The Developments and Utilizations of a Numerical Model for Non-Homogeneous Sheet Heating During Thermoforming Processes

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Abstract

The most common method of heating polymer sheet for thermoforming is radiative heating. In this paper, the numerical model for the large thermoforming product has been developed. The radiative heating of opaque thermoplastic sheet has been studied by using the newly developed numerical modeling. The net-radiation method with the comprehensive view factor has been used to compute the total radiative heat on thermoplastic sheet. Also, for a sample non-homogeneous heating pattern, numerically predicted polymer sheet temperatures are presented and compared with corresponding experimental results. The model is utilized to analyze numerically the effect of spaces between heater and polymer sheet to temperature distribution through out the polymer sheet.

1. Introduction

Thermoforming, or vacuum forming, is a manufacturing process that has been traditionally employed for the production of thin-walled polymer products of relatively simple geometry. During traditional thermoforming, a constant thickness polymer sheet made from a single material is softened by heating and then formed into or over a tool through the application of a vacuum on the tool side of the sheet. Because of the relatively low energy and tooling costs associated with thermoforming, the process offers significant economic advantages when it can be employed. For large products where the costs associated with other processes such as injection molding become prohibitive, thermoforming can be the perfect answer.

The operator-oriented art of thermoforming has been recognized as an inefficient approach to this process, especially with the utilization of zone-heaters. Current efforts to enhance the utilization of thermoforming are motivated by the versatility and cost effectiveness of the process.

An attempt to better control the sheet temperature prior to forming gave rise to zone-heating through individually controlled heaters. This promising technique, designed to obtain desired heating patterns, remains an insufficiently studied, trial-dependent routine that is inefficient and often times unsuccessful. The trial and error-laden thermoforming practice in industry has provoked a new concept for a more science-based approach. “Intelligent Thermoforming”, which is based on the successful characterization of the heated sheet, will enhance the understanding of this process by linking forming temperature and material stiffness patterns directly to final product thickness distributions. This technique will improve the capabilities with applications involving large products, multi-layered products, deep drawing and/or complex mold geometry. The resulting advanced class of thermoforming would in many cases become a formidable, economical alternative to injection molding.

2. Related Previous Developments

Recognizing the inadequate characterization of the heating stage, in other words the lack of sheet temperature information, Taylor, et al. and DiRaddo, et al. combined numerical computation and temperature sensing tools to achieve desired quality parts[1, 2]. In Taylor's group, infrared thermography and finite element modeling were employed to investigate the influence of process variables such as evacuation rate (vacuum), sheet surface temperature, mold temperature, and material slip over the mold surface. DiRaddo, et al. simulated the process with a combination of heating, sagging, and forming numerical models.

Duarte and Covas[3] solved the one-dimensional non-steady (transient) heat conduction problem through the sheet thickness while accounting for radiative and convective boundary conditions. The fully implicit finite difference method, with central difference approximations, was employed to solve for the transient temperature as a function of heating time. As has been observed by others [4], the sheet temperature decreases from the center to the edges when a uniform heater setting is imposed. They suggested an amalgamation of their inverse heating algorithm with a sheet deformation counterpart that will conceptually provide a robust numerical model for the entire thermoforming process. Throne produced an explicit finite difference program in the QBasic computer language, TF505 [4], that outputs the heating time for creating a more uniform sheet temperature distribution. Similar to Duarte and Covas, the one-dimensional transient heat conduction model was used. With the code developed by Throne the radiative and convective boundary conditions can be applied to both the upper and lower sheet surfaces [5]. With both of these two models, however, heat radiation exchange between only the heater elements and polymer sheet elements is considered. The exchange of heat radiation between the polymer sheet and the environment, which can be significant when the temperature of polymer sheet is higher than that of the surroundings, has not typically been included.

In the experimental arena, much attention has recently been given to the determination of polymer sheet temperature at the onset of forming. Along this line, industrial and academic scientists have explored numerous non-contacting temperature sensing systems [6,7]. Geiss [8] integrated an infrared scanning pyrometer system into their commercial thermoformers. Similar temperature line-scanning technology has been implemented elsewhere[7, 10]. Single and multi-point pyrometer systems have also been deployed and tested [8, 9]. The infrared thermal imager is an accurate temperature sensing tool that affords very high resolution (320 X 240 pixels). Taylor's group situated an IR imager with a perpendicular view of the forming area to create a time-dependent sheet thermograph [1]. DiRaddo, et al. mentioned the use of an infrared camera for temperature measurements after the heating stage [2]. Michaeli and Marwick designed a closed-loop control system that automated the thermoforming process to achieve the required temperature profile for quality parts [10]. The measured sheet temperatures were used jointly with the desired profile to calculate a new set of heater values for the next cycle

3. Numerical Analysis

Radiant heating during thermoforming can be modeled by applying traditional conduction heat transfer governing equation with appropriate radiation and convection boundary conditions. Since the thermoplastic sheets of interest possess an "infinitely larger" width and length compared to their thickness and has a low conductivity, a one-dimensional heat conduction analysis is sufficient. Through the conservation of energy on a differential control volume, the heat conduction (or diffusion) equation becomes:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z} \right) \tag{1}$$

where:

ρ = density (kg/m^3)

C_p = specific heat (J/kg.K)

K = thermal conductivity (W/m.K)

To calculate net heat radiation exchange between the heater, the polymer sheet and the environment, in equations (3) and (4) the net radiation method has been applied. In the model configuration assumed, there are three types of surfaces that together make up what can be thought of as a radiative heat exchange enclosure. These are the heater surfaces, the polymer sheet surfaces and surfaces representing side openings. The side openings can be considered as planes of zero reflection, which can also act as a sources of radiation when such energy is entering the enclosure from the environment. If the heaters, the polymer sheet and the side openings are divided into N sub-surfaces, the heat radiation exchange equation for the i_{th} surface is as follows [11].

$$-\frac{q_1}{A_1}F_{i1}\frac{1-\varepsilon_1}{\varepsilon_1}-\frac{q_2}{A_2}F_{i2}\frac{1-\varepsilon_2}{\varepsilon_2}-\ldots+\frac{q_i}{A_i}\left(\frac{1}{\varepsilon_i}-F_{ii}\frac{1-\varepsilon_i}{\varepsilon_i}\right)-\ldots-\frac{q_N}{A_N}F_{iN}\frac{1-\varepsilon_N}{\varepsilon_N}= -F_{i1}\sigma T_1^4-F_{i2}\sigma T_2^4-\ldots+(1-F_{ii})\sigma T_i^4-\ldots-F_{iN}\sigma T_N^4 \tag{5}$$

A summation notation can be used to write equation (5) as.

$$\sum_{j=1}^{N}\left(\frac{\delta_{ij}}{\varepsilon_j}-F_{ij}\frac{1-\varepsilon_j}{\varepsilon_j}\right)\frac{q_j}{A_j}=\sum_{j=1}^{N}(\delta_{ij}-F_{ij})\sigma T_j^4 \tag{6}$$

Where i takes on one of the values 1, 2,…, N corresponding to each surface. In equation (6), F_{ij} is the radiative view factor from surface i to surface j, δ_{ij} is the kronecker delta function defined as

$$\delta_{ij} = 1 \qquad \text{when } i = j \qquad (7)$$

$$\delta_{ij} = 0 \qquad \text{when } i \neq j \qquad (8)$$

and q_i is the net radiation exchange at the i_{th} surface. When the surface temperatures are specified, the right side of equation (6) is known and there are N simultaneous equations for the N unknown q's. Therefore, equation (6) becomes a linear system equations:

$$[A][q] = [B] \qquad (9)$$

$$[q] = [A]^{-1}[B] \qquad (10)$$

Considering the view factor, F_{ij} , in equation (6), Hsu [12] illustrated a method of integration which can be used to calculate the view factor between two arbitrary size rectangles which are placed on mutually parallel planes. By using this formula, heater and polymer sheet elements do not necessary have to be the same size or be lined up directly across from one another.

Equation (1) with the associated boundary conditions can be solved numerically using a number of different approaches. During the present investigation, the solution approach applied was the explicit finite difference approach.

4. Model Validation

To validate the newly developed model, experimental results were required to compare with the numerical results. In the experimentation, the distances "z" from the polymer sheet surface to the top and bottom of the heater were set to be 17.8 cm (7 inches). The materials selected for this research investigation were 1.6 mm. white and opaque Polystyrene (PS) sheets of dimensions 0.6 by 0.9 m. A mesh layer made from chicken wire was used to support the softened polymer sheet during heating in order to eliminate the effect of polymer sheet sag from the present study. Only top heater elements were used in the experiments.

.The temperatures on the middle of polymer sheet were measured using an calibrated infrared thermocouple, a Raytek Thermollert MI, and compared to the numerical results for various heating times. Since each point of experimental data was produced form the different experiments, the repeatability of experimental data was concerned. However after some experiments were tested to measure sheet temperature at the same position and heating time, the results showed the repeatability

The two numerical models that were developed (i.e. those based on the net radiation and local radiation methods, respectively) were evaluated with corresponding experimentation. Note that the local radiation method does not concern about the heat radiation exchange between polymer sheet and environment. In the numerical models, the emissivity of the white Polystyrene sheet was initially set to be 0.9, while that for the ceramic heaters was set to a value of 0.9. The convection heat transfer coefficient for quiescent air was set to be 1.5 Btu/(ft^2 h ^{o}F) [5]. The polymer sheet temperatures at center of sheet was measured as a function of heating time. These were then compared to the numerical simulation results as shown in Figure 1. From Figures, it can be seen that both sets of numerical simulation results were close to the experimental results for shorter heating times. At longer heating times, however, the numerically predicted sheet temperatures rose above those observed experimentally. In these cases, the net radiation method was shown to yield a better temperature prediction.

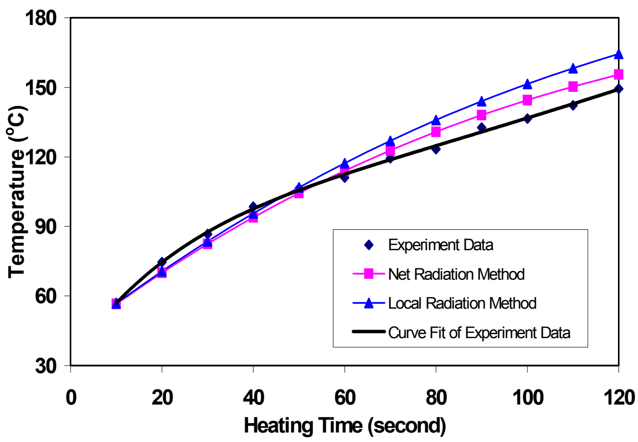


Figure 1: Results associated with numerical model validation

5. Experimental Sheet Temperature Monitoring

To support the numerical modeling effort for non-homogeneous sheet heating, the investigation was configured to include the development of an experimental capability to monitor polymer sheet temperature distributions based on infrared imaging technology. The IR camera employed during the current study was Raytheon's "PalmIR 250". The IR thermal imager was mounted above the forming area of the thermoforming machine, thus creating a capability of viewing the clamped polymer sheet immediately after heating and just before forming. The video output from the camera was fed to a frame grabber

A typical scene of the forming area with two reference hot bodies included is shown in Figure 2. In this gray scale image, a higher saturation of white represents higher temperatures while black denotes lower temperatures.

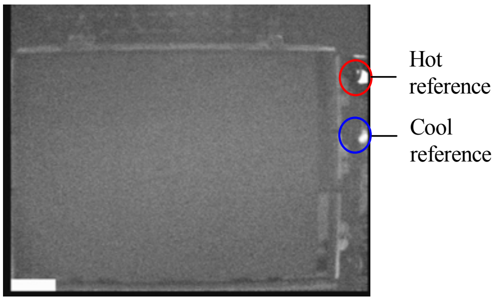


Figure 2: An IR image of the forming area, including the clamps and two black body reference “points” for temperature calibration.

A temperature calibration procedure was completed using a Raytek Thermallert MI infrared thermocouple. The infrared thermocouple itself, however, first had to be calibrated. To accomplish this a K-type surface thermocouple was used to obtain the temperature of a specific area near the polymer sheet center. The emissivity of the infrared thermocouple was then adjusted until the device provided a good comparison with thermocouple readings. This infrared thermocouple was then used to calibrate the IR camera.

Following the IR camera calibration, a case involving a non-uniform heating pattern was studied. This enabled a direct comparison of numerically predicted surface temperature patterns and those obtained through infrared camera imaging. Temperatures of heater elements 2, 4, 5 and 8 of Fig. 3 were set at 132°C , those of heater elements 1, 3, 9, 10, 11 and 12 were set at 250°C, and those of heater elements 6 and 7 were set at 357°C, The heating time for this case study was 180 seconds. The dimension of polymer sheet is also the same as model validation.

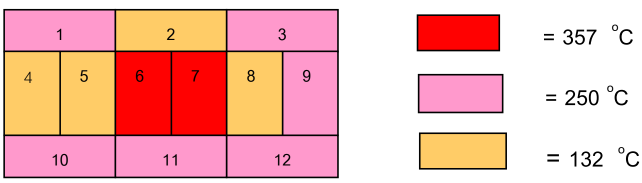
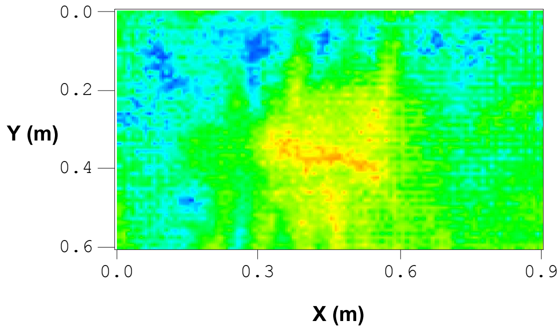
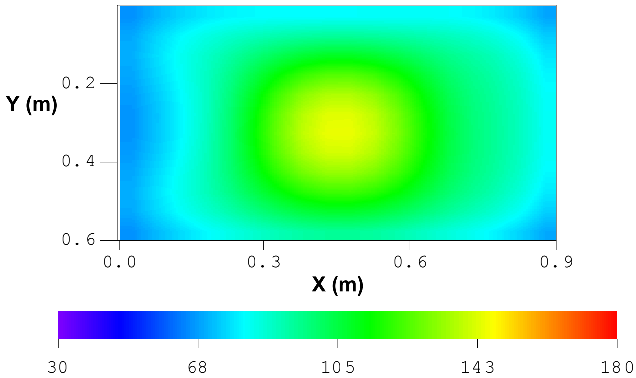


Figure 3: The zone heating patterns for the experimental investigation



(a) Experiment result



(b) Simulation result: Net radiation method

Figure 4: Comparison of theoretical and experimental temperature distributions (°C)

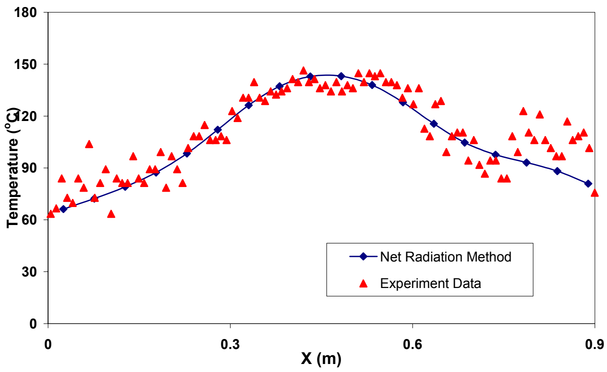


Figure 5: Comparison of numerical simulation and experimental temperature distributions at y = 0.3 m.

Figures 4-a and 4-b display the resultant experimental and numerical temperature distribution for the heater pattern shown in Figure 3. The temperature plots along the selected lines at Y = 0.3 m is presented in Figures 5. As expected, the hot area was located at the center of sheet and the sheet region between Y = 0 and 0.2 m. shows the cooler temperature. From Figure 4-a and 4-b, it can be seen that an excellent comparison between the thermal images of experimental and numerical results was evident. From Figures 5, the numerical results showed very good agreement with those obtained through experimental results.

6. Model Utilizations

There are three main variables in thermoforming processes that effect to the temperature distribution. They are the space between heater and polymer sheet, heating time and heater temperature pattern. For example, to express the effect of space between heater and polymer sheet to the temperature distribution, the net radiation model was utilized. All both top and bottom heater elements were set to 357 °C, and heating time was 120 sec. Figure 6 presents the slice plots of surface temperatures along the middle lines of width (y = 0.3 m.) on the sheet. The spaces between heater and polymer sheet were varied from 5 cm. to 17.5 cm. From Figure, it can be seen that for a smallest space, 5 cm., the temperature distribution illustrated more uniform than those of larger spaces. This can be understood that for small distance between two planes, the effect of view factor to the heat radiation exchange between elements is decreased. On inside area (from 0.1 to 0.8 m) almost heat energy from heater was transferred to the polymer sheet

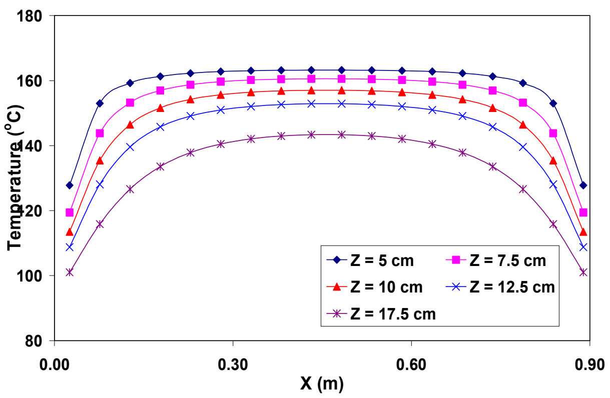


Figure 6: Surface temperature distribution of the different spaces between heater and polymer sheet at width = 0.3 m.

When doing the thermoforming of a thick polymer sheet, a window of forming temperature must be considered. Temperatures of polymer sheet over an forming area from top surface through bottom surface have to fall inside the window of forming temperature. The simulation can be helped to save time and material from trial and error processes.

For example, considering Polystyrene, the forming temperature window is 127 – 182 °C and the normal forming temperature is 149 °C. [5]. If the heater temperature and heating time were fixed, only the space between heater and polymer sheet can be changed to determine suitable distance which make the temperatures through out the polymer sheet fall inside the forming temperature window. Although Figure 7 shows that the top surface temperatures of polymer sheet are in forming temperature range, the temperatures of middle of thickness are still below the lower forming temperature. The infrared thermocouple only can measure surface temperature. Therefore, the simulation model will help to predict the temperatures inside the polymer sheet. As can be seen in Figure 8, the distance between heater and polymer sheet set to 5 cm. seems to be suitable for forming.

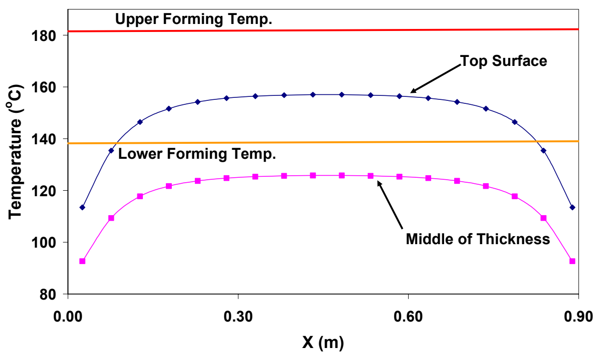


Figure 7: Temperature distribution at width 0.3 m. using Z = 10 cm.

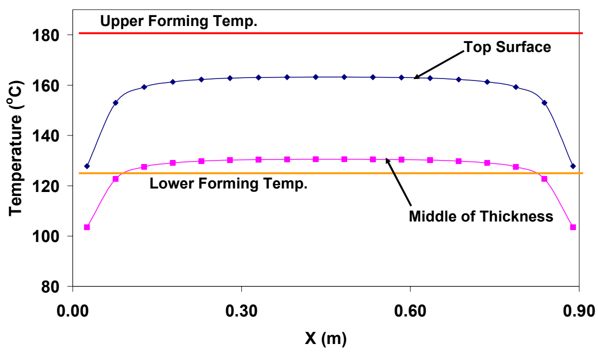


Figure 8: Temperature distribution at width 0.3 m. using Z = 5 cm.

7. Discuss and Conclusions

As result of a comparison between net radiation and localized radiation methods of heating simulation during thermoforming processes, it has been shown that the net radiation method is preferable. A simulation tool has been developed based on this method, and an additional advantage is the ability to fully accommodate non-uniform zone heating patterns with arbitrary sized and distributed rectangular heater and polymer sheet elements. Numerical results obtained with this advanced tool showed good agreement with those obtained through experimental infrared imaging. From model utilization, it was shown that the use of model provided time and material saving.

8. References

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