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Pulsed IR Heating of Thermoplastic Sheets for Thermoforming Applications

This study presents the pulsed heating strategy as an advancement of the current state of the art in industry towards the theoretically fastest method of heating a thermoplastic sheet. Experimental temperature measurements are combined with an explicit finite difference numerical model to describe the pulsed heating method and indicate its added value in IR heating of thermoplastic sheets. Different process settings are evaluated and indicate the effect of the applied heat flux and the time interval t_{OFF} during pulsed heating. When switched off, the residual heating of the heater elements is able to partially compensate for the convective heat losses at the surface of the sheet. This results in a more uniform temperature distribution through thickness without slowing down the overall heating process. The study shows that this effect is lost when the time interval in which the heater element is switched off increases. Applying pulsed heating opens up a large processing window to control the through-thickness temperature difference. When the total amount of applied thermal energy is taken into account, pulsed heating is able to increase the overall heating rate and simultaneously keep the temperature difference through thickness limited.

1 Introduction

Thermoforming of thermoplastic sheets is applied in thin film (< 2 mm) packaging applications as well as for thicker technical parts (> 2 mm) like side panels on agricultural vehicles or medical appliance covers. Next to injection moulding and extrusion, it is the third most important polymer manufacturing process. The process consists out of three different steps: (1) heating of the sheet, (2) deformation and stretching of the sheet on the mould and (3) cooling and demoulding of the product. This last phase is mostly followed by additional finishing steps like drilling, milling or trimming (Throne, 1996). In comparison with injection moulding and extrusion, the thermoforming industry is lagging in the field of process knowledge, control and automation. Especially in thick gauge thermoforming, the production is based on personal operator experience as well as a trial and error approach. Therefore, the most important challenge for the thermoforming industry is currently a higher level of process control (Gilham, 2016).

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A non-uniform thickness distribution in the final part is inevitable in a thermoforming process. This is caused by variations in the local draw ratios as well as temperature differences throughout the initial thermoplastic sheet. Therefore, Lee et al. (2001b) as well as Yousefi et al. (2002) identified the heating strategy as a crucial factor to obtain a final product that meets the desired specifications.

In a thermoforming process, the thermoplastic sheet is heated by means of IR radiation. This radiation is generated by means of ceramic, quartz, carbon, metal foil or halogen heater elements. These elements are arranged in an array in the heater bank of the thermoforming equipment. An in-plane temperature distribution in the sheet can be obtained by adjusting the IR radiation of the heater elements individually or in specific regions (Duarte et al., 2004; Lee et al., 2001a).

The goal of the heating step in thermoforming is to heat the thermoplastic sheet as fast as possible to the desired forming temperature without an excessive temperature difference through thickness. The typically low thermal diffusivity of thermoplastic materials and the radiative surface heating, results however inevitably in a temperature variation through thickness. From a theoretical point of view (neglecting the optical penetration depth at this point), the fastest method to achieve a uniform through-thickness temperature is to heat the outer surface of the sheet to the forming temperature and keep this temperature constant. In this approach the thermal diffusivity of the material determines the rate of heat transfer through the material and the time needed for the core of the sheet to reach the forming temperature (Buffel et al., 2016). Throne (1996) gives an overview of the forming temperature range for most commonly used thermoplastic materials. Pulsed heating is a heating strategy that correlates with this aforementioned optimal heating method. By periodically switching the heater elements on and off, the core of the sheet is allowed to continue heating without overheating the outer surface of the sheet. Specific process settings even allow to keep the surface temperature within a specific range while the core temperature continues to increase. Within a thermoforming process, this leads to a higher productivity and an increase in process control as well as part quality.

In order to obtain a constant sheet surface temperature, the IR heater elements would require a continuous feedback from the measured surface temperature to adjust the emitted IR heat flux accordingly. Ceramic and quartz heater have a too high thermal inertia to do this, while the required heating fluxes would be too low for halogen heater elements. Moreover, the continuous feedback on the surface temperature is hindered by the accuracy of contact-free temperature sensors. Different

factors need to be taken into account when making a contact-free temperature measurement: temperature dependent emissivity of the sheet material, wavelength dependency of the emission and the sensor, directional dependency, and the experimental difficulties to filter out interfering reflectance (Monteix et al., 2001; Haji and Spruiell, 1994a; Haji and Spruiell, 1994b). In reality, measuring errors can add up to 15 °C, while the forming temperature range for some materials is only 10 °C. The forming temperature range is determined by the type and specific grade of the thermoplastic material as well as the complexity of the product. In general, semi-crystalline polymers and complex product shapes require more narrow forming temperature ranges compared to amorphous materials or simpler product shapes with low draw ratios.

For these reasons most thermoforming installations currently apply a sub-optimal heating strategy in which a single or two-step IR heating flux is applied (Buffel et al., 2016). Pulsed heating is brought forward as a compromise between the theoretically fastest heating method and the current state of the art. Although Progelhof et al. (1973) were the first to mention this heating strategy, it has hardly been picked up by industry or been subject to further investigation in literature.

In addition to the importance of the heating step, other material and process parameters are also important to obtain thermoforming products that meet the required specifications. Examples of these material and process parameters are the initial sheet thickness variations, the temperature of the mould and possible assisting plugs (Marathe et al., 2016).

It is important to note the wavelength dependency of the occurring IR emission and absorption. An extensive study on IR heating applied in polymer processing can be found in chapters 12 and 13 of the book edited by N. Boyard (Rousseau, 2016; Le Maout and Schmidt, 2016). Kirchhoff's law states that the amount of absorbed radiative heat flux is equal to the incident radiative heat flux reduced by the amount of reflected and transmitted heat flux. The wavelength dependent transmissivity and reflectance (and thus the absorptivity) is experimentally measured in the near and mid IR range using FTIR spectrometers equipped with an integrating sphere.

Next to the wavelength dependent absorption spectrum of the thermoplastic sheet, also the emitted radiation by the heater elements is wavelength dependent. The high temperature fast response halogen heater elements considered in the present paper, emit the radiative spectrum of a black body with a maximum around 1,7 µm. Lower temperature ceramic heater elements possess radiative spectra that are shifted towards higher wavelengths (4 to 10 µm).

Boztepa et al. (2018) state that the relation between the microcrystalline structure and optical properties of a thermoplastic material, is the key to develop a predictive IR heating model. They demonstrate this by performing FTIR measurements on a semi-crystalline thermoplastic material to determine the occurring transmittance and reflectance. It was concluded that a slight variation in the crystallinity of the polymer has a great effect on its transmission and absorption characteristics, especially in the NIR (near infrared range = 0,8 to 2 µm). This wavelength range corresponds to the emission wavelength range of a typical halogen IR heater. As a change in temperature can introduce a change in the crystallinity of the polymer, the absorption characteristics are temperature dependent as well (Boztepa et al., 2019).

It is thus important to match the spectral emission range of the heater, with the spectral absorption range of the thermoplastic material. This spectral range for most typical used IR heaters is situated in the NIR, as is the influence of the crystallinity on the absorption characteristics of the thermoplastic material.

Different studies have focused on process modelling of the IR heating step. The first efforts were based on a standard enclosure analysis to predict the IR heating of the sheet based on the exact temperature settings of quartz heater tubes (Cunningham et al., 1997; Cunningham et al., 1998) or the electrical power input to the heater elements (Brogan and Monaghan, 1996).

Finite difference (explicit or implicit) is the most widespread method to model the heating of a thermoplastic sheet (Holman, 1997; Gauthier et al., 2005). In this method, the basic thermal energy balance equation is solved in a numerical way. This method allows to take time-dependent process boundary conditions into account as well as temperature-dependent material properties.

The use of virtual sensors and model predictive controllers has been the topic of more recent investigations. In these studies, the in-plane temperature differences are minimized based on a physical model instead of estimating or directly measuring temperatures at specific locations (Chy and Boulet, 2010). Although these types of process control show some potential, the currently required computational effort is too high to implement the method on an industrial scale (Chy and Boulet, 2011a, 2011b, 2012; Modirnia and Boulet, 2013).

So far, the modelling of the heating step was not directly linked to the subsequent forming step. In this regard the work of Bordival et al. (2009) presents an interesting approach. In their study the IR heating of a PET preform for a blow moulding application is investigated. The standard deviation on the wall thickness of the final PET bottle was defined as the cost function that needed to be minimized. By applying an optimization algorithm to this cost function, the temperature distribution along the height of the preform was successfully optimized. A coupled FE-analysis of the blowing step indicated the optimized wall thickness distribution.

In addition to the development of numerical models of the heating of thermoplastic sheets, Cosson et al. (2011) and Dos Santos (2005) emphasized the importance of accurate material data and process description. Next to the thermal diffusivity of the thermoplastic material, the optical penetration depth of IR radiation must be taken into account as well. In his work, Throne (1999) shows that IR radiation is not only absorbed at the outer surface but also partially penetrates the sheet caused by the partially thermal transparent nature of the material. The optical penetration depth is defined as the distance from the irradiated surface to the depth where the radiation intensity has decreased to $1/e$ ($\approx 36,8\%$) (Puehringer et al., 2011). The higher the optical penetration depth, the more volumetric heating is obtained as opposed to pure surface heating. This has a positive effect on the uniformity of the through-thickness temperature distribution. Implementing the optical penetration depth in a numerical model of the IR heating of thermoplastic sheets improves the accuracy with respect to experimental data (Gauthier et al., 2005).

Although, IR heating is the most important type of heat transfer taking place in this stage of the thermoforming process, convective heat losses to the environment should not be neglected. This introduces the need for additional quantitative data on the heating process which is often unknown: the temperature of the air (which is time and location dependent) as

well as the convective heat transfer coefficient itself (Yousefi et al., 2002; Chy and Boulet, 2011a).

The previous sections illustrate the complexity of the IR heating process in thermoforming. Different process and material parameters must be taken into account. Although the present study makes certain assumptions, it proves the added value of pulsed heating as a heating strategy in thermoforming. In this paper the pulsed heating method is presented by combining experimental measurements with numerical modelling. In the following sections, first the experimental measurements are described and followed by the presentation of the applied numerical model to evaluate and predict the pulsed heating of thermoplastic sheets. In the results section, the influence of the applied power in the pulse and time period in which the heater elements are switched off is discussed in detail. In summary, the aim is to use a reverse engineering approach to calibrate the numerical model that allows to evaluate and predict subsequent standard and pulsed heating cycles.

2 Experimental

An experimental test setup was developed to measure the temperature evolution during heating. Embedded thermocouples were used to measure the temperature as a function of time and the through thickness position in the centre of the plate. The test setup consists out of a vertically placed halogen heater element (model Philips Speedium SK15 650 W, Philips, ■■■town, country ■■■) at a fixed distance of 75 mm of an instrumented silicone sheet. An aluminium reflector was placed at the backside of the heater element to direct the IR radiation towards the sheet (Fig. 1).

The temperature of the silicone sheet is registered by 15 type K thermocouples (Fig. 2). The sheet consists out of 4 layers of

silicone that are vulcanized to form a single sheet of 3,9 mm thick. The three thermocouples are embedded at five locations on the top, core and bottom of the sheet. A 0,5 mm thick copper disc with a diameter of 6,5 mm is attached to the end of each thermocouple wire. Since the present study uses a 1D approach, only the three thermocouples in the centre of the sheet are considered. The heating takes place at one side of the sheet. The embedded thermocouples are able to capture the temperature at the heated and non-heated side as well as the core of the material. The material properties of the silicon sheet are summarized in Table 1. The density and thermal conductivity are measured at room temperature. The value for the specific heat capacity is the average for the temperature range from 20 °C up to 180 °C. These material properties are also used in the numerical modelling to account for the thermal diffusivity of the material.

The halogen heater element is controlled with an Arduino script. A typical heating routine is presented in Fig. 3. At first,

Fig. 1. Schematic illustration of the experimental setup. (1) Halogen heater element with an aluminum reflector linked to a Arduino controller, (2) instrumented silicon sheet to measure through-thickness temperature distribution

Fig. 2. Schematic representation of the instrumented silicone sheet with embedded thermocouples. The thermocouples are indicated by the grey circles

Material property	Unit	Value	Experimental method
Density, ρ	kg/m ³	1 380	Archimedes submersion
Specific heat capacity c_p	J/kgK	1 330	DSC TA Q200 sapphire method
Thermal conductivity, k	W/mK	0,18	C-therm TCi modified transient plane source method

Table 1. Silicon sheet material properties

an initial heating step with a constant heat flux q_{init} is applied for a time interval t_0 . Preliminary experiments showed that for the applied experimental set up, setting a t_0 value smaller than 30 s is of no practical use. The temperature difference through thickness does not decrease any further at lower t_0 values while the total cycle time increases.

Secondly a block wave is applied for a number of cycles (n) to obtain a pulsed heating strategy. In this block wave, the IR heating flux is switched on and off for time intervals t_{ON} and t_{OFF} . When the element is switched on a heat flux q_p is applied. It should be noted that the values q_{init} and q_p represent the electrically applied energy, and do not represent the absorbed heat flux values mentioned in later sections of this study.

It was observed that the silicone sheet starts to sag under its own weight at temperatures above 100 °C. To avoid this type of deformations of the silicone sheet, the maximum temperature was kept below 100 °C. Although actual thermoforming temperatures for most thermoplastics are higher, the same principles, methods and conclusions are applicable at higher temperatures and for other thermoplastic materials. Moreover, most thermoforming installations are equipped with sheet sag compensation methods to keep the sheet flat during the heating phase.

3 Numerical Modelling

The finite difference model presented in this study is an elaboration of the model developed by Buffel et al. (2017). In this model, explicit finite difference modelling (Holman, 1997) is applied to solve the general heat balance equation (Eq. 1). The boundary conditions in the present approach include convective heat transfer to the environment as well as time dependent radiative heat transfer. Internally, conductive heat transfer is applied to consider the transport of heat between nodes in the solid material.

$$\frac{dq_{\text{in}}}{dx} - \frac{dq_{\text{out}}}{dx} = mc_p \frac{dT}{dt}. \quad (1)$$

In the present study, only the heat transfer through thickness of the thermoplastic sheet is considered. In this way the general heat balance equation is reduced to a one-dimensional equation. In Eq. 1 q denotes the heat flow, m is the mass, c_p is the specific heat capacity, T is the temperature in Kelvin and t is the time variable.

Fig. 3. Schematic representation of a typical heating routine

Within the explicit finite difference modelling, the sheet thickness is discretized in different layers with thickness Δx . The Courant-Friedrichs-Lewy condition (Eq. 2) is used as a convergence criterion to determine the size of the time step Δt (Courant et al., 1967):

$$\text{CFL value} = \frac{a \cdot \Delta t}{\Delta x^2} < 0,5. \quad (2)$$

In Eq. 2 a is the thermal diffusivity of the thermoplastic material. During the IR heating of the thermoplastic sheet, different boundary conditions are applied. The radiative heat flux q_{rad} [kW/m²] represents the amount of heat absorbed by the sheet. In accordance with the semi-transparent properties of thermoplastics for infrared radiation (Throne, 2016) the heat flux q_{rad} is not only applied to the outer layer of the model, but is distributed to the internal layers. In this respect, the optical penetration depth, d_p , proposed by Puehringer et al. (2011) is taken into account. A high d_p value, corresponds to a deep penetration of the IR radiation into the sheet. Consequently, high d_p values give a more volumetric heating in contrast to a pure surface heating. In general, heater elements with a higher emissive power operate at shorter wavelengths resulting in higher d_p values.

The optical penetration depth d_p is experimentally determined by measuring the wavelength dependent transmission and reflectance spectra of the material in IR-region. As these measurements require specific lab equipment which is not readily available to the industry, a different approach was chosen in the present study. As an alternative, the optical penetration depth was considered to be a modelling variable and is determined during the reverse engineering step in the modelling approach.

The penetration of the IR radiation is applied in the model through the method proposed by Gauthier et al. (2005) (Eq. 3 and 4).

$$\beta = 1 - e^{\Delta x/d_p}, \quad (3)$$

$$q_i = \beta(1 - \beta)^{i-2}(1 - \beta)q_{\text{rad}}. \quad (4)$$

The total heat flux value q_{rad} is replaced by q_i in the heat balance for each layer (i) through the thickness of the sheet. Equation 3 indicates the exponential decay of the amount of incident radiation penetrating the thermoplastic sheet.

On an actual thermoforming installation, the view factors between the different heater elements and the thermoplastic sheet influence the local in plane temperature distribution. This is not taken into account in the present study which focuses on a 1D heating of a thermoplastic sheet by means of IR radiation. Since, in the experimental setup, the sheet is positioned at short distance from the heater element and the measuring location is right in front of the heater, the view factor value is assumed to be one.

Convective heat transfer of the exposed and opposed side of the sheet to the environment is the second boundary condition applied to Eq. 1:

$$q_{\text{conv}} = hA(T_{\infty} - T_i). \quad (5)$$

In Eq. 5 h represents the convective heat transfer coefficient, T_{∞} the air temperature of the environment, T_i the surface temperature and A the exposed surface area. The value for the convective heat transfer coefficient is based on literature values (Holman, 1997) for natural convection. A parameter study indicated that the temperature evolution of the thermoplastic

sheet is insensitive to variations of h in the range between 2 and 15 W/m²K. The air temperature T_{∞} was fixed at 25 °C.

Thirdly the through-thickness transport of heat in the sheet is modelled using Fourier's law (Eq. 6).

$$q_{\text{cond}} = -kA \frac{dT}{dx}. \quad (6)$$

In Eq. 6 k represents the thermal conductivity of the thermoplastic material. Combining Eqs. 3 to 6 allows to solve Eq. 1. As a result the 1D through-thickness temperature as a function of time is calculated.

The time delay between switching on the heater elements and obtaining the requested power (Buffel et al. 2017) is included in the model. However, the time constant in the first order approach to describe this effect is too low (ca. 0,004 s) to significantly influence the results in this study on pulsed heating. Therefore this time delay will be neglected in the following sections.

In order to include pulsed heating processes in the model, the radiative heat flux is made time dependent. In all considered cases, there is an initial heating time, t_0 , with constant radiative heat flux q_{rad} . Following this initial heating time, four parameters control the applied total radiative heat flux

- q_{ON} : the absorbed heat flux when the pulse is switched on,
- q_{OFF} : the absorbed residual heat flux when the pulse is switched off. The value for this residual heat flux is approximated by a percentage (PCT) of q_{ON} ,
- t_{ON} : time interval during which the heater is switched on,
- t_{OFF} : time interval during which the heater is switched off,
- All numerical simulations use the material data presented in Table 1.

4 Results and Discussion

4.1 Experimental Validation of the Model

Different process settings were experimentally tested. These process settings investigate the reproducibility, and the influence of q_{ON} , t_{OFF} and t_0 . As the latter parameter did not significantly influence the results, it is not discussed in detail. For each of these processing conditions, the process parameters in the numerical model were changed according to the experimental conditions. The values for d_p , T_{∞} , h and PCT were determined through reverse engineering, while the experimental values describing the actual process condition (q_0 , t_0 , q_{ON} , q_{OFF} , t_{ON} and t_{OFF}) are directly linked to the experimentally applied boundary conditions. Note that heat flux variables (q_0 , q_{ON} , q_{OFF}) refer to the absorbed thermal energy of the sheet. As the transition from the experimentally known applied electrical flux towards the absorbed IR flux is currently unknown, the numerical values are also part of the reverse engineering step.

The aim of this reverse engineering step is to calibrate the numerical model for the complete working range of the thermoforming process. Afterwards the model can be used to describe and predict the pulsed heating of thermoplastic sheets (Buffel et. al 2017).

All experimental data shown in the next sections refer to the temperatures measured by the thermocouples at the exposed and non-heated side at the centre of the instrumented sheet (Fig. 2).

The reproducibility of the heating curves was evaluated by performing the measurements for each set of process parameters 3 times. As an illustration of this, Fig. 4 presents three temperature evolution curves measured for the same process parameter set. The curves show a similar temperature evolution with a maxim temperature difference smaller than 4 °C between the curves for the heated side and smaller than 3 °C at the non-heated side. Moreover, there is a difference of a few degrees at the start of the measurement, which also affects the temperature difference between multiple measurements. This proves the good reproducibility of the heating process.

A selection of six processing conditions is discussed in the present paper. The parameters of these conditions are summarized in Table 2.

Table 2 summarizes the numerical modelling parameters that give the best fit between experimental data and modelling results. The value for the initially applied heat flux q_{init} was experimentally kept constant in order to keep the absorbed heat flux q_0 constant as well. The best fit results for q_0 in Table 1 show however a small variation ($\leq 5\%$). This variation is caused by both experimental error in temperature measurements as well as uncertainties in the reverse engineering procedure. Moreover, in the present study, the fitting procedure focuses on matching the start and end point of the initial heating stage, rather than matching the overall course of the initial heating stage.

In the first three parameter sets, the applied IR heat flux during the pulsed phase of the process, q_p , was increased. This results in an increase of the absorbed heat flux q_{ON} from 4 up to 6,2 kW/m². The comparison between experimental data and modelling results is shown in Figs. 5 to 7. The forth to sixth parameter set show the influence of the time interval in which the heater element is switched of during the pulsed phase, t_{OFF} . This parameter is varied from 5 to 15 s. The comparison be-

Fig. 4. Temperature evolution for 3 pulsed heating processes showing good reproducibility of the heating process

tween experimental data and modelling results is shown in Figs. 8 to 10. It is important to note that during the interval t_{OFF} the heater elements are completely switched off and no electrical power is applied to the elements.

Figures 5 to 7 indicate that the proposed numerical model is suited to describe the pulsed heating method. The numerically calculated temperature evolution of both the heated and non-heated side correlates well with the experimental data. These 3 figures show the influence of parameter q_{ON} , being the absorbed radiative heat flux during the pulsed heating phase of the process. The higher the value for q_{ON} , the steeper the temperature increases and the larger the temperature difference between heated and non-heated side is.

The temperature evolution at the heated side of the sheet during the intervals when the heater elements are switched off (t_{OFF}) are of particular interest. Although the heat loss to the environment is present during these time steps, the temperature does not decrease. Instead, the temperature stays constant or even increases slightly. This is caused by the residual thermal radiation of the heater elements. When switched on, the com-

ponents of the halogen heater elements, (e.g. the quartz glass bulb and filament wire) are heated. When the electrical power is switched off, these elements start to cool down and continue to emit a radiative heat flux towards the thermoplastic sheet. This residual radiation partially compensates for the convective heat losses of the sheet. These convective heat losses are calculated at every time step, taking the instantaneous surface temperature into account.

The amount of absorbed residual heat flux is quantified in Table 2 as q_{OFF} . This effect is an advantage of the pulsed heating method: the surface temperature of the sheet does not decrease while the heat is conducted through thickness of the sheet resulting in a more uniform temperature distribution. This takes place when no electrical power is applied to the system. In order to exploit this effect, the interval t_{OFF} can be increased.

This is visualised in Figs. 8 to 10 where t_{OFF} is set to 5, 10 and 15 s. These figures indicate the limit to the residual radiation effect. When t_{OFF} increases, eventually the surface temperature of the sheet starts to decrease as well, resulting in an

Parameter	q_0	t_0	q_{ON}	q_{OFF}	PCT	t_{ON}	t_{OFF}
set	kW/m^2	s	kW/m^2	kW/m^2	%	s	s
1	5,9	34	4,0	2,28	57	4	4
2	6,0	34	5,0	2,75	55	4	4
3	6,2	34	6,2	3,08	50	4	4
4	5,9	34	5,9	2,13	53	4	5
5	5,9	35	5,8	1,80	31	4	10
6	5,9	34	5,6	1,40	25	4	15

Table 2. Summary of parameters varied for six different processing conditions

Fig. 5. Temperature evolution for pulsed heating process 1, with $q_{\text{ON}} = 4 \text{ kW/m}^2$ (cfr. Table 1)

Fig. 6. Temperature evolution for pulsed heating process 2, with $q_{\text{ON}} = 5 \text{ kW/m}^2$ (cfr. Table 1)

unwanted loss of heat in the thermoplastic sheet. The correlation between experiments and numerical values even deteriorates with increasing t_{OFF} values, as indicated by Fig. 10. This is caused by the numerical principle that is applied to take the residual radiation into account. In the present study this is done by setting a time-independent heat flux q_{OFF} as a certain percentage of the q_{ON} value. In reality the value for q_{OFF} decreases as a function of time because the heater element components

cool down due to convection and radiation to the environment. This puts the limit on the maximum useful value for t_{OFF} to be lower than 10 s in the present experimental setup.

Since t_{OFF} values larger than 10 s are of no practical use in the thermoforming industry, there is no need to improve the numerical model by replacing the constant q_{OFF} value by a time-dependent coupling of the sheet surface temperature to the convective heat losses to the environment.

Fig. 7. Temperature evolution for pulsed heating process 3, with $q_{\text{ON}} = 6,2 \text{ kW/m}^2$ (cfr. Table 1)

Fig. 9. Temperature evolution for pulsed heating process 5, with $t_{\text{OFF}} = 10 \text{ s}$ (cfr. Table 1)

Fig. 8. Temperature evolution for pulsed heating process 4, with $t_{\text{OFF}} = 5 \text{ s}$ (cfr. Table 1)

Fig. 10. Temperature evolution for pulsed heating process 6, with $t_{\text{OFF}} = 15 \text{ s}$ (cfr. Table 1)

4.2 Comparison of Pulsed Heating to the Current State of the Art

The pulsed heating method is compared to the current common practice heating method in which a single radiative heat flux is applied. The value for this heat flux is based on a compromise between fast heating and controlling the through-thickness temperature differences. To compare the different heating methods, the numerical results are evaluated at the timestep where the heated surface of the sheet reaches 90 °C and the value of q_{rad} is set to a constant value through the complete process. In a first comparison (Fig. 11?), the value for the absorbed radiation (q_{rad}) was set equal to the initial radiative heat flux value applied before the pulsed heating is applied (q_0) until the heated side of the sheet reaches 90 °C ($t_{90^\circ\text{C}}$). In a second comparison (Fig. 12 ■ ■), the value of the absorbed radiation was determined by the actual amount of radiative heat absorbed by the sheet during actively applied radiation in a pulsed heating method to reach 90 °C at the heated surface ($t_{90^\circ\text{C}}$). In this case q'_{rad} is calculated by Eq. 7:

$$q'_{\text{rad}} = \frac{q_0 t_0 + n q_{\text{ON}} t_{\text{ON}}}{t_{90^\circ\text{C}}} \quad (7)$$

With n equal to the number of pulses to reach 90 °C at the surface, t_0 the initial heating time before pulsed heating is started

Fig. 11. Time to reach 90 °C at the heated side of the sheet for 3 different heating methods. Data based on the numerical 1D model

and t_{ON} the pulsed heating time interval in which the heater elements are switched on. The quantitative values for this comparison are summarized in Table 3.

The low variation in the q_{rad} value for all six parameter sets results in little to no variation in the $t_{90^\circ\text{C}}$ and $\Delta T_{90^\circ\text{C}}$ values for the cases with constant radiative heat flux q_0 in the heating process. The temperature difference between heated and non-heated side of the sheet is smaller for all processes in which pulsed heating is applied. On the other hand, the time needed to reach 90 °C is smaller when a constant value of q_0 is applied. This leads to the conclusion that pulsed heating is able to decrease through-thickness temperature difference, albeit at the cost of a higher heating time.

When the applied constant radiative heat flux is linked to the actively applied energy during pulsed heating, this drawback of the pulsed heating method is partially compensated. As long as the convective heat losses during the intervals t_{OFF} are limited (in this study below 10 s), the pulsed heating method is able to reach 90 °C at the surface in a shorter time without resulting in an excessively larger temperature difference through thickness. With respect to the pulsed heating method, the relative difference in $\Delta T_{90^\circ\text{C}}$ between both types of heating is lower than 12 %.

These observations indicate the potential of applying pulsed heating as a method to increase the homogeneity of sheet temperatures through thickness without compromising the heating cycle time.

Fig. 12. Temperature difference through thickness of the sheet when the heated side reaches 90 °C for 3 different heating methods. Data based on the numerical 1D model

	Pulsed heating			q_0 constant			q'_{rad} constant		
	n	$t_{90^\circ\text{C}}$	$\Delta T_{90^\circ\text{C}}$	q_{rad}	$t_{90^\circ\text{C}}$	$\Delta T_{90^\circ\text{C}}$	q'_{rad}	$t_{90^\circ\text{C}}$	$\Delta T_{90^\circ\text{C}}$
	—	s	°C	kW/m ²	s	°C	kW/m ²	s	°C
1	12,5	136,1	11,7	5,9	66,2	23,3	3,0	150,0	12,0
2	8,0	97,8	16,0	6,0	64,7	23,6	3,7	128,0	14,7
3	5,9	80,8	18,8	6,2	62,5	24,2	4,5	96,9	17,9
4	6,2	87,0	17,6	5,9	66,6	23,3	3,9	119,4	15,5
5	7,8	146,1	11,6	5,9	66,2	23,3	2,4	250,6	9,6
6	9,6	224,1	4,7	5,9	66,6	23,3	1,7	506,5	6,8

Table 3. Comparison between pulsed heating and the current state of the art radiative heating methods

Fig. 13. Increased process control by applying pulsed heating method

4.3 Increased Process Control during IR Heating

The current state of the art in radiative heating of thermoplastic sheets is applying a constant (or two step) radiative heat flux to the surface. As a result the tools to control the through-thickness temperature difference are very limited. This is indicated by the graph in Fig. 13. The temperature difference as a function of time follows a fixed path that is difficult to influence in traditional heating configurations.

When pulsed heating is considered, an additional processing window is opened (gray area in Fig. 13). By applying the pulsed heating method and controlling the amount of residual radiation during the t_{OFF} intervals, the temperature difference can be altered. This is illustrated in Fig. 13 by the curves where no residual radiation (limit situation) is considered and the curve in which the residual radiation is set at 50% of q_{ON} .

Figure 14 presents the through-thickness temperature distribution at $t_{90^\circ\text{C}}$. Although the 90°C temperature limit is around 40 to 70°C below the recommended thermoforming range of most thermoplastics the conclusions of this graph are applicable at higher temperatures as well. The 90°C temperature limit was deliberately chosen to avoid sheet sagging or thermal degradation of the instrumented silicone sheet. The curves in Fig. 14 show the typical behavior where the maximum temperature is found at a small distance (ca. 0,5 mm) from the heated side. This is caused by the convective heat losses at the surface which result in a slightly lower temperature at the outer surface. As indicated in Fig. 14, the largest temperature difference between the heated and non-heated side occurs when no pulsed heating is applied. When pulsed heating is applied, the temperature at the non-heated side shifts towards higher temperatures, while the maximum temperature is hardly influenced. This results in a more homogeneous temperature distribution around the targeted value, in this case 90°C . This effect is beneficial for the subsequent forming step in thermoforming, especially in the case of semi-crystalline thermoplastic sheets, where temperature control is the most crucial.

5 Conclusions

In the present study an explicit finite difference model was developed to evaluate the pulsed heating strategy on a silicone

Fig. 14. Through-thickness temperature plot at $t_{90^\circ\text{C}}$

sheet. When combining the model with experimental measurements, the model proved to be able to capture the occurring physical phenomena and accurately describe the through-thickness temperature evolution as a function of time. The results of the study indicate the influence of the applied IR heat flux and time interval t_{OFF} in the pulsed heating stage of the process. When the heater elements are switched off, there is a non-negligible amount of residual radiation being emitted by the heater components. This residual radiation is able to partially compensate convective heat losses at the surface of the sheet. The residual radiation causes the sheet to continue heating during time intervals when no heat is actively added to the process. This beneficial effect is limited by the convective heat losses during the interval t_{OFF} . For the test setup presented in this study, the maximum feasible time interval was 10 s. The numerical model shows that applying a pulsed heating strategy opens up a large processing window to control the through-thickness temperature difference. If the total amount of actively applied heat energy is taken into account, pulsed heating is able to increase the overall heating rate and simultaneously keep the temperature difference through thickness limited. This is an important benefit with respect to the thermoforming process and can lead to better process control.

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Date received: May 04, 2020

Date accepted: January 26, 2021

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DOI 10.1515/ipp-2020-3981

Intern. Polymer Processing XXXVI (2021) 4; page 1–10

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ISSN 0930-777X · 2195-8602