

HEAT TRANSFER MODELLING DURING LIQUID COMPOSITE MOLDING MANUFACTURING PROCESSES: COMPARISON BETWEEN TWO MODELS

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ABSTRACT: During composite molding processes, temperature is one of the most important parameter as an accurate temperature cycle is required to insure good wetting of fibres and good part properties such as final degree of cure, glass temperature and low residual stresses. For an accurate temperature prediction, proper characterization of the resin curing system is needed, as resin kinetics greatly affect temperature profiles. The other basic parameters to consider are the conduction of resin towards the mold walls and convective effects that depends on injection velocity. However local effects were shown to be of great importance as resin flows through a porous medium. Local convective effects that induce heat dispersion must be included in the general energy balance equation. A one-equation model based on the local thermal equilibrium assumption was thus developed using finite difference analysis. However, during fast injection processes the latter assumption does not hold anymore, heat exchange between resin and fibres has to be taken into account. A two-equation model was thus considered using finite element analysis. The comparison between both models shows that the one-equation model is sufficient for steady state analysis purposes, when long parts or slow injection schemes are involved for example. When transient temperature profiles have to be accurately defined, for highly reactive resins or for short part applications, the two-equation model is more appropriate.

KEYWORDS : Composites Manufacturing, Heat Transfer, Dispersion Coefficient

HEAT TRANSFER MODELS IN LCM PROCESSES

Heat transfer in composite manufacturing involves conduction of heat towards the mold walls, convection by the resin as it flows through the preform and heat generation as the resin cures. For LCM processes, two heat transfer models are reported in the literature.

The Non Local Thermal Equilibrium (NLTE) model or the two-equation model is derived by considering the energy balance in the two components (resin and fibers) separately [1-3]:

$$\phi(\rho C_p)_m \frac{\partial \langle T_m \rangle}{\partial t} + (\rho C_p)_m \nabla \cdot (\langle v_m \rangle \langle T_m \rangle) = \nabla \cdot (K_m \cdot \nabla \langle T_m \rangle) + H(T_m - T_f) + \phi \dot{s} \quad (1)$$

$$(1 - \phi)(\rho C_p)_f \frac{\partial \langle T_f \rangle}{\partial t} = \nabla \cdot (K_f \cdot \nabla \langle T_f \rangle) - H(T_m - T_f) \quad (2)$$

where ρ , K and C_p are the density, the heat conductivity tensor and the heat capacity of the materials, ϕ is the porosity of the porous medium, $\langle v_f \rangle$ is the injection average velocity, \dot{s} is the heat generated by the curing reaction, and the subscripts f and m refer to the fiber (fabric) and to the resin (matrix) properties. H is the heat exchange parameter and is defined by [4]:

$$H = a_{fm} h_{fm} \quad (3)$$

where h_{fm} is the heat exchange coefficient between resin and fibers, and a_{fm} is the specific area representing the fibrous architecture at tow scale, expressed for a woven fabric by [5]:

$$a_{fm} = \frac{4}{d_p} \quad (4)$$

d_p being the length scale of the composite, set to be a fiber tow diameter as far as woven fabric is considered.

This model is precise but difficult to use as the heat exchange coefficient needs to be determined [6-10]. The alternative is to use the Local Thermal Equilibrium (LTE) model or the one-equation model based on the assumption that local resin and fiber temperatures are equal:

$$\langle T_m \rangle = \langle T_f \rangle = \langle T \rangle \quad (5)$$

Applying the LTE assumption to equations 1 and 2 and using the volume averaging method [3], the one-equation model is obtained, assuming that no curing reaction is involved:

$$\left(\phi(\rho C_p)_m + (1 - \phi)(\rho C_p)_f \right) \frac{\partial \langle T \rangle}{\partial t} + (\rho C_p)_m \langle v_m \rangle \cdot \nabla \langle T \rangle = \nabla \cdot (K_e \cdot \nabla \langle T \rangle) \quad (6)$$

The effective conductivity tensor K_e is also called the stagnant conductivity and may be estimated as the average of the materials thermal conductivities, as described below:

$$K_e = \phi K_m + (1 - \phi) K_f \quad (7)$$

This assumption is valid under certain conditions. For instance, the temperature gradient between the two phases must be negligible, thus that the ratio of the thermal conductivities should be approximately unity. Numerical computations show that almost no temperature difference exists when non-metallic materials are considered, thus that the local thermal equilibrium assumption can be valid for LCM processes [11]. However, using one model or the other depends on the injection parameters. For instance, it was shown that the one-equation model breaks down when high injection velocities are used or when a significant heat generation occurs in one of the two phases [11-14].

HEAT DISPERSION DURING LIQUID FLOW IN POROUS MEDIA

Local variations of velocity are associated with the thermal conductivity tensor K by adding a thermal dispersion coefficient K_D to the effective thermal conductivity K_e in the one-equation model.

$$K = K_e + K_D \quad (8)$$

This coefficient is expected to depend on the velocity of the flow front, on the porosity and structure of the medium and on the thermal characteristics of the materials [1-3].

Characterization of the heat dispersion coefficient was performed for a given resin /fiber system [14] from an inverse method based on an analytical solution derived from the one-equation model at steady state [15] for a unidirectional non reactive flow through an isotropic preform. Steady state temperature profiles obtained numerically and experimentally are shown on Fig. 1.

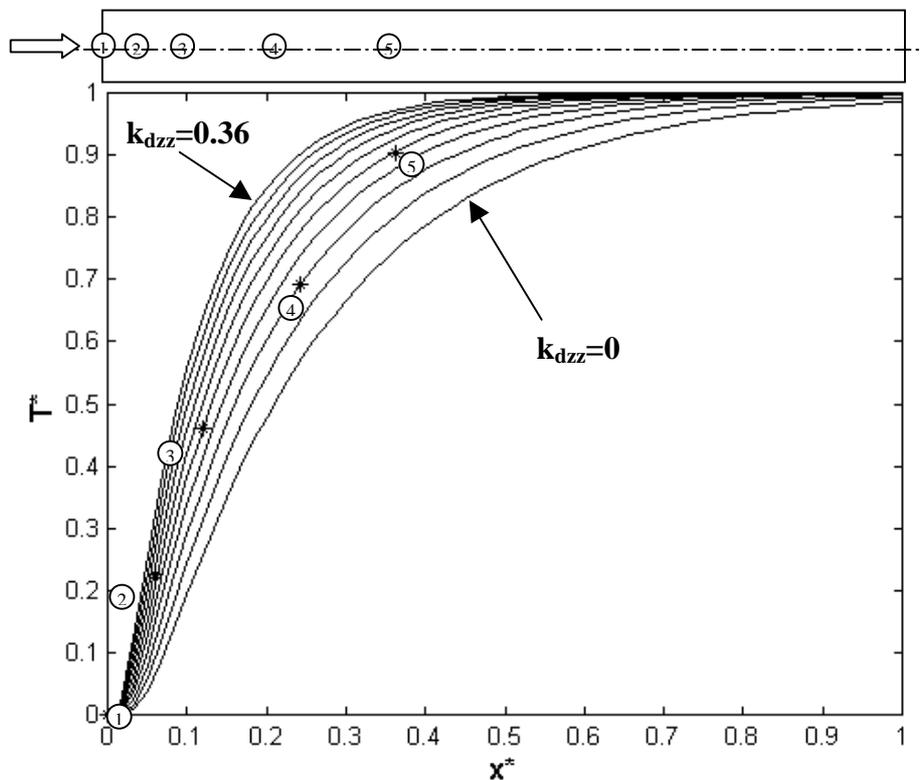
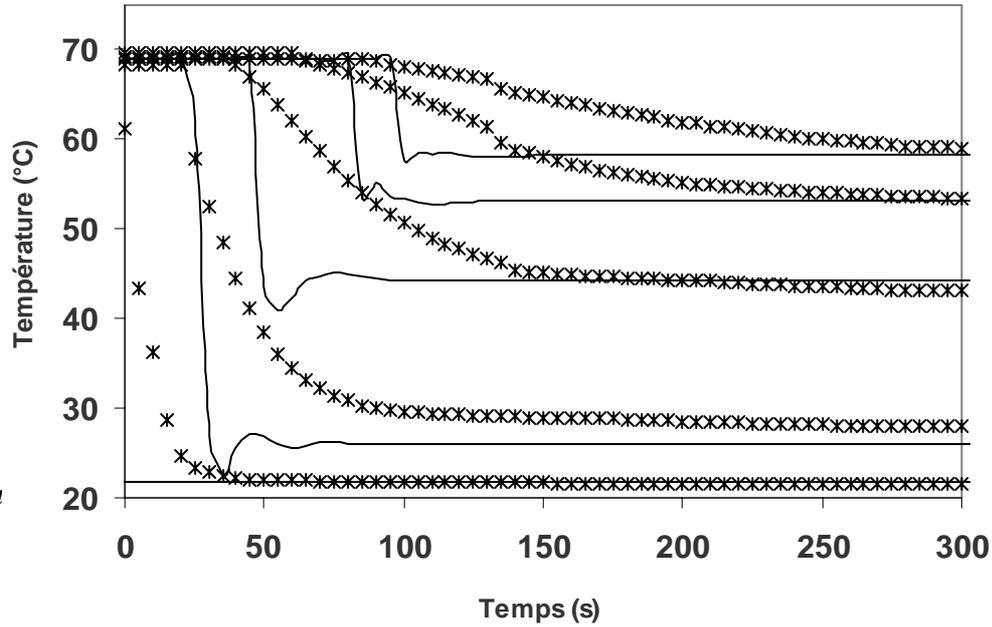


Figure 1 Numerical steady state temperature profiles (solid lines) obtained for different heat dispersion coefficient vs. experimental temperature profile (stars)

Good correlation at steady state is thus obtained between the experimental and the analytical temperature profile along the mold when heat dispersion is considered. However, at the transient stage, large discrepancies are observed, as shown in Fig. 2. The two-equation model is required, thus accurate characterization of the heat exchange coefficient h_{fm} would be needed.



Figur

ical (solid lines) and experimental (dotted lines) transient temperature profiles at different location along the flow front

HEAT EXCHANGE COEFFICIENT DETERMINATION

The method presented here for the heat exchange coefficient is based on an inverse method, the numerical solution being derived from the two-equation model :

$$\phi(\rho C_p)_m \frac{\partial T_m}{\partial t} + (\rho C_p)_m \langle v_m \rangle \frac{\partial T_m}{\partial x} = (k_m + k_d) \frac{\partial T_m}{\partial z^2} + H(T_f - T_m) \quad (9)$$

$$(1 - \phi)(\rho C_p)_f \frac{\partial T_f}{\partial t} = k_f \frac{\partial T_f}{\partial z^2} - H(T_f - T_m) \quad (10)$$

where k_m and k_f are the conductivity of resin and fibers respectively and k_d is the dispersion coefficient. The equations are simultaneously solved using a multiphysics FE-based calculation tool (COMSOL Multiphysics 3.2). The program is inserted in an optimization program written with Matlab 6.5. The numerical temperature-histories for different locations along the flow direction are compared to experimental temperature profiles. The closest numerical solution to the experimental ones will determine the heat exchange coefficient corresponding to the injection considered.

EXPERIMENTAL SET-UP AND RESULTS

Glass fiber woven fabric (plainweave 5x4 woven fabric, Veterotex America) are placed into a closed mold with thermocouples located at the mid section of the preform as shown on Figure 3. A non catalysed vinylester resin (Derakane 411C50, Dow Chemichals) is employed. The recording of the temperature at the different locations is continued until the end of the experiment. When resin reaches the heated fibers, the temperature drops, as the average temperature of resin and fiber will be lower since the injected resin is cold.

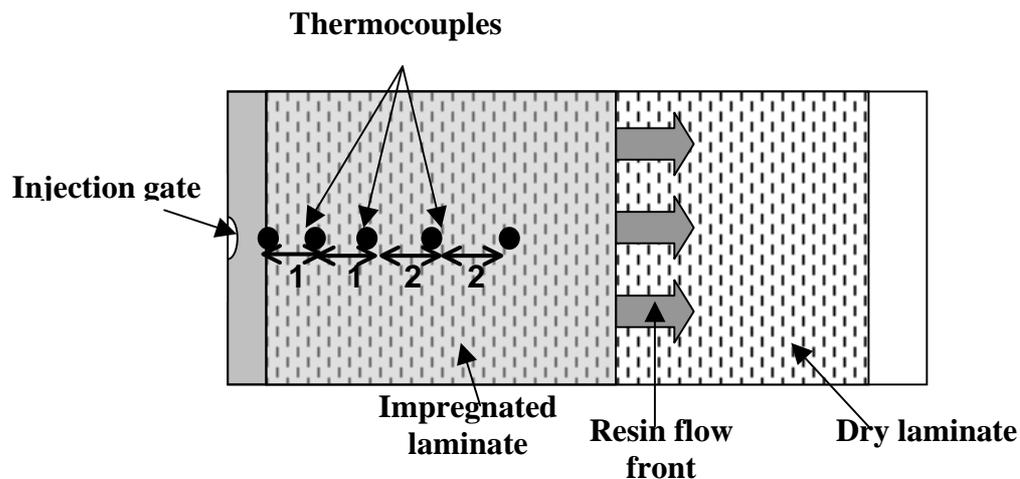


Figure 3 Experimental injection set-up and thermocouples location
(unit : inch)

The heat transfer coefficient is determined by an optimization program that searches for the numerical solution parametered by the heat transfer parameter H closest to the experimental temperature profile.

Figure 4 represents the experimental temperature profiles along with the numerical solution derived from the one- and the two-equation models. Numerical curves fit better the experimental data when a two-equation model that includes the heat exchange effects between resin and fibers is used. Local thermal discrepancies of 15°C can be reached between the two numerical models.

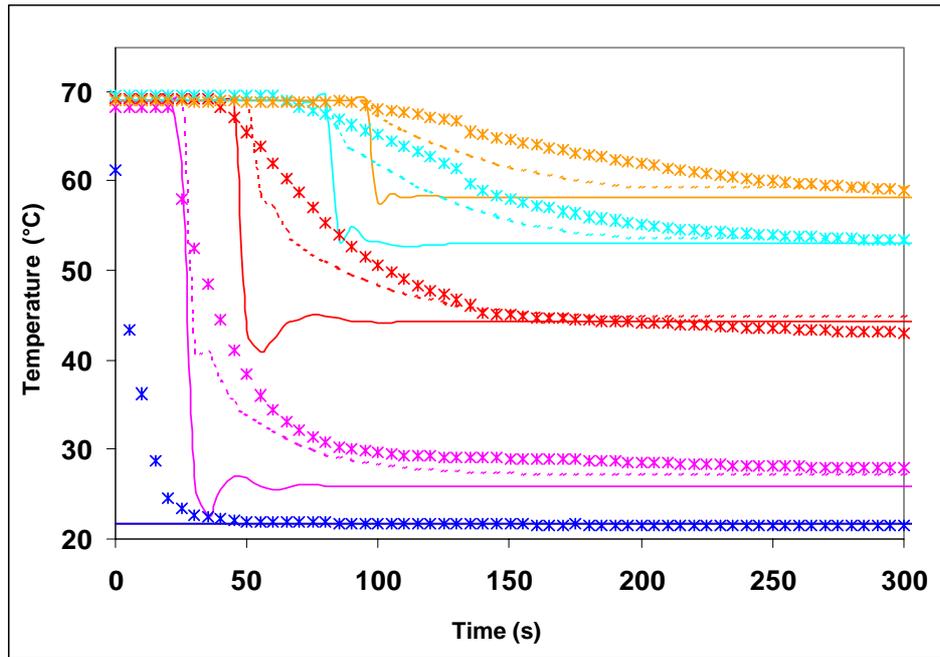


Figure 4 Comparison between one-equation model (solid lines), two-equation model (dotted lines), and experimental profiles (*) at different locations along the flow front direction

CONCLUSION

For accurate prediction of transient temperature profiles during the filling of a fibrous preform, it is necessary to consider the heat transfer coefficient between resin and fibers at the local scale. Numerical temperature profiles were obtained by implementing the two-equation model in a finite element code. The one-equation model without local heat exchange effects was also studied. It was shown that large temperature difference between the prediction of the two models can be obtained. The one-equation model would only give accurate temperature prediction at steady state. This model should only be used in slow processes, with slow temperature changes, whereas the two-equation model is needed for fast injection processes in order to correctly predict the curing kinetics of the resin system.

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