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Key technologies in the design and construction of the JUNO central detector structure

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Abstract

Jiangmen Underground Neutrino Observatory (JUNO) is a large-scale neutrino experiment with multiple physics goals including the measurement of neutrino mass hierarchy, accurate measurement of neutrino oscillation parameters, and detection of neutrinos from super novae, the Sun, and the Earth. JUNO will be the largest liquid scintillator neutrino detector: the main structure of the detector consists of a stainless-steel lattice shell and an acrylic spherical vessel. This vessel will be the largest spherical structure made of acrylic material in the world. Throughout the design, production, and construction process, numerous challenges have been encountered, and several technical solutions have been proposed. This article will discuss the reliability of the detector in long-term operation under significant buoyancy, quality control in the production of low-radioactivity acrylic panels, large-scale thick panel thermal bending technology, prevention of annealing-induced cracking in the acrylic vessel, and the feasibility of stainless-steel structural bolt connections.

1 Introduction

The Jiangmen Underground Neutrino Observation (JUNO) is located in Guangdong Province, China. It is a multi-purpose neutrino experiment that features a 20 kt liquid scintillator (LS) detector with an unprecedented energy resolution of 3% at 1 MeV, situated 700 m deep underground [1]. The main goals of JUNO are to measure the mass hierarchy of reactor neutrinos and to conduct precision measurements of mixing parameters. Additionally, JUNO also aims to study supernova neutrinos, solar neutrinos, geo-neutrinos, atmospheric neutrinos, sterile neutrinos, and carry out dark matter searches, nucleon decay studies, and other exotic searches.

The figure 1 shows a schematic view of the JUNO detector. It is primarily divided into the central detector and veto detector. The main structure of the central detector consists of a 34.5 m diameter acrylic spherical vessel and a 40.1 m diameter stainless steel latticed shell. Inside the acrylic vessel, there will be a 20 kt liquid scintillator. The acrylic vessel is connected to the stainless-steel lattice shell through 590 support rods. The inner surface of the shell is densely populated with 17,612 20-inch PMTs and 25,600 3-inch PMTs. The optical coverage of the PMTs reaches 77.9%. On the outer surface of the shell, there are 2,400 veto PMTs, which are used to detect Cherenkov light in the water pool. The Muon track detector is placed on the top bridge.

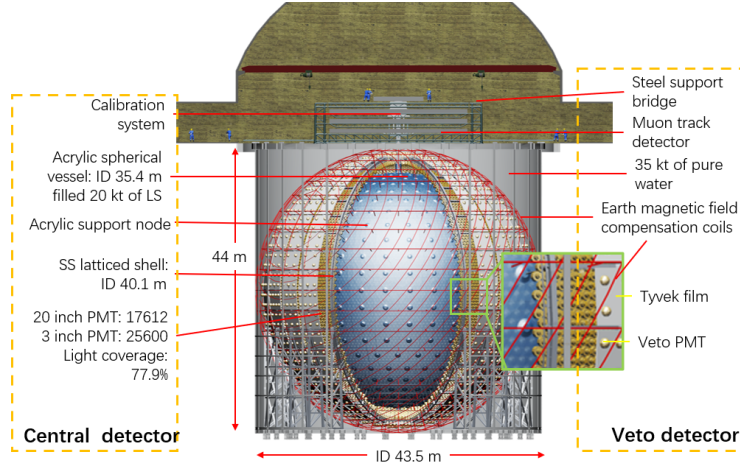


Figure 1: Schematic view of the JUNO detector

2 Status of JUNO

Figure 2(a) shows the central detector in the water pool. Currently, the shell is completed except for the bottom four layers. Inside the shell, the acrylic vessel is being constructed, as shown in figure 2(b). The acrylic vessel is installed from top to bottom, with a total of 23 layers. The panels are transported from the bottom of the pool to the installation platform for assembly, polymerization, annealing, polishing, cleaning, and other processes. Currently, the installation of the equatorial layer of the acrylic vessel has been completed. The top part is covered with yellow water-soluble paper. The glue used for the paper can dissolve in water. And after the completion of the entire vessel, it can be automatically removed by a high-pressure water. On the outer side of the shell, PMTs and electronics are also being installed from top to bottom. The white film is made of Tyvek material, which increases the reflectivity of Cherenkov light. The construction of the entire detector will be completed in 2024.

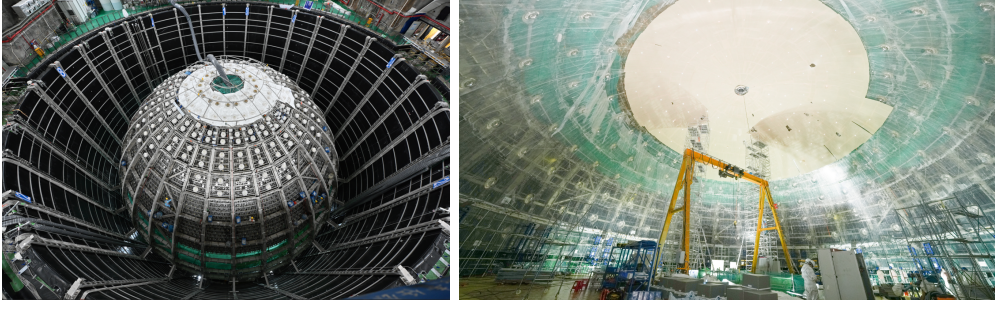


Figure 2: (a)The central detector in the pool (b)Construction progress of the acrylic vessel

3 Challenges and innovative technologies during the design and construction of the detector

The construction of the largest acrylic spherical vessel to hold the LS for the central detector of JUNO is currently underway. Due to the immersion of the detector in pure water, the acrylic vessel needs to withstand over 3000 tons of buoyancy. Therefore, the primary challenge in the design is to address the stress-related issues of the acrylic vessel and ensure the reliability of the detector. During the manufacturing process, the production of large-scale acrylic sphere panels can be quite challenging. Additionally, controlling the radioactivity background of the acrylic sphere panels is crucial to meet JUNO's requirement for extremely low radioactivity materials. The content of U238, Th232, K40 should be less than 1 ppt. During the construction process, it is necessary to improve the bonding quality of the acrylic sphere panels while avoiding cracking during annealing. Additionally, in order to shorten the construction period of the steel structure and the acrylic sphere, some new technological measures have been proposed to ensure the speed and quality of the project construction.

3.1 Central detector structure design

Figure 3(a) shows the main structure of the central detector. The acrylic vessel transmits the buoyancy of over 3000 tons to the shell through 590 support rods. The acrylic vessel is weaker compared to the stainless-steel shell. Therefore, when considering the reliability of the detector structure for long-term operation of 20 years, the focus is mainly on the acrylic vessel, and its stress needs to be controlled within 3.5 MPa. The forces on the support rods between different layers of the acrylic vessel must transition uniformly, and the tension force should be less than 9 tons and compression force less than 15 tons. Additionally, a robust acrylic node is required, with the ultimate load-bearing capacity 6 times of the rod force during operation. Figure 3(b) shows the support rods for the acrylic vessel. One end of the support rod is connected to the acrylic node, which is bonded to the acrylic vessel. The acrylic node is connected via a ball head flange with the connection rod. In the design, to ensure that the rod forces meet the requirements, disc springs are placed inside the steel node of the shell. Figure 4 shows the force distribution of the support rods in different layers. It can be observed that the use of disc springs effectively controls the rod forces to achieve the target values.

Figure 5 shows the finite element analysis of the acrylic node. Under the design rod forces, the maximum stress is only 2.9 MPa. The tensile and compressive ultimate loads of the node can reach 100 tons, which is greater than 6 times the design load [3].

3.2 Manufacturing of acrylic spherical panel in the factory

Due to direct contact with the liquid scintillator, it is necessary to consider avoiding radioactive contamination of acrylic panels during the manufacturing process in the factory. Figure 6

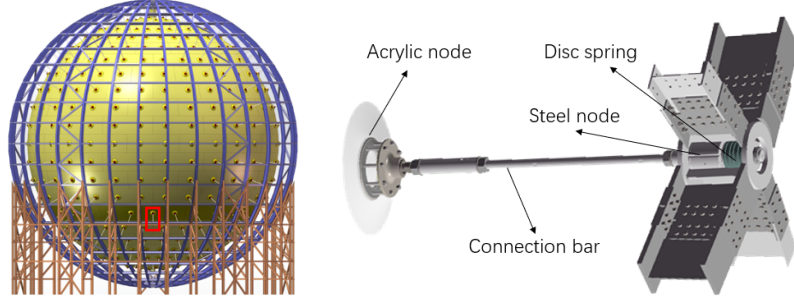


Figure 3: (a) Main structure of the central detector (b) Acrylic vessel support rod

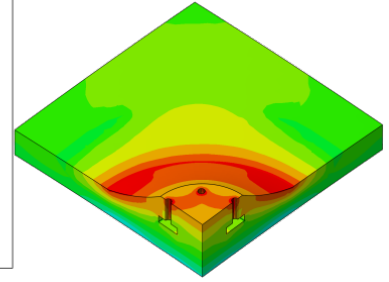
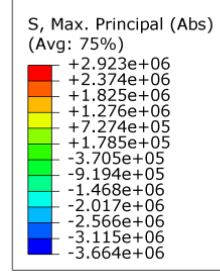
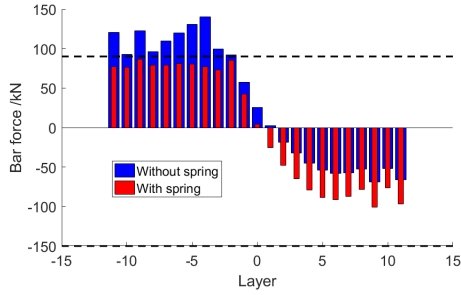


Figure 4: Force distribution of support Rods in Different Layers

Figure 5: Finite element analysis of the acrylic node

illustrates the main production progress of the spherical panel. MMA is transported through dedicated pipelines into glass molds and then placed in a thermostatic water bath for polymerization. For a thickness of 124 mm panel, the polymerization process takes about 40 days. Then the flat panels are protected with a PE film. To obtain spherical panels, the flat panels are subjected to high-temperature baking on a spherical steel mold. The spherical panels are processed on a five-axis machining center, and acrylic nodes are bonded to the surface of the panels. Before the panels are transported to the site, their surfaces are polished to a depth of 100 μm to remove any possible radioactive contamination. Subsequently, the panels are thoroughly cleaned and protected with the film. In this production process, the content of radioactive isotopes U238 and Th232 in the panels is about 0.6 ppt and 0.7 ppt. In the aforementioned production process, the

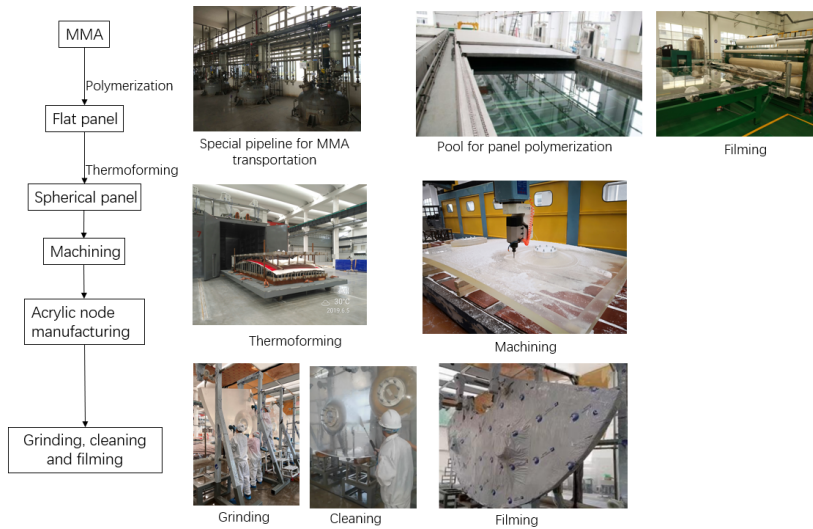


Figure 6: Main production progress of spherical panel

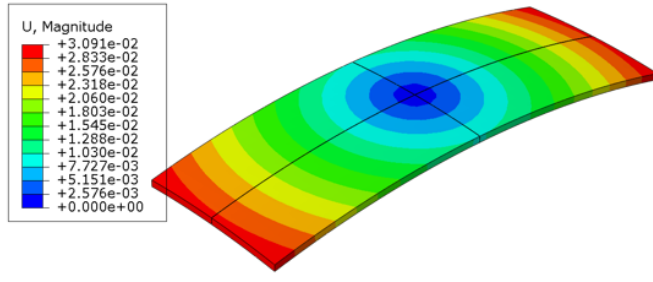


Figure 7: FEA of shrinkage during panel thermal bending

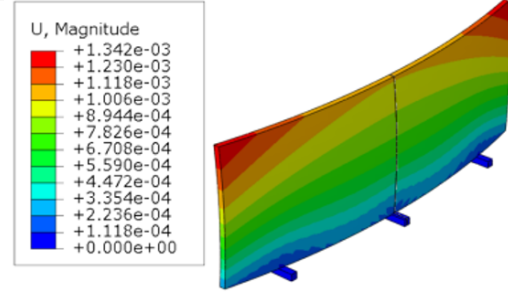


Figure 8: FEA of deformation under self-weight for vertically placed panels

thermoforming of the panels is a crucial step that directly affects key factors such as the bonding gaps and the dimensions of the spherical vessel on-site. Through simulation, it is observed that the panels undergo shrinkage from a high-temperature state to room temperature, as shown in the figure 7. Due to this shrinkage, there is a discrepancy between the actual curvature of the panels and the curvature of the bending molds.

To measure the curvature of the produced panels, it is necessary to eliminate the deformation caused by the weight of the panels, which can affect the curvature. Through finite element simulation, it is observed that the curvature of the panels varies significantly depending on the different support points when the panels are placed horizontally. However, when the panels are placed vertically, the deformation is relatively small, as shown in Figure 8. In this case, the deformation of the panels is only 1.3 mm. Therefore, it can be considered that when the panels are placed vertically, they can accurately reflect their own curvature. Measurements have shown that when the panels are placed horizontally on a mold with a radius of 17799 mm, the measured curvature radius is 17741 mm. However, when the panels are placed vertically, the curvature of the panels is 17217 mm. The panel curvature is approximately 580 mm smaller than the mold curvature. Therefore, to obtain panels with the desired radius of 17700 mm, it is recommended to increase the mold radius by approximately 580 mm when making the bending molds [2].

3.3 Construction on site

The detector is installed in a water pool within the onsite hall. Since welding is not allowed on the site, the stainless-steel shell is connected using bolts to join various components. However, the friction coefficient of stainless steel is usually less than 0.2, which is far below the required value of 0.45 for bolt connections. Therefore, surface passivation treatment is necessary for the stainless steel parts to achieve a friction coefficient of approximately 0.5. Additionally, high-strength stainless steel bolts are also essential. JUNO utilizes a high-strength lockbolt and has developed special riveting equipment to apply pre-loaded force to the stainless-steel bolts. The final radius of the shell is 20530mm, which is only 20mm smaller than the design value.

After the construction of the steel shell, a temporary installation platform is also installed inside the shell for the construction of the acrylic vessel. The construction of the acrylic vessel is done from top to bottom, divided into 23 layers. The equatorial region of the spheres consists of 15 panels, with a circumference of 111 meters. The main process of constructing the acrylic vessel includes: 1. Transporting the panels to the platform, 2. Adjusting the panels into position, 3. Injecting and polymerizing the panels on the same layer, 4. Annealing the bonding lines of the panels on the same layer, 5. Polishing and cleaning the adhesive seams, 6. Connecting support rods.

To shorten the construction period during the process of constructing the panels on the same circumference, a one-time injection and polymerization method is used, allowing for simultaneous polymerization of 15 vertical bonding lines and horizontal bonding lines. However, due to the

use of MMA during the polymerization process, shrinkage occurs, so attention must be paid to the issue of adhesive shortage during one-time polymerization. After polymerization, to further improve the strength of the adhesive seams, heating annealing is required. However, during the heating process, cracking may occur at the bottom of the panels, as shown in figure 9. To prevent cracking, finite element simulation is conducted to optimize the annealing process, reducing the annealing thermal stress from the initial 12 MPa to below 3.5 MPa.



Figure 9: Cracking during Annealing Process

4 Summary

Numerous challenges have been encountered during the design and construction of the detector:

Disc springs are used to evenly distribute the support bars' forces. Additionally, a robust acrylic node has been designed to ensure the safety of the vessel, which must be capable of withstanding an ultimate force of up to 100 tons.

A specialized production process is implemented to achieve low radioactive background panels for JUNO. Furthermore, the study of thermoforming processes has drastically improved the accuracy of the panel's curvature radius.

The adoption of a non-moving panel polymerization process enabled simultaneous polymerization of multiple bonding lines, reducing the construction time. An optimized annealing process has been implemented to prevent cracking of the bonding lines.

The friction coefficient of stainless steel was also improved through surface treatment. the coefficient is about 0.5. This facilitates the construction of the stainless steel shell using bolts. the shell's radius is 20 mm smaller than the original design.

5 Acknowledgments

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