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Heat conditioning modelling of thermoforming process: comparison with experiments

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Abstract

The goal of this study is to improve the efficiency of infrared heating ovens used in the thermoforming process. The heat conditioning of thermoplastic sheets before forming consists in heating up thermoplastic sheets above the glass transition temperature of the polymer. The thickness distribution of the final product is strongly dependent on the initial temperature distribution inside the sheet.

Well-calculated process parameters during the heat conditioning step will allow improvements in, for example, cycle-time reduction. For that, we use different electric heaters that operate in different infrared ranges as: long, medium and short infrared wavelengths respectively. Thermoforming machines are generally equipped with ceramic heaters that operate in long infrared wavelengths. Recently, halogen lamps that are short wavelengths heaters have started to be employed in thermoforming applications. So, an experimental infrared heating set-up has been developed in order to compare the different kinds of heaters and the efficiency of lamp reflectors. The temperature of each infrared heater in the oven is controlled independently in order to optimise the surface temperature distribution of the thermoplastic sheet. For that, an 880 LW AGEMA infrared camera has been used to measure the temperature distribution of different thermoplastic sheets. We have chosen in this study the most commonly employed polymers in thermoforming which are: ABS and PP used for thin gage sheets.

Numerical simulations using software based on control-volume method have been performed and compared with experimental data.

1- Introduction

Thermoforming is an industrial process that involves a heating step before forming. During this heating the thermoplastic sheet temperature increases until a forming temperature is reached. The range of forming temperatures varies from polymer to polymer [1]. Basically, the range is large with amorphous polymers like polystyrene and narrow with crystalline polymers like polypropylene. The thermoforming machines are generally equipped with ceramic heaters that function in the long-waves infrared ($?_{max}$~ 3 µm) [2]. In our study we use halogen lamps that are short-waves infrared ($?_{max}$~ 1.2 µm).
The aim of our study is to understand the radiative transfers between infrared heaters and thermoplastic sheets. We want to measure sheet temperature in order to obtain a better temperature distribution over the sheet surface and through the thickness. We want to study thin-gage and heavy-gage thermoplastic sheet. So it's important to avoid an indication of the temperature gradient inside the sheet. To calculate the radiative transfers, PLASTIRAD® software based on a control volume method is used. A comparison between experimental and numerical results will allow validation of the model.

2- Experimental infrared heating set-up

The "infrared heating set-up" (fig. 1) has been developed in order to study the interaction between the infrared radiation and polymers during the heating step of the thermoforming process. Thermoforming machines do not allow measurement of the sheet temperature during the heating. The infrared device makes these measurements possible. Moreover this tool can optimise the temperature distribution: the power of each lamp is adjustable.

The infrared heating device consists of an aluminium structure (1) that supports an

infrared oven (2) power-regulated by an electrical power box (3), a metallic frame (4) to fix the thermoplastic sheet (5). The aluminium structure has been conceived to change the distance between the sheet and the oven. For the moment this is fixed at 15 cm. A polished aluminium mirror (6) is adjusted at 45° under the sheet to measure the sheet temperature on the surface that isn't directly exposed at the infrared radiation ("back surface"). An infrared camera (7) (880 LW AGEMA) is used.
A pyrometer (8) has been recently disposed to measure the local sheet temperature on the "front surface". We seek to obtain an indication of the temperature gradient through the thickness of the thermoplastic sheet
A "halogen oven" is constituted by eighteen 1000W-halogen lamps (13195Z/98-235 Phlips). A "long-waves oven" is constituted by ten 1000W-ceramic lamps (FSR 1000W-230V Elstein).

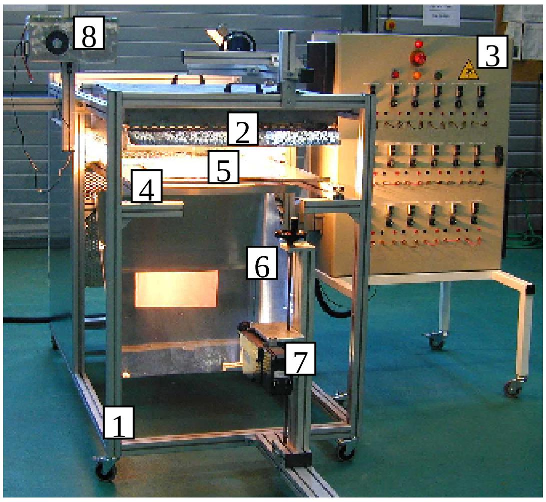

Figure 1- Infrared heating set-up

3- Comparison between different infrared heaters

We want to study the efficiency of the different infrared ovens. So, ten 1000W-halogen lamps (λ=1.2 µm) have been used in the "halogen oven" to compare with the "long-waves oven" (λ=3 µm). The time to reach the same temperature is twice longer with the "long waves oven" (fig. 2).

This is due to the long inertia of ceramic lamps (about 15 minutes measured with a thermopile 0.6-25 µm). It's seven times longer than for halogen lamps.
The polymer used in this comparison is an ABS sheet of surface area 35*35 cm^2 and thickness 0.45 mm.

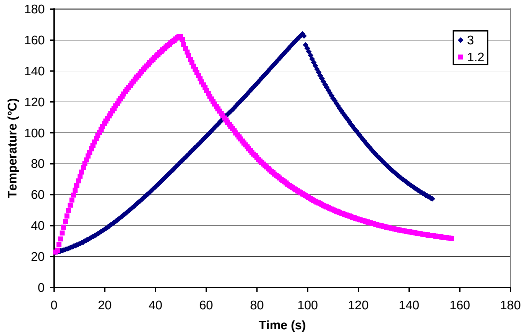

Figure 2- Comparison long-waves/ short waves

4- Optimisation of the temperature distribution

Due to the low inertia of halogen lamps (2 minutes) and their geometry, these infrared heaters have been used to regulate accurately the temperature distribution. For that, we studied the effect of the power regulation of halogen lamps. Each lamp of the "halogen oven" is numbered in the following picture (fig.3)

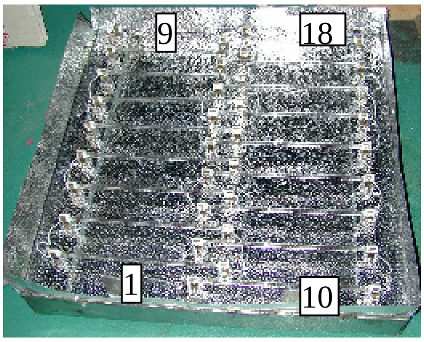

Figure 3- Infrared oven designed with numerical simulations

We studied the effect of five sets of power configurations on the temperature distribution of the ABS sheet. The temperature distribution of the "back surface" is measured with the infrared camera at the end of 25 seconds of heating, just after oven departure.

Set	1	2	3	4	5
HL 1	100	100	100	100	100
2	100	100	100	100	90
3	100	0	100	90	70
4	100	100	50	80	80
5	100	0	50	70	60
6	100	100	50	80	80
7	100	0	100	90	70
8	100	100	100	100	90
9	100	100	100	100	100
10	100	100	100	100	100
11	100	100	100	100	90
12	100	0	100	90	70
13	100	100	50	80	80
14	100	0	50	70	60
15	100	100	50	80	80
16	100	0	100	90	70
17	100	100	100	100	90
18	100	100	100	100	100
Pt(kW)	18	12	15	16.2	14.8
Tmax	154.8	115.6	137.2	153.3	148.7
Tmin	139.2	104.1	113.1	138.2	135
Tave	150.5	109.9	126.5	149.3	144.2
SD	2.4	1.7	5.4	2.2	2.1

Table 1- Influence of the lamp power on the temperature distribution

The power of each halogen lamp (HL) is expressed in percentage from 0 to 100%. The electrical power supplied to the oven P_t is expressed in kW. The maximal temperature T_{max}, the minimal temperature T_{min}, the average temperature T_{ave} and the standard deviation SD of the "front surface" are indicated for each set. The fifth set is a good compromise because SD is suitable in regards with the T_{ave} obtained.

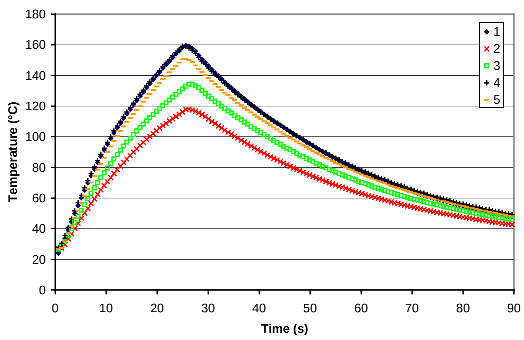

Figure 4- Average temperature evolution

The evolution of the average temperature during the heating and the cooling of the ABS sheet is given for the five sets in figure 4.

The speed of rice in temperature is function of the total power of the halogen lamps and their localisation.

4- Comparison with numerical simulations

Homopolymer polypropylene (HPP) has been already optically studied with an infrared spectrometer [3]. These properties of transmission and reflectivity are necessary to perform numerical simulations.

We carried out temperature measurements of a HPP sheet of surface area 35x35 cm^2 and of thickness 0.45 mm during a heating of 40 seconds. The temperature picture of the "back surface" is given on the following picture.

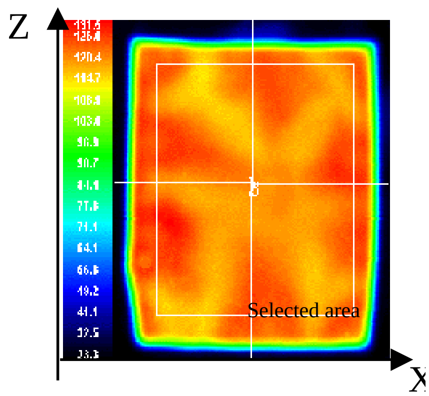

Figure 5- Temperature distribution for HPP

The average temperature of the selected area and the local temperature measured with the pyrometer on the "front surface" are plotted versus time after oven departure. The tendencies of the curves are the same because HPP is largely transparent to infrared waves (average transmissivity coefficient equal to 26% in the wavelength range 8-14µm). So the temperatures obtained with the pyrometer and the camera could be considered as average temperatures through the sheet thickness.

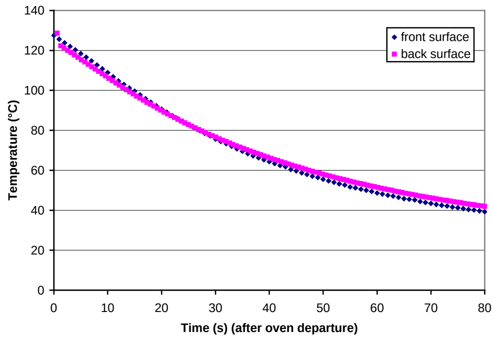

Figure 6- Cooling of the HPP sheet

The temperature profiles in the centre of the thermoplastic sheet along X and Z axis present a low temperature discrepancy lower than 8°C

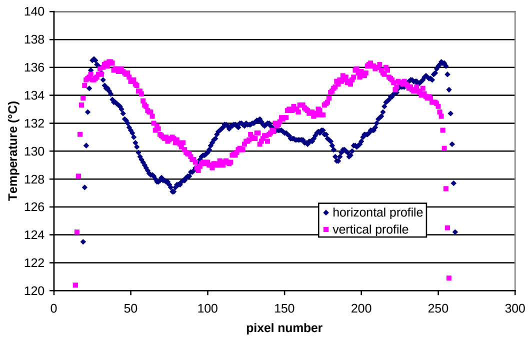

Figure 7- Temperature profiles

Numerical simulations have been performed using the PLASTIRAD® software based on a control volume method and validated for stretch blow moulding applications [].

The interval between lamps in the "halogen oven" is 80 mm. The lamp heating length is taken to 272 mm. The temperature of the tunsten wire and the quartz tube of the halogen lamp considered are indicated in table 2.

	Tungsten wire	Quartz tube
Temperature (K)	2340	816

Table 2- Source temperatures

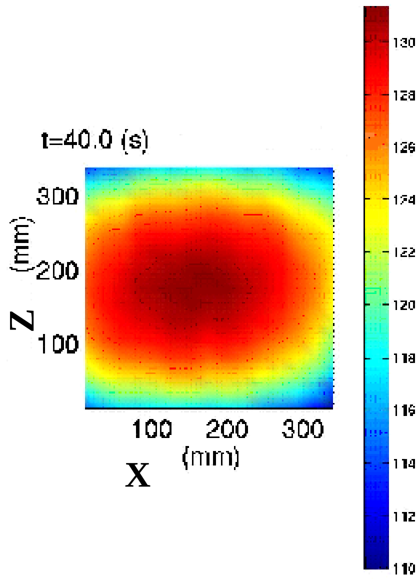

Figure 8- Calculated temperatures

The average temperature inside the thermoplastic sheet is 125.2°C. There is a concentration of the radiation in the centre of the sheet. This is due to the assumption in the model of the absorption that follows a Beer-Lambert law. There is a normalisation of the absorption perpendicularly to the surface of the thermoplastic sheet.

5- Conclusion

The experimental infrared heating set-up is a tool to study and optimise the heating during the thermoforming process. Surface temperature measurements have been successfully performed. Experimental set-up will be useful to perform a zonal heating

PLASTIRAD® software will be improved in order to take into account the real path of the radiative beam and the influence of the reflectors with a ray tracing method.

Acknowledgements

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