Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

INFLUENCE OF STATIC PRESSURE AND SUPPORT ON HYDRO-BULGING PROCESS OF SINGLE-CURVATURE POLYHEDRON OF CONTAINMENT VESSEL

Jianling DONG[1,2], Xingcheng HUANG[2], Ke CHEN[3] Bohao NING[4]

[1]Professor, INET, Tsinghua University, Beijing, P.R. of CHINA (dongjl@tsinghua.edu.cn)
[2] Collaborative Innovation Center of Advanced Nuclear Energy Technology, Tsinghua University
[3] Engineer, Jiangnan Shipyard (Group) Co., Ltd, Shanghai, China
[4] PH.D student, INET, Tsinghua University, Beijing, P.R. of CHINA

ABSTRACT

The integral RPV configuration and layout nuclear reactors eliminate the loop piping and the externally located steam generators, pumps and pressurizer with their individual reactor pressure vessels. Hence, the footprint of the containment can be greatly reduced. This size reduction makes them possible to use small size and high pressure vessels as their containments. Compared with cylindrical pressure vessels, spherical vessels have the advantages of higher pressure bearing capacity and material saving. So for integral RPV configuration reactors, using spherical vessels as their containments and reactor building as a barrier to protect the containment from attack from aircraft is a promising configuration and layout plan.

The traditional spherical vessel technology adopts presses and dies to form the steel sheet blanks into double-curvature orange petals, then to assemble and weld the petals to obtain a spherical vessel, the process is complicated, long production period and higher cost.

The single-curvature polyhedron hydro-bulging technology to manufacture spherical vessel is a new technology for manufacture spherical vessels, which has been used to manufacture spherical vessels in many fields. But up to now, there is no case that the technology is used in the nuclear industry. This paper presents some recent research results on the influence factors of the bulging process, like polyhedron shell support, gravity and static pressure of bulging pressure medium etc.

Keywords: single-curvature polyhedron, spherical vessel, hydro-bulging, spherical steel containment vessel, support, gravity, static pressure of bulging pressure medium

1. INTRODUCTION

In the early days of the nuclear industry, spherical vessels were used as the containment vessels of the nuclear power plant (WOLFGANG K. et al., 1986). Recent years, spherical containment vessel gets attention again (M.D. et al., 2003; IAEA, 2020; Dong Jianling et al., 1992).

The integral RPV configuration and layout nuclear reactors eliminate the loop piping and the externally located steam generators, pumps and pressurizer with their individual reactor pressure vessels. Hence, the footprint of the containment can be greatly reduced. This size reduction makes them possible to use small size and high pressure vessels as their steel containment vessels. Compared with cylindrical pressure vessels, spherical vessels have the advantages of higher pressure bearing capacity and material saving. So for integral RPV configuration reactors, using spherical vessels as their containments and reactor building as a barrier to protect the containment from attack from aircraft is a promising configuration and layout plan.

The single-curvature polyhedron hydro-bulging technology to manufacture spherical vessel is a new technology for manufacture spherical vessels, which has been used to manufacture spherical vessels in many fields(Dong Jianling et al., 1992). Authors of the paper have had a try to use the technology in the nuclear industry(Dong Jianling et al., 2024). The research results in the paper can be summarized are as follows:

(1) The single-curvature polyhedron with 5 zones is suitable to be used for manufacturing spherical vessel with large volume by hydro-bulging;

(2) The maximum out-of-roundness and the maximum deviation from the theoretical sphere of the polyhedron satisfy the requirement of ASME III NE-4200(ASME, 2015);

(3) Maximum thinning rate of the polyhedron wall thickness under different pressure is less than 1.2%.

Therefore, adopting the new single-curvature polyhedron to manufacture the steel spherical containment vessel of the reactor by hydro-bulging process is feasible.

However, as a preliminary research, many factors to influence the bulging process are not taken into consideration in the reference (Dong Jianling et al., 2024). This paper further explores the application of the single-curvature polyhedron hydro-bulging technology for manufacturing spherical vessel in manufacturing steel spherical containment vessel of nuclear reactor and presents some recent research results on the influence factors of the bulging process, like polyhedron shell support, gravity and static pressure of bulging pressure medium etc.

2. PARAMETERS OF THE TARGET SPHERICAL VESSEL

2.1Assumed Design Condition

According to IRIS, the design condition of the target spherical vessel can be listed as follows:

Inner diameter: 25000mm

Medium: steam

Design pressure: 1.0MPa

Design temperature: 180℃

Hydrostatic test pressure: ≥1.25MPa

Weld coefficient: 1

2.2 Material

SA738Gr.B is the commonly used in steel containment of nuclear power plant nowadays. In AP1000, the material is used to manufacture cylindrical steel containment vessel. In order to exempt mandatory post-weld heat treatment, the wall thickness of the steel containment vessel is limited to 44.45mm.

According to the assumed design conditions and the requirement of ASME III NE-3324.4, the calculation wall thickness of the target spherical vessel should be 37.2mm. So, steel plate with thickness of 44.45mm is used to form single-curvature orange petals of the polyhedron. According to

ASME Ⅲ D, allowable stress of the material is 168MPa (at temperature of 180℃). The other mechanical properties are as follows (Xiaoping Zhang, 2016):

Elastic modulus: 202000MPa

Poisson'ratio: 0.3

Yield stress: 415MPa

The strain-stress curve is shown in Fig.1:

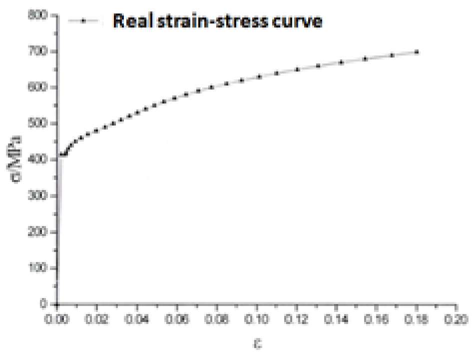
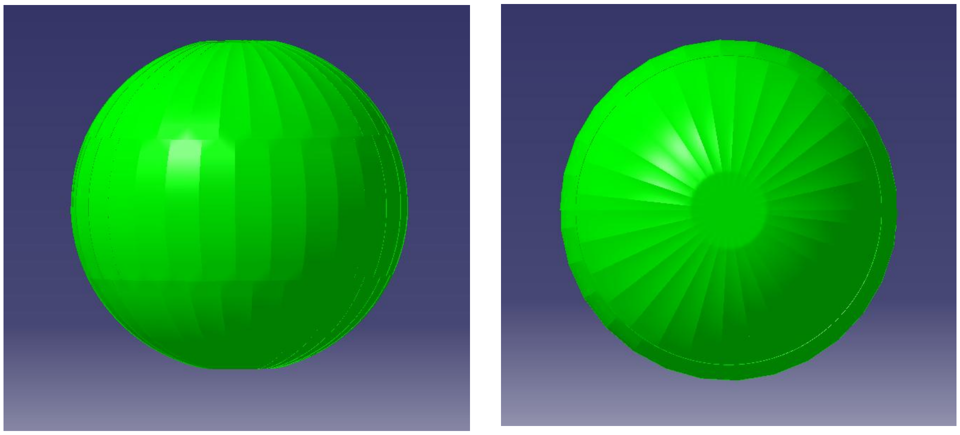


Figure 1. Real strain-stress relationship curve of SA738Gr.B

3. POLYHEDRON STRUCTURE

The diameter of the target spherical vessel is φ25000mm, and volume of which is 8177m^3. For such a large spherical vessel, According to the parameters above, the single-curvature polyhedron with 3 zones is not suitable to use. Jointly considering the develop length of single-curvature polyhedron and the forming ability of the installation company and other factors, a single-curvature polyhedron 5 zone was put forward in reference (Dong Jianling et al., 2024). The polyhedron consists of the upper pole zone, lower pole zone, upper temperature zone, lower temperature zone and equatorial zone. Among them, upper temperature zone, lower temperature zone and equatorial zone consist of 29 double-curvature orange petals each.

The three dimensional structure of the single curvature polyhedron is shown in Fig 2. In the respect of structure, the difference between the target spherical vessel and polyhedron is that upper temperature zone, lower temperature zone and equatorial zone of the latter consist of single curvature orange petals each, and upper pole zone, lower pole zone consists of steel plate blank.



(a) Front view (b) Top view

Figure 2. Single-curvature polyhedron structure

4. ACCEPTANCE CRITERIA FOR HYDRO-BULGING FORMED POLYHEDRON

According the requirements of NE4222.2 (b), NE4221.2(a) and NE-4214 of ASME III NE, the acceptance criteria of the spherical vessel being used as reactor containment vessel are as follows(Dong Jianling et al., 2024):

(1) For the polyhedron after being hydro-bulged, the out-of-roundness which is equal to the difference between the maximum and minimum inside diameters at any cross section through the geometric center of the bulged polyhedron shall be less than 1% of the nominal diameter at the cross section under consideration.

(2) Considering D_o is Φ25088.9mm, L equals to $D_o/2$, that is 12544.45mm, and using Figure NE-4221.2-1, maximum permissible deviation e from a true circular form is 1.2t, that is 53.34mm.

(3) According to ASME NE-3324.4, minimum required thickness of shell or head, after forming, exclusive of corrosion allowance should not be less than 37.2mm.

5. NUMERICAL CALCULATIONS OF THE POLYHEDRON HYDRO-BULGING PROCESS

5.1 Model of Finite Element Analysis, Boundary Condition and Loads.

a) Model: considering the symmetry of the polyhedron, 1/2 enclosed polyhedron is taken to be imported to ABAQUS. Entering the mesh function module, the geometry model with grids can be obtained, as shown in Fig.3.

b) Material: SA738Gr.B is used as the material of the single-curvature orange petal plate. For the finite element model, single-curvature orange petal plates and weld joints are supposed as homogeneous material.

c) Boundary condition:

When 1/2 enclosed polyhedron is taken as analysis model, constrains of boundary condition are apply to the planes of symmetry. Translation and rotation of the nodes on the planes is limited to the plane.

In order to study the influence of a support on the hydro-bulging process, which is a platform and located in the lower pole zone, constrains to represent the support is exerted on the polyhedron.

d) Load: in order to make it clear how gravity and hydrostatic pressure to affect the bulging process of the single-curvature polyhedron during the hydro-bulging process, loads acting on the polyhedron are internal pressure, gravity and hydrostatic pressure.

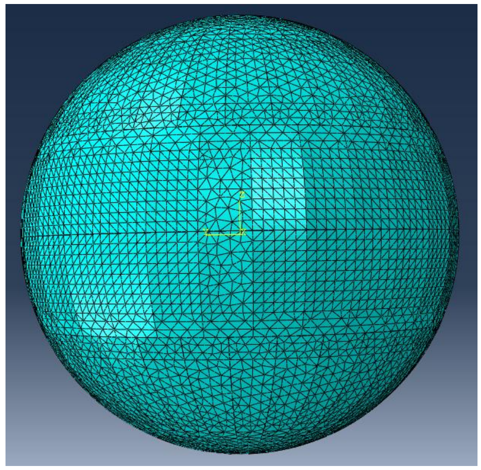


Figure 3. Model grid divisions

5.2 Calculation and result analysis

5.2.1 Influence of the support on the bulging process

The out-of-roundness of the polyhedron under different pressure and maximum deviation from true theoretical form under these pressure values are listed in Table 1. The wall thickness of the polyhedron after bulging process and wall thinning rate is listed in Table 2.

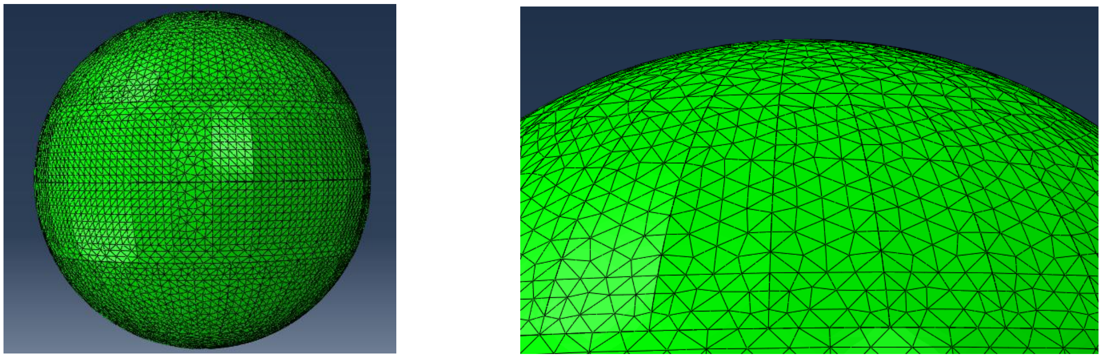
Table 1: The out-of-roundness of the polyhedron under different pressure (MPa)

Parameters	2. 4	2.6	2.8	3.0
Out-of-roundness (%)	0.51	0.46	0.35	0.43
maximum deviation(mm)	47	46.19	44.18	22

Table 2: Maximum thinning rate of the polyhedron wall thickness under different pressure (MPa)

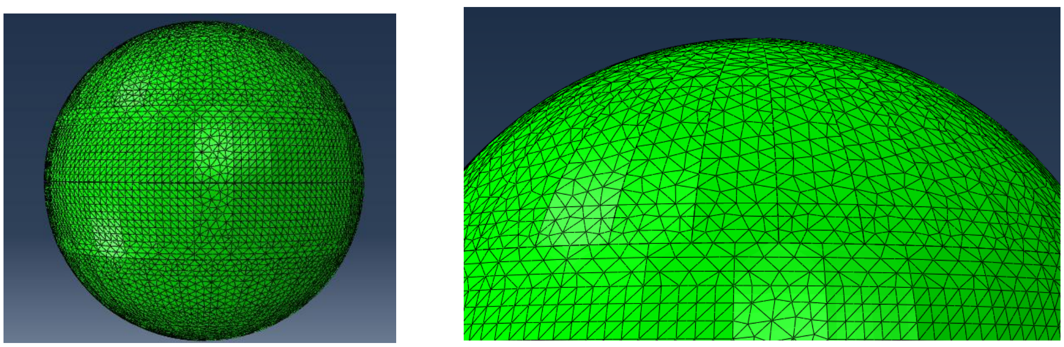
Parameters	2.4	2.6	2.8	3.0
Maximum thinning rate (%)	0. 34	0.33	0.54	0.9 9
Wall thickness (mm)	44.3	44.3	44.2	44

The stress, strain and displacement distributions of the polyhedron are calculated under the internal pressure 2.4, 2.6, 2.8and 3.0MPa. Fig.4 is the single curvature polyhedron before bulging. Fig.5 is the polyhedron after bulging of 2.6MPa and unload. Fig.6, Fig.7 and Fig.8 are the stress, strain and displacement distributions of the polyhedron after the bulging of the pressure of 2.6MPa and unload.



(a) General view (b) Partial view

Figure 4: The single-curvature polyhedron before hydro-bulging



(a) General view (b) Partial view

Figure 5: Single-curvature polyhedron after hydro-bulging under 2.6MPa

From the Table 1, it can be seen that when the internal pressure is equal and greater than 2.4MPa, the out-of-roundness is less than 1% and maximum deviation is less than the maximum permissible deviation 53.34mm. So the two parameters satisfy the requirements of acceptance criteria for hydro-bulging formed polyhedron as spherical containment vessel. From this point, it can be said that the polyhedron can be considered as a spherical containment vessel satisfying relevant requirement in ASME III NE-4200.

From Table 2, the values of the wall thickness of the polyhedron after bulging is greater than 37.2mm, which satisfy the acceptance criteria.

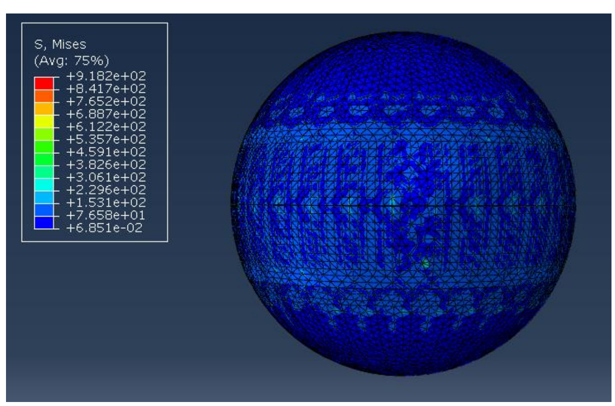


Figure 6: Stress distribution of single-curvature polyhedron under 2.6MPa

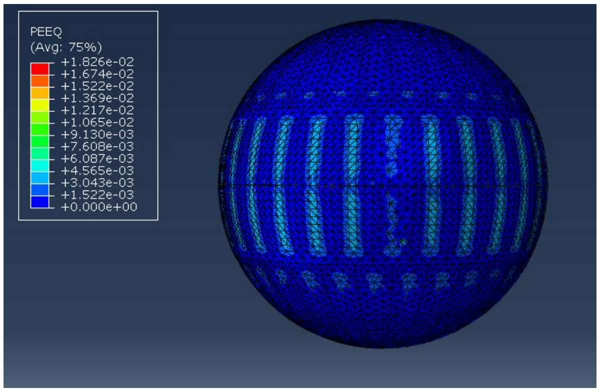


Figure 7. Strain distribution of single-curvature polyhedron under 2.6MPa

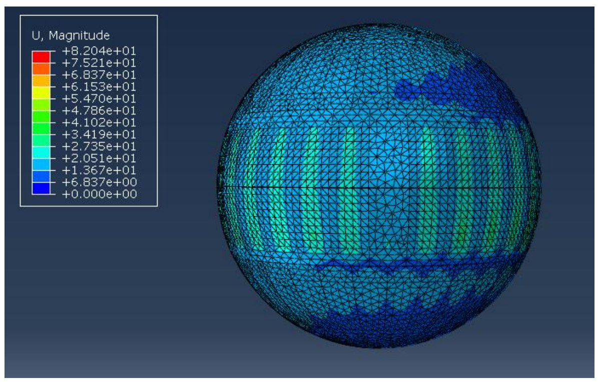


Figure 8. Displacement distribution of single-curvature polyhedron under 2.6MPa

5.2.2 Influence of gravity and hydrostatic pressure on the bulging process

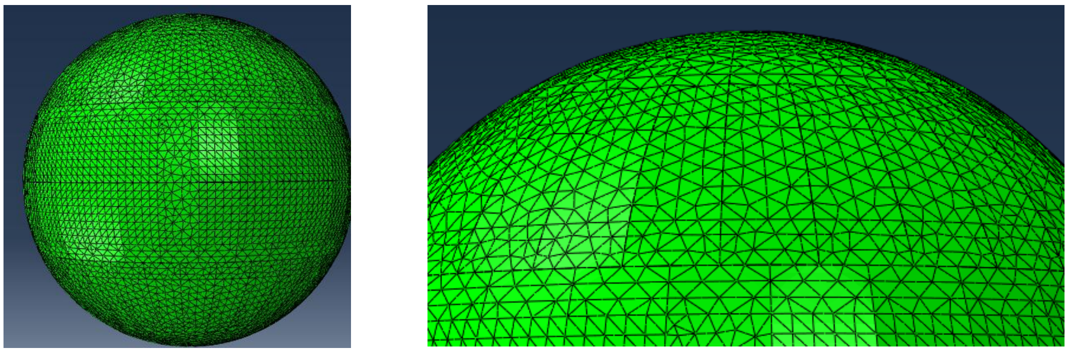
When the polyhedron is supported on the platform, and water is used as pressure medium to hydro-bulge the polyhedron during the bulging process. Gravity and hydrostatic pressure have to be taken into consideration. The density of the polyhedron material and water are taken as 7850kg/m^3 and 1000kg/m^3, respectively. Gravity-acceleration is 9.8m/s^2. The maximum hydrostatic pressure is 0.245MPa and occurs at the bottom inner surface of the polyhedron. The out-of-roundness of the polyhedron under different pressure and maximum deviation from true theoretical form under different pressure values are listed in Table 3. The wall thickness of the polyhedron and the wall thinning rate are listed in Table 4.

Table 3: The out-of-roundness of the polyhedron under gravity, static pressure and different bulging pressure (MPa)

Parameters	2. 4	2.6	2.8	3.0
Out-of-roundness (%)	0.72	0.58	0.45	0.13
maximum deviation (mm)	51.6	39.1	32.0	26

Table 4: Maximum thinning rate of the polyhedron wall thickness under gravity, static pressure and different bulging pressure (MPa)

Parameters	2.4	2.6	2.8	3.0
Maximum thinning rate (%)	0. 1	0.56	0.56	1
Wall thickness (mm)	44.402	44.203	44.205	44.004



(a) General view (b) Partial view

Figure 9: Single-curvature polyhedron after hydro-bulging under gravity, static pressure and bulging pressure 2.6MPa

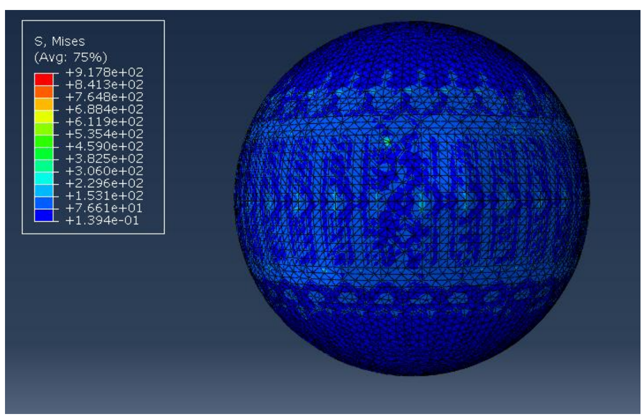


Figure 10: Stress distribution of single-curvature polyhedron under gravity, static pressure and bulging pressure 2.6MPa

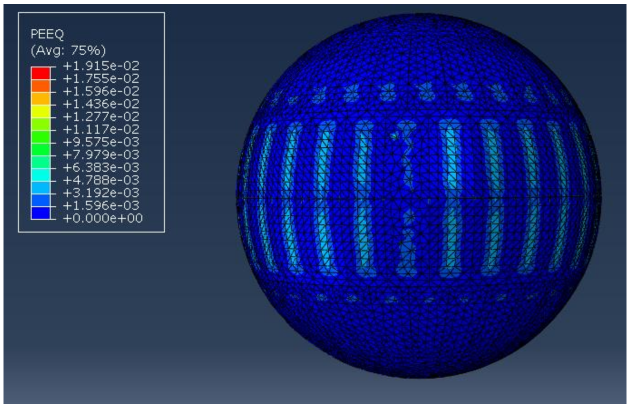


Figure 11. Strain distribution of single-curvature polyhedron under gravity, static pressure and bulging pressure 2.6MPa

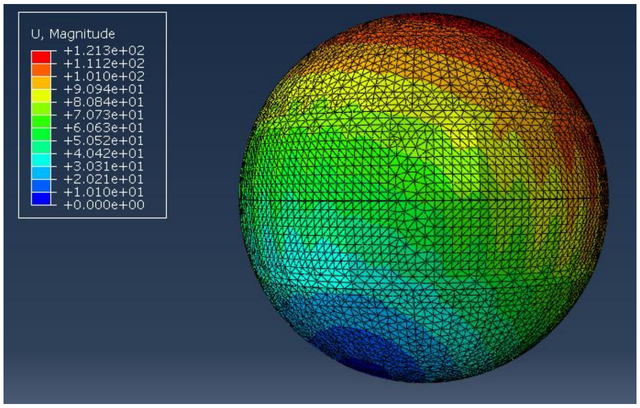


Figure 12. Displacement distribution of single-curvature polyhedron under gravity, static pressure and bulging pressure 2.6MPa

From Table 3， it can be known that when gravity, static pressure are taken into consideration and the internal pressure is greater than 2.4MPa, the out-of-roundness is less than 1% and maximum deviation is less than the maximum permissible deviation 53.34mm. So the two parameters satisfy the requirements of acceptance criteria for hydro-bulging formed polyhedron as spherical containment vessel. From this point, it can be said that the polyhedron can be considered as a spherical containment vessel satisfying relevant requirement in ASME III NE-4200.

From the Table 4, the wall thickness of the polyhedron is greater than 37.2mm. Besides, there is enough allowance for corrosion.

6. CONCLUSIONS

In this paper, the authors try to explore the influence of support of the single-curvature polyhedron on the bulging process to use the single-curvature polyhedron for manufacturing spherical vessel in the construction of a reactor containment vessel. Besides, the influence of hydrostatic pressure and gravity are also taken into consideration. The overall study was based on the target spherical containment vessel, internal diameter of which is 25000mm, wall thickness 44.45mm and material SA738Gr.B. The research results can be summarized are as follows:

(1) When the polyhedron is supported on a platform by the lower polar zone and the internal pressure is between 2.4MPa and 3.0MPa, the maximum out-of-roundness and the maximum deviation from the theoretical sphere of the polyhedron are respectively 0.51% and 47.0mm after the hydro-bulging process and unload. The values satisfy the requirement of ASME III NE4200. Besides, the maximum thinning rate of the polyhedron wall thickness under different pressure is less than 1.0%, which conforms to the requirement of the acceptance criteria.

(2) If the polyhedron is supported on a platform by the lower polar zone, gravity and hydrostatic pressure are taken into consideration and the internal pressure of the polyhedron is between 2.4MPa and 3.0MPa, the maximum out-of-roundness and the maximum deviation from the theoretical sphere of the polyhedron are respectively 0.72% and 51.6mm. These values satisfy the requirement of ASME III NE4200. In addition, the maximum thinning rate of the polyhedron wall thickness under different pressure is less than 1.0%, and the values of the wall thickness of the polyhedron after bulging is greater than 44.4mm which conforms to the requirement of the acceptance criteria.

According to the above numerical calculation results, it can be expected that adopting the new single-curvature polyhedron to manufacture the steel spherical containment vessel of the reactor by hydro-bulging process is also feasible under the influence factors of support, gravity and hydrostatic.

REFERENCE

WOLFGANG K. E. BRAUN and KLAUS HASSMANN, THE REACTOR CONTAINMENT OF STANDARD-DESIGN GERMAN PRESSURIZED WATER REACTORS, NUCLEAR TECHNOLOGY, VOL.72, 1986, pp268~290.

M.D. Carelli L. conwey et al., THE DESIGN AND SAFETY FEATURES OF THE IRIS REACTOR, ICONE 11, 11th International Conference on Nuclear Engineering, Tokyo, JAPAN, April 20-23, 2003.

IAEA, Advances in Small Modular Reactor Technology Developments, 2020, pp41~44.

Dong Jianling, Z.R. Wang, Cengdian Liu, Single-curvature Polyhedron Hydro-bulging Technology for Manufacturing Spherical Vessels, Proceedings of the 7th ICPVT, May 31-June 5, 1992, pp.1007~1012.

Dong Jianling, Huang Xingcheng , Chen Ke, Ning Bo Hao, Study on Application of the Single-Curvature Polyhedron Hydro-Bulging Technology in Metallic Reactor Containment, Proceedings of ICONE31, August 4-8, 2024, Prague, Czech Repulic.

ASME, SECTION Ⅲ, RULES FOR CONSTRUCTION OF NUCLEAR FACILITY COMPONENTS, DIVISION 1, SUBSECTION NE, 2015.

Xiaoping Zhang, Research on Bearing Capacity Testing Machine for Steel Containment Ellipsoidal Heads of Nuclear Power Plant, Master’s thesis of Zhejiang University, 2016.