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COMPOSITES THEORY AND PRACTICE

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SIMPLIFIED SIMULATION OF VARI PROCESS USING PAM-RTM SOFTWARE

The aim of the work was to assess the effectiveness of a simplified simulation procedure of the VARI (*vacuum assisted resin infusion*) process with the use of PAM-RTM® software on mat, plain-woven fabric and unidirectional fabric preforms. The performed experimental determination of permeability, followed by its application in the simulation, exhibits an error of a few to a dozen % of the *resin front range - process time* relation. At the same time, it was stated that the samples with high anisotropy exhibit a larger simulation error. The cause of the simulation errors is the stochastic course of the actual VARI process, disturbed by such factors as: structural anomalies in the fabric, incomplete hermeticity of the vacuum system, non-uniformity of the resin accumulation behind the front and a non-uniform flow of the resin at the initial stage of the process. The simulation error was also affected by: insufficient mesh density, tetrahedral shape of the finite elements as well as a simulation function different than the actual one. The simulation errors observed for the simplified method are not large, considering the stochastic type of the process, and they make it possible to practically apply the simplified simulation method. The latter can be especially attractive for small and medium enterprises, as its only requirement is to perform simple VARI experiments on small samples and to possess the appropriate software and a standard PC (*personal computer*).

Keywords: polymer matrix composite, VARI process, numerical simulation

UPROSZCZONA SYMULACJA PROCESU INFUZJI PRÓŻNIOWEJ (VARI) PRZY UŻYCIU PROGRAMU PAM-RTM

Celem pracy była ocena skuteczności uproszczonej procedury symulacji procesu VARI (pol. *infuzja próżniowa*) z użyciem oprogramowania PAM-RTM na preformach maty, tkaniny plain-woven oraz tkaniny jednokierunkowej. Przeprowadzone eksperymentalne wyznaczanie przepuszczalności, a następnie zastosowanie jej w symulacji wykazuje kilku-, kilkunasto-procentowy błąd zależności zasięg żywicy - czas procesu. Stwierdzono jednocześnie, że próbki o dużej anizotropii pokazują większy błąd symulacji. Powodem błędów symulacji jest stochastyczny przebieg rzeczywistego procesu VARI, zaburzonego m.in. przez: występowanie zaburzeń struktury w tkaninach, niecałkowitą szczelność układu próżniowego czy nierównomierność gromadzenia się żywicy za frontem, nierównomierny przepływ żywicy w początkowym etapie procesu. Na błąd symulacji wpłynęły także: niewystarczająca gęstość meshu, tetraedryczny kształt elementów skończonych, odmienna od rzeczywistej funkcja symulacji. Błędy symulacji uzyskane dla metody uproszczonej nie są zbyt duże, jak na stochastyczny proces i umożliwiają praktyczne zastosowanie uproszczonej metody symulacji. Może być ona atrakcyjna szczególnie dla małych i średnich producentów, gdyż wymaga jedynie przeprowadzenia prostych eksperymentów VARI na niewielkich próbkach oraz oprogramowania i zwykłego PC.

Słowa kluczowe: kompozyty o osnowie polimerowej, proces infuzji próżniowej, symulacja numeryczna

INTRODUCTION

Fiber reinforced polymer (FRP) composite products made by the VARI (*vacuum assisted resin infusion*) method are characterized by a smaller number of structural defects (fibre strand disorders, air-voids) than those made by hand lay-up molding [1]. The method also exhibits higher efficiency and repeatability [2]. In many cases, the use of pressure techniques is necessary to obtain the required laminate quality [3]. The former are comparable with winding technologies [4] or even pre-preg technology [5], whereas VARI is less expensive and more universal. A good current example of the application of the VARI technique is natural fibre reinforced plastic (NFRP) composite products [6, 7]. The high volume fraction of the fibres and the high quality of the structure are necessary to provide products reinforced with (relatively weak) jute or flax fibres with sufficiently good mechanical properties [8, 9]. The VARI technique is also an important way of joining the composite elements and co-laminating the components [10, 11].

The use of simulation software is necessary during the planning of FRP products with the use of pressure methods, such as VARI and RTM (*resin transfer moulding*), especially in the case of large products [12]. The simulation of the process requires determining the boundary conditions (the manner of applying the pressure) as well as making a series of assumptions, such as the compressibility of the preform and its permeability. Especially important is the latter, which takes into consideration both the geometry of the preform and its wettability [13]. Permeability is a resultant of these two properties and is generally defined as a measure of the ability of a porous material to allow fluids to pass through it. It is expressed by m^2. It is a tensor value and the given preform can exhibit anisotropy of permeability [14]. The first attempts at facing the issue of resin flow simulation in fibrous preforms took place in the mid-1990s. Some exemplary works are: [15], discussing the elaboration of software for preform deformation simulation during the pressure process, [16], where the Volume Of Fluid (VOF) program was designed to perform a numerical analysis of the liquid transfer in the preform during the RTM process, as well as [17], which includes a simulation of the progress of filling the preform with resin. Further stages of the research included work on the problem of simulating heat flow during the process and its possible local accumulation [18, 19], as well as the stresses resulting from a non-uniform progression of hardening [20]. Later studies aimed at simulating more complicated types of pressure processes and of more complicated solutions [21, 22]. Those were followed by works on the practical problems related to modelling itself [23, 24]. Determining the appropriate physical assumptions remains the main problem of RTM and VARI process simulation. Obtaining the charge data (preform compressibility and permeability) is often problematic; it requires experimental determination. The existing data libraries are still insufficient and the processes of preform saturation, seemingly simple, is characterized by high stochasticity.

The ANSYS FLUENT program is used for simulating various processes involving a medium flow [25], including pressure saturation of fibrous preforms. It provides good results, yet it is quite complicated to use for the majority of producers [26, 27]. Currently, there are two available programs on the market dedicated to laminate pressure forming processes. One is RTM-WORX by POLYWORX, the Netherlands. It is designed to simulate RTM and CVI (controlled vacuum infusion) processes [28]. The other one is PAM-RTM by the ESI GROUP, France. It has been created especially for the simulation of RTM processes and it is being continuously developed. Since 2004, it has had a separate mode for VARI process simulation [29]. At present, it is a very universal tool for the simulation of a whole range of pressure processes [30, 31]. It also has a mode which supports preform design [32]. A few research teams are performing verification studies on the simulation with the use of this program [22, 26]. The PAM-RTM program has been used in the presented work.

The aim of the work is to evaluate the effectiveness of the simplified simulation procedure for the VARI process with the use of PAM-RTM software on three model glass fibre preforms.

The *simplified procedure* consists in performing the following steps for the given stack of layers which is to be used: 1) performing experimental VARI processes on small preforms in the unidirectional (**linear**) flow of the resin in the basic preform directions and determining the *relation between the resin front range and the process time*, 2) determining the permeability in the basic directions on the basis of the previously established *range-time* relation, with the use of the PAM-RTM program, 3) performing experimental VARI processes on similar preforms in the **diagonal** resin flow direction and determining the *range-time* relation, 4) simulating *diagonal-flow* experiments in the PAM-RTM program with the use of previously established permeabilities, verification of simulation effectiveness by way of comparing the *range-time* relations from the simulations with those from the real experiments.

The simplified procedure does not consider the external determination of compressibility, which is problematic: it requires introducing a *stress-strain* curve for the preform compression into the program (access to a testing machine required) [30, 33]. This is quite unattainable for most producers (that is, the main users of the program). The proposed simplified procedure makes it possible for a potential user to perform a simulation of the VARI process on any preform only on the basis of the permeability obtained in the self-performed simple technological experiments.

MATERIALS AND EXPERIMENTAL PROCEDURE

The VARI tests were performed on 3 types of stacks representing the basic models of laminate reinforcing structures: 1) 18 layers of plain-woven fabric 320 g/m^2 (KROSGLASS, Poland), 2) 8 layers of chopped-strand mat 600 g/m^2 (KROSGLASS, Poland), 3) 24 layers of unidirectional fabric (UD) 220 g/m^2 (INTERGLAS, Germany). Each stack after being compressed under a vacuum bag (gradient −80 kPa) was 5 mm high, which was the criterion for selecting the number of layers. In order to assure repeatable conditions for the tests, all the fabric sheets were cut from the middle sections of the bales and the appropriate directions were maintained (Fig. 1) For the purposes of the study, 3 specimens of each type of preform were prepared.

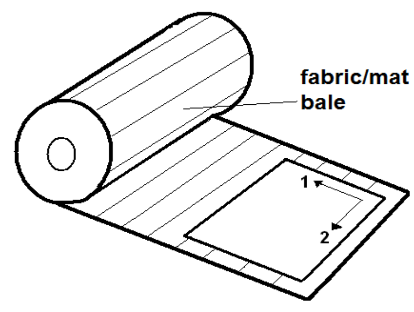

Fig. 1. Sheet cutting s - indications of directions

Rys. 1. Wycinanie przykrojów tkanin z beli - oznaczenie kierunków

In all the experiments, epoxy resin HAVEL LH288 + hardener H281 were used. The experimentally determined initial viscosity of the mixture equaled 580 mPa·s and the gelation time was 63 min. The viscosity change during crosslinking was linear (up to about 62 min) and equaled 1 mPa·s/min, which was considered in the simulation.

The VARI processes were performed on a flat mould, on the stand shown in Figure 2.

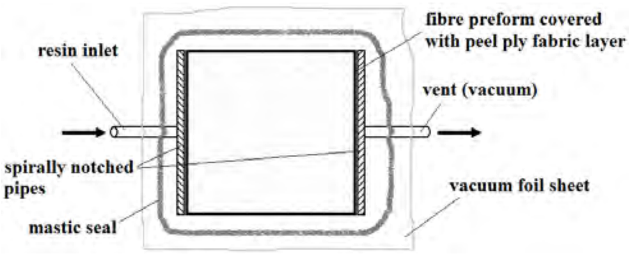

Fig. 2. Diagram of stand for VARI processes performed within study

Rys. 2. Schemat stanowiska dla procesów infuzji próżniowej (VARI) prowadzonych w ramach pracy

To power the processes, an oil vacuum pump TEPRO 1100V (TEPRO, Poland) was used, with the power of 1100 W, which assured a static pressure gradient for each process (with a closed vacuum system) - 80 kPa (–0.80 bar), with the possibility of precise regulation of the accuracy of 1000 Pa. For a linear flow of the resin along the appropriate section of the preform, spirally-incised tubes were used. In the earlier numerous tests conducted by the author, it was discovered that such tubes apply the resin in a uniform manner along their whole length. Within the performed studies, the processes were run in the unidirectional (linear) flow direction and the bidirectional (diagonal) flow direction. In all the preform cases, the saturation in the linear direction was performed separately in each of the main directions in respect of the cutting of the fabric/mat sheets (Fig.1) - Figure 3.

The aim of the VARI experiments was to determine the curves: *resin front range vs. process time* (further referred to as *range-time*). It consisted in marking (and next measuring in respect of the start line) the range of the resin front, which was well-observable through the vacuum foil, after a particular time of the process. The measurements were made after 10, 30, 70, 110, 200, 300, 360 and 570 s. Moreover, the time was additionally measured with the range of 195 mm. The author's own previous studies as well as the available technological knowledge point to the fact that a process of this type should not last longer than 35÷40 min, even for very large objects [34, 35]. The process was performed on 3 specimens of each type of preform. The experimental tests were performed with especially great care.

The obtained results were approximated with a function selected with use of the LAB-FIT program:

$$L = A \cdot \left(\ln \frac{t}{t_0} \right)^B \tag{1}$$

where L is the resin front range, mm, t is the process time, s, t_0 is the unitary time, s (t_0 = 1s), A (m) and B (dimensionless) are the function parameters. Parameters A and B are not easy to physically interpret, however, this function well describes the course of the process and its parameters can be the subject of an additional analysis.

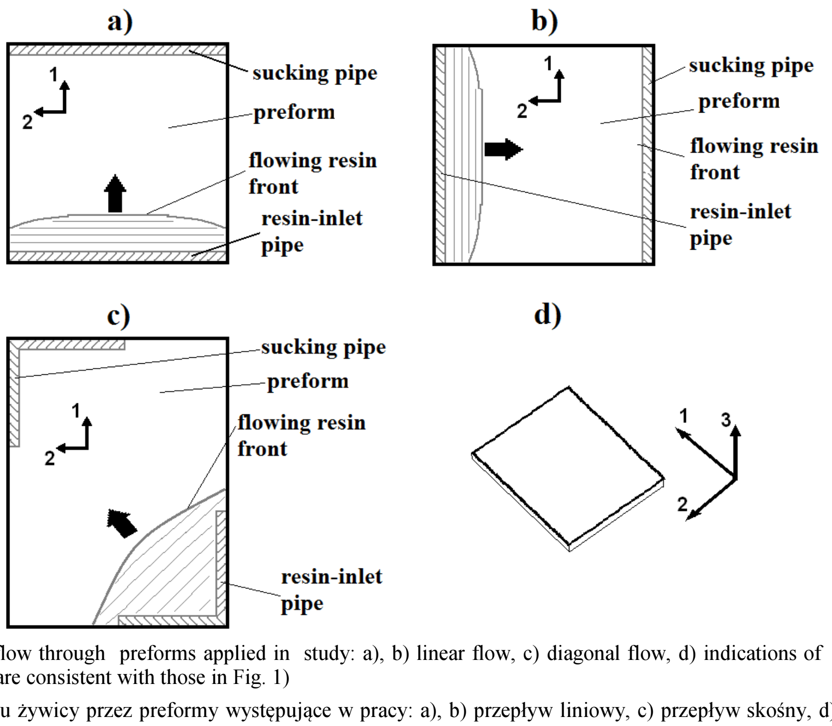

Fig. 3. Diagrams of resin flow through preforms applied in study: a), b) linear flow, c) diagonal flow, d) indications of directions within preform (directions 1 and 2 are consistent with those in Fig. 1)

Rys. 3. Schematy przepływu żywicy przez preformy występujące w pracy: a), b) przepływ liniowy, c) przepływ skośny, d) oznaczenia kierunków na preformach (kierunki 1 i 2 są zgodne z oznaczeniami na rys. 1)

SIMULATION ASSUMPTIONS

The simulations were conducted with the use of the PAM-RTM program, 2009 edition. Two models of plates were used: *square* 200 x 200 x 5 mm (9660 elements - 3346 nodes), to determine the permeability in the linear resin flow, and *rectangular* 300 x 200 x 5 mm (14489 elements - 5019 nodes) to verify the determined permeabilities for the diagonal resin flow. The simulation was performed in the 3D system to assure compatibility with possible later works on thicker plates. During analysis of the results, it was stated that in the presented study the permeability in direction 3 was insignificant (low thickness of the plate).

Boundary conditions: a negative pressure gradient was applied on the suction line. The suction line and the inlet line were 200 mm long or (diagonal flow) were in the corner of the preform, running 100 mm along the perpendicular edges. This is an accurate representation of the spiral tube lines from the real experiment. The value of the applied negative pressure gradient for all the simulations was –80 kPa.

The resin viscosity, according to the results of the experimental assessment, was established as variable - from the level of 580 mPa·s with a linear increase of 1 mPa·s/min.

The compressibility was neglected and the *stress-strain* relation as not introduced during preform compression. It was assumed that it would be considered in the permeability, together with the preform geometry and fibre wettability. The porosity of the compressed preforms was assumed: 61% for the plain-woven fabric, 39% for the mat and 60% for the UD fabric. These values were assumed in relation to the obtained real fibre volume fraction of the individual laminates.

The permeability (tensor K) was determined individually for each examined preform by the repetition method with approximation, on the basis of the experimental *range-time* relations. For the purpose of simplification, in determining K1 and K2, only the result for the time corresponding to 195 mm from the experiment result approximation was considered ("simplified method") and the global mean value from the total of *range-time* results was not calculated. It was assumed that the furthest measured range in determining permeability (the complete length of the resin path equaled 200 mm; the 195 mm line was the last but one of the points in the model) is the most significant - a possible error introduced at an earlier stage will increase together with progression of the process relation. Therefore, such an approach minimizes its effect to the largest possible extent, at the same time significantly simplifying the procedure. The performed error analysis shows whether such a simplified approach is correct. K3 determined in a separate research does not affect the simulation result, which was established in the analysis of the results.

RESULTS - PERMEABILITY DETERMINATION

The permeabilities were calculated by means of the PAM-RTM program on basis of the experimental data. An exemplary set of *range-time* relations as well as the corresponding approximation curves are shown in Figure 4. The determined approximation function parameters (formula 2) are presented in Table 1.

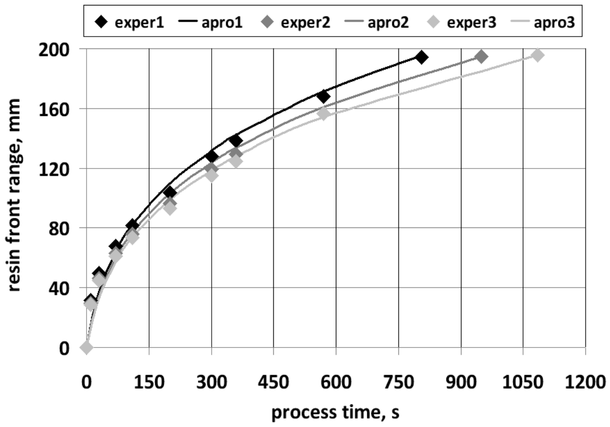

Fig. 4. Exemplary set of *resin front range vs. process time* relations and corresponding approximation curves: plain weave fabric preform, resin flow in direction 1

Rys. 4. Przykładowa rodzina krzywych zależności zasięg frontu żywicy--czas procesu i odpowiadających im krzywych aproksymujących: preforma tkaniny krzyżowej, przepływ żywicy w kierunku 1

TABLE 1. **Approximation parameters (formula (2)) of individual preforms concerning directions of cutting fabric sheets from bale (Fig. 1)**

TABELA 1. **Parametry aproksymacji (wzór (2)) dla poszczególnych preform z uwzględnieniem kierunku wycinania przykrojów z beli (rys. 1)**

Preform type and direction	Approximation parameters	
	A [m]	B
plain-woven fabric - direction 1	1.712 ± 0.106	2.463 ± 0.004
plain-woven fabric - direction 2	2.498 ± 0.078	2.263 ± 0.010
chopped strand mat - direction 1	2.763 ± 0,128	2.428 ± 0.075
chopped strand mat - direction 2	4.906 ± 0.223	2.099 ± 0.058
UD fabric - direction 1	4.323 ± 0.090	1.902 ± 0.034
UD fabric - direction 2	1.062 ± 0.099	2.303 ± 0.031

The function approximation will be used in the further stage of the study (error analysis).

The value of the resin front range on the basis of which the permeability was determined during the real process and simulation in the linear flow equaled 195 mm. By substituting this value and its corresponding time into the linear flow simulation (Fig. 5), the permeabilities for the particular preforms were obtained.

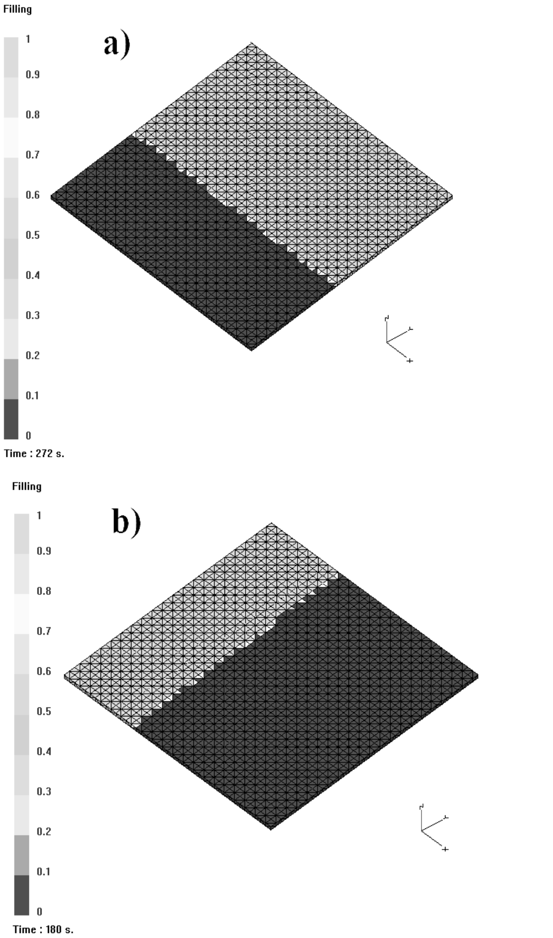

Fig. 5. Screens from PAM-RTM program. Exemplary simulation of filling plain-woven fabric preform: a) direction 2 (Y), b) direction 1 (X)

Rys. 5. Zrzuty ekranu z programu PAM-RTM. Przykładowa symulacja napełniania preformy tkaniny krzyżowej: a) kierunek 2 (Y), b) kierunek 1 (X)

The values of the determined permeabilities are presented in Table 2.

TABLE 2. **Permeabilities of individual preforms concerning directions of cutting fabric sheets from bale (Fig. 1)**

TABELA 2. **Przepuszczalności poszczególnych preform z uwzględnieniem kierunku wycinania przykrojów z beli (rys. 1)**

Preform type	Permeability	
	K1 (direction 1) 10^{-11} m^2	K2 (direction 2), 10^{-11} m^2
plain-woven fabric	2.111 ±0.164	3.147 ±0.202
chopped strand mat	8.987 ±0.413	8.816 ±0.304
UD fabric	2.183 ±0.109	0.481 ±0.112

By comparing formula (1) and Darcy's law, which involves the concept of permeability [14] and which is the basis for the (PAM-RTM) program's algorithm [30], it can be stated that the permeability is proportional to parameter A (parameter B is the power for the constant dependent on t, that is the one which can vary in a wide range; it should thus be treated as 'a deviation' of the given process from the ideal course which is in accordance with Darcy's law, i.e. as some kind of correction for parameter A). By making such an assumption, the author analyzed the relation $K = A \cdot C$ (K - permeability, m^2, A - approximation parameter, m, C - a constant containing the determined quantities: *pressure gradient*, *resin viscosity*, *front width*, *element dependent on time constant* t_0 from formula (1), m). With constant C equaling 1.26 m (value calculated with EXCELL-SOLVER by way of optimizing the element dependent on time constant t_0 from formula (1)), the mean error of the calculated K for the analyzed population equals about 70%. This corresponds to the discrepancy of the actual process from Darcy's law. Parameter B from formula 1 can be treated as the measure of this discrepancy.

RESULTS - SIMULATION VERIFICATION

Verification of the simulation effectiveness, or in fact, verification of the determined permeabilities, was performed in two stages. First, real VARI experiments with a diagonal resin flow were performed on the same types of preforms on which the permeabilities were determined. The parameters of the approximating function in respect of the preform diagonal were determined. Secondly, simulations of the process with the diagonal flow were conducted on the models of the particular preforms, with the use of the permeabilities determined earlier. Theoretically, the permeability should be the same, as it is the preform's physical property of an intense character (independent of the shape or the size). Thus, its application in the model of the preform of a slightly different shape and with a different direction of flow should provide good compatibility of the simulation with the analogical real experiment. This is a good method of verifying the effectiveness of determining the permeability by means of the simplified technique. A photograph of an exemplary process with diagonal flow is presented in Figure 6.

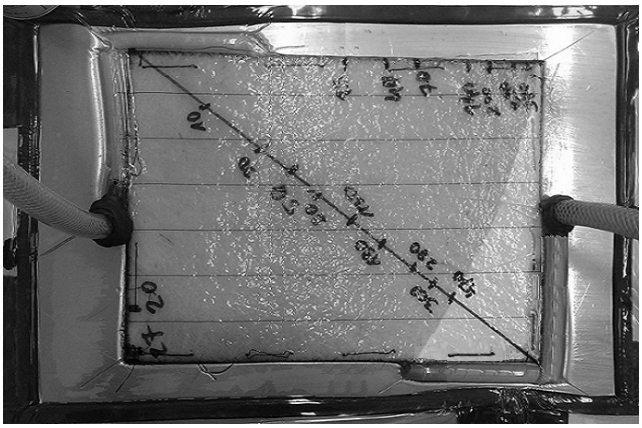

Fig. 6. Exemplary preform (chopped strand mat) processed by VARI, diagonal resin flow

Rys. 6. Przykładowa preforma (mata) podczas napełniania infuzyjnego (VARI), skośny przepływ żywicy

The approximation parameters (formula 2) determined for the diagonal flow along the preform diagonal are included in Table 3.

TABLE 3. **Approximation parameters (formula (2)) for individual preforms, processed at diagonal resin flow. Measurement along diagonal**

TABELA 3. **Parametry aproksymacji (wzór (2)) dla poszczególnych preform napełnianych przy skośnym przepływie żywicy. Pomiary zależności zasięg-czas wzdłuż przekątnej preformy**

Preform type	Approximation parameters	
	A [m]	B
plain-woven fabric	5.591 ±0.228	1.974 ± 0.009
chopped strand mat	16.250 ±1.881	1.561 ± 0.035
UD fabric	9.544 ±0.384	1.604 ± 0.058

An exemplary image of the process simulation with diagonal flow in the PAM-RTM program is shown in Figure 7.

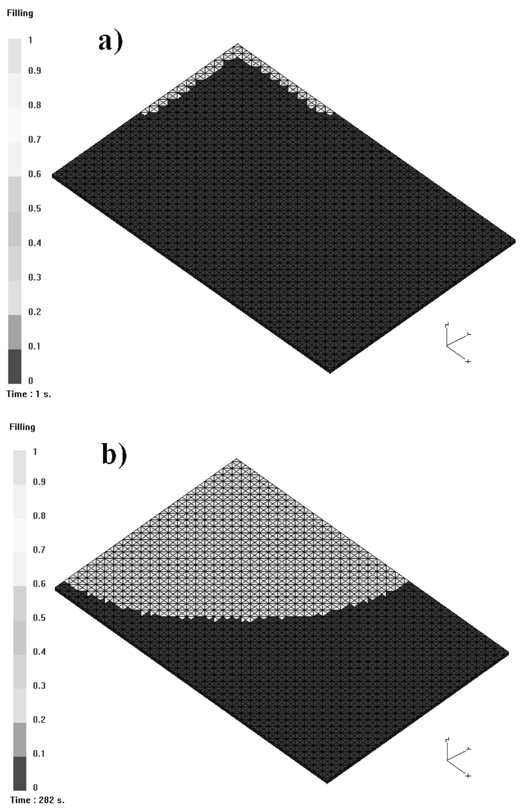

Fig. 7. Screens from PAM-RTM program. Exemplary simulation of filling plain-woven fabric preform in diagonal direction: a) initial phase, b) advanced phase

Rys. 7. Zrzuty ekranu z programu PAM-RTM. Przykładowa symulacja napełniania preformy tkaniny krzyżowej w kierunku skośnym: a) faza początkowa, b) faza zaawansowana

The basis for assessing simulation effectiveness is the establishment and analysis of the errors, that is of the difference between the experiment results and the appropriate simulation results.

ANALYSIS OF DEVIATIONS

Table 4 includes the process time corresponding to five different stages of resin front range.

TABLE 4. **Process time corresponding to given resin front range-diagonal flow direction, measurement along diagonal of preform. Experimental results obtained from approximation and simulation results for individual types of preforms**

TABELA 4. **Czas procesu odpowiadający danemu zasięgowi żywicy-skośny przepływ żywicy, pomiary zależności zasięg-czas wzdłuż przekątnej preformy. Wartości uzyskane z aproksymacji wyników eksperymentalnych oraz wyników symulacji dla poszczególnych preform**

Preform	Process time corresponding to given resin front range [s]				
	Front range 50 mm	Front range 100 mm	Front range 150 mm	Front range 250 mm	Front range 350 mm
fabric - verification (aproximation)	21 ±0.6	74 ±3	199 ±10	950 ±67	3397 ±298
fabric - verification (simulation)	19	90	302	1368	3881
mat - verification (approximation)	8 ±0.4	25 ±2	64 ±5	318 ±38	648 ±100
mat - verification (simulation)	8	33	99	412	613
UD - verification (approximation)	17 ±0.6	76 ±4	262 ±20	2120 ±216	12664 ±1824
UD - verification (simulation)	53	208	595	2749	7573

Figure 8 shows a compilation of the simulation inaccuracy calculated from the formula:

$$d_S = \frac{t_R - t_S}{t_R} \cdot 100 \qquad (2)$$

where: d_S - the simulation inaccuracy [%], t_R - the actual (approximation) time of the real process corresponding to the given resin front range [s], t_S - the time of process simulation corresponding to the given resin front range [s].

The obtained results show that in the case of the plain-woven fabric and the mat, the inaccuracy at the initial stage of the process (L = 50 mm) is small and next it increases, which is followed by its decrease. A different trend is exhibited by the UD fabric, where at first we observe a large negative error (the real process runs much faster than the simulation), which decreases together with the increase in L and next increases in the positive direction (simulation faster than the real process). From L = 150 mm, the trend is the same for all the three preforms.

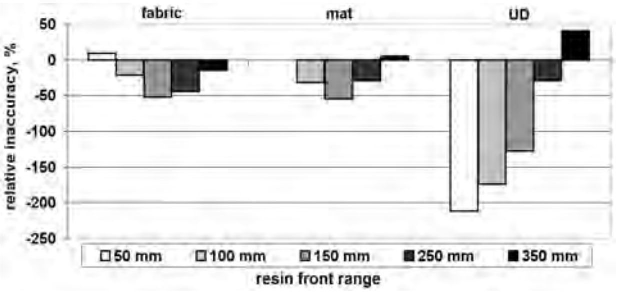

Fig. 8. Relative inaccuracy of simulation time results against experimental (approximation) time results. Diagonal resin flow, measurement *along diagonal of preform.* Negative values mean that real process runs faster for given type of preform in particular phase

Rys. 8. Względna niedokładność wyników czasu procesu uzyskanych w symulacji względem wyników eksperymentalnych (aproksymacja). Skośny przepływ żywicy, pomiary zależności zasięg-czas wzdłuż przekątnej preformy. Ujemne wartości na diagramie oznaczają, że dla danego typu preformy, na danym etapie, rzeczywisty proces przebiegał szybciej niż symulacja

Besides the measurement along the diagonal, during the process with the diagonal flow, the relation *range-time* was also measured on the longer (direction 1) and the shorter (direction 2) edge of the preform. The results are presented in Table 5 and Figure 9.

The trends of the simulation error increase are similar to those for the measurement along the diagonal. In the case of the plain-woven preform, a significantly larger error was observed for direction 1 than for direction 2. This certainly results from the significant anisotropy of the permeability of this preform (Table 2). In the case when K1 and K2 are similar (fabric and mat), the error at the initial stage is small and next it increases, followed by its decrease. In the case when K1 and K2 are significantly different (UD fabric), the error trend constantly decreases, starting from a high initial value. These differences point to the possibility of resin cross-flow in the real process which is not considered in the simulation. The results also show that the preform of high anisotropy (UD fabric) exhibits a larger simulation inaccuracy both at the initial and the advanced stage of the process, as compared to the two remaining preforms.

TABLE 5. **Process time corresponding to given resin front range: diagonal flow direction, measurement *along directions 1 and 2 of preform.* Experimental results obtained from approximation and simulation results for individual types of preforms**

TABELA 5. **Czas procesu odpowiadający danemu zasięgowi frontu żywicy: skośny przepływ żywicy, pomiary zależności zasięg--czas wzdłuż kierunku 1 oraz 2 preformy. Wartości uzyskane z aproksymacji wyników eksperymentalnych oraz wyników symulacji dla poszczególnych preform**

Preform	Process time corresponding to given resin front range [s]			
	Front range 50 mm	Front range 100 mm	Front range 150 mm	Front range 200 mm
fabric - direction 1 (approximation)	51 ±4	184 ±18	468 ±50	1002 ±124
fabric - direction 1 (simulation)	85 ±7	354 ±34	786 ±92	1414 ±170
fabric - direction 2 (approximation)	43 ±2	165 ±13	449 ±37	1029 ±102
fabric - direction 2 (simulation)	54 ±3	233 ±20	537 ±43	956 ±95
mat - direction 1 (approximation)	27 ±4	82 ±14	182 ±37	352 ±87
mat - direction 1 (simulation)	20 ±3	83 ±14	184 ±40	333 ±81
mat - direction 2 (approximation)	22 ±3	73 ±11	185 ±38	402 ±110
mat - direction 2 (simulation)	20 ±3	85 ±15	192 ±40	343 ±86
UD - direction 1 (approximation)	37 ±4	184 ±24	635 ±103	1823 ±361
UD - direction 1 (simulation)	79 ±8	326 ±42	757 ±119	1395 ±278
UD - direction 2 (approximation)	206 ±40	1334 ±291	5331 ±1332	16697 ±5515
UD - direction 2 (simulation)	344 ±68	1472 ±309	3461 ±867	6297 ±2013

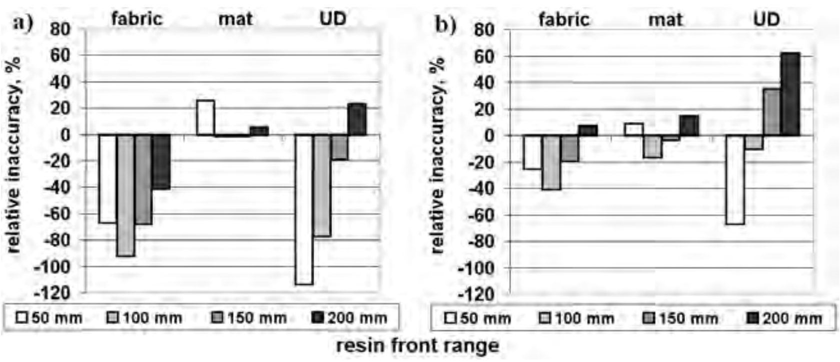

Fig. 9. Relative inaccuracy of simulation time results against experimental (approximation) time results. Diagonal resin flow, measurement along directions 1 (a) and 2 (b) of preform. Negative values mean that real process runs faster for given type of preform in particular phase

Rys. 9. Względna niedokładność wyników czasu procesu uzyskanych w symulacji względem wyników eksperymentalnych (aproksymacja). Skośny przepływ żywicy, pomiary zależności zasięg-czas wzdłuż kierunku 1 (a) oraz 2 (b) preformy. Ujemne wartości na diagramie oznaczają, że dla danego typu preformy, na danym etapie, rzeczywisty proces przebiegał szybciej niż symulacja

In general, the non-uniform course of the error should be explained by the discrepancy of the real process with the theoretical model based on Darcy's law. The theoretical model does not consider the factors affecting the course of the actual process. The set of range-time curves for one type of preform exhibits quite a clear scatter (Fig. 4 and Table 1). This proves the effect of the stochastic factors on the results. Below is an analysis of the factors which were observed within the performed studies.

1. A significant factor affecting the lack of predictability of resin flow in the preform is the ***occurrence of structure anomalies in the fabrics***. The plain-woven fabric has a well organized structure and so, in this case, the effect on the simulation inaccuracy should be lower. The UD fabric is also well organized; however, at the same time, it is "limp", which makes it easy to disorganize during preform preparation. The mat has a stochastic fibre arrangement, which has an undoubted effect on the repeatability of preform permeability. For example, despite the theoretical predictions regarding the isotropy of the plain-woven fabric and the mat in the transverse directions, we can observe evident anisotropy of the flow rate and permeability (Tables 1 and 2).
2. Another factor determining the course of the process which can cause its disturbance is the ***hermeticity of the vacuum system*** (especially within the connection of the foil sheet with the form). The air-tightness of the whole system affects mainly the quality of the produced laminate and so it should be perfect. However, local leaks cause momentary pressure disturbances, which are impossible to be considered when recording the *range-time* relation (the simulation assumes that the pressure is constant).
3. Also significant for the process is the ***repeatability of the vacuum foil stretchability***. With non-uniform stretchability, local differences in the hold-down may occur, which result in non-uniformities in the preform permeability. On the basis of the confrontation of simple hand tensile tests and thickness measurements, it was stated that the stretchability of the foil is not uniform even within the 1 m x 1 m sheet. Additional differences in the foil stretchability are caused by non-uniform stretching of the foil when fixing it to the sealing mastic (Fig. 2).
4. An important phenomenon disturbing the VARI process is undoubtedly the ***non-uniformity of the resin accumulation behind the resin front***. The whole sucked-in resin (its volume increases with the course of the process) is moved by a pump of a constant power and so, if its amount accumulated behind the front is - even slightly - different in different cases, then it is not without an effect on the rate of the process. The PAM-RTM algorithm considers the resin increase behind the front, but it assumes a volume increase limited by the volume of the model (which is constant) and has no way of assessing the actual volume of the resin collected. Under the actual conditions, after the front has passed, we observe a decrease in the vacuum in the area behind the front. The negative pressure present before the front is "relaxed" by the in-flowing resin up to the moment when a pressure balance (between the vacuum at the front and the outer ambient pressure) is established by the supply system. Within the process preparation, the amount of resin necessary to fill the preform is calculated with precision. After this amount is sucked-in, the system is blocked. Usually, a certain excess amount is accumulated in the vicinity of the inlet area, which constitutes a "reservoir" for filling the preform. Until the front reaches the end (the suction line), the whole excess amount should be sucked into the preform (Fig. 10).

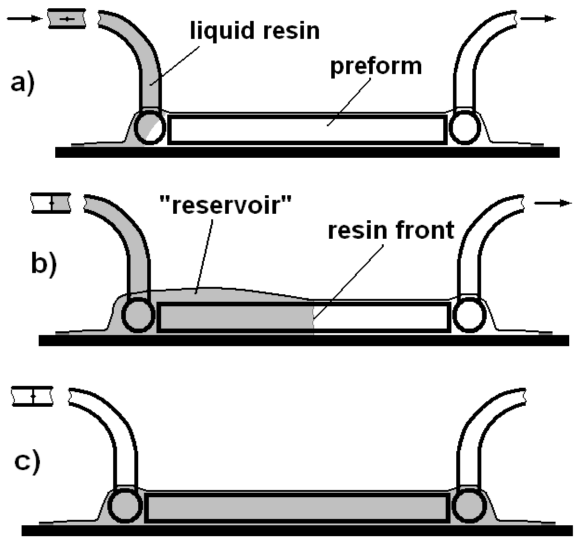

Fig. 10. Stages of VARI process: a) initial stage, b) intermediate stage - creation of "reservoir", c) end of process - preform completely filled with resin

Rys.10. Etapy procesu infuzji próżniowej (VARI): a) etap początkowy, b) etap pośredni, c) koniec procesu - preforma całkowicie napełniona żywicą

The dosed resin amount contains an appropriate allowance, which usually corresponds to the volume of the supply line and suction line channels. The stochastic in-flow of the resin to the preform behind the front can be an explanation of the simulation error increase at the central stage of the process (Figs. 8 and 9), in which the possibility of resin fluctuating to and from the "reservoir" is the highest. The high value of the inaccuracy in the initial stage of the process for the UD preform probably arises from the relatively large number of layers. It gives a bigger "potential" for creating a "reservoir" for this type of preform. A very significant effect of the *non-uniformity of the resin accumulation behind the front* is indicated by reference to the results of work [26], where the simulation exhibits a uniform (and very slight) error in the whole period of the RTM process, in which, as opposed to VARI, the increase in the resin behind the front is continuously uniform (imposed by the constant size of the mould cavity).

The disturbance of the flow rate in the initial phase is partly caused by the inertia of the column of the flowing resin. This inertia is also responsible for the resin in-flow under the foil at a later stage of the process - the creation of the above-mentioned "reservoir".

The factors which may disturb the correct course of the simulation are also undoubtedly the imperfections of the simulation itself.

– One of these factors is the ***insufficient density of the mesh*** of the numerical model. The program assigned a certain period of time for filling each element to a certain degree (see the scale in Figs. 5 and 7). If the mesh is not dense enough, the simulation accuracy drops, as the filling time assigned to a given point of the preform is burdened with an absolute error. This error results from the "phase shift" of the complete filling of neighbouring elements. It is randomly generated by the program algorithm. For example, in a given simulation, with a particular time of the process, an element is 93% filled. In a repeated simulation, with the same charge data and the same process time, the element is 100% filled and additionally, the neighbouring element is 12% filled. For the analyzed model, the element line corresponding to 195 mm, with a few repetitions of the simulation for identical boundary conditions and input data, exhibited diversification of the filling time even of a few dozen seconds. This is a very significant error. At the same time, it cannot be stated that the applied mesh is insufficiently dense. A large element (e.g. a boat hull) is modelled with a similar density - about 2500 elements/100 cm^2, which gives an about a 5 mm length of the element edge - would probably be useless as it would pose too high calculation requirements for commonly available computers.

– The above problem, and perhaps other simulation anomalies as well, may result from the ***shape of the elements***, which are tetrahedral for 3D models. The flow through the net of such elements is not ideally linear - especially for relatively rare net density.

– The comparison performed above of the approximation parameters of the function describing the actual VARI process as well as permeability shows that the program algorithm uses a ***different function*** for the modelling of the resin flow through the preform (a function based on Darcy's law, not given by the authors of the algorithm [30]). The obtained results prove that the real process diverts from the assumptions of the algorithm. There is a high probability that the distinctness of the function has an effect on the simulation error, which is proven, among others, by the characteristic trends of simulation errors reoccurring for the particular preform types.

SUMMARY

The performed research showed that the simplified method of VARI process simulation, applied on three model preform types, exhibits quite significant errors of the *range-time* relation. The relative values of the errors vary in the course of the process and in the final phase of the latter (the most significant from the practical point of view), they equal a few to a dozen percent. At the same time, it was stated that samples of high anisotropy of permeability (UD fabric) exhibit a larger simulation error.

The cause of the simulation errors is the stochastic course of the real VARI process. The process, despite its simple idea, is very complicated and its course depends on many factors. The most significant of those which affect the simulation errors have been established to be: the *occurrence of structure anomalies in the fabrics*, *incomplete hermeticity of the vacuum system*, *lack of repeatability of vacuum foil stretchability*, *non-uniformity of the resin accumulation behind the resin front*, and the *inertia of the column of the flowing resin*. The simulation error was also affected by informatic-deriving factors as: *insufficient density of the mesh*, *tetrahedral shape of the elements* and *simulation function different than the real one*.

In order to eliminate or marginalize the errors, we should analyze the above-mentioned factors of effect and propose an appropriate system of correcting the determined permeability values. An analysis of the factors of effect should be the subject of a continuation of the presented study. One can also propose introducing such elaborated corrections into the program algorithm, which will automatically neutralize possible simulation errors.

The simulation errors obtained for the simplified method are not, in fact, very large for a stochastic process such as VARI and they allow for a practical use of the method (compare the standard deviations from Tables 1-5 and scatter of the curves in Fig. 4). The proposed simplified simulation method can be attractive especially for small and medium producers of laminate elements. It merely requires performing simple VARI experiments on small samples and having access to the appropriate (not very expensive) software and a simple PC. It should be emphasized that experimental determination of the preform permeability performed on a sample of a material used in the production is necessary for appropriate process simulation (this is proven by the evident anisotropy of the theoretically isotropic plain-woven fabric and chopped-strand mat, established in this study). It may be not enough to read and to interpret or to determine the permeability given in some theoretical resources.

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