}) = \nabla \cdot \left(\lambda^a \nabla T\right), \tag{6}$$

Where superscript a denotes the ambient domain. The heat transport is primarily governed by convection, therefore, momentum transport has to be considered.

$$\rho^a \frac{\partial \mathbf{v}}{\partial t} + \rho^a \nabla \cdot (\mathbf{vv}) = -\nabla P + \nabla \cdot \left(\mu^a \nabla \mathbf{v}\right) + \mathbf{b} . \tag{7}$$

$$\nabla \cdot \mathbf{v} = 0 , \tag{8}$$

with $\mathbf{v}$ and P standing for velocity and pressure, respectively. The body force is modelled with Boussinesq approximation

$$\mathbf{b} = \rho_{ref}\left[1 - \beta_T (T - T_{\mathrm{ref}})\right]\mathbf{g} . \tag{9}$$

with $\mathbf{g}$ denoting acceleration due to the gravity, β_T thermal expansion coefficient, ρ_{ref} reference density at reference temperature $T_{ref}[^\circ C]$. On the boundary between power line and ambient following boundary conditions hold

$$T^{al}\left(r_2\right) = T^{a}\left(r_2\right) , \tag{10}$$

$$\lambda^{al}\left.\frac{\partial T^{a}}{\partial \mathbf{n}}\right|_{r2} - \lambda^{a}\left.\frac{\partial T^{a}}{\partial \mathbf{n}}\right|_{r_2} = q_s + q_r , \tag{11}$$

where r_2 stand for radius of power line. Solar heating is modelled as

$$q_s = \frac{\alpha_s I_T}{\pi}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right], \tag{12}$$

where I_T stands for measured solar intensity and α_s for absorptivity, and the radiation term is introduced as

$$q_r = -\sigma_B \varepsilon_s \left(T_s^4 - T_a^4\right)\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]. \tag{13}$$

where σ_B, ε_s and T_s stand for Stefan-Boltzmann constant, emissivity, and power line skin temperature, respectively.

Results (300 words)

The implementation of the model is first tested on a classical test for natural convection simulations, namely the de Vahl Davis test [10] that is defined for the natural convection of the air in the square closed cavity with differentially heated vertical walls and adiabatic horizontal walls. The test is a special case of model presented here. The results of MLSM solution are compared against reference solutions [10, 11] in terms of average cold side Nusselt number and maximal mid plane velocity for range of Rayleigh numbers from $\mathrm{Ra}=10^3$ to $\mathrm{Ra}=10^8$. Further, the convergence of the solution is demonstrated on regular nodal distributions up to $2.5\,10^5$ nodes.

Next, natural convection in a domain with cold vertical walls, adiabatic horizontal walls and eccentrically positioned hot cylinder is considered. Again, the problem is a special case of present model and it has a published solution [12]. The present MLSM solution is compared against [12] for case $\mathrm{Ra}=10^5$ and $\mathrm{Pr}=10$.

Finally, the solution of the full model is presented for different scenarios for overhead power lines Al240Fe40 and Al490Fe65 that are in operative use in Slovenian transmission network. The computed Nusselt number on the skin of the overhead line is compared against IEEE, IEC and CIGRE standards. The results are presented also in terms of temperature contour plots and velocity profiles at different times.

Conclusions and Contributions (300 words)

In this paper a continuum physical model, describing the convective cooling of overhead power lines, is presented. The model, contrary to standard DTR models, does not rely on empirical relation for assessing the convective cooling, but considers heat, mass and momentum transport in vicinity of the line. The model is solved numerically with MLSM spatial discretization, explicit time stepping, and ACM pressure velocity coupling. The most complex parts of the model, i.e. the solution of the fluid flow problem in high Ra regimes and the solution of the fluid flow in an irregular domain are tested on two benchmark problems that can be solved as special cases of the presented model. Finally, the results of a full simulation are presented for two overhead lines that are in operative use in Slovenian power network in terms of Nusselt number analysis on the skin of the line and presentation of velocity and temperature behaviour in the vicinity of the line.

The main contribution of the paper is in more detailed modelling of the convective cooling of the overhead line as it is proposed by leading IEEE, IEC and CIGRE standards.

[1] Howington BS, Ramon GJ. Dynamic Thermal Line Rating Summary and Status of the State-of-the-Art Technology. IEEE Trans on power delivery. 1987;2:851-8.

[2] Morgan VT. The Thermal Rating of Overhead-Line Conductors. Electric Power Systems Research. 1981;5:119-39.

[3] Pytlak P, Musilek P, Lozowski E, Toth J. Modelling precipitation cooling of overhead conductors. Electric Power Systems Research. 2011;81:2147-54.

[4] Kosec G, Maksić M, Djurica V. Dynamic thermal rating of power lines – Model and measurements in rainy conditions. International Journal of Electrical Power & Energy Systems. 2017;91:222-9. 10.1016/j.ijepes.2017.04.001.

[5] Technical Committee 20 — Overhead Electrical Conductors. International Electrotechnical Commission; 2016.

[6] IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors. IEEE Std. 738-2012; 2014.

[7] Guide for Thermal Rating Calculations of Overhead Lines. CIGRE; 2014.

[8] Trobec R, Kosec G. Parallel scientific computing : theory, algorithms, and applications of mesh based and meshless methods: Springer; 2015.

[9] Rahman MM, Siikonen T. An artificial compressibility method for viscous incompressible and low Mach number flows. Int J Numer Meth Eng. 2008;75:1320-40.

[10] de Vahl Davis G. Natural convection of air in a square cavity: a bench mark numerical solution. Int J Numer Meth Fl. 1983;3:249-64.

[11] Wan DC, Patnaik BSV, Wei GW. A new benchmark quality solution for the buoyancy-driven cavity by discrete singular convolution. Numer Heat Transfer. 2001;B40:199-228.

[12] Demirdžić I, Lilek Ž, Perić M. Fluid flow and heat transfer test problems for non-orthogonal grids: Bench-mark solutions. Int J Numer Meth Fl. 1992;15:329–54.