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eRAMZES – A NEW WEB-BASED TOOL FOR REACTIVE MOULDING SIMULATIONS

eRAMZES – NOWE NARZĘDZIE DLA SYMULACJI FORMOWANIA REAKTYWNEGO

A b s t r a c t

This paper describes a unique multiphysics simulation tool allowing one to analyse and optimize the reactive moulding process used for the production of epoxy resin based electrical insulation in many power products. The presented methodology offers fully automated numerical computations of the mentioned process excluding the requirement for high knowledge and experience of the tool end-user in the area of computer simulations.

Keywords: *reactive moulding*, *computational fluid dynamics*, *finite element method*, *automated meshing*, *Web-based computations*

S t r e s z c z e n i e

W artykule przedstawiono unikalne narzędzie do multifizycznych symulacji pozwalające na analizę i optymalizację procesu formowania reaktywnego używanego do produkcji żywicznej izolacji elektrycznej w wielu produktach elektroenergetycznych. Przedstawiona metodologia oferuje w pełni zautomatyzowane obliczenia numeryczne wspomnianego procesu wykluczając konieczność posiadania przez użytkownika narzędzia dogłębnej wiedzy i doświadczenia w dziedzinie symulacji komputerowych.

Słowa kluczowe: *formowanie reaktywne*, *obliczeniowa mechanika płynów*, *metoda elementów skończonych*, *automatyczna dyskretyzacja*, *obliczenia zdalne*

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1. Introduction

APG (Automated Pressure Gelation) process is one of the leading reactive moulding technologies [1] used in the production of many epoxy resin insulated power products. This is a complex multistep process presented schematically in Fig. 1. Due to the mentioned complexity, it was proposed to use advanced computer simulations in order to detect technological problems such as premature gelation, undesired weld-line locations, air traps or cracks [2, 3] even prior to the mould manufacturing.

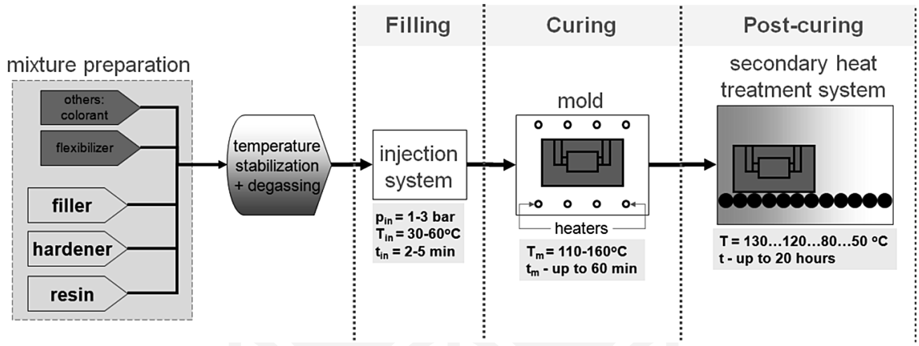

Fig. 1. Stages of reactive moulding manufacturing process

Rys. 1. Poszczególne etapy w procesie formowania reaktywnego

In the traditional approach to the analysis of the reactive moulding process [4] all design stages are executed manually by engineers utilizing different autonomous computer programs that are not directly linked to each other. These operations are time-consuming and require from the user a specialized expertise in many areas connected with numerical modelling. As a consequence, a new Web-based and automated tool linking several state of the art numerical software, called eRAMZES, has been developed to give engineers an online and, hence, unlimited access to advanced reactive moulding simulations [5, 6, 7]. This opened totally new horizons for the analysis and optimization of the products manufactured in reactive moulding technology.

2. Mathematical modelling of the reactive moulding process

The complexity of the reactive moulding process is presented in Fig. 2 illustrating phenomena taking place during all stages involved in APG technology, i.e. filling, curing and post-curing. Each phenomenon is reflected in an appropriate mathematical model implemented in the developed simulation tool. In the case of CFD (Computational Fluid Dynamics) analysis one have to deal not only with numerically unstable multiphase flow calculations, but also with the kinetics of curing reaction and conjugate heat transfer. Additionally, because of the dynamics of the chemical reaction and complexity of the resulting thermal effect, an accurate modelling of the stresses and deformations during mechanical analysis is not an easy task.

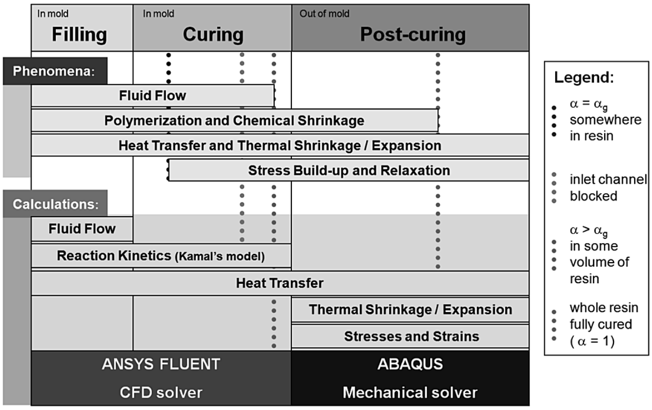

Fig. 2. Mathematical modelling of the reactive moulding manufacturing technology

Rys. 2. Modelowanie matematyczne technologii wytwarzania formowania reaktywnego

2.1. CFD simulations

The transient calculations of the filling and curing stage of APG process are performed in CFD commercial software ANSYS Fluent. For this purpose the standard set of governing equations including continuity equation, Navier-Stokes equation and energy equation is applied [8].

Due to the presence of two different fluids during the mould filling stage (epoxy resin and air) VOF (Volume of Fluid) method is used to predict accurately the location of the interface between both phases. In the VOF approach the volume fraction of resin *a* in each cell is solved from the conservation equation:

$$\frac{\partial a}{\partial t} + \nabla \cdot (au) = 0 \qquad (1)$$

where:

t – time,

u – the velocity of fluid.

The nature of the reactive moulding process causes that it is important to monitor the course of polymerization reaction of thermosetting epoxy resin. For this purpose curing kinetics model in the form of Kamal-Sourour equation is applied [9] and implemented in ANSYS FLUENT by using User Defined Function and User Defined Scalar functionalities [8]. According to this model the value of degree of curing α at time t is defined as:

$$\alpha = \frac{H(t)}{H_\Sigma} \qquad (2)$$

where:

$H(t)$ – the heat of reaction released until time t,

H_Σ – the total heat of reaction.

The progress of the curing phenomenon is linked to the mass conservation and, thus, the degree of curing α is governed by its own un-steady state conservation equation:

$$\frac{\partial(\rho\alpha)}{\partial t} + \nabla \cdot (\rho u \alpha) = S_a \tag{3}$$

In the equation (3), S_a is the source term of degree of curing calculated according to the mentioned Kamal-Sourour model and used to determine the source term of energy equation resulting from the exothermic curing reaction $S_T = S_a H_\Sigma$. S_a is expressed by the equation:

$$S_a = \rho\left[A_1 e\left(\frac{-E_1}{RT}\right) + A_2 e\left(\frac{-E_2}{RT}\right)\alpha^m\right](1-\alpha)^n \tag{4}$$

where:

- m, n – the model constants,
- A_1, A_2 – the pre-exponential factors,
- E_1, E_2 – the activation energies,
- R – the universal gas constant,
- T – the absolute temperature.

It is worth stressing that all parameters of Kamal-Sourour model mentioned above and the total heat of exothermic reaction are determined experimentally (usually by using Differential Scanning Calorimetric technique) and their values are characteristic for each epoxy resin.

2.2. Mechanical simulations

The structural results are obtained in a transient and coupled thermal and stress analyses conducted sequentially. In the first step the effects related to the heat transfer are determined and then chemically driven deformations are calculated. Finally, this leads to the definition of the strains and stresses as a function of the process time.

The chemical shrinkage model was developed based on the assumption that the total strain increment $\Delta\varepsilon^{\mathrm{Total}}$ (in each time-step) can be expressed as a sum of mechanical $\Delta\varepsilon^{\mathrm{Mechanical}}$ and thermal $\Delta\varepsilon^{\mathrm{Thermal}}$ components:

$$\Delta\varepsilon^{\mathrm{Total}} = \Delta\varepsilon^{\mathrm{Mechanical}} + \Delta\varepsilon^{\mathrm{Thermal}} \tag{5}$$

ABAQUS software allows defining thermal component by applying a user-defined subroutine. This component covers both chemical and thermal effects influencing the material density:

$$\Delta\varepsilon^{\mathrm{Thermal}} = \sqrt[3]{\frac{\rho}{\rho'}} - 1 \tag{6}$$

where:

- ρ' – actual density,
- ρ – the value of density from the previous time-step.

It is worth stressing that in order to realize that stage of calculations it was necessary to apply the dependence of temperature and degree of curing on density. This correlation was derived based on the experimental measurements. More information about the modelling of epoxy resin shrinkage can be found in [10].

3. Web-based tool for automated reactive moulding simulations

3.1. The architecture of eRAMZES tool

The eRAMZES tool is controlled by a dedicated multifunctional Web platform linking a number of applications (commercial and developed) interacting between each other. The general workflow of eRAMZES tool is presented schematically in Fig. 3. One can notice that engineer is obliged only to define the geometrical model and process parameters, while the remaining computational steps are executed in an automated manner.

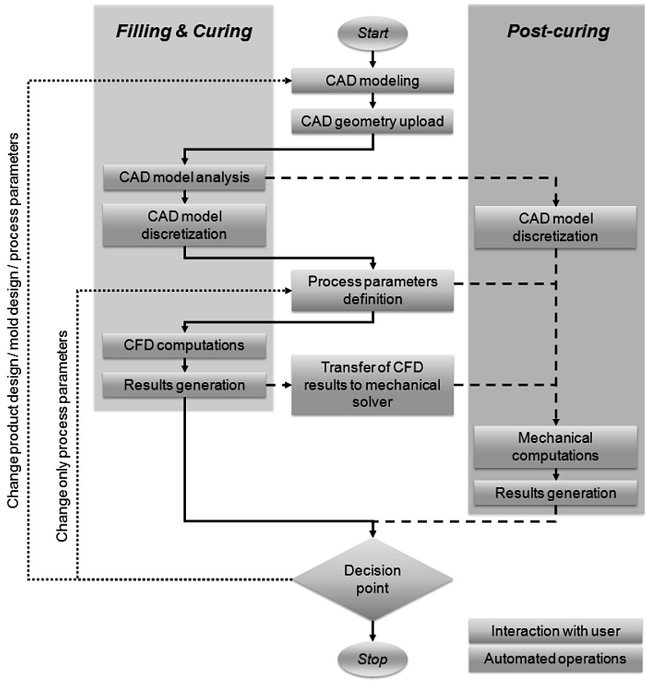

Fig. 3. The principle of working of the eRAMZES tool

Rys. 3. Podstawy działania narzędzia eRAMZES

3.2. CAD model and discretization

The very first step of the analysis that must be taken by user is CAD modelling. Engineer decides at this stage about the geometrical components, their features and possible simplifications, which will be taken into consideration during computations. In the consecutive step the prepared geometry is loaded into eRAMZES by the mentioned Web platform. Next, the CAD geometry is analysed automatically to detect parts included in the model and the gathered data is used further during the meshing and solving operations.

Next stage is geometry discretization which was recognized as one of the most challenging part of the tool development, mainly due to high complexity and diversity of the products manufactured in APG technology. In the proposed approach all operations done on geometry are executed automatically by using dedicated scripts giving commands to the meshing software (HyperMesh and ABAQUS for CFD and mechanical module respectively). In this way the CAD geometry is imported, modified if needed, discretized and exported to solvers. The geometry of an exemplary product (current transformer) analysed by using eRAMZES tool is presented in Fig. 4.

Fig. 4. Geometry of current transformer (left) and its discretization in ABAQUS (right)

Rys. 4. Geometria transformatora (po lewej) oraz jego dyskretyzacja (po prawej)

3.3. Process parameters definition and computations

Definition of the process parameters is another step of the reactive moulding analysis with the eRAMZES tool that requires input from the user side. The Web application uses information gathered during the CAD model analysis and creates dynamically a dedicated Website allowing user to enter all parameters required to configure the simulation. At this stage both the process parameters (e.g. mould filling time, mould heating temperature etc.), material properties, materials assignment to product parts and, finally, basic numerical parameters related to structural computations are selected and then sent automatically to solvers.

Processing is the subsequent fully automated stage of the simulation procedure, executed in a batch mode by using scripts generated automatically and individually for each simulation case. At this stage the CAD model analysed by the tool and the process parameters provided by user in the previous steps are read into processors.

The solver configuration requires the choice of mathematical models used in the reactive moulding simulation (both built-in models like e.g. turbulence model, flow model etc. as well as additionally implemented models like curing kinetics model) and the definition of numerical parameters ensuring reliable and accurate solution of these models. In the consecutive step the transient numerical computations for filling and curing stage are conducted in ANSYS FLUENT and, once done, results are generated and exported.

The computations can be continued if user decides to include the post-curing simulation. In such case temperature results obtained for the end of curing stage are translated by using dedicated in-house developed software [10] and transferred to the mechanical solver ABAQUS to constitute the starting point for post-curing computations.

It is worth noticing that the solution convergence is monitored and controlled automatically, what was recognized as one of the biggest challenges during the tool development as well.

3.4. Results visualization

The simulation results are processed in a batch-mode in ANSYS CFD-Post and built-in ABAQUS post-processor. For this purpose master macros, recorded for each post-processor individually, are executed for each simulation case making the results visualization process automated and repeatable irrespective of the product under consideration. The obtained results are presented to user in different forms like movies, pictures and charts (see Fig. 5) via the Website or as a printable PDF document.

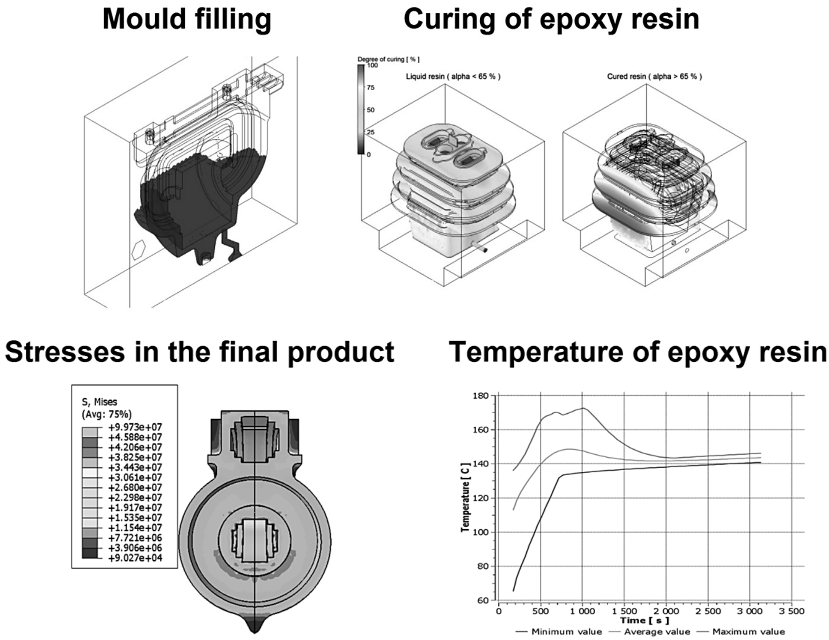

Fig. 5. Exemplary results of eRAMZES computations

Rys. 5. Przykład wizualizacji wyników obliczeń eRAMZES

The developed way of results visualization allows users to observe in details the course of the reactive moulding process and to capture effects inside the mould and product, which cannot be detected in a normal production process or in an experimental way. This includes information about the flow pattern of epoxy resin during the filling stage, distribution of temperature in time during all process stages, distribution of degree of curing in time during the filling and the curing stage, distribution of deformations, stresses and strains during the post-curing stage. The acquired knowledge is then used by engineer to decide whether further process and product optimization is needed or not.

4. Conclusions

The presented novel Web-based tool combining CFD and mechanical simulations can be successfully utilized both for the design of new and optimization of the existing products manufactured in the reactive moulding technology. The tool allow users to observe the influence of changes in the product and/or mould design as well as in the configuration of the process parameters without any interference on the real production process. This was achieved by high quality simulation results presenting details about the process course.

The described automation of the meshing and solving operations executed during CFD and mechanical computations allowed one to shorten significantly the total computational time and to eliminate the requirement for high user knowledge and experience in the field of numerical simulations. Among the other eRAMZES advantages one can notice its user-friendliness, unlimited online access to the tool and the repeatability of the simulation process resulting in manual-error resistance.

All aspects mentioned above lead, on the one hand, to shorter development time of new products manufactured in the reactive moulding technology and, on the second hand, to improved quality of the epoxy based components. Moreover, the presented approach can be adapted to provide the possibility to analyse also other manufacturing processes.

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