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NUMERICAL SIMULATION OF MOULD FILLING PROCESS IN RESIN TRANSFER MOULDING

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ABSTRACT

This paper presents a simulation procedure for mould filling processes in which a field analysis module of a general-purpose finite element package is employed. The formulations used in this procedure are based on the finite element/ nodal control volume approach. The numerical concepts employed for modelling the effects of convective heat transfer on temperature and resin cure are discussed. Numerical implementation of the procedure is presented. The procedure was applied to simulate different mould filling examples under isothermal and non-isothermal conditions. The results show that the developed simulation procedure is numerically valid, stable and provides reasonably accurate predictions.

Key Words: Polymer-matrix composites (A), Curing (B), Computational simulation (C), Finite Element Analysis (C), Nodal control volume

1. INTRODUCTION

Advanced polymer composites consists of fibres such as glass, aramid, boron, carbon or graphite as reinforcement and thermosetting resins as binder. The manufacturing of such composites by resin transfer moulding (RTM) includes two important processes: first, resin impregnation of the porous fibrous media, which is performed to a required shape and placed into the mould, and second, curing of the resin-saturated fibrous media. Both these processes require specified temperature and pressure conditions.

To predict the final quality of a composites product manufactured under such conditions, it is necessary to understand the heat and mass transfer during its fabrication. Experimental studies are often expensive and time-consuming. Alternatively, computer simulation provides a cost-effective tool. Amongst the available numerical methods, the finite element (FE) method is widely employed for simulation as complicated shapes and boundary conditions can be modelled relatively easily.

The commercially available general-purpose finite element (GPFE) packages such as LUSAS, NASTRAN, ABAQUS etc., do not contain a process simulation module and hence cannot be directly used for process modelling. This possibly led many researchers to develop own computer codes to meet their requirements. For example, LIMS^{1,2}, LIMS3D³, ISOFIL⁴ and RTMSIM⁵ and FAN technique⁶ were developed for modelling the mould filling process and a RTM/RFI analysis program^{7,8} was written to simulate RTM and resin film infusion process. However, if a GPFE package can be employed for process simulation, it would avoid costly and time-consuming

development and maintenance of such special-purpose computer programs. In addition, GPFE packages offer many advantages. They contain large FE library making it easy to choose a suitable element type. Their well developed pre- and post-processors provide a ready graphics aid for simulation. The various modules from GPFE packages have many features common. It is therefore easy for the users to work with different modules once the basic structure of the package is known. With all these, process simulation could become more user-friendly, versatile, flexible and cost-effective.

Numerical simulation of a mould filling stage involves modelling of resin flow, heat transfer between the tool and component, and resin cure reaction. The pressure, energy, and species equations have to be solved with appropriate boundary conditions. Most of the commercially available FE packages have a facility to perform field analysis. This particular module, in its basic form, can be employed to conduct pressure and transient conductive heat transfer analyses. However, such packages do not have provisions for solving the resin cure kinetics and the species equation, and, not all packages can deal with convective heat transfer resulting from the flow of reactive resin mass.

This paper presents a procedure by which a GPFE package can be successfully employed to simulate the mould filling process. The detailed development and validation of the procedure are discussed in the paper. Its application is demonstrated by simulating a few mould-filling examples under isothermal and non-isothermal conditions.

2. BACKGROUND

2.1 Darcy's law and pressure equation

The pressure-velocity relationship for flow through fibrous media can be expressed by Darcy's law^{1,3,9,10}. The generalized form of Darcy's law^{1,3} is:

$$\vec{u} = -\frac{\bar{K}}{\eta} \nabla P \quad (1)$$

For incompressible flow, eqn (1) may be substituted into the continuity equation to produce the pressure equation:

$$\nabla \left(\frac{\bar{K}}{\eta} \nabla P \right) = 0 \quad (2)$$

Solution of eqn (2) gives the pressure in the filled portion of the porous media for given boundary conditions. The possible boundary conditions are

- (a) at the injection gate: $P = P_0$ for constant pressure injection and, $\vec{u} = \vec{u}_0$ for constant velocity injection;
- (b) at the flow front: $P = 0$ without vacuum assistance and, $P = -P_{atmospheric}$ if vacuum is applied to assist the filling; and,
- (c) at the mould boundary $K_n \frac{\partial P}{\partial n} + K_t \frac{\partial P}{\partial t} = 0$.

2.2 Energy equation

Experimental studies on flow through fibre mats indicated that the fluid and the fibre medium have the same temperature at each point in slow mould filling processes, such as in RTM¹. It may be, therefore, assumed that the resin and the fibres form a macroscopically homogeneous material system for heat transfer purposes. For the same reason, the thermal dispersion effects are also considered insignificant^{2,9}. The properties

of the saturated preform may be then calculated using the rules of mixture⁹. With the above assumptions, the energy equation governing heat transfer in fibrous media being impregnated with incompressible resin takes the form:^{9,10}

$$\rho_c C_{pc} \frac{\partial T}{\partial t} + \rho_r C_{pr} \left(\frac{\vec{u}}{\varepsilon} \cdot \nabla T \right) = \nabla \cdot (\bar{k}_c \nabla T) + \frac{\partial H}{\partial t} \quad (3)$$

The constant temperature of resin at the injection gate can be described as an initial condition, $T = T_0$. Similarly, appropriate boundary conditions should be used to define temperature at the mould walls.

2.3 Chemical species equation

For a reactive resin, the conservation of the chemical species mass can be expressed as

$$\frac{\partial \alpha}{\partial t} + \frac{\vec{u}}{\varepsilon} \cdot \nabla \alpha = \dot{R}_\alpha \quad (4)$$

As an initial condition, α may be defined as α_0 at the injection gate.

2.4 Conventional flow simulation procedure

The mould filling in RTM is a transient process. However, in conventional finite element/ nodal control volume (FE/ NCV) simulation procedure², the process is treated as a quasi-steady flow process in which the transient solution is treated as a sequence of steady state solutions over small time steps. Various steps involved in FE/NCV approach are briefly discussed below. The details may be found elsewhere^{2,3,7}.

As the name indicates, in FE/ NCV approach, a domain of interest (i.e. a mould cavity filled with preform for pressure analysis and a mould with heating system for heat

transfer analysis) is divided into a number of elements and nodal control volumes are then built around the nodal points. With appropriate boundary conditions, eqn (2) is solved to obtain pressures at these nodal points. The difference between pressures at any two connecting control volumes gives the pressure drop, which is then used to calculate velocity of the flow between those two control volumes using eqn (1). Having known the velocity and area of the surface through which the flow is taking place, the flow rate is calculated. The resin flow is allowed for a certain time such that at least one control volume at the flow front fills completely. Subsequently, the volume of resin in each control volume is calculated. The ratio of volumetric resin content of a control volume to its geometric volume gives f . For an empty control volume, $f = 0.0$, and $f = 1.0$, when the control volume is fully filled with resin. The f of the partially filled control volumes are interpolated to estimate the flow front position. Once f of a control volume becomes one, the pressure boundary condition at the representative node is released. The flow front boundary condition (zero pressure) is then imposed for the neighbouring control volumes that are empty.

All the above steps together form one cycle for isothermal flow simulation. If the flow is taking place under non-isothermal conditions, nodal temperatures are obtained by solving eqn (3) over a particular time step using the velocity field obtained from eqn

(1) as input. For thermosetting resins, $\frac{\partial \alpha}{\partial t}$ is a function of $\frac{\partial H}{\partial t}$ and T , and it is

generally defined as an Arrhenius equation. Subsequent to the temperature calculations,

$\frac{\partial \alpha}{\partial t}$ and α are obtained using the procedure detailed in Ref. 11. Once \vec{u}, T, α and $\frac{\partial \alpha}{\partial t}$

are known, eqn (4) is solved to obtain the rate of cure reaction. Viscosity η of a

thermosetting resin is a function of α and T , and various empirical models are available in the literature¹² for different resin systems. Using one of these models, η values are updated; these values are then used in the pressure analysis to be carried out over the next time step.

In reality, η of thermosetting resins continuously changes with T . However, for most applications, the mould filling stage is very short and the changes in η are insignificant over a particular time step. Therefore, a fairly accurate analysis can be performed using η estimated at the beginning of a particular time step (i.e. η_0 at t_0). Otherwise, it may be assumed that for the each element the resin flow is taking place at η_a , the average of η_0 and η_1 (viscosity at t_1) taken over a time step $\Delta t = t_1 - t_0$. Then all the analytical steps are repeated with η_a as base viscosity. This further leads to new value of η_1 and also η_a . The whole process may be repeated until the value of η_a converges. Once convergence is achieved, the fill factors are calculated to advance the flow front. Subsequently, pressure boundary conditions are also updated.

2.5 Field analysis in GPFE packages

The quasi-harmonic equation defines the behavior of a variety of field problems. Thermal conduction (temperature), seepage flow (hydraulic head), pressure field (pressure), electric conduction (electric potential) are some of examples of such problems.

Where a solution is required to such problems, field analysis may be performed. Two types of field analysis can be performed using GPFE packages: steady state analysis and transient analysis. Steady state field analysis assumes that the loaded body

has developed a steady internal field variable distribution to equilibrate the applied loads. Where time effects are significant in a field problem, a transient analysis may be performed. Temperature dependent material properties or loads render the problem nonlinear.

The following equation is used in LUSAS¹³ for steady state field analysis:

$$\nabla[S_i(\phi)\nabla\phi]=0 \quad (5)$$

where, typically, for thermal conduction ϕ represents the T , $S_i(\phi)$ the \bar{k} . In pressure analysis, the P is represented by ϕ and the $\frac{\bar{K}}{\eta}$ by $S_i(\phi)$.

Heat capacity effects can be included in the analysis as part of the rate of heat generation, $H(\phi)$, to the following transient heat conduction equation:¹³

$$\nabla[S_i(\phi)\nabla\phi]+H(\phi)=\rho C_p(\phi)\frac{\partial\phi}{\partial t} \quad (6)$$

The solution process to field problems is identical to that for structural problems. After discretising the domain of interest using a number of field elements, the material field properties are specified and the equations are solved for the values of the field variable at each nodal point. In field analysis, the localized inflow or outflow of heat (source term) is defined as an equivalent concentrated load. The internal heat generated per unit volume in a control volume is applied as body-force potential. Temperatures or pressures are specified at nodes as prescribed displacements. In addition, environmental temperature may be defined along with the convective and radiative heat transfer coefficients.

3. PRESENT NUMERICAL APPROACH

The present numerical procedure is based on the following scheme. Wherever possible, the facilities from a GPFE package are used and separate computer codes are written to carry out the remaining steps of the simulation procedure. A GPFE package is used as pre- and post-processor, and its field analysis module is employed to solve for pressure distribution and to perform the transient heat transfer analysis over a particular time step. The user-written computer programs are executed in a certain sequence with the FE package in a batch mode to complete the analysis over the chosen time step. The whole procedure is repeated over a number of time steps to advance the flow front until the mould is completely filled.

In addition to the steps involved in the conventional FE/NCV approach, some numerical concepts are necessary when the present scheme of employing a GPFE package is to be implemented. The details of the present approach and the development of the numerical concepts are discussed below.

3.1 Isothermal flow simulation

Since eqns (2) and (5) are identical, the field analysis module from a GPFE package can be used to solve eqn (2) in its original form to obtain the pressure field. The procedure for defining control volumes, calculating the pressure gradients between different control volumes, solving Darcy's equation using these pressure gradients and, calculating and updating the fill factors is well documented in the literature. Separate computer codes are written to perform these steps.

3.1.1 Pressure at injection port/s

At the beginning of RTM simulation, control volumes enclosing the injection points are assumed as fully filled with resin⁹. The injection pressure is assigned as initial loading condition to these control volumes, when the flow is taking place under constant injection pressure. However, when mould filling is to be achieved with a constant injection rate, the pressure at the injection ports is unknown. There are various ways to satisfactorily implement this boundary condition. In the present approach, steady state field analysis is used to obtain the pressure field and constant-injection-flow-rate condition is implemented in the following manner.

To begin with, the pressure at all the injection port/s is assumed as unity. Sometimes the injection flow rate is different at different injection ports. In such a case, the pressure at the injection port with the highest flow rate is assumed as unity. The initial injection pressure at the remaining ports is then scaled down from unity in the ratio of the respective injection rates to the highest flow rate. The FE analysis is performed with these initial conditions and the flow rates from the injection ports are calculated using eqn (1). If these flow rates are different from the required injection rates, the magnitudes of the injection pressure are scaled up or down to achieve the required injection rates. Subsequently the pressure and the flow rates at the remaining control volumes are also adjusted in the same proportion.

3.2 Non-isothermal flow simulation

A field analysis module from a GPFE package can be used to solve eqn (3), only if the term $\rho_r C_{pr} \left(\frac{\vec{u}}{\varepsilon} \nabla T \right)$ is excluded from the equation and the values of $\frac{\partial H}{\partial t}$ are

calculated and given as input prior to the analysis. The calculation of $\frac{\partial H}{\partial t}$ from $\frac{\partial \alpha}{\partial t}$ (i.e. from a species equation without $\frac{\vec{u}}{\varepsilon} \nabla \alpha$ term) and its inclusion in eqn (3) are described in detail by the authors in ref. 11. The same procedure¹¹ is used in the present studies to solve eqn (3) and also eqn (4) without the convective terms. The convective effects are then calculated separately and added onto these results to implicitly complete the solutions of eqns (3) and (4).

In order to estimate the effects governed by the terms $\rho_r C_{pr} \left(\frac{\vec{u}}{\varepsilon} \nabla T \right)$ from eqn (3) and $\frac{\vec{u}}{\varepsilon} \nabla \alpha$ from eqn (4), following two numerical concepts were developed. In the discussion, the former term is referred as the convective effects on temperature and, the latter as the convective effects on the state of cure, as they occur due to the movement of hot reactive resin mass from one control volume to another.

3.2.1 Convective effects on temperature

At any stage of the mould filling process, each control volume should satisfy energy equilibrium. The energy balance for each control volume depends on its temperature governed by the conductive heat transfer and the thermal energy flowing in and/or out of it. The change in a control volume temperature can be evaluated by expressing the energy balance in an equation form.

When a control volume is fully filled, it acts as conduit. The amount of resin flowing into such a control volume is always equal to the amount of resin flowing out of it. The energy balance of such fully filled control volume j may be written as:

$$\rho_j C_{pj} V_j T_j + \rho_r C_{pr} \sum_{i=1}^n \Delta Q_i (T_i - T_j) = \rho_j C_{pj} V_j (T_j + \Delta T_j) \quad (7)$$

Canceling the common terms from both sides of eqn (7) and re-arranging the remaining terms, we get:

$$\Delta T_j = \frac{\rho_r C_{pr} \sum_{i=1}^n (T_i - T_j) \Delta Q_i}{\rho_j C_{pj} V_j} \quad (8)$$

However, at the flow front, resin does not flow out of a control volume. Thus, when there is no outflow from control volume j , the energy balance is:

$$\rho_j C_{pj} V_j T_j + \rho_r C_{pr} \sum_{i=1}^n \Delta Q_i T_i = (\rho_j C_{pj} V_j + \rho_r C_{pr} \sum_{i=1}^n \Delta Q_i) (T_j + \Delta T_j) \quad (9)$$

Expanding and canceling the common terms from both sides of the equation and re-writing the equation, we get:

$$\Delta T_j = \frac{\rho_r C_{pr} \sum_{i=1}^n (T_i - T_j) \Delta Q_i}{\rho_j C_{pj} V_j + \rho_r C_{pr} \sum_{i=1}^n \Delta Q_i} \quad (10)$$

The ΔT_j is then added to T_j to get the final temperature of control volume j .

3.2.2 Convective effects on the state of cure

The solution to the cure kinetics equation provides α for a control volume based on its current temperature and the amount of reaction heat evolved¹¹. When the resin mass from a control volume moves out and mixes with the resin mass from the another control volume, the state of cure, or more specifically α , of the recipient control volume changes by an amount $\Delta\alpha$. For any control volume, $\Delta\alpha$ is proportional to the amount of resin flown in from its neighbouring control volume/s. Therefore $\Delta\alpha$ can be

estimated using the concept of volume average as discussed below.

For control volume j to which resin flows from ' n ' surrounding control volumes,

$$\Delta\alpha_j = \frac{\sum_{i=1}^n (\alpha_i - \alpha_j) \Delta Q_i}{V_j'} \quad (11)$$

where $V_j' = V_j$ for completely filled control volume j . When j is partially filled (i.e. j is at flow front), $V_j' = V_j + \sum_{i=1}^n \Delta Q_i$. The sum of $\Delta\alpha_j$ and α_j gives the final state of cure of control volume j .

The updated values of T_j and α_j then form a set of basic parameters for the subsequent calculations.

3.3 Solution sequence

Fig. 1 provides the flow chart of the present solution sequence. The procedure was computerised on a Personal Computer, Pentium-120MHz, to demonstrate its application. All the user-programs were composed in FORTRAN 77. The batch files were created in PC-DOS environment. PC versions of MYSTRO and GPFE package LUSAS 11_046 were used for pre- and post-processing and FE analysis respectively.

The steps involved in the simulation procedure and the organization of the user-programs are discussed below.

To begin with, MYSTRO is used to create FE model of a mould cavity and if required, of other peripherals and, to generate initial input data files for field analysis.

User-program PREFLOW is written to calculate nodal control volumes from the FE mesh defining the preform. The calculations of two- and three-dimensional control

volumes are different. Separate routines are written to facilitate this. The user-program also includes a routine to define all the necessary input parameters including the location of injection ports, cure kinetics and viscosity models for the resin system, etc.

A number of swap files are created in one of the specified directories on a computer hard disk using the same program. The geometric details of all control volumes are stored onto one of the swap files. Remaining swap files are used as temporary storage for the results of transient heat transfer analysis and pressure field analysis carried out after every time increment and also for the updated control volume properties, flow rates and fill factors etc.

Once all the preliminary input parameters are generated, actual simulation is performed through batch file NISOFLOW. This batch file contains all the necessary commands for non-isothermal flow simulation. The associated steps with these commands are -

Step 1: Perform FE field analysis to obtain pressure distribution in the filled portion of a mould;

Step 2: Execute user-program FLOANA to-

- (a) calculate pressure gradient between any two connected control volumes and the flow rate for a unit time,
- (b) estimate the time required to fill at least one control volume at the flow front and update the flow rates accordingly,
- (c) calculate fill factors to advance the flow front,
- (d) estimate resin-content of all the control volumes and accordingly update their thermal properties ρ_c , C_{pc} and \bar{k}_c using rules of mixture⁹,
- (e) determine the magnitude of energy flowing in and out of each control

volume, and,

(f) store all these parameters onto a swap file for further reference;

Step 3: Calculate convective effects on temperature and state of cure using user-program CONVEC and update the temperature field and state of cure of all the control volumes;

(Once ΔT and $\Delta\alpha$ are known from eqns 7 to 11, these values are added to the results from the conduction analysis and the cure analysis based on it respectively. The updated values of T and α are then used as base parameters in the next step of the analysis. The state of cure is updated after every time step. The temperature field is updated only when at least one control volume at the flow front is completely filled. The execution of CONVEC does not affect any other calculations and therefore its use can be optional. Thus the convective effects can be added or ignored easily from the flow analysis.)

Step 4: Solve for temperature using GPFE package;

Step 5: Carry out cure analysis in user-program CURVIS;

(This includes simulation of cure kinetics and evaluation of $\frac{\partial\alpha}{\partial t}$, α and $\frac{\partial H}{\partial t}$ for all the control volumes.)

Step 6: Execute user-program NEWPRO to calculate material properties $\frac{\bar{K}}{\eta}$, ρ_c , C_{pc} and \bar{k}_c for the finite elements defining the preform from the properties of the corresponding control volumes and create new data files for the next step of analysis.

(NEWPRO is designed to determine the average properties for a finite element depending upon its volume shared by different control volumes. The program

subsequently updates the pressure and temperature boundary conditions, the cure cycle temperatures and the material properties in the FE input data files.)

If during a particular time step the mould is not completely filled, the entire solution sequence may be repeated over the next time step. At the end of every time step the results are written onto a separate file for user's reference and the swap files are updated irrespective of the status of the analysis. The input data files for the next time step are also prepared. This makes it easy to stop and re-start the simulation.

In addition, an utility is included in the batch file to generate and to store the graphics file from LUSAS after a desired number of analytical steps. These files are used to create a graphical display of the pressure and the temperature fields; these provide useful information on the advancement of the flow front.

While simulating isothermal mould filling processes, heat transfer analysis and the related temperature effects are eliminated from the above solution sequence and a new batch file ISOFLOW is written to perform the analysis.

It may be noted that the above solution sequence can be adopted with any GPFE package that has a facility for field analysis. The only requirement is that the user has access to the input and output files. The user-programs can be written in any of the available computer programming languages. The number of steps of the simulation procedure can also be divided in a suitable manner to reduce or to increase the number of user-programs. The batch command file can be written either in a PC-DOS environment or in a shell script under the Unix system.

4. VALIDATION OF THE PROCEDURE

After computerising the developed procedure, it was tested for both the isothermal and the non-isothermal flow conditions.

4.1 Isothermal flow simulation

A simple one-dimensional problem with analytical solution was selected from Duarte's work¹⁴. He reported good agreement between his experimental results and the analytical solution. The geometric details of the problem and a FE model are shown in Fig. 2. The FE model was created using 4-noded quadrilateral field elements. The process parameters and the material properties are given in Table 1. The same properties were used by Duarte¹⁴.

To demonstrate the three-dimensional capability of the procedure, the same example was modelled using 8-noded solid elements. However, to have a slight differentiation, the porosity of the preform was reduced to 0.5 from 0.691. The three-dimensional FE model used is shown in Fig. 3. The injection of resin was simulated under constant-pressure and constant-flow-rate conditions.

Subsequently two central injection RTM problems, with different permeability ratio (i.e. $\frac{K_x}{K_y}$), were chosen to study the shape and the advancement of flow front. The injection at constant flow rate was preferred so that the analytical fill time could be calculated using the rate of injection and the mass of resin entered into the preform. In the first case, a square preform of size 200mm X 200mm X 20mm and in the second case, a rectangular preform of size 400mm X 100mm X 20mm were used.

For both cases, the FE models were created using 256, 8-noded solid elements; the meshes are shown in Fig. 4. The same materials as used by Duarte¹⁴ during his work on RTM, the OCF-M8610 glass fabric and the Glycerol 1-part, were used in these case studies. The material properties and other process parameters are listed in Table 2.

In addition, an example on a 150mm long semi-cylindrical section was also solved. The inner diameter of the shell was 120mm. Its thickness varied linearly from 5mm at one end to 20mm at the other. A square hole of size 70mm X 50mm was introduced at the mid-length of the section. The FE model is shown in Fig. 5. Flow with constant injection rate was modelled under isothermal conditions with $\frac{K_x}{K_y} = 1.0$. The material properties and the process parameters used were the same as those given in Table 2.

4.2 Non-isothermal flow simulation

A classical test problem was used to prove the non-isothermal flow simulation capability of the present procedure. The example was selected from Brusckke's work². He used this example to validate LIMS. It is a case of one-dimensional heat convection in the direction of fluid flow and it verifies the complete temperature solution.

The geometry of the selected test problem (with $L = 3m$ and $h = 1m$) and the corresponding FE mesh are shown in Fig. 6. Due to symmetry, only half of the mould was modelled using 48, 4-noded, quadrilateral elements. The various parameters used are listed in Table 3.

4.3. Results and discussion

4.3.1 Isothermal flow simulation

The mould filling time t for one-dimensional isothermal flow under constant pressure can be obtained analytically by assuming the pressure gradient in Darcy's law as constant. The final equation can be written as:

$$t = \frac{\eta \varepsilon L^2}{2KP} \quad (12)$$

Similarly, the fill time t for isothermal flow under constant flow rate may be obtained analytically by:

$$t = \frac{\varepsilon V_c}{q} \quad (13)$$

It should be noted that eqn (13) is applicable to one-, two- and three-dimensional cases.

Eqn (14) can be used to obtain the injection pressure for one-dimensional isothermal flow under constant flow rate conditions:

$$P = \frac{\eta q L}{AK} \quad (14)$$

The comparisons between the numerical and analytical fill times for the two examples on one-dimensional isothermal flow under constant pressure (the one with quadrilateral elements and the another with solid elements) are shown in Figs. 7 and 8 respectively. Eqn (12) was used to obtain the analytical fill times for both the cases.

Fig. 9 presents the numerical fill time and the analytical fill time obtained by using eqn (13) for the one-dimensional example with constant injection flow rate. The variation in the injection pressure obtained by the presented numerical procedure and

eqn (14) is shown in Fig. 10.

All the case studies (Figs. 7-10) show excellent agreement between the numerical and analytical results. It may be noted that the initial impregnation length that is observed in Figs. 7-10 at the onset of the mould process indicates the size of the fully filled control volumes that surround the injection nodes.

In central injection problems, the resin flows in radial directions. This leads to a flow front of a shape of an ellipse such that the ratio of its major axis to the minor axis

$\left(\frac{a}{b}\right)$ is equal to $\sqrt{\frac{K_x}{K_y}}$. The predicted shapes of the flow front using the present

numerical approach for the square and rectangular preforms are shown in Fig. 11.

For the square preform, $K_x = K_y$ and, thus, as expected, the flow front was always circular. For the rectangular preform, $K_x = 16K_y$, and therefore the flow front had the expected elliptical shape with $\frac{a}{b} \approx 4.0$. The numerical fill time matched well with the analytical results obtained from eqn (13) throughout the mould filling process. The error was less than 0.01% for the whole analysis.

The pressure profile in the semi-cylindrical section obtained at a particular fill time is shown in Fig. 12. The picture was created in MYSTRO using the LUSAS-generated graphics file. The pressure distribution reveal the manner in which the flow front has moved during the filling process. The comparison between the analytical (eqn 13) and numerical fill times shows that the error was negligible.

4.3.2 Non-isothermal flow simulation

The analytical temperature profiles for the non-isothermal example were

obtained from the equation²:

$$\theta(x', y) = \sum_{n=0}^{\infty} \theta_0 \frac{2(-1)^n}{\lambda_n h} e^{-\lambda_n^2 x'} \cos \lambda_n y \quad (15)$$

where $x' = \frac{x}{\eta}$, $\theta = T - T_{wall}$ and $\lambda_n = \frac{(2n+1)\pi}{2h}$. Fig. 13 gives the numerical and

analytical distribution of temperatures across the mould at two levels: $y = 0.0m$ and $y = 0.5m$.

The excellent correlation seen from Fig. 13 indicates that the approach developed for modelling the convection effects on temperature is numerically stable and gives accurate results.

5. CONCLUSIONS

A procedure is developed to employ a GPFE package for the numerical simulation of mould filling process in RTM. The procedure is validated for isothermal and non-isothermal flow problems. The obtained results show that the developed numerical procedure is stable and gives excellent results with moderately coarse FE meshes for both the flow conditions. The presented examples demonstrate the flexibility and the versatility of the procedure in solving one-, two- and three-dimensional mould filling problems.

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7. NOMENCLATURE

a	Major axis of ellipse
b	Minor axis of ellipse
A, A_*	Area
C_p	Specific heat
f	Fill factor
h	Height or thickness
H	Rate of internal heat generation (e.g. heat of cure reaction)
K, K_*	Permeability of porous media
k, k_*	Thermal conductivity
L	Length
n	Number variable
P, P_*	Pressure
q	Flow rate
Q, Q_*	Amount of resin flown in or out
\dot{R}_α	Rate of the cure reaction
S_*	Field properties of material
t, t_*	Time
Δt	Time step
T, T_*	Temperature
u	Velocity
V, V_*	Volume
X, Y, Z	Orthogonal axes system
α, α_*	Degree of cure
ρ, ρ_*	Density
η, η_*	Dynamic viscosity
ε	Porosity of fibrous media
ϕ	A field variable (temperature, pressure etc.)

* - *an appropriate subscript*

Operators and descriptors -

∇	Differential operator
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$\frac{d}{dt}$	Rate
Δ	Small quantity descriptor
\rightarrow	Vector descriptor
$-$	Tensor descriptor

Subscripts -

c	composites or saturated preform
o	initial parameter
r	resin
i,j	variable descriptors
n	normal direction
t	tangential direction
$1,2$	numeric descriptors

Superscripts -

j	control volume
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7. REFERENCES

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FIGURES

- Fig. 1. Flowchart of the developed numerical simulation procedure for mould filling process in RTM.
- Fig. 2. Geometric details and FE model of the test problem on one-dimensional isothermal flow.
- Fig. 3. Three-dimensional FE model of the preform used in one-dimensional isothermal flow simulation studies.
- Fig. 4. FE models of the test problems used in two-dimensional flow simulation studies.
- Fig. 5. FE model of the semi-cylindrical section.
- Fig. 6. Geometric details and FE model of the non-isothermal mould filling example.
- Fig. 7. Fill times for one-dimensional isothermal flow simulation example with quadrilateral elements (constant injection pressure).
- Fig. 8. Fill times for one-dimensional isothermal flow simulation example with solid elements (constant injection pressure).
- Fig. 9. Fill times for one-dimensional isothermal flow simulation example with solid elements (constant flow rate injection).
- Fig. 10. Injection pressures for one-dimensional isothermal flow simulation example with solid elements (constant flow rate injection).
- Fig. 11. Flow front positions at different stages of filling in square and rectangular preforms.
- Fig. 12. Pressure profiles in semi-cylindrical section (The resin flow is from darker region to lighter region. White region shows the dry preform).
- Fig. 13. Temperatures profiles for non-isothermal problem shown in Fig. 6.

TABLES

- Table 1. Process parameters used in the one-dimensional flow simulation studies.
- Table 2. Process parameters used in the two-dimensional flow simulation studies.
- Table 3. Process parameters used in the non-isothermal flow simulation studies.

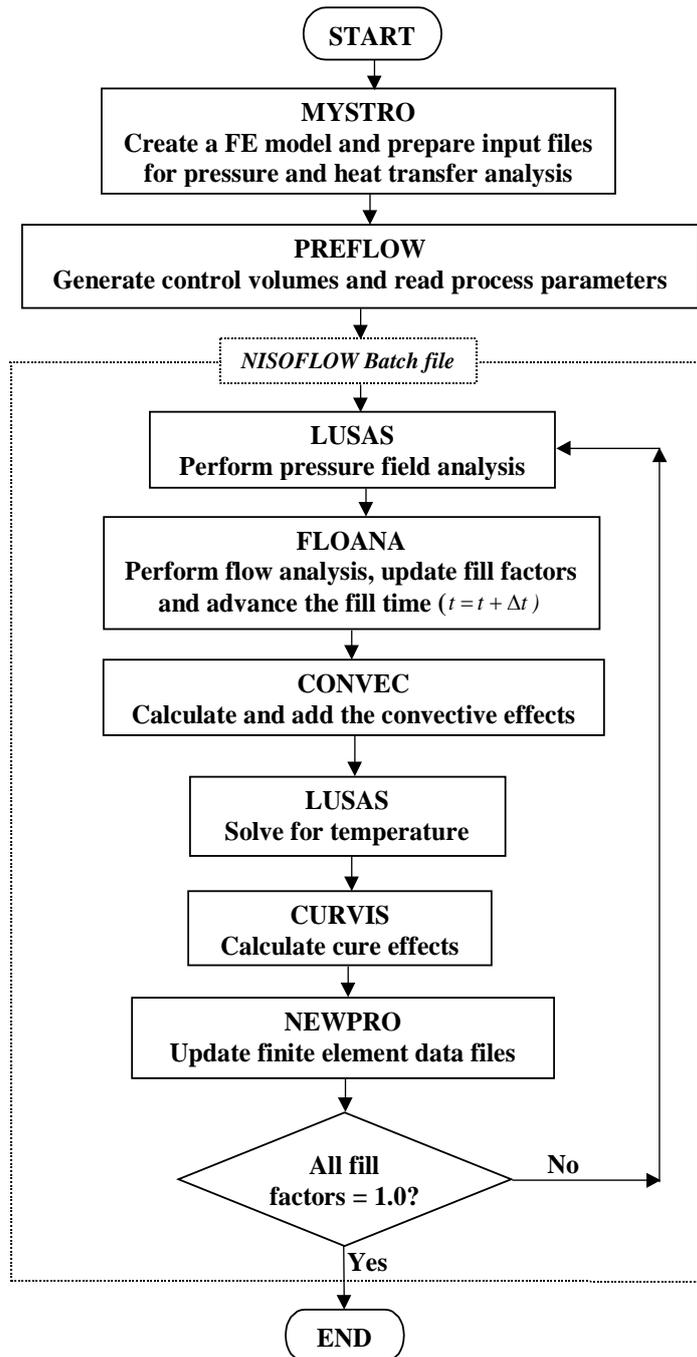


Fig. 1. Flowchart of the developed numerical simulation procedure for mould filling process in RTM.

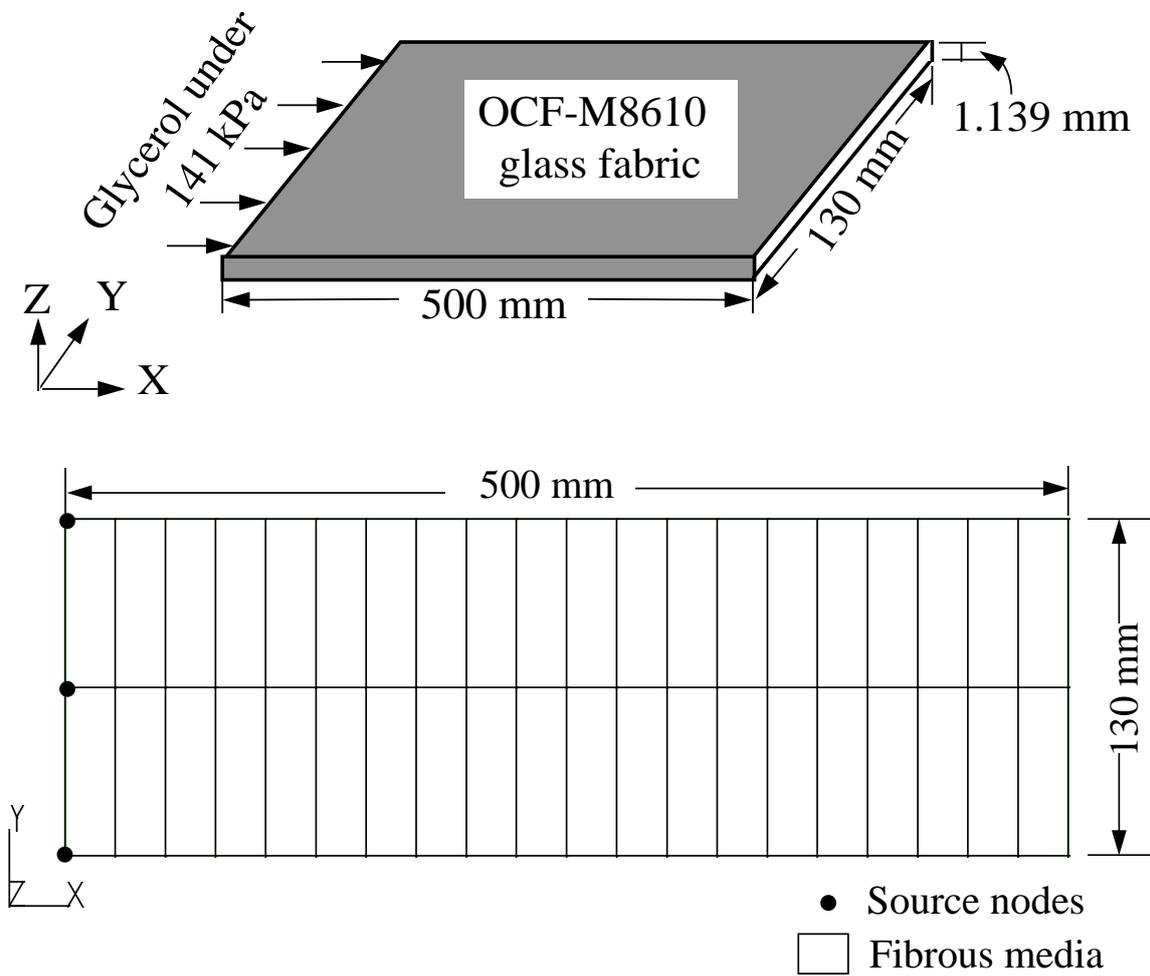


Fig. 2. Geometric details and FE model of the test problem on one-dimensional isothermal flow.

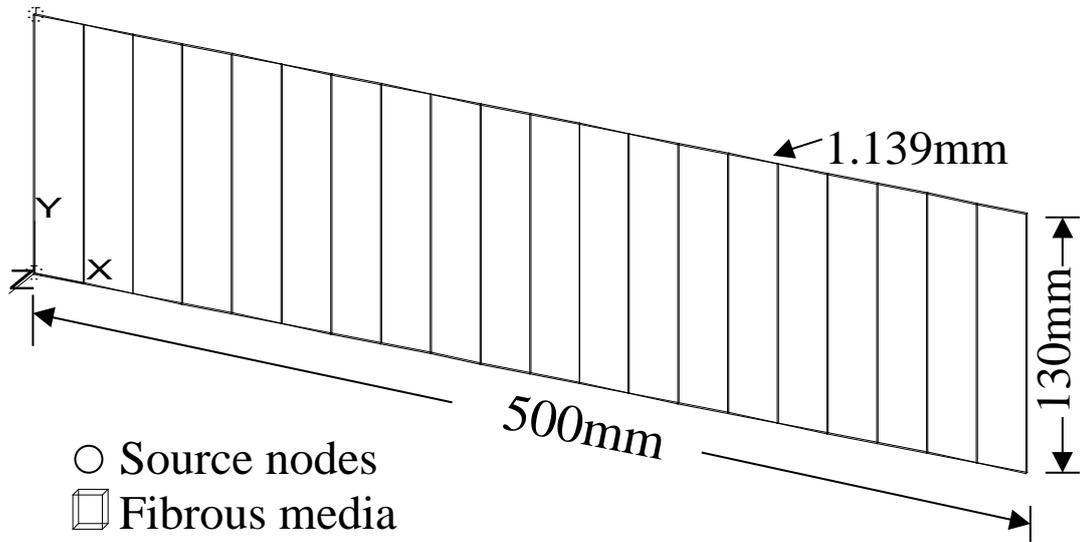
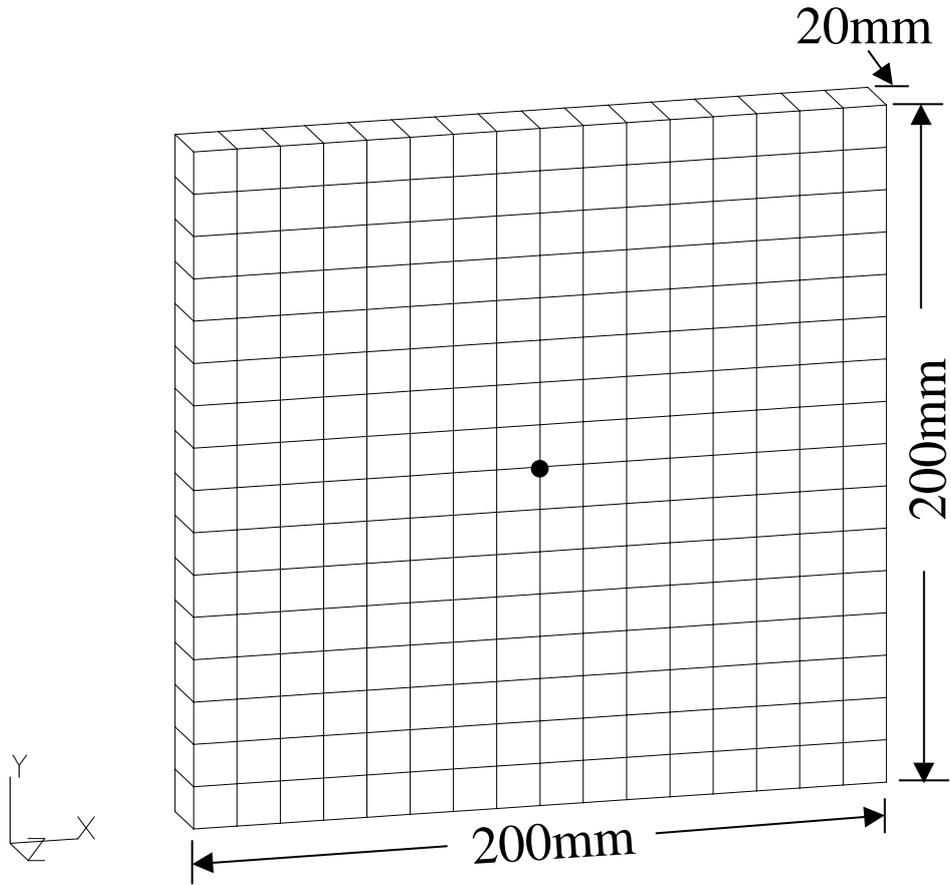
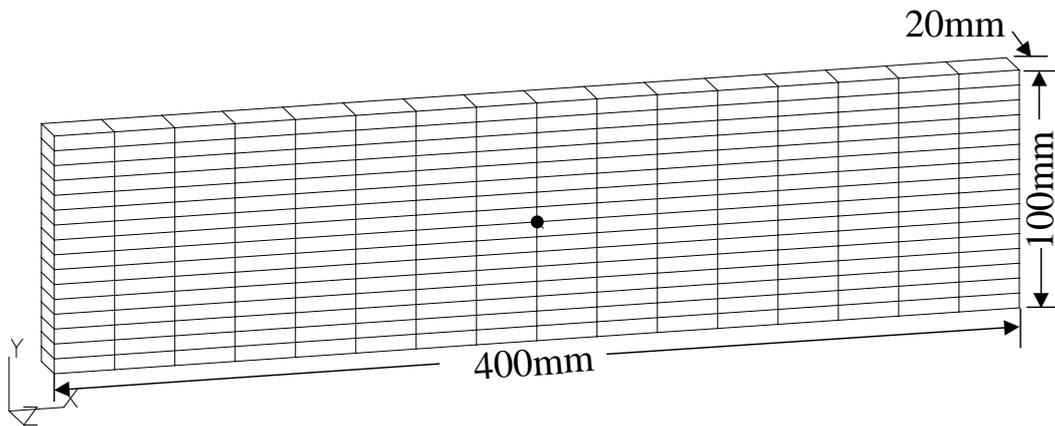


Fig. 3. Three-dimensional FE model of the preform used in one-dimensional isothermal flow simulation studies.



a: Square preform



b: Rectangular preform

Fig. 4. FE models of the test problems used in two-dimensional flow simulation studies.

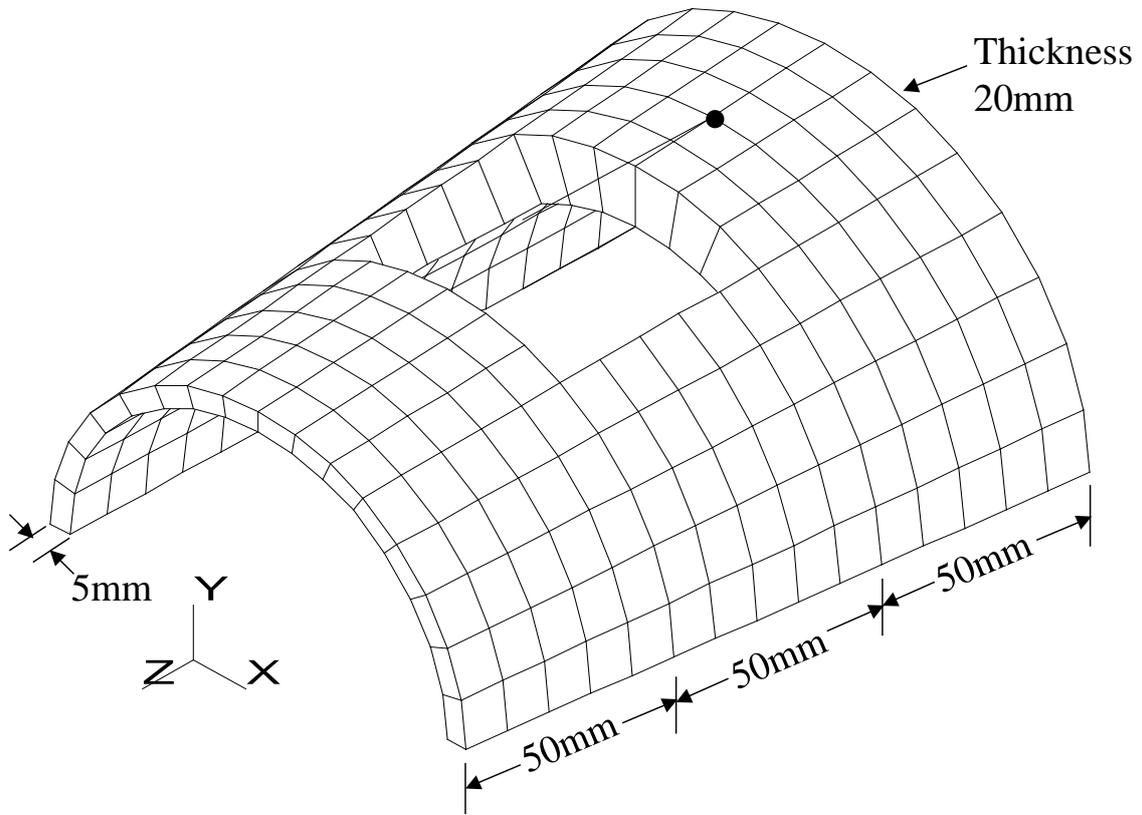


Fig. 5. FE model of the semi-cylindrical section.

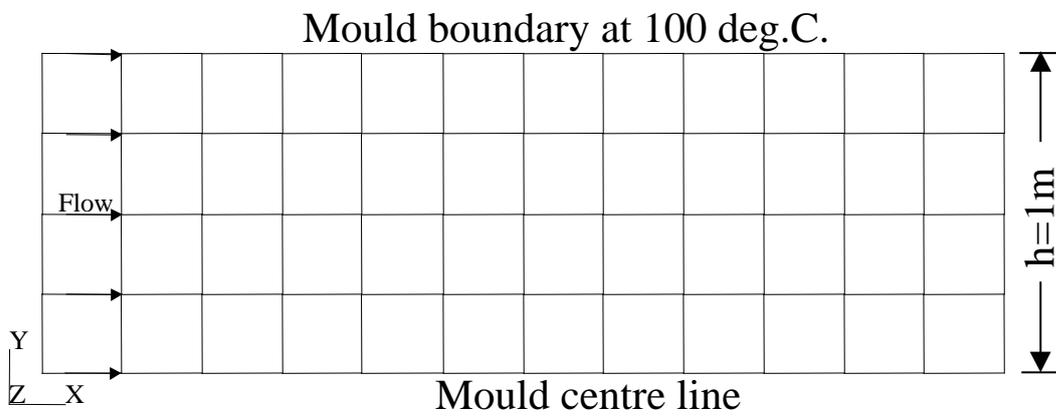
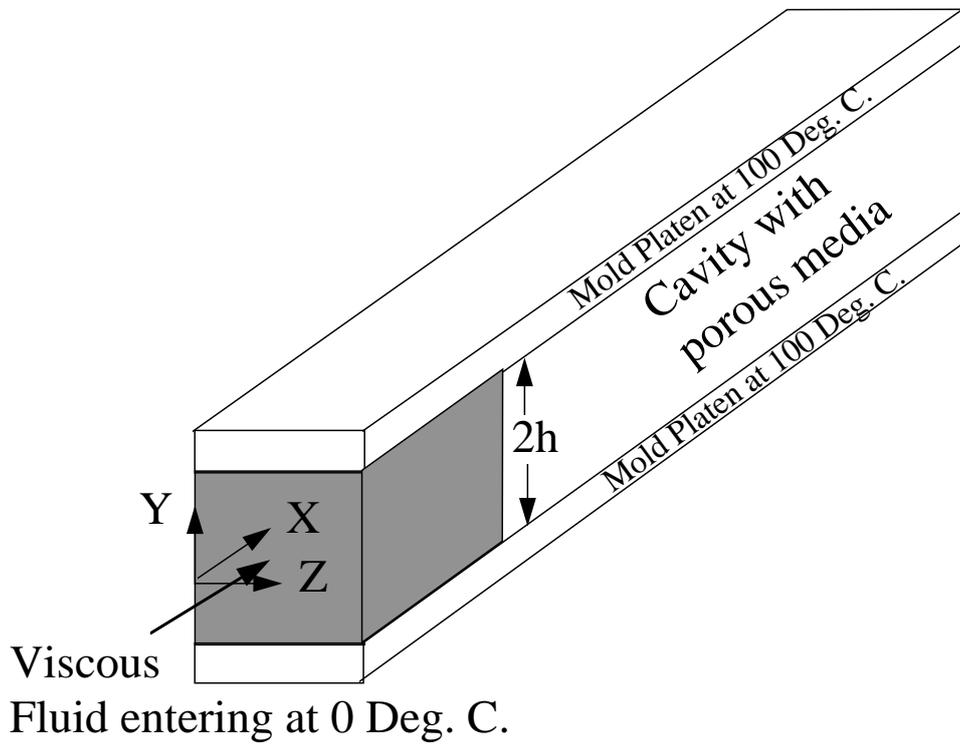


Fig. 6. Geometric details and FE model of the non-isothermal mould filling example.

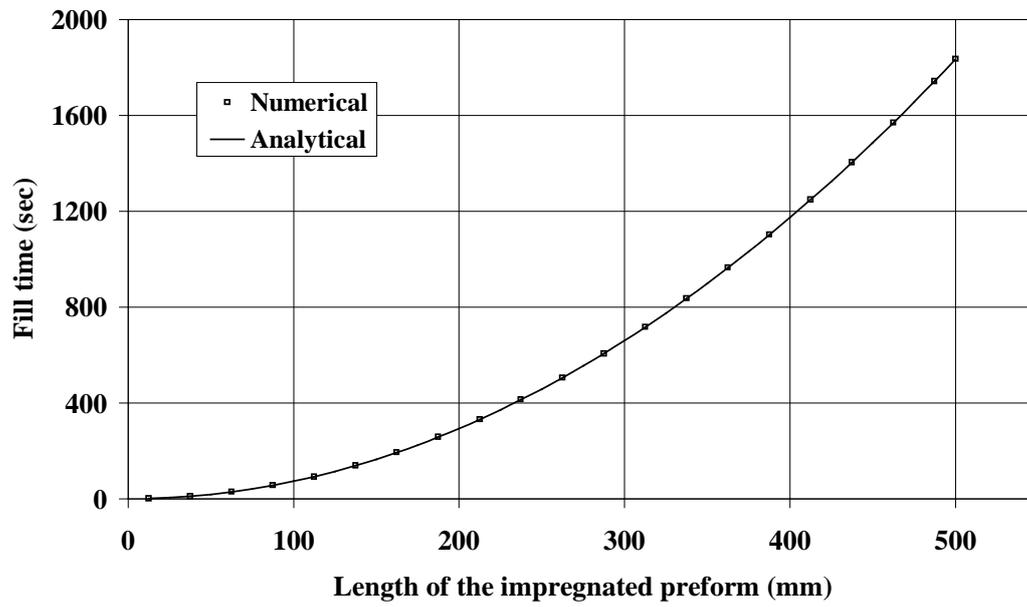


Fig. 7. Fill times for one-dimensional isothermal flow simulation example with quadrilateral elements (constant injection pressure).

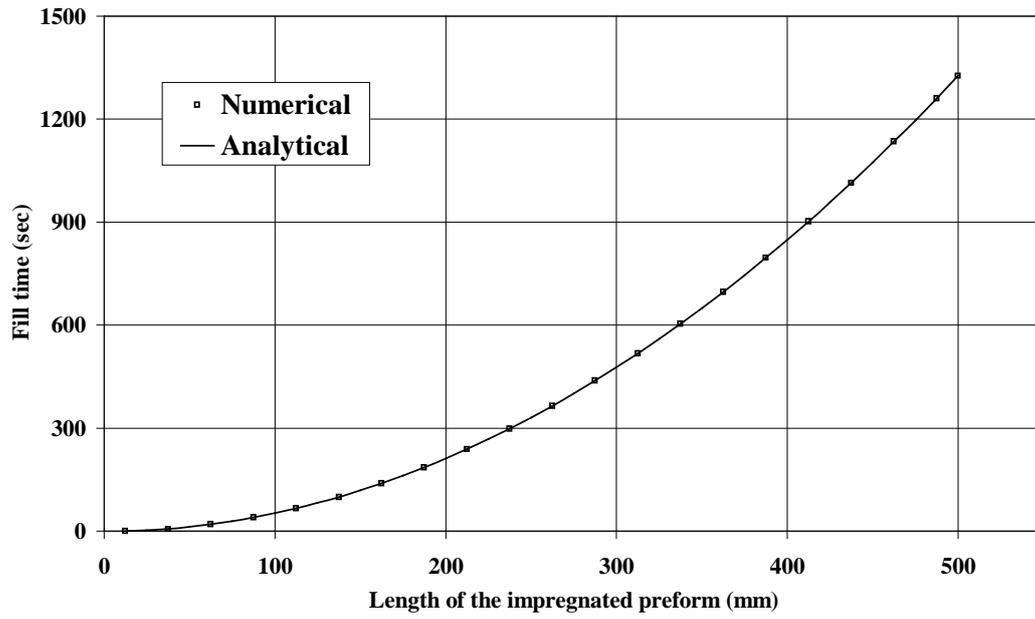


Fig. 8. Fill times for one-dimensional isothermal flow simulation example with solid elements (constant injection pressure).

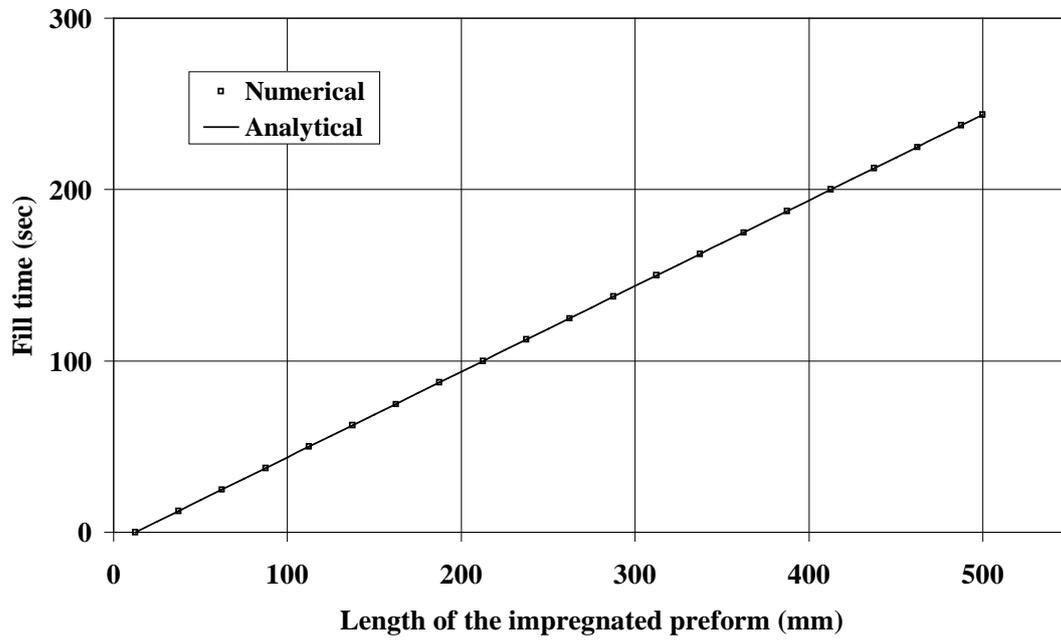


Fig. 9. Fill times for one-dimensional isothermal flow simulation example with solid elements (constant flow rate injection).

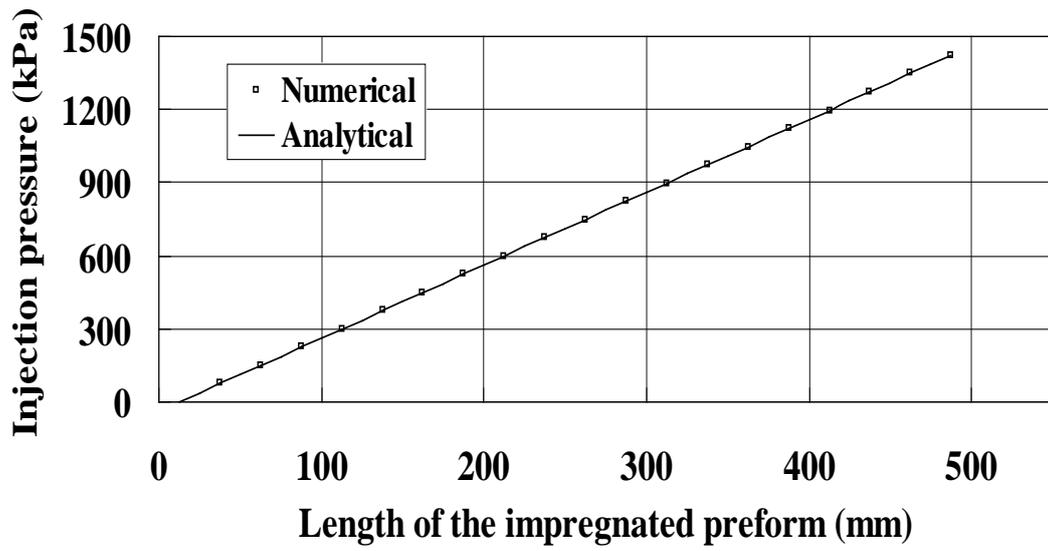


Fig. 10. Injection pressures for one-dimensional isothermal flow simulation example with solid elements (constant flow rate injection).

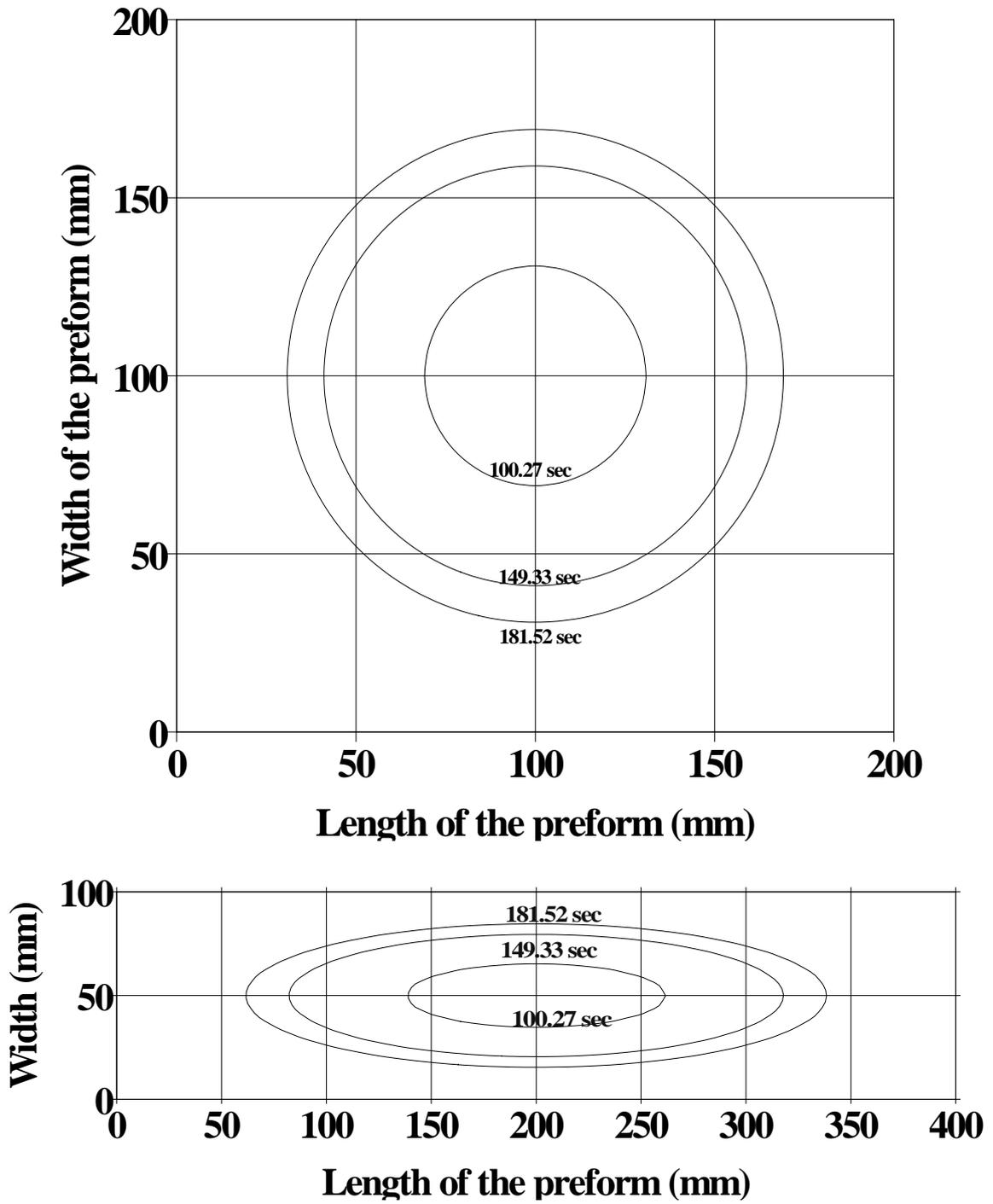


Fig. 11. Flow front positions at different stages of filling in square and rectangular preforms.

Fill time at the
current flow front
Numerical 60.65 seconds
Analytical 60.64 seconds

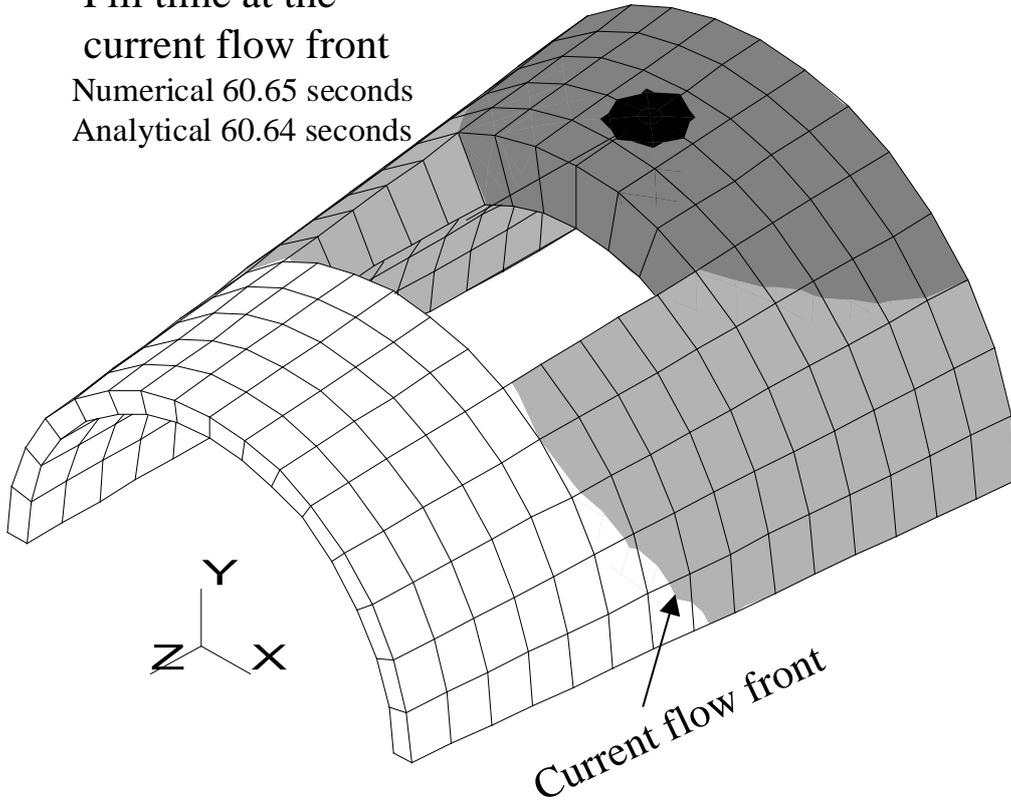


Fig. 12. Pressure profiles in semi-cylindrical section (The resin flow is from darker region to lighter region. White region shows the dry preform).

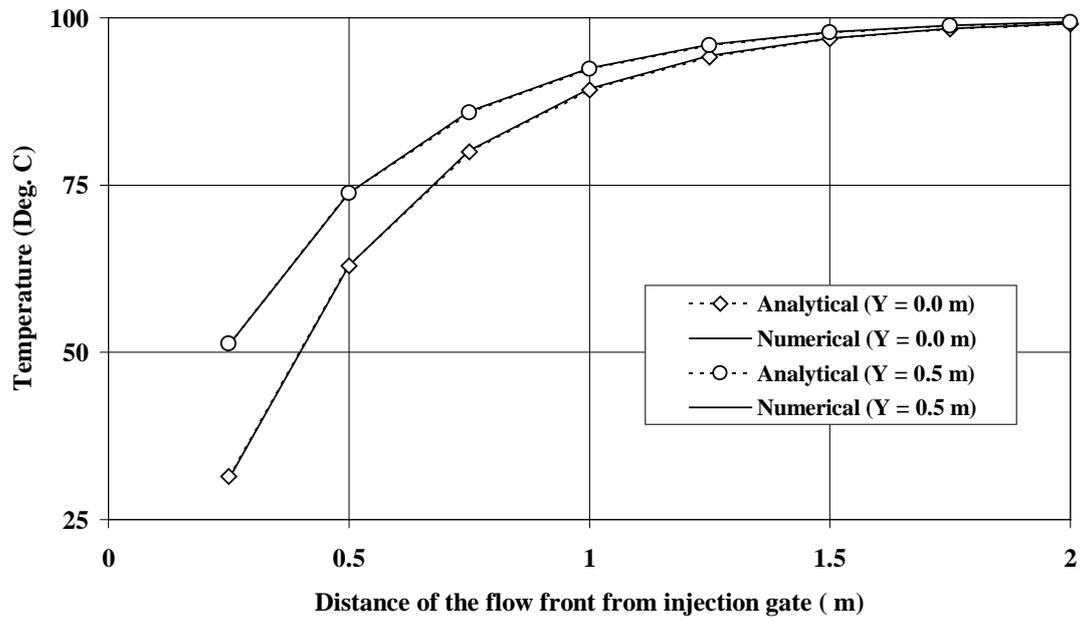


Fig. 13. Temperatures profiles for non-isothermal problem shown in Fig. 6.

Table 1 Process parameters used in the one-dimensional flow simulation studies.

Parameter	Magnitude
P N/mm ²	0.141
q mm ³ /sec	130.0
η N/mm ² .sec	1.149E-06
ε	0.691 & 0.5
$K_x = K_y$ mm ²	3.837E-04

Table 2. Process parameters used in the two-dimensional flow simulation studies.

Property	Magnitude
q mm ³ /sec	2000.0
η N/mm ² .sec	1.639E-6
ε	0.5
K_x mm ²	3.118E-3
K_y mm ²	For the square preform: $K_y = K_x$, For the rectangular preform: $K_y = K_x/16$
K_z mm ²	3.118E-3

Table 3. Process parameters used in the non-isothermal flow simulation studies.

Property	Magnitude
u m/sec	1.0
η N/m ² .sec	1.0
ε	1.0
k W/m ² .K	1.0
ρ kg/m ³	1.0
C_p J/kg.K	1.0