

Article

Experimental and Numerical Study of Vacuum Resin Infusion for Thin Walled Composite Parts

Sergey Shevtsov ^{1,*}, Igor Zhilyaev ², Shun-Hsyung Chang ³, Jyun-Ping Huang ⁴
and Natalia Snezhina ⁵

¹ Southern Scientific Center of Russian Academy, Russia; sergnshevtsov1@gmail.com

² Institute of Polymer Engineering, The University of Applied Sciences Northwestern Switzerland FHNW, Switzerland; zhilyaev@mail.com

³ National Kaohsiung of Science and Technology, Taiwan; stephenshchang@me.com

⁴ Southern Federal University, Russia; jas3-3@hotmail.com

⁵ Don State Technical University, Russia; snezhina_nataly@mail.ru

* Correspondence: sergnshevtsov1@gmail.com

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Abstract: This paper considers a new approach to the modeling of the vacuum infusion process at the manufacturing three-dimensional composite parts of complex shape. The developed approach and numerical methods are focused on the reliable prediction with the needed accuracy and elimination the unrecoverable defect of composite structure such as the dry spots. The paper presents some experimental results, which demonstrate two cases of dry spots formation in large aircraft composite panels, and analyses the reasons of these defects arising. Our numerical technique is based on the vacuum infusion of the liquid resin into porous preform as the two phase flow, which is described by the phase field equation coupled with the Richards equation describing the fluid motion in unsaturated soils with spatially varied pressure dependant porosity and saturation. This problem statement allowed to correctly reconstruct the resin front motion and formation of inner and outer dry spots depending on its movement. For the rapid detection of preform zones that are suspicious for defect formation two indicators calculated during process simulation are proposed and tested at the numerical experiments. The auxiliary program tool has been developed in MATLAB environment to correctly detect the times of formation, localization and dimensions of the arising dry spots by using the results of the finite element model simulation.

Keywords: polymeric composites; composite technology; vacuum infusion; process modeling and optimization

1. Introduction

A process of vacuum assisted composite fabrication is widely used for producing large components with good quality, and widely applying in aircraft [1-3], shipbuilding [1, 4 - 7], automotive [8], wind energy [4,7,9,10] and defense industries [5,10], due to its low cost, time - consuming, simplicity of the required equipment and better ecology conditions at the manufacturing.

The technical details and components of the vacuum composite manufacturing, sometimes named by the vacuum assisted resin transfer molding (VARTM) are described in a lot of the papers, technical reports and dissertations [1,6, 11-13 and oth.]. This process contains the position of preform – dry fabric or laying glass or carbon fiber reinforcement in the mold, which provides a desirable shape of the part; then covering of the whole preform by the flexible vacuum bag and sealed. Vacuum is applied through vent (outlet) inside the preform's cavity whereby the atmospheric pressure acting on the vacuum bag compacts the reinforcing structure of the preform. The liquid

resin is then introduced into vacuumed porous preform through a resin gate (inlet), where a resin pressure maintained constant or subject to controlled change. A pressure gradient arises between the atmospheric pressure at the inlet and vacuum at the flow front, which causes it to spread and fill the volume of the dry fabric with liquid resin. Meanwhile, due to the preform's compaction its porosity and permeability for the liquid resin changes because a compressive stiffness of the preform grows as it is filled with resin. The consequence of this is a permeability to flow is higher near the inlet and reduces closer to the flow front. Thus the flow of resin during the VARTM process is dependent on resin viscosity, the compaction and permeability characteristics of the preform material. In the case of ideal conditions, resin fills whole volume of prepreg without for infusion failure or serious flaws, such as voids and incomplete saturation. Last stage of the VARTM process is the composite cure that can be realized by application of temperature to the filled preform according to some controlled temperature schedule up to full solidification of the resin.

The history of the vacuum infusion process in the production of composites should be dated back to 1945, when two engineers at Marco Chemical, Inc. I.E. Muscat and N.J. Plainfield proposed a new Method of Molding, patented by them in 1950 [11]. Despite the extremely great attention of specialists and scientists, which was manifested in the large number of patents and publications issued, in the development of its various kinds (VAP, RFI, SCRIMP, DP-RTM) [14], the industrial use of the process remains insufficient.

Meanwhile, some modifications of the VARTM processes have been developed to improve its quality, versatility and performance that allowed to significantly expand the scope of the process in the practice of composites manufacturing. Among these contrivances, which were able to overcome the difficulties associated with low permeability of the preforms, are a high permeability (HPM) and flow distribution media [5,15], air-permeable membrane [5], use of multiple injection lines and vents with independent control of resin and vacuum pressure [5,6,16-21]. A distributed thermal control sometimes is used to reduce the resin viscosity while ensuring a low degree of the resin cure at the end of the preform filling [20,22-28].

Due to the above mentioned improvements in vacuum infusion processes, they were successfully implemented in the manufacture of aircraft structures (usually, shell type) [1-3], blades of wind turbines [1,9,10,27], ship's hulls [1,4,6,27,29], large-sized parts of cars bodies [30], details of spacecraft etc. [1,29].

Despite the abundance of completed and increasing number of ongoing studies of the process, in each case, the developer must solve a number of difficult problems due to the features of vacuum infusion. The most important feature of infusion processes is due to the presence of a flexible vacuum bag that covers the upper surface of the infused preform, which distinguishes the process from traditional RTM. This causes the compressive effect of atmospheric pressure on the preform, and the result of this action is the compression deformation of the porous preform, which changes according to the location of advancing front of the resin. In the dry region, where the low air pressure p_{vac} is supplied due to connection to the vacuum vent, the compressive pressure exerting a compression effect on the preform is equal to $p_{comp}^{void} = p_{atm} - p_{vac}$, whereas in the region filled with liquid resin, the pressure approaching the atmospheric pressure counteracts the external, atmospheric pressure $p_{comp}^{fill} = p_{atm} - p_{res}$ [14]. This phenomenon, which significantly changes the permeability of the preform for the moving liquid resin, as well as the fact that the pressure of the infusible resin during the vacuum process is much lower than with the traditional RTM, when the vacuum is deficient before the start of preform's filling [10], can contribute to the creation of incompletely saturated zones and dry spots [4,5,19,29-31].

The presence of differently oriented layers in laminated preform leads to the appearance of undesirable phenomena: the impregnation of the layers depends on their permeability in the direction of the resin front propagation, as well as leads to the layers deformation that disrupt their packing [13,23].

During infusion of large-sized thin-walled aircraft structures, the resin can transform from a liquid to a gel state, without having time to fill the entire preform due to the long path [3,6,17,32]. This fact makes it necessary to thoroughly analyze the thermal-kinetic and rheological state of the

resin during the infusion process. Such problem can cause to the formation of insufficient impregnation and dry spots, which are not repairable.

A change in the compressing state along the porous preform and the binder rheology during the process can cause difficulty in ensuring the uniformity of the product's thickness and the homogenous distribution of the reinforcing and binder fractions [15,33,34].

The listed problems, the solution of which using the trial and error method requires considerable time, financial expenses due to the high cost of the components, make a very important the development of process modeling tools that allow taking into account with maximum accessible precision the following process features:

- geometry of preform and mould;
- their mechanical and thermal properties, which determine the effect of pressures and temperatures on the spread of liquid resin in a medium with varying porosity and permeability;
- the dependence of the thermal-kinetic and rheological properties of the resin on time and temperature;

- a process scheme including numbers, locations and shapes of the liquid resin gates and vacuum vents. Such a modeling system would make it possible to reconstruct the nature of the motion of the resin front and its state throughout the entire technological cycle, to select the optimal process parameters to ensure the production of defect-free products. The need to create such modeling systems, caused not only by the possibility of solving important manufacturing problems with their use, but also by the possibility of a deeper understanding of the processes occurring in such a complex process as vacuum infusion, led to significant efforts by specialists to develop such modeling systems. Historically, the first such system was the LIMS software [11,16,19,35], the theoretical foundations of which were presented in the 90s of the 20th century and presented in [36]. Late the kind of the similar systems has been developed and used by some scientists: PAM-RTM [16,20,22,37]; RTM-WORKS [4,6,9]; 3DINFIL [38]; RTMSim [39]; Moldex3D RTM [40] and the ANSYS Fluent module [3,7]. All of these systems are based on the use of the so-called Finite Element / Control Volume (FE / CV) method, which uses special means of monitoring the front movement of the resin to eliminate the need to work with the moving boundaries and the deformed finite element mesh. Some features of the FE / CV method are present here to justify the proposed approach.

In the fundamental work [36], an approach was developed to predict the free surface of the resin stream and its interaction with heat transfer and curing during the movement of the resin through the fiber preform. The simulation part that describes the resin flow process is based on the FE / CV method. The modeled parts were assumed to be non-planar, such as shell-like, the thickness of which is much smaller than other dimensions of the part. This approach was implemented in almost all later works [7,10,17,37], including the most recent ones [20]. The construction of the resin flow theory in these works always begins with Darcy's law:

$$\mathbf{u} = -[K]/\mu \cdot \nabla p, \quad (1)$$

where \mathbf{u} is the superficial resin velocity, $[K]$ is the permeability tensor of the porous medium, μ is the viscosity, and ∇p is the pressure gradient in the liquid phase. The disadvantage of methods that require redefinition of the finite element mesh is the large computational complexity and, as the analysis of the cited works shows, insufficient accuracy. The FE / CV method proposed in [36] and used in all subsequent works is an attractive alternative, since it does not require rebuilding of the mesh as the resin front moves in areas with complex geometries. A key feature of the FE / CV method is a rough approximation of the shape of the modeled region, combined with careful consideration of mass conservation. Three basic steps are needed to simulate a FE / CV flow [36]: (1) use the FE solution to obtain the pressure distribution in the area filled with resin; (2) calculate the resin flow rate; and (3) trace the front of the resin flow. The commonly used approach to constructing control volumes introduces an error when using skewed elements, which is almost always observed in the case of complex part geometry. For such cells, the mass conservation condition may be violated. In some works, a modification of the method is proposed, according to which the finite elements and control volumes coincide.

Tracking the interface between the air and the resin is performed by solving the continuity equation for the volume fraction of resin V_r [7, 10, 17, 20, 36, 37]:

$$\frac{\partial}{\partial t}(V_r \phi \rho_r) + \nabla(V_r \phi \rho_r \mathbf{u}) = 0, \quad (2)$$

where ϕ is a preform porosity, ρ is a resin mass density.

In the paper [41], the Brinkman's correction of the Darcy's law was proposed to take into account the pressure drop due to shear stresses at the interface liquid – porous region:

$$-\nabla p - \frac{\mu}{K} \mathbf{u} + \frac{\tilde{\mu}}{\phi} \nabla^2 \mathbf{u} = 0. \quad (3)$$

Comparing with Eq. (1), the correction is seen in the third term involving an effective viscosity $\tilde{\mu}$. Given the overall uncertainty in model parameters such as K and ϕ , the appropriateness of introducing an effective viscosity additive is doubtful.

Heat transfer and thermal-kinetic processes affecting the binder rheology have been simulated in a number of works [14,20,26-29,43-45]. The influence of process parameters, in particular heating rates and holding times, on the resin viscosity and laminate infiltration was evaluated during experimental tests and confirmed by monitoring the process. The importance of accounting for changes in resin rheology is due to the need to reduce the filling time of the preform and eliminate dry spots.

To correctly take into account the preform compacting and the resulting change in its permeability at the vacuum infusion processes, the following models were most widely used [14,33]: compacting model - changes in the volume fraction of the reinforcing fraction (see Figure 1):

$$V_f = V_{f0} \cdot P_{comp}^B, \quad (4)$$

where the compacting pressure P_{comp} is the difference between atmospheric pressure and the pressure in the region inside the preform, V_f is the reinforcing fiber volume fraction, and the Kozeny-Karman model for the permeability K of the porous medium:

$$K = k \cdot (1 - V_f)^3 / V_f^2, \quad (5)$$

where the Kozeny constant k , determined experimentally, reflects the structure of the porous medium, i.e. depends on the geometry of the reinforcement. Combining equations (4) and (5), it is easy to obtain the dependence of permeability on compacting pressure. Using the relation between porosity ϕ and V_f , the dependence of permeability can also be expressed in terms of the porosity

$$K = K_0 \cdot \phi^3 / (1 - \phi)^2. \quad (6)$$

These models have been used in our study; their graphical representations are present in Figure 1 and 2 together with the experimental data used for these models identification.

There are also a number of works (e.g. [11, 35]) focused on the construction of analytical models of infusion processes. Despite the relative simplicity and impossibility of using analytical approaches for modeling real structures, they can be used to test more complex models on simple systems, as well as in experimental evaluation of the properties of preforms and binders.

It is of certain interest to note two other approaches that differ sharply from those considered above. In article [40], a flow front control system was developed using a real-time assessment of the permeability / porosity ratio on the base information obtained by the visualization system monitored the porous panel infusion. In the proposed control system, the metamodel of the radial basis function (RBF) of the artificial neural network obtained as a result of training is used to predict the position of the front of the future flow by entering the injection pressure, the current position of the flow front and the calculated ratio. By carrying out optimization based on a metamodel, the injection pressure value is obtained, which must be implemented at each stage.

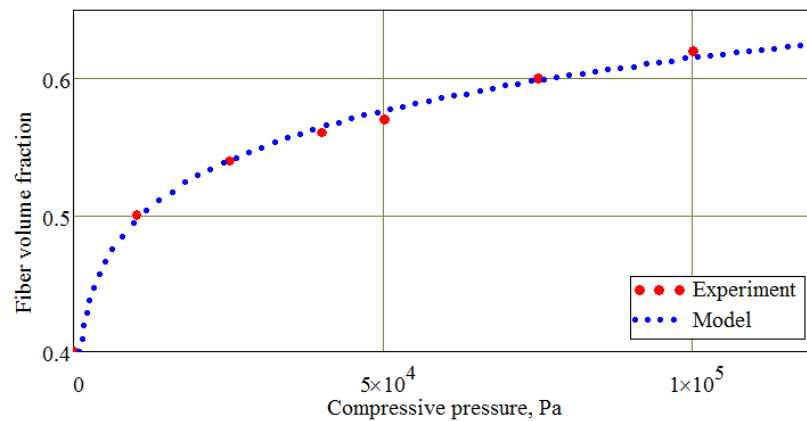


Figure 1. The dependence of the reinforcement volume fraction V_f on the compacting pressure: experimental data borrowed from the article [14] and their approximation by model (4) with the parameters: $V_{f0} = 0.21$; $B = 0.093$

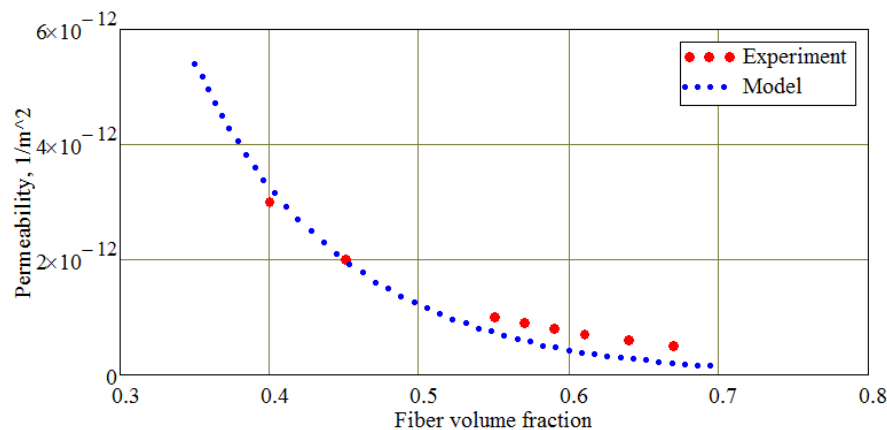


Figure 2. The dependence of the porous medium permeability K on the reinforcement volume fraction V_f : experimental data borrowed from the article [14] and their approximation by model (5) with the parameter $k = 2.41 \cdot 10^{-12}$

The work [42] presents the lumped model of VARTM with parameters, developed using mechanical-electrical analogy. This model was intended to describe the flow of fluid through preform's macropores and the absorption of resin by micropores in fiber bundles. To characterize the double fiber reinforcement, two physical phenomena are used, described in the work by lumped elements: resistance to the flow of liquid resin and the effect of its absorption during infusion.

In some works, the problem of process optimization is considered, by which, in the broad sense, we mean the determination of the values of controlled parameters (design variables) that ensure the achievement of the best results (objectives). Optimization approaches and technologies can be divided into 4 kinds.

First kind includes the classical investigations of the process output at the varying its controlled parameters (inputs) using some experimental methods. The paper [29] reports about a microscopic study of the void content at the locations near the inlet as well as near the outlet of the infused preform at the varying independently controlled the resin gate and vacuum vent pressures. A minimum filling time and absence of the dry spots were accepted as objectives in the experimental work [14], where design variables are: parameters of the temperature cure cycle (heating rate at the 1st and 2nd ramps, temperatures and durations during dwell sections).

The second kind of the optimization problems is based on the numerous computer simulations and their results analysis to choose the better process conditions. Dong [16,17] optimizes the filling time of preform and try to eliminate the dry spots by varying the resin gate and vacuum vents diameters, numbers and locations using FE / CV based software. An influence of the heating rates and isothermal holds on the uniformity of the temperature and degree of cure fields during resin

impregnation were studied in [28] using the finite element software ABAQUS. In order to provide a resin flowing profile uniformity and make infusion time less than resin gel time the authors of [4,6] used RTM-Worx software at the optimization the manufacturing process of the boat hulls by manual changing injection gate position, length, and spacing of minor pipes for parallel and fish-bone arrangements of the pipes for the resin infusion.

The third type combines the methodology of the two previous ones: computer simulation and experiment, the results of which are used to setting parameters and validate the model of the infusion process. In the paper [37] Zhao with co-workers inform about minimization of the filling time in grooved foam sandwich composites changing the resin sources pattern at the experiments and numerical simulations. Paper [40] reports about development of ANN (Artificial Neural Network) based meta-model, which was trained by Moldex 3D simulation module that was tuned using the information acquired by a visualization system. According to the optimization results based on the meta-model, the injection pressure can be adjusted online to control the velocity of the flow front.

Most advanced fully functional optimization systems include a process simulation module (forward problem solver) and optimizer, which carries out the multiple calls of the forward problem according to some optimization strategy, and forms the optimum solutions set in the objective space. The structure, organization, and logic of the prototype of such the optimization systems are described with the necessary completeness in pioneering work [19], which uses FE / CV modeling technique developed by the University of Delaware experts and published in [36]. Most important part of this paper is aimed to the problem of the dry spots formation, detection and evolution during infusion. It considers in detail conditions and evidence of dry spots formation at its surrounding by the inner and outer flow fronts. On the base of the numerous fulfilled simulations the authors of the LIMS software formulate the very useful recommendations that can be used in a practice to minimize the number of check for ineffective process options. The dry spot detection algorithm, which is explained in [19], requires the significant computational efforts, therefore it is not very efficient, especially for the parts of complex 3D geometry. Moreover, the proposed technique includes rebuilding of FE meshing in the vicinity of the flow front to supply the necessary accuracy of its configuration [36].

In order to eliminate these disadvantages some later works proposed the partial improvements. But these perfectionings were used at the optimization of the relatively simple objective - minimization of the filling time by varying the number of vents, their location, injection pressure and temperature [9,18,21]. Any defects formation did not modeled in these works. The multiobjective optimization problems were solved in two last works [20,26], where the filling time, maximum degree of cure at the end of filling and maximum degree of cure gradient through thickness experienced by the part during the curing process at each time step are minimized in 2D cases using the FE solver PAMRTM (forward problem solver) linked with genetic algorithm optimizer.

Concluding our analysis of the considered works, it should be noted that the most important problem of the dry spots formation in the infusible preform was not solved with the necessary accuracy and reliability, which is due to the difficulties in reconstructing the movement of the binder front. The reason for this is the extremely high computational complexity of solving the problem of the resin dynamics in a porous medium at moving boundaries, as well as the insufficient accuracy of the widely used FE / CV method, which makes strict requirements to the design of cells of a control volume. Therefore, the main purpose of the present work is development of a system for diagnosing and reliably predicting the occurrence of incompletely saturated and dry places in preforms during vacuum infusion of resins. This system should provide reconstruction of the motion of the resin front in preforms of complex 3D geometry, identification of the dry spot formation, and effectively simulate the resin infusion dynamics to work as the forward problem solver that will be repeatedly called by the optimization module.

Because this paper is motivated by the main purpose to develop a soft tool, which should be able to reliably detect formation of the dry spots during the vacuum infusion process, it is organized

as follows. First we present some results of two experimental studies with large CFRP panels during vacuum infusion, where resin front advancement and dry spots formation were monitored in time. Next part contains the problem statement where we formulate the resin infusion model as coupled two phase media / resin dynamics problem, where the phase field equation is accepted as the ruling one, which is distinct from the traditional FE / CV approach. In order to simplify the verification of new modeling approach we neglect the heat transfer and thermal-kinetic effects. On the base of the problem statement we present its computer implementation in the environment of FE software Comsol Multiphysics and describe the model's structure and function, especially intended to identify the time instants and location of dry spots. Finally, we present some simulation results and consider the ways of the model use together with the optimization module, and the abilities of the developed MATLAB module destined to determine the evolution of formed dry spots by using the FE solution postprocessing analysis.

2. Vacuum infusion of large CFRP parts. Experiment

In order to understand, how the dry spots are formed during resin front advances in the porous preform, the experimental vacuum infusion processes for two different CFRP panels were carried out. At the manufacturing of both panels the carbon fibre fabric CC245 with weaving twill 4/4, mass density 240 g/m^2 , and thickness $0.28 \text{ mm} \pm 15\%$ was used. To speed up the filling, Gerster HPM tape was laid in accordance with the selected method. A semi-permeable membrane VAP3D-C2003 was used to effectively remove air while retaining resin in a preform. The infused epoxy compound SR1710 with hardener SD8822 (Sicommin) had viscosity $\sim 0.1 \text{ Pa}\cdot\text{s}$ at 25°C . The air dissolved in a binder was evacuated before the start of the process in the special vessel Vacmobiles RT 19/11 where low air pressure was supplied by the vacuum station Vacmobiles 20/2.

The first thin walled rectangular panel of dimensions (800x700) mm with thickness 1.5 mm was 8 layered cross-ply symmetric balanced laminate. Laying of HPM, hoses for pumping out vacuum and resin injection was carried out along three sides around the perimeter of the panel. Vacuum infusion process was carried out at the ambient temperature 19°C ; the averaged preform temperature in the filled region and resin front position recorded every 5 minutes (see Figure 3). The dynamics of the preform resin infusion is illustrated by a series of photographs in the Figure 4.

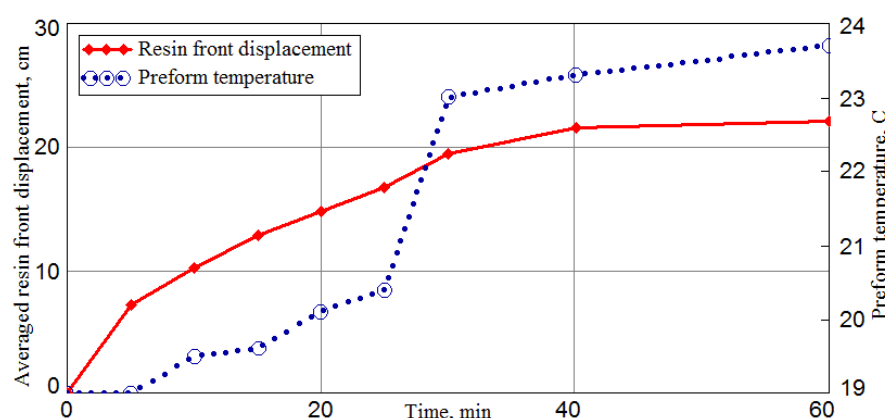


Figure 3. The time histories of the resin front advances and preform's temperature in the filled area

The propagation speed of the binder front began to decline sharply after 40 minutes from the start of the process. Obviously, this is caused in part by the polymerization reaction of the resin, accompanied by an increase in temperature (see Figure 3), partly by the closure of the binder fronts encountered, as a result of which the conditions for the penetration of vacuum to the dry preform region surrounded by the binder worsened (see Figure 4,d). After 2 hours and 20 minutes, the movement of the binder ceased. A gradual decrease in the front velocity in the time interval 0–40 minutes is in full agreement with the observations [10,11,15,34,38,39].

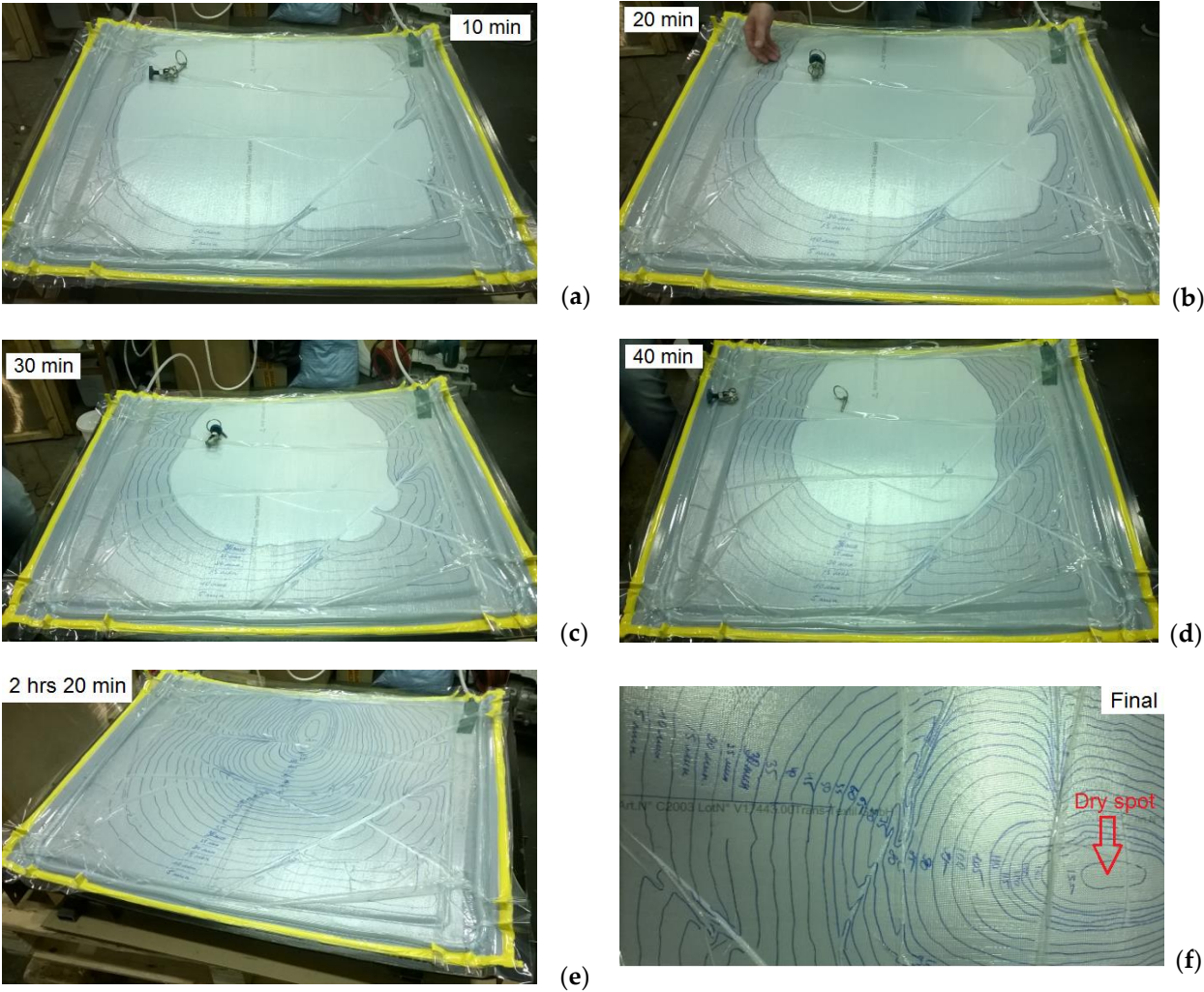


Figure 4. The sequence of the snapshots, which demonstrate the resin front propagation in the vacuum infused rectangular CFRP panel

Photograph of the ready infused panel is shown in Figure 5, where the formed dry spot is clearly visible. It arose as a result of the closure of the resin front, called in the paper [19] as inner front, i.e. surrounding the void area with resin in the inner part of the preform.

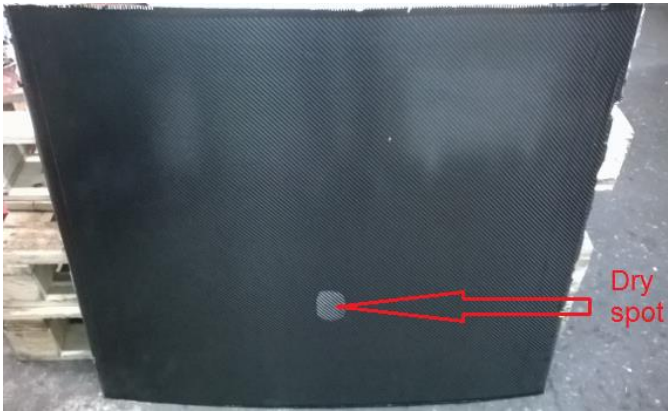


Figure 5. Defected CFRP panel after curing with dry spot

Much more difficult in terms of ensuring the quality of impregnation is the tail panel of a light aircraft with an overall size of more than 2 meters. At the assembly of the technological packet 4 layers

of carbon fabric are laid sequentially over the entire area of the tooling, then foam plates (see Figure 6,a). The space between these foam plates is filled with carbon fabric ribbons (8 layers), and whole sandwich is covered with 4 layers of carbon fabric, semi-permeable membrane (see Figure 6,b), vacuum bag film that is sealed around the perimeter. The binder feed channel is shown in Figure 7 by red lines. The resin front propagation in time is present in Figure 8, and its positions at the different time instants of the infusion process are shown together in Figure 9.

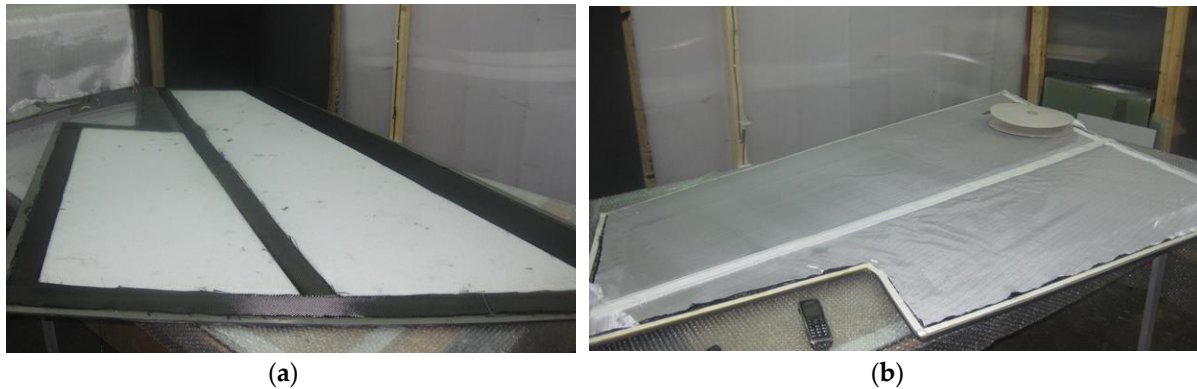


Figure 6. Assembly of the technological packet for the vacuum infusion of the sandwich tail panel

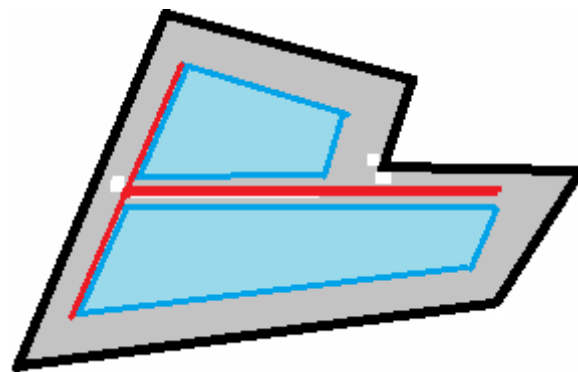


Figure 7. The resin feed channel (red line) for the vacuum infusion of the sandwich tail panel

One can see in Figure 9 that within 1 hour and 45 minutes, the resin front did not reach the forward edge of the panel and to the corner at its rear. This caused the fatal defect of the panel, which is shown in Figure 10 after polymerization. The experiment showed the formation of dry spots as a result of stopping the outer front, as described in [19].

The considered defects most often arise during the infusion of large-sized structures of complex geometry, when the spread of the resin front is bizarre. The cost of such tests by trial and error is very high. Thus, the ability of modeling systems replacing the trial and error method to correctly restore the front movement is the most important quality of such systems. The approach presented below is aimed specifically at achieving this ability in the system being created.

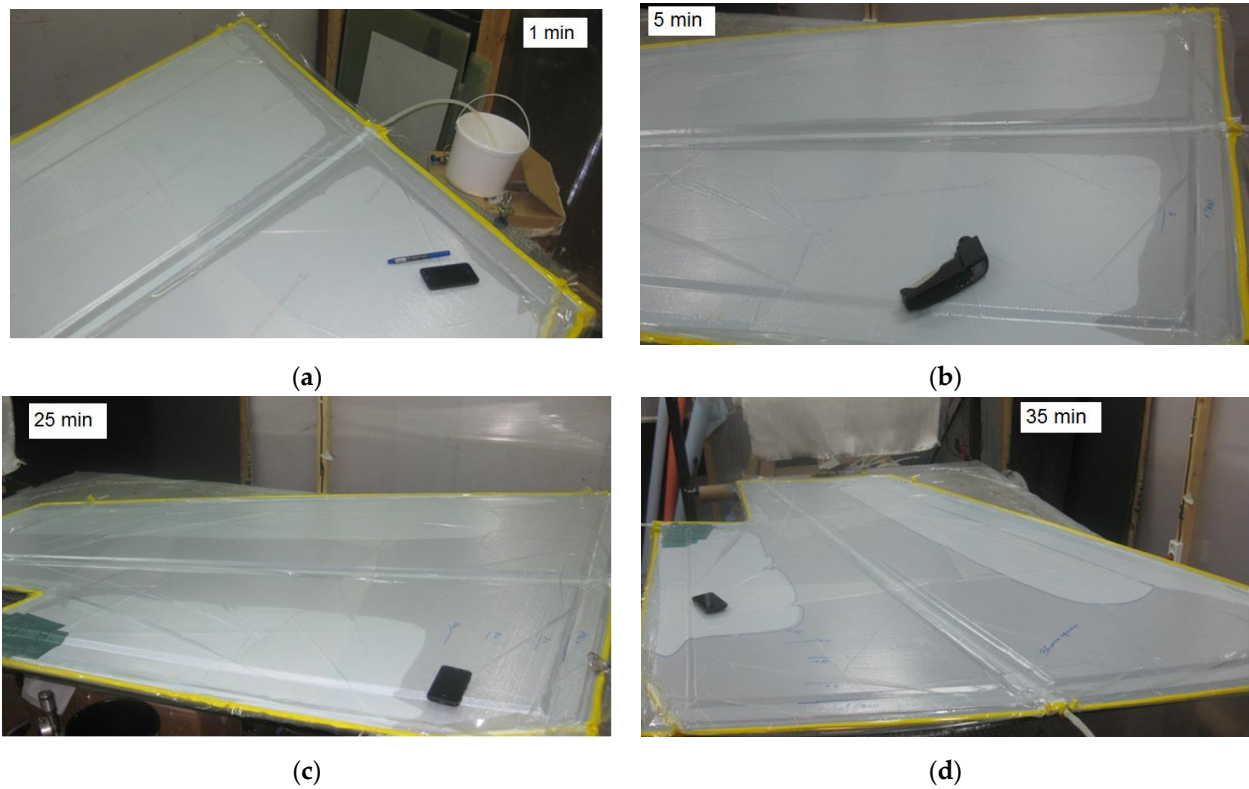


Figure 8. The spreading of the resin front at the vacuum infusion of the tail sandwich panel



Figure 9. The resin front positions during the vacuum infusion of the tail sandwich panel



Figure 10. The non-impregnated edges of the cured tail panel in its corners (right) and on the periphery (left)

3. Model of the resin infusion. Problem statement

The fundamental difference between the proposed approach and those considered above is the interdependence of the equations of the coupled problem, the solution of which describes the dynamics of a liquid resin in a porous preform. The approaches discussed above used the Darcy' equation as the leading (ruling equation), while the proposed approach is based on the use as the leading equation, describing the motion of the interface between two contacting phases - the front of the moved resin. In this case, the calculation of the velocity field, depending on the pressure gradient in the liquid, will be made based on the result obtained when determining the shape and position of the front. To some extent, this approach repeats the methodology used in [46], where a new numerical algorithm is proposed for modeling the dynamics of the interface between two immiscible phases. This interface is a thin layer, across which its physical properties change sharply, but continuously, and its evolution is determined by a phase field variable, which obeys the Cahn-Hilliard convection-diffusion-type equation. Its solution allows you to directly monitor the interface and provides the correct interfacial tension due to the free energy accumulated in the separation layer. The phase field method does not require a regular FE mesh, a computational domain of simple form and spatial periodicity, which is required by other methods (e.g., the FE / CV method). This is important for modeling large-scale stream systems with complex and multiple interfaces, especially in three-dimensional (3D) cases.

Let the system includes two immiscible phases A and B. The phase field variable ϕ is introduced so that the concentrations of components A and B are $(1+\phi)/2$ and $(1-\phi)/2$, respectively. Note that hereinafter everywhere, in order to avoid unacceptable confusion of quantities, the phase field variable will be denoted as ϕ , and preform porosity as V_ϕ . For the mixing energy, we take a form analogous to the form of the Lagrangian of the Ginzburg-Landau equation for the complex field of Cooper's pairs

$$f_{mix}(\phi, \nabla \phi) = \frac{1}{2} \lambda |\nabla \phi|^2 + \frac{\lambda}{4\varepsilon^2} (\phi^2 - 1)^2, \quad (7)$$

where λ is the mixing energy density with force dimension, and ε is the capillary width, which scales with the thickness of the diffuse interface. As $\varepsilon \rightarrow 0$, the ratio λ/ε gives the interfacial tension σ in the classical sense:

$$\sigma = 2\sqrt{2}\lambda/3\varepsilon. \quad (8)$$

The equation describing the evolution of a phase field variable is the Cahn-Hilliard equation [47]:

$$\partial \phi / \partial t + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \gamma \nabla G \quad (9)$$

where G (Pa) is a chemical potential:

$$G = \lambda \left[-\nabla^2 \phi + \phi (\phi^2 - 1) / \varepsilon^2 \right], \quad (10)$$

and γ (m³s/kg) is the phases mobility. Mobility γ determines the time scale of the Cahn-Hilliard diffusion and should be large enough to maintain a constant interfacial thickness, but small enough so that the convective terms are not excessively damped. Mobility γ is a function of the thickness of the interface according to $\gamma = \chi \varepsilon^2$, where χ is the mobility setting parameter. The Kahn-Hilliard equation forces a value of 1 or -1, with the exception of a very thin region at the interface between two media.

The Comsol FE system, in which the simulation was performed, uses the splitting of the fourth-order equation (9) into two second-order partial differential equations (PDE):

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \quad (11)$$

$$\psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1) \phi. \quad (12)$$

The local filling of the micro volumes of the preform V_r can be expressed through the phase field variable ϕ by the relation

$$V_r = (\phi + 1)/2 \quad (13)$$

so that a completely filled volume ($V_r = 1$) corresponds to a value $\phi = 1$, an empty volume ($V_r = 0$) corresponds to a value $\phi = -1$.

The boundary conditions of the phase field equation are:

$$\text{Resin injection gate} \quad \phi = 1 \quad (14)$$

$$\text{Wetted walls boundary conditions:} \quad \begin{aligned} \mathbf{n} \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi &= 0; \\ \mathbf{n} \cdot \varepsilon^2 \nabla \phi &= \varepsilon^2 \cos(\theta_w) |\nabla \phi|, \end{aligned}$$

$$\text{where } \mathbf{n} \text{ is an unit vector normal to the preform boundaries, } \mathbf{n} \cdot \varepsilon^2 \nabla \phi = 0 \quad (15)$$

and the contact angle θ_w is accepted as $\pi/2$

$$\text{Vacuum vent} \quad \phi = -1 \quad (16)$$

The initial condition for the variable ϕ defined everywhere in the volume of preform

$$\phi = -1. \quad (17)$$

The following values for the problem parameters were accepted at the FE model implementation:

$$\text{Interface thickness for the variable } \phi \quad \varepsilon = h_{\max} / 2 = 0.0025 \text{ m} \quad (18)$$

$$\begin{aligned} \text{The maximum size of the finite elements at} \\ \text{the used FE meshing} \quad h_{\max} = 0.005 \text{ m} \end{aligned} \quad (19)$$

$$\text{Surface tension coefficient} \quad \sigma = 1 \text{ N/m} \quad (20)$$

$$\text{The mobility setting parameter} \quad \chi = \frac{\sqrt{2}}{3} \frac{u_{\max}}{\sigma} \frac{h_{\max}}{\varepsilon} = 0.001 \text{ m}^2\text{s/kg} \quad (21)$$

$$\text{Estimated maximum resin velocity} \quad u_{\max} = 0.001 \text{ m/s} \quad (22)$$

The second equation of the coupled problem describing the dynamics of the viscous binder should be an equation connecting the field of the resin's driving pressures with the velocities field of the medium. The Richards equation [48] representing fluid motion in unsaturated soils is adopted as such an equation:

$$\partial(V_\phi S)/\partial t - \nabla \cdot \left(\frac{K \cdot k_r}{\mu} (\nabla p) \right) = 0 \quad (23)$$

which models the behavior of saturation S as a function of pressure p , permeability and porosity. Permeability in (23) is the product of constant permeability K and relative permeability $k_r \in [0;1]$. The saturation S in equation (23) is an analogue of the filling, i.e. resin volume fraction V_r . As for the dependence of permeability, it is defined by relations (4)-(6). In equation (23), the value of the saturation can be expressed as some function of pressure that activates the movement of the liquid [48]. In the work [49], on the base of the results of van Genuchten's research [50], it was shown that the saturation dependence on the pressure can be satisfactorily described by function

$$S(p) = 2/\pi \cdot a \tan(\alpha p) \quad (24)$$

where a variable α is determined experimentally, which was implemented in [49]. Satisfactory agreement with the experimental data was achieved for the value $\alpha = 1/p_{ref}$, where the reference pressure p_{ref} is taken equal to the current atmospheric pressure. Thus, after performing time differentiation equation (23) is transformed to the form

$$V_\phi \frac{2}{\pi} \frac{\alpha}{1 + (\alpha p)^2} \frac{\partial p}{\partial t} - \nabla \cdot \left(\frac{K}{\mu} \nabla p \right) = 0. \quad (25)$$

It supplements the phase field equation, is connected with it through porosity, and allows us to establish a relationship between pressure and fluid flow rate using relation (1) of Darcy's law, which includes the pressure value determined from equation (25). The pressure field in the preform, determined from equation (25), is used to calculate the compacting pressure $P_{comp}(\mathbf{r})$ acting externally on the porous structure of the preform

$$P_{comp}(\mathbf{r}) = p_{atm} - p(\mathbf{r}), \quad (26)$$

and, therefore, changing its porosity and fiber volume fraction according to (4).

Equation (25) must be valid in the entire volume of the preform, both in filled and in empty areas. Consequently, the values of permeability and viscosity should vary in accordance with the resin filling V_r and porosity V_ϕ . A resin permeability dependence on the fiber volume fraction is described by Eq. (5). The study of the air permeability along and transverse of the hexagonally arranged fabrics with different fiber volume fractions suggest the following relations for these permeabilities [51]

$$K_{long}^{hex} = \frac{8r^2}{c_{hex}} \cdot \frac{(1 - V_f)^3}{V_f^2}; \quad K_{trans}^{hex} = C_{hex} r^2 \left(\sqrt{V_f^{max}/V_f} - 1 \right)^{5/2} \quad (27)$$

where these models parameters are: $c_{hex} = 53$, $C_{hex} = 16/(9\pi\sqrt{6})$, $V_f^{max} = \pi/2\sqrt{3}$ and $r \approx 3 \mu\text{m}$ is a fiber radius. The validity of the relations (27) is confirmed by numerous experimental data for different CFRP and GFRP fabrics, e.g. [51, 52]. These dependencies are present in Figure 11. Comparison of Figures 2 and 11 demonstrates a very close coincidence of the nature of permeability for liquid and air, therefore, the dependence of permeability for both contacting phases is assumed to be the same, and it was calculated by the formula (5).

However, the viscosities of the liquid resin and air differ many times. Since temperature effects are neglected into account at this stage of the study, the viscosity of the resin is assumed to be unchanged and equal to 0.1. The air pressure does not affect to the air viscosity in a wide pressure range, whereas its dependence on the temperature is significant [53]. This dependency (see Figure 12) will be used at the modeling of thermal effects during following stage of our study. But in the present study the air viscosity is accepted as $2 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$.

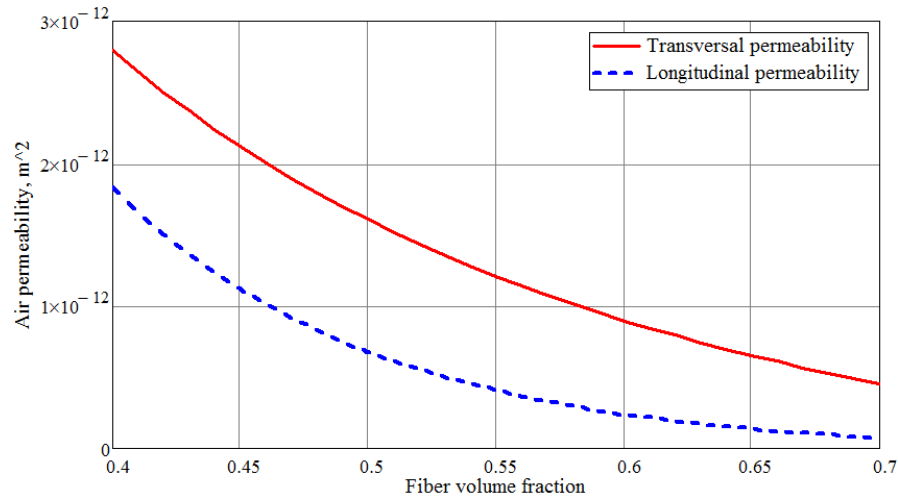


Figure 11. The dependencies of the air permeability along and transverse CFRP fabric with hexagonal woven arrangement (calculated according to Eq. 27)

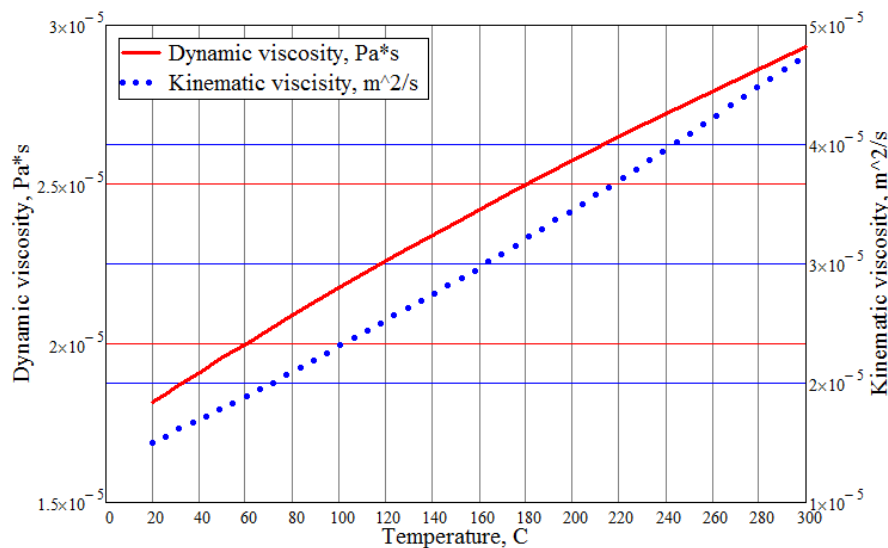


Figure 12. The dependencies of the air dynamic and kinematic viscosity on the temperature [53]

The boundary conditions of equation (25) are:

$$\text{Resin injection gate} \quad p_{gate} = p_{gate}(t) \quad (27)$$

$$\text{Vacuum pump vent} \quad p_{vent} = p_{vent}(t) \quad (28)$$

The initial condition for the pressure specified everywhere in the preform's volume

$$p(t=0) = p_{vent}(t=0) \quad (29)$$

The system of equations above closes the formulation of the problem of 3D modeling the dynamics of a liquid resin in a porous preform. Beyond the scope of this problem, there remains the issue of localization of dry spots - closed air "traps" observed experimentally (see Figures 4, 9). During the infusion process, several traps can form, but the formation of the first such trap indicates a violation of the manufactured structure's quality. Hence, if the modeling module works under the control of the optimization module, the resulting solution may be discarded without further consideration, and calculations can be continued at the changed process design variables. When the module is operating in standalone mode, the simulation can continue to identify all critical time instants and other formed dry spots. To perform such an analysis, an MATLAB algorithm for the

processing of simulation results has been developed. In such cases, the simulation continues until the blocking of the vacuum vent by the resin flow. An indicator of this blockage is a condition

$$V_{r,out} = \min_{\Gamma_{out}}(V_r) \cong 0.25 \quad (30)$$

at the boundary Γ_{out} surrounding the vacuum port.

In order to identify time instant when a first dry spot arises and its localization the use of change in averaged pressure in the non filled zones of the prepreg has been proposed. The essence of the method is as follows. Let pressure in the vacuum vent varies rather slowly according to the sinusoidal law so that the period of these oscillations is, e.g. ~ 30 sec:

$$p_{vent} = p_{vac}^0 + p_{vac}^{amp} \cdot \sin(2\pi / T_{vent}), \quad (31)$$

where the mean value and amplitude of the pressure variation are accepted as $p_{vac}^0 = 2 \cdot 10^4$ Pa and $p_{vac}^{amp} \approx 0.5 \cdot 10^4$ Pa, respectively. The pressure in a void area connected to the vacuum vent must be uniform in every points of this area due to the insignificant air viscosity. As the resin front advances, some area may become blocked from the one connected to the vacuum line. But in this area, as well as in those connected with vacuum, resin fraction is very small, i.e. $V_r(\mathbf{r}) \cong 0$. However, as a result of blocking, this region remains under the pressure at which it was blocked - not under a sinusoidally changing one. As an indicator of the moment of an void trap closure, we introduce the expression:

$$\langle p_\phi \rangle = \int_{\Omega} d\Omega \cdot [1 - H(V_r^{low})] p / \int_{\Omega} d\Omega \cdot [1 - H(V_r^{low})], \quad (32)$$

where H is the Heaviside function, and V_r^{low} is the low resin filling, below which integration is performed. Formula (32) calculates at each simulation step the time-varying average value of pressure in all "low filled" areas, or, more precisely, in areas separated from the filled ones by the resin front. Until the first trap closes, approximate equality $\langle p_\phi \rangle \cong p_{vent}$ will take place, signaling that the ratio between the mean pressure and the amplitude of its variation is almost unchanged. After the closure, the newly formed empty region is isolated from the vacuum line; and the pressure in it cannot vary according to (31). Hence, the ratio $p_{vac}^{amp} / p_{vac}^0$ will be changed, which is easily recorded, and can serve as a trigger for stopping the simulation. The computational cost of the integration (31) is very small, in addition, after recording the moment of formation of a dry spot, the simulation can be stopped when searching for the best solution between of a large number of them. Obviously, the sensitivity of the proposed indicator of the void traps formation will depend on the period of pressure oscillations, which, however, should be an order of magnitude greater than the time integration step.

The dry spots localization and their shape evolution can be studied by means of special algorithm processing the simulation results. Its main functions and components will be presented on the example of simulated vacuum infusion, which has been implemented at the different process conditions.

4. FE simulation of the vacuum infusion process. Results and their analysis

The study of the developed approach capabilities was carried out using CAD models of a group of rotorcraft composite structures with geometry like thin-walled shells of complex shape (see Figure 13). The original CAD models were adjusted to correct topological errors (poor joining of the whole surface's patches), which prevent high-quality finite element meshing, as well as some local simplifications to exclude mesh thickening in areas with increased curvature. This part of the work is very important because violation of C^0 or C^1 continuity of the surface and sharply changed FE meshing can cause front distortion and a change in the direction of its spreading.

The remainder of this article presents and discusses the modeling of the infusion process in the last cowling shown in Figure 13. The system modeling was implemented in Comsol Multiphysics environment, where the phase field equation (11) - (12), which is built-in simulation mode, was accepted as a ruling equation coupled with the modified Richards equation (25), which was built in the coefficient form PDE mode. FE mesh and resin gate with vacuum vent locations are present in Figure

14. All boundary conditions and numerical value of the model parameters correspond to the above. The HPM tape 5 cm wide was laid around the part's perimeter, which was taken into account at the HPM locations by increasing the preform permeability.

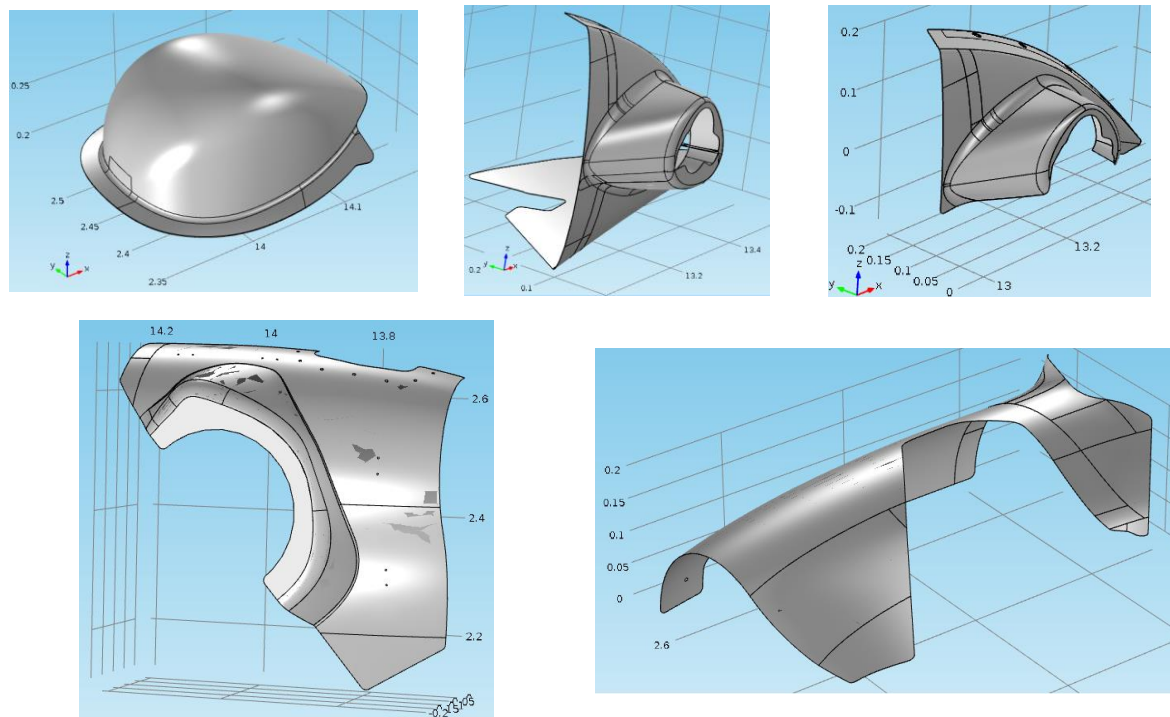


Figure 13. A group of the composite rotorcraft cowlings intended for manufacture by vacuum infusion technology

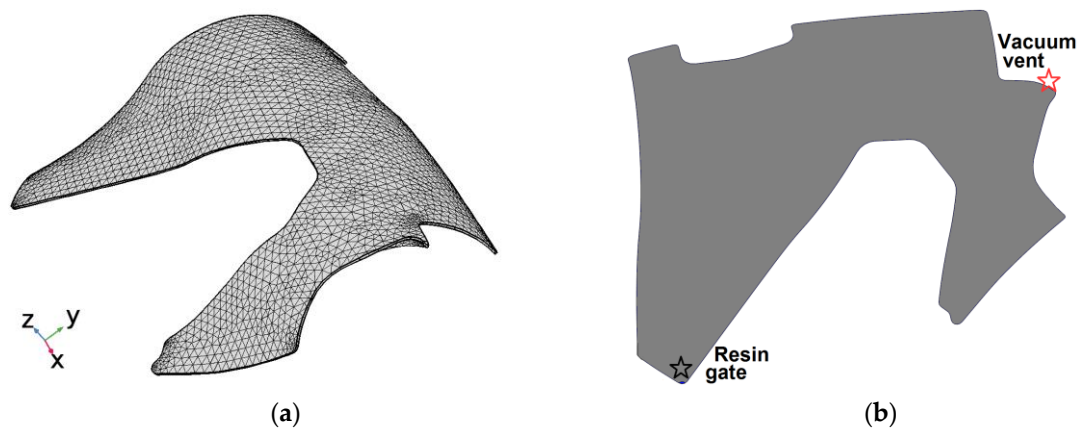
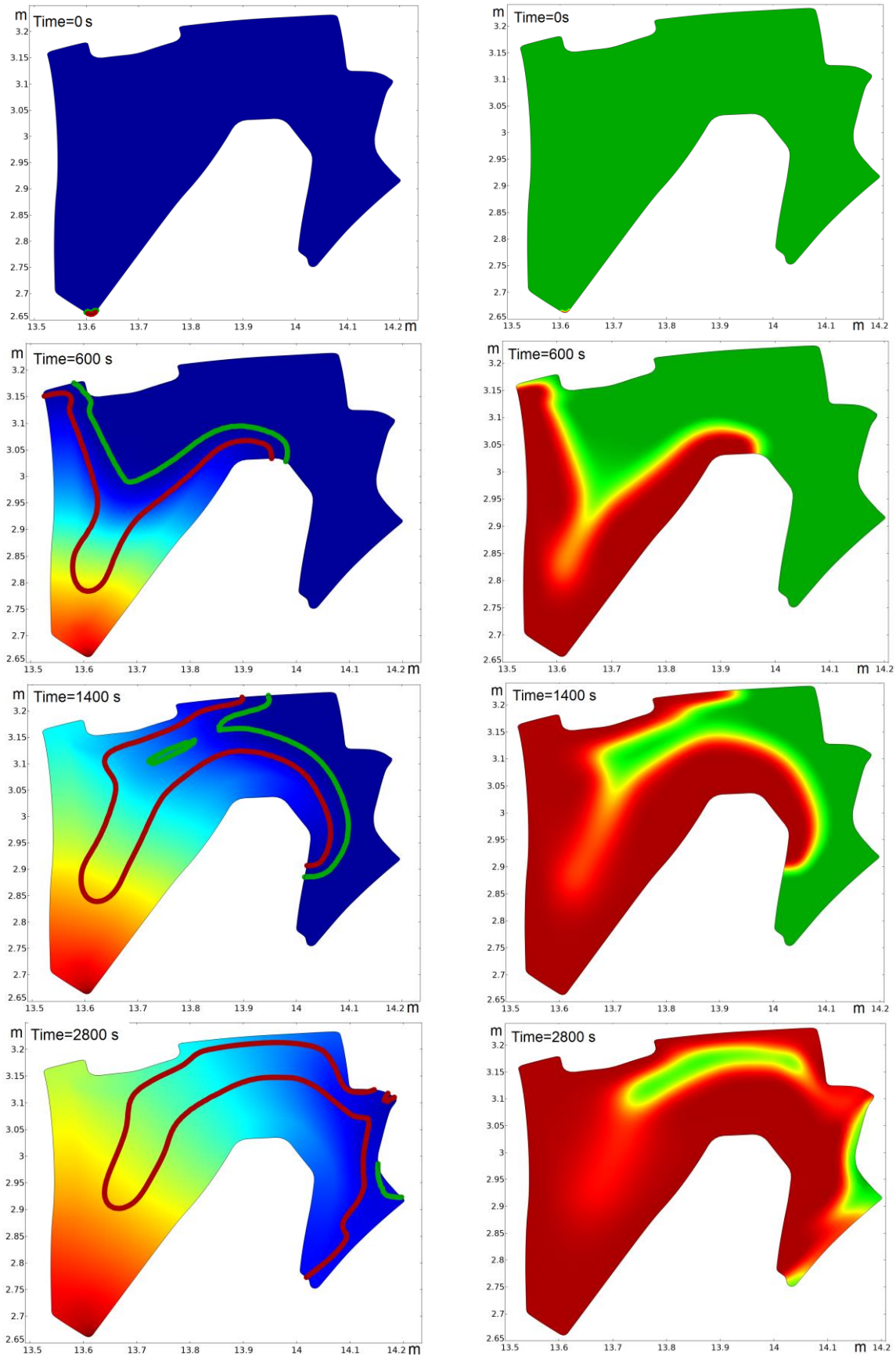


Figure 14. The finite element meshing of the infused part geometry (a); resin gate and vacuum vent location (b)

Some snapshots of the resin volume fraction and driving pressure distribution in the preform during model simulation are shown in Figure 15. The left column of this Figure shows the plots of the pressure distribution in the preform combined with the lines of two V_r levels: 0.1 and 0.9, whereas the right column contains the resin filling V_r distribution plots at the different time instants. Several important features of the simulation can be identified when considering these images.

The use of HPM tapes located around the perimeter of the infusing preform can lead to a significant local expansion of the front of the binder (see time 600 s) and even to the formation of low pressure and saturation areas inside the resin flow front (see time 1400 s).

With the closure of some internal areas by an inner front, the filling of these areas with a binder gradually increases, although the nature of the pressure distribution inside such partially filled areas is not violated (see times 2800 s, 3600 s, 6000 s).



Continued

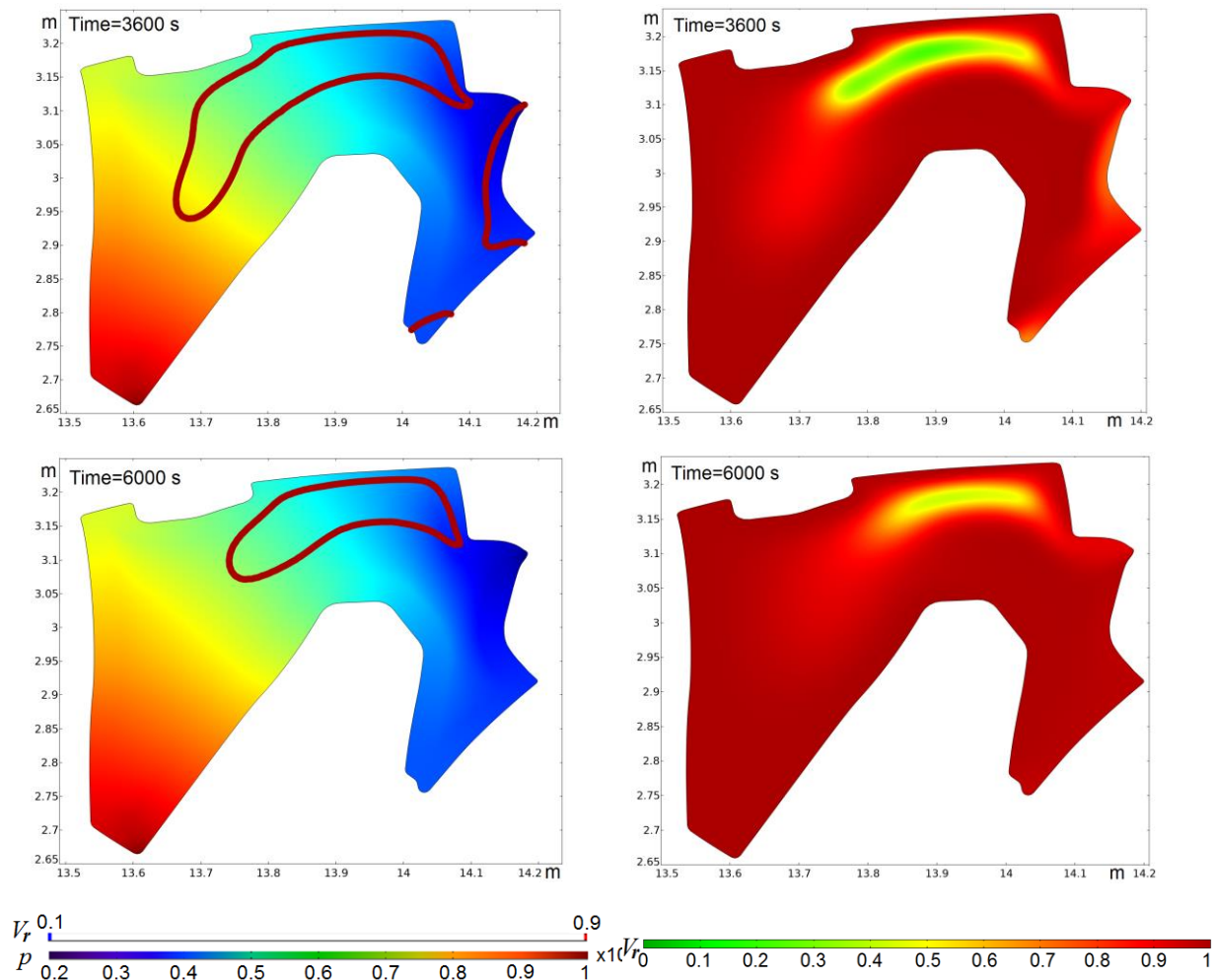


Figure 15. Some snapshots of the driving pressure combined with the level lines of the resin volume fraction at $V_r=0.1$ (green lines) and $V_r=0.9$ (red lines) (left column); and resin volume fraction (right column)

It can be explained by the real diffusion of the resin as well as by the mobility γ , which determines the time scale of diffusion in the Cahn-Hilliard equation (9). Estimation the actual magnitude of this mobility presents significant difficulties, but the occurrence of such closed contracting areas indicates the possibility of the formation of dry spots. A similar phenomenon is observed when the outer front approaches the protruding corners of the preform contour (see times 600 s and 2800 s). This slow mixing of two phases on the surface of their contact, is inherent for all interacting systems. But in real infusion processes, such mixing is constrained by an increase in air pressure inside the contracting empty area and a gradual increase in the viscosity of the resin over time under the influence of temperature due to polymerization. A detailed analysis, which is able to confirm or exclude the formation of an empty area in the real infusion process, can be performed using the algorithm processing the simulation results described below. But some justified guess-works can be made during simulation, which is very important when each simulation is controlled by an optimization algorithm that carries-out the multiple calls of the forward problem with changed process conditions. But some justified guess-works can be made during simulation, which is very important when simulations are controlled by an optimization algorithm that carries-out the multiple calls of the forward problem with varied process conditions. Such guess-works should exclude from consideration potentially “dangerous” situations that contribute to the formation of dry spots.

In order to detect the potentially forming dry spots two global variables have been calculated during simulation: the averaged pressure in partially filled areas of preform (31) and the flow rate through the vacuum vent's boundary:

$$\Xi_{vac} = \int_{\Sigma} (\mathbf{u} \cdot \mathbf{n}) d\sigma \quad (33)$$

where \mathbf{n} is unit normal to the vent surface Σ . Figures 16-19 illustrate the changes in process infusion state at time interval 2000 - 2400 s. This time interval is noted by the cross markers on the time axis.

Figure 16 demonstrates a closing of the low resin filling region in the specified time interval. The state of the resin filling is illustrated by Figure 17,a, whereas the change of the averaged pressure in the partially filled regions surrounded by the resin volume fraction $V_f=0.5$ is present in Figure 17, b. One can see in Figure 18 how the harmonic component's amplitude of the pressure drops sharply during separation of the closable region from the rest of the unfilled volume, in which the amplitude of the pressure oscillations is kept constant according to Eq. (31). Such monitoring is performed during simulation, and it can signal the formation of potentially dangerous dry areas. Of course, the sensitivity of such a registration method depends on the magnitude of the closable volume; the larger this volume, the greater the change in the average amplitude of the pressure oscillations. Attention should also be paid to a sharp decrease in the vent's air flow rate shown in Figure 19, which can also serve as an additional source of information about the formation of a possible dry spot.

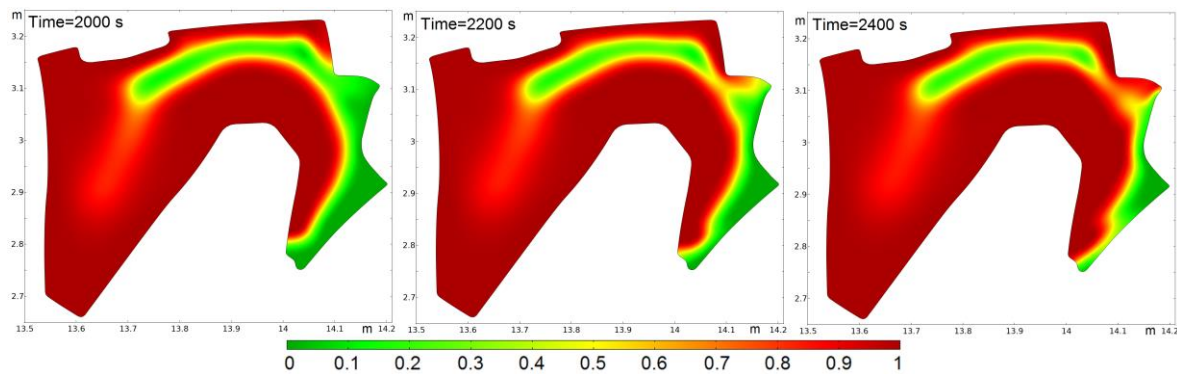


Figure 16. Closing an unfilled region of the preform by the inner resin flow front. Three snapshots show a sequential change of the resin volume fraction distribution in the preform

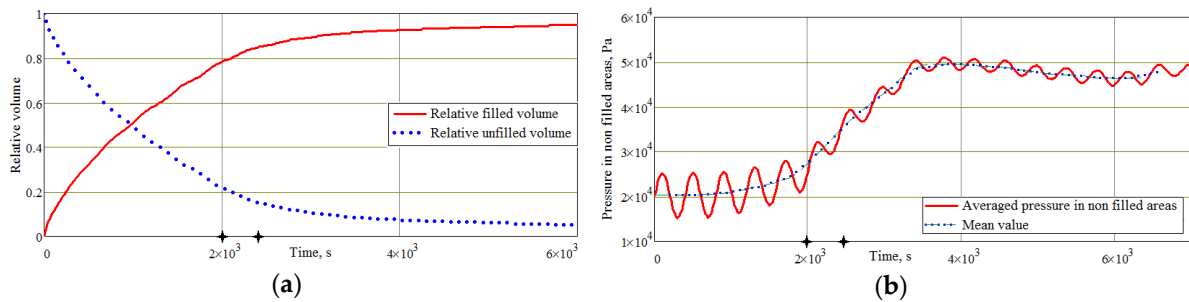


Figure 17. Change of the relative resin filled and unfilled volume (a) and the averaged pressure inside the unfilled regions (b) during vacuum infusion

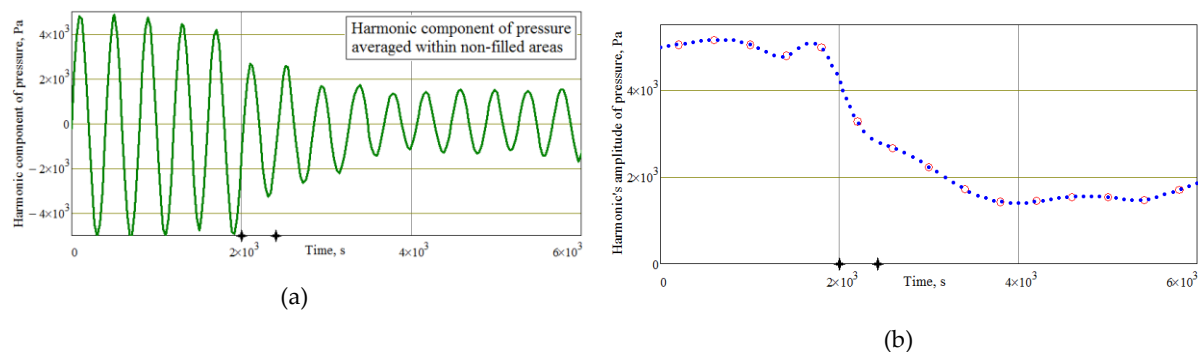


Figure 18. Change of the harmonic component (a) and its amplitude (b) of the averaged pressure inside the unfilled regions during vacuum infusion

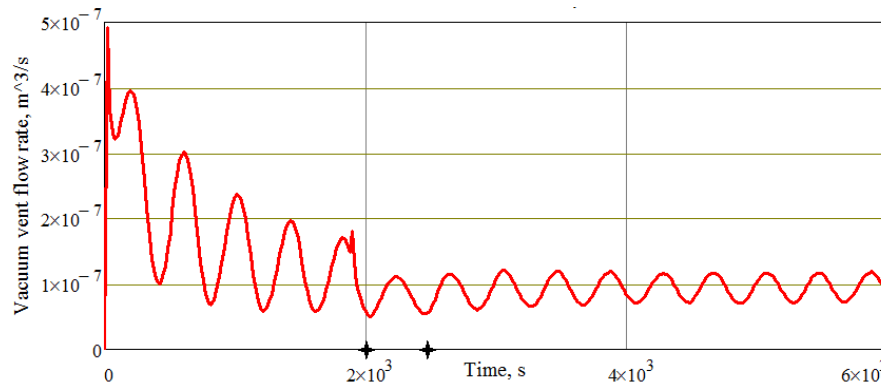


Figure 19. Time history of the vent's air flow rate during vacuum infusion

The considered results demonstrate that proposed computations can be used to exclude the suspicious modeling scenarios in which the formation of dry places is possible. However, much more reliable conclusion about the process quality at its accepted conditions can be made using the algorithm processed the simulation results. The most important elements and results of this algorithm working in the MATLAB environment are described below.

This algorithm includes the following sequential steps, which are illustrated for three different situations: (a) no dry spot formation; (b) dry spot is formed by the inner flow front, and (c) dry spot is formed by the outer resin flow front (see Figure 20).

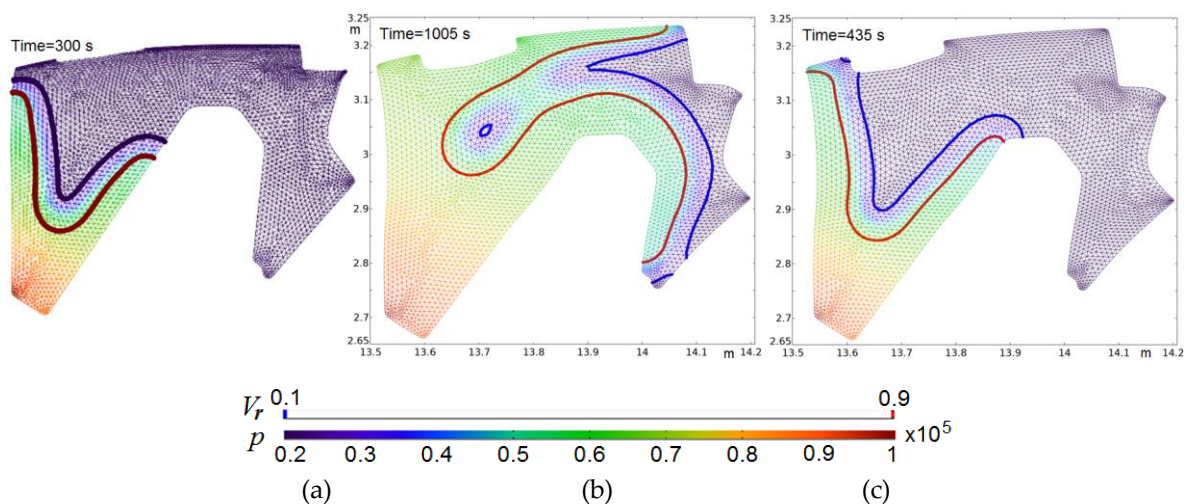


Figure 20. Three snapshots corresponding the time instants when no dry spot formation (a), dry spot formations by the inner, and (c) by the outer resin flow front.

This algorithm imports after completing solution the coordinates of all nodes together with the resin volume fraction and pressure for all time steps during simulation. Next the time instants $t_{01}(i)$, $\forall i \in [1;n]$ when the resin volume fraction first surpasses a value 0.1 are determined for all nodes of FE mesh (see Figure 21, a-c).

For these found nodes their environment with filled nodes is determined and identification of the arisen dry "traps" is made during the following steps (see Figure 22). Then a sorting all the trapped nodes and identification of the dry spots separated from each other is performed. Figure 23,a demonstrates these separated spots, which are depicted, by the bold dots of various colors, and each spot is highlighted in its own color. Reconstruction of the closing resin front shapes (the original contour of the closing unfilled area) is performed by the analysis of $t_{01}(i)$ for all nodes belonging to the selected spots. These original contours of all closed spots are shown in Figure 23,b at the time instants of their closing.

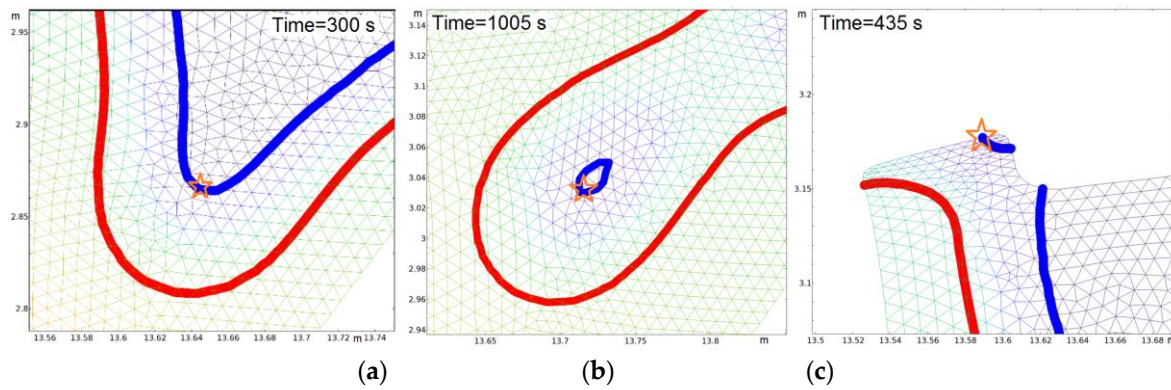


Figure 21. Determination of the filling start instants for all nodes

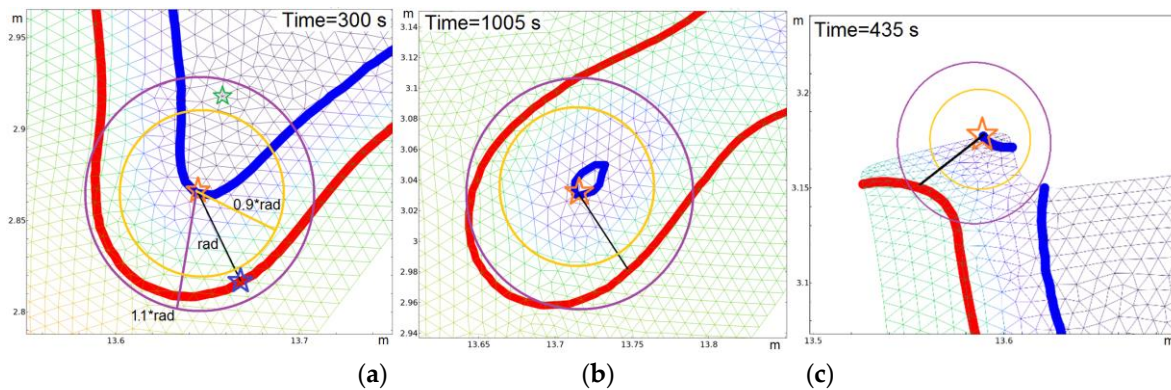
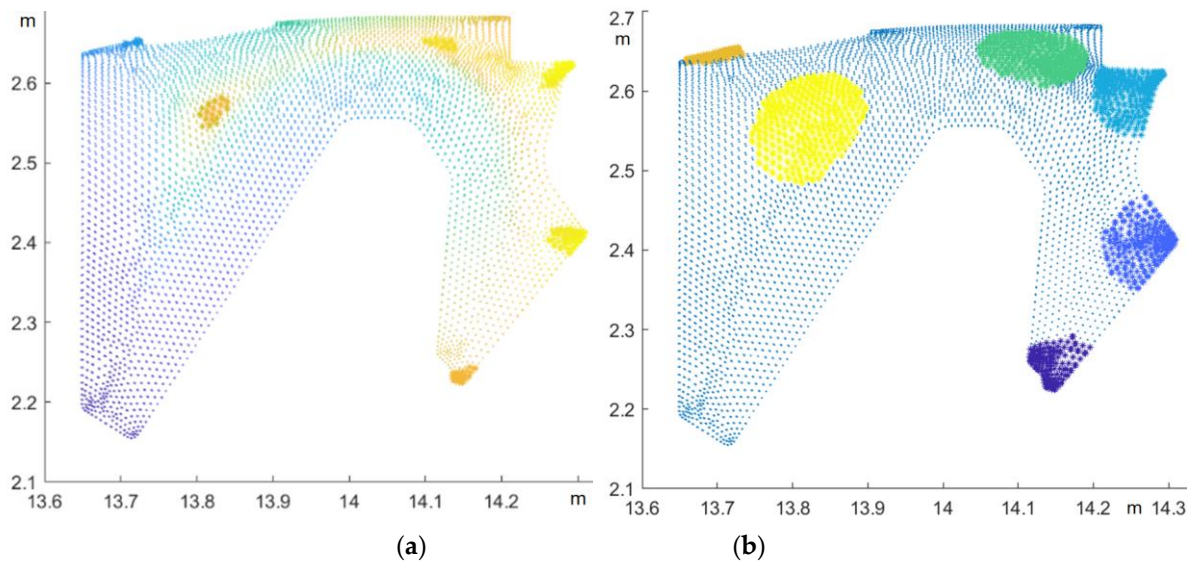
Figure 22. Determination of the filled nodes that surround the considered one at the time $t_{01}(i)$ when it starts filling

Figure 23. Separation of individual closable spots (a) and reconstruction of their original shape at the time of closure (b)

In order to estimate the changes of these closed unfilled areas and their volumes two assumptions are accepted. The first thing is that the air in the closed areas obeys the gas law at the constant temperature $p \cdot V = \text{const}$, and the second is that the contraction of such areas occurs around their geometric center. Therefore, these centers of the spots are determined, and then each area is contracted so that the pressure inside and outside it is equalized, while it takes a rounded shape. At these contraction deformations a change of the nodes number inside the spot is calculated. The results of these two final steps of the algorithm are shown in Figure 24, a,b.

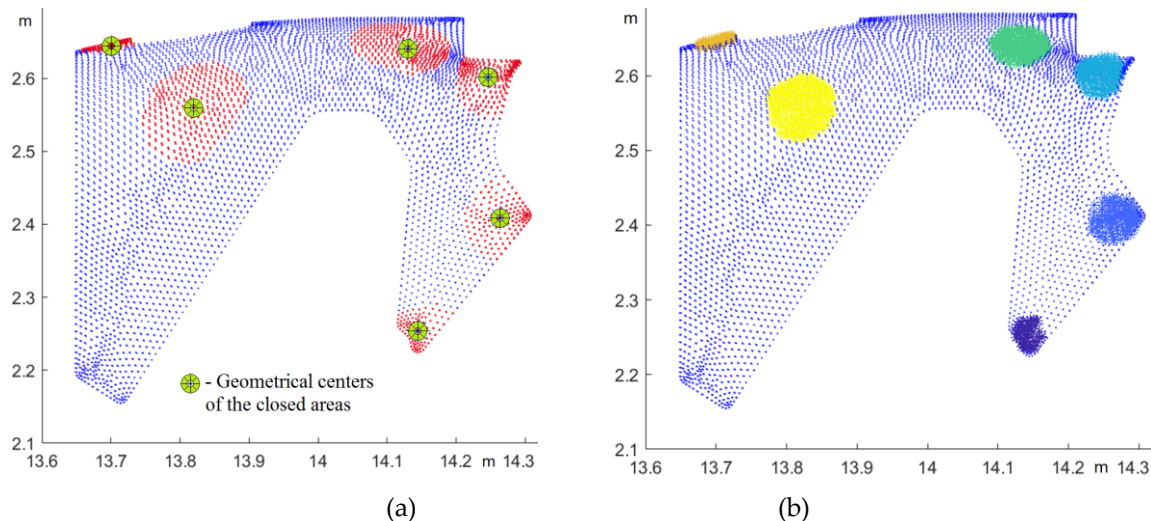


Figure 24. Determination of the geometrical centers for all closed spots (a) and their final dimensions after contraction (b)

Consequently, the considered MATLAB tool can be effectively used both for preliminary selection of the arrangement of resin gates and vacuum vents, their geometry and boundary conditions, and for a detailed analysis of the optimized technological solution that can be obtained using the above discussed FE-based tool for the vacuum infusion process simulation.

5. Conclusion and future works

The main purpose of the developed approach and numerical methods presented in this article are intended to the modeling and optimization the vacuum infusion process quality, especially to correctly predict and eliminate the dry spot formation at the manufacturing, which is most important for the high strength three-dimensional composite parts of complex geometry. We consider the liquid resin advancement in the preform at the vacuum infusion as two phase flow in a porous medium where the motion and configuration of the resin front are controlled by the phase field equation, which is the ruling equation of the coupled forward problem describing the process dynamics. The second equation of the coupled problem is the Richards equation with the medium saturation in the form proposed by van Genuchten. This equation represents fluid motion in unsaturated soils with spatially varied pressure dependant porosity and saturation. The proposed numerical technique was implemented in the Comsol Multiphysics environment that allows to easy compatibility with the advanced optimization tools of MATLAB. In order to use our FE model as part of an optimization software package with multiple calls of the forward problem simulation we proposed two indicators to interrupt the computing process at the obvious formation of dry spots: closing the vacuum vent by the resin front and artificial means, which consists of harmonically change of the vacuum pressure with calculation of the averaged pressure within the unfilled areas of preform. These indicator were demonstrated the satisfactory sensitivity to the formation of relatively large dry spots. The auxiliary program tool that is able to correctly reconstruct the times of formation, localization and dimensions of the arising dry spots realizes the numerical processing of the FE simulation results, which is very important for the decision about the choice of reliable and high quality technology conditions from some set of solutions proposed by the numerical optimization.

In our article, we intentionally examined a detail of a complex design and a not entirely suitable process scheme in order to demonstrate the predictive capabilities of the developed method in terms of detecting the facts and the nature of the resulting fatal defects - dry spots. The next step of our investigations will be the inclusion into consideration the thermal, kinetic and rheological phenomena caused by the cure processes controlled by the temperature and time, and also, the deeper experimental studies to verify and improve the correctness and reliability of developed numerical methods.

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