FPCM-9 (2008)
The 9th International Conference on Flow Processes in Composite Materials
Montréal (Québec), Canada
8 ~ 10 July 2008

ANALYSIS OF MULTIPLE ZONE HEATING IN RESIN TRANSFER MOLDING

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SUMMARY: Because of the critical importance of temperature in composite processing, it may be advantageous to heat the mold locally with more than one control temperature. Then the following questions arise: how many zones should one consider? What is the best injection temperature? The present work aims to explore with numerical simulation and analytical calculations the new opportunities that arise in Resin Transfer Molding by considering multiple zone heating. The ultimate goal is not only to speed up the fabrication process, but also to improve part quality by determining temperature ramps to even out the evolution of cure in the part. This study aims to assess the relevance of multiple zones heating and compare the performance of one, two or three heating zones in a mold. Numerical simulations will be carried out in a one-dimensional test mold to evaluate the feasibility of heating molds with multiple heat sources. First, the injection time is calculated analytically as a function of the temperatures of the heating zones. Then, an analytical model is developed in the one-dimensional case in order to find the best mold heating temperatures for a resin injected at a given temperature. The modification of one temperature control influences the injection time and, as a result, the polymerization of the resin in the mold. An optimization strategy will be devised for a unidirectional injection in a rectangular mold, taking into account the injection conditions, resin cure kinetics and viscosity, and the heating of the mold and resin. Finally, the sensitivity of the optimization results will be analyzed with respect to the data, the ultimate objective being to verify experimentally this approach in the 1D case before application to a complex mold.

KEYWORDS: RTM, heating, cure, resin polymerization

INTRODUCTION

In Resin Transfer Molding, the mold is usually heated in order to decrease the resin viscosity and enable the polymerization reaction. Several means exist to heat molds, such as embedding heating pipes in the mold core, through which a heating fluid is injected, or by incorporating electrically heated cartridges in the mold base/cover. The assigned heating temperature is usually set to a constant value. A heating fluid may be provided from the same heating source, then split through embedded pipes, or the heating cartridges may be controlled simultaneously by the same electrical current. Hence, despite the critical importance of temperature in composite processing, the heating process has always been considered in a “global way”.

Usually only one temperature degree of freedom is available or sometimes two, to control the temperature of the bottom and top molds. The present report aims to analyze the new opportunities in resin transfer molding arising from multiple zone heating. The ultimate goal is not only to speed up the fabrication process, but also to improve the part quality by determining temperature ramps to even out the evolution of cure in the composite, and hence reduce residual stresses and warpage. The investigation reported here includes the development of analytical solutions and numerical simulations. In order to keep things simple, two cases are considered, two and three zone heating in a rigid rectangular mold as typically used in Resin Transfer Molding (RTM).

MODEL DESCRIPTION

As a typical model, the cross-section of a planar rectangular mold is considered in Fig. 1. The length is set to 1 m and the total thickness including the mold base, mold cover and cavity is 20 cm. The height of the cavity where fiber impregnation takes place is 3 mm, the targeted part thickness (see Fig. 1). The relative injection pressure with respect to the atmospheric pressure is P0 at the inlet gate. It decreases to zero on the flow front located at position x_f along the mold longitudinal axis at time t.

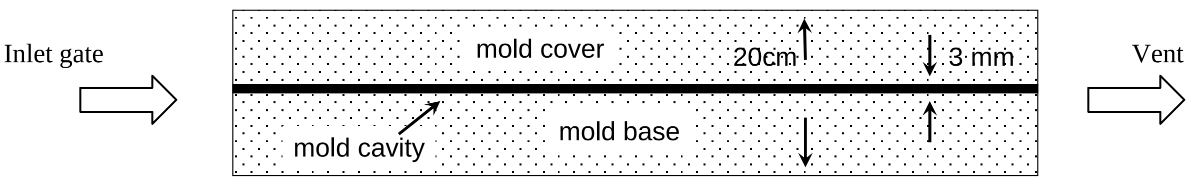

Fig. 1 Vertical cross-section of a typical rectangular mold.

The mold is assumed to be made of epoxy and aluminum with the intrinsic material properties of Table 1 calculated by the rule of mixture. The permeability of the fibrous reinforcement is set to 10-9 m2 and the porosity is 0.3. Since the goal of this analysis is to improve temperature control during the curing stage, typical resin kinetics based on Kamal-Sourour autocatalytic model is selected, in which the degree of cure is expressed by:

$$\frac{d\alpha}{dt} = \left(K_1 + K_2\,\alpha^m\right)\left(1-\alpha\right)^n \tag{1}$$

Resin viscosity depends on the temperature and degree of cure and is often represented by an exponential function:

$$\mu = \mu_\infty\, e^{\left(-\frac{U}{RT} + K_\mu \alpha\right)} \tag{2}$$

TWO ZONE HEATING

In this section the isothermal case at 390°K will be compared to two zone heating. Heating of the mold can be carried out with two heating pipes near the inlet and two heating pipes near the vent embedded respectively in the mold cover and base (see Fig. 3). Note that resin is injected only after the preheating of the mold is complete, namely when the temperature has reached a steady state.

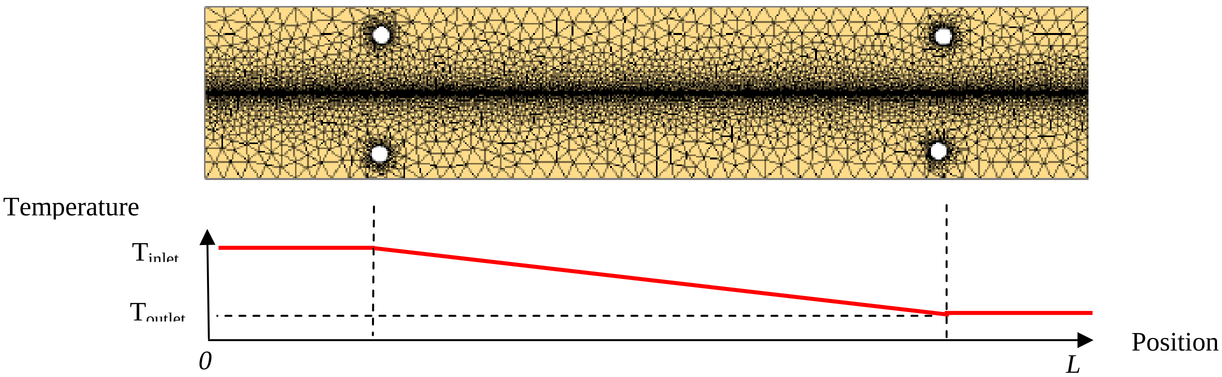

Fig. 3 Mould mesh

The resulting temperature evolution is described along a central longitudinal axis in the mold by a ramp in the range of the boundary conditions assigned to the heating pipes. This analytical solution was verified by a 2D finite element calculation for the mesh shown in Fig. 3. Since a mean temperature of 390°K is targeted in the mold, once the inlet temperature is set, the vent temperature is then uniquely defined.

Analytical Approach

To develop an analytical model of cure evolution, the molding process is divided in two stages: (1) in the first one, the cure evolution is predicted during the filling stage; and (2) in the second one, only resin polymerization is considered. During the first stage, a major hypothesis is made, namely that the viscosity of the resin is not affected by the chemical reaction of polymerization. This assumption is based on the relatively slow resin kinetics in the operating temperature range. At a first glance, this assumption appears unrealistic, but during the impregnation stage polymerization remains an undesirable effect as one seeks to minimize the total filling time. In this case, equation (2) simplifies to:

$$\mu = \mu_{\infty} e^{-\frac{U}{RT}} \qquad (12)$$

The next step consists of finding a mathematical expression for the total filling time. For this, one has to look back to the resin transport. The resin velocity is given by Darcy's law as follows:

$$v = \frac{K}{\phi\,\mu}\nabla p \tag{13}$$

Temperature varies following a ramp from the inlet to the vent, and thus can be written as a function of position between the two heating pipes:

$$T\left(x\right) = a\,x + b \tag{14}$$

Space is then uniformly discretized, in which case the velocity at a given position xn may be expressed as follows:

$$v = \frac{K}{\phi\,\mu_{\infty} e^{-\frac{U}{R\left(a\,x_n + b\right)}}}\left(\nabla p\right)_n \tag{15}$$

where $\left(\nabla p\right)_n$ denotes the pressure gradient at position $x_n = n\Delta x, 0 \leq n \leq N \ with \ N\Delta x = L$. We get

$$\left(\nabla p\right)_0 = \frac{P_0 - p(\Delta x, t)}{\Delta x} \tag{16}$$

$$\left(\nabla p\right)_n = \frac{p\left[n\Delta x, t\right] - p\left[(n+1)\Delta x, t\right]}{\Delta x} \tag{17}$$

$$\left(\nabla p\right)_{N-1} = \frac{p\left[(N-1)\Delta x, t\right] - p\left[N\Delta x, t\right]}{\Delta x} = \frac{p\left[(N-1)\Delta x, t\right]}{\Delta x} \tag{18}$$

At any given time during resin impregnation the instantaneous velocity is the same everywhere in the domain, since a flat plate of uniform thickness is being filled by an incompressible fluid. If the injection is performed at constant pressure, the velocity will change in time, but it remains uniform everywhere in the saturated preform. If the injection is carried out at constant flow rate, the velocity is not only uniform in the cavity at any given time, but it remains also constant in time. Using equation (15) between two successive points, one can therefore write for $1 \leq n \leq N - 1$:

$$\left(\nabla P\right)_{n+1} = \frac{e^{-\frac{U}{R\left(a\,x_{n+1} + b\right)}}}{e^{-\frac{U}{R\left(a\,x_n + b\right)}}}\left(\nabla P\right)_n \tag{19}$$

Hence by recurrence we get

$$\left(\nabla p\right)_n = \frac{e^{-\frac{U}{R(ax_n + b)}}}{e^{-\frac{U}{Rb}}}\left(\nabla p\right)_0 \tag{20}$$

Moreover, the pressure gradients along the spatial discretization sum up to the total gradient from the inlet to the outlet of the mold:

$$\sum_{0}^{N_f-1}(\nabla P)_n = \frac{P_0}{\Delta x} \tag{21}$$

Another simplification comes from the temperature ramp that has a relatively small slope. Consequently, $a\,x_n << b$, which leads to:

$$e^{-\frac{U}{R(a\,x_n+b)}} = e^{-\frac{U}{R\,b\left(\frac{a}{b}x_n+1\right)}} = e^{-\frac{U}{R\,b}\left(1-\frac{a\,x_n}{b}\right)} = e^{-\frac{U}{R\,b}}\,e^{\frac{a\,U\,x_n}{R\,b^2}} \tag{22}$$

Hence, summing over the discrete points gives:

$$(\nabla p)_0\left[\sum_{0}^{N_f-1} e^{-\frac{U}{R(ax_n+b)}}\right] = \frac{P_0}{\Delta\,x}e^{-\frac{U}{Rb}} \tag{23}$$

Using the properties of a geometric progression, the following expression is obtained:

$$\sum_{0}^{N_f-1}\left(e^{\frac{aU\Delta x}{Rb^2}}\right)^n = \frac{P_0}{\Delta x(\nabla P)_0} = \frac{1-\left(e^{\frac{aU\Delta x}{Rb^2}}\right)^{N_f}}{1-e^{\frac{aU\Delta x}{Rb^2}}} = \frac{1-\left(e^{\frac{aU\Delta x}{Rb^2}}\right)^{N_f}}{-\frac{aU\Delta x}{Rb^2}} \tag{24}$$

and after rearrangement:

$$(\nabla p)_0 = -\frac{P_0 Ua}{Rb^2\left(1-e^{\frac{aUx_f}{Rb^2}}\right)} \tag{25}$$

Therefore the velocity of the resin is given by:

$$v_f = \dot{x}_f = \frac{K\,aU\,P_0}{-\phi\,\mu_\infty R\,e^{-\frac{U}{Rb}}\,b^2\left(1-e^{\frac{aU\,x_f}{Rb^2}}\right)} \tag{26}$$

Setting the initial time at the beginning of resin injection and integrating gives the time t(x) when the resin front reaches position x in the mold,

$$t(x) = -\frac{\left(x - \frac{b^2 R\, e^{\frac{U a x}{R b^2}}}{a U} + \frac{b^2 R}{a B} \right) \phi \mu_\infty b^2 R\, e^{-\frac{U}{Rb}}}{K P_0\, a\, U} \qquad (27)$$

This mathematical development shows that the total injection time can be readily obtained by assuming that the polymerization is slow enough so as not to influence the resin viscosity mold during filling, which is the case usually in the RTM process. To carry out the analysis, four points are chosen to follow numerically the degree of cure at L/8, 3L/8, 5L/8, 7L/8, L being the total length of the mold cavity. To calculate the degree of cure at the end of the injection for each selected sensor location, the effect of polymerization on viscosity can be neglected, and simplified resin kinetics used, namely:

$$\frac{d\alpha}{dt} = A_1 e^{\frac{E_1}{RT}} \qquad (28)$$

This equation allows estimating the degree of cure at each sensor location at the end of mold filling. For example, the resin reaching the first sensor stayed t(8L/8) – t(7L/8) sec under a temperature aL/16+b, which allows calculating the degree of cure.

Once the degree of cure has been estimated at the end of mold filing, the full Kamal-Sourour model is considered and discretized in time in order to predict the evolution of cure after mold filling as a function of time. Afterwards, for some chosen times (1 min, 1 min 30 s, 2 min, 2 min 30 s), the difference between two neighboring sensors can be easily determined. The algorithm calculates the maximum cure difference between any two successive sensors. The procedure is repeated for different temperatures to evaluate the effect of temperature on the spatial variations of the degree of cure. The results are then compiled to determine the temperature that minimizes these variations along the composite. The temperature for which the cure gradient is the lowest (11.3%) is 420°K at the mold inlet and therefore 360 °K at the vent (see Fig. 4). Note that in the case of isothermal mold heating, the gradient of the degree of cure exceeds 25%, whereas a linear temperature distribution results in gradients of less than 12%.

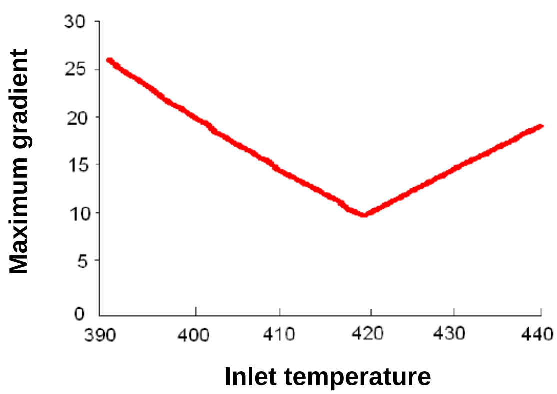

Fig. 4 Maximum cure gradient along the length of the composite part as a function of the inlet temperature for two heating zones (recall that a mean mold temperature of 390°K was selected).

THREE ZONE HEATING

In the case of three zone heating, the temperature distribution follows two linear functions distributed along two portions of the mold: $ax + b$ in the first half, and $cx + d$ in the second half, with of course a continuity condition in the center of the mold. When the first half of the mold is filled, the evolution of the flow front remains the same as detailed in the previous section (two heating zones). One can then write for

$$t < -\frac{\left(\frac{l}{2} - \frac{b^2 R\, e^{\frac{U a l}{2 R b^2}}}{a U} + \frac{b^2 R}{a U}\right) \phi\, \mu_\infty b^2 R\, e^{-\frac{U}{R b}}}{K P a U} \tag{29}$$

the filling time as:

$$t(x) = -\frac{\left(x - \frac{b^2 R\, e^{\frac{U a x}{R b^2}}}{a U} + \frac{b^2 R}{a U}\right) \phi\, \mu_\infty b^2 R\, e^{-\frac{U}{R b}}}{K P a U} \tag{30}$$

Analogously, in the second half of the mold:

$$\sum_0^{\frac{l}{2}} e^{-\frac{U}{R(a x_n + b)}} + \sum_{\frac{l}{2}}^{n} e^{-\frac{U}{R(c x_n + d)}} = \frac{P}{\Delta x (\nabla p)_0}\, e^{-\frac{U}{R b}} \tag{31}$$

Using the same approximations as in the previous case, we get:

$$\frac{b^2 R}{a U}\left(1 - e^{\frac{a U l}{2 R b^2}}\right) + \frac{d^2 R}{c U}\, e^{-\frac{U}{R}(\frac{1}{d} - \frac{1}{b})} e^{-\frac{c U l}{2 d^2 R}} \left(1 - e^{\frac{c U x}{d^2 R}}\right) = \frac{P}{(\nabla p)_0} \tag{32}$$

Therefore

$$(\nabla p)_0 = \frac{P U}{R\left(\frac{b^2}{a}\left(1 - e^{\frac{a U l}{2 R b^2}}\right) + \frac{d^2}{c}\, e^{-\frac{U}{R}(\frac{1}{d} - \frac{1}{b})} e^{-\frac{c U l}{2 d^2 R}} \left(1 - e^{\frac{c U x}{d^2 R}}\right)\right)} \tag{33}$$

Integrating and applying boundary conditions gives:

$$t(x) = \frac{\phi\, \mu_\infty R\, e^{-\frac{U}{R b}} \left(\left(x - \frac{1}{2}\right)\left(\frac{b^2}{a}\left(1 - e^{\frac{a U l}{2 b^2 R}}\right) + \frac{d^2}{c}\, e^{-\frac{U}{R}(\frac{1}{d} - \frac{1}{b})} e^{-\frac{c U l}{2 d^2 R}}\right) - \frac{d^4 R}{c^2 U}\, e^{-\frac{U}{R}(\frac{1}{d} - \frac{1}{b})} e^{-\frac{c U l}{2 d^2 R}} \left(e^{\frac{c U x}{d^2 R}} - e^{\frac{c U}{2 d^2 R}}\right)\right)}{K\, U\, P_0} + t(1/2) \tag{34}$$

which is the time necessary for the resin to reach the position x located in the second half of the mold. In a similar way, with a_i and b_i the parameters of heating zone i, the expression of the pressure gradient along the part is the following:

$$(\nabla p)_0(x) = \frac{P_0 U}{R\left(\left[\sum_{i=1}^{n-2} \frac{b_i^{\,2}}{a_i}\left(1 - e^{\frac{a_i U i l}{(n-1) R b_i^2}}\right) e^{-\frac{U}{R}\left(\frac{1}{b_i} - \frac{1}{b_1}\right)} e^{-\frac{a_i U (i-1) l}{(n-1) R b_i^2}}\right] + \frac{b_{n-1}^{\,2}}{a_{n-1}} e^{-\frac{U}{R}\left(\frac{1}{b_{n-1}} - \frac{1}{b_1}\right)} e^{-\frac{a_{n-1} U (n-2) l}{(n-1) b_{n-1}^{\,2} R}} \left(1 - e^{\frac{a_{n-1} U x}{b_{n-1}^{\,2} R}}\right)\right)}$$

In order to determine the optimal temperature that reduces the gradient of the degree of cure, the heating slopes may be varied just by changing the temperature in the center of the mold. Fig. 5 shows the maximum cure gradient along the central longitudinal axis in the mold as a function of the temperature in the center of the mold.

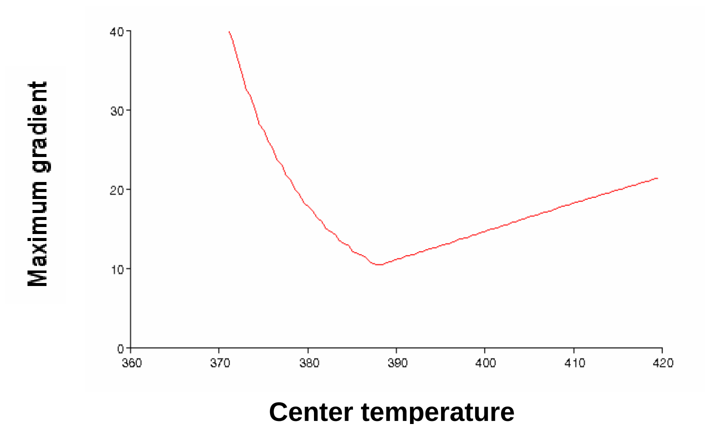

Fig. 5 Maximum cure gradient along the composite part as a function of temperature in the center of the mold for three heating zones.

Note that for a temperature of 390°K, the result of the previous section is recovered. The minimum cure gradient is obtained at T = 388°K. In this case the cure gradient is 10.5% (compare to 26% with a single heating zone). By adding two new heating zones, the sequence 420°K - 399°K - 384°K - 373°K - 360°K gives a gradient of 7.5%.

NUMERICAL SIMULATION

Let us consider two and three heating zones between 420°K and 360°K. The numerical simulations are carried out with PAM-RTM software. In the zone heated at 420°K, the resin viscosity decreases; this facilitates the flow. Meanwhile, the zone at 360°K does not increase much the degree of cure of a resin that has already been through the 420°K zone. Therefore, this lower temperature evens out the degree of cure. The total injection time is 17 s, and a time of 280 s is needed for the whole part to exceed 95% polymerization. This represents already a 50 s gain compared to a single heating strategy. Fig. 6 and 7 show the evolution of the degree of cure as a function of time along the composite part for two and three heating zones respectively. The degree of cure is more uniform along the part as seen in Fig. 7. Thus for three heating zones, the injection time as well as the time necessary to reach a 95% degree of cure is almost the same as for two heating zones. However, the degree of cure is more uniform.

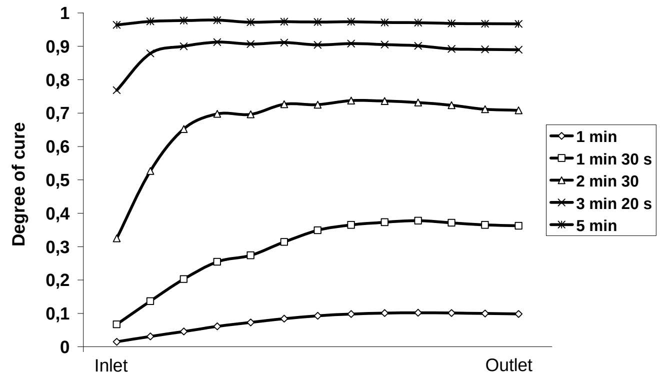

Fig. 6 Evolution of the degree of cure as a function of time along the composite part for two heating zones.

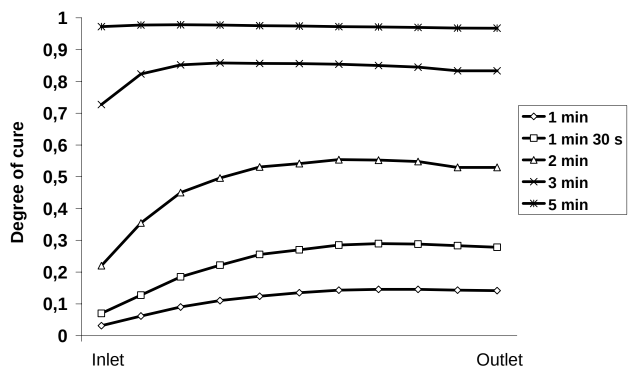

Fig. 7 Evolution of the degree of cure as a function of time along the composite part for three heating zones.

CONCLUSION

Multiple zone heating allows obtaining a better uniformity in the degree of cure, while maintaining an acceptable injection time. However, one has to ensure that there is enough improvement in the part quality to compensate for the cost of a more sophisticated heating system.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. John Owens, from General Motors Laboratory, Detroit, USA, for his advises regarding the orientation of the research, and General Motors (GM) of Canada, the Canada Research Chair program and the National Science & Research Council of Canada (NSERC) for their financial contributions. The support of “Centre de recherche en plasturgie et composites” (CREPEC) and of “Consortium de recherche et d’innovation en aérospatiale du Québec” (CRIAQ) for the infrastructure of the Laboratory of the Chaire sur les Composites à Haute Performance (CCHP) are also gratefully acknowledged.