V European Conference on Computational Fluid Dynamics
ECCOMAS CFD 2010
J. C. F. Pereira and A. Sequeira (Eds)
Lisbon, Portugal, 14–17 June 2010

FIRST INDUSTRIAL APPLICATION OF THE 3D SILICONE MOLDING SIMULATION TOOL

Lukasz T. Matysiak, Piotr Saj and Robert M. Sekula

ABB Corporate Research
Starowislna 13a, 31-039 Krakow, Poland
e-mail: {lukasz.matysiak, piotr.saj, robert.sekula}@pl.abb.com

Key words: Silicone molding, Numerical modeling, Experimental validation, Process optimization

Abstract. *Silicone molding becomes more and more popular technology for the manufacture of insulation of many medium and high voltage products. An increasing interest in the silicone insulation is mainly dictated by its outstanding electrical and mechanical performance, operational safety, compactness and lower weight with respect to the classical ceramic units. However, the final product quality and reliability is affected to a considerable degree both by the product design as well as by the proper course of the manufacturing process. It is not easy to work out the optimal solution, since the considered technology is accompanied by many complex physical phenomena. In this connection it is usually necessary to perform real experiments, which are most often time-consuming and expensive. Instead of that the 3D simulation tool (based on FVM and commercial CFD software) capable of modeling the full-scale silicone molding process was built and successfully validated by comparing the experimental and simulation data. The developed tool allows to get rid of the financial expenses characterizing the mentioned real trials and to limit the time to market being one of the most important factors influencing the company competitiveness. Even more important is an insight into the process course resulting in its much better control, what in turn enables exclusion of the potential problems (e.g. air gaps generation, premature gelation, material overheating etc.) prior to the production launching and/or the process optimization.*

1 INTRODUCTION

Silicone molding becomes more and more popular technology for the manufacture of insulation of many medium and high voltage products like surge arresters, bushings, insulators and cable terminations [1, 2]. An increasing interest in the silicone insulation is mainly dictated by its outstanding electrical and mechanical performance, operational safety, compactness and lower weight with respect to the classical ceramic units.

However, it should be stressed that the final product quality and reliability is affected to a considerable degree both by the product design as well as by the proper course of the manufacturing process. It is not easy to work out the optimal solution, since the considered technology is accompanied by many complex physical phenomena. In this connection it is usually necessary to perform real experiments, which are most often time-consuming and expensive.

Generally, silicone molding can be divided into two main stages, i.e. filling lasting usually few minutes and curing that is much longer (up to one hour). In the first stage the heated mold is filled with thermosetting silicone and the fluid viscosity is dependent on the shear rate arising in the flowing material and on its temperature. The filling stage is followed by the curing phase, during which the mold heating temperature is usually increased to accelerate the cross-linking process. This stage is also characterized by high pressures generation inside the mold due to the silicone thermal expansion.

As a consequence of the technology complexity, the 3D simulation tool was built and successfully validated by comparing the experimental and simulation data. The validation was performed for two real products, i.e. medium voltage surge arrester and high voltage bushing. The tool is based on FVM (Finite Volume Method) and commercial CFD (Computational Fluid Dynamics) software ANSYS FLUENT and is capable of modeling the full-scale silicone molding process.

The developed simulation approach accounts for the unsteady multiphase mass flow, conjugated heat transfer, heat generation due to the curing reaction course, increase of pressure inside the mold related to the silicone thermal expansion and influence of the shear rate and temperature on the silicone viscosity. In this connection the governing continuity, momentum and energy equations are supplemented with additional formulas describing the mentioned curing kinetics, pressure effects and flow effects connected with the variable silicone viscosity.

Modeling of the silicone molding process allows to get rid of the financial expenses characterizing the real trials and to limit the time to market being one of the most important factors influencing the company competitiveness. In case of the proposed numerical approach the only cost is time related to the model preparation and computations. However, cost and time savings are not the biggest benefits of the tool utilization. Even more important is an insight into the process course resulting in its much better control. This in turn enables exclusion of the potential problems (e.g. air gaps generation, premature gelation, material overheating etc.) prior to the production launching and/or the process optimization.

2 INJECTION MOLDING PROCESS FOR LIQUID SILICONE RUBBERS

Silicone rubber is broadly used as an indoor or outdoor insulation in many electrical devices, beginning from low voltage, through medium voltage and finishing with high voltage products. So big diversity of the possible material applications results in different variants of the silicone molding technology, which in turn requires various material formulations characterized by different physical properties. Consequently, the following types of silicone rubber are processed within the silicone molding: LSR (Liquid Silicone Rubber), RTV (Room Temperature Vulcanizing) and HTV (High

Temperature Vulcanizing) silicone rubber. The developed simulation tool is dedicated to the analysis of the LSR injection molding. LSR processing by using the injection molding technology is presented schematically in Figure 1. More information on this topic can be found e.g. in [3, 4, 5, 6]. Basically, the total cycle time, time of its particular stages and the process parameters depend on the product to be casted, however the whole process usually lasts between 30 and 60 min.

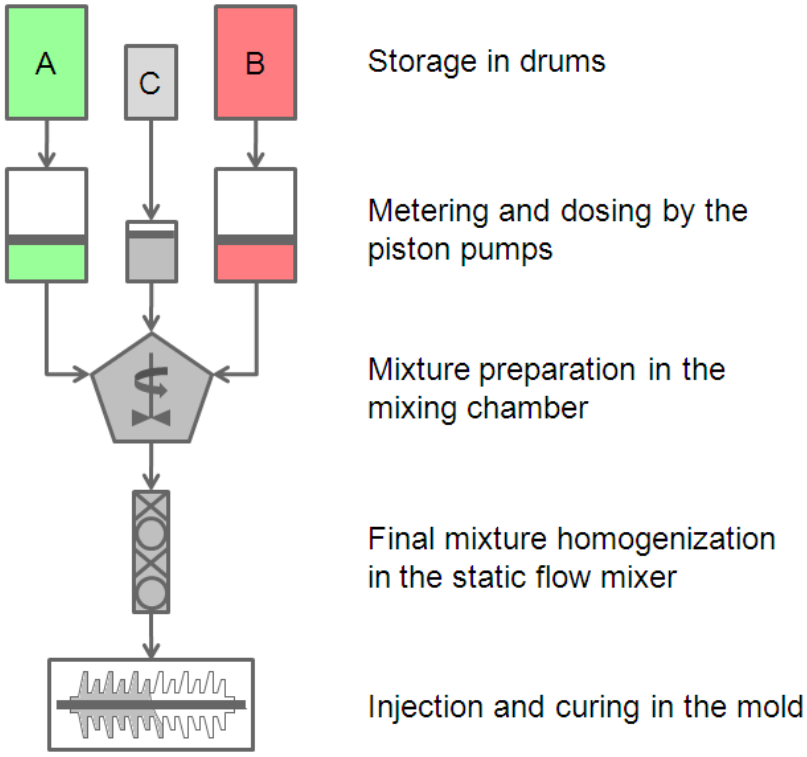

Figure 1: Scheme of the LSR injection molding process.

At the very beginning of the silicone molding process the internal device parts are placed inside the mold, which is then closed by using the clamping machine. These inserts have either ambient temperature or are initially preheated (usually to about 60÷80°C). The mold is also heated up prior to the injection process and its temperature during the filling stage is equal most often to around 80°C.

In the consecutive step two transparent silicone components (A and B) and pigment (C), stored in separate drums, are metered and pumped by using the piston pumps into the mixing chamber, where the initial mixing takes place. The mixing ratio for compounds A and B is usually 1:1. It must be emphasized that one of the components contains catalyst (typically platinum based), but also other additives can be added to the mixture (e.g. filler) to modify the material properties and fulfill in this way the specific requirements for the given application.

Next, the tentatively prepared mixture is passed into the static flow mixer, where the final mixture homogenization occurs. The typical viscosity values for such prepared mixture are in the range of 5 and 100 Pa·s, what is much below values met in case of RTV and HTV silicone rubbers. The main reason for this is different filler content in the material (lower in case of LSR). It should also be stressed that the LSR viscosity is strongly dependent both on the shear rate arising during the fluid flow and temperature and hence it can reach even higher values during the filling stage. The mixture temperature is equal to the ambient one in the standard approach, although the initial preheating is also utilized (known as Advanced Vulcanization Technology). It is

sometimes combined with the cold runner system to prevent curing of the inflowing silicone in the injection channel and its blocking prior to the finish of the mold filling.

After the mixture preparation the mold is closed by using the clamping machine and the injection process starts. It is performed either under the atmospheric pressure or in the vacuum conditions. The value of the injection pressure depends on the product to be molded, however it is most often between 50 and 200 bars, what corresponds to the volumetric flow rate on the level of 1÷3 l/min and the filling time in the range of 1 and 10 min. During this stage the silicone phase transformation from the liquid to the solid state is already initiated and thus much attention must be paid to avoid the premature gelation of the material.

The next step is the curing stage lasting between 20 and 50 min. During this phase the mold heating temperature is usually increased to 115÷125°C to accelerate the cross-linking reaction. This chemical phenomenon is connected with the exothermic effect, which can result in the material overheating. The vulcanization process is also accompanied by the significant pressure growth inside the mold (up to few hundred bars) due to high thermal expansion of the silicone.

The curing stage is often followed by the initial cooling stage, which is conducted, when the silicone is cured and the product is still inside the mold. This is done by reduction of the mold heating temperature back to more or less 80°C.

The final operation is the product demolding and its eventual cooling in the ambient conditions.

3 NUMERICAL MODELING OF THE SILICONE MOLDING PROCESS

The presented numerical approach allowing to model the silicone molding process is boiled down to the most important stages of the process, i.e. to the simulation of the filling and curing stage. The reason for this is that the most crucial phenomena affecting the final product quality and reliability occur during these stages. The complexity of the investigated problem is explained in Figure 2, which depicts the mentioned phenomena and their reflection in the mathematical models constituting the simulation tool [7, 8].

In the real process the main flow of silicone and air is observed during the injection stage. It is accompanied by a meaningful dependence of the silicone viscosity on the shear rate, temperature and degree of cure. After the filling stage only small-scale and local silicone movement takes place before reaching the gelation point, i.e. the moment when the material undergoes phase transformation from the liquid to the solid state. The mentioned flow of the silicone during the curing stage is a consequence of the variations of the material density due to the temperature changes and the proceeding chemical reaction. These two phenomena are also the reason for the shrinkage and expansion of the silicone, what in turn results in the residual stresses formation in the cured silicone and their relaxation as a function of time and temperature. High thermal expansion of the silicone causes also significant increase of pressure inside the mold. Another visible influence of the curing process is its exothermic effect. This means that in the analyzed system apart from the conjugate heat transfer between fluids and solids also additional heat generation must be considered.

Due to high complexity of the silicone molding process several simplifications are incorporated in the developed tool. They do not downgrade the value of the simulations outcome, accelerating simultaneously the computations to a considerable degree. Firstly, the constant value of the silicone density is assumed, what means that the mentioned local fluid rearrangements are omitted due to their negligible influence on the process. Another simplification relates to the exclusion of the calculations of the chemical expansion and thermal and chemical shrinkage. This means that the stresses

generation and their relaxation are not considered. The influence of the value of degree of cure on the silicone viscosity and consequently on the silicone flow is also omitted. This is justified by the fact that degree of cure reaches low values during the filling stage and in this connection it does not affect the process considerably. In turn, during the curing stage flow is not computed and hence dependence between degree of cure and the silicone viscosity must not be included.

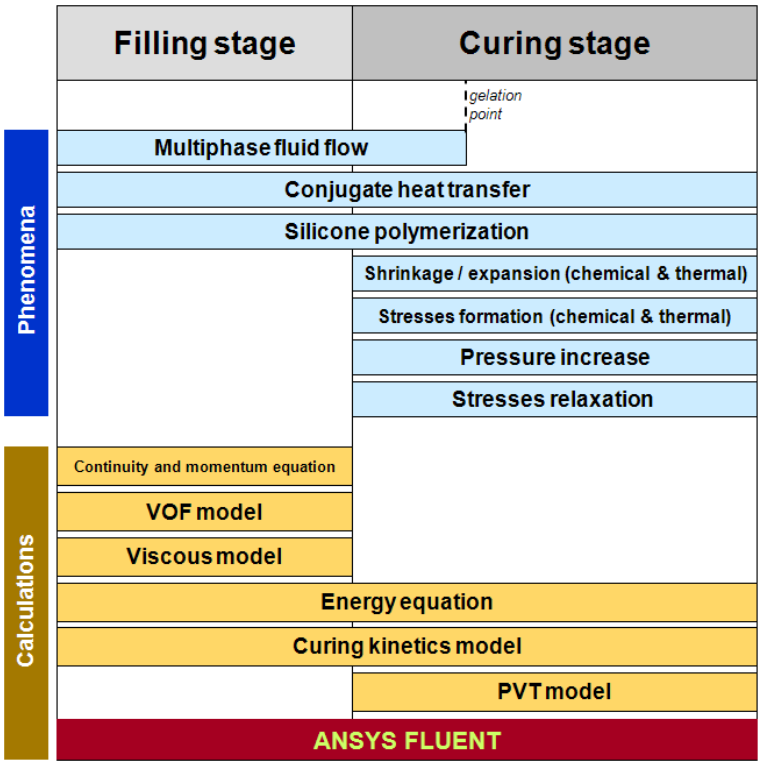

Figure 2: Numerical modeling of the physical phenomena occurring during the silicone molding process.

Such structure of the described tool causes that its main benefits are connected with an insight into the injection and curing process. The silicone flow in the mold as well as the distribution of temperature and degree of cure in time can be easily observed. This allows to detect the possible problems with the mold filling like undesired air gaps formation (does not apply to the process conducted under the vacuum conditions), which lower the insulating properties of the silicone coating or wrong curing front propagation (e.g. premature gelation in the injection channel or its neighborhood and the consequent incomplete mold filling). Monitoring of the thermal effects of the curing reaction is also feasible and gives an opportunity to recognize the places, where the local overheating of the processed material can occur. Finally, observation of the pressure generation inside the mold during the curing stage is important because of the safety reasons and the proper choice of the clamping force.

Consequently, the developed simulation tool can be applied both to analyze and optimize the silicone molding process for the existing devices as well as to develop the totally new products. In both cases it excludes the necessity of time-consuming and expensive trial and error methods. This in turn results in lower development costs and accelerates this process, what in the final effect leads to the increase of the company competitiveness. Moreover, in case of the new products the potential manufacturing problems can be recognized and solved even prior to the production launching.

3.1 Governing equations

In spite of the introduced simplifications the presented numerical tool consists of many mathematical models describing the course of the silicone molding process. The whole approach is based on the FVM and commercial CFD software ANSYS FLUENT. It means that the solution of the considered problem is searched by applying the control volume based technique to convert the governing equations to the algebraic equations that can be solved numerically. This involves decomposition of the whole solution domain into the finite number of control volumes (or cells) and integration of the governing equations over the cells faces to find the discrete values for each cell center. For more detailed information refer e.g. to [8, 9].

The developed tool consists of the standard governing equations available in ANSYS FLUENT software (continuity, momentum and energy equation) and additional formulas like the viscous model, the curing kinetics model and the PVT (Pressure Volume Temperature) model. All equations constituting the simulation tool are discussed briefly in the further part. It is worth noticing that the analyzed process has an unsteady character and the governing equations are solved numerically by using the implicit first-order time discretization, while in case of the convection terms the first-order upwind discretization is used.

Because of the fluid flow considered during the filling stage the solution must satisfy the continuity equation (mass conservation equation). It states that the overall mass of the system is conserved and has the following form:

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \cdot \boldsymbol{w}) = 0 \tag{1}$$

where ρ is the fluid density, t is time, $\boldsymbol{\nabla}$ is the Nabla operator and $\boldsymbol{w}$ is the vector of the fluid velocity. Generally, for incompressible flows $\frac{\partial \rho}{\partial t} = 0$, however in this particular case the multiphase fluid flow occurs. In this connection the average mixture density (composed of air and silicone) in cells changes during the injection stage and hence $\frac{\partial \rho}{\partial t} \neq 0$.

The laminar motion of the mixture is expressed by Navier-Stokes equation known also as momentum equation, which is derived from Newton's second law:

$$\rho \cdot \frac{D\boldsymbol{w}}{Dt} = \mu \cdot \nabla^2 \boldsymbol{w} - \boldsymbol{\nabla} p + \rho \cdot \boldsymbol{g} \tag{2}$$

where term $\frac{\boldsymbol{Dw}}{\boldsymbol{Dt}}$ is the substantial (time) derivative of the velocity vector $\boldsymbol{w}$ and represents the flow acceleration, $\boldsymbol{\mu}$ is the fluid dynamic viscosity, $\boldsymbol{\nabla^2}$ is the Laplacian operator, term $\boldsymbol{\nabla p}$ stands for the static pressure gradient and $\boldsymbol{g}$ is the vector of the gravitational acceleration. The left-hand side of the equation above includes both the unsteady and convective term, while the first term on the right-hand side is the diffusion term and the second one together with the third one represents the source term. In the analyzed case a single momentum equation is solved and the computed velocity field is shared among the air and silicone phase. The momentum equation is dependent on the volume fraction of each phase through the material properties like density $\boldsymbol{\rho}$ and the dynamic viscosity $\boldsymbol{\mu}$.

Due to the strong influence of the shear rate and temperature on the silicone viscosity the viscous model considering these effects is implemented in the developed numerical tool. For this purpose the viscosity measurements for several liquid silicone rubbers were performed by using rheometer and cone and plate method. They were conducted

for different temperature and shear rate levels, what allowed to work out the following formula describing the mentioned dependencies:

$$\mu = e^{[a_1 + a_2 \ln \dot{\gamma} + a_3 \ln (T)^2]} \tag{3}$$

where $\dot{\gamma}$ is the shear rate, T is temperature, while a_1, a_2 and a_3 are the model parameters characteristic for the given material.

Another governing formula constituting the presented approach is the energy equation, which ensures conservation of the energy balance and is also shared among the phases:

$$c_p \rho \frac{\partial T}{\partial t} + c_p \rho \boldsymbol{\nabla} T \cdot \boldsymbol{w} = \boldsymbol{\nabla} \cdot (k \boldsymbol{\nabla} T) - p \boldsymbol{\nabla} \cdot \boldsymbol{w} + S_T \tag{4}$$

where c_p stands for the specific heat capacity, k is the thermal conductivity, p is pressure and S_T is the source term. In this equation the left-hand side is sequentially composed of the accumulative and advective term, while the first term on the right-hand side is known as the diffusive (or conductive) term, the second one represents the reversible conversion between the kinetic and thermal energy and the third one is called the generation term accounting for the internal heat sources. In this particular case the generation term describes the exothermic effect of the curing reaction and is expressed as:

$$S_T = S_a H_\Sigma \tag{5}$$

where H_Σ is the total heat released during the curing reaction and S_a is the source term present in the additional unsteady state conservation equation solved for degree of cure α. It has the following form:

$$\frac{\partial (\rho \alpha)}{\partial t} + \nabla (\rho \boldsymbol{w} \alpha) = S_a \tag{6}$$

The source term S_a is represented by Kamal's equation, which describes the curing kinetics of thermosetting materials [10, 11]:

$$S_a = \rho (K_1 + K_2 \alpha^m)(1 - \alpha)^n \tag{7}$$

where m and n are the model constants, while K_1 and K_2 are the reaction rate constants computed from the formula below:

$$K_i = A_i e^{\frac{-E_i}{RT}} \tag{8}$$

where $i = 1, 2$, A_i is the pre-exponential factor, E_i is the activation energy and R is the universal gas constant.

In turn, degree of cure α is defined as the ratio between the heat of the curing reaction released by time t and the total heat of the curing reaction H_Σ:

$$\alpha = \frac{H(t)}{H_\Sigma} \tag{9}$$

All parameters present in Kamal's model, i.e. m, n, A_1, A_2, E_1, E_2 together with the total amount of heat released during the curing reaction H_Σ are material dependent and hence are determined experimentally most often by using DSC (Differential Scanning Calorimetry) measurements.

Another optional formula implemented in the presented tool allows to monitor the pressure generation inside the mold during the curing stage due to high thermal expansion of the silicone rubber. This equation is based on the PVT model, which is

characteristic for each material and hence must be determined experimentally. The PVT model expresses pressure p as a function of the specific volume v and temperature T:

$$p = \mathrm{f}(v, T) \tag{10}$$

3.2 Multiphase flow modeling

As it was mentioned, one of the main benefits related to the utilization of the developed numerical tool is ability to track the interface between the inflowing silicone and the evacuated air during the filling stage. This allows to observe when and if the mold is completely filled with silicone. In this connection the presented tool is equipped with the VOF (Volume of Fluid) model, which enables accurate prediction of the location of the interface between silicone and air [8].

The VOF formulation relies on the fact that the air and silicone phase do not interpenetrate. The tracking of the interface between both phases is accomplished by the solution of the additional continuity equation for the volume fraction of the secondary (silicone) phase φ_2:

$$\frac{\partial \varphi_2}{\partial t} + \boldsymbol{\nabla} \cdot (\varphi_2 \cdot \boldsymbol{w}) = 0 \tag{11}$$

The volume fraction of the primary (air) phase φ_1 is computed from the following condition:

$$\varphi_1 + \varphi_2 = 1 \tag{12}$$

The equations above are solved for each cell and there are three possible situations, i.e. when the given cell is:

- filled with air ($\varphi_2 = 0$),
- partially filled with silicone ($0 < \varphi_2 < 1$),
- filled with silicone ($\varphi_2 = 1$).

Due to the multiphase character of the considered problem the material properties present in the transport equations like density $\boldsymbol{\rho}$, the dynamic viscosity $\boldsymbol{\mu}$ and the thermal conductivity $\boldsymbol{k}$ are calculated in each cell as the volume-weighted averages:

$$\phi = \frac{1}{V} \sum_{j=1}^{r} \phi_j V_j \tag{13}$$

where ϕ is the scalar value representing the given material property, V is the cell volume, r is the total number of phases, j stands for the phase index and V_j represents the volume occupied in a single cell by the j-th phase.

In case of the specific heat capacity c_p and temperature T appearing in the energy equation the mass-weighted average values are used:

$$\phi = \frac{\sum_{j=1}^{r} \phi_j \rho_j V_j}{\sum_{j=1}^{r} \rho_j V_j} \tag{14}$$

where $\boldsymbol{\rho_j}$ represents the j-th phase density.

4 EXPERIMENTAL VALIDATION OF THE SIMULATION TOOL

Each numerical tool must be validated in order to prove that it enables simulation of the given process in the reliable and accurate way. Validation comes down to checking if the chosen governing equations model the process appropriately. The presented

silicone molding simulation tool was tested based on the analysis of the LSR injection molding process for the 30 cm height medium voltage surge arrester and almost 2 m height high voltage bushing. Results of the conducted time-dependent temperature measurements were compared to the simulation outcome, what allowed to judge how accurately the developed approach is able to simulate the reality. In the further part the detailed description of the experimental validation performed for the medium voltage surge arrester is included.

4.1 Silicone molding experiments

The mold used for the purpose of the mentioned measurements and the investigated surge arrester are presented in Figure 3. The experimental stand was equipped with a dozen or so sensors monitoring temperature in the system. Their location can be seen in Figure 4. Data recorded by these thermocouples were used either to define the initial and boundary conditions or to validate the simulation results.

Figure 3: Experimental mold (left) and medium voltage surge arrester (right).

In sum several experiments were performed to confirm the measurements repeatability and validity. The internal parts and mold were preheated prior to the injection process to 80°C and 90°C respectively. The mold was filled with a standard two-component LSR. This stage lasted 1 min and was conducted under the vacuum conditions. After that the mold temperature was increased to 100°C to enhance the polymerization process. Time of the curing stage was 25 min.

4.2 Geometrical model and its discretization

The real geometrical data were used to prepare the CAD (Computer Aided Design) model illustrated in Figure 4. It can be seen that both some elements of the clamping machine (e.g. the heating side plates) as well as the inserts placed inside the mold prior to the filling stage were taken into account in the numerical analysis.

The geometrical model of the analyzed system was decomposed into the finite number of cells. The prepared unstructured numerical mesh is presented in Figure 5. It consisted of almost 2.2 million of elements having different topologies, among which the tetrahedral cells constituted the majority.

4.3 Input parameters for the simulation

All parameters introduced into the simulation were defined according to the experiments. Most of the material properties were provided by the product and mold

manufacturer. However, some material characteristics had to be determined experimentally. This concerns additional models (the curing kinetics and the viscous model) that were incorporated into the ANSYS FLUENT software to extend its basic capabilities.

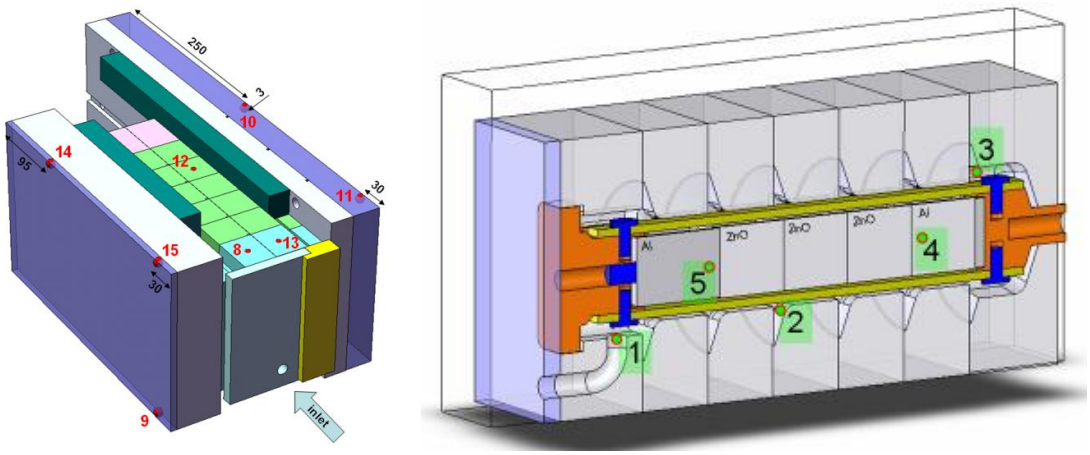

Figure 4: Geometry of the analyzed system and the sensors location.

The parameters of Kamal's model describing the cross-linking process of the considered silicone rubber were obtained thanks to the DSC measurements. The correlation between results determined experimentally and predicted by the curing kinetics model is shown in Figure 6. It should be stressed that the initial conversion of the inflowing silicone on the level of 1% was assumed in the simulation to take into account the reaction proceeding during the mixture preparation.

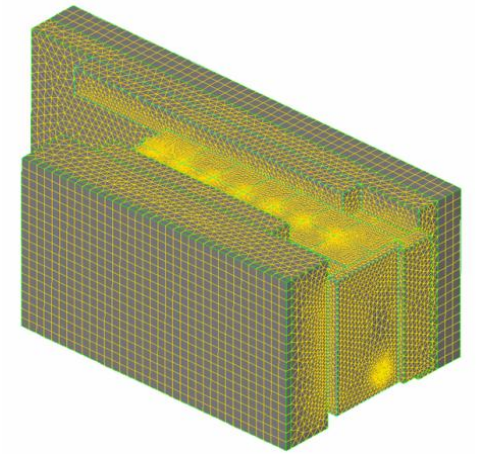

Figure 5: Finite volume mesh generated for the analyzed system.

The silicone viscosity measurements were performed for different temperature and shear rate levels by using rheometer and cone and plate method. Results of these experiments allowed to obtain the parameters of the viscous model. Comparison of the silicone viscosity predicted by the viscous model and measured experimentally is depicted in Figure 7.

4.4 Simulation outcome

Exemplary results of the numerical analysis conducted by using the described silicone molding simulation tool are shown in Figure 8, 9 and 10. The flow pattern of

the silicone during the injection stage can be observed based on Figure 8, while Figure 9 presents the distribution of temperature and degree of cure after the mold filling. Finally, Figure 10 depicts the curing front propagation. Interpretation of these results allows to judge if the chosen process parameters ensure its trouble-free course.

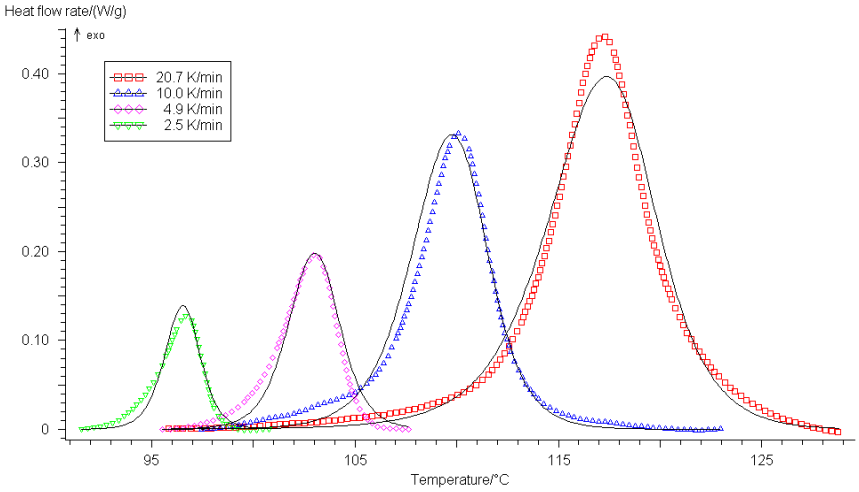

Figure 6: Accuracy of the curing kinetics model (continuous lines) in comparison with the DSC measurements (symbols).

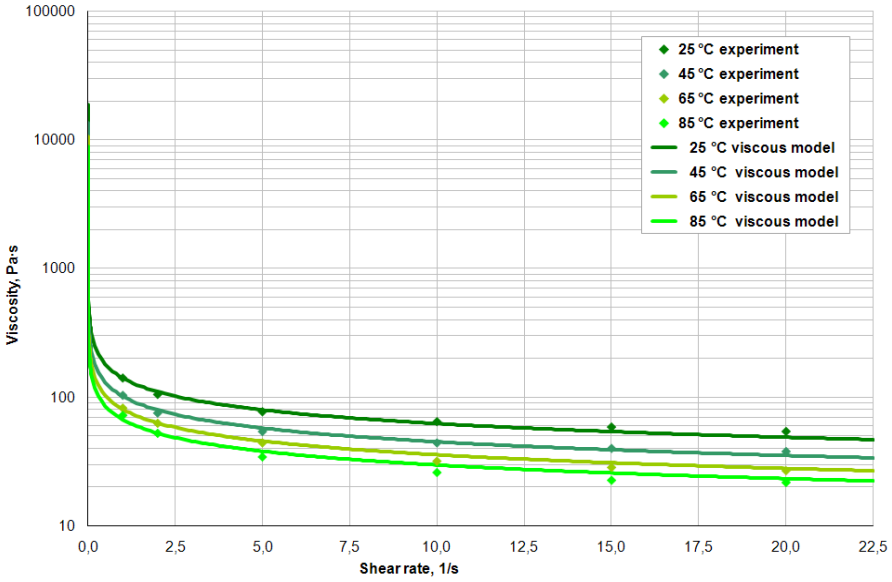

Figure 7: Comparison of the silicone viscosity predicted by the viscous model (continuous lines) and measured experimentally (dots).

4.5 Validation results

The correlation between temperatures measured experimentally and computed in the simulation at points 2÷5 is illustrated in Figures 11÷14. The first two sensors (2 and 3) were located more or less in the space between the internal parts and mold, where the flow occurred, while the remaining ones (4 and 5) were mounted inside the inserts. It can be concluded based on the presented results that the obtained agreement between the experimental and simulation data is on a good level, since the maximum deviation does not exceed 5°C.

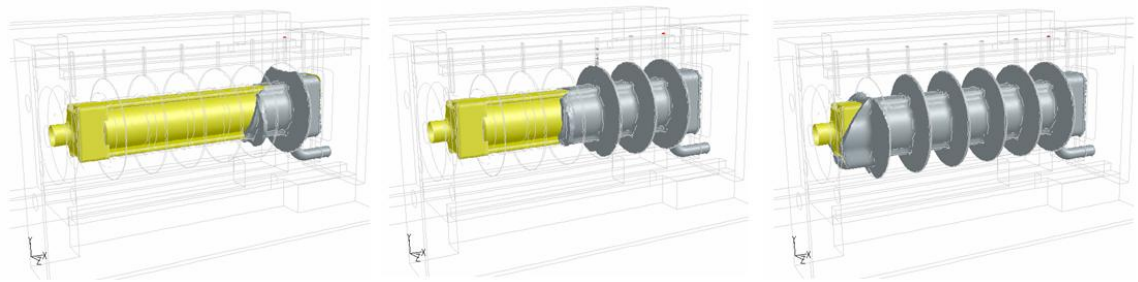

Figure 8: The course of the filling stage (left – 14.3 s, middle – 30.3 s, right – 56.3 s).

The injection stage can be easily recognized in Figures 11÷14 due to the clear temperature drop during the first minute of the process. The cooling effect related to the silicone inflow was observed faster in case of the sensors located closer to the injection channel (point 2 and 5). These regions were also longer in contact with the fresh inflowing silicone (having ambient temperature) and consequently they were cooled down to lower temperatures during the filling stage than in case of point 3 and 4.

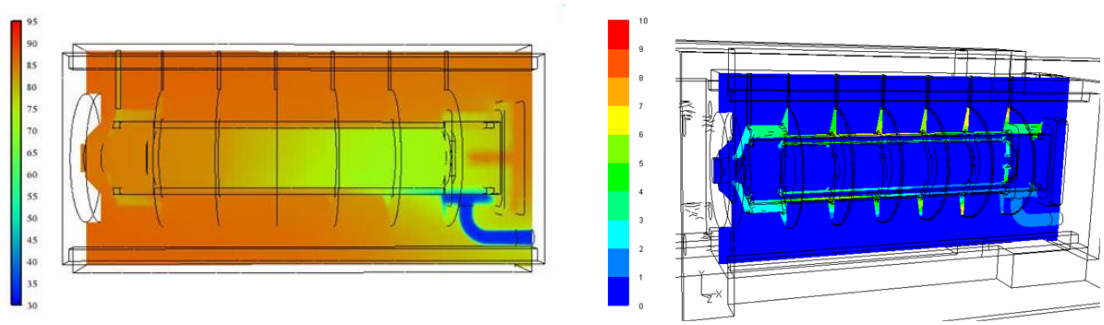

Figure 9: Distribution of temperature (left) and degree of cure (right) after the filling stage.

Another interesting effect was observed at point 5. It turned out that the internal parts were cooled considerably by the silicone during the filling stage. This caused that longer time was needed to heat them during the curing stage than in case of the fluid flow region, which was in close contact with the hot mold. It is also probable that another reason for the discussed phenomenon was big mass of the solid parts (comparing to the silicone), which had to be heated.

The analyzed results showed also that each monitoring point achieved the similar level of temperature at the end of the curing stage.

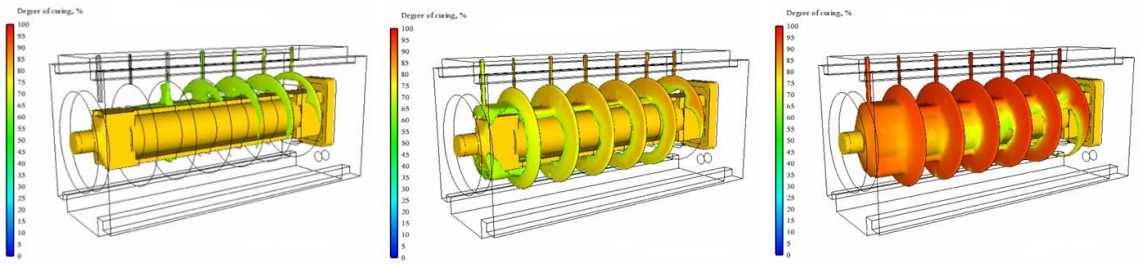

Figure 10: The course of the curing stage (left – 150 s, middle – 169 s, right – 205 s).

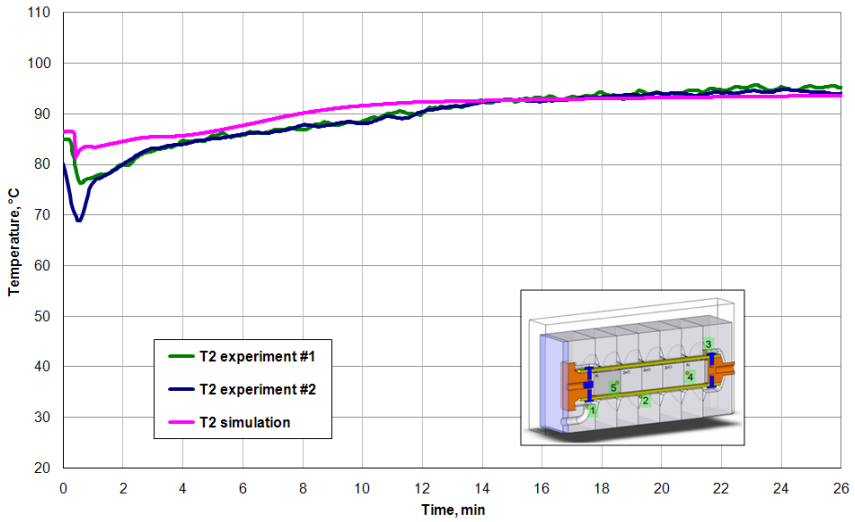

Figure 11: Comparison of the experimental and simulation data at point 2.

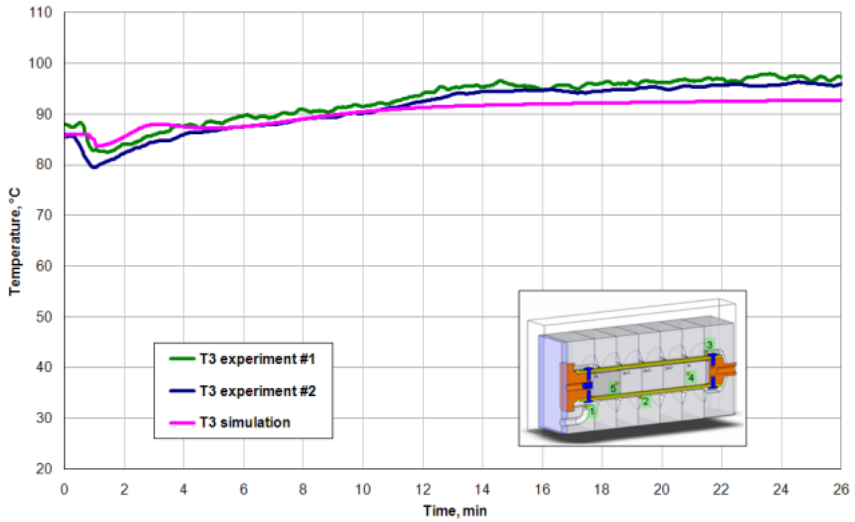

Figure 12: Comparison of the experimental and simulation data at point 3.

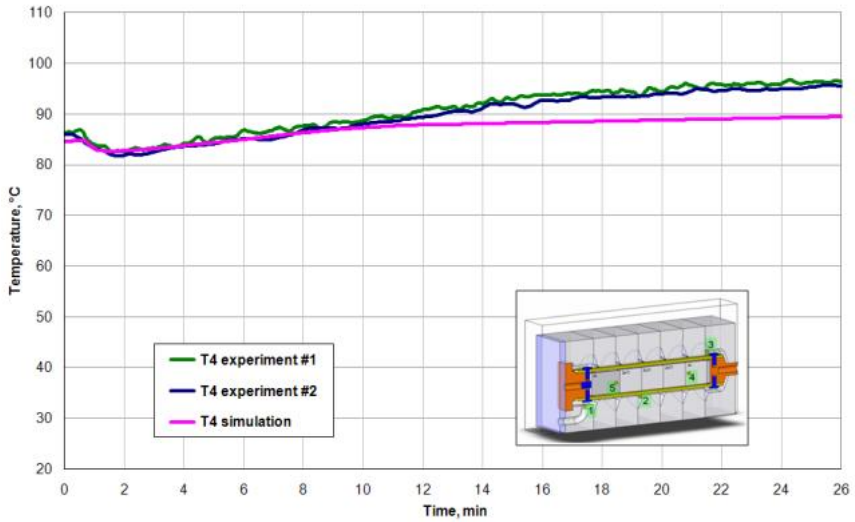

Figure 13: Comparison of the experimental and simulation data at point 4.

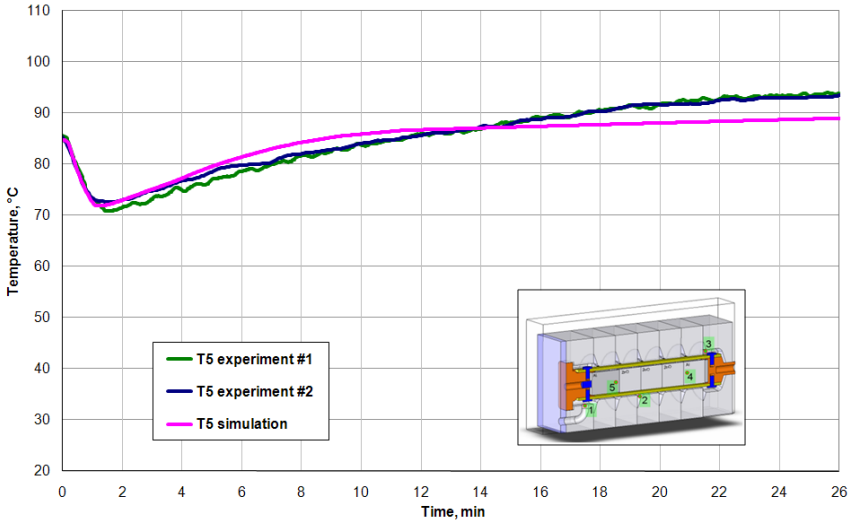

Figure 14: Comparison of the experimental and simulation data at point 5.

5 CONCLUSIONS

The presented simulation tool was validated experimentally during the LSR injection molding trials conducted for the medium voltage surge arrester. The obtained agreement between the temperature measurements and simulation data was on a good level in spite of the complexity of the analyzed process.

Apart from the standard equations describing the multiphase fluid flow and conjugate heat transfer also other formulas extending the basic capabilities of the used commercial CFD software were developed. They allowed to:

- track the course of the polymerization reaction and its exothermic effect,
- take into account the influence of the shear rate and temperature on the silicone viscosity,
- reflect the pressure generation inside the mold due to high thermal expansion of the silicone rubber.

It should be stressed that consideration of the mentioned curing and viscous effects involved experimental determination of the material characteristics.

As a consequence of the successful validation, the numerical approach can be applied for the analysis of the silicone molding process for other industrial products. Visualization of the simulation results gives an insight into the mold both during the injection and curing stage. This in turn enables the profound analysis of the process, which allows to verify the correctness of its course and to exclude many potential manufacturing problems affecting the final product quality and reliability. Air gaps generation, premature gelation, wrong propagation of the curing front and hot spots formation are just few examples. Moreover, different process parameters and product/mold designs can be investigated by using the proposed approach in the fast way and without financial expenses characterizing the standard trial and error methods.

Summing up, the developed silicone molding simulation tool can be utilized both for improvement of the existing products and development of the new ones as well as for shortening of the process cycle time.

REFERENCES

[1] L. Stenstrom, D. Gustavsson, D. Windmar, I. Gutman, W. L. Vosloo, Optimized use of HV composite apparatus insulators: field experience from coastal and inland test stations, *Proceedings of the 40th CIGRE Session* (2004)

[2] Remote Plant Plays Key Role in ABB Insulator Business, *Insulator News & Market Report Quarterly Review*, Vol. 13, pp. 54-61 (2005)

[3] P. Szaplonczay, D. Grcic, I. Pasztor, Green Future With LSR-Based Technologies, *Proceedings of the 1st Hedrich World Congress*, Frankfurt (2006)

[4] W. Schmidt, Direct on Molding of Silicone Insulation for High Voltage Applications, *Proceedings of the 1st Hedrich World Congress*, Frankfurt (2006)

[5] H. Janssen, Present and Future Production Methods for MV and HV Insulations Using Liquid Silicone Rubber, *Proceedings of the 1st Hedrich World Congress*, Frankfurt (2006)

[6] H.J. Winter, LSR & XLR® silicones to manufacture hollow core insulators, *Proceedings of the 1st Hedrich World Congress*, Frankfurt (2006)

[7] R. Sekula, P. Saj, T. Nowak, K. Kaczmarek, K. Forsman, A. Rautiainen, J. Grindling, 3-D Modeling Reactive Molding Processes: from Tool Development to Industrial Application, *Advances in Polymer Technology*, Wiley (2003)

[8] ANSYS FLUENT 12.0/12.1 Documentation, *ANSYS Inc.* (2009)

[9] A.J. Nowak et al., Advanced Numerical Techniques in Energy Transfer. International Workshop for PhD Students, *Institute of Thermal Technology, Silesian University of Technology*, Gliwice (2004)

[10] M.R. Kamal, S. Sourour, Kinetics and thermal characterization of thermoset cure, *Polymer Engineering and Science*, Vol. 13, No. 1 (1973)

[11] M.R. Kamal, S. Sourour, M. Ryan, Integrated Thermo-rheological Analysis of the Cure of Thermosets, *Proceedings of the 31st Annual Technical Conference*, pp. 187-191, Quebec (1973)