International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

Thermal Analysis of The Heating Stage of the Thermoforming Process

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Abstract: Thermoforming is one of the most utilized polymer processing technique, where heated sheet polymer sheets are transformed into useful products. These sheets are usually deformed at a temperature higher than the glass transition temperature of the polymer sheet. The physical and mechanical properties of the sheet change significantly at this temperature. Therefore, forming temperature is the key parameter governing the process output, and by monitoring it, process parameter can be decided for higher quality output and minimum rejections. Temperature monitoring usually carried out using sensors and thermal imaging system, which demands open access of the surfaces to be monitor. In the case of closed forming setups use temperature, monitoring devices are favorable. In order to cope with the mentioned scenario present study proposed to use finite element analysis for temperature monitoring. The objective of the present study is to investigate the heating stage of the thermoforming process for Poly methyl methacrylate (PMMA) sheet just prior to deformation carried out in close forming setup. Numerical studies were performed to study the temperature distribution across the sheet during its heating. In order to validate the proposed numerical model, experimental investigations were carried out, and good agreement was found between simulated and experimental result. The results obtained from the present study could be useful to determine the required process parameters such as deformation pressure. Moreover, the heating stage could be optimized to reduce energy consumption and cycle time.

***KEYWORDS: PMMA, Thermoforming,* Transient Thermal Analysis, Finite element analysis.**

I. INTRODUCTION

Polymers are highly utilized material, used by mankind since decades. Polymers are light in weight, high strength, corrosion resistant, and highly transparent, which makes them suitable for numerous applications. Automobile parts, medical devices, industrial applications, and aviation are the major area of polymer applications. Polymers are used in raw and processed form. Various methods are used to process the raw polymers into a useful product such as blow molding, compression molding, and thermoforming. Among all stated methods, a huge amount of products were produced by thermoforming process due to the ease of processing and low cost of production. The thermoforming process is a secondary forming process, in which the readily available polymer sheets are heated at a particular temperature where the sheet is transformed from solid state to a pliable, flexible sheet. The temperature where the sheet is deformed into the desired shape is called the forming temperature, which is higher than the glass transition temperature of the polymer sheet being processed. Depending upon the mode of deformation, the thermoforming process is divided into three types, viz. pressure forming, vacuum forming, and contact forming [1]. In pressure forming, the differential pressure is created on the top sheet, and because of this, the sheet gets deform. In vacuum forming, a vacuum is created beneath of the sheet surface for deformation, while in contact forming, the sheet is deformed in required shape with the help of punch movement inside the die cavity.

The thermoforming process starts with the heating of the polymer sheet above the glass transition temperature and ends with the cooling of the transformed polymer sheet to room temperature or temperature below from glass transition temperature. Due to higher energy consumption during sheet heating, investigation of the heating stage has gained importance in the past decades. Moreover, polymer properties are highly temperature dependent. With the change in temperature, especially above glass temperature, the mechanical response of the polymer material changes drastically [2]. The above reasons motivated the researchers to investigate the heating stage of such a process, in order to optimize it for minimum energy consumption and also to find out the optimum processing parameters.

In order to investigate the process, the researcher has used experimental as well as numerical techniques. The temperature dependent material response was investigated by the researchers. DMTA (Dynamic mechanical thermal analysis), uniaxial test, and drop weight impact were the some the mechanical characterization technique used by researchers to investigate the mechanical response of the material. Dong et al. [3] used DMTA and observed that the glass transition temperature of the polymer and investigate mechanical behavior at different temperature by performing uniaxial tests. The prime objective of the investigation was to generate required material data for realistic simulation. Whereas Liu et al. [4]

Revised Manuscript Received on 30 July 2019.
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conducted impact tests at low-velocity and different temperatures to investigate the mechanical response of cast acrylic plates. Effect of type of loading on the mechanical behavior of PMMA/MWCNT composites was investigated by Jindal et al. [5]. Static, as well as dynamic mechanical behavior, was investigated. Effect of temperature on the dynamic behavior of PMAA was investigated by Suo et al. [6]. In their study, the mechanical behavior under varying temperature (299K, 313K, 333K, 353K, and 373K) and strain rates (550 s^{-1}, 0.1 $s^{-1}$and 0.001 s^{-1}) were studied experimentally, and theoretically using ZWT material model. Experiments were conducted (quasi-statically) on an axial testing machine (compression), and dynamically on Split Hopkinson pressure bar. It was found that for a constant strain rate, the flow stress decreases with the increase in temperature, whereas for a fixed temperature with the increase in strain rate an increase in the flow stress was observed. McCool et al. [7] investigated the effect of different process parameter on the thickness distribution of the product. Sheet temperature, plug temperature, plug speed, plug displacement, air pressure, and plug shape were chosen parameters in their study. It was observed that the plug displacement, sheet temperature, plug temperature, and plug shape have a significant effect on thickness distribution of the final product, whereas plug speed and air pressure have a negligible effect on product thickness variation.

In the case of thin products, temperature distribution across the thickness is nearly uniform during the heating process, which is not the same for the thick sheet products. In the case of the thick sheet products, the temperature distribution along the thickness is not-uniform, and special care should be taken. Labeas et al. [8] used FEM (Finite element method) to simulate the heating stage of a diaphragm thermoforming of carbon/polyethylenimine (PEI) sheets to calculate the sheet temperature distribution. Different parameters such as plate thickness, number of lamps, heating time were investigated to optimize the heating stage to achieve an isothermal state for the sheet. Later, a different type of infrared heat source was investigated by Schmidt et al. [9]. They have compared the efficiency of the short-wave infrared heater with medium range and long-wave emitter heater. It was observed from the experimental observations that the short-wave emitter has the highest efficiency for heating a thermoforming of PS sheet

Heat transfer during the deformation of polymer sheet into the final product was addressed by the researchers, Choo et al. [10] investigated the amount of heat transfer between forming setup (die, clamping arrangement and punch) and the sheet. The experimental setup was built to determining the thermal contact conductance between mating surfaces. Aus Der Wiesche [11] simulated the thermoforming process used to produce an automobile fuel tank. They have predicted the wall thickness distribution of the automobile fuel tank by incorporating both the structural and thermal aspect in the numerical simulation. Furthermore, the effect of temperature-dependent thermophysical properties on the process was addressed. All three stages of thermoforming were simulated, and it was observed that the thermal aspect of the process should be incorporated for realistic results. Wang et al. [12] used temperature-dependent material properties for investigation of sheet heating. The inverse approach was used in their study, for the prediction of the initial temperature distribution of Acrylonitrile butadiene styrene (ABS) raw sheet. FEM, in conjunction with an optimization procedure, used to predict the optimum initial temperature distribution of the raw sheet. It was observed that the nonlinear behavior of the material is an important parameter for thickness prediction. From the literature review, it can be noted that polymer material behavior is highly temperature dependent and forming temperature is one of the key parameters determining the final output of the process (thickness distribution of the formed product). Therefore, in order to achieve the desired product quality with a minimum cost of production, the temperature of the polymer sheet prior to deformation must be predicted. Present work aims to investigate the heating stage of the pressure thermoforming process in order to predict sheet temperature with the help of numerical simulations.

II. NUMERICAL MODEL (HEATING STAGE)

The thermoforming process begins with heating of polymer sheet; sheet is heated to a temperature higher than the glass transition temperature of the polymer. About 60-70 % of energy is consumed during sheet heating, which should be optimized for higher efficiency. Three types of heating methods are mostly used by the manufacturer to bring the sheet to a formable state. Hot air is circulated around the sheet and because of convective heat transfer sheet gets heated. In the second type, sheets are allowed to make contact with the heated surface, which heats up the polymer sheet due to conduction. In the third type, thermal radiation is bombarded on the sheet surface, and by absorbing it, the sheet gets heated [13]. Among all heating source, it was found that heating of polymer sheet using radiative heaters is the most efficient heating source [14]. For the present study, a muffle furnace was used as a heat source. Figure 1 shows the geometric model of heating of the pressure thermoforming process. Where forming setup is placed inside the heating cavity of the furnace and to avoid direct contact with furnace wall an insulating material is placed between the furnace wall and the bottom surface the of the forming setup. Heating of forming setup takes place due to the mixed type of heat transfer phenomenon, viz. radiant heating by the furnace walls, convective heating by hot air trapped inside the heating zone and direct heat transfer from the bottom the furnace wall through the insulating material. As heat transfer progresses, heated forming setup heats up the sheet by conduction and radiation. Therefore, in order to simulate the heating stage, all mode of heat transfer must be incorporated into the numerical model. A transient heating simulation of forming setup was carried out from room temperature to forming temperature of the sheet. Simulations were performed using a commercial finite element code ANSYS.

2.1. Geometric model and discretization

The geometric model for heating stage simulation is consists of the furnace walls and closed forming setup.

The forming setup comprises of the raw sheet, die, and clamping plate. In order to avoid direct contact with the bottom surface of the heating zone, a wooden plate is placed between the bottom surface and die surface. Forming setup placement is such that only half geometric model is symmetric, hence for numerical ease, the numerical domain is symmetric in nature. Figure 1 shows the considered geometric model for the heating stage. The geometric model was built using CATIA V5 CAD modeler. Required dimensions of muffle furnace heating zone and forming setup were taken from actual setups. The furnace has a heating volume of 200 × 200 × 900 mm^3, whereas pressure forming setup is cylindrical, having 200 mm diameter and 100 mm height. Forming setup has a hemispherical die cavity to produce a hemispherical dome of 55 mm dome height from a circular raw sheet of 160 mm diameter and thickness of 5 mm.

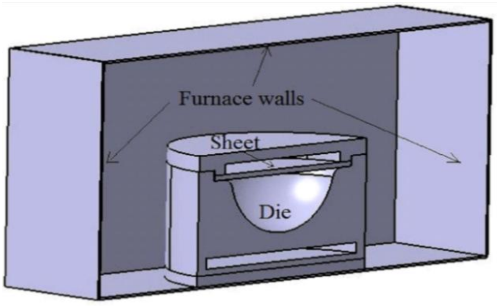


Figure 1: Geometric model.

Discretization of the geometric model was carried out using a three-dimensional, higher order thermal bricks element. In order to limit the numerical error, discretization was carried out carefully. To make a balance between solution accuracy and computational cost mesh sensitivity analysis was carried to it was found that 95678 elements were optimum for present simulation. Figure 2 shows the zoomed view of the discretized geometric model.

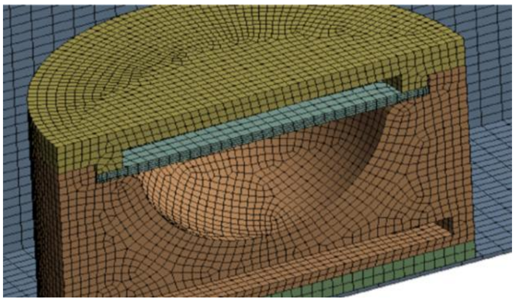
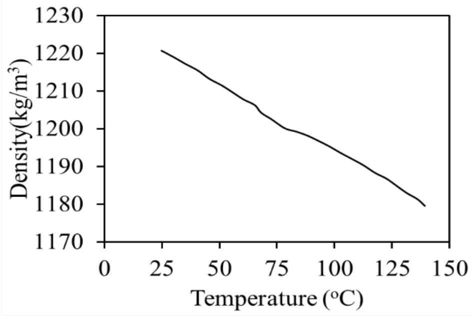


Figure 2: Discretized geometric model.

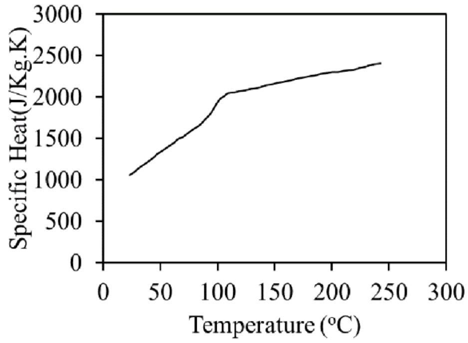
2.2. Material model

Exact material behavior is a key parameter for realistic simulations, and it was found that the accuracy of the simulation depends on the temperature dependency of material properties [11]. Therefore, temperature dependency must be incorporated into material models. As the present numerical study is purely thermal type, only thermophysical properties are required for simulation, which is the density of material (to account transient heat transfer), specific heat and thermal conductivity. Acrylic as sheet material, SS316 is used as a forming setup material. Insulating material like wood was placed between furnace wall and die surface. The main reason behind placing insulating material is to allow maximum heat transfer by radiation. However, from a practical point of view, at higher temperature wood as insulating material should not be used. For the current study, wood properties were used for simulation purposes only. All required material properties (temperature dependent) was taken from available literature and ANSYS material library [15].

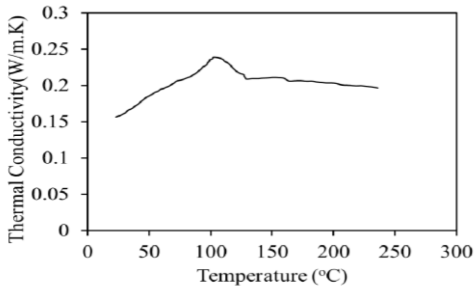
2.2.1. Sheet material properties



(a) Density Vs. Temperature.



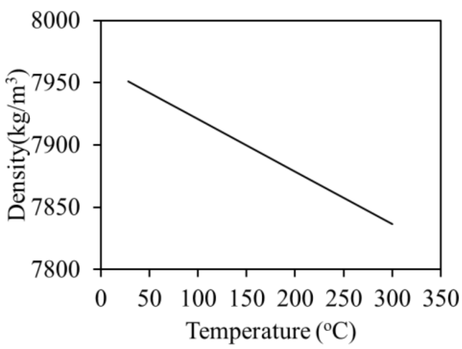
(b) Specific Heat Vs. Temperature.



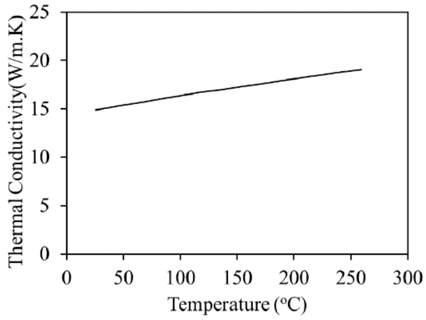
(c) Thermal conductivity Vs. Temperature.

Figure 3: Temperature-dependent thermophysical properties of PMMA [15].

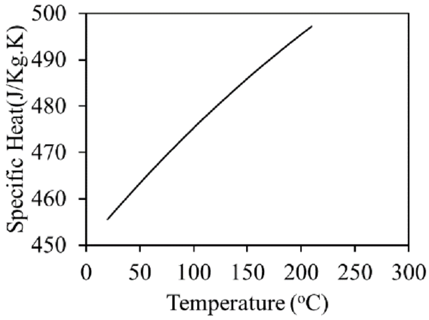
2.2.2. Forming setup Material properties



(a) Density Vs. Temperature.



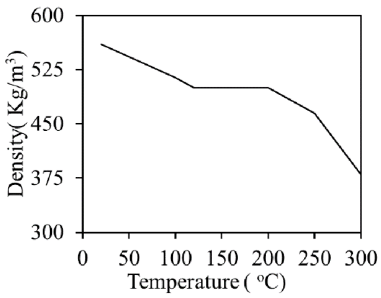
(b) Thermal conductivity Vs. Temperature.



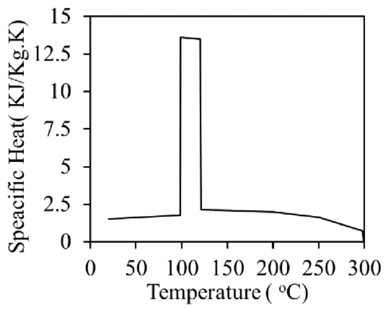
(c) Specific Heat Vs. Temperature.

Figure 4: Temperature-dependent thermophysical properties of SS316[16].

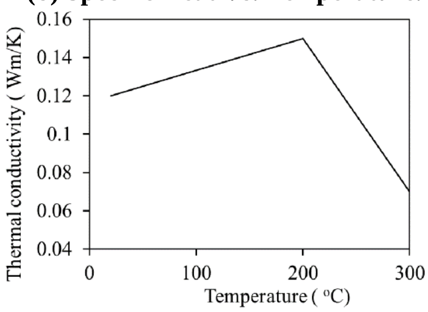
2.2.3. Wood material properties



(a) Density Vs. Temperature.



(b) Specific Heat Vs. Temperature.



(c) Thermal conductivity Vs. Temperature.

Figure 5: Temperature dependent thermophysical properties of wood[17].

2.3. Boundary conditions

The ability of the numerical model to reproduce a particular phenomenon exactly depends on the type of boundary conditions imposed to solve the numerical model. Therefore, for realistic simulations, realistic boundary conditions must be imposed. For present numerical study, heating of forming setup using the furnace as a heat source is simulated. The considered furnace as a heat source is a muffle furnace which is sophisticated equipment usually used for isolated heating. In case of muffle furnace dominating heat, transfer mode is radiation emitted by the furnace wall inside the heating zone. Heating of furnace walls is mainly because of resistance heaters placed inside the furnace wall. Once a sufficient amount of currents passes, heaters get heat up and start emitting the heat radiation which heats the material inside the heating cavity. For the present study, it was assumed that furnace is maintained at the desired temperature., whereas the heating zone and furnace walls have a temperature of 250 ^{o}C. In order to allow radiative heat transfer among the different components, the emissivity of each surface and surface temperature is imposed on the respective surface (the method used to calculate surface emissivity is described in a subsequent section). Along with dominating radiative heat transfer, the air inside the heating zone also contributes to the heating process. A convective heat transfer coefficient of 10 W/m^{2}K [18] was imposed on respective die surfaces for convective heating. The initial boundary condition of 28 ^{o}C body temperature was imposed on forming setup (sheet, die, clamp, and wooden piece).

2.3.1. Surface emissivity

Most important boundary condition in radiation heat transfer is emissivity of surfaces and their temperature. The emissivity of each surface taking part in radiative heat transfer is determined with the help of a thermal imaging system[19]. In order to measure surface emissivity, first of all, the surface was cleaned and marked with thermal black paint having know emissivity of 0.90. In order to determine the emissivity of the surface at a known temperature, the first thermal camera is focused on region marked with black paint and emissivity in the thermal camera is manually set to 0.9. Later, the focus of the thermal camera is slightly shifted away from the marked area, and emissivity is changed until the surface will show the known temperature. For the present study, it was observed the variation in the emissivity with temperature is negligible and emissivity measured at 100 ^{o}C is imposed on respective surfaces. The measured emissivity of the different surfaces was tabulated in table 1.

Table 1. Emissivity of Components.

Component	**Emissivity**
Aluminum block	0.15
Die surfaces	0.4
Furnace wall	0.93
Acrylic sheet	0.9

Retrieval Number: B2301078219/19©BEIESP
DOI: 10.35940/ijrte.B2301.078219
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III. NUMERICAL PROCEDURE

A transient heating simulation of pressure forming setup was carried out into two steps to represent the actual heating stage. In actual practice, forming setup is placed inside the pre-heated furnace, a similar approach is followed in simulation. In the first step, simulation is stared with initial conditions of forming setup where the furnace wall is at 250 ^{o}C, and setup is at 28 ^{o}C. As simulation progress heat transfer takes place among the different component and forming setup start heating, which later heats up the sheet clamped on the die cavity.

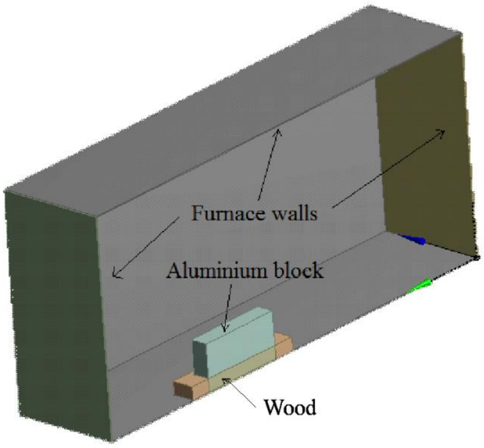
In actual practice, after a sufficient amount of heating, the power supply of the furnace is switched off which stop the future heating of the forming setup by the furnace walls. To simulate a similar kind of effect, radiative and convective heating of the die surface is neglected in the second step of the simulation. Where heating of the sheet is mainly due to the thermal mass of the forming setup, heating of the sheet is due to the thermal energy stored by die. With the time progression, stored energy transfers into the sheet by the conduction and radiation among the internal surface of the die and sheet surface.

IV. VALIDATION OF THE NUMERICAL MODEL

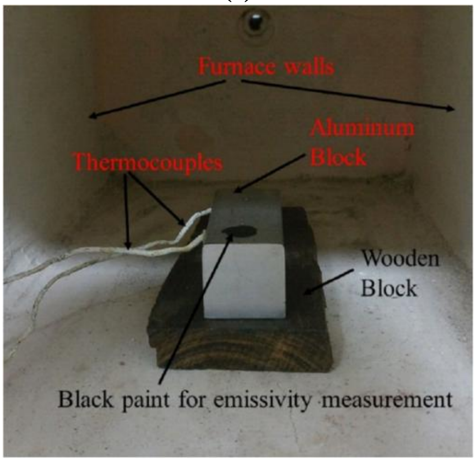
In order to validate the proposed numerical model, experiment of heating aluminum block inside the muffle furnace (maintained at 250 ^{o}C) was conducted. The aluminum block has of dimension 31×31×82 mm^3 and was placed inside the furnace on a wooden block, as shown in figure 6(a). For a longer heating time, instead of wood other insulating material such as thermal brick is recommended. In the present study, a wooden block serves the purpose without any degradation. For temperature measurement, during the heating of the aluminum block, thermocouples were used. For accurate measurement of temperature, two thermocouples were attached through a drill hole, as shown in figure 6(b). During heating, temperature data were recorded with a one-minute interval. In order to simulate the process, above mentioned boundary conditions were imposed along with material properties taken from ANSYS material library. Figure 7 shows the thermal history of the aluminum block during heating, where solid line is thermal data obtained from numerical simulation, and the dotted line is averaged experimentally measured temperature. It can be noted that the numerically obtained temperature is in good agreement with experimentally measured temperature. Thus, the imposed boundary conditions can be used to simulate the heating of the pressure thermoforming setup.

V. RESULT AND DISCUSSION

Heating stage of the thermoforming process was simulated with the required material properties and boundary condition. Heating process was simulated for 7200 seconds, to heat the forming setup from 28^{o} C to 250^{o} C. As mentioned above, furnace heating was captured using a two-step analysis. In the first step, the furnace wall heats the die surface, which ultimately heats the sheet. In the penultimate step, heat transfer will happen because of pure conduction and radiation within the forming setup.



(a)



(b)

Figure 6: (a) Geometric model of heating of aluminum block, (b) Experimental heating setup.

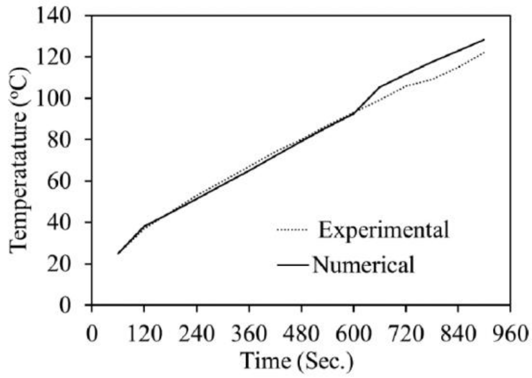


Figure 7: Change in temperature of aluminum block throughout heating.

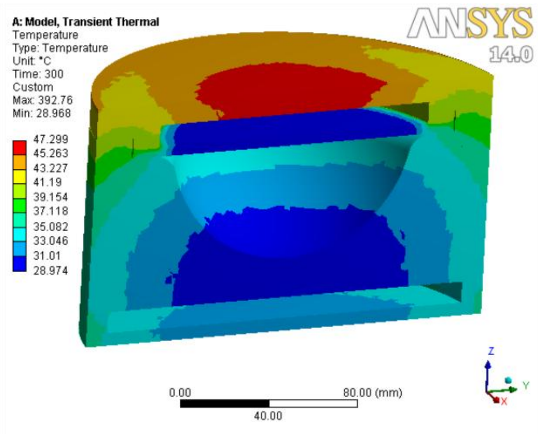
5.1. First step

Figure 8 shows the thermal history of the thermoforming setup during the first step of the simulation. At the beginning of heating, very less amount of heat was transferred from furnace walls and die surface. This can be noted in figure 8(a) where temperature rise of die setup is very small, and the sheet has a maximum temperature at the outer edge. The die surface heats up rapidly, which is closer to the furnace wall, which further heat up the sheet region
heat to the furnace wall.

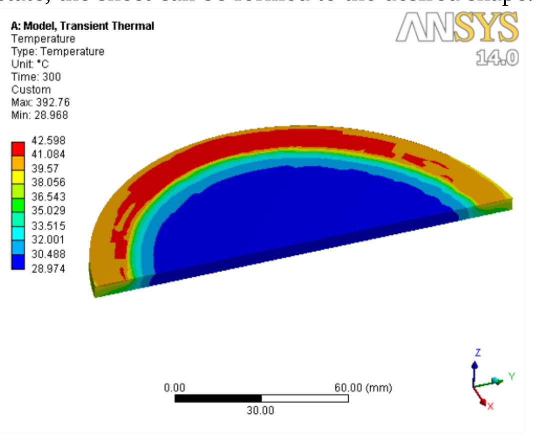
With an increase in heating time, more amount of heat energy was absorbed by the die and sheet. Heat is transferred in the radial direction, which can be observed in figure 8(b). At the end of heating time, the maximum amount of energy had transferred from furnace walls to the sheet. However, it can be noted that the sheet has a non-uniform temperature distribution. Clamped sheet region has a maximum temperature, whereas the central sheet region was at the lowest temperature.

5.2. Second step

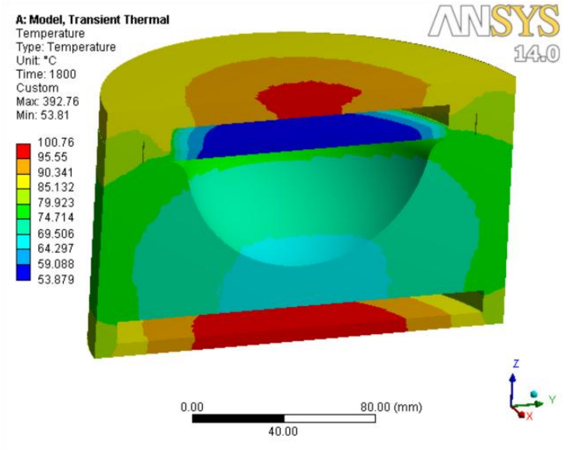
In the second step, heating by the furnace walls was stopped, and the heat was transferred from hotter die region to the sheet. As heat transfer progress, there was a decrease in die temperature, and the sheet tends to achieve an isothermal state. For the present study, the desired thermal state of the sheet is when the sheet temperature variation is less than 5°C, which can be observed in Figure 9. After 7200 seconds the average sheet temperature is 133.45°C, which is more than the glass transition temperature (120 °C) of acrylic sheet. At this state, the sheet can be formed to the desired shape.



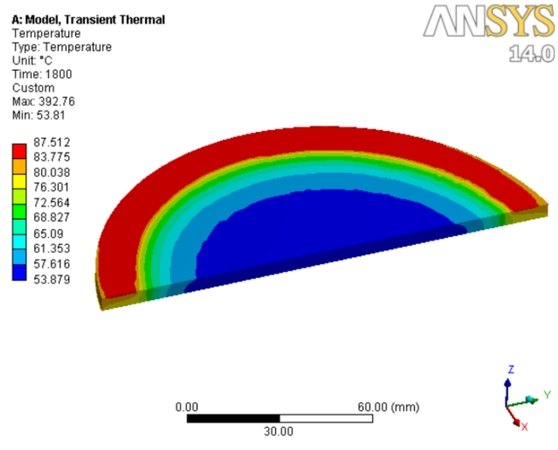
(a) Temperature distribution of setup at 300 sec.



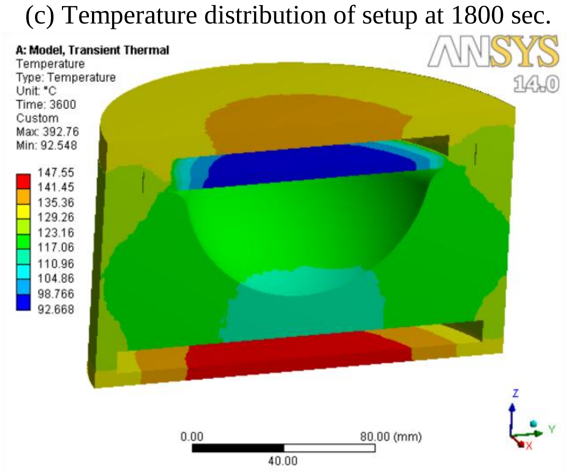
(b) Temperature distribution of sheet at 300 sec.



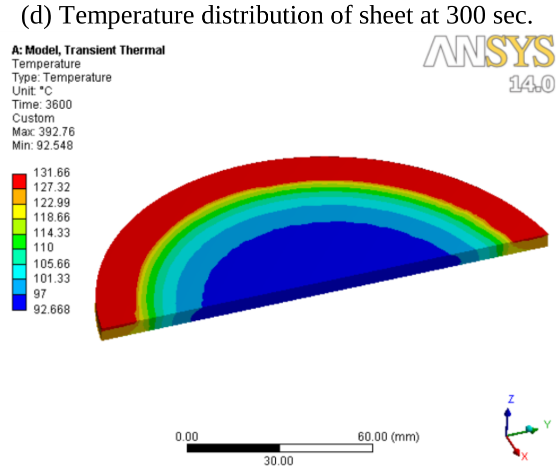
(c) Temperature distribution of setup at 1800 sec.



(d) Temperature distribution of sheet at 300 sec.

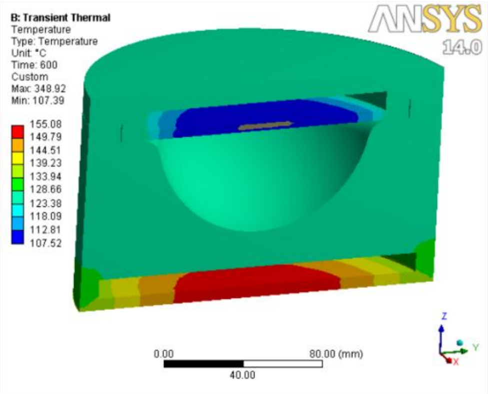


(e) Temperature distribution of setup at 3600 sec.

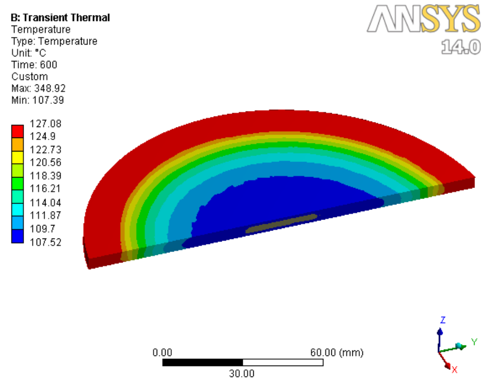


(f) Temperature distribution of sheet at 3600 sec.

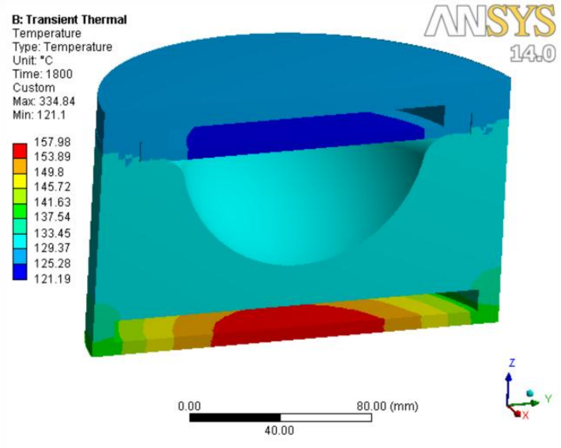
Figure 8: Thermal history of forming setup during the first step.



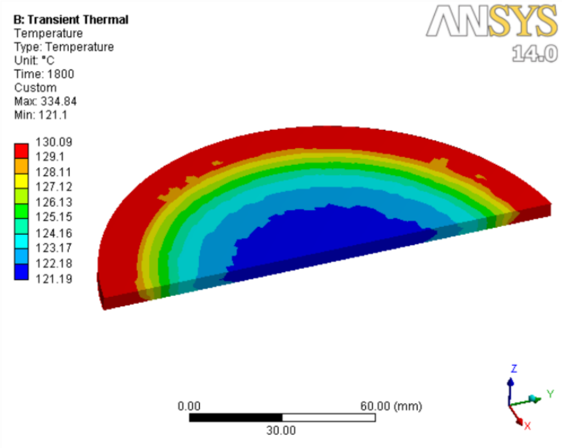
(a) Temperature distribution of setup at 600 sec.



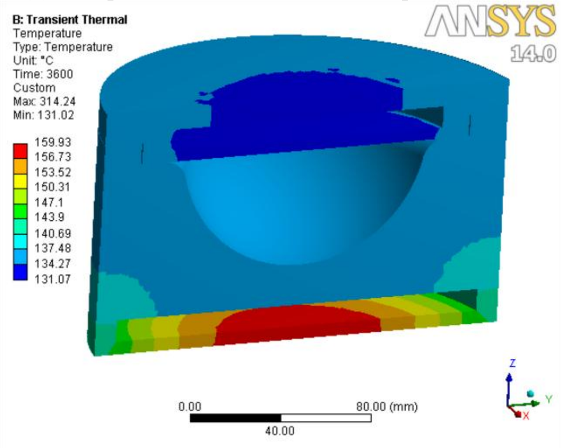
(b) Temperature distribution of sheet at 600 sec.



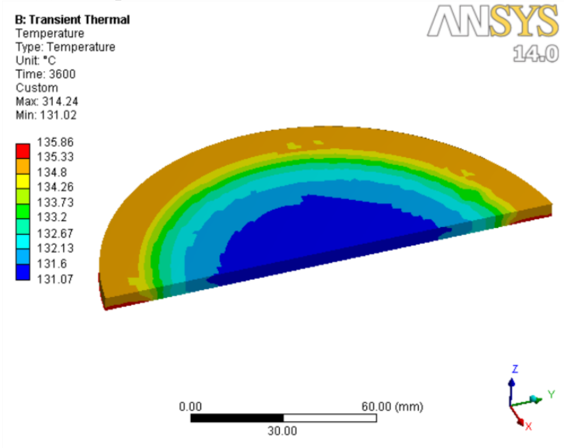
(c) Temperature distribution of setup at 1800 sec.



(d) Temperature distribution of sheet at 300 sec.



(e) Temperature distribution of setup at 3600 sec.



(f) Temperature distribution of sheet at 3600 sec.

Figure 9: Thermal history of forming setup during the second step.

VI. CONCLUSIONS

Numerical investigation of the heating stage of thermoforming has been addressed successfully. It was observed that with proper boundary conditions and discretization criteria, prediction of sheet temperature is possible. Finite element method could be used to predict the sheet temperature, where experimental sheet temperature measurement is not possible. Furthermore, it was observed that radiative heat transfer is highly meshed size dependent and for accurate results, special care should be taken to mesh the surfaces which involved in heat transfer by radiation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest in the presented work.

REFERENCES

1. Throne, JL , Understanding Thermoforming, Carl Hanser Verlag GmbH & Co. KG, 2008. doi:10.3139/9783446418554.fm.
2. Gilormini, P Chevalier, L and Régnier, G , "Thermoforming of a PMMA Transparency near Glass Transition Temperature", Polymer Engineering & Science, Vol. 15,10, pp. 2004–12, 2010.
3. Dong, Y Lin, RJT and Bhattacharyya, D , "Determination of critical material parameters for numerical simulation of acrylic sheet forming", Journal of Materials Science, Vol. 40,2, pp. 399–410, 2005. doi:10.1007/s10853-005-6096-0.
4. Liu, Y and Liaw, B , "Drop-weight impact tests and finite element modeling of cast acrylic plates", Polymer Testing, Vol. 28,6, pp. 599–611, 2009. doi:10.1016/j.polymertesting.2009.04.008.

5. Jindal, P Sain, M and Kumar, N , "Mechanical Characterization of PMMA/MWCNT Composites Under Static and Dynamic Loading Conditions", Materials Today: Proceedings, Vol. 2,4–5, pp. 1364–72, 2015. doi:10.1016/J.MATPR.2015.07.055.
6. Suo, T Li, Y Yu, H Xu, F Tang, Z and Li, L , "Temperature effect on the mechanical behavior of acrylic polymers under quasi-static and dynamic loading", Shanghai Jiaotong Daxue Xuebao/Journal of Shanghai Jiaotong University, Vol. 38, pp. 1–6, 2004.
7. McCool, R and Martin, PJ , "The role of process parameters in determining wall thickness distribution in plug-assisted thermoforming", Polymer Engineering & Science, Vol. 50,10, pp. 1923–34, 2010. doi:10.1002/pen.21718.
8. Labeas, GN Watiti, VB and Katsiropoulos, C V , "Thermomechanical Simulation of Infrared Heating Diaphragm Forming Process for Thermoplastic Parts", Journal of Thermoplastic Composite Materials, Vol. 21,4, pp. 353–70, 2008. doi:10.1177/0892705708089480.
9. Schmidt, FM Le Maoult, Y and Monteix, S , "Modelling of infrared heating of thermoplastic sheet used in thermoforming process", Journal of Materials Processing Technology, Vol. 143–144,1, pp. 225–31, 2003. doi:10.1016/S0924-0136(03)00291-7.
10. Choo, HL Martin, PJ and Harkin-Jones, EMA , "Measurement of heat transfer for thermoforming simulations", International Journal of Material Forming, Vol. 1,SUPPL. 1, pp. 1027–30, 2008. doi:10.1007/s12289-008-0233-7.
11. Aus Der Wiesche, S , "Industrial thermoforming simulation of automotive fuel tanks", Applied Thermal Engineering, Vol. 24,16, pp. 2391–409, 2004. doi:10.1016/j.applthermaleng.2004.03.003.
12. Wang, C-H and Nied, H , "Temperature Optimization for Improved Thickness Control in Thermoforming", Journal of Materials Processing & Manufacturing Science, Vol. 8, pp. 113–26, 1999. doi:10.1106/L8QJ-JG1C-444T-7P1H.
13. Florian, J , Practical Thermoforming: Principles and Applications: Second Edition, Taylor & Francis, 1996.
14. Cunningham, JE Monaghan, PF Brogan, MT and Cassidy, SF , "Modelling of pre-heating of flat panels prior to press forming", Composites Part A: Applied Science and Manufacturing, Vol. 28,1, pp. 17–24, 1997. doi:https://doi.org/10.1016/S1359-835X(96)00089-9.
15. Gunel, EM and Basaran, C , "Damage characterization in non-isothermal stretching of acrylics. Part II: Experimental validation", Mechanics of Materials, Vol. 43,12, pp. 992–1012, 2011. doi:10.1016/j.mechmat.2011.09.003.
16. Institute, A iron and steel , "High Temperature Characteristics of Stainless Steel", . http://www.nickelinstitute.org/~/Media/Files/TechnicalLiterature/High_TemperatureCharacteristicsofStainlessSteel_9004_.pdf (accessed February 9, 2019).
17. Mahmood Tabaddor , "Modeling the Thermal and Structural Behavior of Wood Beams in a Fire Environment", . https://ulfirefightersafety.org/docs/2009_NIST_ARRA_Appendix_E.pdf (accessed February 14, 2019).
18. Kang, GU Chung, BJ and Kim, HJ , "Natural convection heat transfer on a vertical cylinder submerged in fluids having high Prandtl number", International Journal of Heat and Mass Transfer, Vol. 79, pp. 4–11, 2014. doi:10.1016/j.ijheatmasstransfer.2014.07.077.
19. Technologies, K , "How to Measure the Unknown Thermal Emissivity of Objects/Materials Using the U5855A TrueIR Thermal Imager", . https://literature.cdn.keysight.com/litweb/pdf/5992-0222EN.pdf (accessed February 15, 2019).