Mathematical model of cavitation during resin film infusion process

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Abstract

The objective of this paper is to develop a mathematical model of pore formation during the resin film infusion (RFI) process. An analytical model is developed to describe the cavitation conditions in the resin during the RFI process. This approach leads to an understanding of the influence of different process parameters on bubble formation. Utilising a non-linear equation of filtration allows us to define the pressure distribution inside viscous liquid resin as a function of the external flux. The numerical simulation utilises a Flow Analysis Network technique to predict and track the movement of the free surface and a finite element method (FEM) to solve the set of governing equations for each successive flow front location. The fibres that form the woven fabric are assumed to behave as linearly elastic bodies with known moduli and the resin is a non-Newtonian viscous fluid. Based on the results obtained from this model, it is possible to carry out some practical recommendations related to the process parameters as well as to the design of specific moulds. Moreover, the optimum temperature profile is obtained based on the consideration of applied pressure and cavitation pressure. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The resin film infusion (RFI) method of producing composite structures has been developed to overcome the problems encountered in resin transfer moulding. These problems include low fibre content, necessity of using expensive matched moulds, long distances for resin to flow to completely wet out the fibrous preform, and void formation. In addition, the operator is not exposed to uncured liquid resin systems during the RFI process and no volatile components are emitted into the workplace atmosphere. It should be noted that these are also major problems for hand lay-up methods, especially when using unsaturated polyester or vinyl-ester resins, which emit styrene vapour into the work environment.

The resin film infusion process utilises a vacuum bag to debulc or compact parts of the reinforcement material laid in the mould. The preform is first placed in an open mould that includes engraved microchannels, perpendicularly connected to a wider main channel serving as a resin gate. Alternatively, a layer of highly porous material placed on top of the preform can replace the network of microchannels. A flexible plastic film is placed on top of the preform to close the mould. Air is drawn from the preform using a vacuum pump; this process compresses the preform and draws the resin through it. High quality composite parts can be manufactured from a wide range of fibre and resin combinations using resin infusion technology.

The RFI process was originally developed for autoclave processing using a vacuum bag/tooling combination for shaping parts. RFI is easily adaptable to unidirectional or woven fabric preforms to produce either monolithic or sandwich type structures with flat or curved shapes and various types of matrices. This process has the potential advantage of reducing the cost of manufacturing of 3D structural composites by eliminating the expensive moulds needed in the resin transfer moulding. In addition, the resin film infusion process reduces the void content of 3D structural composites. Thus, the RFI method is suitable from the viewpoint of the above considerations on which the choice of the specific manufacturing technique is based.

Recently, RFI became one of the most promising methods particularly for the shipbuilding and defence industries. The method was firstly patented by L. Letterman (Boeing Materials Technology, USA). Now it is under development particularly in the United States.
(University of Washington, Seattle; Virginia Polytechnic Institute, Blacksburg) and Great Britain (University of Plymouth). Similar methods were used in Group Lotus Car Ltd. to manufacture structural components such as car side-impact panels for Lotus sport cars. However, the main applications of the resin film infusion process are still in shipbuilding and aerospace. This method, for example, allows one to inflate large boat hulls (13–18 m) in 1 h and takes two men 10 days to prepare the lay-up. The US Navy is using a variant of RFI (VARTM – vacuum assisted resin transfer moulding) to manufacture half-scale mid-ship sections of Corvette class military vessels, and Shepherd Manufacturing Group has also developed a textured thermoplastic polyester high temperature vacuum bagging film, which has an embossed pattern in order to avoid the use of a resin distribution membrane and other ancillaries such as bleeder and breather plies in the RFI process.

The RFI process compresses the preform and draws the resin through it producing high quality composite parts from a wide range of fibre and resin combinations. However, flaws that may originate from the process can severely degrade the material properties of structures obtained by RFI. One major source of imperfections arises if voids are formed in the resin during manufacturing. The voids may occur at different stages of the process and a thorough understanding of the mechanisms of void formation requires several aspects of the process to be taken into account. There have been a number of studies in recent years explaining the void formation in composites and offering ways of reducing the void content [1–6]. It is generally accepted that one of the most common features of voids is that they are formed at the resin flow front [4–6].

The objective of the research presented in this paper is to develop a mathematical model of pore formation during the RFI process. An analytical model is developed to describe cavitation conditions in the resin. This approach leads to an understanding of the influence of temperature on bubble formation. The use of a non-linear equation of filtration allows for definition of the pressure distribution inside viscous liquid resin. The fibres, which form the woven fabric, are assumed to behave as linearly elastic bodies and the resin as a non-Newtonian viscous fluid. Based on the results obtained from this model the optimum temperature profile for this process is obtained.

2. Fracture of liquids

When the tension in a liquid becomes rather high, it becomes possible for a bubble to nucleate homogeneously. This process is called cavitation, or fracture of a liquid. Fisher [7] showed that the rate of nucleation of bubbles \( I_V \) is given by the following equation:

\[
I_V = \frac{N_A k T}{V_M h} \exp \left[ - \left( \frac{Q + \frac{16\pi \rho V}{3(P - p_V)}}{kT} \right) / kT \right] \tag{1}
\]

where \( N_A \) is Avagadro’s number, \( k \) the Boltzmann’s constant, \( h \) the Planck’s constant, \( V_M \) the molar volume of liquid, \( Q \) the activation energy for molecular transport across the liquid/vapour interface, \( T \) the absolute temperature, \( \gamma_{LV} \) the liquid/vapour interface energy and \( p_V \) is the pressure of vapour in the bubble; \( P \) is the stress in the liquid (which is equal in magnitude to the external pressure, but opposite in sign; thus \( P \) is positive, when the liquid is in tension). The nucleation rate \( I_V \) has significant dependency on \( P \), as illustrated in Fig. 1 the pressure changes by only about 10% as \( I_V \) varies by six orders of magnitude, so the fracture pressure is quite well defined; moreover it is weakly dependent on \( Q \). Cavitation occurs at such a high tension, that \( P \gg p_V \), and so the vapour pressure can be neglected. Therefore setting \( Q = 0 \) and, \( p_V = 0 \) and choosing a detectable nucleation rate of \( I_V = 1 \times 10^{6} \text{ m}^{-3} \text{ s}^{-1} \), the fracture stress is accurately approximated as

\[
P^* \approx \frac{16\pi \rho V}{3 k T \ln(10^6 N_A k T / V_M h)} \tag{2}
\]

Since the logarithmic term varies little for different liquids, Eq. (2) can be further approximated by

\[
P^* (\text{GPa}) \approx 19.8 \gamma_{LV}^{3/2} / T^{1/2}, \tag{3}
\]

where \( \gamma_{LV} \) is in Nm and \( T \) is in K. The corresponding critical nucleus size for bubbles is

\[
r^* = \frac{2\gamma_{LV}}{P^*} \approx \frac{3 k T \ln(10^6 N_A k T / V_M h)}{4\pi \rho V} \tag{4}
\]

or

\[
r^*(\text{nm}) = 0.16 \sqrt{T / \gamma_{LV}}. \tag{5}
\]

Bubbles with radii larger than \( r^* \) grow, while smaller bubbles shrink.

![Fig. 1. Homogeneous nucleation rate at T = 400 K calculated from Eq. (1) for epoxy resin.](image)
The typical temperature conditions which are used in the RFI process and corresponding dependencies for \( P^* \) and \( r^* \) are shown in Fig. 2. It is quite clear that cavitation is more likely to occur when resin infusion is performed at higher temperatures. Certainly, these calculations refer to homogeneous nucleation only, whereas nucleation typically occurs at a much lower tension by a heterogeneous mechanism. This mechanism is a subject of further research.

### 3. Pressure in the injected resin

Let us consider resin film injection through the pores of rigid network with a uniform pore size \( r_p \) as shown in Fig. 3. In Fig. 3(a) no resin flux is occurring. The liquid resin penetration into the woven material is initiated by reducing the tension \( P \) which develops in the liquid according to the Gibbs–Thompson equation:

\[
P = -(RT/V_m) \ln (p_V/p_0),
\]

where \( R \) is the ideal gas constant, \( p_V \) the partial pressure of the vapour and \( p_0 \) is its equilibrium value. If the contact angle \( \theta \) between the resin and network is less than 90°, fingering menisci start to form in the mouths of the pores at the resin front as soon as the liquid resin begins to propagate as in Fig. 3(b). The radius of the meniscus is related to the tension in the resin by Laplace’s equation:

\[
P = -2\gamma_{LV}/r_m,
\]

where \( r_m \) is the radius of curvature of the meniscus. The flow of resin through the woven material \( j_r \) obeys Darcy’s law, viz.,

\[
j_r = \frac{D}{\eta} \nabla P,
\]

where \( D \) is the permeability of the woven material \( \eta \) the viscosity of the resin and \( \nabla P \) indicates the pressure gradient. Mathematically the problem of the resin flux through the woven material is a variation of the well-known Stephan’s problem. Thus, an additional equation to describe the resin film penetration into the woven material is required to solve this moving boundary problem. Denoting the co-ordinate of the interface as \( h(t) \), the following equation can be used [8]

\[
\nabla P = -\frac{\eta (1 + C_S(0)PC/K_W - C_s(0))}{D} \frac{dh(t)}{dt},
\]

when \( x_3 = h(t) \),

where \( K_W \) is bulk modulus of the woven material, \( C_S(0) \) the initial concentration of the solid phase and \( PC \) is a critical value of pressure at the resin front.

Using Eqs. (8) and (9), the following equation for the pressure field in the resin can be derived

\[
\frac{\partial P(x_3, t)}{\partial t} - \frac{K_W}{\eta K_W} \nabla \cdot (D\nabla P(x_3, t)) + \frac{D}{\eta} (\nabla P)^2 = 0.
\]

In obtaining Eq. (10) the permeability \( D \) of the woven material changing with the solid concentration was taken into account and it was also assumed that the bulk modulus of the liquid is essentially less than that of the solid. The solution of (10) has to satisfy the following boundary condition:

\[
\frac{D}{\eta} \nabla P(0, t) = j_{ext},
\]

where \( j_{ext} \) denotes the external flux. The corresponding illustration is given in Fig. 4.
4. Method of solution

A basic outline of the numerical procedure is shown in Fig. 5. Starting with the resin film located at the top of the woven material a boundary condition is specified. These may be given in terms of constant pressure at a point (Dirichlet), inlet velocity through the side of an element (Neumann) or a flow rate at a point. The Dirichlet boundary condition was used in the most recent study. A flow analysis network [9] technique is then used to calculate the free surface location at a new time step. After each time step the free-surface boundary conditions are reset, and the governing equations are solved for new pressure values using the finite element method. Once the new pressure solution is known, the process is repeated: The FAN technique is used to advance the resin flow front, new free-surface boundary conditions are set and the FEM is used to find the pressure distribution. This iterative process is repeated until the woven material is completely saturated. The technicalities involved in calculating the flow front advancement using the FAN technique, and obtaining the pressure distribution using FEM are discussed in detail below.

4.1. The FAN algorithm

The FAN technique is a method for tracking flow front location in fluid dynamics problems involving flow with a free surface. In contrast to algorithms that rigorously track flow front location using re-meshing schemes, the FAN technique allows for approximate tracking of the flow front using a fixed mesh. The first step in implementing the FAN technique is the formation of a macroscopic flow network. The network is composed of individual flow cells that are formed from the finite element and/or finite difference mesh. Collectively, the flow cells have properties of not overlapping, and completely fill the flow domain [10]. The flow front is advanced in the technique by calculating the macroscopic fluxes passing from full to empty flow cells. The principal advantages of this approach are computational efficiency and stability, calculations are only performed on portions of the mesh in which certain “flow cells” are full. Little computational time is spent advancing the flow front as special rules are not required to handle the many different types of flow conditions that can occur, complicated situations such as coalescing flow fronts and flow around objects, which can be unstable using re-meshing schemes, are easily handled with FAN.

There are three basic components of the FAN algorithm: flow cell formation, flux calculation, resin flow front penetration.

4.1.1. Flow cell formation

When used in conjunction with FEM, there are two parts to forming flow cells: first, local flow cells are formed within each individual finite element. The number of local flow cells is equal to the number of nodes in the element. Global flow cells are then formed from the local cells in a manner analogous to standard FEM assembly procedures [11]. Thus, there is one global flow cell associated with each node of the FEM mesh. The global cells collectively form the flow network and are used to advance the flow front.

The formation of flow cells is illustrated for the case of triangular elements (that are used in the present analysis) in Figs. 6 and 7. In Fig. 6, points 1, 2, and 3 are the nodes of the FEM mesh associated with the element, points $a$, $b$, and $c$ are the mid-points of the sides, and the point $o$ is the element centroid. The regions 1ao, 2boa, and 3cob define local flow cells. The formation of global flow cells from the local cells for a mesh of triangular elements is illustrated in Fig. 7. Each of the shaded

![Fig. 6. Intra-element notation used in the FAN technique for linear triangular elements. Points $a$, $b$, and $c$ are the mid-points of the sides, and $o$ is the element centroid.](image-url)
regions surrounding a node indicates a global flow cell. Note that they are not all necessarily of the same shape.

4.1.2. Flux calculation

In a manner, analogous to flow cell formation, there are two parts of the flux calculation. First, local fluxes are calculated for each of the local flow cells in the element. Then, global fluxes are calculated by assembling the individual local flux contributions. The first step in defining the local fluxes for triangular elements is to compute the following integrals:

\[ I_1 = h \int_{oa} n \cdot j_{ext} \, dS_{oa} = \int_{oa} n \cdot F \, dS_{oa}, \]
\[ I_2 = h \int_{ob} n \cdot j_{ext} \, dS_{ob} = \int_{ob} n \cdot F \, dS_{ob}, \]
\[ I_3 = h \int_{oc} n \cdot j_{ext} \, dS_{oc} = \int_{oc} n \cdot F \, dS_{oc}, \]

where \( n \) is the unit outward normal vector to corresponding line. The local fluxes associated with each flow cell of the element are calculated then from \( I_j \) according to formulae:

\[ j_1 = \delta_1 I_1 - \delta_3 I_3, \]
\[ j_2 = \delta_2 I_2 - \delta_1 I_1, \]
\[ j_3 = \delta_3 I_3 - \delta_2 I_2, \]

where \( \delta_i \) are equal to zero if the global flow cell associated with local flow cell \( j \) is empty and one if it is filled. Once the local flow cell flux calculations are complete, the global cell fluxes are calculated by assembling the individual element contributions. Note, that when a global flow cell is filled, the sum of its local fluxes is zero by reason of the equation of mass conservation being solved. Also Eq. (13) for the local fluxes do not involve integrals along the line segments from the nodes to the mid-side points because in assembling the global fluxes such contributions cancel out at interior nodes and are zero along boundaries.

Assembling contributions from individual elements drives both, the formation of global flow cells and the formation of global cell fluxes. This procedure automatically enables elements of different dimensions to be used in the same simulation because all computations of local flow cell size and flux contributions are done in terms of volume.

4.1.3. Resin flow front penetration

Once the global flux contributions are calculated, there are three steps involved in penetration of the resin flow front. First, the smallest time step needed to fill just one flow cell is calculated. This is given by the formula:

\[ (\Delta t)^{\text{min}} = \min \left( \frac{V_{jC} - V_j^f(t)}{J_j(t)} \right), \]

where \( V_j^C \) is the volume of \( j \)th cell, \( V_j^f(t) \) the total volume of fluid that has entered flow cell \( j \) at time \( t \), and \( J_j(t) \) is the flux into the flow cell at time \( t \). Once the minimum time step is known, the volume of fluid that flows into each of the cells in that interval can be calculated. Nodal fill fractions are then calculated to keep track of whether or not a flow cell is empty, partially filled or completely filled. The nodal fill fractions \( \Delta_j \) are given by the formula:

\[ \Delta_j(t + \Delta t) = \frac{V_j^f(t) - (\Delta t)^{\text{min}} J_j(t)}{V_j^C}. \]

This process is repeated at every time step until the woven material is completely saturated. After each time step the free boundary conditions are reset and the governing equations are solved for new pressure values. A node is defined as a boundary node if at least one flow cell element is a member of, is completely filled. Boundary conditions are set in terms of pressure. An example is shown in Fig. 8.

![Fig. 8. Illustration of the procedure for setting free-surface boundary conditions. The global flow cell for node i is filled. Thus, free-surface boundary conditions are set at nodes j and l of element ijl and nodes k and l of element ilk.](image-url)
The final technical issue in the resin front penetration can be termed flow cell averaging. As the front is being advanced, two times are tracked: the time at which a flow cell begins to fill and the time at which it becomes completely filled. The nodal fill time for a cell is calculated as the average of these two times. Thus, although the flow front location, as defined by the flow cell boundaries, is quite jagged (and in a sense is undefined for cells that are only fractionally filled), by the use of averaging, smooth flow front patterns through elements can be defined once all the global flow cells associated with it are filled.

5. Numerical results and discussion

The viscosity of the resin depends significantly on the temperature of the process. The dependence proposed by Dusi et al. [12] was used in the most recent study, viz.

\[ \eta(T) = \eta_0 \exp \left( \frac{\mu}{T} + \kappa \xi \right) \]

where \( \mu, \xi \) and \( \kappa \) are constants, which have to be obtained from experiment; \( \xi \) denotes the degree of cure and \( T \) is the temperature at which the process takes place. As an example, the data obtained by Kang et al. [13] were used, i.e. \( \xi = 0.2, k = 26.89, \mu = 1034.5 \).

For simplicity, external pressure was not considered in this analysis. However, it can be taken into account by means of superposition. The following mechanical parameters were used in the study for resin and solid woven material: viscosity \( \eta_0 = 5.5 \times 10^{-5} \text{ Pa s} \); critical pressure \( P_c = 280 \text{ MPa} \); compressibility modulus of resin \( K_L = 130 \text{ MPa} \); initial volume fraction of fibres \( C_s(0) = 0.5 \); permeability of the woven material \( D = 1.42 \times 10^{-12} \text{ m}^2 \); bulk modulus of the woven material \( K_W = 4.2 \text{ GPa} \); Poisson’s ratio of the woven material \( \nu = 0.25 \).

The pressure distribution along the plate thickness is presented in Fig. 9 at different times for various temperatures. \( t_f \) is the time at which the preform is completely saturated. In the present study isothermal process conditions were assumed for simplicity. The temperature decrease during the RFI process has two effects. On the one hand, it reduces the pressure in the resin since the resin viscosity becomes lower. On the other hand it also reduces the cavitation pressure \( P^c \). Therefore a minimax problem has to be solved to determine the optimal temperature profile of the process with the pressure \( P \) being minimised and the cavitation pressure \( P^c \) being maximised. For simplicity, the resin cure is not considered in this study. Thus only two parameters are significant: the pressure field and the thickness of the saturated zone of woven material. The basic criterion to compute the optimum temperature profile can be formulated as the maximisation of the relation \( P^c/P \). The corresponding plot is presented in Fig. 10. The value used for liquid/vapour interface energy is \( \gamma_{LV} = 3 \times 10^{-2} \text{ Nm} \). The dotted line corresponds to the recommended regime, which also has to be convenient for the manufacturer.

6. Conclusions

An analytical model was developed for the resin film infusion process, which is used for autoclave processing of composite structures with a high fibre volume content. The model was used to simulate the RFI process and to study the void formation during the process. These defects reduce the strength of the fibre composite component manufactured by this process and can even lead to the premature failure of the component. Micro-damage formation is governed by the pressure distribution in the resin infused into the fibrous preform. Pressures are related to the rate of infusion, preform permeability and resin viscosity and are governed by Darcy’s law.
In the present study it was assumed that the compressibility coefficient of fibres is essentially higher than that of the resin. However, fibrous preform, which may be considered as a porous medium, is assumed to be sufficiently compressible. Due to the moving front of the resin, the problem can be stated as a moving boundary problem, which becomes a particular case of the well-known Stephan’s problem. This problem was solved by the finite element method using flow analysis network. An analytical model for the cavitation pressure is developed. It is shown that temperature variation leads to change in the capillary pressure as well as in the cavitation pressure. The resulting minimax problem was solved in order to obtain the optimal temperature profile for the process.

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References


