Temperature Assessment of Heating Stage for a Thermoforming Equipment

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Abstract. Thermoforming is a well-known manufacturing process in the productions of various plastic household and industrial solutions. The heating of a plastic sheet allows the plastic to soften and within its forming window temperature the sheet can replicate a required shape when pressed against a mould. Hence, the heating process is an important thermoforming stage that determine uniformity of the material distribution. This article proposed an experimental approach to investigate the thermal characteristics of the heating section of a low cost thermoforming equipment designed for teaching and research purposes. The temperatures of air and a model of a stretched heated plastic sheet were measured and analysed. The experimental data indicates that the spatial temperatures distribution was not localised and the temperature history of the infrared heating agrees well with those given by fast response thermocouples. The findings suggest that the spatial uniformity of temperature can be reasonably evaluated by using the proposed method.

1. Introduction

In thermoforming, a thermoplastic sheet is heated to a pliable condition at a suitable forming temperature. In order to replicate the shape of the mould, the sheet is then stretched onto a mould with positive or negative air pressure. The area in which the heated sheet first contacts retains as the thickest area and decreases throughout the walls of the mould. As a result, thickness variation in the thermoformed part are developed.

Thermoforming, aside from efficient, is also a cost-effective manufacturing process that produces flexible, strong and durable parts. Massive and light-weight parts can easily be formed economically by thermoforming. Low tooling costs, the ease of creating aesthetically desirable finishes, rapid productions, and the fast adaptation to the market, are some of the useful properties that makes thermoforming one of the fastest growing production in the plastics industry.

There have been several studies in the literature reporting on the factors that affect the wall thickness distribution of thermoformed parts. Poller and Michaeli (1992) investigated the effects of plug and film temperatures on the wall thickness distribution [1]. They indicated that plug and film temperatures are the major attributing parameters on wall thickness distribution when a plug-assist thermoforming method is used. Meanwhile, Ayhan and Zhang, (2000) carried out a study on the effects of process parameters such as forming temperature, forming air pressure and heating time on wall thickness distribution in plug-assist thermoformed food containers using multi-layered material [2]. They discovered that the forming temperature of the plastic sheet attributes the most in the wall thickness distribution of food containers. Apart from forming temperature, Erdogan and Eksi (2014) showed that the geometry of clamping rings affected the most in the wall thickness distributions of thermoformed parts [3]. As to this, to produce thermoformed parts with uniform wall thickness distribution, not only the forming temperature is a crucial factor, but the geometry of the clamping ring also attributes in the wall thickness distribution of the thermoformed part.

Thermoforming advantages in low manufacturing cost and efficiency, but the key drawback is difficult to control the thickness of the final part [4]. The temperature distribution after preheating process affects to the thickness of the final products [5]. An early research found that many researchers applied the infrared heaters to the preheating process of thermoforming to decrease the temperature differences between the surface and the centre of the plastic sheet [6]. Ren et al. (2010) conducted a study on a method of decreasing the preheating time under the condition of satisfying temperature for forming window. In their study, they found that the preheating time cannot be decreased unconditionally as it can affect the quality of the part. As to that, according to their study, the results revealed that the decrease in preheating temperature leads to an increase in temperature difference between the surface and the centre of the plastic sheet, thus developing non-uniformity in terms of temperature distribution in the plastic sheet.

The material distribution of the thermoformed part is highly dependent on the initial temperature distribution of the thermoplastic prior to forming. This is because, a uniform temperature distribution of thermoplastic sheet allows the sheet to be formed uniformly as the condition of the sheet is the same, while oppositely if varied. In any thermoforming process, the fundamental objective should be the attainment of uniform temperature throughout the sheet surface and across the sheet [5].

Temperature uniformity analysis in plastic manufacturing affects in the final products. Athanasopoulos et al, (2013) proposed the usage of thermocouples as temperature sensors to measure the temperature distribution on a mould of a manufacturing process. The thermocouples were placed on a flat surface of the mould and the temperature was measured [7]. Thermocouples are also used in the temperature measurements of mould in injection moulding process [8]. In another work, thermocouples are used in the temperature measurements of polymer sheets that were stretched at thermoforming temperatures [9]. These studies shows that thermocouples are able to withstand high temperatures which is suitable for measuring elevated temperatures such as in thermoforming.

2. Experimental Setup

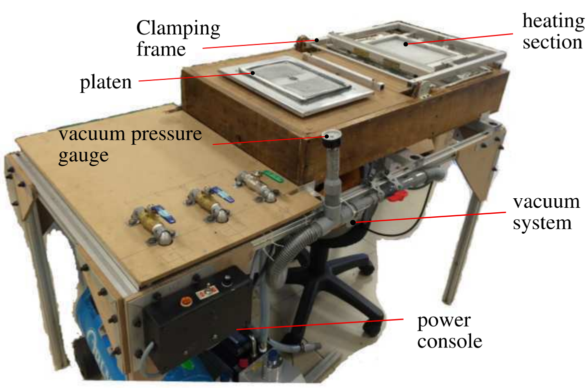


Figure 1. Assembly of Hobby-Vac 12X18 model as specific purpose built thermoforming equipment.

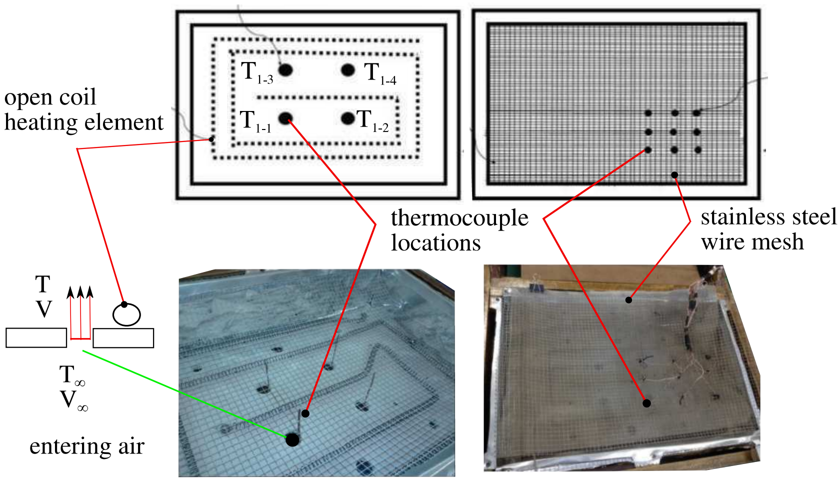


Figure 2. Schematics and physical arrangement of thermocouples for full- and quarter-configurations experimental setup.

The experimental facility as shown in Figure 1 comprises a Hobby-Vac 12X18 vacuum forming machine and a low vacuum pressure system, both alternately powered by a 240V 13A 50 Hz single phase AC power supply. At the time this article is written, the equipment incorporates an analoque vacuum pressure gage with a computer controlled and data acquisition system.

Three experimental configurations were designed to analyse the temperature response during the heating stage in thermoforming process. The first setup referred to as the full-configuration is constructed by using four different type-T fast response thermocouples from Omega Engineering Inc. Each thermocouple was projected to a height from the open coil heating element through an orifice fitted to a ceramic bed . The arrangement of the thermocouples is symmetric from the center plane of the heating section and to accommodate the working area of the plastic heating. Figure 2 (a) shows schematic representation of natural convection of air through the orifices during the heating stage. The plan view and pictorial image of the full-configuration are shown in Figure2(b). The figure also shows the coil layout over the ceramic bed. For convenience, the numbering of thermocouple is given to identify the number of sensor being used and its quadrant. For example T_{1-1} correspond to first sensor in the quadrant 1. Temperature values was acquired during heating and cooling for a prescribed amount of time, τ of 2000 s.

The second setup referred to as the quadrant-configuration was constructed by using nine different thermocouples. Each thermocouple was attached to a stainless steel mesh in the 3rd quadrant at a typical heating plane. The thermocouples were fitted to the mesh in 3 by 3 arrangement to accommodate better spatial resolution of measurement than the full-configuration setup. Figure 2 (b) shows the plan view and pictorial image of the quadrant-configuration setup for thermocouple arrangements. For convenience, the numbering of each thermocouple was given to identify its row and column position relative to the center of heating plane. The T_{11} located at the center and correspond to first sensor in the 3rd quadrant. Three different types of commercial grade thermocouples from RS components were used; type T, K and N. Temperature values was acquired during heating for a prescribed amount of time, τ of 2000 s.

The third setup referred to as the full-plate-configuration was constructed by using nine different thermocouples fitted to a model of blank material. The instrumented aluminium plate

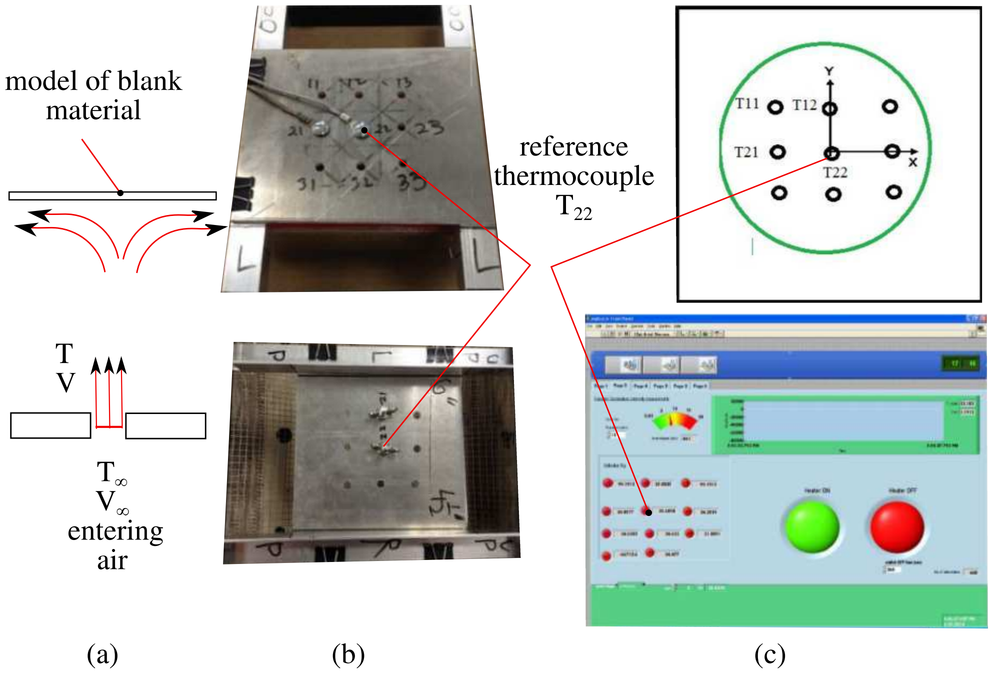


Figure 3. Physical and monitoring arrangement for full plate-configuration experimental setup.

was clamped and positioned to cover the working area at a typical heating plane. Nine holes were drilled and the thermocouple junction were bolted temporarily to the plate. The thermocouples were placed in 3 by 3 arrangement to accommodate better spatial resolution of measurement than the full-configuration setup. Figure 3 (a) shows schematic representation of natural convection of air through the orifices during the heating stage. The plan and bottom views of thermocouple locations are shown in the pictorial image of Figure3(b). For convenience, the numbering of each thermocouple was given to identify its row and column position relative to the center of heating plane. The T_{22} located at the center of working area and was used as the reference temperature. Only type-K thermocouple were used in the experiment. The daily room temperature T_∞ varies between 10 to 15 ^{o}C and was measured using a type-K thermocouple. However the temperature was virtually constant throughout the experiments.

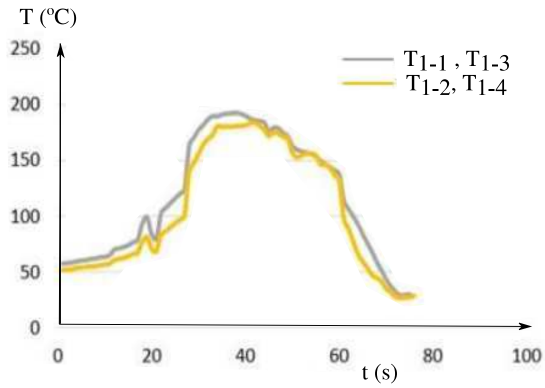
A specific purposed built graphical user interface shown in Figure 3 (c) was also designed using LabVIEW for heating performance calibration of quadrant- and full-plate configurations. All thermocouples during the experimental setup were connected to a signal conditioning block of a Data Acquisition device (DAQ) for monitoring purposes.

3. Results and Discussion

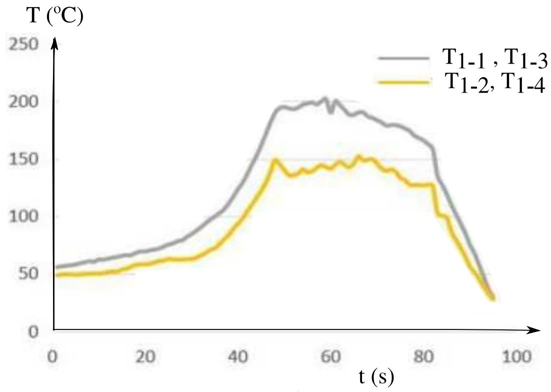
Figure 4 (a) and (b) shows the temperature history in the full-configuration setup to simulate the conditions at which the air temperature is not affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection over a blank sheet.

It is shown that the temperature in the quadrant 1 and 3 given by T_{1-1} and T_{1-3} respectively are virtually equal and higher than T_{1-2} and T_{1-4}. However the difference of measured values are relatively smaller during the cooling stage. It is expected as more net radiation heat transfer was produced by the pole of heating element which is closer to the location of T_{1-1} and T_{1-3}.

In heating the actual thermoplastic sheet for sagging experiment not reported in the present article, the sag geometry and material thickness distribution indicated that the plastic received more heat energy in these area.



(a)



(b)

Figure 4. Temperature histories for full-configuration experiment. using fast response type-T thermocouples

Figure 5 (a) and (b) shows the temperature history and growth respectively in the full-plate-configuration setup to simulate the conditions at which the air temperature is affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection in the presence of blank sheet. The measured temperatures on the bottom surface of the instrumented plate are transient and virtually increase exponentially. Visual inspection for comparison with Figure 4 shows that the commercial grade thermocouple has greater thermal inertia and provide much greater uncertainty in the actual surface temperature of the heated plated. Figure 5(b) shows that the uniformity of temperature distribution in the working are virtually takes around one minute if the heating begin when the air temperature between 20 to 50 ^{o}C. High starting temperature shown in the figure implies that the experiment was carried out at the end of a cooling experiment.

Figure 6 shows the temperature histories in the quadrant-configuration setup to simulate the conditions at which the air temperature is not affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection over a blank sheet. Figure 6 (a) compare the spatial distribution of measured temperature using commercial grade gas thermocouple at two different time stamp to indicate the effects of daily room temperature, T_∞. It is shown that T_∞ has weak influence on the temperature variation across the working area compare to the measured temperature rise. Visual inspection for comparison with Figure 4 shows that the thermal and geometrical properties of thermocouple junction are important to determine the actual air temperature. However, not much variaton can be seen between magnitude and characteristics of air temperature between full-plate and quadrant–configurations experiments given in Figure 5(a). Figure 6 (b) shows that the temperature rise is less than 10% at the end of after 500 seconds of heating.

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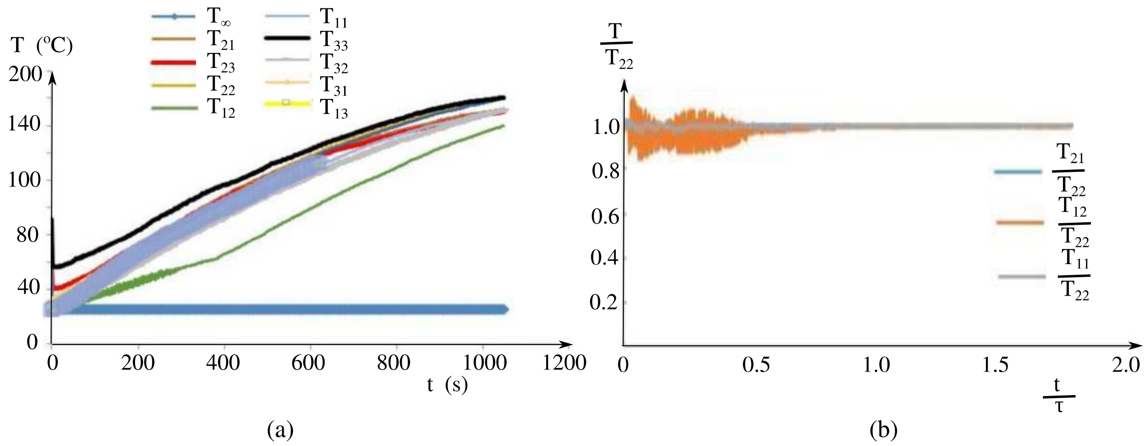

Figure 5. Temperature histories for full-plate-configuration experiment. using commercial grade thermocouples

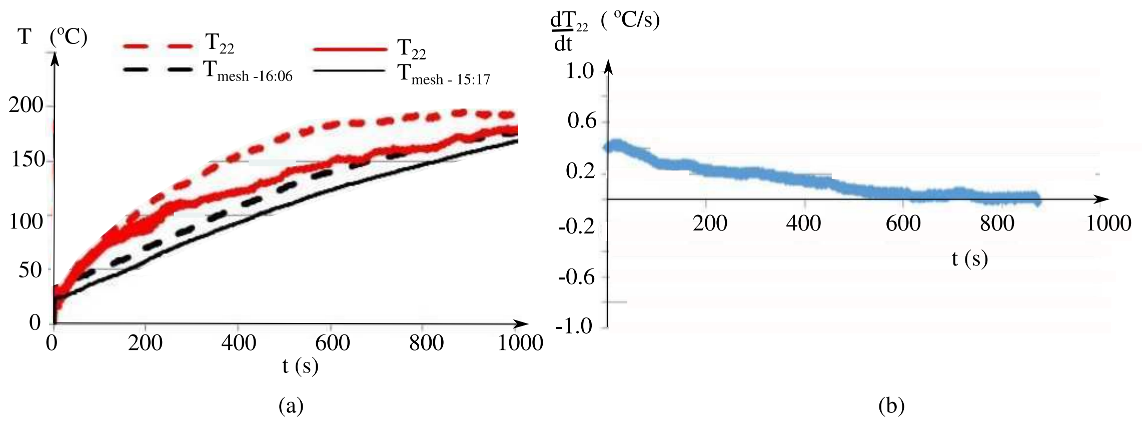

Figure 6. Temperature measurement on mesh profile using aluminium plate.

4. Conclusions

Thermoforming process requires a significant measurement in the heating stage to determine uniform temperature distribution of the plastic sheet. In order to obtain this, a method in measuring the temperature of plastic sheet to determine the uniformity of temperature was carried out. Several thermocouples were used to measure the temperature of the plastic sheet during the heating stage in which an aluminium plate was used to substitute the plastic sheet. The alumium plate was used instead of a plastic sheet in order to allow precise position of the thermocouples and in addition to enable a longer life span of material which does not melt when heated at a high temperature.

During temperature measurement the heating element, the temperature distribution on plastic sheet during heating stage in thermoforming affects the quality of the thermoformed part in terms of material distributions. This affects the temperature measured between the centre of the mesh profile and on locations appointed on the mesh whereby an insignificant difference between the two points and that the temperature is assumed to be uniform across the mesh profile.The gradient decreased gradually and remained constant at a maximum temperature. The data shows that the heater will continue to heat until it exceeds a maximum temperature and remains constant. Therefore, the findings suggest that the uniformity in temperature of the plastic sheet is able to be measured by using this method.

A development in the temperature measurement of plastic sheet in using other practical methods are to be experimented. The use of sensors to detect the temperature would be a great improvement rather than manually monitoring the temperature readings using grahical user interface.

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