

Modelling Heat Generation and Transfer during Cure of Thermoset Composites Processed by Resin Transfer Moulding (RTM)

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ABSTRACT

The development of a heat transfer model for the curing stage of the RTM process is presented. Despite the intense interest in the modelling and simulation of this process the relevant work is currently limited to development of flow models of the filling stage. The principles of heat transfer modelling of composites cure have already been reported and applied to the autoclave process by many investigators. In the present investigation, the same concept is used for the implementation of Galerkin finite element approach to RTM curing. The mathematical basis of the resulting semidiscrete model is presented here and the temporal algorithm is described. The experimental mould, which will be used to evaluate and validate the model is also described.

1. BACKGROUND

Resin Transfer Moulding process involves the placement of a dry fibre preform in a cavity, the impregnation of resin into the preform and the heating of the component. Although the technique has been employed for composite production over the past 20 years ⁽¹⁾, its potential has been only lately recognised by the aerospace industry. The possibility of automation has made the modelling and simulation of the processes involved in RTM very important ⁽²⁾.

The research on this field has been up to now focused on the filling stage of the process ⁽³⁾. In some cases heat transfer phenomena are taken into account when non-isothermal filling is considered ^{(4),(5)} and the temperature range is insufficient to initiate curing. The curing of the resin has only been treated in conjunction with the flow during filling ⁽⁶⁾, a combination that would be inappropriate in production since the cure progress would influence rheological properties and would inhibit impregnation. Experimental investigation of the temperature evolution during the whole process has demonstrated the existence of significant temperature gradients during the cure ⁽⁷⁾, indicating the requirement for the implementation of a heat transfer model for this stage of the process.

Heat transfer modelling of thermoset composite cure during manufacturing has already been performed successfully for the autoclave process, by many investigators. The model developed by Loos and Springer ⁽⁸⁾ solves the one dimensional heat transfer equation and simultaneously considers the heat generated by the cure reaction, in the frame of a general model for the autoclave production of composites, taking into account flow phenomena, residual stresses development and voids formation. Numerous other models have been constructed, based on the same approach, each one using a different kinetic expression and dependence of thermal properties on the temperature and material state ^{(9),(10),(11)}.

The present paper describes the development of a model designed specifically to consider curing of a carbon fibre composite in an RTM mould. The possibility of a generalisation of the model concept, to make it responsive to the changes in the thermal properties of the composite and independent of the exact kinetics of the cure reaction, has been considered.

2. DESCRIPTION OF THE MODEL

The finite element method has been applied to the general, three dimensional, non-linear, transient energy balance equation,

$$\rho c_p \frac{\partial T}{\partial t} - \rho H_{tot} \frac{d\alpha}{dt} = \sum_{i,j=x,y,z} \frac{\partial}{\partial i} \left(K_{ij} \frac{\partial T}{\partial j} \right), \quad (x, y, z) \in \Omega \quad (1)$$

subject to the boundary conditions,

$$T(x, y, z, t) = F(x, y, z, t), \quad (x, y, z) \in \Gamma_1 \quad (2)$$

$$q(x, y, z, t) = n(x, y, z, t), \quad (x, y, z) \in \Gamma_2 \quad (3)$$

where K_{ij} is the thermal conductivity tensor, ρ is the density, c_p is the specific heat capacity, α is the degree of cure, H_{tot} is the total heat of the cure reaction per unit mass, and Ω is the domain of the problem. The boundaries Γ_1 and Γ_2 could be, in the case of an RTM mould, the heated bottom plate and the air convection controlled top plate respectively. The domain of the equation is discretised and the continuous solution is related to the nodal temperatures T_i , by the polynomial interpolation functions N_i i.e.

$$T(x, y, z, t) = \sum_i T_i(t) N_i(x, y, z) \quad (4)$$

Application of the Galerkin approximation solution method⁽¹²⁾ gives the system of equations,

$$[H_{ji}][T_i] = [C_{ji}] \frac{\partial T_i}{\partial t} + f_j \quad (5)$$

where

$$\begin{aligned} H_{ji} &= \int_{\Omega} \nabla N_j [K] \nabla N_i d\Omega - \int_{\Gamma_1} N_j N_i d\Gamma - \int_{\Gamma_1} N_j [K] \nabla N_i d\Gamma \\ C_{ji} &= \int_{\Omega} -\rho c_p N_j N_i d\Omega \\ f_j &= \int_{\Omega} \rho H_{tot} \frac{d\alpha}{dt} N_j d\Omega + \int_{\Gamma_2} q N_j d\Gamma \end{aligned} \quad (6)$$

The integration of the system with respect to time is performed using the theta-finite difference method⁽¹³⁾, resulting in :

$$[H_{ji}][[T_i^n](1-\theta) + [T_i^{n+1}]\theta] = [C_{ji}] \frac{([T_i^{n+1}] - [T_i^n])}{\Delta t} + f_j \quad (7)$$

where the superscript represents the time step and Δt is the time step magnitude.

Since the situation examined is non-linear, i.e. the thermal properties are dependent on the temperature, an iteration procedure is necessary at each time step.

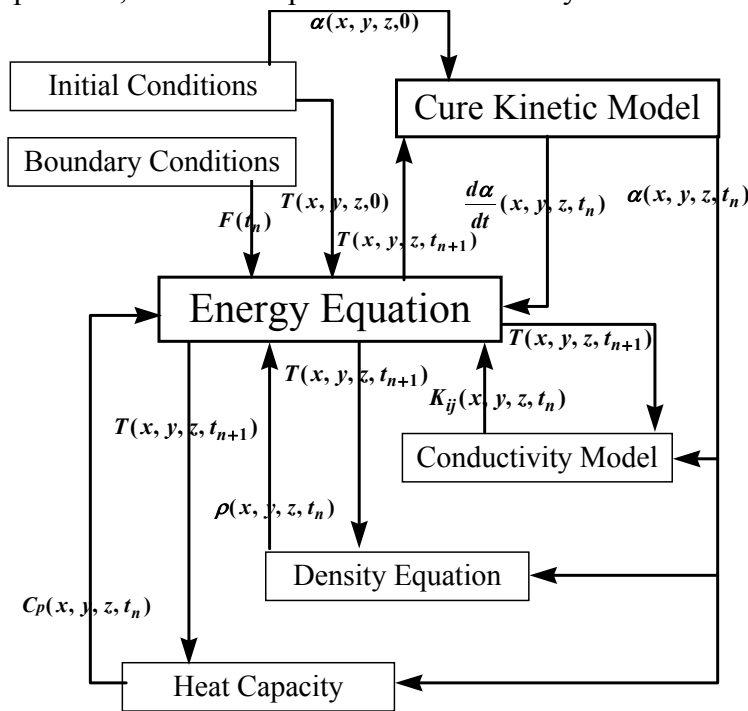


Figure 1. Flow diagram representing the interdependencies of the various parts of the model

The structure of the model and the interdependencies of the various submodels are illustrated in Fig. 1. It can be observed that for each time step the reaction rate, the heat capacity, the thermal conductivity and the density are calculated and used for the solution of the energy equation in the next time step.

At the present time, the various submodels are under development. For the reaction rate submodel, kinetic equations already available for specific systems⁽¹⁴⁾ can be easily implemented, but a more general method is being assessed. The reaction rate is determined as a function of temperature and degree of cure by using an interpolation

procedure, applied on data obtained by isothermal calorimetric experiments. An exponential interpolation is adopted, based on the Arrhenius dependence of the reaction rate on temperature.

The thermal properties are determined by Modulated Differential Scanning Calorimetry^{(15),(16)}. A mapping of their values, as functions of temperature and degree of cure, is performed and a linear interpolation gives the values at an intermediate temperature and degree of cure. Thermal conductivity demonstrates the special feature, namely that a simple law of mixtures cannot be adopted for the calculation of the composite property. Therefore, the geometrical characteristics of the fibre must be considered in order to estimate the thermal conductivity tensor from the principal conductivities i.e. the conductivities parallel and perpendicular to the fibre⁽¹⁷⁾.

3. DESCRIPTION OF THE EXPERIMENTAL MOULD

The RTM mould designed and built at Cranfield is represented schematically in Fig. 2. The mould was manufactured from an Alcoa aluminium cast machined plate. Clamping pressure is introduced to the glass top plate through a clamping plate in which windows have been machined, in order to visualise the resin flow.

The temperature profile of the mould cavity surface is mapped with eighteen K-type mineral insulated thermocouples. Each thermocouple can be positioned at different heights so that temperature in the Z-direction can also be measured. Temperature data can be downloaded into a personal computer through a DAS-TC thermocouple input board.

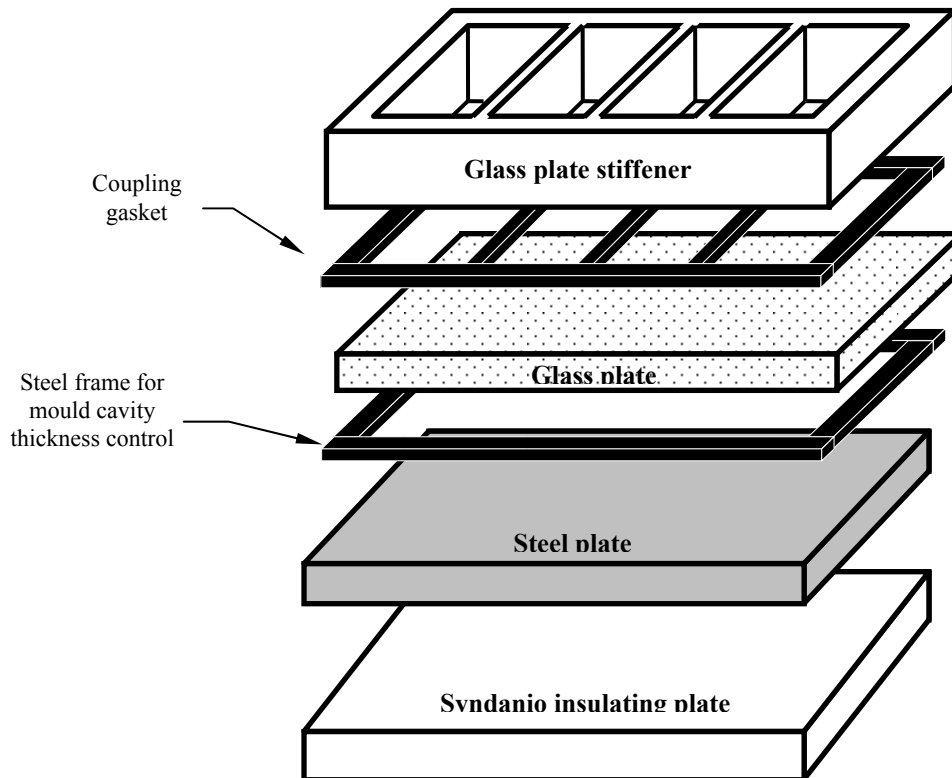


Figure 2. RTM tool used for the validation of the model

Mould heating is provided by electrical resistance heating elements positioned at the bottom of the tool and can achieve an operating temperature of 200 °C. The temperature is set via a Eurotherm 808 controller connected to one of the central thermocouples of the mould. The controller can be programmed and data are downloaded into a PC via a RS-422 interface.

4. CURE MONITORING AND CONTROL

Dielectric sensors for cure monitoring can be integrated anywhere the curing component. This technique has been demonstrated capable of delivering real time information on the local state of resin flow and resin cure^{(18),(19)}. Current work aims to progress the predictive capability of the technique⁽²⁰⁾, leading ultimately to feedback-loop control of the RTM process.

The ability to model spatial distribution of temperature in the curing component, also in real time, is an essential pre-requisite of success in this context.

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