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Numerical modelling and optimization of infrared heating system for the blow moulding process

M. Bordival[1], F.M. Schmidt[1], Y. Le Maoult[1]

[1]*CROMeP - Ecole des Mines d'Albi Carmaux*
Campus Jarlard - 81000 Albi, France
URL: www.enstimac.fr *e-mail: bordival@enstimac.fr;*
schmidt@enstimac.fr; lemaoult@enstimac.fr

ABSTRACT: In the blow moulding process, the thermal conditioning of thermoplastic preforms is a critical stage. In the aim of achieving high quality parts, it is crucial to control the preform temperature field at the end of the heating step, by determining an optimum processing window. For that, a software devoted to the numerical simulation of the infrared heating has been developed. This software allows the computation of the three dimensional temperature field of a rotating preform, thanks to the control-volume method. Radiative transfers between infrared emitters (halogen lamps) and preforms are simulated by taking into account front and back reflectors. Since polymers (for example PET) constitute semi-transparent media, the radiative flux absorption is computed according the Beer Lambert law, under the assumption of the non-scattering cold medium. In a second step, this software has been coupled to a non linear constrain optimization algorithm, in order to find the best set of design parameters for the oven geometry, according to a cost function representing the surface temperature uniformity.

Key words: blow moulding process, infrared lamp, PET preform, radiative heat transfer, control-volume method, Beer Lambert law, optimal design.

1 INTRODUCTION

In a typical blow moulding process, a polymeric amorphous preform is heated to its forming temperature and brought into contact with a mould of the desired shape. Due to the low polymer thermal conductivity (0.25 W/m.K for PET), the heating step is performed using infrared (IR) lamps, which enable short heating times. The final thickness of the part, and consequently the final product quality, is drastically controlled by the initial temperature distribution inside the preform. For this reason, optimizing the heating stage is crucial in order to ensure an improved process control.
The thermal problem during blow moulding process results from a coupling of conductive, convective and radiative three-dimensional unsteady transfers. Moreover, the modelling of heating device, constituted of different rows of lamps associated to reflectors, is complex. Thus, to find optimum process parameters, inverse methods are generally used.

1.1 Blow moulding reheat modelling approaches

Different recent investigations focused on the preform reheating modelling. Huang [1] used the commercial finite element software ANSYS® to solve the 3D non steady energy equation, under the assumption that the PET is opaque regarding to the short infrared. Some investigators modelled the radiation absorption with the Beer-Lambert law, as Monteix [2] and Champin [3]. They have developed their own 3D infrared reheating software, based respectively on the 3D control volume method, and the finite element commercial software FORGE3®. Nguyen [4], proposed an inverse technique to reconstruct the temperature distribution over the thickness of a part, using the surface temperature measurement. To solve the inverse problem, the conjugate gradient algorithm was used.
As a conclusion, no inverse method has been used to find oven optimum geometric parameters.

1.2 Goals of the present study

We propose an inverse method, permitting to optimize the oven geometry, and to obtain a three-dimensional temperature field at the end of the heating stage. This temperature field is computed using a heat transfer solver (developed in CROMeP [2]) based on control-volume method. This software allows the heating step simulation of a rotating preform, taking into account both front and back reflectors. The absorption of the radiative flux is evaluated using the Beer-Lambert law. In a second step, a non linear constrain optimization method (Sequential Quadratic Programming) is used, in order to find the best set of oven geometric parameters.

2 HEAT BALANCE EQUATION

In its classical form, the heat balance equation can be written as:

$$\rho c_p \frac{dT}{dt} = \nabla \cdot (k \vec{\nabla} T) - \nabla \cdot \vec{q_r} \quad (1)$$

where T = temperature, q_c = conduction heat flux, q_r = radiation heat flux, ρ = density, c_p = specific heat, k = thermal conductivity. To compute the temperature distribution through the thickness of the preform, this equation is solved using a 3D control-volume software [2].

2.1 Control-volume method

The preform is meshed using cubic or hexahedral elements called control volumes. Equation (1) is integrated over each control volume and over the time from t to $t+\Delta t$:

$$\int_{\Delta t}\int_{\Omega e} \rho c_p \frac{\partial T}{\partial t} d\Omega dt = \int_{\Delta t}\int_{\Gamma e} (k \vec{\nabla} T . \vec{n}) d\Gamma dt - \int_{\Delta t}\int_{\Gamma e} (\vec{q_r} . \vec{n}) d\Gamma dt \quad (2)$$

where Ω_e = control volume. The unknown temperatures are computed at the cell centre of each element. The method used to calculate the radiative source term is divided into two steps:

- First, incident fluxes are estimated thanks to the computation of view factors, with a spectral dependency.
- Then, since PET preforms constitute semi-transparent media, incident fluxes are absorbed in the thickness. This absorption is modelled using the Beer-Lambert law.

2.2 Computation of view factors

The view factor F_{12} is the fraction of radiative flux, emitted from an elemental surface dS_1, and directly received (without any reflexion or transmission) by an other elemental surface dS_2.

$$F_{12} = \frac{1}{\pi S_1} \int_{S_1}\int_{S_2} \frac{\cos\beta_1 \cos\beta_2}{d^2} dS_1 \, dS_2 \quad (3)$$

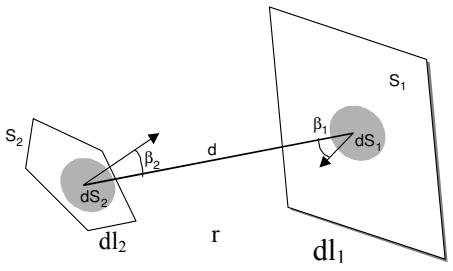


Fig. 1. View factor definition.

Many numerical methods exist to compute view factors. One of them is the contour method [5], based on the theorem of Stokes to transform the integrals of surface of the equation (3), in curvilinear integrals:

$$F_{12} = \frac{1}{\pi S_1} \int_{C_1}\int_{C_2} \ln r \; dl_2 \cdot dl_1 \quad (3)$$

Then integrals are computed with the Gauss method. Different ways exist to evaluate the radiative heat flux absorption. One of them is the Beer-Lambert model.

2.3 The Beer-Lambert law

The main idea of this law is that the radiative flux is absorbed in the medium according to a decreasing exponential:

$$q_\lambda(x) = q_{0\lambda} \exp(-\sigma_{a\lambda} x) \quad (4)$$

where $q_\lambda(x)$ = monochromatic radiative flux at the location x, $q_{0\lambda}$ = incident monochromatic radiative flux, $\sigma_{a\lambda}$ = spectral absorption coefficient of PET. Although this law avoids long computation times, it is reserved to non scattering cold media [6]. This law is integrated over the frequency in the spectral band [0.2 - 10μm].

3 INFRARED OVEN OPTIMIZATION

The analytical computation of irradiance is coupled to an optimization method, to automatically modify

oven geometric parameters at each iteration, as shown in figure 2. The problem being non linear, continuous, and constrained, an adapted Sequential Quadratic Programming method is developed using Matlab® [7].

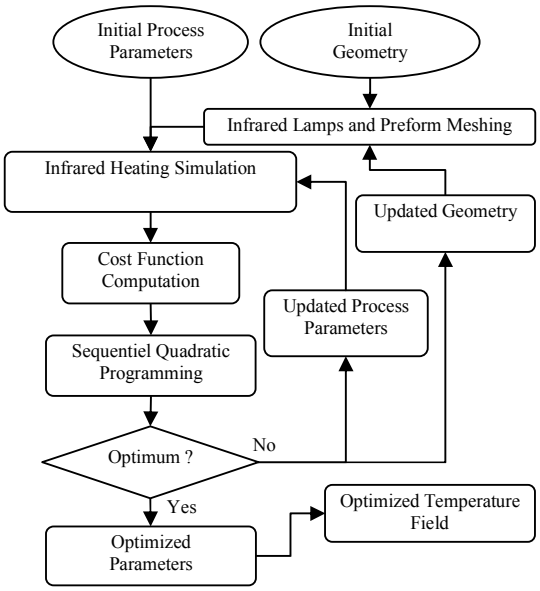


Fig. 2. Heat transfer simulation / optimization coupling.

3.1 Cost function

The optimisation objective is mathematically represented by a cost function F to minimize, function of oven design parameters X. We propose to establish the function (5) related to temperature uniformity at the surface of the preform, and to a desired mean value of temperature.

$$F(X) = 0.5\frac{\sigma(X)}{\sigma^0} + 0.5\left\|\frac{(\overline{T}(X) - \overline{T}_{OBJ})}{\overline{T}_{OBJ}}\right\| \quad (5)$$

$$with \quad \sigma(X) = \frac{1}{\sqrt{n}}\sqrt{\sum_{i,j}^{n}(T_{ij} - \overline{T})^2} \quad (6)$$

where $\overline{T}(X)$ = mean temperature computed at each iteration, $\overline{T}_{OBJ}$ = desired mean temperature, $\sigma(X)$ = standard deviation of computed temperatures at each iteration, σ_0 = standard deviation of computed temperatures with initial conditions, n = number of preform surface elements. This function permits to obtain not only a uniform temperature field, but a desired mean value of temperature too.

3.2 Parameters

Both process and geometric parameters can be included in the optimisation. In this study, we focus on geometry only. Parameters concerned are: distances between IR lamps and the preform (X_1, X_2, X_6, Y_7), and the distance between lamps (E), as shown in figure 3.

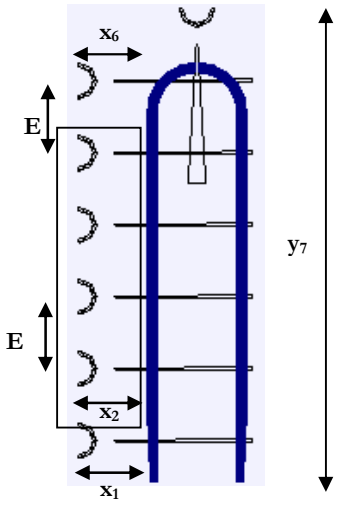


Fig. 3. Adopted configuration / parameters notation.

3.3 Constraints

Geometric parameters are bounded. For example the distance between lamps must be greater than 20 mm, in order not to damage IR lamps. These constraints can be expressed as inequality relations between several parameters.

4 APPLICATION

The method developed is used to optimize the geometry of an oven constituted of seven halogen lamps 1 kW, according to the cost function (5). The objective mean value of temperature is 110 °C. Dimensions of the PET preform are: 110 mm height, 25 mm diameter, 2 mm thickness. It is meshed into 4600 elements.

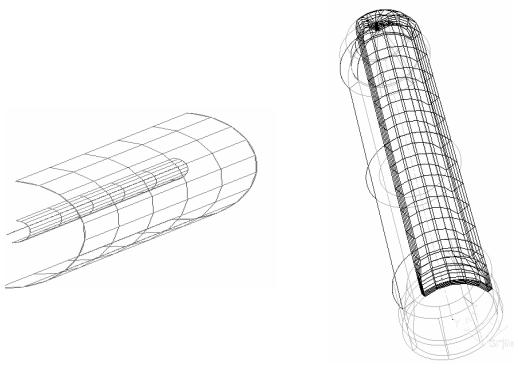


Fig. 4. Preform and lamp meshes.

The value of the convective coefficient, applied to preform surface during heating stage, is equal to 30 W/(m².K). Results are reported in table 1.

Table1. Initial and final parameters

Parameters (mm)	X_1	X_2	X_6	Y_7	E
Initial	20	20	20	130	20
Final	20	30	30	129	19

Parameters (°C)	σ	Tmean	Tmean objective
Initial	12.9	118	110
Final	7.9	108	

CPU time: 02:30:00 (Pentium M 1.8 GHz, RAM: 512 Mo).

The optimization method converges after 26 iterations.

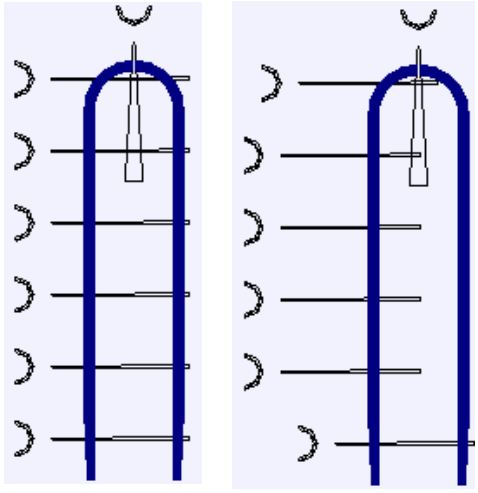


Fig. 5. Initial and updated oven geometry.

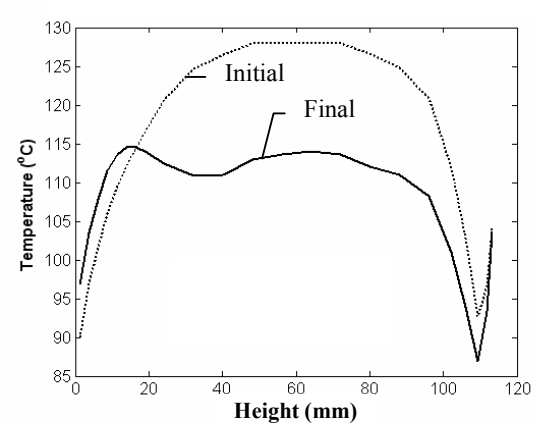


Fig. 6. Front surface temperature distribution after 15 s heating, computed with Termoray. Initial and updated oven geometry.

As shown in figure 6, a more homogeneous temperature distribution over the preform surface is obtained using updated oven geometry, even after 15 s heating. The gain of uniformity is equal to 38%.

5 CONCLUSIONS

A complete numerical model of the heating stage has been developed. Using a control-volume software, the 3D heat balance equation is solved with convective and radiative boundary conditions. The radiative flux absorption is computed according to the Beer-Lambert law. Concerning the optimization, the SQP algorithm coupled with the thermal solver permits to design optimally ovens geometry, in order to increase the surface temperature uniformity. Actually the optimal temperature field may not be uniform. That's why it is crucial to determinate by a numerical or an experimental way, the real optimal temperature field. Then the goal will be to optimize either the preform mean temperature, but the temperature profile.

The others tasks for the future work will consist in taking into account lamps powers in optimization, and to define a new cost function including the process efficacy.

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