Optimization of radiant heating using the ray tracing method: Application to thermoforming

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(Received 13, October 2004 Accepted 31, January 2005)

Thermoforming is a very popular method of plastics processing, because it is simple and inexpensive. There is a growing interest for thermoforming in the case of applications which are more and more technical, i.e. for automotive industry. This implies to better control and optimize the process. One key step is the heating of the plate in order to reach the viscoelastic state of the material, the heat required for this change of state being mainly transferred in a radiative form.

Therefore the energy distribution in the plate should be carefully optimized. Classical methods based on the "view factors concept" are known to be difficult to operate in the case of complex geometries and/or spectral diffusion sources. In this study, an approach using the "ray tracing method" is used. The principle of this method consists in discretizing the heating source surface and associating to each element several rays which carry a given amount of energy. Each ray interferes with the plate, directly or after reflection on the reflectors, and transfers its energy to the plate. The energy distribution on the plate surface is easily deduced and the temperature field can be calculated, providing the bases for the inverse problem which is more interesting from the process point of view : starting from a required temperature distribution on the plate, the adequate sources (emissivity, shape...) and their relative locations with respect to the heated plate will be predicted.

Keywords : Thermoforming, ray tracing, heat transfer, numerical simulations

I. INTRODUCTION

Often the industry of plastic materials processing resorts to a high number of tests before starting a mass production, which causes expensive operations. It is the same when developing new products, or improving the already existing process. Under these conditions, numerical simulation becomes a justified alternative to analyze and to improve the manufacturing process. The mathematical models will be useful for the industrial machines control, after validation by pertinent tests.

In order to study numerically, and to optimize the step of radiative heating of polymers during the

thermoforming process, the method of ray tracing is used. This method based on purely geometrical considerations, is simple and allows us to get rid of the extremely difficult and approximate calculation of the shape factor, especially for complicated geometries.

In this study, we showed that we can control the distribution of temperature on the surface of the heated plates. This will enable us to better control the deformations of material during processing, exploiting the geometry of the heating sources and their reflectors.

II. THE THERMOFORMING PROCESS

The technique of thermoforming primarily consists in heating a thermoplastic sheet on a framework in order to soften it and give it a shape by means of a mould. The sheet adopts the exact shape of the predefined mould. The pressure can be exerted either by air evacuation or by compression of the hot sheet between a concave mould (hollow surface) and a convex mould. The traditional cycle of thermoforming is composed of 5 steps:

- Connecting a rigid sheet on a framework ;
- Heating the plate up to the processing temperature
- Forming and maintaining the deformation of the sheet until the end of cooling ;
- Cooling at ambient temperature ;
- Removing from the mould and cutting off the edges if necessary.

Thermoforming offers numerous advantages:

- The equipment is less expensive than the one used in injection or similar methods ;
- It is possible to manufacture both thin and large parts ;
- It is possible to reduce the complete cycle.
- The adjustments of the moulds and the tools are not expensive.

II-A. Product thickness

Thermoforming takes advantage of the elasticity of the material and its stretching ability. In order to avoid very weak thicknesses in certain zones of the sheet, it is necessary to use a counter mould. The material will solidify in contact with this counter mould which guarantees the correct thickness. Our study consists in solving this problem of thickness by controlling the heating phase rather than using a counter mould. Indeed, the final thickness of the product after forming depends not only on the intensity of its deformations but also on the temperature to which it becomes deformed. The lower the temperature, the smaller the deformation and consequently this heated zone at low temperature is thicker. Thus, by controlling the heating system we can control the final thickness of the product. In order to control the temperature distribution on the plate, the heating system composed of the heating sources and their reflectors will be modeled, simulating the thermal radiation by the ray tracing method.

III. THE RAY TRACING METHOD

The first algorithm was created in 1968 but has been exploited only since 1980 by Whitted (1980). The ray tracing method is regarded as one of the most interesting ways to create realistic synthesized images. Its principle is as follows: the rays which leave the light sources "rebound" until they touch the sensor (camera). We allocate a wavelength to each ray received by the pixels of the camera. The color of a pixel is calculated starting from the first object that the initial ray meets. Secondary rays are then launched to the light sources and possibly in the directions of reflexion and refraction. The process goes on until obtaining the color of the pixel by combining the received energies, as presented by Phong (1975), who takes into account the reflexions, the refractions, and the solids shadows.

Several types of ray tracing are related in the literature : Marks (1990), Heckbert (1984) and Dadoun (1985) use the pyramidal beams tracing to treat the effects of reflections in the synthesis images and to reduce the calculation time, Muller (1986), Whitted (1980) use the classical ray tracing, Marks (1990) use the conic beams tracing, and other authors use hybrid methods, in order to improve the results, to optimize the visibility or the calculation of shades, by mixing the various alternatives of the ray tracing, see for instance Ghazanfarpour (1992- 1998) or Choi (1998).

III-A. The ray tracing method

Given that the heating step in thermoforming is carried out by radiation, it is thus possible to apply the ray tracing method to simulate this phase of the process, like in Modest (2003), or Coelho and al. (2003).

We follow the rays emitted from the heating source (Fig. 1). They "rebound" on the reflectors until they touch one of the facets of the surface to be heated. A quantity of energy is associated to each ray. When a ray is emitted by a surface element of the source, it receives a proportion of the total energy emitted by the whole surface of the heating source. When this ray reaches another surface (reflectors or polymer plate), it contributes to the illumination and heating of this surface. In spite of its simplicity, ray tracing has several disadvantages: large computing times and the ignorance of certain small objects. In order to avoid these problems, several alternatives of ray tracing were studied in the literature as presented below.

Fig.1. Diagram of the principle.

III-B. Hypothesis

- The heating source is discretized in several hemispherical point sources, which are no diffuse and no reflective.
- The reflectors are not discretized. We choose to change the angle of inclination of the rays. Indeed, if the reflectors are discretized, it means that we will study the interactions between the facets.
- Several geometries of reflectors can be studied.

The algorithm of calculation is shown in the Fig. 2.

Fig.2. Algorithm of the ray tracing method.

III-C. Type of radiative heating source

One of the sub-functions which are defined before the main program is used to define the way in which the source will emit its energy. The rays emitted by the points sources will be characterized by the energy transported, which will depend on the angle of emission in the case of a not-diffuse sources. We chose for our study a Gaussians distribution, as presented in Figs. 3a and 3b.

To study a case of diffuse source, it is enough to put the energy of the rays constant some is their angle of emission. With this program, it is thus possible to study sources of any type of emission's distribution.

Fig. 3. a. Normalized Gauss energy distribution.

Fig 3. b. Energy distribution versus the emission angle.

IV. RESULTS

IV-A. Sensitivity of the numerical results

The more important the density of rays received by the facets is, the more accurate the calculation. In other words, the higher the number of rays, the better the precision, as shown in the following comparison (Fig. 4), for 5000, 7500 and 10000 rays, everything being kept constant (same total energy, same source and reflectors).

The points represent the energy density received by the heated plate versus the spatial location. The relative uncertainty in the results is less important when the thickness of the pack of points is thinner.

Once numerical optimization is obtained, several simulations of the distribution of energy on a heated plate are carried out, in order to study the influence of the various geometrical parameters:

Fig.4. Density of energy distribution on the plate for several quantities of launched rays.

IV-B. Influence of the reflectors geometries

The following figures (Fig.5-8) show various profiles of energy distributions on the surface of a thick film, for reflectors of different geometries, the other parameters being identical (total source energy, distance from the source to the plate...). We observe that the choice of the reflectors clearly influences the heating of the plate, from both the points of view of the maximum intensity of energy on the plate and of its distribution. For example, the triangular reflectors used in Fig. 5 present one peak of energy at the center on the plate, which is completely different from the energy profile in Fig. 6 (rectangular reflector), in which we can see two peaks of energy, not located at the center, and having a lower intensity.

In each figure, we present also the orientation and the intensity of all the rays received by the heated plate. This information can be used to take into account the optical non isotropic behavior of polymers.

Fig. 5. Triangular reflector.

Fig. 6. Rectangular reflector.

Fig. 7. Circular reflector.

Fig 8: Parabolic reflector.

IV-C. Influence of the location of heating sources in the reflectors

In order to control the distribution of energy on the plate, it is interesting to be able to change the location of the source in the reflectors. The following figures show that depending on the relative locations of the source and the reflector, the concentration of energy in the center of the plate is more or less important, and the same is observed for the width of the central zone with strong radiant intensity. The example illustrated in Fig. 9 is computed for a parabolic reflector, with a heating source at different locations H , between the center of the source and the base of the parabolic reflector.

Fig.9. Influence of the reflectors geometry (continued).

Fig.9. Influence of the reflectors geometry.

IV-D. Influence of the reflectors opening

To illustrate the influence of the opening (base) of the reflectors, an example is presented in Fig. 10 (parabolic shape). The aim is to see the energy distribution profiles on a plate generated by the same heating source and same reflector geometry, having variable openings (bases). This example is a representative case of what we industrially wish to have in thermoforming, in order to prescribe a distribution of energy and thus of temperature on the surface of the plate. This simulation clearly shows that adjustable reflectors is a response to this industrial wish.

On Fig. 10a, the two peaks of maximum of energy density are due to the fact that the opening (base) of the reflectors is too narrow, which induces more important reflexions of the rays in no central points on the heated plate. By increasing the opening (Fig. 10b), the profile of energy is reduced in its width at the center, to diverge by accentuating the opening (Fig. 10c). According to whether we desire to heat more or less in the center of the plate, we choose one configuration or another one.

IV-E. Application to the heated plate

To evaluate the temperature distribution within the heated plate, we consider that the density of energy calculated before is a flux boundary condition in a problem of pure conduction. An example is presented by considering a simple 2D problem of non stationary bidirectional heat conduction, with the following assumptions:

- No diffuse source.
- The plate is isotropic, with constant thermal conductivity.

Fig.10. Influence of the reflectors base.
The heated surface is located at 15 cm below the heating source.

The boundary conditions are:

- Temperature imposed on the edges of the plate
- Radiant flux imposed on the upper surface (calculated using ray tracing)
- Symetry condition on the lower face.

The heat equation is then:

$$\vec{\nabla} \cdot (k \vec{\nabla} T) = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

The result in Fig. 11 shows a maximum profile of temperature in the medium of the plate, as imposed by the distribution of the thermal flux on the upper surface.

Note that the perturbations are due to the real values of the computed heat flux using the ray tracing method, not to numerical artifacts.

Fig. 11. Temperature profiles within the plate.

V. CONCLUSION

Thermoforming is a very simple manufacturing process in its principle. However, the optimization of the temperature distribution in the material can be difficult to achieve. The distribution of the thermoformed material thickness strongly depends on the thermomechanical behavior of the material, and thus of the distribution of the temperature in it. This study is a first step towards the control of the material deformation during thermoforming, by controlling the phase of radiant heating in the process. To predict the energy distribution on heated plates, we used the ray tracing method, to model the heating system. After a study of numerical sensitivity, we showed that this method is well adapted for numerical simulation of the heating phase of the thermoforming process. The next step would be to study the three-dimensional case, to apply the simulations to real cases, and to compare with experimental measurements (in progress). The ultimate objective is to solve the inverse problem which is of prime interest for industrial applications: how to predict a heating system so that to obtain an imposed temperature field on the plate?

ACKNOWLEDGMENTS

The authors wish to thank the Rhône-Alpes Region for funding this study.

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Presented at 5th Japan France Seminar on Intelligent Materials and Structures (October 13-15, 2004)