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A Soft Sensor System for the Estimation of Sheet Internal Temperature Distribution in Thermoforming

By

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A Thesis Submitted to the Faculty of Graduate Studies and Research in Partial Fulfillment of the Requirement for the Degree of Master of Engineering

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Abstract

Thermoforming is a generic term for the manufacturing of plastic components through a vacuum or a pressure forming process. The first and most critical phase in thermoforming is sheet heating. For a thick-gage plastic sheet, the combination of conduction and radiation energy, which conducts and transmits into the sheet interior, controls the heating cycle time. In order to predict the formability of a thick-gage sheet and improve production efficiency, we need to know the internal temperature of the plastic sheet during the heating phase in thermoforming. Unfortunately, the internal temperature of the sheet is impossible to measure directly. To overcome this problem, it is possible to use a soft-sensor technique, which uses the surface temperature of a plastic sheet that can be measured by infrared sensors to estimate the internal temperature of the sheet.

A soft sensor system was defined by using a finite difference equation. Experiments and simulations were performed to determine how well the soft sensor was able to predict the temperature distribution inside a plastic sheet. The sensitivities of some key parameters, e.g., material absorptivity, thermal diffusivity, view factor and oven air temperature, are analyzed and discussed.

Résumé

Thermoforming est un terme générique pour les fabrications de pièces en matière plastique par un vide ou une pression un procédé formant. Le premier et la plupart de critique introduit progressivement thermoforming est le chauffage de drap. Pour un épais gage un drap en matière plastique, la combinaison d'énergie de conduction et rayonnement, qui dirige et transmet dans l'intérieur de drap, règle le temps de cycle chauffant. Dans l'ordre pour prédire le formability d'un drap d'épais gage et améliore l'efficacité de production, nous avons besoin de savoir que la température interne du drap en matière plastique pendant le chauffant introduit progressivement thermoforming. Malheureusement, la température interne du drap est impossible de mesurer directement. Pour surmonter ce problème, c'est possible d'utiliser une technique de doux détecteur, qui utilise la température de surface d'un drap en matière plastique qui peut être mesuré par les détecteurs infrarouges estimer la température interne du drap.

Un système doux de détecteur a été défini en utilisant une équation de différence finie. Les expériences et simulations ont été exécutés pour déterminer comment bien le détecteur doux pouvait prédire la distribution de température dans un drap en matière plastique. Les sensibilités de quelques paramètres principaux, par ex., absorptivity matériel, diffusivity thermique, le facteur de vue et la température d'air de four, est analysé et est discuté.

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Chapter 1: Introduction

Thermoforming is a generic term for the manufacturing of plastic components through a vacuum or a pressure forming process. The thermoforming process is composed of three basic phases: heating, forming and solidifying. In a sequence, the process involves heating a plastic sheet inside an oven to its softening temperature, then stretching the hot and softened material against the contours of a mold by using vacuum or pressure, and finally cooling the part until it solidifies and holds the shape of the mold.

1.1 Background

Figure 1 illustrates typical steps in a thermoforming process. First, a plastic sheet is heated in an oven, by radiative and convective mechanisms, between an upper and lower bank of heaters. Once the sheet is heated for the specified time, it exits the oven and moves to the mold forming station. At the forming station, the sheet is stretched with the assistance of a plug while vacuum is applied to the mold. When the plug is pulled back, cool air is blown into the mould to speed the solidification of the part. Finally after the mold is taken away, the excessive plastic is trimmed from the part.



Figure 1: The steps in a typical thermoforming process

Thermoforming is one of the oldest methods of forming polymer articles. In the 1870s in the USA, John Wesley Hyatt, considered the father of modern plastic processing, and his colleague, Charles Burroughs, were the first to use thermoforming technology to shape a polymer pipe. Thermoformed products are typically categorized as industrial products and disposable products. Often, disposable thermoformed products are used in packaging. Typical disposable products include blister packs, bubble packs, slip sleeve containers, audio/video cassette holders, hand and power tool cases, cosmetic cases, meat and poultry containers, vending machine drink cups, egg cartons, etc. Typical industrial products include equipment cabinets for medical and electronic equipment, tote bins, single and double deck pallets, transport trays, automotive inner-liners, instrument panels, aircraft cabin wall panels, overhead compartment doors, swimming and wading pools, boat hulls, seating of all types, etc. A best estimation of the entire US consumption of thermoformed products in 1992 is about 1181 million kg or 2600 million pounds. About 800 million kg and 1760 million pounds is thermoformed into disposal products [Throne 96]. According to recent market surveys, the world market for thermoforming is growing at around 7% to 10% per year. From the surveys, the estimated size of the worldwide thermoforming market in the year 2000 was about 16,000 million pounds (7200 million kg), with a value of about US \$35 billion.

Thermoforming has a number of advantages compared to other polymer forming technologies. First of all, the cost of forming molds used in thermoforming is relatively low. Secondly, thermoforming can handle multi-layer, foams and coated materials. Finally, thermoforming can allow for the mass production of large and thick industrial parts. However, thermoforming also has distinct disadvantages, e.g., the complexity of the thermoformed part is limited. Primarily, thermoforming is a high waste process, which means that the process needs to improve production efficiency and part quality. The research on thermoforming shows that the most critical phase of thermoforming is sheet heating, which will directly affect subsequent phases of the thermoforming process. Close temperature control for this phase results in reducing rejected product, decreasing energy consumption, and shortening cycle time in production.

As shown in Figure 2, all thermoforming polymers have forming windows, defined by the lower (Tlower), and upper (Tupper) forming temperature. The polymer surface is prone to

color change or blistering while being formed if the forming temperature is above Tupper. On the other hand, the polymer is too stiff to be formed or will have micro-cracks while being formed if the forming temperature is below Tlower. The lower and upper forming temperatures determine the absolute boundary of formability. This boundary is called the forming window. For a thin-gage sheet, the sheet internal centerline temperature is practically the same as the surface temperature. The heating process is controlled by the rate at which radiation and convection energy are delivered to the sheet surface. The energy arriving at the sheet surface controls the heating cycle time.



Figure 2: Polymer forming temperature range

For a thick-gage sheet, the sheet internal centerline temperature is significantly below the surface temperature due to the relatively slow thermal diffusive character of polymer sheet. The energy absorbed at the sheet surface must be conducted to the interior, and moreover, a large part of energy is absorbed as radiation by the plastic sheet interior layers. Thus, a combination of radiation and conduction energy controls the heating cycle time. The heating rate must be controlled to prevent deficient forming, surface overheating and material degrading. For example, if the sheet in Figure 2 is dramatically increased in thickness, the temperature profile of Figure 3 is obtained. From Figure 3, the surface temperature of the heavy gage sheet is far above the thermoforming window while the sheet centerline temperature is still below the thermoforming window. If we use this energy input, the sheet temperature profile will directly result in rejected product.



Figure 3: Polymer forming temperature for heavy-gage sheet.

To get the temperature into the forming window, the heating rate must be decreased (Figure 4). As identified from previous research and experimental work [B. Moore 01], the heating cycle time and heater element performance need to be controlled by feedback temperature measurement. This results in greatly consistent production of complex plastic parts and significant reduction in the number of rejects.



Figure 4: Effect of decreasing energy input rate for heavy-gage sheet

In order to control the heating rate, and to predict the cycle time for polymer sheets with different thicknesses, we need to acquire and measure the sheet temperature, especially the

internal centerline temperature. Unfortunately the internal centerline temperature of a thermoforming sheet is impossible to measure directly. To overcome this problem, it is possible to use a soft-sensor technique, which uses the variables that can be measured to estimate the variables that cannot be measured. A soft-sensor system can be defined as an algorithm that estimates inaccessible state variables of a specified process based on the mathematic models of the process and the direct measurements of other process variables. In another words, a soft sensor or virtual sensor is a common name for embedded software algorithms, which in turn require an efficient and appropriate process model. Well-known software algorithms that act as soft sensors are Open Loop Observer, Kalman Filters, Neural Networks and Fuzzy Computing.

1.2 Thermoforming Control and Simulation

Thermoforming processes are typically characterized by highly uncertain, coupled multivariable dynamics that often include transport delays. Meanwhile, process dynamics have a tendency to change over time, so that controller robustness and tuneability are typically necessary for satisfactory long-term operation. In a very competitive international commodity market, their accurate control is key to a profitable operation.

Exiting controllers including feedback controls and computer numerical controls are commonly used to control machine actuators, e.g., heater elements in thermoforming. Figure 5 illustrates that the machine actuators are regulated at the innermost level in a system view. The controller regulates the operation of machine actuators based on manual inputs. At the second level, the state variables, e.g., the surface and internal temperatures of a thermoforming sheet, are controlled to track pre-specified profiles. Soft sensor technology is applied at this level. This will provide more advanced and precise control for the process to achieve efficient operation. At the outermost level, the nominal levels of machine inputs are adjusted so as to improve the performance of the machine and the quality of final product with the application of fault diagnosis, neural fuzzy networks and adaptive control.



Figure 5: System view and control loop

- Loop 1: Exiting feedback system and CNC controller
- Loop ____ 2: State variables control and soft sensor.
- Loop ... 3: Cycle by cycle control, fault diagnosis, neural fuzzy networks.

On the other hand, the use of thermoforming simulation software for product design is also increasing. A number of simulation packages are now commercially available. T-Sim from Accuform is recognized as one of the first simulation packages available to the thermoforming industry. C-Mold, which offers the popular Moldflow injection molding simulation software, also has a thermoforming simulation package. Sherwood Technologies is in the process of developing Java Based programs for the simulation of sheet heating and cooling phases. Among all these commercial available simulation software, FormSim that was developed by Industrial Material Institute, National Research Council, is specifically designed to address the unique simulation requirements of the blow molding/thermoforming industry. BlowView incorporates finite element analysis, materials modeling and user interface technology in one integrated easy to use package. FormSim also supports the inverse analysis function to estimate the initial thickness and interior temperature distribution of the sheet to obtain final molded products of the correct designated thickness and quality.

1.3 Motivation

To cope with the demand of advanced control systems and to exploit the recent advances in the development of simulation tools and process know-how in the field of polymer part manufacturing, a broad research and development program in the model-based control of forming processes has been created with a team from McGill University, the Industrial Materials Institute, National Research Council, and Quality Thermoforming (Toronto).

The reputation for excellence of the quality of teaching and research in the Faculty of Engineering at McGill University is recognized around the world. As a result, the Faculty attracts the highest quality of professors and students to its campus in Montreal. Mechanical Engineering is one of the leading departments in the Faculty of Engineering at McGill University.

National Research Council's (NRC) Industrial Materials Institute (IMI) is a research and development center focused on materials, their formulation and forming, as well as the control of manufacturing processes. IMI works primarily in the sections of polymer, metallurgy, aerospace and automotive. Its activities extend over all regions in Canada, and have a significant impact at the international level. At IMI, the Process Modeling and Instrumentation section is investing major R&D efforts into developing process simulation and modeling tools, as well as diagnostic techniques using sensors that permit real-time monitoring of processes. The goal is to increase the efficiency and speed of the forming processes, and to optimize part design.

In 2001, a research program for developing model-based control of forming processes was initiated by Professor Vince Thomson and Professor Benoit Boulet, McGill University, and Mr. Robert DiRaddo and Mr. Patrick Girard, Industrial Materials Institute, National Research Council. The program conducted in the area of process modeling targets the development of computerized models and analysis software programs that will allow us to better control the thermoforming process. The research will offer industry the advantage of maintaining high levels of quality, in spite of the complexity of the parts to be produced and the inevitable parametric variations of the base materials and processes.

The program for the intelligent control of forming operations is divided into following projects.

- 1. Soft sensor systems and fault diagnosis for forming operations.
- 2. Robust in-cycle control of forming operations.
- 3. Adaptive model-based control of forming operations.
- 4. Control architectures for forming operations.

These four projects constitute the activities for developing an intelligent controller for polymer forming processes. Project 1 involves the development of the soft sensor and fault diagnosis system that considers the process sequence and process parameter interaction. Mathematical models and finite element simulation results are employed as the soft sensor for estimating the interconnections between the process parameters, represented as a series of sensitivities. Then, with a strategy, based on neuro-fuzzy approach, the model acts as an adaptive controller and fault diagnosis system for process operation. Both blow molding and thermoforming are considered. The work described here, "A Soft Sensor System for the Estimation of Sheet Temperature Distribution in Thermoforming", is a part of project 1.

1.4 Thesis Objective

The objective of this thesis is to develop an infrared soft sensor based measurement system for estimating the temperature distribution inside a thermoforming sheet.

The thesis is presented in six chapters. Chapter 1 is the introduction of thesis that includes problem description, initial goal, basic concepts and the objective of this work. Theory background and review are given in Chapter 2. Following the exploration of theory, Chapter 3 gives the methodology for analyzing problems, developing solutions and evaluating applicability. The experiments for verifying the methodology are described in Chapter 4. In addition, Chapter 5 discusses the results based on experimental data and soft sensor predictions. Finally, Chapter 6 states the summary of the thesis and also gives recommendations for future research.

Chapter 2. Theoretical Background

This thesis is concerned with the details of the heating phase in thermoforming. Thermoforming looks like a simple and easy process, but in fact what happens inside the heating phase is quite complicated. A mathematical model representing the heating process can only be possible with a deep understanding of heat transfer theory and material properties.

2.1 Introduction of Polymeric Materials

Polymeric materials are characterized by long chains of repeated molecule units known as "mers". These long chains intertwine to form the bulk of the plastic. The nature by which the chains intertwine determines the plastic's macroscopic properties. The most common way of classifying polymers is to separate them into three groups: thermoplastics, thermosets, and elastomers. The thermoplastics can be divided into two types, those that are crystalline and those that are amorphous.



Figure 6: Polymer types

Thermosets usually are three-dimensional networked polymers in which there is a high degree of cross-linking between polymer chains. They are intrinsically cross-linked with a narrow mesh in all directions. The cross-linking restricts the motion of the chains and leads to a rigid material. Because thermosets are densely cross-linked, they are impossible to dissolve and quite difficult to swell. They are hard and rigid at room temperature and usually cannot be reused or returned to their original form. Thermosets are primarily used in automobiles and construction, i.e., electrical outlets are manufactured from thermosets. A

simulated skeletal structure of a network polymer with a high cross-link density is shown in Figure 7.



Figure 7: Simulated skeletal structure of a thermoset polymer molecule

Elastomers are cross-linked, but have a low cross-link density. The polymer chains still have some freedom to move, but are prevented from movement permanently. Elastomers are rubbery polymers that can be stretched easily to several times their original length and will rapidly return to their original dimensions when the applied stress is released. Elastomers cannot be fused or dissolved, but can be swelled. They are lightly cross-linked with a wide mesh, and therefore, exit in a soft, elastic condition at room temperature. Rubber bands and other elastics are made of elastomers (Figure 8).



Figure 8: An elastomer polymer molecular structure

Thermoplastic polymers are characterized by exceptionally long two-dimensional, nearly linear organic molecules, usually having saturated or single covalent bond carbon-carbon backbones. In their final form, thermoplastics are thermally and chemically stable at processing conditions. This mean that they can be softened or melted, formed into useful articles, then re-softened or re-melted and reused. More than 80% of all polymers used in the

world today are thermoplastics. Thermoplastics have a wide range of application because they can be formed and reformed into many shapes. Some examples are food packaging, insulation, automobile bumpers, and credit cards. Highly crystalline polymers are rigid, high melting, and less affected by solvent penetration. Crystallinity makes polymers strong, but also lowers their impact resistance. One example of a simulated structure is given in Figure 9.



Figure 9: A crystalline polymer molecular structure

When polymer chains with branches or irregular pendant groups cannot pack together regularly enough to form crystals, these polymers are said to be amorphous. A twodimensional schematic of an amorphous polymer is shown at Figure 10. Amorphous thermoplastics are similar to glass with respect to molecular structure. They are distinguished from semi-crystalline thermoplastics, which have a milky, opaque appearance.



Figure 10: An amorphous polymer molecular structure

Semi-crystalline polymers have both crystalline and amorphous regions. The crystals in semi-crystalline structure are small and connected to the amorphous regions by polymer chains so there may be no sharp well-defined boundaries between the two types of regions. For some polymers, such as polyvinyl alcohol, there is a fairly distinct separation between the crystalline and amorphous regions, although, in other cases, e.g., High Density Polyethylene (HDPE), the structure basically is crystalline with uniformly distributed flaws and imperfections. Figure 11 displays a semi-crystalline polymers molecular structure.



Figure 11: Semi-crystalline polymers molecular structure

Semi-crystallinity is a desirable property for most plastics because it combines the strength of crystalline polymers with the flexibility of amorphous polymers. Semi-crystalline polymers can be tough with an ability to bend without breaking. The percentage of the polymer that is crystalline is called the percent crystallinity and this has an important influence on the properties of the polymer.

2.2 Deformation Characteristics of Plastics

Polymeric material displays different characteristics when heated. These characteristics depend on various factors, including the chemical structure of polymer molecules and the type of intermolecular bonding forces. A polymer is a hard material at room temperature because the individual macromolecules barely move and intermolecular forces hold them together. An increase in temperature causes the macromolecules to move with greater intensity. When a polymeric material is heated, the intermolecular forces of the amorphous polymer have become so weak that the influence of external forces can cause the macromolecules to slip apart from one another once the glass transition temperature T_g has been exceeded. At this temperature, the amorphous region becomes rubbery. When an amorphous polymer is in its rubbery state, it is soft and flexible. The glass transition temperature is the absolute lowest temperature at which the polymer can be formed. As

processing temperatures increase above T_g , amorphous polymers become increasingly easier to process.

Crystalline thermoplastics, cross-linked thermoplastics, and certain thermosetting polymers have glass transition temperatures as well. In crystalline polymers, the morphological order in the crystalline region restricts amorphous chain mobility until the melting temperature is reached. For thermosets, chain mobility is restricted by the three-dimensional molecular network until the thermal degradation temperature is reached.

As the temperature continues to increase, the intermolecular forces are almost completely eliminated. The polymer proceeds in a continuous manner from the thermo-elastic state to thermoplastic or molten state. This transition is described as the range of the flow temperature T_f . This temperature cannot be specified precisely. Primary processing methods such as injection molding are carried out within the thermoplastic range. If heating continues beyond the decomposition temperature, the polymer is destroyed.



Figure 12: Schematic of temperature dependent modulus

The existence of two different states side by side, so to speak, within a semi-crystalline thermoplastic distinguishes it from an amorphous thermoplastic. One region is the crystalline region, in which the molecules are tightly packed in an orderly arrangement. The other is the amorphous region, in which the molecules lie at a great distance from one another in a disorderly arrangement. The glass transition is a property of only the amorphous portion of a semi-crystalline solid. The crystalline portion remains crystalline during the glass transition.

The intermolecular strength is much greater in the crystalline state than in the amorphous state. The amorphous portion of the polymer softens above its glass transition temperature. The crystalline regions of the polymer melt when the crystalline melting temperature is exceeded. When the crystalline melting temperature is exceeded, strength decreases sharply and elongation reaches its highest value.

Some thermoplastic polymers such as polyethylene can be further toughened by crosslinking. Cross-linked thermoplastics remain very soft, thermo-formable solids rather than becoming fluid above their melting points. Cross-linking does not allow melt processing. Most of thermoforming materials are cross-linked semi-crystalline structures. Some critical temperatures for typical thermoformable polymers are given in Table 1.

Polymer	Glass	Melt	Lower	Upper	Normal
(Appendix B)	transition	temperature	forming	forming	forming
	temperature (C^0)	(C ⁰)	temperature (C^0)	temperature (C ⁰)	temperature (C^0)
Amorphous polymers			and an entropy of the second		
Polystyrene	94	-	127	182	149
PMMA	100	-	149	193	177
PMMA/PVA alloy	105	-	143	182	171
ABS	88-120	-	127	182	146
Polycarbonate	150	-	168	204	191
Rigid PVC	77	-	104	154	138
Crystalline polymer					
LDPE	-25	115	116	168	132
HDPE	-110	134	127	182	154
Cellulose acetate	70,100	230	127	182	146

 Table 1: Characteristic temperatures of thermoforming polymers

Cellulose butyrate	120	140	127	182	146
Polypropylene,homo-	5	168	132	166	185
Polypropylene,co-	-20	150-175	143	193	204
GP PP	5	168	129	232	277
Polymethyl pentene	47	235	260	288	182
PVDC	0	245	163	199	149
PET	70	255	121	166	274
PBT	-80,70	245	260	288	224
Nylon 6	58	220	216	238	227
Nylon 66	78	255	249	288	274
			Construction of the local same spin age and the second		
Foams					
Polystyrene	70-85	158-185	88	113	220
Rigid PVC foam	70	158	110	171	290

2.3 The Heat Transfer Model

In the simplest of terms, the discipline of heat transfer is concerned with only two things: temperature, and the flow of heat. Temperature represents the amount of thermal energy available, whereas the heat flow represents the movement of thermal energy from place to place. On a microscopic scale, thermal energy is related to the kinetic energy of molecules. The greater a material's temperature is, the greater the thermal agitation of its constituent molecules is. It is natural for regions containing greater molecular kinetic energy to pass this energy to regions with less kinetic energy. Heat transfer mechanisms can be grouped into 3 broad categories: conduction, convection, and radiation. All the heat transfer mechanisms are present in the context of a cup of coffee.



Figure 13: Heat transfer context of a cup of coffee

Convection: You can hold your hand over the cup and feel how the heat flux rises and heats your hand. Radiation: You can hold your hand close to the side of the cup and feel the heat

emitting from the cup. Conduction: You can touch it and feel that the cup is hot. The heat transfers from the cup to your fingers.

2.3.1 Convection Heat Flux

Convection is where energy is transferred by a flowing substance. When heat conducts into a static fluid, it leads to a local volumetric expansion. As a result of gravity-induced pressure gradients, the expanded fluid parcel becomes buoyant and displaces, thereby transporting heat by fluid motion. Such heat-induced fluid motion in initially static fluids is known as free convection. The cases where the fluid is already in motion are known as forced convection, which requires a pressure gradient to drive the fluid motion, as opposed to a gravity gradient to induce motion through buoyancy.

Introduction to Convection Heat Flux

Heat transfer in fluids generally takes place via convection. Convection currents are set up in the fluid because the hotter part of the fluid is not as dense as the cooler part, so there is an upward buoyant force on the hotter fluid, making it rise while the cooler, denser, fluid sinks. Heat energy transfers between a solid and a fluid when there is a temperature difference between the fluid and the solid. This is known as "convection heat transfer". Generally, convective heat transfer cannot be ignored when there is a significant fluid motion around the solid.

The temperature of the solid due to an external field such as fluid buoyancy can induce a fluid motion. This is known as "natural convection" and it is a strong function of the temperature difference between the solid and the fluid. Blowing air over the solid by using external devices such as fans and pumps can also generate a fluid motion. This is known as "forced convection". Forced convection is often used for heating, e.g., forced-air furnaces or cooling, e.g., fans, automobile cooling systems. As opposed to the microscopic transfer of heat between atoms that is involved in conduction, convection energy within a turbulent flow is moved from one point to another by movement of the turbulent eddies. Since quite large regions of fluid can be involved in these movements and the turbulence is significant, this

method of heat transfer can be much more effective than conduction heat transfer which moves energy from one molecule to the next.

The keys to convection energy transfer are the flow rate of the fluid along with fluid viscosity and thermal properties. A measure of convection energy transfer is the heat transfer coefficient, which is the proportional factor between the thermal driving force and the amount of energy transferred. Convective heat transfer is described by Newton's Law:

$$\frac{Q}{A}\Big|_{\theta,x=L} = h[T(\theta) - T_{\infty}(\theta)]$$
(2.1)

The term h is the convection heat transfer coefficient. θ represents the elapsed time. T(θ) is the sheet surface temperature and T_{∞}(θ) is the temperature of the environment. These temperatures are time-dependent.

Convective Heat Transfer Coefficient

The convective heat transfer coefficient, h, is defined as a proportionality constant. When the energy source is a fluid, energy is transferred between the bulk moving fluid at temperature $T\infty$ and the solid surface at temperature T across a thin near-stagnant fluid layer. The heat transfer coefficient is a measure of the resistance to heat transfer across this layer as the bulk fluid motion increases.

To theoretically evaluate the natural convective heat transfer coefficient, empirical equations are used. These equations are generally of the following forms:

$$\overline{N}u = \text{characteristic dimension / average distance for heat conduction} = \frac{hL}{K}$$
$$= CRa_{L}^{n}$$
(2.2)

where $\overline{N}u$ is the average Nusselt number, which represents the ratio of convection heat transfer for fluid in motion to conduction heat transfer for motionless layer of the fluid, h is the heat transfer coefficient, K is the thermal conductivity of air, C and n are constants.

The Rayleigh number,
$$\operatorname{Ra}_{L}^{n} = \frac{g\beta(Ts - T\infty)L^{3}}{v\alpha}$$
 (2.3)

Rayleigh number is based on the characteristic length L of the geometry defined as follows:

 $L = A_s/P$ (2.4) where A_s and P are the plate surface area and perimeter, g is the local acceleration due to gravity, β is the thermal expansion coefficient, T_s is the plate surface temperature, T_{∞} is the air temperature, ν is the kinematical viscosity and α is the thermal diffusivity of air. The following equation gives the heat transfer coefficient for the upper surface of a heated plate:

$$\overline{N}u = 0.54 \, CRa_{L}^{1/4}$$
 $10^4 \le Ra_{L} \le 10^7$ (2.5)

Similarly, the heat transfer coefficient for the lower surface of a heated plate is:

$$\overline{N}u = 0.27 \, CRa_{L}^{1/4}$$
 $10^{5} \le Ra_{L} \le 10^{10}$ (2.6)

Representative ranges for heat transfer coefficients are given in Table 2.2. As is apparent, air is a poor convective heat transfer medium, water is more efficient than air, and condensing steam is an excellent heat transfer medium.

	Convectional heat transfer coefficient		
Fluid	$(10^{-3} \text{ W/cm}^2 \text{ S }^{\circ}\text{C})$	(Btu/ft ² h °F)	
	and the property of the second second		
Quiescent air	0.5-1	0.8-2	
Air moved with fans	1-3	2-5	
Air moved with blowers	3-10	5-20	
Air and water mist	30-60	50-100	
Fog	30-60	50-100	
Water spray	30-90	50-100	
Oil in pipes	30-180	50-300	
Water in pipes	60-600	100-1000	
Condensing stream in pipes,	600-3000	1000-15000	

Table 2: Convectional heat transfer coefficient

2.3.2 Radiation Heat Flux

Radiation is where energy is interchanged between two non-touching substances that have different temperatures. All materials radiate thermal energy in amounts determined by their temperature. The energy is carried by photons of light in the infrared and visible portions of the electromagnetic spectrum. When temperatures are uniform, the radiation flux between

objects is in equilibrium and no net thermal energy is exchanged. The balance is upset when temperatures are not uniform, and thermal energy is transported from the surfaces of higher temperature to the surfaces of lower temperature. The key to radiation energy transfer is that the two substances have different temperatures. The radiation wavelength-dependent energy absorption characteristics are also weighted importantly. No medium need exist between the two bodies for heat transfer to take place, as is needed by conduction and convection. Rather, the intermediaries are photons that travel at the speed of light. Energy transmission by radiation is most effective in a vacuum. The radiation is electromagnetic, the same in principal as light or radio waves. Heat radiation is associated with objects, such as the sun or red-hot metals. Sometimes they are so hot that they also give out visible light, but in most cases they do not emit visible light. When an object is not quite hot enough to radiate visible light, it will emit most of its energy in the infrared. For example, hot charcoal may not give off light but it does emit infrared radiation, which we feel as heat. Warmer objects emit more infrared radiation than cooler objects.

The heat transferred into or out of an object by thermal radiation is a function of several components. These include its absorptivity, transmissivity, reflectivity, surface area, temperature, and geometric orientation with respect to other thermally participating objects. In turn, an object's surface reflectivity, emissivity and absorptivity are a function of its surface conditions (roughness, finish, etc.) and composition.

Electromagnetic Spectrum

The electromagnetic spectrum includes gamma rays, X-rays, ultraviolet, visible, infrared, microwaves, and radio waves. The only difference between these different types of radiation is their wavelength or frequency. Wavelength increases and frequency (as well as energy and temperature) decreases from gamma rays to radio waves. All of these forms of radiation travel at the speed of light. In addition to visible light, radio, some infrared and a very small amount of ultraviolet radiation also reaches the Earth's surface from space. Fortunately for us, our atmosphere blocks out the rest, much of which is very hazardous to life on Earth.



Figure 14: Electromagnetic radiation spectrum

Gamma rays, X-rays are characterized by very short wavelengths. Ultraviolet rays have wavelengths less than 0.4 μ m. Visible light wavelength range is 0.4 μ m to 0.7 μ m. Infrared waves have wavelengths longer than visible and shorter than microwaves, and have frequencies that are lower than visible and higher than microwaves. Near infrared wavelength range is about 0.7 μ m to about 2 μ m. Far infrared wavelength range is from 2 μ m to 8 μ m. Longer wavelength electromagnetic energy includes microwave, radio and ultrasonic. The important wavelength range for most radiant thermoforming processes is a portion of the far infrared. The primary source of infrared radiation is heat or thermal radiation. Any object that has a temperature, i.e., anything above absolute zero (-273.15 degrees Celsius or 0 degrees Kelvin), radiates infrared energy. Even objects that we think of as being very cold, such as an ice cube, emit infrared energy.

Black Body

A black body is defined as an object or surface that absorbs all incident thermal radiation of all wavelengths. In radiant heat transfer a black body does not reflect any wavelength of radiation. This is an important simplifying concept.

Nothing can emit more energy at given temperature and wavelength than a blackbody. All infrared energy that strikes a black body is completely absorbed and nothing reflected. There is no ideal blackbody in real life, but there are some examples of equipment, which work very close to it and are used for calibration of infrared instruments. We know that infrared energy emitted by a blackbody relates to temperature and wavelength. That relationship is described by Planck's law and can be shown as Planck's Blackbody Curves (Figure 15)



Figure 15: Planck Blackbody Curve

These curves show us that:

- The amount of energy increases at all wavelengths as the temperature of a blackbody increases.
- With increasing temperature, the peak of the energy of a black body moves toward shorter wavelengths.

Stefan and Bottzmann have independently used classical thermodynamics to show that the total emission from a surface varies with the fourth power of absolute temperature. This result can also be derived from Planck's Law by integrating the total wavelength at a particular temperature under the curve for that temperature:

$$q = \sigma T^4 \qquad wm^{-2} \tag{2.7}$$

where q is emissive heat flux as the thermal radiation emitted from a surface per unit time per unit surface area, T is absolute temperature in degrees Kelvin, σ is the Stefan-Boltzmann constant of 5.67 x 10⁻⁸. This equation is one of the governing equations of radiant heat transfer and forms the basis of all radiant heat transfer calculations.

Gray Body Radiation

We cannot find a blackbody in the real world. All the objects with a temperature above absolute zero emit, absorb and reflect infrared energy. The notion that a non-black surface emits less than a black surface leads to the concept of emissivity. We can define the total emissivity as the total emissive flux at temperature T to the total emissive flux from a black body at the same temperature:

$$\varepsilon = \frac{q}{q_b}$$
(2.8)

In this assumption, a gray body is defined as one where the rate of heat radiation from the surface at all wavelengths (or temperatures) is only a fraction ε of that from a black body. So if we make the gray body assumption, then, $\varepsilon = \text{constant regardless of temperature and Kickoff's law tells us that <math>\alpha = \varepsilon = \text{constant regardless of temperature}$.

Figure 16 shows a curve indicating an approximate behavior for a real surface, which may differ considerably from that of either an ideal black body or ideal gray body. For analysis purposes surfaces are usually considered as gray bodies with emissivity taken as the integrated average value.



Figure 16: The relation among black body and gray body and real body

Absorptivity and Transmissivity

The sum of the transmissivity, τ , absorptivity, α , and reflectivity, ρ , of a material must add to unity:

$$\rho + \alpha + \tau = 1 \tag{2.9}$$

Reflectivity can be related to the difference in indices of refraction between plastic and air, which represents no more than 5% of total incident energy. Usually we can ignore the reflectivity factor for most plastic sheets. Therefore, we can approximately assume that

$$\tau + \alpha = 1 \tag{2.10}$$

By stating that a body's surface emissivity ε is equal to its absorption fraction, Kirchhoff's Identity binds incoming and outgoing radiation into a useful dependent relationship,

 $\alpha = \varepsilon \tag{2.11}$

It said that the ratio of the emissive power of a body to the emissive power of a blackbody at the same temperature is equal to the absorbtivity of the body. The emissivity and absorptivity are the total properties of the particular material. They represent the integrated behavior of the material over all wavelengths. Real substances emit less radiation than ideal black surfaces as measured by the emissivity of the material. In reality, the emissivity of a material varies with temperature and the wavelength of radiation.

View factor

A surface generally emits radiation in all directions simultaneously. If the receiving surface is located some distance away from the radiation source, not all the radiation leaving the source will impinge on the receiving surface. As the surface moves towards the source, increasingly more radiation is received. This is obvious in daily life. The closer we are to a heat source, the hotter we feel. Clearly the source is not emitting more radiation as we get closer, but a larger proportion is landing on us. This leads to the concept of a view factor.

There is one important property of view factors, known as the summation relation. Consider an enclosure containing N surfaces. Since all the radiation emitted from surface 1 must land somewhere in the enclosure, we can write: $\sum_{j=1}^{j=N} F_{ij} = 1$. When the source and sink are infinite

planes, radiation interchange occurs without any loss due to geometry. When the source and sink are finite however, a portion of the radiation emitted by the source does not impinge on the sink. Instead, this radiation is lost from the interchange. In thermoforming, energy interchange has a maximum at the center of the sheet and is lowest at the corners of the sheet. This is sometimes referred to as the energy dome effect (Figure 17).



Figure 17: Dome Effect

The relative effect between sheet dimensions and heater-to-sheet spacing is given in terms of the geometric factor F. For most thermoforming applications, F is usually greater than about 0.7. In other words, at least 70% of the energy transfer is between the sink and the source. On the other hand, almost 30% of the energy transfers goes into heating non-sheet, i.e., rails, clamp frames, oven sidewalls and items other than the sheet. It should be noted that the value of F is an average. Radiation view factors can be analytically derived for simple geometries and are tabulated in several references on heat transfer [Holman 86]. They range from zero (e.g., two small bodies spaced very far apart) to 1(e.g., one body is enclosed by the other).

View Factor F can be represented in a mathematical model in equations 2.12:

$$F_{ij} = \frac{1}{\pi A_i} \Sigma_i \Sigma_j \frac{\cos \theta_i \cos \theta_j}{d^2} A_i A_j$$
(2.12)

where θ_i and θ_j are the direction cosines of the ith element of the source and the jth element of the sheet. d is the distance between these elements, A_i and A_j are their respective surface areas.

As a sheet of plastic is heated, it becomes less rigid and gradually sags in the middle due to its own weight. The sheet sag is predicted with the K-BKZ viscoelastic constitutive model, which has shown to be capable of predicting the viscoelastic deformation of most thermoforming grade plastic during the forming processes including their deformation under the gravity load. The K-BKZ model relates the stress to the stain history as follows (2.13).

$$\sigma = -q\delta + \frac{1}{1-\theta} \int_{-\infty}^{t} m(t-\tau)h(l_1, l_2)(C^{-1}(\tau, t) + \theta_c(\tau, t))d\tau$$
(2.13)

where m is a memory function given by the Maxwell relaxation spectrum, q is the hydrostatic pressure, δ is the identity tensor, c is the Cauchy deformation tensor, c⁻¹ is the Finger deformation tensor, h is a damping function based on the Cauchy strain invariants, and θ refers to the second normal stress difference in the deformation (biaxial effect). The thermal dependence of the K-BKZ model is accounted for with the WLF equation [A.Yousefi 01].

Heat Exchange Between Two Surfaces

All radiation transfer problems involving surfaces are built around a consideration of the radiant energy on and leaving a given surface. The net transfer of radiation heat energy directly from surface 1 to surface 2 is :

$$Q_{rad} = \alpha_{abs} \sigma F_{12} \varepsilon_{eff} A(T_h^4 - T_s^4)$$
(2.14)

As a consequence, the radiation heat flux at the boundary of heating a sheet takes the following form:

$$q_{rad} = \alpha_{abs} \sigma F_{12} \varepsilon_{eff} (T_h^4 - T_s^4)$$
(2.15)

where q_{rad} is the radiation heat flux incident on the surface, α_{abs} is a radiant absorbance at the surface, σ is the Stefan-Boltzmann constant, T_h is the heater temperature, Ts is the sheet surface temperature, F is a geometric factor, or view factor, ε_{eff} is the effective emissivity of the sheet heater system, also known as a non-black body correction factor. As a result, for planar surfaces, ε_{eff} is given as:

$$\varepsilon_{\rm eff} = \left[\frac{1}{\varepsilon_{\rm h}} + \frac{1}{\varepsilon_{\rm s}} - 1\right] \tag{2.16}$$

where ε_h is the emissivity for the heater and ε_p is the emissivity for the sheet. Typically, as a first approximation, radiant heaters used in thermoforming can be assumed to be gray bodies. And most polymer sheets can also be assumed to be gray bodies, where $\varepsilon_s = 0.90$ to 0.95 [Throne 96]

The heat flux which transmitted through the sheet is absorbed in the volume and it can be represented using the following equation:

$$q_{abs} = (1 - \alpha_{abs}) \sigma F_{12} \epsilon_{eff} (T_h^4 - T_s^4) e^{-\kappa x}$$
(2.17)
where α_{abs} is radiation absorbance at the surface, κ is absorptive coefficient, and x is sheet thickness.

2.3.3 Heat Conduction Model

Conduction is where energy is moved through a solid or non-flowing substance. Regions with greater molecular kinetic energy will pass their thermal energy to regions with less molecular energy through direct molecular collisions, a process known as conduction. Thermal conductivity is the key parameter to conductive energy transfer. In effect, conductive energy transfer decreases as the thermal conductivity of the substance decreases. Conduction is the flow of kinetic energy from one molecule to the next by direct contact between the two molecules. Owing to high vibrational and rotational mobility of electrons and regular crystallographic structure, metals achieve high levels of conduction energy transfer. Polymers, on the other hand, have less molecular mobility, and therefore, very poor thermal and electrical conductors.

One-dimensional steady-state heat conduction across the sheet thickness is given as:

$$q = \frac{Q}{A} = -k(\frac{\Delta T}{\Delta x})$$
(2.18)

Here, q is heat flux defined as Q/A, K is the polymer thermal conductivity, ΔT is the temperature difference and Δx is the sheet thickness.

As discussed in Chapter 1, the combination of radiation and conduction energy that is absorbed by the sheet interior controls the heating rate. The rate at which energy transfer occurs is called transient one-dimensional heat transfer. The time-dependent net energy equals to the change in heat flux within the plastic sheet. Net enthalpy change per unit time is:

$$\frac{\partial H}{\partial \theta} \approx \rho C_p \frac{\partial T}{\partial \theta} = \frac{\partial}{\partial x} \left[K \frac{\partial T}{\partial x} \right] + \frac{\partial q_{abs}}{\partial x}$$
(2.19)

where T is the local temperature, x is the distance into the sheet, θ is the elapsed time, and K is material thermal conductivity. The last term in the right hand side, q_{abs} , is taken into

consideration when there is heat absorption or heat generation in the volume. q_{abs} is defined by equation (2.17).

Hence, we obtain
$$\frac{\partial T}{\partial \theta} = \frac{K}{\rho C_p} \frac{\partial^2 T}{\partial x^2} + \frac{\partial (q_{abs})}{C_p \rho \partial x} = \alpha_{diff} \frac{\partial^2 T}{\partial x^2} + \frac{\partial (q_{abs})}{C_p \rho \partial x}$$
 (2.20)

Thus, thermal diffusivity $\alpha_{diff} = K/\rho C_p$, where ρ is polymer density and C_p is thermal heat capacity.

2.3.4 Symmetry Condition

If the energy input is equal on both sides of a thermoforming sheet, the thermal gradient in the sheet is symmetrical about the mid-plane. The energy conducted from one side just equals the energy conducted from the other side. Thus, the heat flux at the symmetry plane is zero, Q/A = 0. The plane of symmetry is given as:

$$\frac{\partial T}{\partial x}\Big|_{\theta, X=0} = 0 \tag{2.21}$$

This means that the heat fluxes from each surface are equal.

2.3.5 Boundary Condition

The total heat flux at the sheet surface is given as:

$$q_{\text{tot}} = q_{\text{rad}} + q_{\text{conv}} = \alpha_{\text{abs}} \sigma \varepsilon_{\text{eff}} F (T_h^4 - T_s^4) + h (T_\infty - T_s)$$
(2.22)

where q_{rad} is the radiation heat flux on the surface, q_{conv} is the convective heat flux, α_{abs} is radiation absorbance at the surface, σ is the Stefan-Boltzmann constant, T_h is the heater temperature, Ts is the sheet surface temperature, F is a geometric factor, or view factor, 0 < F < 1, ε_{eff} is effective emissivity of the sheet heater system, also known as a non-black body correction factor, $0 < \varepsilon_{eff} < 1$, h is the natural convective heat transfer coefficient, and T_{∞} is the air temperature.

2.4 Summary

This chapter introduces the properties of polymeric material and the theory of heat transfer, which were concerned with the heating phase in thermoforming.

- 1. The polymers are divided into three groups: themoplastics, thermosets and elastomers.
- 2. Polymeric material displays different characteristics when heated. Most thermoforming sheets are cross-linked, semi-crystalline structures, which remain soft and thermo-formable solids rather than becoming fluid above their melting temperature.
- 3. All three modes of heat transfer are applied in thermoforming. Energy from the heater source reaches the sheet surface and internal layers of plastic sheet by radiation. Heat may be added to or removed from the sheet surface to the air surrounding the sheet by convection. Energy is also transferred from the sheet surface to the sheet interior by conduction.
- 4. The convection and radiation energy input is consigned to the surface of the thermoforming sheet while energy is moved throughout the sheet by a combination of conduction and radiation.
- 5. The transient heat transfer equation (2.20) with equation (2.22) for boundary conditions is valid to represent the mathematic model of the soft sensor to predict sheet interior temperature.

In order to be able to use equations (2.20) and (2.22) as a soft sensor solution, an embedded software algorithm needs to defined. Furthermore, experiments need to be done to validate whether the software algorithm can represent a soft sensor system for the estimation of sheet temperature distribution in thermoforming.

Chapter 3. Methodology

The purpose of a soft sensor is to be able to estimate a plastic sheet internal temperature distribution during the heating phase of a thermoforming process. Under the current scheme the controller provides the necessary control action to track a given set point of sheet surface temperature in the presence of disturbances whereas a soft sensor estimates the sheet internal temperature and indicates the time of sheet heating inside the oven. The estimation is based on on-line measurement of various operating parameters including sheet surface temperatures, oven air temperatures and heater element temperatures.

3.1 General Reviews

There are three main options available when implementing this soft sensor methodology: Linear Kalman Filters, Non-linear Prediction, and Open Loop Observer.

Theory behind the linear Kalman filter is well established, well documented, and it has been used successfully in a broad range of applications. But the one of the limitations of this method is that it is based on linear systems theory. This does not pose a problem in all applications since many nonlinear processes can be described quite well with linear models if the process is operated within a small linear range. Unfortunately, this is not the case with thermoforming. The mathematical models describing the radiant heat transfer contain hard nonlinear phenomena, and furthermore, the process is not restricted to a narrow operating range. The sheet temperature must necessarily progress from room temperature to forming temperature, typically a range of 20 0 C to 200 0 C. Therefore, it is clear that a linear model is not applicable in this case.

A theory for nonlinear prediction based on state space models also exits, but it is in an early stage compared to the linear system theory, and as such, it is not yet well established, let alone ready to implement a successful solution. More particularly, many of the nonlinear systems require well-defined models. The nonlinear state space model that has been developed for the thermoforming reheat process cannot be considered to be well defined. The model contains a high degree of uncertainty, which may seriously affect the accuracy of a soft sensor design.

The open-loop observer approach is a simple and expandable approach that uses the nonlinear state space equations to predict sheet temperatures. In other words, the open-loop observer can be called an on-line simulation. For a thermoforming control scheme, the surface temperature is controlled directly through the feedback measurement of infrared thermometers. A soft sensor gives the prediction of the sheet internal temperature and indicates when the sheet should be removed from the oven. Figure 18 describes the relation between the soft sensor and the heating process model. For thin-gage thermoforming, the sheet interior temperature is approximately same as the surface temperature, but for heavy-gage thermoforming the sheet interior temperature is significantly below the surface temperature. A soft sensor observer (on-line simulation) is implemented to predict the sheet interior temperature during the heating phase of thermoforming.



Figure 18: Soft sensors and heating process model

Normally, running a model in open loop to obtain state variables is ineffective because the disturbances and model errors cause significant differences between the predicted and actual state variables. However, a few modifications can be applied in this particular application. First of all, the level of uncertainty can be reduced through more accurate evaluation of the

input parameters. Secondly, a technique that tunes the results of observer to the actual sensor outputs of the machine is proposed through the implementation the correction method. Then, the observer with the corrected input can be used as a generalized soft sensor for the process.

3.2 Numerical Solution

Because the heating model of thermoforming obtained in equation (2.20) of Chapter 2 is a second order differential formulation that involves nonlinear boundary conditions, a numerical method, which is also easy to implement with a computer algorithm, is applied to solve this equation. The finite-difference method (FDM) and finite-element analysis (FEA) are the two basic approaches generally used in the numerical methods. For heat transfer, FDE is simple to understand and to implement. FDM is well developed and proved to be an efficient method. The solution that will be explored is a simplified, or reduced-order soft sensor that is directly related to the state space modeling equations. The modeling equations describe a finite dimensional system in which the sheet has been reduced to a number of isothermal zones. Therefore, the soft sensor design will be capable of estimating sheet temperature at a finite number of locations across the sheet. Furthermore, to simplify the problem, the solution is split into two cases as: sheet zones with infrared sensors and sheet zones without infrared sensors.

3.2.1 Finite-difference approach

In general, the finite-difference approach involves the following steps:

- Develop a nodal network
- > Define a finite difference approximations
- > Apply a standard energy formulation
- > Build a computer algorithm for the nodal network

1. Nodal network

Usually, the thermoforming sheet is geometrically and thermodynamically thin when compared with its planar dimensions. This allows us to consider the sheet as one-dimensional in the thickness direction only.

As it is shown in Figure 19, we designate a number of discrete nodal points at which the temperature is to be approximated. These nodal points are established by subdividing the entire system into sub-volumes, with the distance between adjacent nodes represented by Δx . Each sub-volume is treated as a lumped subsystem, where the temperature of a node is assumed to represent the average temperature of its sub-volume.



Figure 19: Nodal networks design

2. Finite-difference approximations

The first order finite difference approximation is expressed in terms of the nodal network for steady conditions by writing the forward difference:

$$\frac{\partial T}{\partial x} = \frac{T_{m+1,n} - T_{m,n}}{\Delta x} \quad \text{at } m, n$$
(3.1)

A second order finite difference approximation can be established at a nodal point (m, n) by writing:

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{m+1,n} - 2T_{m,n} + T_{m-1,n}}{\Delta x^2} \quad \text{at m, n}$$
(3.2)

3. Standard energy formulation

The first law of the thermodynamic gives:

$$\Sigma \dot{E}_{i} = \Sigma \dot{E}_{o} + \frac{\Delta E_{s}}{\Delta t}$$
(3.3)

where \dot{E}_i and \dot{E}_o represent the rate of energy transfer in and out of the system, respectively,

and $\frac{\Delta E_s}{\Delta t}$ is the rate of energy change stored within the system.

Apply this equation into our case:

$$\Delta q_{x} + \dot{q}\Delta V = \Delta q_{x+\Delta x} + \frac{\Delta E_{s}}{\Delta t}$$
(3.4)

where Δq_x and $\Delta q_{x+\Delta x}$ represent the rate of energy transfer in and out of the system respectively. They are represented by equation (2.18) of Chapter 2 and $\frac{\Delta E_s}{\Delta t}$ is the rate of change in energy stored within the system, which is described as equation (2.19). The term $\dot{q}dV$ represents the rate of energy generated within the control volume. In this case, $\dot{q}dV$ is referred as q _{abs} that is defined by equation (2.17) as the part of the radiative flux absorbed by the sheet internal layers.

The first law of thermodynamics is applied to each interior and exterior node at an instant of time t. To develop a numerical finite element formulation for unsteady conductive heat transfer in a solid with internal energy generation, the system is subdivided into m sub-volume, with the temperature at each node designated by T_m^{τ} , where the time index τ takes on integer values and is defined in terms of the time increment Δt by $t = \tau \Delta t$.

3.2.2 Sheet Zones with Infrared Sensors

For the case of sheet zones with infrared sensors, the surface temperature of the sheet is available via the non-contact infrared temperature sensors. The surface temperature measurements service the boundary conditions in the state space equation.

Now, with the top and bottom surface temperature directly available, the equations for Node 1 and N are not required, and the temperatures for Nodes 2 and N-1 (the layers directly below the top and bottom surface layers respectively) can be derived by equation (3.4).

Then, an explicit finite-difference energy balance is developed for one of interior nodes (m) by writing

$$-kA\frac{T_{m}^{\tau}-T_{m-1}^{\tau}}{\Delta x}+q_{abs}=-kA\frac{T_{m+1}^{\tau}-T_{m}^{\tau}}{\Delta x}+\rho c_{v}A\Delta x\frac{T_{m}^{\tau+1}-T_{m}^{\tau}}{\Delta t}$$
(3.5)

Hence, we obtain

$$T_{m}^{\tau+1} - T_{m}^{\tau} = \frac{\alpha_{diff} \Delta t}{\Delta x^{2}} (T_{m+1}^{\tau} + T_{m-1}^{t} - 2T_{m}^{\tau}) + \frac{\Delta t}{\rho c_{v} \Delta x} q_{abs}$$
(3.6)

The solution for $T_m^{\tau+1}$ is

$$T_{m}^{\tau+1} = \frac{\alpha_{\text{diff}} \Delta t}{\Delta x^{2}} (T_{m+1}^{\tau} + T_{m-1}^{t}) + (1 - 2\frac{\alpha_{\text{diff}} \Delta t}{\Delta x^{2}}) T_{m}^{\tau} + \frac{\Delta t}{\rho c_{v} \Delta x} q_{abs}$$
(3.7)

where t refer to time index, m represents the number of nodes, the temperature at each node and each instant of time is designed by T_m^{τ} , Δx represent an effective grid space, α_{diff} is thermal diffusivity, and q_{abs} is defined by equation (2.17) of Chapter 2.

To maintain stability, the coefficients associated with T_m^{τ} term for each nodal equation must equal or be greater than zero. Therefore, we require

$$(1 - 2\frac{\alpha_{\text{diff}}\Delta t}{\Delta x^2}) \ge 0$$
(3.8)

Thus, the model can be run in open loop as in a normal simulation to obtain the temperatures of the middle layers. The only difference is that the normal radiation and convection boundary conditions, which are quite often very uncertain, are replaced by sensor measurements. The major source of uncertainty in the soft sensor measurement now becomes the material properties, i.e., k, ρ and c_p , which can be estimated to a much higher degree of certainty than the parameters associated with radiative and convective heat transfer. Also, if the accuracy of the infrared temperature sensors and material properties are known, uncertainty analysis can give the overall accuracy of the soft sensor.

3.2.3 Sheet Zones without Infrared Sensors

In large systems, many more sheet zones need to be considered. Unfortunately, it is not economically feasible to use the method discussed above since every sheet zone would require two (top and bottom) infrared sensors. An innovation is therefore required in order to practically implement the open-loop soft sensor scheme on large systems since the feedback,

in the form of sheet surface temperature measurements, is not be available for every zone. Again the nonlinear open loop is applied to obtain the sheet temperatures.

Now applying the numerical solution and boundary condition into equation (3.4), the numerical equations for node 1 to M can be described as:

Node 1:

$$Q_{rad} + Q_{con} + Q_{abs} = -kA \frac{T_{m+1}^{\tau} - T_m^{\tau}}{\Delta x} + \rho c_v A \Delta x \frac{T_m^{\tau+1} - T_m^{\tau}}{\Delta t}$$
(3.9)

The solution for $T_m^{\tau+1}$ is

$$T_{m}^{\tau+1} = \frac{\alpha_{\text{diff}} \Delta t}{\Delta x^{2}} (T_{m+1}^{\tau} + T_{m-1}^{t}) + \frac{\Delta t}{\rho c_{v} \Delta x} (q_{abs} + q_{rad} + q_{con})$$
(3.10)

Node 2 \sim m-1:

$$-kA\frac{T_{m}^{\tau} - T_{m-1}^{\tau}}{\Delta x} + q_{abs} = -kA\frac{T_{m+1}^{\tau} - T_{m}^{\tau}}{\Delta x} + \rho c_{v}A\Delta x\frac{T_{m}^{\tau+1} - T_{m}^{\tau}}{\Delta t}$$
(3.11)

Therefore, we have:

$$T_{m}^{\tau+1} = \frac{\alpha_{\text{diff}} \Delta t}{\Delta x^{2}} (T_{m+1}^{\tau} + T_{m-1}^{t}) + (1 - 2\frac{\alpha_{\text{diff}} \Delta t}{\Delta x^{2}}) T_{m}^{\tau} + \frac{\Delta t}{\rho c_{v} \Delta x} q_{\text{abs}}$$
(3.12)

Node m:

$$q_{rad} + q_{con} + q_{abs} = -kA \frac{T_{m+1}^{\tau} - T_{m}^{\tau}}{\Delta x} + \rho c_{v} A \Delta x \frac{T_{m}^{\tau+1} - T_{m}^{\tau}}{\Delta t}$$
(3.13)

The solution for $T_m^{\tau+1}$ is

$$T_{m}^{\tau+1} = \frac{\alpha_{diff} \Delta t}{\Delta x^{2}} (T_{m+1}^{\tau} + T_{m-1}^{t}) + \frac{\Delta t}{\rho c_{v} \Delta x} (q_{abs} + q_{rad} + q_{con})$$
(3.14)

where t refers to time index, m represents the number of node, the temperature at each node and each instant of time is designed by T_m^{τ} , Δx represent an effective grid space, α_{diff} is thermal diffusivity, q_{rad} is the part of radiation heat flux transmitted to sheet surface, q_{con} is the convection heat flux occurring on the sheet surface, and q_{abs} is the part of radiation heat flux absorbed by the sheet internal layers. Even in case of sheet zones without infrared sensors, the predictive capabilities may be improved by estimating one or more key parameters using the temperature measurement from sheet zones with infrared sensors. The one key parameter that is most uncertain is the absorptivity of radiation heat transfer, which can be obtained by rearranging the model equation with infrared sensor measurements as follows:

Node 1:
$$Q_{rad} + Q_{con} + Q_{abs} = -kA \frac{T_{m+1}^{\tau} - T_m^{\tau}}{\Delta x} + \rho c_v A \Delta x \frac{T_m^{\tau+1} - T_m^{\tau}}{\Delta t}$$
 (3.15)
where $Q_{in} = Q_{rad} + Q_{conv} = \alpha_{abs} \sigma \epsilon_{eff} FA (T_h^4 - T_s^4) + h A(T_\infty - T_s)$

To simply equation (3.14), we assume that $-kA\frac{T_{m+1}^{\tau}-T_m^{\tau}}{\Delta x}$ equals a constant E_{out} and

 $\rho c_{v} A \Delta x \frac{T_{m}^{\tau+1} - T_{m}^{\tau}}{\Delta t}$ equals a constant E_{st} because these values are relatively small and stable compared with Q_{rad} and Q_{conv}. Therefore, we have

$$\alpha_{abs} = \frac{E_{out} - hA(T_{\infty} - T_s) + E_{st} - Q_{abs}}{\sigma \varepsilon_{eff} FA(T_h^4 - T_s^4)}$$
(3.16)

This equation shows that absorptivity α_{abs} depends on both the heater temperature and the sheet temperature. The estimate of the absorptivity of radiation heat transfer, α_{abs} , is obtained with the measurement of surface temperature with infrared sensor and it can then be used to improve the open-loop predictions of the sheet zones without infrared sensors.

3.2.4 Computer Algorithm

The program flowchart of a FDE numerical approach for the soft sensor system in thermoforming process is shown in figure 3.3.



Figure 20: Computer algorithm of a FDE soft sensor solution

3.3 Sensitivity Analysis

As discussed above, the accuracy of the soft sensor system is depended on the uncertainty level of the material properties, i.e., k, ρc_p and α_{abs} . Sensitivity analysis involves the uncertainty treatment through more accurate evaluation of the input parameters and it becomes very important to the use of an open-loop observer. Heat capacity, thermal conductivity and thermal diffusivity are three important physical properties of polymers used extensively in thermoforming.

3.3.1 Heat capacity

Heat capacity at constant pressure, Cp, is a thermodynamic property, defined as the isobaric change in polymer enthalpy with temperature:

$$Cp = \frac{\text{enthalpy}}{\text{temperature}} = \left(\frac{\partial H}{\partial T}\right)_{P} \quad [\text{cal/g}^{\circ}\text{c}]$$
(3.17)

The enthalpy curves for amorphous polymers are usually quite linear with temperature. Heat capacity values are therefore only slightly dependent on temperature above the glass transition temperature. But crystalline polymer enthalpy curves usually show dramatic changes near the melt temperatures of the polymer and exhibit discontinuities at the melt temperature. As a result, it is difficult to give specific values for heat capacity of crystalline polymers. Experimentally, the entire temperature-dependent heat capacity curve for any polymer can be obtained.

3.3.2 Thermal Conductivity

Thermal conductivity, a measure of energy transfer extension, is governed by the same energy elements that contribute to heat capacity. Thermal conductivity is one of the most difficult transport properties to measure. Fortunately, thermal conductivity is not strongly temperature dependent and so evaluation at one temperature is sufficient for use at another temperature. Typical, thermal conductivity values for amorphous polymers tend to be in the range of 3 to 5 x 10^{-4} cal/g °C. Owning to the higher degree of order for crystalline polymers,

the value of crystalline polymer can be about twice that for amorphous polymers. More detailed values of polymer thermal conductivity are available from thermal properties tables.

3.3.3 Thermal Diffusivity

Thermal conductivity is a measure of the extent of energy transmission through a solid body. In contrast, thermal diffusivity is a measure of the rate at which energy is transferred. Metals have values that are hundreds of times larger than polymers.

Thermal diffusivity is represented by
$$\alpha = \frac{K}{\rho C_P}$$
 [cm²/s] (3.18)

where K is thermal conductivity, ρ represents material density and C_P is the heat capacity at constant pressure. Value for all polymers are typically 5 to 10 x 10⁻⁴ cm²/s. More details are available in tables of thermal properties of polymers [Throne 96a].

D 1	1	1	1		
Polymer	Density	Thermal	Heat capacity	Thermal	Thermal
	$\left[\text{kg/m}^3 \right]$	conductivity	$[cal/g ^{\circ}C \times 10^{-4}]$	diffusivity	expansion
		$[Cal/s cm °C x 10^{-4}]$		$\int cm^2/s \times 10^{-4}$	coefficient
				[[$[^{0}C^{-1} \times 10^{-6}]$
Amorphous polymers					
Polystyrene	1050	4.3	0.54	7.66	70
PMMA	1200	4.3	0.615	5.9	70
PMMA/PVA alloy	1300	3.3	0.6	4.2	79-142
ABS	1050	2-3	0.4	4.8-7.1	60-130
PVC	1350	3.45-4.1	0.365	7-8.4	70-80
Crystalline polymer					
LDPE	920	7.57-9.6	0.88-1.05	7.85-11.9	250
EVA	940	8.27	0.95	9.26	160-200
HDPE	960	9.0-12.1	0.88-1.15	8.1-14.3	200
PET	1370	5.7	0.44	9.5	70
PBT	1310	5.0	0.54	7.1	60
Nylon 6	1130	6.9	0.71	8.6	80
Nylon 66	1140	5.5	0.71	6.8	80
POM	1415	5.9-7.2	0.61	6.8-8.4	90-110

Table 3: Therma	l Properties of	thermoforming	polymers	at 25	°C
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3.3.4 Absorptivity Analysis

The Beer-Lambert law is the linear relationship between the absorbance and concentration of an absorber of electromagnetic radiation. The general Beer-Lambert law is usually written as:

$$q(\lambda) = q_0(\lambda)e^{-\alpha(\lambda)d}$$
(3.19)

where $q(\lambda)$ is the measured radiation, $q_0(\lambda)$ is a wavelength-dependent radiation, α is the absorptivity, and d is the thickness of the plastic sheet. By transforming this equation into logarithmic form, we obtain:

$$-\ln\tau_{\lambda} = A_{\lambda}d + C_{\lambda}$$
(3.20)

where A_{λ} and C_{λ} are the spectral absorption coefficients, τ_{λ} is the transmissivity of the material, and d is the thickness of a plastic sheet.

As shown in equation (2.10) of Chapter 2, absorptivity and transmissivity in radiative heat transfer of a thermoforming material are related, $\tau + \alpha = 1$. Hence, the absorptivity can be defined as $\alpha_{abs}=1-\tau$.

3.4 Observer Tuning

Even after the uncertainty treatment of several key parameters in thermoforming process, there are still some discrepancies between the predicted and measured parameters due to variations in the material properties and errors in the assumptions for the simulation model. To overcome these disturbances, a tuning technique that adjusts the results of the open-loop observer to the actual sensor outputs of the forming machine is proposed. The tuning method consists of the calculation of a correction vector to observer inputs. With the corrected inputs, the observer can then be used as a generalized soft sensor for the process.

The observer and experimental process can be represented in the vicinity of the setup point by the following equation:

 $[O] = [K]^*[X] + [B]$ (3.21)

where [O] is the output vector of either the open loop observer or the experimental system, [K] is system matrix, [X] is the set point vector for the experimental point, and [B] is a constant vector. The tuning method consists of the calculation of a correction factor that is applied to the observer to match the experimental results. Manipulating equation (3.21) for the experimental and soft sensor values gives:

$$[O_e] = [O_e]^* [O_s]^{-1} * [K_s]^* [X] = [K_s]^* [X_{corr}]$$
(3.22)

where $[O_e]$ represents experimental output vector and $[K_s]$ is simulation system matrix. $[X_{corr}]$ refers to the correction factor, which can be calculated as a corrective vector:

 $[X_{corr}] = [K_s]^{-1} [O_e] * [O_s]^{-1} * [K_s] * [X]$ (3.23)

The value of the system matrix pertaining to the heating phase can be calculated by varying the A_{λ} and C_{λ} coefficients of the Beer Lambert equation in the simulation for a given element temperature [P. Girard 02]. Since we are adjusting the observer in the vicinity of the set point, and not identifying a complete model for the process, a linear adjustment process is adequate. As the parameterization coefficients represent the state variables and are derived from numerous data points, the system is very immune to noise in the input data. The tuning process is repeated with several element temperatures, resulting in a set of temperature dependent correction coefficients.

3.5 Summary

The purpose of a soft sensor is to be able to predict the sheet interior temperature distribution during the heating phase of thermoforming. The methodology is presented as follows:

- 1. The open loop observer is chosen to act as the soft sensor solution for thermoforming control.
- 2. The finite-difference method (FDM) is applied to solve the partial differential equation represented as the soft sensor mathematic model (2.20).
- 3. The FDM approach involves the steps of developing the nodal network, defining the finite difference approximations, applying the standard energy formulation and building the computer algorithm.
- 4. The FDM solution is split into two cases as: sheet zones with infrared sensors and sheet zones without infrared sensors.

- 5. For the case of sheet zones with infrared sensors, the radiation and convection boundary conditions, which are the most uncertainty term, are replaced by infrared sensor measurements.
- 6. For the case of sheet zones without infrared sensors, the predictive capabilities may also be improved by estimating the key parameter, i.e., absorptivity α_{abs} , which can be obtained by using the temperature measurements from sheet zones with infrared sensors.
- 7. The sensitivity of some key parameters of the material properties is also analyzed in order to reduce the uncertainty of the soft sensor methodology.
- 8. A tuning method consisting of the calculation of a correction vector applied to observer inputs is proposed.

Chapter 4. Experimental Setup

To verify the result of the methodology presented in Chapter 3, experimental trials were performed on industrial scale thermoforming machines located at the IMI facility. Totally, three experiments have been carried out in sequence. The internal temperatures of a plastic sheet at different depths across the sheet thickness were measured. The purpose of the second experiment was to analyze the thermal diffusivity influence on heat transfer for plastic sheets. Further to these two tests, a third experiment was scheduled to explore the relation between the absorptivity of the plastic sheets and the temperature of the heating elements.

4.1 Thermoforming Materials

The thermoplastic materials used in the experiments are cross-linked, semi-crystalline, highdensity polyethylene sheets (HDPE DMDA-6200) supplied by Petromont Inc. HDPE DMDA-6200 is a high-density polyethylene copolymer resin. This material is commonly used in the thermoforming industry. The HDPE sheets were cut to the size of 210 mm x 210 mm x 12 mm for the experiments. The dimension of the sheet as well as the physical properties of HDPE DMDA-6200 is given in Table 4.

Length (mm)	210	
Width (mm)	210	
Thickness (mm)	12	
Density (kg/m ³)	955	м,
Thermal conductivity (W/M/°C)	0.253	
Specific heat at 180 (J/kg/°C)	2730	-
Absorption coefficient, $\kappa(m^{-1})$	1300	
Heat transfer coefficient (W/m ² /°C)	48	

 Table 4: Material properties of HDPE DMDA-6200

4.2 Thermoforming Machines

The experiments were performed on two commercial shuttle-type thermoforming machines, manufactured by the AAA Plastic Equipment Inc. in Fort Worth, Texas. The model number of the machines are MBE –2436 A and MBE –2438 M. These machines were available in the machine shop of the Industrial material Institute (IMI), National Research Council Canada

(NRC), located at the outskirts of Montreal in Boucherville, Quebec.

A typical thermoforming machine can basically be divided into a heating section and a forming section. The oven of model MBE-2436A has an upper and a lower heater bank of ceramic elements for profiled control over 2×3 zones. The MBE-2438M has an upper and a lower heater bank of ceramic elements for profiled control over 6×3 zones. The heaters are ceramic, 650W, shown in Figure 21. The typical distance between a sheet and the heaters is 150 mm. The temperature of the heater is measured using the embedded thermocouples.



Figure 21: A view of ceramic heater elements of model MBE-2438M machine

A typical thermoforming machine has the following seven basic functions and features:

- > An oven to heat the sheet material to a pliable plastic state.
- > An aluminum frame to clamp and hold the heated sheet .
- > A pneumatic mechanism to manipulate top and bottom platens.
- > A vacuum system to assist product forming in the mold.
- > A temperature control cabinet for the heating elements.
- > A control panel for the pneumatic and mechanical operations.
- > Safety devices.

The thermoforming machines in IMI are designed to automatically perform thermoforming functions by pneumatic and mechanical operations in a pre-programmed sequence, except for

sheet loading and unloading. The control panel, which automates the pneumatic and mechanical operations, controls the following operations: 1) pushing the clamped plastic sheet into the heater section, 2) pulling the heated sheet to the forming section, 3) moving platens and molds to the correct position, 4) applying vacuum air pressure, 5) cooling the formed part. The electromechanical system of the thermoforming machine can control up to 12 sequential steps for automatic operations in a thermoforming process. The duration of each step is determined by the setting of a calibrated dial on the front panel. The time control for each step may be supplemented by external controls from limit switches, photocell or other sensors mounted on the thermoforming machine. This combination of time-base and inpoint control provides control flexibility. Actuation of the switches is independently controlled by plug-in pins in program drums. Position of the pins determines the machine function that can be actuated sequentially, simultaneously or in an overlapped mode.

Most thermoplastic processing demands closely controlled temperatures to obtain optimum performance. The simplest and most common way to control a heater unit is by on/off switching. Such switching can easily be activated manually, but the basic on/off temperature controllers can create strong temperature fluctuation. To meet the requirement of more precise temperature control from the thermoforming industry, an automated temperature control system needs to be implemented. Proportional-integral-derivative (PID) controllers are used for the thermoforming machines at IMI. This PID controller derivatively applies the temperature input signals to an integrator, which can adjust and slow down the power input ratio when the actual temperature approaches the set point. The model of the controller used for the thermoforming machine in IMI is MPI VT 20.

Some features of MPI VT 20 temperature controller are as follows:

- > Dual Display PID AUTOTUNE
- > 1/16DIN max (1 output + 1 Alarm)
- > 1/8 & 1/4DIN max (2 output + 2 Alarm)
- ➢ Ramp-to-setpoint
- > AUTO / MANUAL

A view of the model MBE-2436A of thermoforming machine at IMI is shown in Figure 22.



Figure 22: The model MBE-2436A thermoforming machine at IMI

4.3 Thermocouples and Infrared Sensor

The experiments done at IMI were scheduled to measure the temperature profile of the sheet in the heat phase of thermoforming. Therefore, temperature sensors played an important part in these experiments.

The heating element temperatures, air temperatures and sheet internal temperatures during the heating phase of a thermoforming process were measured by thermocouples supplied by OMEGA Engineering Inc. A thermocouple is a sensor for measuring temperature. It consists of two dissimilar metals, joined together at one end, which produce a small unique voltage at a given temperature. This voltage is measured and interpreted by a thermocouple thermometer. Thermocouples are available in different combinations of metals or calibrations. The four most common calibrations are J, K, T and E. Each calibration has a different temperature range and environment. Type K thermocouples were used to measure heating element temperatures because the maximum measuring temperature can go up to $+900^{\circ}$ C. Type J thermocouples were used to measure the air temperature and internal layer temperature of the heating sheet with a temperature range of 0°C to $+250^{\circ}$ C.

Infrared thermometers provide straightforward temperature measurement applications where thermocouples are impossible to measure. Figure 23 illustrates an example of infrared sensor. The noncontact optics of infrared sensor receives infrared energy from the distant measurement target and the detectors convert the infrared energy to an electrical signal, which is then amplified and interpreted into a temperature value based on the instrument's internal algorithms and the target's emissivity.



Figure 23: An infrared sensor example

The model of the infrared sensors, which were used at IMI to measure the bottom and top surface temperature of sheets, is RayMID 10-4 provided by Raytek Canada. The Raytek MID is a two-piece infrared temperature measurement system with miniature sensing head and separate electronics. The sensor is small enough to be installed inside the thermoforming machine and the sensor is housed in a rugged stainless enclosure to ensure long-term performance. To prevent overheating of the infrared sensor heads, an air cooling jacket is used to protect the infrared sensor heads that were mounted inside the oven of the thermoforming machine. Some features of RayMID 10-4 (Figure 24) are the follows:

- > Small sensing head fits most industrial environments.
- > Ambient operating range up to 85° C without cooling.
- Accessories for cooling and air purging.
- > Adjustable emissivity, peak hold, valley hold and averaging functions.
- > 1% accuracy from -40° C to 1200° C.

- ➤ Choice of 2:1 or 10:1 optics.
- > Powered by 12-24 VDC at ≤ 100 ma.
- ▶ RS-232 or RS-485 digital communications.



Figure 24: RayMID 10-4 Infrared Sensor

4.4 Experimental Design:

In order to measure the internal temperatures of a plastic sheet at different thicknesses, the first experiment was conducted in June 2002. To minimize heat leaks along the thermocouples, lead holes were drilled at a 30-degree angle and the sheet was heated from the non-drilled side only. The HDPE sheets used in the experiment were 210 mm wide, 210 mm long, and 12 mm thick. The sheets were drilled with five holes to accommodate thermocouples that were used to measure the sheet interior temperatures. The holes were drilled at the same angle β , but with different drilling depths L. The drilling angle was fixed at β = 30 °C with the help of a special clamp stand. The depth L of each hole was measured by caliper. Accordingly, the vertical distance h from the hole up to the sheet surface was calculated by: h = L*sin β . The designed depths h were 1mm, 3mm, 6mm, 9mm and 11mm respectively. See Figure 25 for detail specifications.



Figure 25: Experimental setup of a HDPE sheet

Three element temperatures were investigated in order to ascertain the temperature wavelength dependency of the heater elements. Moreover, a thick metallic sheet was inserted on the non-heated side to keep alternate side chassis temperatures near ambient. After heating, the sheet was removed from the oven and subjected to a cooling phase. A two-speed fan was used to produce three levels of air velocity during the heating and equalization phase. Altogether, 21 experimental trials were conducted in the first experiment (Table 5).

Fable 5: Experimental	design f	or heavy gage	e thermoforming	in June 20	002
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No. of test	Heater temp. setting (⁰ C)	Fan	Top Anemo meter (ft/min)	Heating time (min)	Cooling time (min)	Scan interval (s)	Remarks	
		1.401204				And the set of the set of the		
		-		Top he	eater on			
1	280	0	10	16	2	1		
2	280	1	20	40	5	1		
3	280	2	80	60	5	5		
4	380	0	6	40	5	5		
5	380	1	22	45	5	3		
6	380	2	60	54	3	3		
7	450	0	2	5	2	1	Zone2heater 400	
8	450	1	18	10	2	1		
9	450	2	30	15	2	1		
10	450-380	0	5	5-25	1	1	First heat 5 mins at 450°C then 25 min under 380°C	
Bottom heater on								
11	280	0	1	40	2	2		
12	280	1	15	40	2	2		
13	280	2	85	40	2	2		

14	380	0	3	40	2	2	TSC5, TSC4 open due to sag
15	380	1	40	40	2	2	TSC5 open
16	380	2	50	40	2	2	TSC5, TSC4 open
17	450	0	20	15	2	1	
18	450	1	30	15	2	1	TSC5 open
19	450	2	60	16	2	1	
				Both l	neaters	on	
20	450-380	0	0	5-7	2	1	First heat 5 mins at 450°C then 7 mins under 380°C
21	450-380	0	0	4.5-6.5	2	1	First heat 4.5 mins at 450°C then 6.5 mins under 380°C

The oven air temperatures of the thermoforming machine were measured using Omega type k thermocouples, midway between the heaters and the HDPE sheet. The points where the air temperature measurements were performed correspond to those of sheet surface temperature measurements. In order to avoid the impact of radiation heat disturbance on the measurement of the oven air temperature, the thermocouples have been inserted into a galvanize pipe. The transient sheet surface temperatures (both upper and lower surface of the sheet) were measured at the designed middle spots using mounted infrared sensors of type RayMID 10-4. An Agilent 34970A Data Acquisition Unit was used to log and record the temperature measurement. The data was logged every 1 second and the scanning process was launched 10 seconds before the heating step. The data acquired by the Agilent 34970A Data Acquisition Unit were transferred to a laptop for post processing with HP BenchLink Data Logger Software. A picture of a plastic sheet after heating phase is shown as Figure 26.



Figure 26: A picture of thermoforming sheet after the heating stage

In order to investigate the conductive diffusivity influence, a second experiment was conducted in August 2002. Instead of heating the sheet inside an oven, the sheet was cooled with iced water. The sheet floated on the iced water with the bottom surface in contact with the iced water. In this way, there was neither a radiative nor a convective influence, but only a conduction flux going through the sheet. As in the first test, five thermocouples were inserted into drilled holes in order to measure the sheet interior temperature. Experimental data was collected by using the Agilent 34970A Data Acquisition Unit. The experimental record and setup is shown in Table 6.

No. of test	Cooling Scan Air time (min) interval(s) temperature (°C)		Surface temperature (start/stop)	Remarks	
			计逻辑 深語意		· 注意的是是在中国的资源。
1	18	1	25.2	28/8	
2	2 20		24.5	26/4.3	
3	10 1 24.7		24.7	26/6	·····
4	14	1	1 26.8 26/4		No water on the surface
5 12 1		1	25.4	27/7	No water on the surface
6 4		1	26	26/6	

Table 6: Experimental record and setup for the test of iced water cooling

Based on the above two experiments, the third experiment was carried out in October 2002. The purpose of this experiment was to explore the relation between the absorptivity of the HDPE plastic sheet and the temperature of the heating element. The experiment design was the same as the first experiment but this experiment was performed on the Model MBE-2438M thermoforming machine. In order to analyze the absorptivity of the HDPE thermoforming sheet, the sheet was heated inside the oven with heater element settings of 280 °C, 320 °C and 450 °C. Furthermore, a cooling phase test was included. After being heated in the oven, the sheet was removed out of the oven to cool down. An auxiliary fan was used to assist the cooling process. Three fan speeds (fan off, medium speed, maximum speed) were used to analysis the heat conduction and convection influences with different air velocity values at the cooling stage of thermoforming. Table 7 shows the setup of this experiment.

No. of test	Heater temp. setting (°C)	Fan	Top Anemo - meter (ft/min)	Heating time (min)	Cooling time (min)	Scan intervał (s)	Remarks
						1.200	
				Top he	eater on		
1	280	0	3	65	13	1	
2	280	1	190	65	13	1	
3	280	2	280	65	13	1	
4	380	0	10	60	15	1	
5	380	1	190	60	15	1	
6	380	2	320	60	15	1	
7	420	0	18	20	15	1	
8	420	1	120	20	15	1	TC1 measurement is lower than TC2 and TC3
9	420	2	220	20	15	1	TC 1 was almost piercing the PE
				Bottom	heater of	n	
11	280	0	8	65	13	1	
12	280	1	110	65	13	1	
13	280	2	300	65	13	1	
14	320	0	20	60	15	1	TSC5 out of the plate
15	320	1	150	60	15	1	Fan stayed open during the first 25 minutes of heating
16	320	2	200	60	15	1	TSC5, TSC4 out of the plate
17	420	0	6	20	15	1	Support added on the sides (vertical)
18	420	1	170	20	15	1	
19	420	2	230	20	15	1	Support moved horizontally

Table 7: Experimental setup for heavy gage thermoforming in October 2002

4.5 Summary

To verify and analyze the methodology presented in Chapter 3, experiments were performed on thermoforming machines in the workshop of IMI, NRC. Here is the summary of the experimental setup.

- 1. The type of plastic materials used in the experiment was HDPE DMDA-6200. The HDPE sheets were cut to the size of 210 mm x 210 mm x 12 mm for the experiments.
- 2. The first experiment in June 2002 was designed to measure the surface and interior temperatures of the plastic sheet during a heating process.
- 3. The sheet surface temperatures were measured by Raytek MID 10-4 infrared sensors.
- 4. The interior temperatures of the sheets were measured by the thermocouples inserted into the pre-drilled holes at the depths of 1mm, 3mm, 6mm, 9mm and 11mm inside the sheet.
- 5. The oven air temperatures were measured by thermocouples. An auxiliary fan was used to

blow air into the oven to investigate the impact of ambient air fluctuation.

- 6. The second experiment was carried out in August 2002 in order to analyze and investigate thermal diffusivity of the HDPE plastic sheet using iced water as a cooling medium.
- 7. The third experiment was carried out in October 2002. The purpose of this experiment was to explore the relation between the absorptivity of the plastic sheet and the temperature of the heating elements.

Chapter 5. Results and Discussion

Figure 27 presents typical experimental heating curves. Figure 28 shows the start of the heating phase for the data in Figure 27. It was noted that all the thermocouple signals start to vary within a five second time span. This confirms that a combination of radiative and conductive heat flux is transmitted to the interior of sheet. In order to validate this conclusion, the same sheet of material was cooled by immersion in iced water. In this case a delay of more than 5-10 seconds typical of conduction heating was noted (Figure 29 [Patrick 03]). This delay can be related to the relatively lower diffusivity value of the polymer material compared with the diffusivity value of metals. Typically, polymers have thermal diffusivity values that are hundreds of times lower than those of the metals. The experimental sheet dimensions are 210mm x 210mm x 12mm and the temperature measurements were made at 1mm, 2mm, 6mm, 9mm and 11mm inside the plastic sheet (shown in Table 4).



Figure 27: A typical experimental heating curve for bottom heating at 280°C



Enlargement of the start of the heating process





Figure 29: The first 60 seconds of the cooling process for the ice test

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From Figure 30 and Figure 31, the impact of air velocity on the heating phase was investigated. During the experiment, an auxiliary fan was placed in front of the oven so that air could blow into the oven. Using the same temperature setting at 280°C for the heater elements, the experimental trials were carried out with fan speed settings of medium, high and off respectively. The curves in Figure 30 and 31 show that there is little variation in the sheet temperatures with respect to the different fan speed settings. Therefore, we can conclude that the change of airflow around the oven has little influence on the heating phase of a thermoforming process.

Bottom heating at 280oC, fan off



Figure 30: Experimental heating curves for bottom heating at 280°C with fan-off





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Figure 32 shows a case with the different temperature settings of the heater elements done in steps. First, the temperature of the heater elements was set at 450° C. The surface and interior temperatures of the heating sheet went up sharply at this temperature setting. To prevent surface overheating, after the first 370 seconds of heating at 450° C, the setting of the heater elements was reduced to 380° C. As a result, the surface and interior temperature of the sheet continued to increase, but went up more slowly. This proved that an optimum heating strategy can be achieved through controlling the temperature setting of the heating elements for the best process effectiveness.

Top heating from 420oC to 380oC



Figure 32: Experimental heating curves with different temperature settings

Figure 33 presents the experimental heating curves for heater elements at 280°C, heating from the top elements. As discussed in the methodology of Chapter 3, the soft sensor solution is divided into two cases: 1. sheet zones with infrared sensors, and 2. sheet zones without infrared sensors. For case 1, the sheet surface temperatures can be measured by infrared sensors while the surface temperatures service as the boundary conditions for the soft sensor model. Figure 34 shows the soft sensor output curves under the same setting of Figure 33. The curves were generated by the soft sensor program in Matlab (App. C). Figure 35 shows the comparative result of the sheet internal centerline temperature curves from the soft sensor prediction and from experimental measurements. By comparing the curves in Figure 33,

Figure 34 and Figure 35, we find that the temperature profiles from simulation and experiment are consistent in spite of some variance due to the fact that the thermocouple measurements are not exactly at the designed thickness because of sheet sag effect. Figure 36 shows the soft sensor solution curves for the sheet internal temperature with respect to its thickness, increasing in the time interval of 250 seconds. The curves were generated by Matlab codes as well. It shows that with the increase of sheet surface temperature, the slope of the sheet temperature curves changes as well. When the surface temperatures reach a stabilized condition, the temperature curves become linear. From all these comparisons and discussion, we conclude that the soft sensor solution developed in this thesis works well.



Figure 33: Temperature curves from the experiment for top heating at 280°C.



Legend setting :

- \Box 1mm inside the sheet
- $\frac{1}{2}$ 3mm inside the sheet
- \diamond 6mm inside the sheet
- \triangle 9mm inside the sheet
- 11mm inside the sheet



The centerline temperature



Legend setting :

 □ centerline temperature from experiment
 ☆ centerline temperature

from simulation





Figure 36: Predicted temperature curves with respect to sheet thickness for top heating at 280°C

For case 2 (sheet zones without infrared sensors), the boundary conditions of the soft sensor solution need to be predicted with the FDM equations (3.10) and (3.13) in Chapter 3. Because the soft sensor solution for case 2 involves the calculation of high uncertainty non-linear radiative and convective flux, the heating model of the FormSim simulation software, which was introduced in section 1.2 of Chapter 1, is chosen to act as soft sensor solution. FormSim not only supports the inverse analysis function to estimate the interior temperature distribution of the sheet, but also takes into account the dynamic view factor for radiative flux, which is determined by the K-BKZ viscoelastic models supported by WLF temperature shift equation

Several simulation trials were performed with the FormView software. The comparative diagrams of the sheet internal centerline temperature curves from simulations and experiments are shown as Figure 37 and Figure 38. These diagrams show that there is an obvious deviancy between the experimental curves and simulation curves. By trying to input the different values of A_{λ} and C_{λ} which are related with material absorptivity introduced in equation (3.20) of Chapter 3, the sheet centerline temperature at the final step of heating phase can approach the experimental result but the slope and trend of the curve remain the same. Up to now, the absorptivity value used in FormView is independent from the sheet temperature that gradually varies during the heating phase in thermoforming. From the equation (3.16) of Chapter 3, we find that the absorptivity of the sheet is changing with both the heater temperature and the sheet temperature. This assumption can also be proven with the theory of Plank Blackbody Curve (Figure 15), which describes that the peak radiant energy of a black body moves toward shorter wavelengths as the temperature of black body is increased. Also from the experiments, this assumption can be demonstrated that the appearance of the plastic sheet was changing from opaque to translucent during the heating phase of thermoforming. The absorptivity of a plastic can be obtained by integrating the wavelength dependent absorptive curve over the wavelength range of the incident radiation. Further research to reveal the relation between the sheet and heater temperature, and the absorptivity value of different polymeric materials should be continued to in order to analyze this phenomenon.

Top heating at 280oC



Figure 37: Sheet internal centerline temperature curves for top heating at 280°C





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In spite of estimating the complicated absorptivity value of a specific thermoforming process, a robust and fast method was sought to adapt the simulation to the experiment [Patrick 03]. The first step is to identify the main variables of the process. Based on the above discussion, the material absorptivity was identified as the main variable of the process. The second step was to parameterize the identified process variables. In this phase we tried to parameterize state parameters that could be used for process identification by applying transformations to the heating areas in Figures 27. The result is presented in Figures 39.



Figure 39: Fitted experimental heating curve for bottom heating at 280oC(1000 to 3500s)

It can be seen that the heating section of the experiment can be transformed into mostly linear curves. As a result, the heating phase of a thermoforming process can be represented by the following state parameter equation:

$$\theta_{t,d} = \exp[\frac{a_1}{(a_3 + d)t} + a_2]$$
(5.1)

where θ is the temperature, t is the time, d is the depth

The three a_i coefficients represent state variables for the system. The state parameter equations (5.1) can be used for a very fast and accurate calculation of the temperature at any time and depth in the plastic sheet. The transforming result obtained from the state parameter equation is shown Figures 40.



Figure 40: Fitted simulation heating curve for bottom at 280oC (1000 to 3500 s)

The method is suitable for estimating the sheet internal temperature distribution in the vicinity of the set-up point. Three a_i coefficients of state parameter equation are related to the spectral absorption coefficients A_{λ} and C_{λ} of the Beer-Lambert law, which was introduced in section 3.3.4 of Chapter 3. Table 8 compares the temperature output from the FDM (finite-difference method) soft sensor and State Parameter Observer with respect to the experimental measurements in Figure 27.

Position in sheet (depth inside sheet) cm	Experimental measurement (temp.) oC	PDM soft sensor output (temp.) oC	State Parameter Observer output (temp.) oC	Remarks
1	132	133	137	PDM soft sensor is only valid with available of
3	130	130	132	infrared sensor measurement
6	128	127	127	State Parameter observer
9	123	124	123	can act a soft sensor without infrared sensor.
11	117	116	118	1

 Table 8: The soft sensors results and experimental measurement at 2500s

From the data in Table 8 and Figure 40, we find that, at the position of 1mm inside the sheet, the state parameter observer output has 5° C difference compared with experimental measurement, whereas the PDM soft sensor matches the experiment result. The FDM soft sensor agrees well with measurements because it generates an output based on infrared

sensor measurements that replace the term with the most uncertainty, the radiation and convection boundary conditions, in the modeling the heating phase of a thermoforming process. On the other hand, the state parameter observer generates an output without using data from infrared sensors measurement. It acts as a soft sensor in the case of sheet zones without infrared. To overcome disturbances due to the variation in the heat transfer coefficient and material properties, a tuning technique that adjusts the results of the observer to the actual sensor outputs of the forming machine is proposed. The tuning method was introduced in section 3.4 of Chapter 3, which consists of the calculation of a correction vector to observer inputs. With corrected inputs, the observer can then be used as a generalized soft sensor for the thermoforming process.

Summary:

An analysis of the temperature curves from the experimental results and temperature prediction from the soft sensor system gives the follows:

1. A combination of radiation and conduction, rather than only conduction, are responsible for heat transfer into the HDPE sheet interior.

2. The normal change of airflow around an oven has little influence on the heating process.

3. An optimum heating strategy can be achieved through varying the temperature setting of the heating elements for the best process effectiveness.

4. The FDM soft sensor solution was proven to be a successful predictor of the sheet interior temperature with the boundary conditions provided by direct infrared sensor measurements.

5. The value of the material absorptivity is not a constant and the value changes with both heater element temperature and sheet temperature.

6. The state parameter equation (5.1) can be used for a very fast and accurate response suitable for in-cycle process control in the vicinity of the set point.

In conclusion, the soft sensor developed in this thesis can be applied as a soft sensor system for estimation of the sheet temperature distribution in thermoforming. Further research on the relation among the absorptivity of the sheet, the temperature of heater elements and the temperature of sheet during the heating phase in thermoforming should be continued. The state parameter equation (5.1) can act a soft sensor observer for a very fast and accurate calculation of the temperature at different process times and depths inside the sheet in the case of sheet zones without infrared sensors. With the corrected inputs induced from a tuning technique, the observer can then be used as a generalized soft sensor for the thermoforming process.

Chapter 6. Conclusion

This thesis gives a solution fro a soft sensor system for estimating the sheet internal temperature in the heating phase of the thermoforming process. In Chapter 1, the background of the soft sensor system in thermoforming is introduced and the objective of the work is defined. Also an overview of thermoforming control and the motivation of the project are identified. Chapter 2 gives a description of polymer material structures, properties and its deforming characters. More particular, since the thesis focuses on the research of the heating phase in thermoforming, this chapter explains in detail the heat transfer theory behind this oven heating mechanism. All three modes of heat transfer are applied in thermoforming. Energy from the heater source reaches the sheet surface and internal layers of the plastic sheet by radiation. Heat may be added or removed from the sheet surface to the air surrounding the sheet by convection. Energy is transferred from the sheet surface to the sheet interior by conduction. In other words, we can say that the convection and radiation energy input is consigned to the boundary condition of the mathematical model while energy is moved throughout the sheet by conduction and radiation. Based on the theory exploration of radiation, conduction, and convection heat transfer, the transient heat transfer equation (2.20) with the boundary equation (2.22) is valid to represent the mathematic model of the soft sensor system.

Based on this mathematic model, the methodology of the soft sensor system is developed in Chapter 3. In a thermoforming control scheme, the surface temperature is controlled directly through the feedback temperature measurement by infrared thermometers. On the other hand, based on infrared measurements, a soft sensor gives the prediction of the sheet internal temperature and indicates when the sheet should be removed from the oven. The open loop observer is chosen to act as the soft sensor solution for thermoforming control. Since the mathematic model of soft sensor obtained in Chapter 2 is a second order partial differential equation with non-linear boundary condition, the finite-difference method (FDM) is applied to solve this equation. The finite-difference approach involves the steps of developing the nodal network, defining the finite difference approximations, applying the standard energy formulation, and building the computer algorithm. To simplify the problem, the FDM solution is split into two cases: sheet zones with infrared sensors and sheet zones without infrared sensors. In the case of sheet zones with infrared sensors, the normal radiation and convection boundary conditions, which are quite often very uncertain, are replaced by sensor measurements. However, in the case of sheet zones without infrared sensors, the predictive capabilities may be improved by estimating the key parameter, i.e., absorptivity α_{abs} . The value of this parameter can be obtained by using the temperature measurement from sheet zones with infrared sensors. Moreover, the sensitivity of some key parameters of the material properties is also analyzed in order to reduce the uncertainty of the soft sensor methodology. Finally, a tuning method consisting of the calculation of a correction vector to observer inputs is proposed.

To verify and analyze the results of the methodology presented in Chapter 3, experiments were performed on the thermoforming machines at the workshop of IMI. This is described in Chapter 4. The plastic sheets used in the experiment were HDPE DMDA-6200. The first experiment in June was designed for measuring the surface and interior temperature of the plastic sheet during a heating process. The sheet surface temperatures are measured by Raytek MID 10-4 infrared sensors. The interior temperatures of the sheets were measured by the thermocouples that were inserted into pre-drilled holes of different designed depths inside the sheet. The oven air temperatures were also measured by thermocouples. Furthermore, an auxiliary fan was used to blow air into the oven in order to investigate the impact of ambient air fluctuations. The second experiment was carried out in August 2002. This time, the sheet was cooled down with its bottom surface in contact which iced water in order to research heat conduction phenomena. Also the interior temperatures were measured by thermocouples. The third experiment was carried out in October 2002. The purpose of this experiment was to explore the relation between the absorptivity of the plastic sheet and the temperature of the heating element. The third experiment was performed on the new thermoforming machine, model MBE-2458M. The experimental setup and design were similar to the first experiment, but the cooling process was included in the experiment to evaluate the value of the convective coefficient.

Finally, a discussion on the results from the experiment and the prediction from the soft sensor system is presented in Chapter 5. The curves from experimental data show that a combination of radiation and conduction, rather than only conduction, determines heat transfer into the HDPE sheet interior. The normal change for airflow around the oven has no influence on the heating process. Moreover, an optimum heating strategy can be achieved through varying the temperature setting of the heating elements for best process effectiveness. The curves generated by the soft sensor program in Matlab show that the soft sensor solution works well to predict the sheet interior temperature with the boundary conditions provided by direct infrared sensor measurements. However, for the case of sheet zones without infrared sensors, there is obvious deviance between experiment and simulation results due to fact that the absorptivity value of the material changes with both the heater element temperature and the sheet temperature. However, a fast and accurate method was sought to adapt the simulation to the experiment. The method includes a state parameter equation for a very fast and accurate calculation of the temperature at any time and depth in the sheet and a tuning technique applied to adjust the results of the observer to the actual sensor outputs of the forming machine.

Further Research:

Some further improvements in the soft sensor system may be possible with the use of artificial neural networks, especially for the sheet zones without infrared sensors measurement. Artificial Neural Networks (ANN) could be used to obtain a more generic and accurate model for the prediction of heater surface temperatures. This would greatly reduce the amount of uncertainty associated with the sheet heating process model. As shown in Figure 41, an ANN could be used to implement an error predictor where the final predicted output would be: $\hat{y}_{pred} = \hat{y}_{nom} + \hat{y}_{error}$





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Finally, an ANN could also be used to estimate nonlinear uncertainty parameters in the process such as material absorptivity and convection heat transfer coefficient. Either an offline or an on-line training algorithm could be employed to enable an adaptive model based control.

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Appendix A: List of symbols

Symbol	Description	Units
<u>T</u>	Temperature	<u>K, °C</u>
<u>t</u>	Time	<u>S</u>
Q	Heat energy	J, Cal
đ	Heat flux	kw
<u>A</u>	Surface area	\underline{M}^2
<u>k</u>	Thermal conductivity	<u>W/m²K</u>
$\underline{\alpha}_{diff}$	Thermal diffusivity	<u>m²/s</u>
<u>σ</u>	Stephan-Boltzman Constant	W/m^2k^4
<u>F</u>	View factor	=
<u>3</u>	Emissivity	=
$\underline{\alpha}_{abs}$	Absorptivity	=
<u>Q</u> _{rad}	Radiation heat flux on the sheet surface	kw
<u>Q</u> _{conv}	Convection heat flux	<u>kw</u>
<u>Qabs</u>	Radiation heat flux through the sheet interior	<u>kw</u>
<u>h</u>	Convection coefficient	<u>W/m²S^oC</u>
Nu	Nusselt number	=
Ra	Rayleigh number	=
ĸ	Absorption coefficient	<u>m⁻¹</u>
<u>Cp</u>	Heat capacity	cal/g/°C
ρ	Density	kg/m ³
L	Thickness	<u>cm</u>

Appendix B: Abbreviations for thermoforming polymers

Abbreviation	Definition
ABS	Poly (acrylonitrile-butadiene-styrene)
СА	Cellulose acetate
LDPE	Low-density polyethylene
HDPE	High-density polyethylene
РАб	Polycaprolactam or nylon 6
PA66	Poly or nylon 66
PS	Polystyrene
PVC	Polyvinyl chloride
РММА	Polymethyl methacrylate
PE	Polyethylene
РР	Polypropylene
PVDC	Polyvinylidene chloride
РЕТ	Polyethylene terephthalate
PBT	Polybutylene terephthalate

Appendix C: Matlab Codes for Soft Sensor

```
%Matlab program of Soft-sensor project
%D:\bh\matlab\soft_sensor\heat2
%Author : Hou, Bengiang
$Date :March 20,2001 update:Janauary 2003
ⴻ
%To develop a numerical finite-difference formulation
%for unsteady conduction heat transfer across a sheet solid
%with energy generation, the system is divided into designed
$subvolume.The heat-transfer rates are specified by unsteady
%Finite-difference approximations for the Fourier law of conduction
%based on an energy balance equation.
% initialize the normal model parameters
clear all;
global l
              %the sheet thickness
global layer
             %total number of nodes uesd in simulation
global k
              %thermal conductivity (w/m.k)
global alpha
              %thermal diffisivity
global cp
              %heat capacity
global sigma
             %stephan_boltzman constant;
global view
              %view factor
global absorp
              %absorptivity of the materials
global T h
              %heater element temperature
% try a GUI solution
%prompt = {'Please input sheet thickness:
          %,'please input the grid/layer size: '
          %, 'please input thermal conductivity: '
          %, 'please input thermal diffusivity: '};
%title = 'Input for thermoforming centerline temperature predicting
program';
%lines= 1;
%def
      = \{ '1.2', '12', '50', '0.0005' \};
%answer = inputdlg(prompt,title,lines,def);
```

```
%input for geometric parameters;
1=1.2;
%l = input('please input the sheet thickness (1.2cm):
                                                         ');
%input for grid size;
layer=13;
$layer=input('please input the grid/layer size (12): ');
%input for properties;
k=50;
%k=input('please input thermal conductivity (50 w/m*k): ');
alpha=0.0005;
%alpha=input('please input thermal diffusivity (0.0005):
                                                            ');
m_tb1=[73,96,111,119,124,126,128,129,130,131,132,133,133,134,135,135,135,13
6];
m_tbm=[61,83,95,103,107,110,111,112,114,114,115,116,116,117,117,117,118,118
];
tini=21;
%input for initial conditions
for e=1:1:layer-1
sheet_temp(1,e)=tini;
end
%apply boundary condition
t_siz=size(m_tb1,2);
for q=1:1:t_siz
tb1=m_tb1(q);
tbm=m_tbm(q);
dx=1/(layer-1);
sheet_temp(1,1)=tb1;
sheet_temp(1,layer)=tbm;
%begin unstead solution with tou=1
tau=1;
```

```
%inputs for time increment
s=alpha*tau/dx<sup>2</sup>;
%input time span
while tau<250
%calcilate future nodal temperation temp(j,2)
    for j=2:1:layer-1
%q_abs=(1-absorp)*sigma*view*emiss*(T_h^4-T_s^4)*exp(-k*j*dx);
    sheet_temp(tau+1,j) = (sheet_temp(tau,j+1)+sheet_temp(tau,j-1))*s+(1-
2*s)*sheet_temp(tau,j);
    end
    tau=tau+1;
    sheet_temp(tau,1)=tb1;
    sheet_temp(tau,layer)=tbm;
end
%update temp_plot matrix
temp_plot(q+1,:) = sheet_temp(tau,:);
sheet_temp(1,:) = sheet_temp(tau,:);
end
%initialize frist row
temp_plot(1,:)=21;
%calculating time matrix
for q=2:1:t siz+1
time(q) = 250*(q-1);
end
time(1)=0;
%plot soft sensor output curves
temspline=spline(time,temp_plot(:,1),time);
plot(time,temp_plot(:,1),'-b','LineWidth',1);
hold on;
temspline=spline(time,temp_plot(:,3),time);
plot(time,temp_plot(:,3),'-b','LineWidth',1);
hold on;
temspline=spline(time,temp plot(:,6),time);
```

plot(time,temp_plot(:,6),'-b','LineWidth',1); hold on; temspline=spline(time,temp_plot(:,9),time); plot(time,temp_plot(:,9),'-b','LineWidth',1); hold on; temspline=spline(time,temp_plot(:,11),time); plot(time,temp_plot(:,11),'-b','LineWidth',1); hold on; end

```
%Matlab program of Soft-sensor project
%D:\bh\matlab\soft sensor\heat2
%Author : Hou, Bengiang
%Date :March 20,2001 update:Janauary 2003
۶
%To develop a numerical finite-difference formulation
%for unsteady conduction heat transfer across a sheet solid
%with energy generation, the system is divided into designed
%subvolume.The heat-transfer rates are specified by unsteady
%Finite-difference approximations for the Fourier law of conduction
%based on an energy balance equation.
% initialize the normal model parameters
clear all;
global l
              %the sheet thickness
global layer
              %total number of nodes uesd in simulation
global k
              %thermal conductivity (w/m.k)
global alpha
              %thermal diffisivity
global cp
              %heat capacity
global sigma
             %stephan_boltzman constant;
              %view factor
global view
global absorp
              %absorptivity of the materials
global T_h
              %heater element temperature
```

```
% try a GUI solution
%prompt = {'Please input sheet thickness:
            %,'please input the grid/layer size: '
            %,'please input thermal conductivity:
                                                    1
            %, 'please input thermal diffusivity: '};
%title
         = 'Input for thermoforming centerline temperature predicting
program';
%lines= 1;
def = \{ 1.2', 12', 50', 0.0005' \};
%answer = inputdlg(prompt,title,lines,def);
%input for geometric parameters;
1=1.2;
%1 = input('please input the sheet thickness (1.2cm): ');
%input for grid size;
layer=12;
%layer=input('please input the grid/layer size (12): ');
%input for properties;
k=50;
%k=input('please input thermal conductivity (50 w/m*k): ');
alpha=0.0005;
%alpha=input('please input thermal diffusivity (0.0005): ');
T h=280;
absorp=0.9;
view=0.9;
sigam=5.67*10^-8;
%input infrared senser measurement as boundary condition
m_tb1=[73,96,111,119,124,126,128,129,130,131,132,133,133,134,135,135,135,13
6];
m_tbm=[61,83,95,103,107,110,111,112,114,114,115,116,116,117,117,117,118,118
];
tini=21;
```

%input for initial conditions

```
for e=1:1:layer-1
  sheet_temp(1,e)=tini;
  end
  %apply boundary condition
  t_siz=size(m_tb1,2);
  for q=1:1:t siz
  tb1=m_tb1(q);
  tbm=m_tbm(q);
 dx=1/(layer-1);
  sheet_temp(1,1)=tb1;
 sheet_temp(1,layer)=tbm;
 %begin unstead solution with tou=1
 tau=1;
 %inputs for time increment
 s=alpha*tau/dx^2;
 %input time span
 while tau<250
 %calcilate future nodal temperation temp(j,2)
               for j=2:1:layer-1
 %q_abs=(1-absorp)*sigma*view*emiss*(T_h^4-T_s^4)*exp(-k*j*dx);
               sheet_temp(tau+1,j) = (sheet_temp(tau,j+1) + sheet_temp(tau,j-1)) * s + (1 - 1) + sheet_temp(tau,j-1) * s + (1 - 1) + sheet_temp(tau,j-1)) * s + (1 - 1) + s + (1
2*s)*sheet_temp(tau,j);
               end
               tau=tau+1;
               sheet_temp(tau, 1) =tb1;
               sheet_temp(tau,layer)=tbm;
end
%update temp_plot matrix
temp_plot(q+1,:)=sheet_temp(tau,:);
sheet_temp(1,:)=sheet_temp(tau,:);
end
%initialize frist row
temp_plot(1,:)=21;
%calculating time matrix and thickness matrix
for q=2:1:t_siz+1
```

```
time (q) =250* (q-1);
end
w= [0:layer-1];
thickness=dx*w;
%plot spline from temp_plot matrix
siz=size(temp_plot,1);
for p=1:1:siz
temper=temp_plot(p,:);
temspline=spline(thickness,temper,thickness);
plot(thickness,temper,'*',thickness,temspline,'-b','LineWidth',1);
hold on;
grid on;
end
```