Study of the effect of permeability coefficients in a three-dimensional formulation for fabrics various types of fabric structures

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Abstract. The results of theoretical and experimental studies of the kinetics of the impregnation process for 4 types of woven structures depending on the thickness of the molded parts are presented. The calculations were carried out with and without the permeability coefficient in the z plane. All calculations were performed in the PAM-RTM program. It has been established that considering the permeability coefficients along the x, y, z axes allows to increase simulation accuracy. As a result of the research it was found that with increasing laminate thickness more than 3 mm, it is necessary to consider the influence of the coefficient of permeability in the z-plane. Simulation error without taking into account the through thickness permeability coefficient increases from 6% to 22%.

1. Introduction
Polymer composite materials (PCM), made of glass, carbon fabrics and epoxy binders, are now widely used in the manufacturing of different products, which is associated with a unique set of their technological, mechanical and thermal properties [1, 2]. One of the main disadvantages, which limiting the application of PCM in the industry, is their high cost. Recently, more and more attention has been paid to direct molding methods, where dry fabric is used, without prepregs. The most widely used technologies in the fiber reinforced products are vacuum infusion and resin transferred molding. The main technological operations of these technologies are: the manufacture of a binder, fabric pattern, laying up, impregnation and curing. Quality losses can occur at each of these technological operations, but the most complex is the impregnation operation [3, 4]. To optimize the impregnation technology, the PAM-RTM software is used, which allows to determine the binder supply channels, the duration of the impregnation process, etc. These mechanical characteristics of final products depend on the fabric structure, including the type of weaving. When laying up the fabrics on the mold with double curvature surface, then in the process, all structures of the unit cell are deformed, which leads to a change in the values of permeability coefficients [9].

Currently, numerous studies have been carried out in which methods are proposed for determining the values of permeability coefficients in a two-dimensional formulation, i.e. along the X and Y axes. However, the permeability coefficient through the thickness of the fabric laminate also has impact on the kinetics of the impregnation processes.

The purpose of this work is to determine the values of permeability coefficients in a three-dimensional formulation, which will improve the accuracy of calculations when simulating the impregnation process.

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2. Methodology

The flow rate of the impregnation process was determined in accordance with the law of Darcy [5].

\[ V = -\frac{K \Delta P}{\mu L} \]  

(1)

where \( V \) – flow rate of resin; \( \Delta P \) – pressure drop; \( \mu \) – resin viscosity, \( K \) – fabric permeability; \( L \) – length of specimen.

In a three-dimensional model, the permeability coefficient is a symmetric tensor with components \( K_{xy} = K_{yx} \); \( K_{xz} = K_{zx} \); \( K_{yz} = K_{zy} \)

\[
[K] = \begin{bmatrix}
K_{xx} & 0 & 0 \\
0 & K_{yy} & 0 \\
0 & 0 & K_{zz}
\end{bmatrix}
\]  

(2)

Fabrics, as a rule, were considered as two-layer porous [1], which have different permeabilities in the \( x \) and \( y \) planes. Permeability in the plane of the laminate with \( S \) number of layers was investigated by the method of Mogavero and Advani [2]:

\[ K_{xx,yy} = \frac{1}{L} \sum_{i=1}^{S} t_i K_i \]  

(3)

where \( t_i \) – thickness \( i \)-layer, \( K_i \) – permeability coefficient \( i \)-layer, \( S \) – number of layers.

In this work, it is assumed that the fibrous thread consists of parallel impermeable filaments. It is assumed that the impermeable filaments, in turn, are located in a periodic pattern. The pattern considered are a quadratic array and a hexagonal array. For two cases of quadratic and hexagonal arrangement of fibrous filaments, Gehbart [4] describes permeability as

\[ K_{i,xx} = \frac{8R_f^2 (1 - V_f)^3}{c_1 V_f^2} \]  

(4)

\[ K_{i,yy} = c_2 \left( \frac{V_{fmax}}{V_f} - 1 \right)^{5/2} R_f^2 \]  

(5)

where \( V_f \) – fiber volume fraction in the thread, \( R_f \) – filament radius, \( c_1, c_2, V_{fmax} \) – constants.

For these two arrays, constants are defined as according to the recommendation of Gebart [8].

For the case of quadratic arrangement of filaments in the thread

\[ c_1 = \frac{16}{9\pi\sqrt{2}} \]

\[ c_2 = 57 \]

\[ V_{fmax} = \frac{\pi}{4} \]

For the case of hexagonal arrangement of filaments in the thread

\[ c_1 = \frac{16}{9\pi\sqrt{6}} \]

\[ c_2 = 53 \]

\[ V_{fmax} = \frac{\pi}{2\sqrt{3}} \]
To determine the value of the permeability coefficient in the z plane, the authors of [6, 7] proposed equation (6)

\[ K_{zz} = \frac{N\pi r^4 \sin\beta}{8A} \]  

(6)

In this case,

\[ \pi r^2 = \pi n_f R_f^4 \]  

(7)

\[ K_{zz} = \frac{Nn_f R_f^4 \sin\beta}{8A} \]

where \( N \) – number of pores consisting in the fabric surface area (\( N = 1 \) for unit cell), \( r \) – radius of warp and weft, \( n_f \) – number of filaments in the warp and weft, \( R_f \) – radius of filament, \( \beta \) – angle between the warp and fabric axis, \( A \) – area of unit cell structures.

2.1. Objects

The object of the research is an aircraft fairing model made of fiberglass with various types of weaving and epoxy binder. The geometrical parameters of the aircraft fairing are shown in figure 1. Four types of fiberglass produced by Interglas, differing in the type of weaving (Table 1) were used in this study.

| Type of Interglas | Weaving types | \( V_f, \% \) | Layer thickness, mm | \( R_f, \mu m \) | Liner density, tex | Unit Cell |
|------------------|--------------|-------------|---------------------|-------------|----------------|----------|
| 92110            | Plain        | 55          | 0.23                | 4.3         | 400            | Length, mm 6.6  | Width, mm 6.6  |
| 92125            | Twill (2/1)  | 52          | 0.3                 | 5.9         | 200            | Length, mm 7.4  | Width, mm 7.4  |
| 92140            | Twill (2/2)  | 50          | 0.17                | 5.7         | 200            | Length, mm 8.5  | Width, mm 8.5  |
| 92145            | Satin        | 58          | 0.36                | 6.1         | 400            | Length, mm 4.9  | Width, mm 4.9  |

In this work, the permeability coefficient values were calculated (table 2) using equations (4-7). All calculations were made on the assumption that the fiber content of fabrics in polymer composite is from 50 to 58%. The permeability coefficients in the x and y axes are equal.

| Type of Interglas | Permeability coefficients in the direction of the axes, \( m^2 \times 10^{11} \) | \( K_{xx}, K_{yy}, K_{zz} \) |
|-------------------|------------------------------------------------|----------------------------|
| 92110             | 1.4, 0.4                                         |                            |
| 92125             | 1.62, 0.67                                       |                            |
| 92140             | 1.9, 0.88                                        |                            |
| 92145             | 1.12, 0.15                                       |                            |

In this research, the simulation of the duration of the impregnation process depending on the number of layers of fabric (thickness) was carried out (figure 2). Theoretical studies were performed on two-dimensional and three-dimensional models, i.e. without taking into account the permeability coefficient in the z plane. To assess the adequacy of theoretical calculations, experimental studies were carried out, as a result of which the total duration of the impregnation process was also evaluated depending on the
structure of the fabric used and the thickness of the sample (figure 3). The comparison between the modelling and experimental results are presented in figure 4.

2.2. Results
As a result of the research it was found that with an increase in the number of layers (thickness of the laminate), the influence of the kinetics of the impregnation process in the z plane increases. It is shown
that for a thickness of 1 mm the error between the theoretical and the experiment is not very visible, for 5 mm thickness it increases significantly. Considering the permeability coefficient in the z-plane, the error is much less than without taking into account $K_{zz}$ in the comparison with the experiment.

3. Conclusion

The permeability coefficients in the directions $x$, $y$, $z$ of the fabric with different weaving pattern are determined. Then the analytical values are used to investigate the effects of permeability coefficient in the $z$ direction when simulating the impregnation process of the aircraft nose cone by vacuum infusion method. As a result of the research it was found that with increasing laminate thickness more than 3 mm, it is necessary to consider the influence of the coefficient of permeability in the $z$-plane. Simulation error without taking into account the through thickness permeability coefficient increases from 6% to 22%.

4. References

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