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FLOW BEHAVIOUR IN SATURATED AND UNSATURATED UNIDIRECTIONAL FIBER BEDS – A FLOW MODEL

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SUMMARY: The permeability of the preform material is a key value for an appropriate simulation of the Resin Transfer Moulding (RTM) process. However there are two different characteristics: The permeability for saturated and for unsaturated flow. In some cases it is much easier to obtain the permeability for saturated flow (e.g. permeability in thickness direction) but unfortunately for simulation purposes it is necessary to know the unsaturated permeability. Thus a relationship of saturated and unsaturated flow is needed. In this paper we present a study of flow experiments with unidirectional aligned glass fibers parallel and transverse to flow direction. In one experimental setup the saturated and unsaturated permeability was measured using constant injection pressure. For flow parallel to the fibers the unsaturated permeability was found to be larger than the saturated value whereas for flow transverse to the fibers we detected the opposite tendency. Since the available models were not able to predict the values of the measured permeability we suggest a new model to describe the flow behaviour in saturated aligned fibrous media. The model is based upon the inter-tow and intra-tow permeability and its change due to tow compression. This compression is caused by the liquid pressure in the inter tow space while the intra tow space is not or only partially impregnated. With the model we are able to understand the experimentally found tendencies of the ratio of saturated and insaturated permeability.

KEYWORDS: Liquid Composite Molding, Permeability, Porous Media, Flow Model, Saturated Flow, Unsaturated Flow

INTRODUCTION

Resin Transfer Molding (RTM) is an efficient process for manufacturing polymer composite structures. During RTM a liquid thermoset resin is injected into the mold cavity containing a pre-placed dry fabric preform. Due to relative low injection pressure applied in processing this technique is expected to offer potential for cost reduction in the fabrication of large parts of complex shape. However, in practice, much time is spent in optimizing processing parameters and in properly designing the mold in order to avoid problems such as void formation and dry spots. The common trial and error tactic while determining optimized parameters makes the process development expensive. Thus numerical modeling of the mold filling process is very important. Many simulators are available for this purpose. In these simulations it is assumed that the pore volume of the portion of the preform behind the flow front is fully saturated with resin. But a few years ago some researchers have indicated that this assumption may not be correct. During surveys of flows with constant injection volume rate [1], [2] in varying reinforcement structures like randomly oriented fiber and woven fabric different authors ascertained that the required injection pressure is only given correctly by Darcy's law when using randomly oriented fibers. In woven fabrics, non-crimp fabrics or similar structures the pressure distribution at the injection port will vary noticeably from the prediction made by Darcy. This variation of pressure distribution indicates a changing permeability during the impregnation process of the fibers. But the findings of several authors are partly contradictory. While Martin and Son as well as Williams et al. (in [3]) measured a permeability in unsaturated material which was 20 % higher than the one in saturated material, Pillai [4] and Parseval [1] assume the opposite case. In [3] Parnas et al. find both cases. This leads to the statement, that this effect seems to be dependent on the material and the direction of the flow.

The varying permeability in saturated and unsaturated material is ascribed to the fundamental differences in the microstructural scale of length of randomly oriented fiber mats and non-crimp/woven fabric structures. In randomly oriented fiber mats the individual fiber appears inordinately so the microstructure has only one scale of length whereas in the case of a non-crimp/woven fabric the fibers are merged in fiber tows, which are made up of about 1000 to 3000 fibers. The space between the fibers in the fiber tow represents the first scale of length. Now the fiber tows will now be merged into a preform by sewing, weaving, knitting or similar processes. Thus flow channels are formed which are much bigger than the space between the individual fibers in the fiber tow and which represent the second scale of length in the microstructure of the material. For this reason such structures are mostly named in literature as "dual scale media" [2] or "dual porosity media" [5].

The texture of the materials leads to an effective permeability which depends on the saturation level. Thus Parseval [1] divides the area behind the flow front into three sections. In the first section only resin in the flow channels is present, the second section is defined by the impregnation of the fiber tows. This section starts as soon as the resin penetrates the fiber tow and ends when the tow is fully impregnated. The third section contains the completely impregnated fabric. Using this model he defines a piecewise linear permeability in the different saturated regions.

However the variation of the permeability introduced in this model does not take into account the microstructure. Some authors [4], [6] model the flow channels and the fiber tows with two different permeabilities. The permeability of the fiber tows is considerably lower which leads to the fact that the tow at a predefined coordinate will be impregnated later than the flow channel. In the equation of continuity this flow performance is described by an additional sink, which quantifies the resin which flows from the flow channel into the fiber tow. Chan et al. [6] use circular cylinders as fiber tows which are impregnated in radial direction. That way cylindrical inclusions are formed. The pressure in such an inclusion can be calculated via the ideal gas equation. However by implementation of the model in a flow simulation Pillai [4] shows that this model is not consistent with experiments. This is led to an unrealistically low flow rate into the fiber tow due to the inclusions and the very high fiber volume fraction in the tows.

On the basis of rectangular fiber tows with adjoining flow channel Pillai [4] develops a parametrical model using a sink function. He investigated different variations of sink functions. He studied a constant sink, which describes the fiber tow as an infinite volume, and a constant on/off-type sink which can be switched off after complete impregnation. Additional parameters of his model are the ratio of the volume of the fiber tow and the flow channel. The permeability in the flow channel can be derived via the Hagen-Poiseuille equation, the permeability in the fiber tow is taken from an earlier study about the capillary effect in the fiber tow [7]. With this model the inlet pressure differing from the prediction of Darcy's law can be explained.

The models having been developed there predict for dual-scale media a lower unsaturated permeability in comparison to the saturated one. This contradicts to the results of other authors [3] as well as to our own results. It has been found, that the saturated permeability is lower than the unsaturated one when dealing with unidirectional fabrics an flow along the fibers. This is the reason for developing a model which makes it possible to mirror the tendency of the results of our own experiments. The model should determine the saturated and unsaturated permeability in unidirectional material for the flow in fiber direction (0°) as well as for the flow in transverse direction (through thickness direction and 90° direction).

THE FLOW MODEL

Description of the model

Starting point is a model of the UD-structure, consisting of fiber tows and flow channels. The required geometrical parameters are determined experimentally, the permeabilities used in the model will be determined analytically and experimentally. The model is shown schematically in Fig. 1.

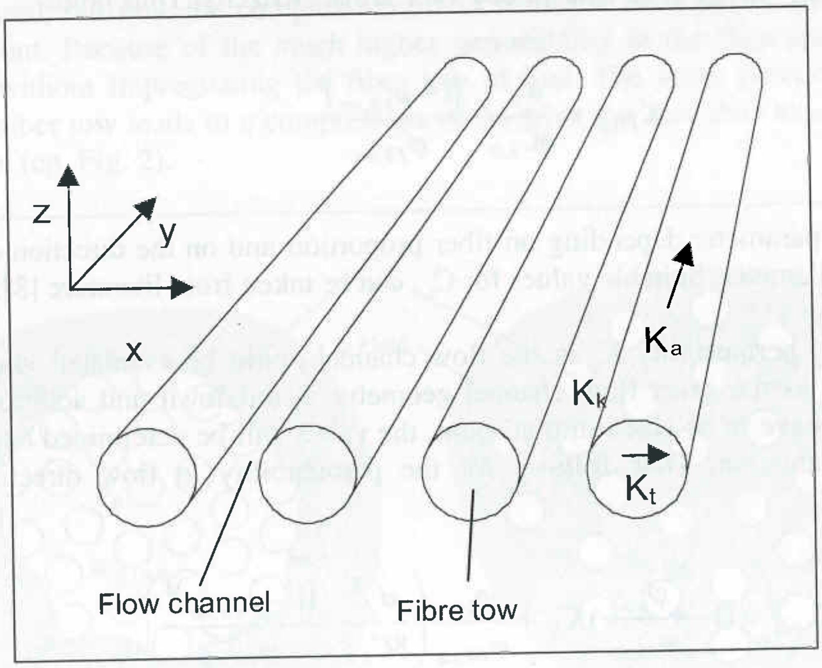

Figure 1 Dual-Scale-Model for the determination of the saturated and unsaturated permeability

Saturated permeability in axial direction (fiber direction)

When describing the flow in the stationary case with the use of Darcy's law a linear pressure distribution is found over the flow path in y direction. This applies to the fiber tows as well as to the flow channels. Thus at each coordinate y the pressure gradient in x direction is 0, in particular between the fiber tows and the flow channels. This means that there are no velocity components in y direction and that the flow in the flow channels and the flow in the fiber tows can approximately be seen as independent. The two flows of different velocities are only coupled due to the permeability difference results from the inner friction of the fluid. This effect will be neglected here. When observing independent flow in fiber tow and flow channel the saturated permeability $K_{sat,II}$ in axial direction case is given by a weighted parallel connection of both permeabilities. From this follows

$$K_{sat,II} = (1-\beta_{FB,sat})K_K + \beta_{FB,sat}K_{FB,II} \tag{1}$$

Here K_k is the permeability in the flow channel, $K_{FB,II}$ is the permeability in the fiber tow in axial direction and $\beta_{FB,sat}$ is the fraction of the fiber tow volume of the total volume of the cavity. $\beta_{FB,sat}$ can be calculated from the total fiber volume fraction φ_{ges} via

$$\beta_{FB,sat} = \frac{\varphi_{ges}}{\varphi_{FB,sat}} \tag{2}$$

where $\varphi_{FB,sat}$ is the fiber volume fraction in the fiber tow.

The permeability $K_{FB,II}$ can be determined via Carman-Kozeny. Thus holds

$$K_{FB,II} = \frac{d_f^{\,2}}{8C_{k,II}} \cdot \frac{(1-\varphi_{FB,sat})^3}{\varphi_{FB,sat}^2} \tag{3}$$

Here $C_{k,II}$ is a parameter depending on fiber proportion and on the direction of the flow, d is the fiber tow diameter. Suitable values for $C_{k,II}$ can be taken from literature [8].

The (isotropic) permeability K_k in the flow channel could be estimated via hydro-dynamic equations, but as the exact flow channel geometry is unknown und additionally correction factors would have to be taken into account, the value will be determined experimentally via parameter revaluation. Thus follows for the permeability in flow direction in saturated material

$$K_{sat,II} = (1-\frac{\varphi_{ges}}{\varphi_{FB,sat}})K_K + \frac{\varphi_{ges}}{\varphi_{FB,sat}}\left(\frac{d_f^{\,2}}{8C_{k,II}} \cdot \frac{(1-\varphi_{FB,sat})^3}{\varphi_{FB,sat}^2}\right) \tag{4}$$

The parameters in this model which are to be determined experimentally are consequently the permeability in the flow channel K_K, the fiber volume proportion of the fiber tow and the total fiber volume proportion.

Saturated permeability in transverse direction

In transverse direction the total permeability $K_{sat,\perp}$ can be calculated by the use of a series connection of the single permeabilities in transverse direction. Via the use of the volume fraction of the fiber tows and the fiber tows this results in

$$K_{sat,\perp} = \frac{\frac{\varphi_{ges}}{\varphi_{FB,sat}} K_{FB,\perp} \cdot (1 - \frac{\varphi_{ges}}{\varphi_{FB,sat}}) K_K}{\frac{\varphi_{ges}}{\varphi_{FB,sat}} K_{FB,\perp} + (1 - \frac{\varphi_{ges}}{\varphi_{FB,sat}}) K_K} \quad (5)$$

The permeability in transverse direction of the fiber tow results from Carman-Kozeny, but with the use of $C_{k,\perp}$ as Kozeny-constant.

$$K_{FB,\perp} = \frac{d_f^{\,2}}{8C_{k,\perp}} \cdot \frac{(1 - \varphi_{FB,sat})^3}{\varphi_{FB,sat}^2} \quad (6)$$

$C_{k,\perp}$ can be taken from literature [8], for K_k the same value as in axial direction is used, as it can be assumed that the permeability in the flow channel is isotropic.

Unsaturated permeability in axial direction

For the calculation of the unsaturated permeability the same relations as the one in the former paragraph are used, but now the compression effect from the fluid on the fiber tow will be taken into account. Because of the much higher permeability in the flow channel the fluid advances here without impregnating the fiber tow at first. The outer pressure by the flow channel on the fiber tow leads to a compression of the fiber tow and thus to an expansion of the flow channel (cp. Fig. 2).

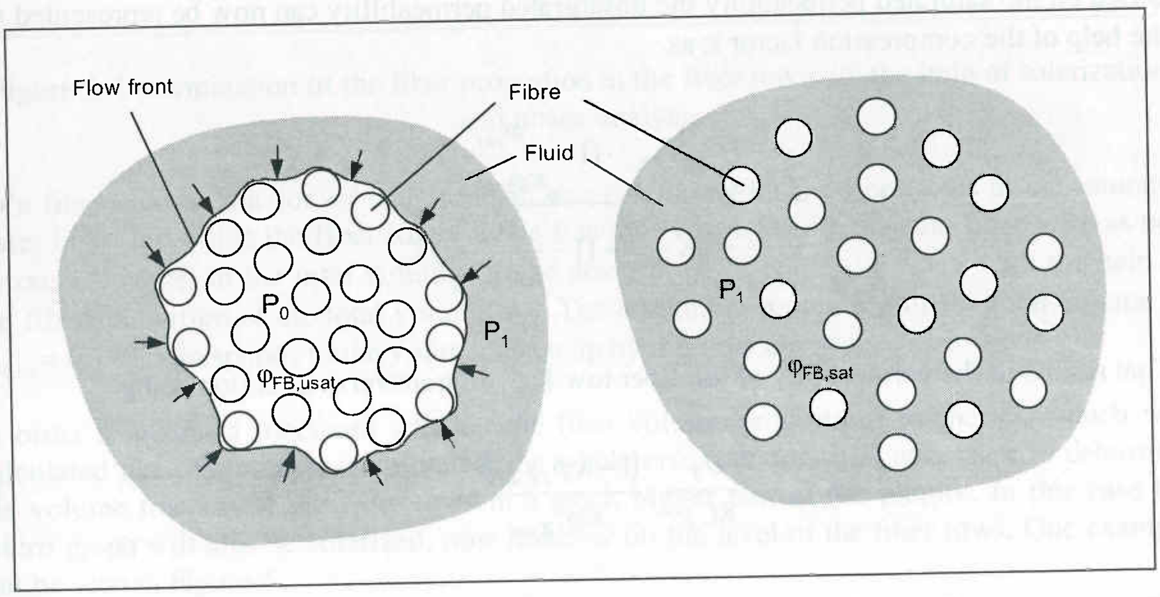

Figure 2 Compression of the fiber tow due to the pressure of the fluid

Thereby two contrary effects form: While on the one hand the permeability in the fiber tow subsides due to the increase of the fiber volume proportion to $\varphi_{FB,usat}$, on the other hand the flux in the flow channels increases due to the diameter increment of the latter. At every coordinate of the total impregnated length of the flow channel a pressure can be found which is higher than the one in the fiber tow. This is caused by the advance of the fluid in the flow channel. Thus the compression effect persists until the total flow length is fully impregnated. Under these boundary conditions the unsaturated permeability in axial direction is given by equation (7).

$$K_{usat,II} = (1 - \frac{\varphi_{ges}}{\varphi_{FB,usat}})K_K + \frac{\varphi_{ges}}{\varphi_{FB,usat}}\left(\frac{d_f^{\,2}}{8C_{k,II}} \cdot \frac{(1-\varphi_{FB,usat})^3}{\varphi_{FB,usat}^2}\right) \tag{7}$$

Now a compression factor κ is introduced, which is defined as the ratio of the fiber volume proportion in the unsaturated case and in the saturated case, thus

$$\kappa = \frac{\varphi_{FB,usat}}{\varphi_{FB,sat}} \tag{8}$$

Consequently the unsaturated permeability in axial direction finally is given by

$$K_{usat,II} = (1 - \frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}})K_K + \frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}}\left(\frac{d_f^{\,2}}{8C_{k,II}} \cdot \frac{(1-\kappa\varphi_{FB,sat})^3}{\kappa\varphi_{FB,sat}^2}\right) \tag{9}$$

The only free parameter in this equation is the compression factor κ.

Unsaturated permeability in transverse direction

Based on the saturated permeability the unsaturated permeability can now be represented with the help of the compression factor κ as

$$K_{usat,\perp} = \frac{\frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}} K_{FB,\perp} \cdot (1 - \frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}})K_K}{\frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}} K_{FB,\perp} + (1 - \frac{\varphi_{ges}}{\kappa\varphi_{FB,sat}})K_K} \tag{10}$$

That results in the permeability of the fiber tow $K_{FB,\perp}$ in transverse direction being

$$K_{FB,\perp} = \frac{d_f^{\,2}}{8C_{k,\perp}} \cdot \frac{(1-\kappa\varphi_{FB,sat})^3}{\kappa\varphi_{FB,sat}^2} \tag{11}$$

The parameter $C_{k,\perp}$ will be the same as in the case of saturated fibers as only minor oscillations of the fiber volume content are to be expected.

EXPERIMENTAL DETAILS

Determination of the geometrical model parameters

At first the fiber proportion in the fiber tow for fully impregnated fabric has to be determined. For this a test panel made of epoxy resin is manufactured. The preform used for the test is a UD glass fiber preform with 4 layers at a total thickness of 2 mm. With the use of the grammage of the preform the total fiber volume proportion is calculated to be φ_{ges} = 48,8 Vol.-%.

Visually the fiber distribution over the cross section of the panel is determined. This is done with the help of micro graphs, which are handled with image processing. In the first step the fiber proportion for the saturated fiber tows $\varphi_{FB,sat}$ inside the fiber tow is determined. For this a detail of a picture of a fiber tow gets solarized (conversion into a binary black and white picture) and the surface proportion of the fibers is determined. One example for this can be seen in Fig. 3.

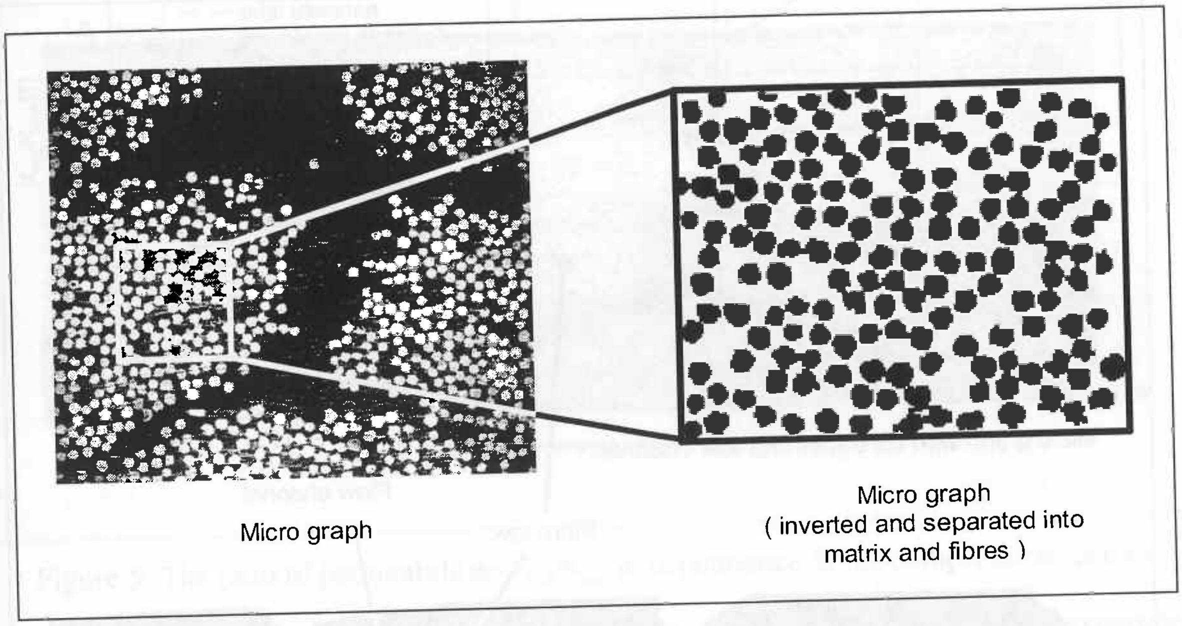

Figure 3 Determination of the fiber proportion in the fiber tow with the help of solarization and image analysis

So a fiber volume fraction of $\varphi_{FB,sat}$= 0,556 was calculated for the fiber tows in the saturated state. From this value the fiber tow volume fraction (when considering the fiber tows as non porous elements) of the total volume can be determined to be $\beta_{FB,sat}$ = 0,878 with the help of the fiber proportion of the total volume φ_{ges}. The remaining proportion of the total volume 1-$\beta_{FB,sat}$ = 0,122 corresponds to the volume taken up by the flow channels.

In order to obtain a statement whether the fiber volume proportion in the tow which was calculated like that is representative for the whole cross section, it is necessary to determine the volume fraction of the fiber tows in a much bigger part of the picture. In this case the micro graph will also be solarized, now however on the level of the fiber tows. One example can be seen in Figure 4.

The proportion of black image parts represents the proportion of fiber tows on the total cross section. That way a mean value for the volume proportion of the fiber tows of the total volume was determined to be $\beta_{FB,sat}$ = 0,876. Thus remains a fraction of $\beta_{K,sat}$ = 0,124 of the total value of the unit for the free flow channels. The values having been determined with the help of Fig. 4 agree fairly well with the volume ratios calculated from the fiber tow and from the grammage. Thus the fiber volume proportion of the fiber tow describes a representative mean value.

Calculation of the permeabilities

For the calculation of the saturated permeability the Kozeny-parameters $C_{k,II}$, $C_{k,\perp}$ and the permeability in the flow channels K_k are needed. $C_{k,II}$ und $C_{k,\perp}$ will be taken from a numerical study by Bruschke [8], where the Kozeny-constant is determined for different fiber volume fractions and different flow directions. Bruschke gives $C_{k,II}$ = 3 as the value for the Kozeny-constant for the flow in fiber direction for a quadratic packing with a fiber proportion of about 55 Vol.-%. For the flow in transversal direction with given porosity he gives the constant to be $C_{k,\perp}$ = 10.

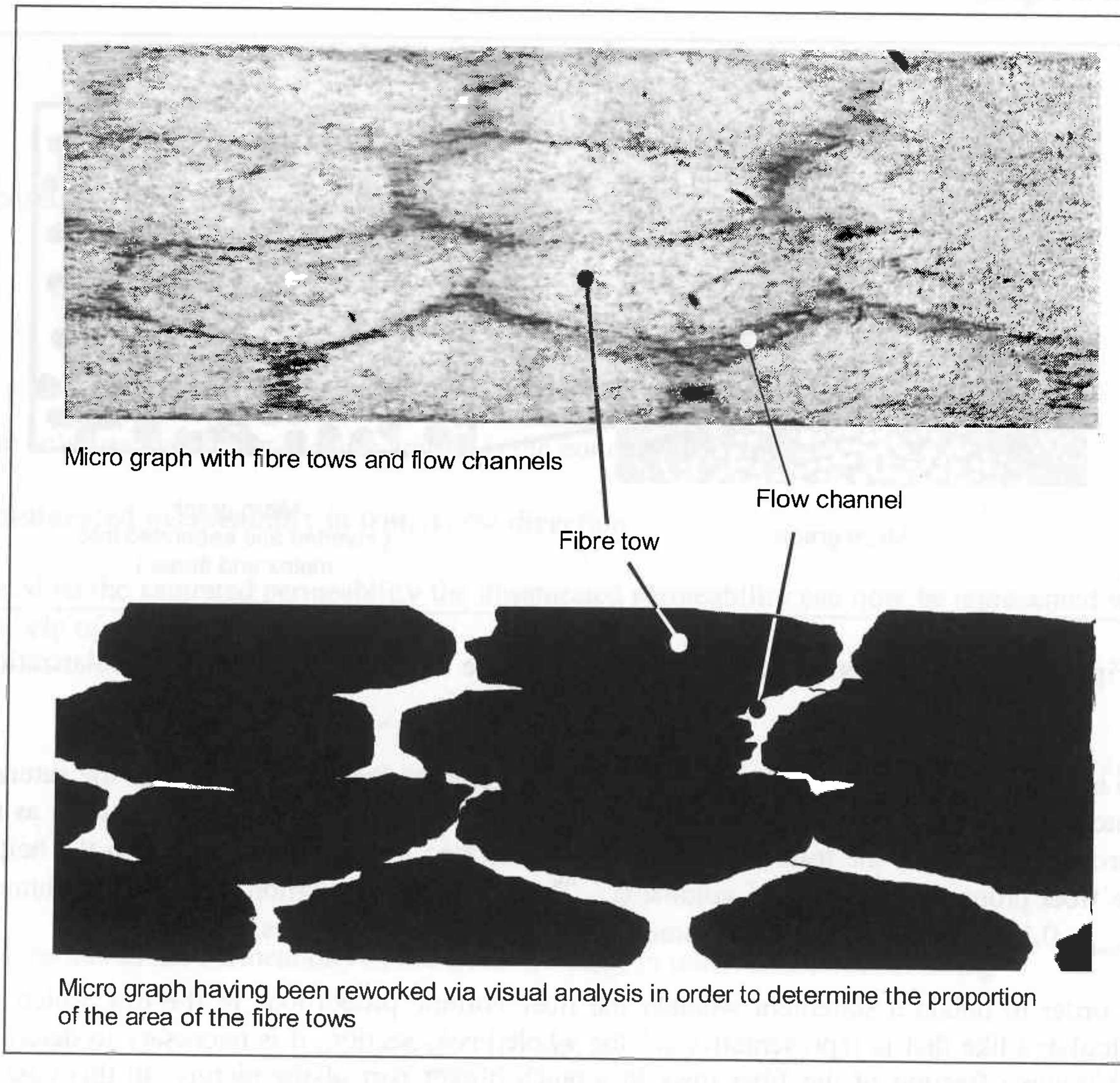

Figure 4 Determination of the surface proportion of the fiber tow of the total cross-section by solarisation and image analysis

For the determination of the permeability in the flow channel a stationary flow experiment is realized. A 4 layer UD glass fiber preform is used and as test fluid corn oil with a viscosity between 48 and 51 mPas comes into operation. Via the measurement of the volume flow the permeability is determined to be $K_{sat,II} = 5{,}1 \cdot 10^{-11}$ m². For the permeability a value of $K_K = 4{,}1 \cdot 10^{-10}$ m² is found using equation (4). If this value is inserted into equation (5) $K_{sat,\perp}$ is calculated to $K_{sat,\perp} = 2{,}0 \cdot 10^{-12}$ m². In Fig. 5 the ratio of the saturated permeability and the unsaturated permeability $\frac{K_{sat}}{K_{usat}}$ is pictured in dependence of the compression factor κ. These results are valid for a fixed total fiber fraction and a fixed $\beta_{FB,sat}$. For the 0°/90° preform the total permeability was determined simplified as arithmetic mean of the single permeabilities $K_{sat,II}$ and $K_{sat,\perp}$ resp. $K_{usat,II}$ and $K_{usat,\perp}$.

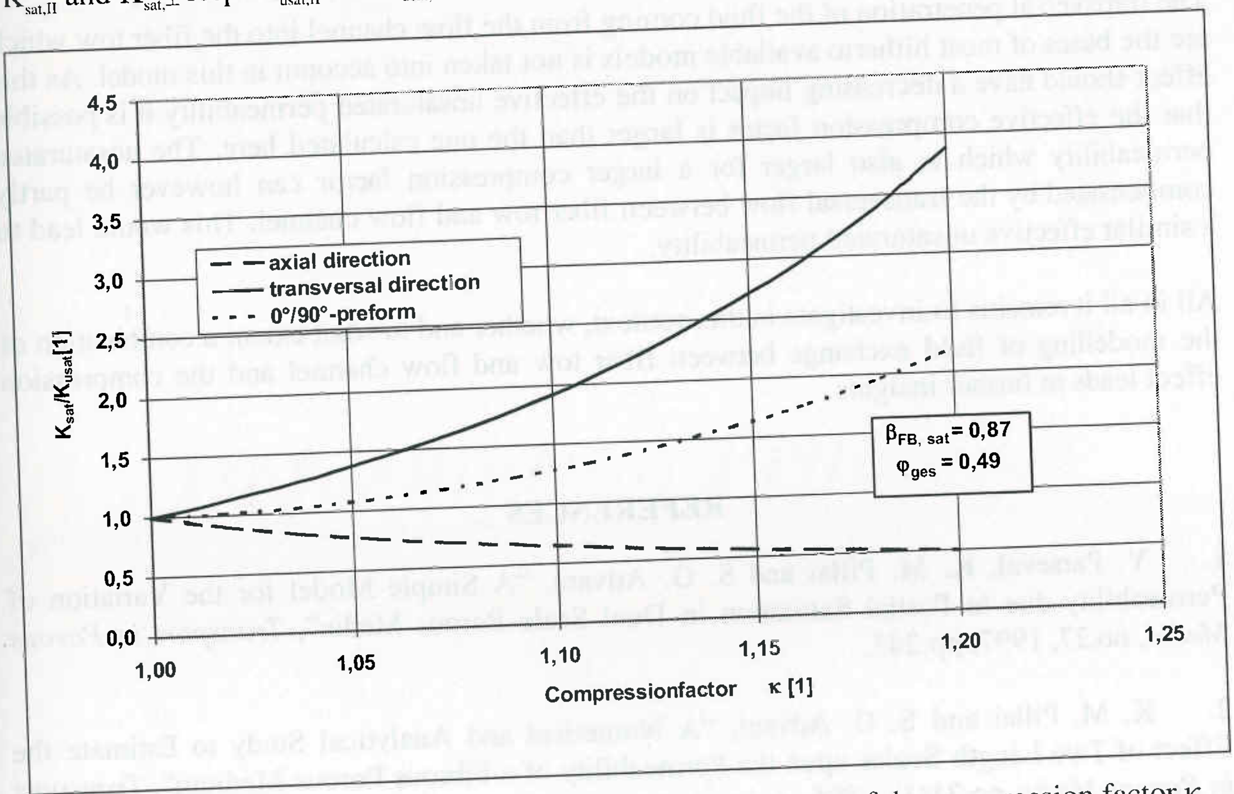

Figure 5 The ratio of permeabilities K_{sat}/K_{usat} in dependence of the compression factor κ

Now a series of flow experiments is performed where at each case in the UD flow experiment the saturated and the unsaturated permeabilities are measured. Here 0°, 90° and 0°/90° preforms are used. For each experiment the ratio of saturated and unsaturated permeabilities is determined. These experiments and the evaluation of Figure 5 result in a value for the compression factor κ = 1,04. This factor was adjusted to the results of the 90° flow experiments as on the one hand these experiments showed the lowest scatter and on the other hand because the model being described here features the smallest degree of simplification for the transverse direction. In Table 1 the results of the flow experiments and of the model prediction are opposed.

CONCLUSIONS

The suggested model is able to deliver the trend of the permeability ratio K_{sat}/K_{usat} correctly. In comparison to hitherto available models a reversed trend of the permeability ratio is predicted for the case of a UD material in flow direction, this could be validated experimentally. A critical force in the model is the compression factor κ which depends on the total fiber fraction as well as on the injection pressure. On this further investigations will be necessary.

Table 1 Comparison experiment/model for the ratio K_{sat}/K_{usat}

Orientation of fibers	K_{sat}/K_{usat} (experimentally)	K_{sat}/K_{usat} (model, κ=1,04)
0°	0,69	0,83
0°/90°	0,90	1,04
90°	1,25	1,26

The transversal penetration of the fluid coming from the flow channel into the fiber tow which are the bases of most hitherto available models is not taken into account in this model. As this effect should have a decreasing impact on the effective unsaturated permeability it is possible that the effective compression factor is larger than the one calculated here. The unsaturated permeability which is also larger for a larger compression factor can however be partly compensated by the transversal flow between fiber tow and flow channel. This would lead to a similar effective unsaturated permeability.

All in all it remains to investigate in this context, whether and to what extent a combination of the modelling of fluid exchange between fiber tow and flow channel and the compression effect leads to further insights.

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