Global Advanced Research Journal of Engineering, Technology and Innovation (ISSN: 2315-5124) Vol. 1(5) pp. 113-123, August, 2012
Available online _http://garj.org/garjeti/index.htm

Full Length Research Paper

Realization of heating phase of plastic sheet through heat transfer equation

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Accepted 03 July 2012

This paper presents an improved mathematical model to represent a more accurate relationship among inputs and outputs of the heating phase of the thermoforming process. The proposed state-space model of the heating phase of thermoforming process can present and explain some incidents which are impossible to explain using the existing model. The main purpose of the paper is to improve the quality of predictions of the system's output and state through more accurate evaluation of the inputs and system properties. First, the modeling is developed based on the heat transfer method and system's behaviour. Then, a series of specialized experimental data were compared with the simulation data obtained from the developed model to validate it. All three kind of heat transfer methods (conduction, convection and radiation) are considered in the development of the model of a thermoforming machine. The proposed state space model is simulated using a Simulink model to compare with real time results. The input output relationship of the proposed model almost accurately follows the real time relationship of the inputs and outputs at different operating conditions. The proposed model gives the improved results compared to the existing model with the real time experimental data even there was some discrepancy of the existed model result with the real time data. The accuracy of the proposed model is evidenced by the results.

Keywords: Thermoforming process, Modeling, Heating phase, Infrared sensor, Conduction, Convection, Radiation heat transfer, Emissibity, Absorbity and Real-time Implementation.

INTRODUCTION

Hermoforming process becomes popular day by day with the increase of the use of polymer product in various manufacturing industries like automotive, aerospace, refrigeration and packaging industry (Throne and James, 1996). These products are gradually supplanting traditional materials such as aluminum, glass, wood and paper. This diversity and large use of the process encourage the researchers to develop more sophisticated and cost-effective ways for the process (Nam and Lee, 2001 : Rozant et al ., 2000 : Gross, 1984 : Moore, 2000). A thermoforming process consists of three phases which are named as heating phase, forming phase and solidification phase. The first and most important part of a thermoforming process is heating the sheet to the softening temperature, which is called heating phase. So it becomes an important issue for the researchers to develop an efficient method to control the heating phase of thermoforming process. Most of the improved and recently developed control techniques depend on the mathematical model of the system. An accurate mathematical model is very important to get idea about

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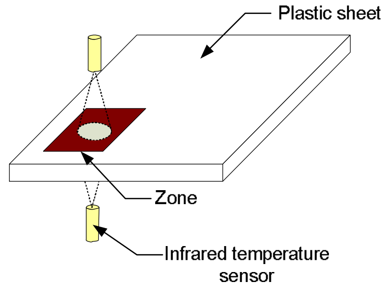

Figure 1. Zone and IR temperature sensors

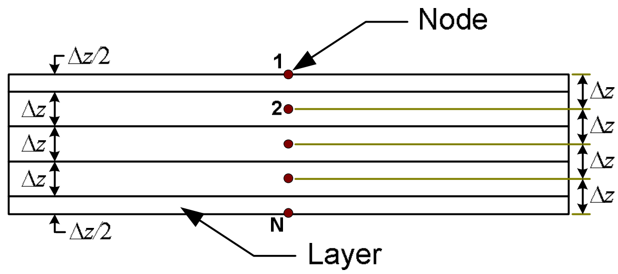

Figure 2. Layers and nodes

the system's behavior and for the simulation of the developed control technique to guarantee future prospect of the proposed technique before it is implemented in real-time. System modeling is a useful tool in efficient controller design to achieve the desired output temperature of the sheet at the end of the heating cycle in the thermoforming process. Some researchers have developed a simple idea of heat transfer method in heating phase of the thermoforming process (Moore, 2000 : Throne, 1996). They are focused on various mechanisms of heat transfer methods for a variety of polymers processing techniques. In (Moore, 2000), Moore introduces the modeling of sheet reheat phase of the thermoforming process considering heat transfer by the combination of conduction, convection and radiation. He proposed the discrimination of the plastic sheet across its thickness to consider heat propagation through its thickness. In (Throne, 1996), Throne developed a model for heat transfer in semitransparent polymers for heating phase of the thermoforming process considering the wavelength dependency of sheet absorptivity and heater emissivity. In (Vijay Kumar, 2005), the researcher analyzed the dependency of the absorbity and emissivity of the sheet on the wavelength of the transmitted heat that influence the development of the model of the heating phase. In (Schmidt et al., 2003), researcher established the spectral properties of infrared heat emitters. In (Yousefi et al., 2004), the authors analyzed the uncertainty of the model parameter those are related to input – output relationship of the modeling of heating phase. This work focuses on the treatment of parameter uncertainty in the simulation of the sheet reheat phase of the thermoforming process In (Monteix et al., 1998), the researchers gave emphasis to the importance of optimizing the reheating stage in blow moulding and thermoforming process. For that analysis, they come up with a model to predict the transient temperature distributions over both thin and thick-gage polypropylene thermoformed sheets using a radiative heat transfer analysis using an effective radiative heat transfer coefficient and the effective bulk temperature. Mark Ajersch (Ajersch, 2004) improves that modeling incorporating the absorption of heat within the sheet as it heated. Gauthier (Guy Gauthier, 2008), proposed certain improvements of the heating phase of a thermoforming machine based on the previous model developed by Ajersch. Although the researchers developed a good model for the heating phase of the thermoforming process, still there are some existing discrepancies between the simulation and experimental results. In this paper, an improved model is developed for the heating phase of the thermoforming process through some development of the existing model developed by Ajersch resulting into superior quality of predictions through more accurate evaluation of input parameters. Section II, the existing model of the heating phase reviewed. In section III includes discrepancy of the existing model with experimental results presented. In that section some possible ways to improve the model is presented too. Section IV discussed some improvement techniques of the proposed method. In section V, the model of the actuator is developed and in the following section the experimental setup was discussed. Section VII compares some real-time results with the prediction of the model.

Modeling of sheet reheat phase in thermoforming

The model used in this paper is developed in (Gauthier et al., 2005). Interested readers are encouraged to get

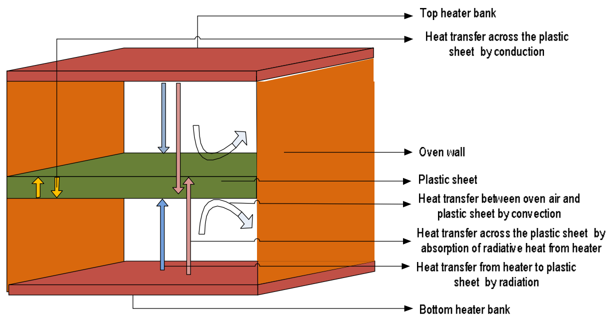

Figure. 3. Heat transfer in existing model of heating phase in thermoforming process

details of the model from that reference. The developed model is briefly discussed here. Each IR temperature sensor looks at an area on the plastic sheet to perform the temperature measurement. Each area where the sensors are pointing is designated as a “zone”. To facilitate modeling, we assume that there are two IR sensors for each zone of the plastic sheet, one looking at the sheet from above and the other from below (Fig.1).

To analyze the propagation of the heat inside the plastic sheet, heat transfer equations must be defined for some points inside the sheet. To do so, each zone is divided into layers throughout the thickness of the sheet (Fig.2). The layers have the same thickness, and at the middle of each layer there is a point referred to as a node. For each node, a differential equation describes the heat exchange of the corresponding layer. Since the surface of the plastic sheet is an important boundary of energy exchange, a node is located directly at the surface, see Fig.2. This forces the layer containing this point to have only half of the volume inside the plastic sheet, and hence, its thickness is only half of that of internal layers. The layers having their node at the surface are identified as “surface layers” and the other layers are designated as the “internal layers”.

For each node, a differential equation describes the heat exchange of the corresponding layer. There are three ways (conduction, convection and radiation) to exchange energy between heaters, ambient air and nodes. Neglecting the conduction of heat between two zones, the conduction heat transfer between surface node and its adjacent node can be expressed as,

$$\frac{dT_{su}}{dt} = \frac{2}{\rho V C_p}\left[\frac{kA}{\Delta z}\left(T_{in} - T_{su}\right)\right] \tag{1}$$

where, ρ is density of the plastic sheet, C_p is the specific heat of the sheet, k is the heat conduction constant, Δz is the layer thickness, A is the zone area, V is the volume of the layer, T_{su} is the surface node temperature and T_{in} is the temperature of the adjacent node of the surface. The convection has an effect only on the nodes of surface layers and expresses heat exchange between the ambient air and the sheet. The heat transfer can be expressed as,

$$\frac{dT_{su}}{dt} = \left(\frac{2}{\rho V C_p}\right) h\left(T_{\infty} - T_{su}\right) \tag{2}$$

where, h, the convection coefficient, T_{su} is the surface node temperature and T_{∞} is the ambient air temperature. The radiant energy exchange transmits energy from the heaters to all the nodes of the plastic sheet which can be expressed as,

$$\frac{dT_i}{dt} = \left(\frac{2}{\rho V C_p}\right)\sigma \varepsilon_{eff} A_h \left[\sum_{j=1}^{M}\left(\theta_j^4 - T_i^4\right)F_{k,j}\right] \tag{3}$$

where, σ is the Stefan Boltzmann constant, ε_{eff} is the effective emissivity, A_h is the area of the heater bank, $F_{k,j}$ is the view factor between the j-th heater bank and the k-th

zone,θj is the j-th heater bank temperature. Details of the method for calculating effective emissivity and view factors can be found in (Ehlert and Smith, 1993), respectively. If the infrared radiation is able to penetrate inside the plastic sheet, the surface node will not be able to absorb all the heat from the received incident radiant energy and if it penetrates through the thickness of the sheet, it will heat every node on its way and a part of the incident radiant energy is transmitted through the plastic sheet depending on the transmissivity factor. Combining all three forms of heat transfer into the equation for 2M heaters, Z zones and 2 nodes for each zone, and taking the transmissivity into account in the energy transfer from the radiant heaters to the plastic sheet, the model for the j-th zone in the heating phase becomes,

$$\frac{dT_{j,top}}{dt} = \frac{2}{\rho V C_p}\left\{\begin{array}{l}\left(\frac{kA}{\Delta z}\left(T_{j2} - T_{j,top}\right)\right) + h\left(T_{\infty_{top}} - T_{j,top}\right) \\ + \beta_1 Q_{RT_j} + \beta_1(1-\beta_1)(1-\beta_2)^{N-2} Q_{RB_j}\end{array}\right\} \tag{4}$$

$$\frac{dT_{j,bottom}}{dt} = \frac{2}{\rho V C_p}\left\{\begin{array}{l}\left(\frac{kA}{\Delta z}\left(T_{j,N-1} - T_{j,bottom}\right)\right) + h\left(T_{\infty bottom} - T_{j,bottom}\right) \\ + \beta_1(1-\beta_1)(1-\beta_2)^{N-2} Q_{RT_j} + \beta_1 Q_{RB_j}\end{array}\right\}$$

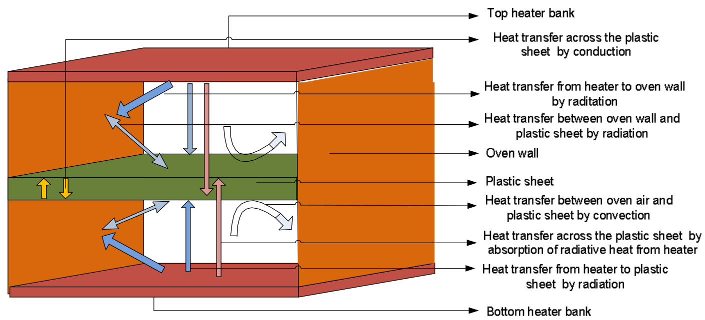

Figure 4. Heat transfer in new model of heating phase in thermoforming process

the model for internal node i of j-th zone the heating phase becomes,

$$\frac{dT_{j,i}}{dt}=\frac{1}{\rho VC_p}\left\{\begin{array}{l}\left(\frac{kA}{\Delta z}(T_{j,i-1}-2T_{j,i}+T_{j,i+1})\right)\\ +\beta_2(1-\beta_1)\{(1-\beta_2)^{i-2}Q_{RT_j}+(1-\beta_2)^{N-2-i}Q_{RB_j}\}\end{array}\right\} \quad (5)$$

where,

$$Q_{RT_j}=\sigma\varepsilon_{eff}A_h\left[\sum_{m=1}^{M}\left(\theta_m^4-T_{j,top}^4\right)F_{mj}\right]$$

$$Q_{RB_j}=\sigma\varepsilon_{eff}A_h\left[\sum_{m=M+1}^{2M}\left(\theta_j^4-T_{j,bottom}^4\right)F_{mj}\right]$$

$$\beta_1:=1-e^{-A\Delta z/2}$$

$$\beta_2:=1-e^{-A\Delta z}$$

Shortcoming of The Existing Modeling

The prediction of the output of the system for certain inputs hence the design of a controller depends on the accuracy of the plant model. As heating phase is the first phase of the thermoforming process among all three different phases, error in the prediction of the output temperature of the sheet will be followed by the erroneous prediction of the subsequent phase like molding and cooling phase. If the controller is dependent on the model such as in adaptive controller, model predictive controller, it becomes even more important to get an accurate model. According to the model developed by the previous researcher, the way the sheet gets heated as follows:

1. Heat radiation from the heater banks to the surface of the plastic sheet.
2. Heat conduction from the surface of the plastic sheet through its thickness.
3. Heat convection at the surface of the plastic sheet by oven air.
4. Absorption of the radiated heat throughout the plastic sheet thickness from the heater bank depending on the absorption coefficient of the plastic sheet.

This model is not complete as certain behaviors of the heating phase of thermoforming machine cannot be explained by the model. It is observed that the sheet gets heated faster than is expected from the model (Guy Gauthier, 2008 : Xuan-Tan Pham, 2005 : Gauthier et al., 2005). Thus, there is some other form of heat transfer happening in the sheet. As the increase in temperature occurs immediately after the sheet enters the oven and there is no delay in the transfer of heat, the extra heat gained is by radiation. So there must be some other heat source working as a radiator to heat the sheet. When a wall of the oven gets heated by the heaters, it works as another source that heats the sheet. The walls get heated by the heaters and when a new sheet placed in the oven it gets heated not only by heaters, but also by the oven walls and hot air in the oven. In the developed model, the convection heat transfer coefficient is considered to be constant at the top and bottom surfaces of the plastic sheet, which cannot be true. Convection heat transfer largely depends on the geometric area and

orientation of the heater which means a face up heater surface to the air passing above the surface should be different as compared to the convection heat transfer from a face down heater surface to the air passing below the surface. In the same way, the heat transferring from the sheet to the air at the top surface is higher than the heat transferring from the sheet at the bottom surface (when sheet temperature is higher than the air temperature and vice versa when sheet temperature is lower than the air temperature). Oven air temperature plays a big role in convection type of heating. But this model excludes the modeling of the oven air temperature and it has no explanation about the heating process of the air. It cannot explain the relationship of the air temperature with the heaters and sheet temperature. Heat convection coefficient highly depends on the geometrical arrangement of the heater surface (face up, face down, perpendicular) and the heating medium as convection type heat transfer depends on the geometrical arrangement of the heater surface. Some researchers worked to calculate convection heat transfer coefficients for different geometrical areas and orientations of the

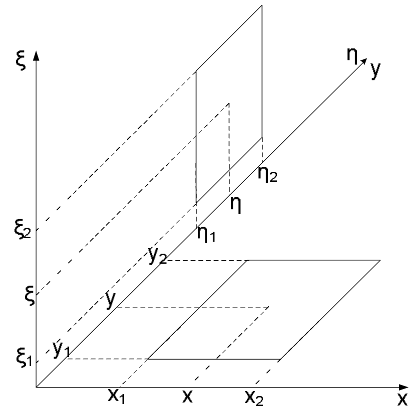

Figure 5. Calculation of view factor for perpendicular plates

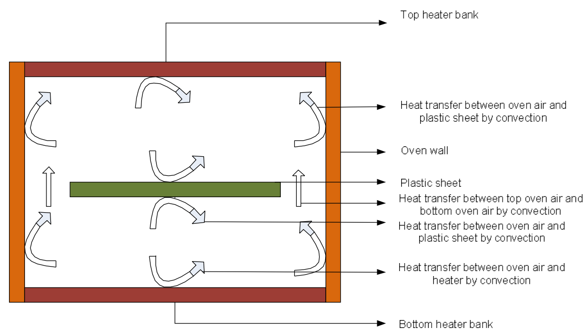

Figure 6(a). Heat transfer to top and bottom oven air of heating phase in thermoforming process (front view)

heater surface (Ehlert and Smith, 1993). So convection heat transfer coefficients for face up heaters, face down heaters, face up plastic sheet surface, face down plastic sheet surface, perpendicular oven walls will be different which can be calculated from different heat transfer research work that is already well established. Certain parameter of heat transfer equation like conduction coefficient, sheet density, sheet specific heat constant, heater emissivity, sheet absorbity depend on process condition and wavelength of the transmitted heat. In the present model, all those parameter considered to be constant. A more accurate evaluation of the heat transfer parameter should be made to get a more accurate model. Another fact that cannot be explained using the present model is the experimental observation which shows that the air and plastic sheet temperature at the top surface of the sheet is higher than the air and sheet temperature at the bottom surface of the sheet (Ajersch, 2004). One of the reasons behind this is the internal heat transfer between the air above the sheet and the air below the sheet.

Improvement of the modeling of sheet reheat phase

To predict the output of the heating process using a better model of the system, all the shortcoming of the developed model should be solved. Firstly, the radiative heat transfer from heater to the oven wall and oven wall to sheet surface are included into the model. The increase in oven wall temperature due to the radiative heat transfer between heater and oven wall can be expressed as,

$$\frac{dT_{wall}}{dt} = \frac{2}{\rho_{wall} V_{wall} C_{p_{wall}}} \sigma \varepsilon_{eff_{wall}} A_h \left[\sum_{m=1}^{M} \left(\theta_m^4 - T_{j,su}^4 \right) F_{mj} \right] \quad (6)$$

Where view factor between heater and the perpendicular oven wall can be calculated using the equation in (Ehlert and Smith, 1993).

$$F_{12} = \frac{1}{(x_2 - x_1)(y_2 - y_1)} \sum_{l=1}^{2} \sum_{k=1}^{2} \sum_{j=1}^{2} \sum_{i=1}^{2} (-1)^{(i+j+k+l)} G(x_i, y_j, \eta_k, \zeta_l)$$

$$G = \frac{1}{2\pi} \left\{ (y-\eta)(x^2+\zeta^2)^{1/2} \tan^{-1} \left[\frac{(y-\eta)}{(x^2+\zeta^2)^{1/2}} \right] \right.$$

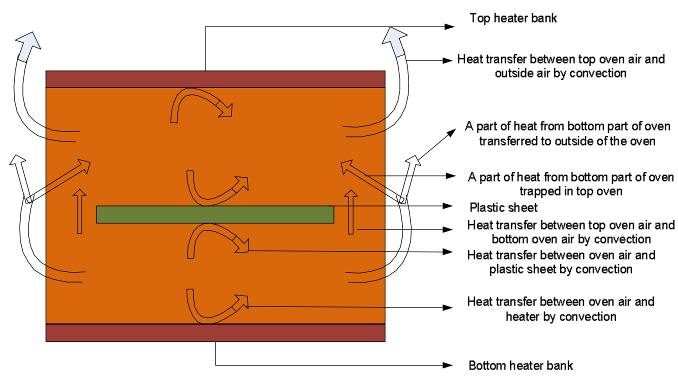

Figure 6(b). Heat transfer to top and bottom oven air of heating phase in thermoforming process (cross sectional side view)

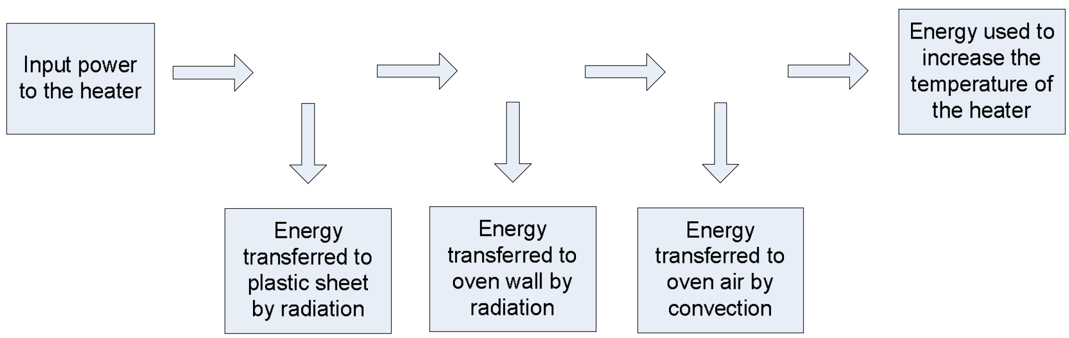

Figure 7. energy transfer model in heater of thermoforming process

$$-\frac{1}{4}\left[(x^2+\zeta^2)-(y-\eta)^2\right]\ln\left[(x^2+\zeta^2)-(y-\eta)^2\right]\Big\} \quad (7)$$

The heat transfer between oven wall and sheet depends on the corresponding temperature. At the beginning of the cycle, when the entering sheet is at room temperature, it will be heated by the hot oven wall and at the end of the cycle, when the sheet is already heated to a temperature that is higher than the oven wall, the heat energy will transfer from sheet to the oven wall. So, depending on the temperature of the sheet and the oven wall, the corresponding radiative heat transfer equation will be included in the model. To theoretically evaluate the natural convective heat transfer coefficients, well developed empirical equations are developed by the researcher. These well established equations can be used as follows:

$$Nu_L = \frac{hL}{k} = CRa_L^n \quad (8)$$

where Nu_L is the average Nusselt number, h is the heat transfer coefficient for convection, *k* is the thermal conductivity of air**,** and C and n are constants. The Rayleigh number, defined as the product of Grashof number and Prandtl number, is based on the characteristic length L of the geometry defined as follows:

$$Gr_L = \frac{g\beta(T_s-T_\infty)L^3}{v^2} \qquad \Pr = \frac{v}{\alpha}$$

$$Ra_L = Gr_L \Pr = \frac{g\beta(T_s-T_\infty)L^3}{v\alpha}$$

Where *g* is the local acceleration due to gravity, β is the thermal expansion coefficient, *T* is the plate surface temperature, T_∞ is the air temperature, *v* is the kinematic viscosity and *α* is the thermal diffusivity of air. To calculate the heat transfer coefficient for convection in case of a horizontal plate heater/cooler, the characteristic length *L* can be defined as the ratio of the surface area to the perimeter (Lloyd and Moran, 1974),

$$L = \frac{A_s}{P}$$

As some physical properties are dependent on the temperature, it is recommended that all those parameters should be calculated in the arithmetic average temperature of plate and air. The following equations give the heat transfer coefficients for the facing down of a heated plate or the facing up of a cooled plate as proposed by Mcadams (McAdams, 1954):

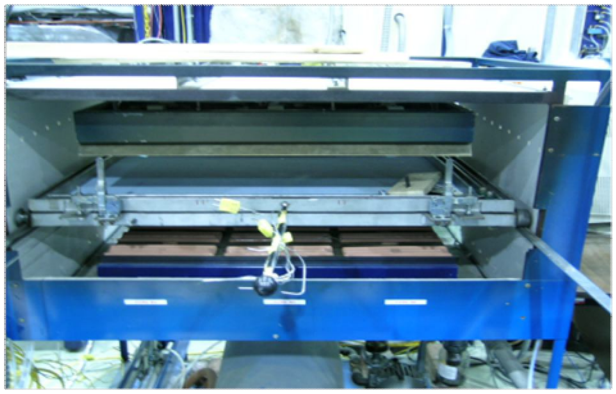

Figure 8. Experimental set-up of a Thermoforming oven

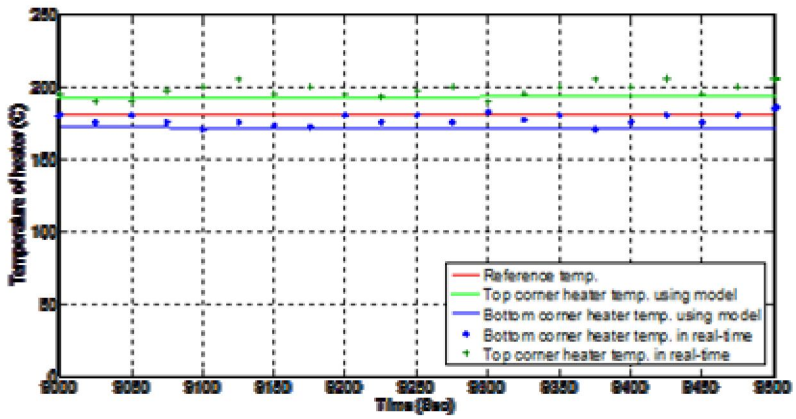

Figure 9. comparison of real-time top and bottom heater temperature with the corresponding simulated results.

$Nu_L = 0.27 Ra_L^{1/4}$ for $3\times10^5 \le Ra_L \le 3\times10^{10}$ (9)

The heat transfer coefficient for the face up lower surface of a heated plate or the face down upper surface of a cooled plate is:

$Nu_L = 0.54 Ra_L^{1/4}$ for $10^5 \le Ra_L \le 2\times10^7$ 10(a)

$Nu_L = 0.14 Ra_L^{1/3}$ for $2\times10^7 \le Ra_L \le 3\times10^{10}$ 10(b)

Churchill and Chu [18] proposed two relation as stated below to calculate the heat transfer coefficient for a vertical surface of a heated plate. To calculate the heat transfer coefficient with both laminar and turbulent flow :

$$Nu_m^{1/2} = 0.825 + \frac{0.387 Ra_L^{1/6}}{[1+(0.492/\Pr)^{9/16}]^{8/27}} \quad \text{for} \quad 10^{-1} < Ra_L < 10^{12}$$

(11)

To calculate the heat transfer coefficient with only laminar flow:

$$Nu_m = 0.68 + \frac{0.67 Ra_L^{1/4}}{[1+(0.492/\Pr)^{9/16}]^{4/9}} \quad \text{for} \quad 10^{-1} < Ra_L < 10^{9}$$

(12

Where mean Nusselt number, $Nu_m = \frac{h_m L}{k}$, h_m is the mean heat transfer coefficient for convection and in case of vertical plate heater/cooler, the characteristic length *L* can be defined as the height of the plate.

The internal heat transfer within the oven if the sheet is smaller than the oven size can also be taken into consideration using convection heat transfer between the air above the sheet and the air below the sheet. If the sheet size is smaller than the size of the oven, hot air from the bottom part of the oven will pass to the top part of the oven due to a lower density and gets trapped at the top surface of the oven. This increases the temperature of the air at the top and hence increases the sheet temperature at the top surface. In the case of semi-closed or open ovens, is that a percentage of the heat comes out due to convection heat transfer between the air of the oven and the air temperature outside the oven. A part of the heat comes out from the bottom part of the oven trapped again in own way to the top part of the oven and increases its temperature. The heat transfer with the air temperature inside the oven is involved with the

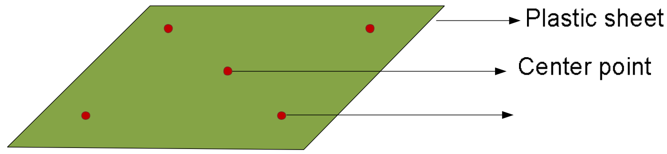

Figure 10. Corner and center point of the sheet

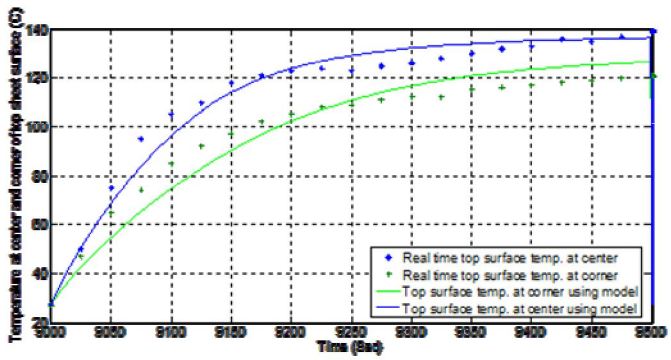

Figure.11. comparison of real-time sheet temperature at center and corner point of top surface of the sheet with the corresponding simulated results

following type of heat transfers as mentioned below:

1.Convection heat transfer between the air above the plastic sheet and face down heater at the top of the oven.

2.Convection heat transfer between the air below the plastic sheet and face up heater at the bottom of the oven.

3.Convection heat transfer between the air above the plastic sheet and face up top surface of the plastic sheet.

4.Convection heat transfer between the air below the plastic sheet and face down bottom surface of the plastic sheet.

5.Convection heat transfer between the air and the perpendicular wall surface in case of semi closed and closed oven.

6.Convection heat transfer between the air of the oven and the air temperature outside the oven.

The parameters of heat transfer equation like conduction coefficient of the sheet, sheet density, sheet specific heat constant are dependent on the sheet temperature. These parameters for different sheet temperatures are usually available from the manufacturer which can be used by least square method to establish a relationship between the sheet temperature and sheet conduction coefficient, sheet density, sheet specific heat constant.

Modeling of the actuator / heating element

The modeling of the actuator is important in order to completely know the behavior of the system. As the controller controls the process through actuators, control of a process becomes easier with a quick and powerful actuator. Although the actuator of the thermoforming process is weak and slow, modeling of the actuator is necessary to get the relationship between control input and actuator output. Ajersch and Yang did some experiment to determine the maximum rate of heating and cooling to develop a model of the heater bank (Ajersch, 2004), (Yang and Shuonan 2008). Although it can give some primary idea about the maximum heating and cooling rates, the heating and cooling rates that also depend on the operating condition of the system like the input power, the heat consumed by the sheet, the heat consumed by oven air and oven wall (that largely depend on sheet, the oven air and the oven wall temperature). The total energy transfer model of the heater which relates electric energy input to the heater and temperature output of the heater shown in Fig.7. Since the maximum electrical power input to the heater is bounded, it is quite understandable that the maximum heating rate is bounded too. The boundary of the maximum heating and cooling rates of the heater depend on the amount of heat transfer to the plastic sheet, oven wall by radiation and to oven air by convection. The heat energy emitted from the heater depends on the emissivity of the heater and the heaabsorbing material. The emissivity of a material is the ratio of energy radiated by the material to energy radiated by a black body at the same temperature. It is a measure of a material's ability to radiate absorbed energy. On the other hand, the energy radiated by the heater hitting at a material may be absorbed or reflected and depends on another crucial parameter which has a significant role in the material and is known as absorptivity of the material. The emissivity and absorptivity are properties of the

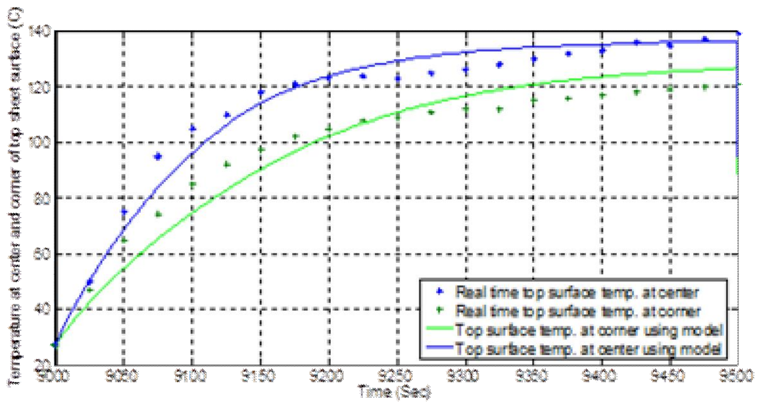

Figure 12. comparison of real-time temperature at center and corner point of bottom surface of the sheet with the corresponding simulated results.

material that depend on the wavelength of the radiated energy and temperature of the body (Vijay Kumar, 2005), (Yousefi et al., 2004). So, the radiated energy from the heater as well as the absorbed energy by the sheet, air and the oven wall depends on the sheet temperature. In most of the cases, either these properties of the polymer material are not available from the manufacturer, of the material, or consideration of these properties makes the model too complex to handle. Sometimes a constant value of emissivity and absorbity gives an accurate model that the dependency of the emissivity and the absorpity on heater temperature and wavelength neglected in the model.

Experimental set up

The developed modeling of the heating phase of thermoforming machine is compared with the data in real time using the AAA thermoforming machine same as in reference (Yousefi et al., 2004). Both top and bottom heater bank are composed of 6 heating zones each. Each zone consists of 3 heating elements connected in parallel. A thermocouple is embedded in the central heating element of each heat zone to sense the temperature of the heater. In order to sense the sheet surface temperature of the sheet, 7 infrared sensors (the Raytek thermalert MICtm) at top and 5 infrared sensors at bottom are connected in the machine such that they can measure the sheet temperature at the point without direct contact with the sheet very fast and accurately. This infrared sensor must be operated within a certain ambient temperature range which is ensured by using some cooling system with the sensor. The OPAL-RT RT-LAB software package is used in real time implementation. The software runs on a hardware package with command station, compilation node, target nodes, communication links and I/O boards. Two different PC workstations work as command station and target node. The command station uses windows 2000 as operating system to run the original software, generate code and control the parameters of the RT-LAB simulation whereas the target node uses QNX as its operating system for real-time implementation. The Target node is used as the real-time processing computer for real-time execution of the simulation and communication with I/O devices. The target node first debugs the user's source code then compiles it in C code and finally loads it onto the target node. The I/O board is used to receive the IR sensors' outputs, thermocouple outputs and sends the set points of the heaters. The embedded thermocouples output is very low (in the range of mili-volt) and nonlinear which requires some signal conditioning before they are processed by the A/D. The controller outputs from the RT-LAB pass through the output board and go to solid-state relays for each zone. The solid-state relays will be on or off depending on the signal. When the relay switch is on it will allow the ac current to pass current through the heating element to heat it. On the other hand, if the switch is off, it will block the current. The total experimental set-up is shown in Fig.8.

Comparison with Experimental Data

In this section, a comparison made between the simulation result of the developed model for AAA thermoforming machine and real time data that obtained with the same thermoforming machine from reference (Yousefi et al., 2004). All the data used in this paper to compare the real-time data with simulation results were for only one cycle of the process with 500 second length (from 9000 second to 9500 second). The oven is started long time before the data is considered so that the data will be more reliable due to more uniform air temperature.

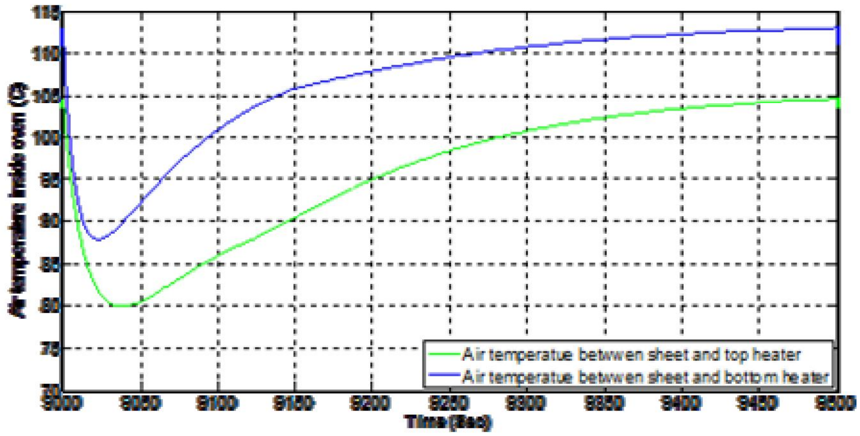

Figure 13. Average air temperature between sheet and top heater, average air temperature between sheet and bottom heater predicted from the model.

In Fig.9, real-time data of the upper and lower heater temperature are compared with the corresponding simulation results for the heaters set point 180˚C in a single cycle of the process. Same inputs were provided for all the heaters in top and bottom parts of the oven. The existing model shows the temperature of the heater will be same for both upper and lower heater for same input. But in real time data it is found that the upper heater attained higher temperature than lower temperature even for the same input. It is observed that the simulation results (solid lines) can gives pretty much accurate value as the real-time data (points). In the following two figures the sheet temperature predicted at different point for the developed model are compared with the real-time values of the oven. The location of different point in the sheet that is used to compare the simulation and real time data is shown in Fig.10. In Fig.11 and Fig.12, the sheet surface temperatures measured at these two different locations in the top surface and bottom surface within a cycle. The sheet is heated in open loop with all top and bottom heaters are heated at 160C. The measured data are taken after certain number of cycle. As expected, for certain sheet surface the temperature at the center is higher than the temperature at corners. The temperature is decreasing towards the peripheral of the sheet. This can be explained by using the concept of view factor that diminishing towards the corner. In Fig.12, It is observed that the temperature at the bottom surface of the sheet is higher than the temperature at top surface of the sheet as the convection heating process is more active in the lower surface because of higher convection coefficient. It is observed that the developed model simulation data can predict real-time data pretty accurately. There is a discrepancy between real-time data and simulated results in case corner point of the sheet. The point is located closer to outer part of the oven that can be cooled by the environment temperature. In the simulation model, it is assumed that the air inside the oven attained same temperature which is less accurate in case of corner point. In Fig. 13, the predicted data for average air temperature between top heater and sheet as well as average air temperature between bottom heater and sheet is shown. As the air temperatures inside the oven were different at different point, the overall average temperature could not be computed using real-time temperature sensor. So the real-time data could not be compared with this predicted data. The air temperature between sheet and bottom heater is higher than the air temperature between sheet and top heater. This can be explained by using convection heat transfer concept because convection heat transfer co-efficient is higher between bottom heater and air than top heater and air.

CONCLUSION

An experimental set-up has been developed in order to compare the simulation results of the developed model with experimental data. The comparisons of the result of the experiment show that the developed model can predict the experimental results quite well. These preliminary models can be extended considering the rapid deformation of the sheet during the heating process using finite element methods.

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