Optimization of infrared heating system for the thermoforming process

M. BORDIVAL, S. ANDRIEU, F.M. SCHMIDT, Y. LE MAOULT, S. MONTEIX
Research Center on Tools, Materials and Processes
Ecole des Mines d'Albi Carmaux
Campus Jarlard - Route de Teillet 81013 ALBI CT Cedex 09 FRANCE

ECOLE DES MINES D'ALBI C A R M A U X
e-mail : schmidt@enstimac.fr
http://www.enstimac.fr

Introduction

Determining an optimum processing window in thermoforming process is critical in the aim of achieving high quality parts. The infrared heating step is crucial, the final thickness distribution of the thermoformed part being closely related to the initial temperature field inside the sheet.

To reduce the time needed to design the heating device, an automatic optimization method of ovens geometric parameters has been developed.

The optimization method can be devided into three steps:

- Accurate direct simulation of radiative transfers, based on the RayTracing method.
- Optimization of the heat flux over the sheet surface, using a non linear constrain optimization method (Sequential Quadratic Programming).
- Computation of the 3D temperature pattern, using THERMORAY, a heat transfer solver based on control-volume method.

Heat transfers simulation

Heat balance equation applied to the thermoplastic sheet::

$$\rho\, c_p \frac{dT}{dt} = \nabla\cdot(k\,\vec{\nabla} T) - \underbrace{\nabla\cdot(\vec{q_r})}_{\text{Radiative source term}}$$

Radiative source term

Control-volume method: the sheet is meshed using cubic elements called control volumes. Heat balance equation is integrated over each control volume and over the time from *t* to *t+Δt*.

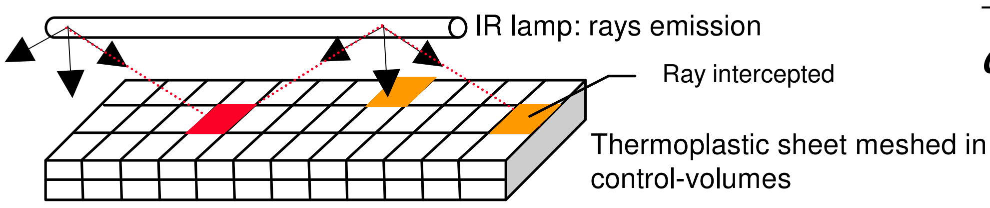
$$\int_{\Delta t}\int_{\Omega e} \rho\, c_p \frac{\partial T}{\partial t}\, d\Omega\, dt = \int_{\Delta t}\int_{\Gamma e} (k\,\nabla T.\vec{n})\, d\Gamma\, dt - \int_{\Delta t}\int_{\Gamma e} (\vec{q_r}.\vec{n})\, d\Gamma\, dt$$

The unknown temperatures are computed at the cell centre of each element.

Radiative transfers modelling

Computation of the radiative heat flux over the sheet:

This method permits to model accurately the IR lamps, taking into account emitters geometry and optical properties, which depend on temperature and frequency, as well as back reflectors.



Computation of the radiative heat flux absorption: Rosseland approximation.

- Reserved to optically thick media.
- Avoids long computation times.

The heat balance equation is solved in a pure conduction approach. The radiation heat flux reduces to:

$$\vec{q}_r = -\underbrace{k_{Ross}}_{}(T)\,\vec{\nabla} T$$

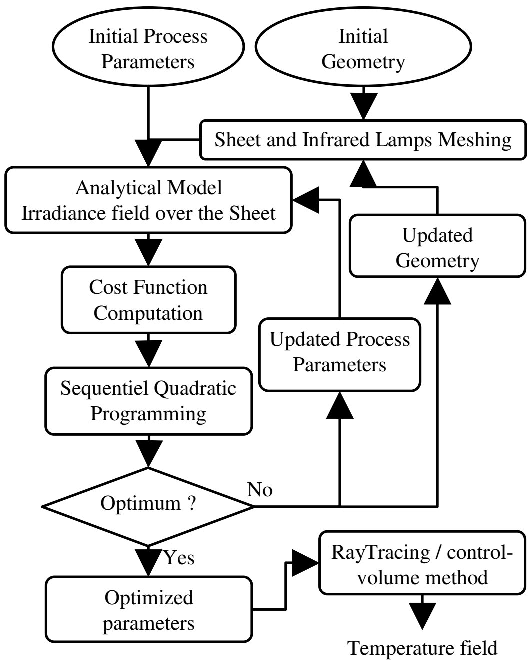
Rosseland conductivity (*W.m^{-2}.K^{-1}*)

Optimization of the infrared oven geometry (using SQP algorithm)

Cost function: The optimisation objective is mathematically represented by a cost function *F* to minimize, function of oven geometric parameters *X*. We propose to establish a function related to radiation heat flux uniformity at the surface of the sheet, and to a desired mean value of irradiance.

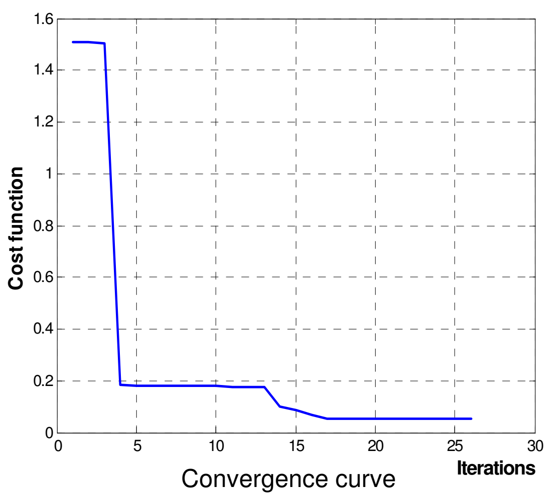
$$F(X) = 0.5\frac{\sigma(X)}{\sigma^0} + 0.5\left\|\frac{(\overline{E(X)} - \overline{E_{OBJ}})}{\overline{E_{OBJ}}}\right\| \quad with \quad \sigma(X) = \frac{1}{\sqrt{n}}\sqrt{\sum_{i,j}^{n}(E_{ij} - \overline{E})^2}$$

where $E(X)$ = mean irradiance computed at each iteration, E_{OBJ} = desired mean irradiance, $\sigma(X)$ = standard deviation of computed irradiances at each iteration, σ^0 = standard deviation of computed irradiances.



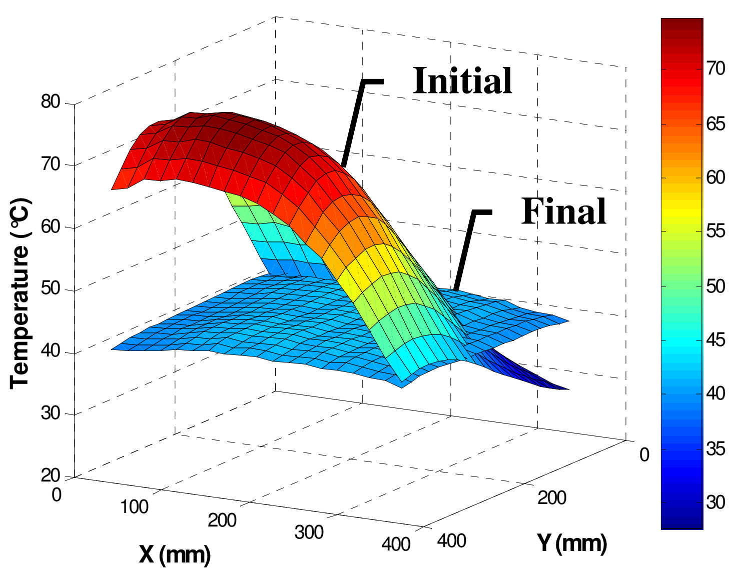
Heat transfer simulation / optimization coupling

Parameters (W/m²)	σ	Emean	Emean objective
Initial	4350	10345	6000
Final	233	6000	



Convergence curve

RayTracing: 8 IR lamps / 563 million rays followed.



Front surface PSB temperature distribution after 15 s heating: Initial and updated oven geometry

Conclusions

- A complete numerical model of the heating stage has been developed.
- The accurate RayTracing method permits to compute the radiative heat flux over the sheet.
- The irradiation absorption is approximated by the Rosseland model.
- The 3D temperature field is computed using Thermoray, a thermal solver based on the control-volume method.
- Results show that it is possible to increase the surface temperature uniformity, using the SQP algorithm in order to design optimally ovens geometry.

Future work

Further continuation of this work includes :

- Enlarging the radiative model to optically thin media, using the RayTracing method, in order to compute the irradiation absorption.
- Taking reflectors into account in the optimization.