FE Analysis on the Thermoforming Behaviour of Large Spherical PMMA Panel applied in JUNO

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Abstract. Jiangmen Underground Neutrino Observation (JUNO) mainly focuses on determining neutrino mass hierarchy. The central detector is one of the keys to JUNO experiment, which is a spherical liquid scintillator detector with 20 kton target mass. The target vessel of the central detector is a huge acrylic vessel with a diameter of 35.4 m. Its construction will certainly face many enormous challenges and difficulties. This paper introduces the thermoforming process for huge acrylic spherical panel, which is a very important step in panel production. The effect of temperature on panel’s curvature during thermoforming is discussed. The temperature field and thermal deformation of the panel during thermoforming are analysed by finite element method. The temperature field affects the panel’s shape and cause its radius smaller than the thermoforming mold’s. The paper presents some suggestions on improving the shape of spherical panel. The temperature at concave and convex surfaces of panel should be controlled as equal as possible during thermoforming. The other method to get a spherical panel with design radius is increasing the forming mold’s radius appropriately.

1. Introduction

The Jiangmen Underground Neutrino Observatory [1, 2] (JUNO) is a multipurpose neutrino experiment with a 20-thousand-ton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) at 700-meter deep underground. The 20kton liquid scintillator is carried by a huge acrylic vessel, as the target mass. The acrylic vessel supported by a stainless steel structure, as shown in figure 1, is 35400 mm in diameter and 120 mm in thickness, which is much larger than SNO’s [3, 4]. The spherical vessel is divided into 23 layers, and will be assembled and bonded underground from 263 pre-formed panels, as shown in figure 2. The biggest panel is located at the equator, which is about 3m×8m.

One of the biggest challenges is how to thermoform such thick and huge panel to be spherical with the correct shape. Throne [5] and Harkinjones [6] introduce how to shape a panel of plastic by using thermoforming. Bourgin [7] even develops a computer code to improve the understanding of thermoforming process of plastic panels. The acrylic, as a kind of Polymer Materials, could also be thermoformed into any shape. However, the huge acrylic panel may shrink and rebound after thermoforming, resulting in inconsistent dimensions between board and mold dimensions. In order to
understand the dimension changing of panel, the paper firstly introduces the thermoforming process and obtains the oven’s temperature during thermoforming. Then the paper builds a FEA model for the solution of thermal conduction and deformation of panel. The results are shown in the section 4 and some conclusion are got in section 5.

Figure 1. Spherical acrylic vessel supported by stainless steel structure.

Figure 2. Acrylic spherical vessel.

2. Introduction of Thermoforming Process

To study the thermoforming process, a piece of 3 m × 9 m × 120 mm acrylic panel is produced and formed to be spherical. A carbon steel fixture is used for this forming, as shown in figure 3. The spherical mold is 3.4 m × 9.2 m in size. An acrylic panel is put on the mold when formed.

Since the spherical surface of mold is un-polished and unclean, there are double layers of blanket covering on the mold to prevent the acrylic panel from being contaminated during thermoforming process. This forming process can control the radioactivity background [2] of the panel coming from dust of mold, but it will also cause the temperature of panel surfaces to be inconsistent.

The temperature curve in the heating oven is a key point for thermoforming. The first stage of thermoforming is heating. At this stage, the temperature in the heating oven will be increased rapidly to about 150 °C which is over the elastic state of the acrylic material. The second stage is temperature holding. The acrylic panel will be kept at this temperature for about 24 hours in order to make the interior of the panel reach the same temperature of exterior. The last stage for thermoforming is cooling. The cooling speed for this stage should not be too fast which is useful to avoid introducing the residual stress and panel deformation. The cooling rate is smaller than 2 °C/h. When the temperature is below 60 °C, the cooling mode will be changed from temperature control to the natural cooling in oven. Figure 4 shows the temperature curve for thermoforming process in the oven. The total process including above 3 stages takes about 10 days. There are some temperature fluctuations at the second stage, which is caused by workers entering and operating in the heating oven.

Figure 3. Thermo-forming fixture.

Figure 4. Oven’s temperature during thermoforming progress.
3. FEA for the Thermal Conduction and Thermal Deformation

In order to understand the influence of temperature on the final shape of the panel, the temperature distribution and deformation during the thermoforming process are simulated by the finite element method. When the panel is heated above the hot deformation temperature of PMMA, the material becomes soft and produce permanent deformation under external load. The temperature of the panel’s surface is considered to vary with the oven temperature. However, the surface temperatures of panel on concave and convex faces may be inconsistent for the influence of mold and blanket contacting the concave face. This inconsistent may bring more thermal deformation and further effect on the curvature of the panel. Some sensors are installed and used to monitor the surface temperature of panel during thermoforming process.

The FEA is used to understand the panel’s temperature field and its thermal deformation. The thermal expansion coefficient of acrylic is about 70e-6 to 90e-6 mm/mm·℃ when the temperature is from 20 °C to 80 °C. Thermal conductivity of acrylic is 0.14 w/M·K to 0.19 w/M·K. The glass transition temperature and hot deformation temperature of acrylic is about 127 °C and 96 °C respectively. The Young’s modulus of PMMA is decreased with increasing temperature [8, 9]. And it is worth mentioning that linear reduction in the Young’s modulus was observed both below and above the glass transition point [10]. Table 1 shows some properties of PMMA.

| Item                              | Symbol | Unit        | Environment          | Value          |
|-----------------------------------|--------|-------------|----------------------|----------------|
| Density                           | ρ      | Kg/m³       | -                    | 1190           |
| Thermal expansion coefficient     | α      | mm/mm·℃     | 20-80 °C             | 70e-6-90e-6    |
| Thermal conductivity              | λ      | w/M·K       | Above 20 °C          | 0.14-0.19      |
| Specific heat capacity            | c      | J/kg·K      | Above 20 °C          | 1424-1549      |
| Glass transition temperature      | Tg     | ℃           | -                    | 127            |
| Hot deformation temperature       | HDT    | ℃           | -                    | 96             |
| Young's modulus                   | E      | GPa         | Room temperature     | 3.2            |
| Poisson ratio                     | μ      | -           | Room temperature     | 0.35           |

3.1. Solution of Thermal Conduction

Since during the heating process of thermoforming there will be a temperature gradient in the acrylic panel, the main heat transfer mechanism will be the conduction. When the panel is in the oven, the surface temperature of the panel is almost equal to the oven temperature. Therefore, the paper does not consider the temperature change caused by heat radiation of the panel. In this paper, the surface temperature of panel is already known. The temperature sensors are set on the surface during thermoforming process. Therefore, the issue of FEA is focused on the solution of heat conduction equation without heat source [11,12]. For a given space object \( G \), assuming that the temperature of point \((x, y, z)\) in \( G \) is \( u(x, y, z, t) \) at time \( t \), the three-dimensional heat conduction equation without heat source is

\[
\frac{\partial u}{\partial t} - \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) = 0
\]  

(1)

In the equation, \( \lambda \) is the thermal conductivity and \( c \) is the specific heat capacity. We need to determine the initial value of temperature \( u \) and the boundary condition in order to solve the equation. The initial value of \( u \) at time \( t = 0 \) is

\[
t = 0: u(x,t) = \phi(x,y,z), (x,y,z) \in G
\]  

(2)
Before thermoforming, the temperature of panel is the same as the room temperature. During the thermoforming, the surface temperature of panel is monitored. Therefore, the boundary condition for solving the equation can be considered as the Dirichlet boundary condition:

$$u|_\Gamma = g(x, y, z, t), (x, y, z) \in \Gamma, t > 0$$

(3)

3.2. Solution of Thermal Deformation
The object will be deformed with the change of temperature. In this paper, the thermal deformation will not affect the distribution of temperature field. Therefore, the thermal deformation of panel is:

$$\delta = L_0 \alpha \Delta T$$

(4)

In the equation, $L_0$ is the size of panel, $\alpha$ is the thermal expansion coefficient, and $\Delta T$ is the value of temperature change.

3.3. Geometry Model of FEA
Figure 5 is model of 1/4 acrylic panel. There are two symmetric faces in this model. The radius of concave face is 17700 mm.

4. FEA Results
In this section, we show the FEA results of two cases, consistent temperature case and inconsistent case. Consistent temperature means there is no temperature difference between the concave and convex surface during thermoforming. In fact, due to the existence of blanket between the acrylic panel and the steel mold, the temperature of concave surface is inconsistent with the temperature of convex surface when the panel is thermoformed.

4.1. Consistent Temperature Case
The initial temperature of panel is 23.7 °C, which is the room temperature. Figure 6 shows the temperature change of surfaces and center. The surface temperature is monitored by the sensors on the surfaces and the center temperature is simulated by FEA. From the temperature curve in Figure 6, we can find that the surface temperature is higher than center’s at the stages of heating and heat holding, but the reverse situation happens at the cooling stage.

Figure 7 shows the simulated temperature field of panel during thermoforming. The initial temperature of panel is 23.7 °C before heating. The surface temperature of panel reaches 144 °C and its center temperature is 137 °C after heating 24 hours, shown in figure 7b. Figure 7c is the temperature field at the cooling stage after 95 hours. The maximum temperature is less than 96 °C, which is the acrylic hot deformation temperature. Below this temperature, it would produce thermal deformation. Figure 8 shows the temperature distribution in thickness direction at time = 95 h. The concave and convex surface temperature is same and the center has the maximum value. The curve is symmetric.
Figure 6. Temperature curve during thermoforming.

Figure 7. Temperature field of panel (1/4 model) at consistent temperature case. (a) time = 0 h, (b) time = 24 hours, (c) time = 95 hours, (d) time = 240 hours.

Figure 8. Temperature distribution in thickness direction (time = 95 h) at consistent temperature case.

Figure 9 shows the thermal deformation of panel when the temperature cooled down from 96 °C to 21 °C. The center point of panel is set to be a reference point as zero deformation. Therefore, the panel would shrink from four sides to the center. The total deformation is about 30.9 mm. In polar coordinates, the displacements in three directions are 3.0 mm, 29.2 mm and 10.2 mm, respectively.
Figure 9. Thermal deformation of panel from 96 °C to 21 °C at consistent temperature case: (a) total deformation, (b) R direction deformation, (c) length direction, (d) width direction.

4.2. Inconsistent Temperature Case
In this case, the temperature of concave and convex surfaces shown in figure 10 is monitored by temperature sensors during thermoforming process. The black curve is the temperature of convex surface and the maximum temperature is 144 °C. The red curve shows the temperature of concave surface and the maximum temperature is 130 °C. The blue one is the center temperature by simulation and the maximum temperature is 136 °C.

Figure 10. Temperature curve during thermoforming at case of inconsistent temperature.

Figure 11 shows the simulated temperature field of panel during thermoforming. The initial temperature is 23.7 °C as the room temperature. After 24 hours, the concave surface temperature becomes lower than the convex surface and center of the panel. After 95 hours, the inner of the panel reaches the maximum temperature which is about 96 °C. Figure 12 shows the temperature distribution in thickness direction at this time. From this figure, we can see that the temperature of concave surface is higher than the convex surface, and the maximum temperature is not in the center of panel, but about 3mm away from it.
Figure 11. Temperature field of panel (1/4 panel model) at inconsistent temperature case by FEA: (a) time = 0 h, (b) time = 24 hours, (c) time = 95 hours, (d) time = 240 hours.

Figure 12. Temperature distribution in thickness direction (time = 95 h) by FEA at case of inconsistent temperature.

Figure 13 shows the thermal deformation of panel when the temperature cooled down from 96 °C to 21 °C at case of inconsistent temperature. The total deformation is about 31.7 mm. In polar coordinates, the displacement in three directions is 8.4 mm, 29.1 mm and 10.3 mm, respectively.

4.3. Comparison of the Two Cases
Table 2 shows the comparison of panel deformation in cases of consistent and inconsistent temperature. The deformations in these two cases are much the same both in length and in width directions. The biggest difference is the deformation in R direction, the deformation in the case of inconsistent temperature is more than two times of the case of consistent temperature in R direction. The thermal deformed contours of central line in the two cases simulated by FEA are compared to the design contour, as shown in figure 14. The design curvature radius of the panel is 17700 mm. Although the shape variation in R direction is only 3mm for the case1, the radius becomes 17632 mm after panel cooling down, which is 68 mm smaller than the original design. The curvature radius of deformed panel is 17470 mm for the case 2, which is 230 mm smaller than the original design. Therefore, in order to control the panel's shape and make the radius close to 17700 mm, it is necessary to control and keep the same temperature of the concave and convex surfaces as much as possible.
Figure 13. Thermal deformation of panel from 96 °C to 21 °C at case of inconsistent temperature. (a) total deformation, (b) r direction, (c) length direction, (d) width direction.

Table 2. Comparison of panel deformation at cases of consistent and inconsistent temperature.

| Case                | Total deformation (mm) | Deformation in polar coordinates (mm) | Radius (mm) |
|---------------------|------------------------|--------------------------------------|-------------|
| (1) Consistent      | 30.9                   | R direction 3.0                      | 17632       |
| temperature         |                         | Length direction 29.2                |             |
| (2) Inconsistent    | 31.7                   | Width direction 10.2                 | 17490       |
| temperature         |                         |                                      |             |

Figure 14. Comparison of design contour and thermal deformed contour of central line.

5. Conclusion
Based on the FEA of thermal deformation, the temperature field could affect the panel’s curvature during thermoforming. For the 3 m × 9 m panel with design contour radius of 17700 mm, the
curvature radius of the formed panel becomes smaller than it of the mold. When the temperature is consistent on different surfaces, the curvature radius of the panel is about 68mm smaller than it of the mold. When the temperature is inconsistent, the result becomes worse, and the FEA result shows that the curvature radius of the formed panel is about 230mm smaller than it of the mold. Therefore, in order to reduce the influence of temperature to curvature radius, the surface temperatures of concave and convex should be controlled consistently as much as possible during thermoforming. To get a spherical panel in 17700 mm curvature radius, increasing about 230mm in curvature radius of the mold could be considered.

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