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A Study on the Thermal Distribution of the Thermoforming Process for Polyphenylene Sulfite (Polyphenylene Sulfide) PPS Composites Towards Out of Autoclave Activity

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ABSTRACT

The thermoforming process is a widely utilized manufacturing technique for shaping thermoplastic materials into various products. Achieving uniform and controlled thermal distribution within the material during thermoforming is crucial to ensure high-quality products and minimize defects. This study investigates and enhances the understanding of thermal distribution in thermoforming processes through simulation analysis before it is done via experiment. This research investigates the thermal distribution in the thermoforming process of Polyphenylene Sulfide composites. The heating element distances were varied during the simulations of the thermoforming process of Polyphenylene Sulfide (PPS) composites, focusing on understanding how different distances affect the material's deformability, dimensional accuracy, and overall quality. Three heater temperatures with three heater distances are tested. The distance between two heated surfaces is 200, 300 and 500 mm for 320°C, 360°C and 400°C heated surfaces. The desired PPS temperature (320°C) and maximum heater temperature (400°C) are parameters. The test result shows that to achieve 320°C thermoplastic temperature, we can use 385°C IR heater temperature with a heater

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distance of 200 mm. However, this 200 mm distance might be too close for the operation, and a larger distance might be needed. Using 300 mm or 500 mm can achieve close to 320°C if the heater temperature is set to 400°C. In conclusion, this value is a reference for the distance of the material between the heater during the fabrication process.

Keywords: Polyphenylene Sulfide composites, thermoforming, thermal distribution

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INTRODUCTION

Thermoforming, a versatile manufacturing process, has gained recognition as a sustainable solution in various industries (Valente et al., 2023). Thermoforming has emerged as an environmentally friendly method for producing plastic and composite products, focusing on resource efficiency, waste reduction, and recyclability. This process involves the transformation of flat thermoplastic sheets into three-dimensional shapes using heat and pressure (Ekşi et al., 2019). Thermoforming has become essential in pursuing sustainability in modern manufacturing practices by optimizing material usage, minimizing energy consumption, and promoting recycling.

One of the key factors contributing to the sustainability of thermoforming is its inherent material efficiency. Unlike other manufacturing processes that require extensive material removal, thermoforming utilizes sheets of thermoplastic materials with precise dimensions, minimizing waste generation. The ability to mold the sheets into complex shapes using custom-made molds or tooling ensures that the required materials are used effectively without excess or unnecessary scrap. This efficiency helps reduce raw material consumption, conserve natural resources, and lower production costs.

Additionally, thermoforming offers significant advantages in terms of energy efficiency. The process involves heating the thermoplastic sheets to their pliable state, which requires less energy compared to melting and re-molding processes used in other manufacturing techniques. The energy savings are further amplified by the ability to heat only the specific areas of the sheet that need molding, reducing overall heating time and energy consumption. By optimizing energy use, thermoforming minimizes its environmental impact and contributes to a greener and more sustainable manufacturing landscape.

Moreover, thermoformed products have exceptional recyclability, making them ideal for sustainable packaging and product solutions. Thermoplastics used in thermoforming can be easily recycled and reprocessed into new materials, closing the loop and reducing the demand for virgin resources. Additionally, the lightweight nature of thermoformed products contributes to energy savings during transportation and distribution, further reducing the overall carbon footprint. These recyclability and lightweight characteristics make thermoformed products an environmentally responsible choice for industries seeking sustainable packaging and design alternatives.

Thermal distribution in the thermoforming process is critical to achieving high-quality, defect-free products. However, variations in the temperature distribution during heating can lead to inconsistent material behavior and defects in the final formed parts. Understanding and optimizing the thermal distribution in the thermoforming process is essential to improve product quality, reduce waste, and enhance energy efficiency. Thus, in this study, the heat distribution with respect to the heating element distance was studied to understand the optimum process parameter well. It is important to avoid material waste during the thermoforming process.

Literature Review

In aerospace industries, the thermoplastic composite process differs from traditional thermoset composite. In order to fabricate thermoplastic, one of the processes is the thermoforming process (Nadlene et al., 2021). The thermoforming thermoplastic process is mainly different from the curing process, which is Reinforced Thermoplastic Laminate; RTL does not involve any autoclave for curing. On the other hand, thermoplastic composite only needs 5 to 10 minutes to complete the process and undergoes a thermoforming process since thermoplastic composite was supplied in RTL form (Akkerman & Haanappel, 2015).

Thermoforming is the most widely applied processing of thermoplastic prepregs. In some literature, thermoforming is the matched die-forming process (Ropers, 2017). According to Patil et al. (2019a), thermoforming is a technique in which, by imposing sufficient heating and pressure, a thin polymer film is softened and deformed over a mold into the desired shape. Generally, the thermoforming process for suitable mold temperature control involves long cycle times of up to several minutes. Before the forming stage, thermoforming molds should be heated to higher than the softening temperature of the polymer film and then cooled below the softening temperature after the forming stage for proper demolding (Lee et al., 2017).

According to Margossian et al. (2016), thermoforming processes are complex production processes that involve several factors that affect the consistency of the final product. Parameters such as temperature, forming speed and die geometries, stack properties such as original blank dimensions and layout design play an important role in the final result of the forming process (Process temperature seems to be especially significant among these). Thermoplastic composites display very distinct temperature behaviors due to their complex molecular structures.

Once thermoplastic composites become molten, they weaken and act as viscous materials when heated above their melting temperatures. Due to this behavior change, good temperature regulation within the laminate during development is important. Erchiqui et al. (2020) mentioned that the quality and characteristics of the manufactured parts in the plastics industry depend particularly on the heat transfer in the thermoplastics used. The precision of the results depends on the consistency of the thermo-physical characterization and the kinetics of the plastic crystallization, as well as on the working conditions associated with the shaping process (Figures 1 and 2).

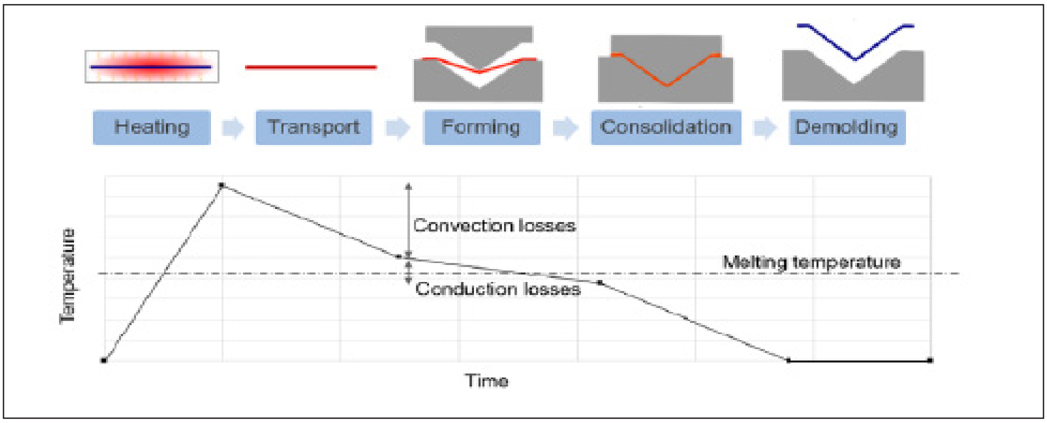

Figure 1. Principal steps of thermoplastic thermoforming process (Xiong et al., 2019)

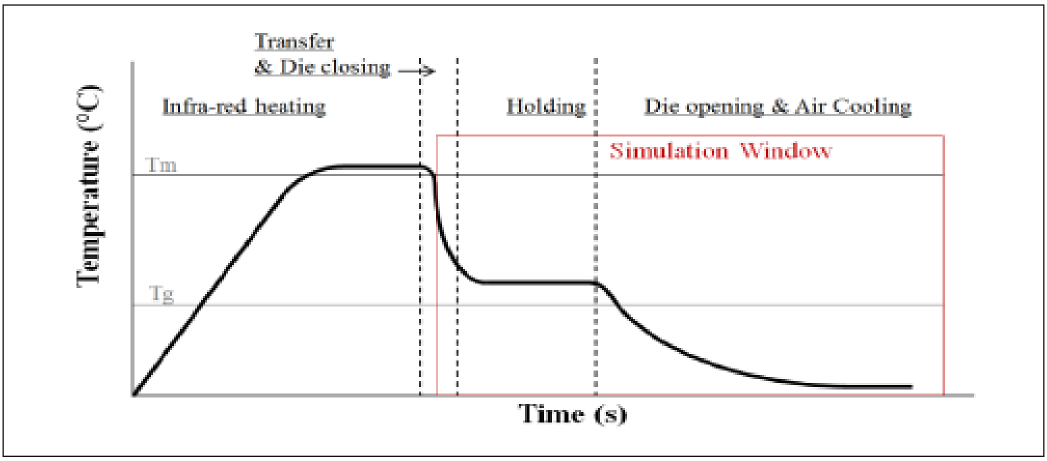

Figure 2. Temperature profile in thermostamping (Ste-marie, 2018)
Note. *T_m: Melting temperature, T_g: Glass Temperature

Shrivastava (2018) states that the amount of crystallinity in the material is affected by the processing technique. During the melt processing time, the plastics with a higher percentage of crystalline regions require longer to solidify. It allows the molecular chains to arrange themselves into crystalline form. However, if it is cooled rapidly, quenching the molecular chains does not receive sufficient time to align themselves properly and freeze as amorphous materials. Therefore, the crystalized plastic varies from material to material.

The sheets need to be heated above their glass transition T_g for the amorphous polymers and slightly below their melting point for the semi-crystalline polymers. It is necessary to ensure that the form is completed before the sheet temperature falls below these levels to form the thermoplastic composites within the process—the thermoplastic matrices, a very short process over the thermoset. During thermoforming, the temperature influences the formation of a flat laminate into a 3D shape (Günther et al., 2021).

MATERIALS AND METHODS

Thermoforming is an industrial process that involves a heating step before forming. This step is performed in most forming machine machines using an infrared oven containing infrared emitters. In industry, process start-up and control is still based on personal experience and trial and error methods. It leads to varying machine settings, and eventually high start-up times and costs.

This research requires PPS sheet materials to be heated to 320°C within 8 minutes using two infrared (IR) heated surfaces. Therefore, the study aims to determine the heater surface distance and temperature to achieve the requirement. An unsteady numerical radiative transfer method is developed to compute the heat distribution between the heater and a thermoplastic sheet. 3D control-volume software, called ANSYS, has been developed to compute heat transfer during the infrared-heating step. At the end of the simulation, it is hypothesized to determine the heated surface temperature and distance between two heated surfaces.

Table 1 shows the nine case studies investigating the relation between heater distance and temperature to the thermoplastic temperature. Three heater temperatures with three heater distances are tested. The distance between two heated surfaces is 200, 300 and 500 mm for 320°C, 360°C and 400°C heated surfaces. The desired PPS temperature of 320°C and maximum heater temperature of 400°C are parameters. At the same time, the distance of the heater is based on the comfortable movement of the specimen during the process.

The geometry domain in the present task for the heating area is a simple cuboid shape with a 600 mm × 600 mm base area. The domain height that represents distance varies according to the simulated case. Figures 3 and 4 show the domain geometry of the simulated case for 200 mm and 300 mm heater distance, respectively. The thickness of the plastic plate is constant at 6 mm per PPS sample thickness, and the modeling for the PPS heated process for a 500 mm distance between two heated surfaces in ANSYS can be illustrated in Figure 5.

Table 1
Summary of the case study

Case number	Heater temperature (°C)	Heater distance (mm)
1	320	200
2	320	300
3	320	500
4	360	200
5	360	300
6	360	500
7	400	200
8	400	300

The maze cell size is 1.0 × 102 m with a minimum of 4.9×10^{-4} m. For this geometry,

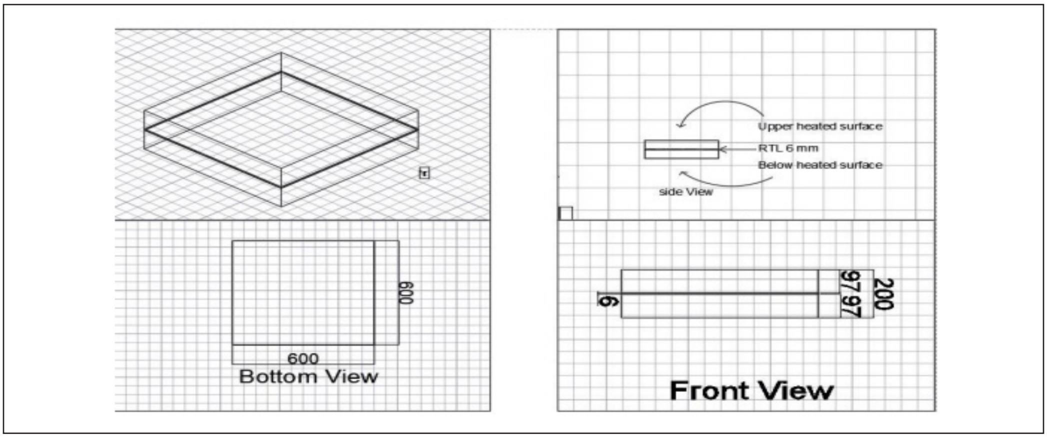

Figure 3. 3D modeling for PPS heating process for 200 mm distance between two heated plates. All units in mm

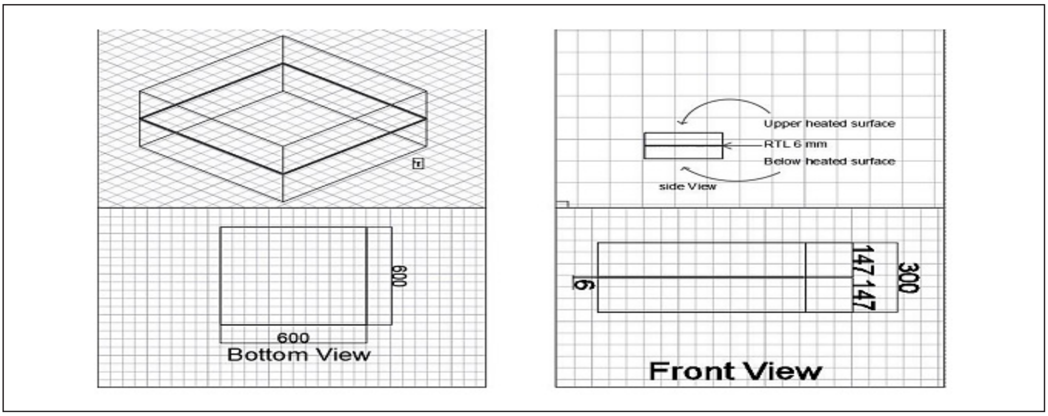

Figure 4. 3D modeling for PPS heating process for 300 mm distance between two heated plates. All units in mm

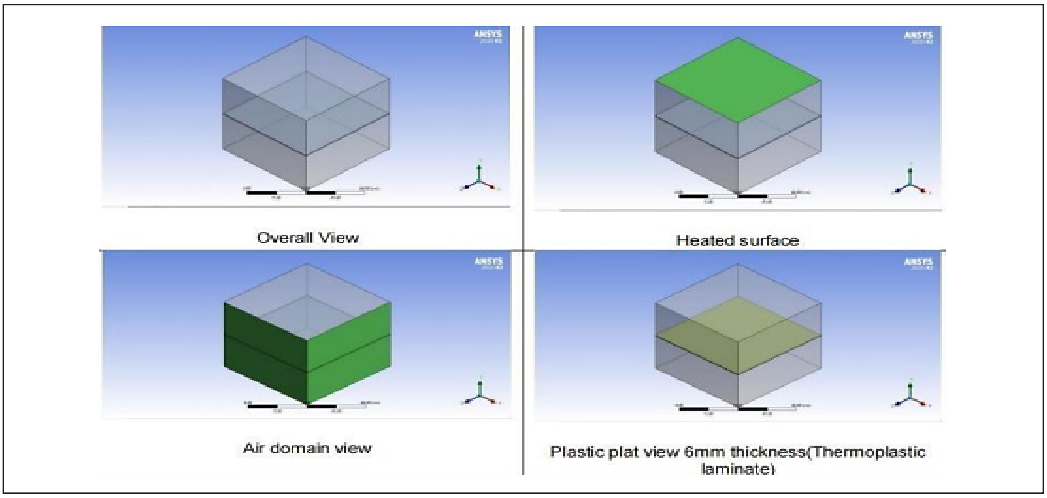

Figure 5. The modeling for the PPS heated process for a 500 mm distance between two heated surfaces in ANSYS

the number of elements is 183,600. All cases have similar face sizes but different elements depending on domain size. A separate study shows that this mesh number achieves the grid-independent test.

The present study's boundary condition comprises two main parts (Figure 6). The first is the heated surface at the domain's upper and bottom. Depending on the case studied, these two heated surfaces imposed free-to-stream and radiative temperatures at either 320°C, 360°C or 400°C. The heat transfer coefficient is 20 W/m^{2}K as the general value for the contacting air undergoing natural convection. The detailed value of the boundary conditions is provided in Table 2. The second part is the side wall of the domain, consisting of four surfaces. All surfaces of this domain are assumed to have zero heat flux, which means no heat loss will occur. Although this assumption is impractical due to non-zero heat loss for real situations, the study's outcome is concerning for the ideal and worst-case scenarios.

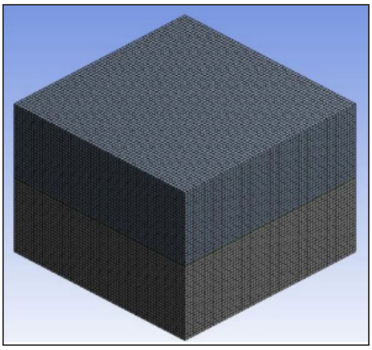

Figure 6. The mesh modeling with a maximum size of 6 mm size element

Table 2

Boundary condition use in the present task

Properties	Heated surface	Domain wall
Mode of heat transfer	Mixed (Rosseland radiation)	Insulation
Free stream temperature (°C)	320/360/400	N/A
Heat Flux	0	0
Heat transfer coefficient (W/m^{2}K)	20	N/A
External emissivity	0	N/A
External radiation temperature	320/360/400	N/A
Heat generation rate	0	N/A

RESULTS AND DISCUSSION

In this study, steady-state thermal analysis was used in ANSYS Workbench software. It evaluated the thermal achievement target temperature of 320°C (Figure 7) as early as 6 minutes and as high as 360°C (Figure 8) after 8 minutes. Therefore, the choice of 400°C (Figure 9) heater temperature and 20mm heater distance could fulfill the requirement criteria.

Figure 10 shows the temperature distribution of the thermoplastic plate at 8 minutes for the 400°C heater temperature and 200 mm infrared heater distance. As seen, the temperature is uniform with 624 K (351°C).

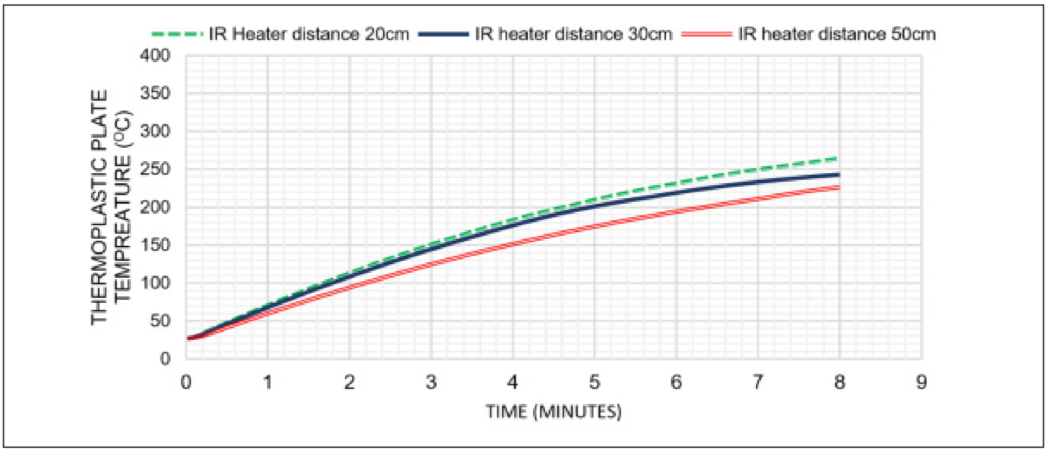

Figure 7. PPS plate temperature at heater temperature 320°C for various infrared (IR) heater distance

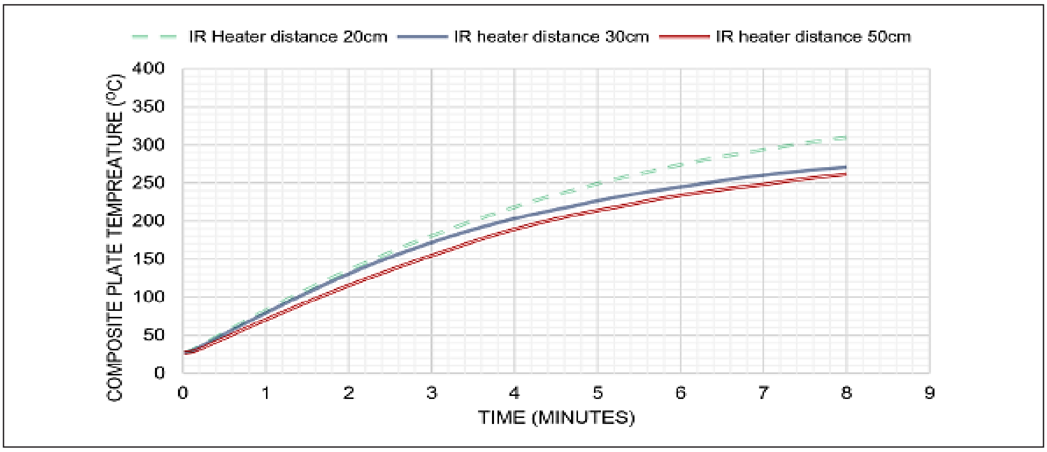

Figure 8. PPS plate temperature at heater temperature 360°C for various infrared (IR) heater distance

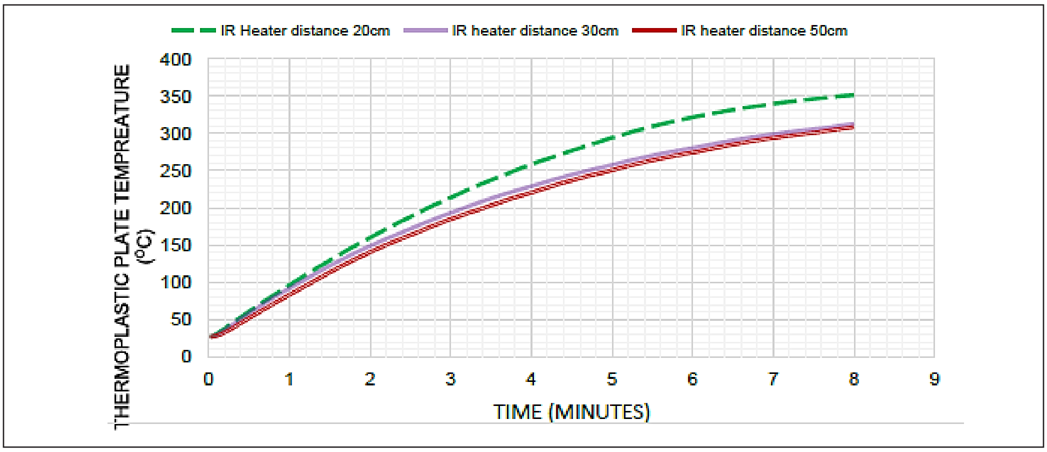

Figure 9. PPS plate temperature at heater temperature 400°C for various infrared (IR) heater distance

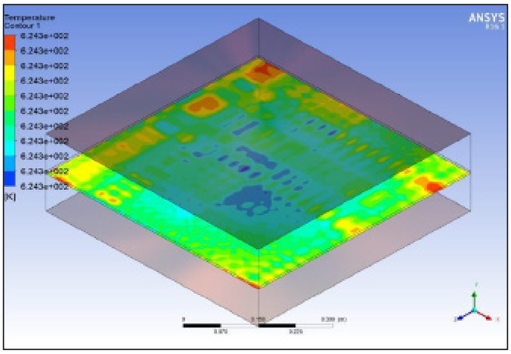

Figure 10. Sample contour shows uniform temperature distribution at 400℃ heater and 200mm heater distance

Two additional results are present. There is the effect of heater distance at different heater temperatures and effects of heater temperature at different heater distances. These two results could provide estimated data not lying in previous simulated cases.

For example, in Figure 11, which shows the relation of thermoplastic plate temperature against IR heater distance for different heater temperatures, one can predict the thermoplastic temperature at 400 mm heater distance (not in the previous simulated case) and 400℃ heater temperature. As can be seen, the maximum thermoplastic temperature that can be achieved is 310°C. Furthermore, if the required temperature of thermoplastic is 320℃, the pre-setting heater distance should be around 275 mm with 400℃ heater distance. In addition, the IR heater temperature of 360℃ and 400℃ did not affect the thermoplastic temperature for the heater distance between 350 mm and 500 mm.

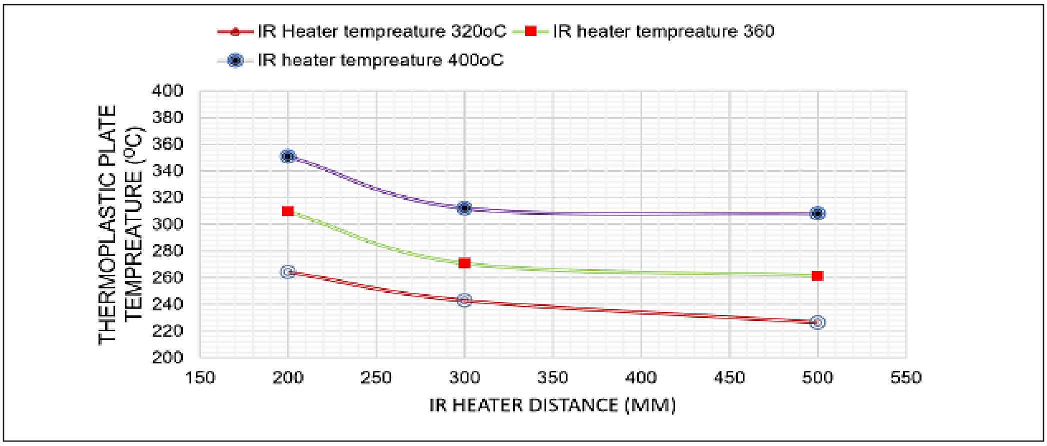

Figure 11. PPS plate temperature at 8 minutes for various infrared (IR) heater temperature

Figure 12 shows the relation of thermoplastic temperature to the IR heater temperature with different IR heater distances. To achieve 320°C thermoplastic temperature, we can use 400℃ IR heater temperature with a heater distance of 200 mm. However, this 200 mm distance might be too close for the operation, and a larger distance might be needed. Using 300 mm or 500 mm can achieve close to 320℃ if the heater temperature is set to 400°C. The obtained results might not be the same as the experiment in the thermoforming process due to the other environmental factors, machine capabilities, and varieties (Singh et al., 2019). In the simulation process, the thermoforming process is ideal, with perfect

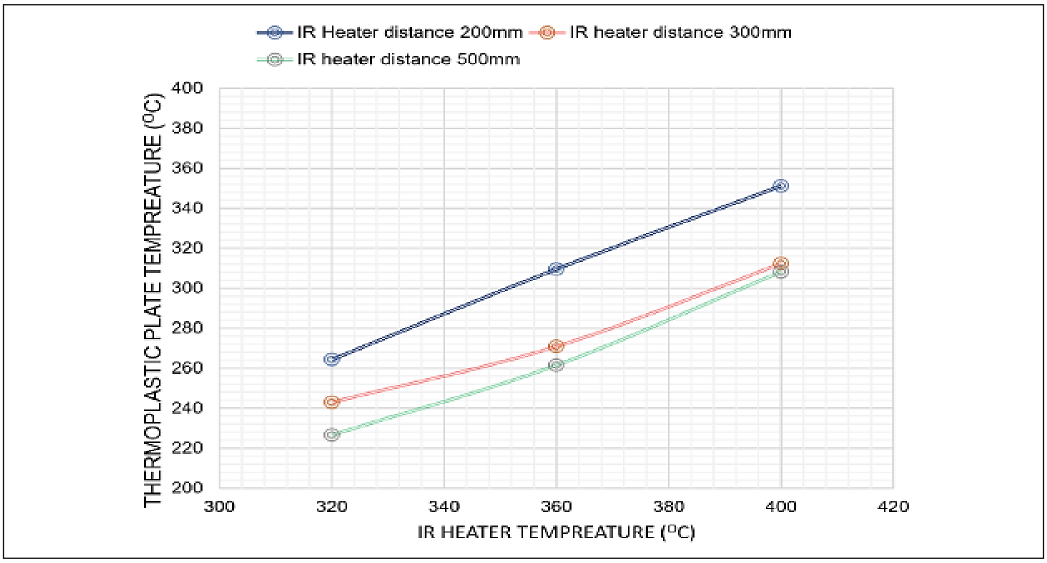

Figure 12. PPS plate temperature at 8 minutes for various infrared (IR) heater distance

heat control by the machine. The significance of finding the reference value in the molding press contributes to reducing the production cycle time and energy saving, enhancing the surface quality requirements and the final mechanical performances of the molded part (Sisca et al., 2020)

The findings of the research have significant implications for the aerospace. The simulation study reduces the uncertainty value and obtains reference value to reduce defect and time consumption during the thermoforming process (Hsiao & Kikuchi, 1999). If the thermoforming process can effectively replicate the mechanical and thermal properties of autoclave-cured PPS composites, it could lead to a paradigm shift in composite manufacturing (Choo et al., 2008; Allard et al., 2018). The potential benefits include reduced energy consumption, shorter cycle times, and improved manufacturing scalability (Nardi & Sinke, 2021). However, challenges related to maintaining consistent temperature distribution, achieving desired curing kinetics, and ensuring adequate fiber-matrix bonding must be addressed (Patil et al., 2019b).

CONCLUSION

This study examines the effect of heater distance at different heater temperatures and the effects of heater temperature at different heater distances. Setting up the maximum temperature of 400°C could achieve a minimum of 320°C for a distance of at least 270 mm. However, a larger distance of up to 500 mm manages to have at least 300°C for the PPS plate temperature. Unfortunately, the PPS plate will not achieve 320°C within 8 minutes if the heater temperature is below 350°C. Ideally, the temperature of 400°C with an IR heater distance of 250–300 mm could yield the PPS plate to the temperature of 300–320°C. The recommendation for future study might be exploration how different mold designs, including surface textures and cooling channels, affect thermal distribution. It could involve experimental and simulation studies to optimize mold geometry for improved uniformity.

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