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THERMAL CONTROL OF THE RESIN TRANFER MOLDING PROCESS

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SUMMARY: This study consists of determining the optimal set point of the temperature of the fluid flowing through heat exchangers in a RTM mold so as to reach a predetermined thermal history in the composite part. The metallic mold is composed of several parts. Assembling these parts is not possible without introducing imperfect contacts that perturb heat transfer between them. Then in order to estimate the optimal set point of the temperature of the fluid, it is necessary in a first stage to evaluate the most influent thermal contact resistances between the parts. The determination of the TCR is achieved by an optimization approach and carried out on a 2D transverse cut of the mold. Experimental temperature measurements in the mold are matched to the computed responses of the heat conduction model. A least square criterion is minimized by using the conjugate gradient algorithm. The gradient of the criterion is determined by solving a set of adjoint equations. After the identification of these parameters, the same optimization method is used to compute the optimal set point of the fluid temperature. It is notable that the same set of adjoint equations is used to solve both problems.

KEYWORD: Optimization, conjugate gradient algorithm, inverse method, RTM, metallic mold.

INTRODUCTION

The use of structural pieces made of composite materials for aeronautic applications has increased a lot these last years. The Resin Transfer Molding is one of the processes used for the manufacture of such pieces. This process consists in injecting with low pressure a thermoset resin into a dry preform previously disposed into a closed mold. After the filling of the mold, the curing of the resin occurs. Then after the curing the piece is removed from the mold and the next cycle begins. To keep this process profitable in front of other ones [1], time cycles must be reduced and quality of pieces controlled. Heat transfer appears to be a key point to reach these conditions in the different stages of the process. In the case of aeronautic applications the molds are often metallic. The thermal regulation of these molds is achieved most of the time with the help of air oven. The use of air oven generates several constraints among which the financial investment is one of the most significant. Furthermore size of the manufactured pieces which become increasingly large may prevent the use of air oven. In these devices air is the fluid which transfers heat. However the thermal inertia of air is so weak that even with a high circulating velocity the heat transfer remains slow. As a consequence temperature cycles are long and the accurate control of temperature is difficult. For these reasons a prototype mold was designed to enable a better control of heat transfer in the piece [2] while increasing the rate of output. This mold possesses its own heat exchangers what makes it autonomous the use of air oven being useless. The temperature of the fluid circulating in these exchangers can be controlled. Then from a desired cycle of temperature in the preform one can determine with the appropriate method the temperature to impose on the heat exchangers.

EXPERIMENTAL PROCESS

The mold is composed of several metallic elements as indicated by the cut view in Fig.1. The heating and the cooling of the mold and the piece are ensured by heat exchangers positioned on the external surface of the mold. The temperature of the fluid which flows in the exchanger is controlled. The composite part manufactured with this mold (grey part in Fig.1) is a beam which has a shape of H. It is composed of carbon reinforcement and epoxy resin. It possesses a length of about 9 m and a thickness varying from 5 mm to 9 mm.

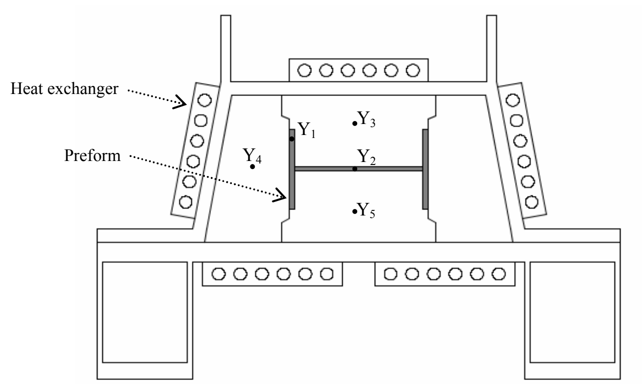

Fig. 1 2D cut view of the mold.

Thermocouples are inserted at different locations in the part and in the mold. In the followings the readings of these sensors will be denoted by $(Y_i)_{i=1,5}$. As indicated in Fig. 1, Y_1 and Y_2 are located in the preform; Y_3, Y_4 and Y_5 at different positions in the mold. The goal of this work is to determine the temperature of the fluid so as to reach a predetermined cycle in the preform. This cycle of temperature imposed by the manufacturer consists in heating the preform at a first level of temperature where the resin is injected. After the end of the injection, it is heated again to reach a second level of temperature so as to polymerize the resin. In the last part of the cycle it is cooled down to ambient temperature where the part can be removed from the mold. However as described before assembling the different parts of the mold is not possible without introducing imperfect contacts that perturb heat transfer between the parts. Thermal contact resistances (TCR) allow modeling the influence of these perturbations on the temperature field in the mold. To point out the influence of TCR, two numerical resolutions of the conduction problem were performed by considering two different values of TCR ($10^{-3}\,m^2.K/W$ in the first case and $5.10^{-3}\,m^2.K/W$ in the second case). The difference of temperature in the preform obtained between these two cases reaches 5°C for an increase of 35°C what is not negligible. Then in order to estimate the optimal set point of the fluid temperature, it is necessary in a first stage to evaluate the most influent thermal contact resistances between the parts.

NUMERICAL PROBLEM STATEMENT

As explained before two inverse heat conduction problems must be solved. The first one consists in estimating the values of the different TCR and the second one in determining the optimal temperature set-point of the fluid in the heat-exchanger. The spatial domain used to compute the numerical solution of the problems is represented on Fig.2. It is simplified compared to the initial one. For reasons of symmetry, only half of the mold is represented. The frame of the mold is not represented either, the thermal losses in this part are sufficiently weak to be neglected. Finally the heat exchangers are not modeled. Indeed meshing the heat exchangers will increase the number of unknowns and will not improve significantly the results. Then in the first problem (estimation of TCR) a temperature imposed on the external surface of the mold on the sites of the exchangers is used as boundary condition. In the second problem instead of determining directly the temperature in the heat exchanger we estimate the optimal heat flux on the boundaries $(\Gamma_i)_{i=1,2,3}$. Then by using the same kind of inverse method, one can calculate the temperature of the fluid inside the channels of the exchanger to reach this wall temperature.

Six different domains are considered. Each domain presents non perfect contact with its neighbors. By solving the sensitivity problem according to the different TCR it is shown that the contacts on internal boundaries Γ_{11}, Γ_{12} have a very weak influence on the temperature field. For this reason, the TCR on these boundaries are fixed to a constant value and will not be estimated. Moreover since contacts on boundaries Γ_{13} and Γ_{16} occur in the same conditions (material, shape) we model it by the same TCR value. The same reasoning leads to choose only one value for boundaries Γ_{15} and Γ_{17}. Then only four TCR have to be estimated. For convenient reasons inverse of TCR (i.e., equivalent to heat transfer coefficients) are estimated. Then in the followings, these parameters will be noted $(h_i)_{i=1,4}$: h_3 corresponds to boundary Γ_{14}; h_4 to boundary Γ_{12}; h_5 to boundaries $\Gamma_{13} \cup \Gamma_{16}$ and h_6 to boundaries $\Gamma_{15} \cup \Gamma_{17}$.

For practical reasons only heat transfer equations of the sub-domain Ω_2 are presented (Eqn. 1). These equations can easily be generalized to the whole domain. In Eqn. (1) $q(t)$ is a heat flux, h_∞ is the heat transfer coefficient with the surroundings and T_∞ is the ambient temperature. Thermophysical properties (ρ, Cp, λ) are proper to each sub-domain Ω_i. It is noticeable that the resin is not modeled. Indeed the mold has such an important thermal inertia that the effects of the resin are negligible. In particular the heat released by the polymerization of the resin will not be taken into account in the model.

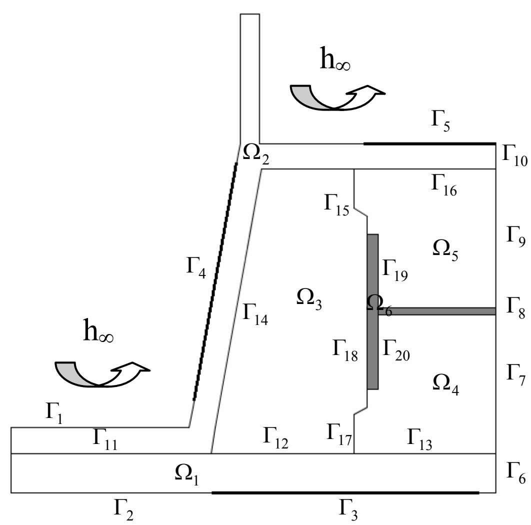

Fig. 2 2D spatial domain used for solving the numerical problem.

$$\rho Cp \frac{\partial T_{\Omega_2}}{\partial t} = \nabla.\left(\lambda \nabla T_{\Omega_2}\right) \quad in\ \Omega_2, t>0$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_{16}} = h_5\left(T_{\Omega_5} - T_{\Omega_2}\right) \quad on\ \Gamma_{16}, t>0$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_{10}} = 0 \quad on\ \Gamma_{10}, t>0$$

$$T_{\Omega_2} = T_0 \quad in\ \Omega_2, t=0$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_{14}} = h_3\left(T_{\Omega_3} - T_{\Omega_2}\right) \quad on\ \Gamma_{14}, t>0$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_1} = h_\infty\left(T_\infty - T_{\Omega_2}\right) \quad on\ \Gamma_1, t>0 \tag{1}$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_4 \cup \Gamma_5} = q(t) \ \text{ or } \ T_{\Omega_2}\big|_{\Gamma_4 \cup \Gamma_5} = T_{set}(t) \quad on\ \Gamma_4 \cup \Gamma_5, t>0$$

Both inverse problems are formulated in the least-square sense and consist in determining the optimal solution which minimizes the functional:

$$J(\beta) = \sum_j \int_0^{t_f} \left\| Y_j(t) - T\left(x_j, y_j, t; \beta\right) \right\|^2 dt \tag{2}$$

where β corresponds to the parameters which have to be determined and T is the solution of heat equation (1) on the whole domain. The unknown to be determined are:

- $\beta = (h_i)_{i=1,4}$ for the identification problem, and $q(t)$ is imposed.
- $\beta = q(t)$ for the input problem, and $(h_i)_{i=1,4}$ are known.

Conjugate Gradient Algorithm (CGA)

These two problems are solved by using the classical CGA. This algorithm is iterative and consists at each iteration *k+1* in correcting the previous estimate β^k according to

$\beta^{k+1} = \beta^k + \rho^k w^k$ in order to obtain $J(\beta^{k+1}) < J(\beta^k)$. In this expression w^k is the search direction and ρ^k the descent length. By naming ∇J the vector gradient of the functional J, the vector w^k and the scalar ρ^k are determined according to the gradient equations:

$$w^k = -\nabla J^k + \gamma^k w'^{k-1} \tag{3}$$

$$\gamma^k = \frac{\left\|\nabla J^k\right\|}{\left\|\nabla J^{k-1}\right\|} \text{with } \gamma^0 = 0 \tag{4}$$

The length of descent ρ is computed to minimize the following scalar function $\phi(r)$ either by solving the sensitivity problem or by using a minimization algorithm [3]:

$$\phi(r) = \sum_j \int_0^{t_f} \left\| Y_j(t) - T\left(x_j, y_j, t; \beta^k + r w^k\right) \right\|^2 dt \tag{5}$$

The Adjoint Problem

Let us introduce the Lagrange multiplier ψ [4,5] and the Lagrangian $L(\psi, T, \beta)$ associated to the optimization problem defined by (2) and the constraint corresponding to the first equation of the system (1):

$$L(\psi, T, \beta) = \int_{t=0}^{t_f} \left\{ \left(\sum_j \left\| Y_j - T_j \right\|^2 \right) - \left\langle \psi, \rho Cp \frac{\partial T}{\partial t} - \nabla.(\lambda \nabla T) \right\rangle_{(\Omega_i)_{i=1,4}} \right\} dt \tag{6}$$

When the adjoint variable is fixed the differential of L is equal to:

$$\delta L = \frac{\partial L}{\partial T} \delta T + \frac{\partial L}{\partial \beta} \delta \beta \tag{7}$$

the Lagrange multiplier is then chosen in order to verify:

$$\frac{\partial L}{\partial T} \delta T = 0, \forall \delta T \tag{8}$$

This condition leads to find the Lagrange multiplier so as to be the solution of the following set of adjoint equations [6]. As for the direct problem, only the adjoint equations concerning the sub-domain 2 are presented.

$$\begin{aligned} &\rho Cp \frac{\partial \psi_{\Omega_2}}{\partial t} + \nabla.\left(\lambda \nabla \psi_{\Omega_2}\right) = \\ &\sum_j (Y_j - T) \delta\left(x - x_j\right) \delta\left(y - y_j\right) \end{aligned} \quad in\ \Omega_2, t > 0 \qquad \left. -\lambda \frac{\partial \psi_{\Omega_2}}{\partial n} \right|_{\Gamma_{14}} = h_3\left(\psi_{\Omega_3} - \psi_{\Omega_2}\right) \quad on\ \Gamma_{14}, t > 0 \tag{9}$$

$$-\lambda \frac{\partial \psi_{\Omega_2}}{\partial n}\bigg|_{\Gamma_{16}} = h_5\left(\psi_{\Omega_5} - \psi_{\Omega_2}\right) \quad on\ \Gamma_{16}, t>0$$

$$-\lambda \frac{\partial \psi_{\Omega_2}}{\partial n}\bigg|_{\Gamma_{10}} = 0 \quad on\ \Gamma_{10}, t>0$$

$$\psi_{\Omega_2} = 0 \quad in\ \Omega_2, t = t_f$$

$$-\lambda \frac{\partial \psi_{\Omega_2}}{\partial n}\bigg|_{\Gamma_1} + h_\infty T_{\Omega_2} = 0 \quad on\ \Gamma_1, t>0$$

$$-\lambda \frac{\partial T_{\Omega_2}}{\partial n}\bigg|_{\Gamma_4 \cup \Gamma_5} = 0 \ \text{ or } \ \psi_{\Omega_2}\big|_{\Gamma_4 \cup \Gamma_5} = 0 \quad on\ \Gamma_4 \cup \Gamma_5, t>0$$

When the adjoint variable is determined from the set of equations (9), the differential of L is equal to $\delta L = \frac{\partial L}{\partial \beta}\delta\beta$. Furthermore, when T verifies equations (1) of the direct problem, we get $\delta L = \delta J$. Note that the adjoint problem remains the same for the two problems considered.

Gradient Components

- Identification problem: $\beta = (h_i)_{i=1,4}$.

$$\frac{\partial J}{\partial h_i} = \int_{t=0}^{t_f} \int_{\Gamma_{h_i}} (\psi_m - \psi_n)(T_n - T_m)\, d\Gamma dt \quad for\ i=1,4 \tag{10}$$

where Γ_{h_i} corresponds to the boundary on which the parameter h_i is applied. ψ_m and ψ_n represent the adjoint fields on the domains Ω_m and Ω_n delimited by the boundary Γ_{h_i}.

- Input problem: $\beta = (q_i)_{i=1,p}$

The heat flux q(t) is approximated in the form $q(t) = \sum_{k=1}^{p} q_k \sigma_k(t)$, where σ_k is a given set of N_p basis functions over the time interval. The gradient components are then equal to:

$$\frac{\partial J}{\partial q_k} = \int_{t=0}^{t_f} \int_{\Gamma_3 \cup \Gamma_4 \cup \Gamma_5} \psi_i \sigma_k\, d\Gamma dt \tag{11}$$

RESUTS AND DISCUSSION

In this article the results are only numerical. What is called “pseudo-experimental” results corresponds to the temperatures resulting from the direct problem (1). For reasons of confidentiality the results are dimensionless. Variables are then defined by:

$$t^* = \frac{t}{t_{ref}}\ ;\ T = \frac{T - T_0}{T_{\max} - T_0}\ ;\ q^* = \frac{q}{q_{\max}} \tag{12}$$

where t_{ref} is a given time, T_0 the initial temperature, T_{max} the maximal temperature and q_{max} the maximal heat flux received by the mold.

Estimation of Contact Resistances

Fig. 3 represents the pseudo-experimental readings of the thermocouples $(Y_i)_{i=1,5}$ as well as the evolution of the wall temperature imposed on boundaries $(\Gamma_i)_{i=3,4,5}$. Experimentally this temperature is measured by a thermocouple placed between the heat exchanger and the external surface of the mold.

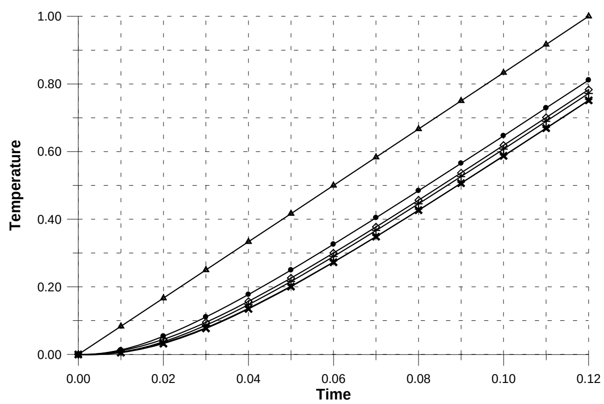

Fig. 3 Temperature of the set-point (Δ) and of the thermocouples (Y_1 +, Y_2 ×, Y_3 ◊, Y_4 **O**, Y_5 ✱).

Fig. 4a represents the evolution of the norm of the LS-criterion *J*. About 1700 iterations are necessary to reach the solution with an initial guess of 100W/m².K for each $(h_i)_{i=1,4}$. Fig. 4b represents the evolution of the four parameters versus the iteration number. The maximum error between the exact and computed values is of 0.5%.

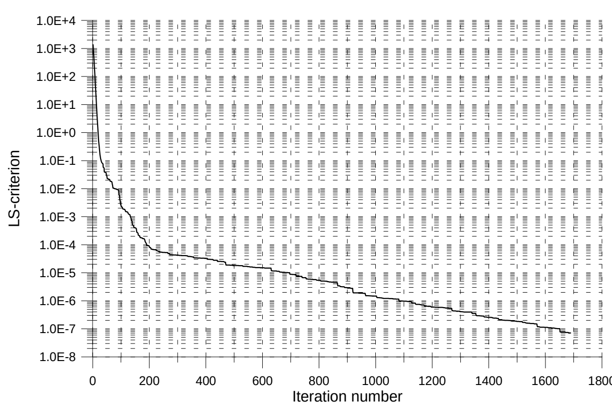

Fig. 4a Norm of the LS-criterion.

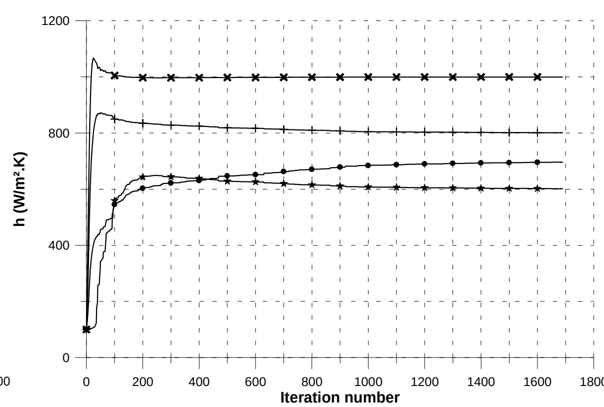

Fig. 4b Estimated coefficient (h3 +, h4 •, h5 ×, h6 ✱).

Determination of the Optimal Set-Point

Once the TCR are estimated one can determine the optimal heat flux which is estimated on boundaries $(\Gamma_i)_{i=3,4,5}$ (Fig. 2). The design of the mold allows considering that the predetermined temperature in the preform can be reached by applying the same heat flux in each heat exchanger. However this method also permits to estimate different heat fluxes in each heat exchanger. The heat flux is searched as a linear piecewise function defined by $q(t)=\sum_{k=1}^{p} q_k \sigma_k(t)$ with p = 70 which means that 70 unknowns have to be estimated. The temperatures used in the functional J are those coming from the thermocouples placed in the reinforcement (Y_1 and Y_2). Indeed the desired temperature is defined only at these two points. Fig. 5a represents the desired and estimated temperature in the preform in the location of Y_1 and Y_2. This figure shows the really good agreement between the two sets of temperatures during the whole cycle.

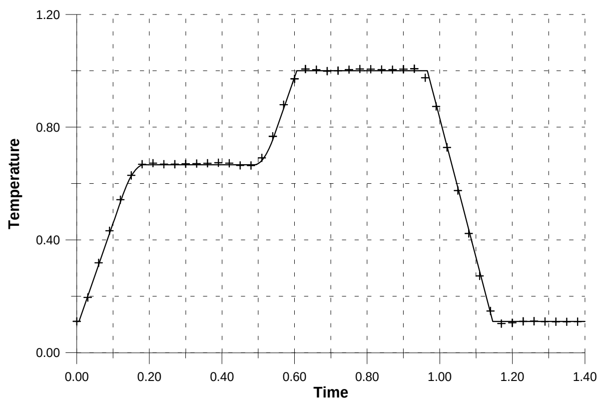

Fig. 5a Desired (▬) and estimated (+) temperatures.

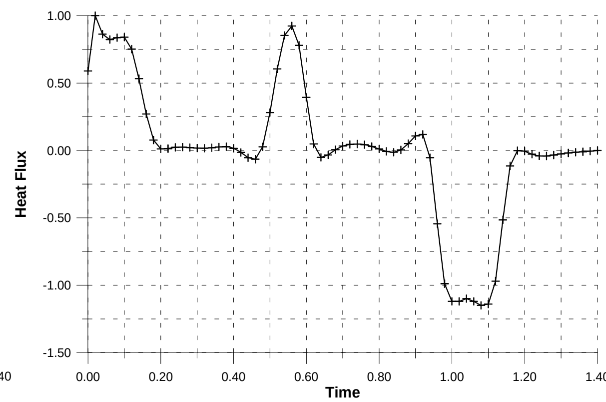

Fig. 5b Optimal heat flux.

Fig. 5b represents the heat flux determined by the algorithm to reach the predetermined temperature. During the first heating ramp the heat flux remains constant during half of the rise and then decreases linearly to reach zero at the beginning of the first isothermal stage. The same kind of evolution occurs during the second heating ramp and then during the cooling. The fact that the heat flux equals zero during isothermal stages indicates that the mold is thermally insulated with the surroundings ($h_\infty = 0$ in Eqn.1). It is also noticeable that the heat flux anticipates the evolution of the temperature so as to vanquish the thermal inertia of the mold and of the preform. Fig. 6 represents the temperature in the preform as well as the temperature to be imposed on the fluid in the exchanger. This temperature is computed from the heat flux determined by using the same kind of inverse method.

CONCLUSION

An RTM autonomous metallic mold was developed for aeronautic applications. This mold is equipped with heat exchangers. By using this type of mold air oven is not needed which present several advantages among which one can note: less investment, possibility to manufacture large sized parts, better control of temperature cycle than in air oven. The conjugate gradient algorithm was used to evaluate the most significant thermal contact resistances between the different parts of the mold. Then the optimal heat flux allowing reaching a predetermined cycle of temperature into the preform was estimated. The results show a very good agreement between the computed and desired temperatures. Although the results presented here are only numerical the results coming from the first molding with this tool are encouraging. Complementary moldings are actually carried out to validate this methodology.

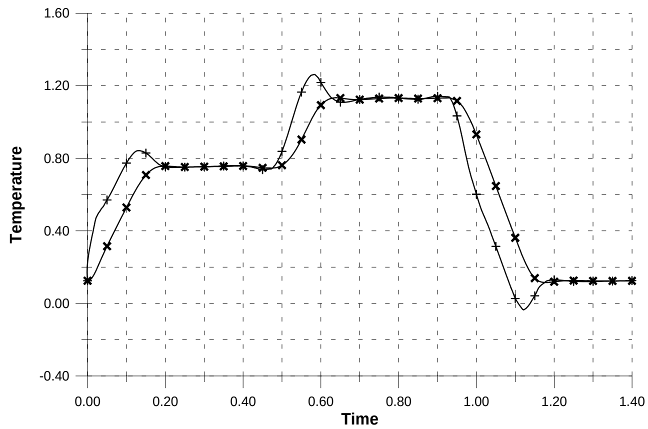

Fig. 6 Temperature in heat exchanger (×) and in the preform (+).

Fig. 6 shows that the determination of this profile of temperature is not intuitive and that this type of method can be very efficient to reach the optimal set-point of temperature.

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REFERENCES

1. J. Verrey, M.D. Wakeman, V. Michaud, and J.-A.E. Manson, "Manufacturing Cost Comparison of Thermoplastic and Thermoset RTM for an Automotive Floor Pan", *Composites: Part A*, Vol. 37, Issue 1, pp 9 (2006).
2. V. Sobotka and D. Delaunay, "Analysis and Control of Heat Transfer in an Industrial Composite Mold in RTM Polyester Automotive Process", *J. of Reinf. Plast and Comp.*, Vol. 26, pp. 881 (2007).
3. R.P. Brent, "Algorithms for Minimization without Derivatives", *Prentice-Hall*, 1973, Dover, (2002).
4. Y. Jarny, "The Adjoint Method to Compute the Numerical Solutions of Inverse Problems", *Inverse Engineering Handbook*, Woodbury K.A. editor, CRC Press LLC,.ISBN: 0-8493-0861-5, (2003).
5. J.-L. Bailleul, V. Sobotka, D. Delaunay. and Y. Jarny, "Inverse Algorithm for Optimal Processing of Composite Materials", *Composites: Part A*, Vol. 34, pp. 695 (2003).
6. R. Abou khachfe and Y. Jarny, "Determination of Heat Sources and Heat Transfer Coefficient for Two-Dimensional Heat Flow – Numerical and Experimental Study", *International Journal of Heat and Mass Transfer*, Vol. 44, Issue 7, pp. 1309, (2001).