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INITIAL INVERSE PROBLEM IN THE VACUUM PAPER DRYING PROCESS

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ABSTRACT

A crepe paper is very often used as an insulation material in production of electrical transformers or bushings. For high voltage bushings, conductor core is wrapped with crepe paper, impregnated with the epoxy resin and then cured. This is so called resin-impregnated paper (RIP) technology. Electrical properties of a such paper-resin composition are greatly dependent on the moisture content within the paper. Therefore paper used for bushings insulation has to be carefully dried. One of the most effective drying technologies is the vacuum drying. In this process dried material is heated up in a chamber to some prescribed temperature and then pressure inside chamber is reduced to a few hPa, which is causing a rapid water evaporation from the paper. Such a cycle heating-vacuum is repeated couple of times. Since this drying method is very energy consuming it is of great importance to be able to optimise it ([3]). For this purpose mathematical model of this process was developed.

Mathematical model of the vacuum paper drying model was created utilising a commercial Computational Fluid Dynamic (CFD) software *Fluent* ([1]). In proposed model continuity, momentum and energy equations are solved for the humid air. Paper is treated as a porous medium, which is in thermodynamic equilibrium with a humid air. As a consequence only one energy equation, common for both phases, is solved. Water distribution within paper is resolved by solving so-called lumped diffusion equation ([1], [2]). In this model water is treated as a one phase regardless it state, *i.e.* whether it is free or bounded water. In such a case lumped water diffusion coefficient depends on the water content and temperature. Since deep vacuum and high humidity of the air inside the vacuum chamber thermal radiation is an important heat transfer mode, therefore it was also considered in the model. Both phases, air and paper, were treated as media participating in radiation. Radiation transport equation was integrated with the Discrete Ordinate method. Water evaporation was modelled by Hertz-Knudsen equation [2].

In described model value of the evaporation constant in the Hertz-Knudsen equation is uncertain. To verify value of this constant, experimental stand which allowed us to carry out one cycle (heating-vacuum) of the vacuum drying process was built (Figure 1). Vacuum drying experiment consisted of

heating stage, which lasted about 6 hours and about half an hour of vacuum. During whole experiment temperatures on the walls of the vacuum chamber as well as temperatures inside the paper were recorded (Figure 1c).

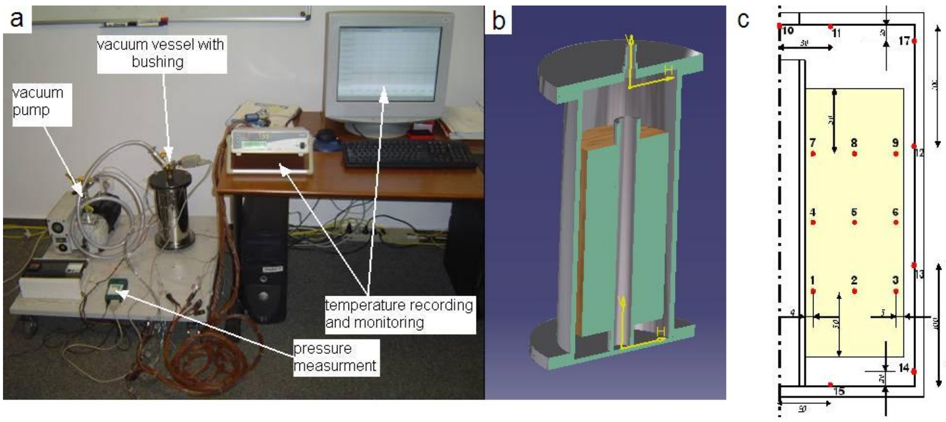

Figure 1: Paper vacuum drying experimental stand: a - complete stand, b - vacuum chamber, c - thermocouples arrangement

Based on the recordings of the temperature inside the paper, value of the evaporation constant was found by minimisation of the sum of squares of temperature deviations at the measurement points:

$$\chi^2 = \left(\boldsymbol{T} - \tilde{\boldsymbol{T}}\right)^T \boldsymbol{W}^{-1} \left(\boldsymbol{T} - \tilde{\boldsymbol{T}}\right) \tag{1}$$

where $\tilde{\boldsymbol{T}}$ is the vector of measured temperatures, $\boldsymbol{T}$ is the vector of temperature values at the measurement points obtained from the model and $\boldsymbol{W}$ stands for the covariance matrix. Since the evaporation constant estimation was done based just on the first 50 seconds of temperature recordings, it was necessary to incorporate into analysis also the estimation of the initial water distribution (it was not known in that moment). Least squares problem specified by Equation (1) was solved with Levenberg-Marquardt method [4]. This procedure requires generally to calculate sensitivity matrix in each iteration. However, in the presented problem it would extremely lengthen calculation time and because of that it was calculated only once, just for the initial guess of the unknown parameters.

As already mentioned, starting 50 seconds of temperature recordings were used to determine uncertain/unknown parameters: evaporation constant and initial water concentration. Remaining measurement data are used for validate the final model. Comparison of the calculations done with the estimated from inverse analysis values of evaporation constant and initial water distribution revealed satisfactory agreement with the measurements.

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