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Finite Element Analysis of the Displacement Adjustment Scheme for Column Bases of a 10000 m^3 Spherical Tank during Whole-Body Heat Treatment

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Abstract

The stress of spherical tank and displacement of column bases were calculated by finite element method, considering the uneven gravity loads on support columns which was caused by manufacturing and setting errors. The preliminary displacement adjustment scheme for column bases was made, according to the safety range of column bases displacement which was determined by the maximum stress restricted by allowable stress at the set heat treatment temperatures. The final scheme was made after checking the preliminary scheme. The method of making adjustment scheme of column bases for a 10000m^3 spherical tank during the whole-body heat treatment may provide a reference for other large spherical tank.

Keywords: Finite element; Spherical tank; Heat treatment; Displacement of column bases

1. Introduction

With the progress of equipment manufacturing technology, the spherical tank is increasingly developed to large-scale. The postweld heat treatment is an important procedure during the construction of spherical tank, especially for the spherical tank working in stress corrosion environment. Usually, the whole-body heat treatment is adopted, for which there are rich practical experiences for middle and small spherical tank but lack of technical support and practical experience accumulation for large scale one.

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Compared with middle and small sized spherical tank, large scale spherical tank has following features: heavy weight, great difficulty of error control during manufacturing and larger expansive capacity when heated. Those may cause excessive stress in spherical tank during heat treatment. In order to ensure the safety of the spherical tank during the whole-body heat treatment, some literature[1] suggests that: during heat treatment, the displacement of column base plates shall be monitored, and be adjusted in time with respect to the calculated displacement. Generally, adjusting once per 100℃ temperature change is preferable. But this suggestion does not consider some details which are likely to cause security problem, taking heavy weight and manufacturing errors for examples. In literature [2] the body strength and rigidity were checked for a 10000m^3 spherical tank during the heat treatment and the displacement safety range of column bases was calculated at the set heat treatment temperature points under the consideration of existing manufacturing errors of support columns and temperature difference load. But the specific adjustment scheme of column bases during heat treatment was not given.

The studies on the displacement adjustment scheme of column bases were carried out in this paper, taking a 10000m^3 spherical tank for example, considering the uneven gravity load on support columns caused by manufacturing and setting errors and temperature difference load during heat treatment.

2. Finite element model

2.1. Geometric model and finite element mesh

Figure 1 shows the structure diagram of the 10000 m^3 spherical tank. Main material of the spherical tank is Q345R, wall thickness is 36 mm, diameter is 26800 mm, with 14 support columns. The connection type of support columns to spherical shell is U bracket column type.

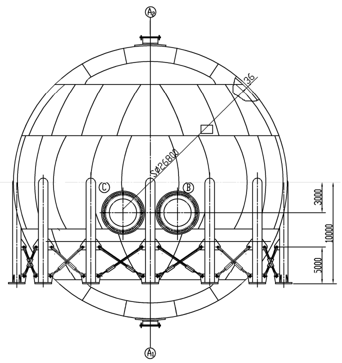

Fig. 1. Structure diagram of the 10000m^3 spherical tank.

The tie rods were not modeled, for the turn buckles of the tie rods are completely loosing during heat treatment which would not affect the stress state of the spherical tank.

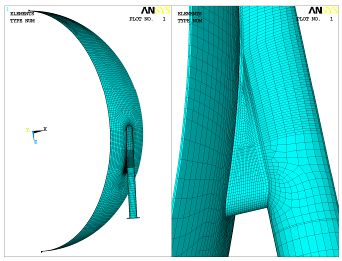

Fig. 2. Finite element calculation model.

The structure of the spherical tank is symmetrical, but the loads of the whole spherical tank are not symmetrical under the consideration of uneven gravity loads on support columns caused by manufacturing and setting errors. In order to decrease the calculation scale, it was assumed that gravity loads on other support columns were equal to the gravity load on some one of them which maybe larger or smaller than the average gravity load in this paper. The 1/14 model of the spherical tank was shown in Fig. 2, in which Solid95 element was adopted. The number of grid level was 2 in the thickness direction of the spherical shell, and the grids were refined around the connection of support column to spherical shell where the excessive stress may appear.

2.2. Load and boundary condition

As the boundary condition of stress calculation, the temperature filed of the 10000m^3 spherical tank during heat treatment must be calculated previously[3]. It was assumed that the temperature T of heating gas was evenly distributed in spherical tank. It is convection heat transfer between heating gas and inner wall of the spherical tank. The outer wall of the spherical tank is covered with 50mm thick insulating layer. The outer wall of the insulating layer convects with the outside gas with temperature T' which determined by local temperature when heat treatment conducted. It is radiation heat transfer in the confined space surrounded by spherical shell, support column and U bracket.

Before the stress filed calculating, the insulating layer elements were deleted. The gravity load caused by insulating layer was applied on the spherical shell by means of equivalent density. The gravity acceleration in vertical direction was set to $g'=ag$ (a, the uniformity coefficient of gravity loads on support columns, $0\leq a < i$, i=14, the number of support columns of the spherical tank). Temperature load was applied by reading the resultant file of temperature field previously calculated. The vertical displacement of the column base plate and the normal displacements of the symmetry planes of the spherical shell were constrained. The radial equivalent friction $f'=bf$(b, the uniformity coefficient of friction on the column base plate, $b=a$; f, the mean radial friction on the column base plate when the spherical shell expanded as the heat treatment temperature increased, $f=mg\mu/i$; m, the mass of spherical tank and insulating layer; μ, friction coefficient between column base plate and foundation of the spherical tank[1]) was applied on the column base plate.

2.3. Material properties

During heat treatment, the temperature of the spherical tank changes and there also maybe large temperature gradient in some local areas. The thermophysical and mechanical properties of the main material of the spherical tank in different temperatures are listed in table 1[4][5].

Table 1. Thermophysical and mechanical properties of the main material of the spherical tank in different temperatures.

Material properties	20℃	200 ℃	350 ℃	500 ℃	630 ℃
Elastic modulus E（10^3MPa）	201	191	178	149	127.993
Poisson ratio ν	0.3	0.3	0.3	0.3	0.3
Thermal expansion coefficient α(10^{-6}mm/℃)	10.904	12.25	13.24	14.22	14.86
Thermal conductivity λ(W/m℃)	52	48.6	44.5	39	32

3. The safety range of displacement of column bases at different heat treatment temperature

According to literature[1], the displacement of column base plates was recommend to adjust once per 100℃ temperature change. In this paper, the equivalent friction f' in radial direction and the gravity acceleration g' in vertical direction changed with b and a, which increased from 0 to some appropriate value, were applied on the finite element calculation model at the following six heat treatment temperature points of 100℃, 200℃, 300℃, 400℃, 500℃, 600℃ respectively. The calculation results showed that the maximum stresses of the spherical tank were all located in the connection of U bracket to support column, shown in Fig. 3 and Fig. 4 (heat treatment temperature: 100℃ and 600℃, *b=1.0*, for example). According to literature[6],the stress includes the stress produced by thermal should be classified to secondary stress(Q), the sum of local primary membrane stress(P_L), primary bending stress(P_b) and secondary stress(Q),namely P_L+P_b+Q, should be restricted by the allowable stress $2R_{el}^t$.

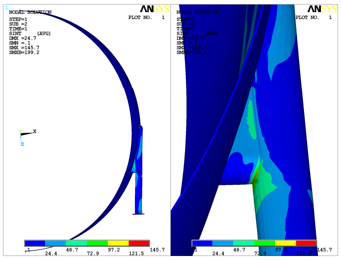

Fig. 3. Stress contour map at the condition when heat treatment temperature is 100℃ and b=1. 0.

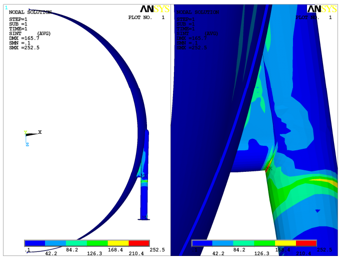

Fig. 4. Stress contour map at the condition when heat treatment temperature is 600℃ and b=1. 0.

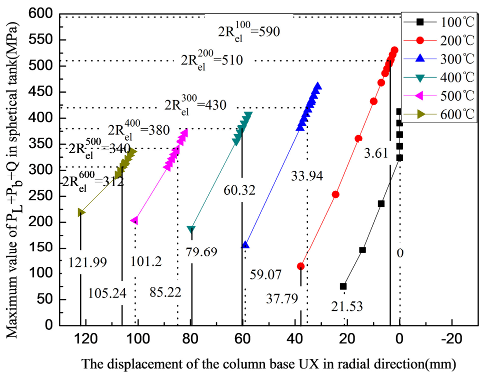

Fig. 5. The relationship between the maximum values of P_L+P_b+Q and the displacement of column base under different conditions.

When the value of b increased from 0 to some appropriate value, the relationship between the maximum values of P_L+P_b+Q in the spherical tank and the displacements of column bases at the above heat treatment temperature points are shown in Fig. 5. The allowable minimal displacement of the column base $U_{x\min}^t$ can be obtained when the maximum value of P_L+P_b+Q equals to the value of $2R_{el}^t$ at the heat treatment temperature point t. The allowable maximum displacement of the column base $U_{x\max}^t$ can be obtained when b=0. The spherical tank is safe when the displacement of the column base is between $U_{x\min}^t$ and $U_{x\max}^t$ at the heat treatment temperature t.

From Fig. 5, the safety ranges of the displacements of the column base at above heat treatment temperature points are as follows: 100 ℃ , U_x^{100} =0~21.53mm ; 200 ℃ , U_x^{200} =3.61~37.79mm ; 300 ℃ , U_x^{300} =33.94~59.07mm ; 400℃, U_x^{400} =60.32~79.69mm; 500℃, U_x^{500} =85.22~101.2mm; 600℃, U_x^{600} =105.24~121.99mm. It can be found that there are no overly areas for the two safety ranges at the adjacent heat treatment temperature points of t and (t+100) from t=300℃, namely $U_{x\max}^{t} < U_{x\min}^{t+100}$, which means that adjusting the displacement of the column bases once per 100℃ temperature change as literature[1] suggested is most likely to be unsafe for the spherical tank. For this case, the safety ranges of the displacements of the column base at the heat treatment temperature points of 350℃, 450℃ and 550℃ were calculated. The results are shown in Fig. 6.

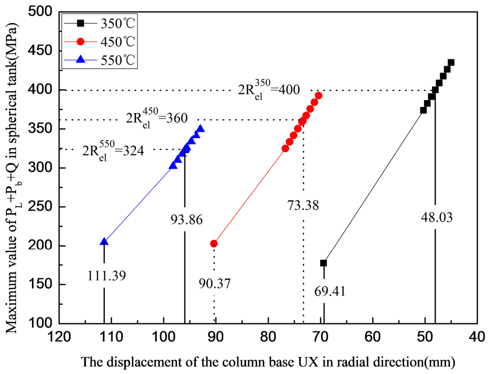

Fig. 6. The relationship between the maximum values of P_L+P_b+Q and the displacement of column base under different conditions.

4. Preliminary scheme of adjustment of column base

The adjustment schemes of different column bases are different, due to the difference of radial equivalent frictions on the column base plates when the spherical shell expands as the heat treatment temperature increases. The radial equivalent friction on the specified column base plate, determined by the value of b(uniformity coefficient of friction on the column base plate), was assumed to be invariable during the heat treatment. So, it is reasonable and feasible to make the adjustment scheme of the column base by judging the value of b previously. Fig. 7 shows the maximum values of P_L+P_b+Q in spherical tank change with the values of b at different heat treatment temperature points (Fig. 7 does not include the heat treatment temperature point of 100℃, due to its smaller stress shown in Fig. 5). The allowable maximum values of b can be obtained when the maximum values of P_L+P_b+Q equal to the values of $2R_{el}^{t}$ at different heat treatment temperature points.

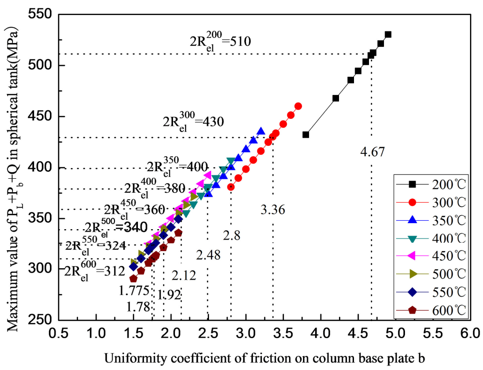

Fig. 7. The maximum values of P_L+P_b+Q in spherical tank change with the values of b at different heat treatment temperature points.

From Fig. 7, it is not necessary to adjust the displacement of the column base artificially, when $b<1.775$; the displacement of the column base should be adjusted from the heat treatment temperature point of 500℃ artificially, when $1.775\leq b<1.92$; the displacement of the column base should be adjusted from the heat treatment temperature point of 450℃ artificially, when $1.92\leq b<2.21$; the displacement of the column base should be adjusted from the heat treatment temperature point of 400℃ artificially, when $2.21\leq b<2.48$; the displacement of the column base should be adjusted from the heat treatment temperature point of 350℃ artificially, when $2.48\leq b<2.8$; the displacement of the column base should be adjusted from the heat treatment temperature point of 300℃ artificially, when $2.8\leq b<3.36$; the displacement of the column base should be adjusted from the heat treatment temperature point of 200℃ artificially, when $3.36\leq b<4.67$. The preliminary adjustment scheme of column base was made, according to Fig. 5, Fig. 6 and Fig. 7, shown in table 2.

Table 2. The preliminary adjustment scheme of column base(the displacement should be adjusted to at the corresponding heat treatment temperature point of t/mm)

The point of heat treatment temperature *t* /℃ The value of *b*	200	300	350	400	450	500	550
$b<1.775$	—						
$1.755\leq b<1.92$	—					101.2	111.39
$1.92\leq b<2.12$	—				90.37	101.2	111.39
$2.12\leq b<2.48$	—			79.69	90.37	101.2	111.39
$2.48\leq b<2.8$	—		69.41	79.69	90.37	101.2	111.39
$2.8\leq b<3.36$	—	59.07	69.41	79.69	90.37	101.2	111.39
$3.36\leq b<4.67$	37.79	59.07	69.41	79.69	90.37	101.2	111.39

The relationship between the displacement of the column base and the value of b at the heat treatment temperature point of 200℃, calculated by using finite element, are shown in Table 3. The values of b can be obtained by checking Table 3, according to the results of measurement on the displacements of the column bases when the heat treatment temperature is 200℃ on site.

Table 3. The relationship between the displacement of the column base and the value of b at the heat treatment temperature point of 200℃.

The value of *b*	1	1.2	1.4	1.6	1.8	2	2.2
Displacement of the column base/mm	30.32	28.87	27.41	25.95	24.5	23.04	21.59
The value of *b*	2.4	2.6	2.8	3	3.2	3.4	3.6
Displacement of the column base/mm	20.13	18.68	17.22	15.77	14.31	12.85	11.4
The value of *b*	3.8	4	4.2	4.4	4.6	4.8	
Displacement of the column base/mm	9.94	8.49	7.03	5.58	4.12	2.67	

5. Reasonableness check of the preliminary scheme

The safety ranges of the displacement of the column bases, calculated above, at the heat treatment temperature points of 200℃, 300℃, 350℃, 400℃, 450℃, 500℃, 550℃ and 600℃ show that there are overly areas for the two safety ranges at the adjacent heat treatment temperature points, namely $U^{t}_{x\max} > U^{t+50}_{x\min}$ ($U^{t}_{x\max} > U^{t+100}_{x\min}$ when t<300℃), which means that the safety of the spherical tank can be guaranteed to a certain extent during the heat treatment as long as adjusting the displacement of the column base to $U^{t}_{x\max}$ at the heat treatment temperature point of t when the temperature increases from the heat treatment temperature point of t to t+50(t+100, when t<300℃). But the unsafety may exist, for the values of b corresponding to the values of $U^{t}_{x\min}$, which are shown in Table 4, are most likely not equal to the values measured on site. For example, the displacement of the column base should be adjusted to $U^{400}_{x\max}$ artificially at the heat treatment temperature point of 400℃ if b_0=2.4 measured on site according to Table 2, but the value of b=2.12 corresponding to the value of $U^{450}_{x\min}$ is not equal to b_0, so as to the spherical tank maybe not safe with the boundary condition as follows: displacement of $U^{400}_{x\max}$ of the column base which assumed to keep invariant when the heat treatment temperature increases from 400℃ to 450℃, a=b_0, t=450℃.

Table 4. The values of b corresponding to the values of $U^{t}_{x\min}$ at different heat treatment temperature point.

$U^{t}_{x\min}$	$U^{200}_{x\min}$	$U^{300}_{x\min}$	$U^{350}_{x\min}$	$U^{400}_{x\min}$	$U^{450}_{x\min}$	$U^{500}_{x\min}$	$U^{550}_{x\min}$	$U^{600}_{x\min}$
b	4.67	3.36	2.8	2.48	2.12	1.92	1.775	1.78

For the case above, the preliminary scheme in Table 2 should be checked. According to Table 2, the displacement of the column base should be adjusted to $U^{t}_{x\max}$, when $b_i \le b < b_j$ at the heat treatment temperature point of t. The checking boundary conditions are as follows: a.the temperature filed calculated previously at the heat treatment temperature point of t=t+50(n+1)(t=t+100(n+1), when t<300℃, n=0, 1, 2, 3…, t≤600℃); b.the displacement of the column base $U^{t+50n}_{x\max}$ ($U^{t+100n}_{x\max}$ when t<300℃); c.the gravity acceleration in vertical direction $g'=a_j g$($a_j=b_j$). The results of checking were listed in Table 5–10.

Table 5. The results of checking when 1.775≤b<1.92.

Heat treatment temperature point t/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
550	291.66	324	Passed
600	279.293	312	Passed

Table 6. The results of checking when 1.92≤b<2.12.

Heat treatment temperature point t/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
500	306.989	340	Passed
550	296.033	324	Passed
600	283.075	312	Passed

Table 7. The results of checking when 2.12≤b<2.48.

Heat treatment temperature point t/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
450	318.703	360	Passed
500	314.873	340	Passed
550	303.903	324	Passed
600	291.647	312	Passed

Table 8. The results of checking when 2.48≤b<2.8.

Heat treatment temperature point t/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
400	311.664	380	Passed
450	325.725	360	Passed
500	321.882	340	Passed
550	310.899	324	Passed
600	298.707	312	Passed

Table 9. The results of checking when 2.8≤b<3.36.

Heat treatment temperature point t/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
350	317.515	400	Passed
400	324.055	380	Passed
450	338.02	360	Passed
500	334.147	340	Passed
550	323.142	324	Passed
600	311.062	312	Passed

The preliminary scheme in Table 2 should be modified, for the results of checking at some heat treatment temperature points did not pass when $3.36 \le b < 4.67$, which shown in Table 10. The heat treatment temperature points of 425℃, 475℃, 525℃, 575℃ were added and the values of $U^{t}_{x\max}$ were calculated. The modified scheme was shown in Table 11.

The modified scheme was checked newly when $3.36 \le b < 4.67$. The boundary conditions are as follows: *a*.the temperature filed calculated previously at the heat treatment temperature point of $t=t+25(n+1)$($n=0, 1, 2, 3\ldots$, $t \le 600$℃); *b*.the displacement of the column base $U^{t+25n}_{x\max}$; *c*.the gravity acceleration in vertical direction $g'=4.67g$. The results of checking were listed in Table 12.

The results of checking were all passed after modification, shown in Table 12. The scheme in Table 11 is the final scheme of adjustment of column bases which combines with Table 3 can be as a reference for monitor and adjustment of the column bases during the heat treatment for a 10000 m^3 spherical tank on site.

Table 10. The results of checking when 3.36≤b<4.67.

Heat treatment temperature point *t*/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
300	424.990	430	Passed
350	346.620	400	Passed
400	353.064	380	Passed
450	367.054	360	Did not pass
500	362.966	340	Did not pass
550	351.784	324	Did not pass
600	339.966	312	Did not pass

Table 11. The modified adjustment scheme of column bases(the displacement should be adjusted to at the corresponding heat treatment temperature point of *t*).

Heat treatment temperature point of *t*/℃ The value of *b*	200	300	350	400	425	450	475	500	525	550	575
b＜1.755	—										
1.755≤*b*＜1.92	—							101.2	—	111.39	—
1.92≤*b*＜2.12	—					90.37	—	101.2	—	111.39	—
2.12≤*b*＜2.48	—			79.69	—	90.37	—	101.2	—	111.39	—
2.48≤*b*＜2.8	—		69.41	79.69	—	90.37	—	101.2	—	111.39	—
2.8≤*b*＜3.36	—	59.07	69.41	79.69	—	90.37	—	101.2	—	111.39	—
3.36≤*b*＜4.67	37.79	59.07	69.41	79.69	85.01	90.37	94.74	101.2	106.3	111.39	116.8

Table 12. The results of checking when 3.36≤b<4.67 after modification.

Heat treatment temperature point *t*/℃	Maximum value of P_L+P_b+Q/MPa	Allowable stress/MPa	Result
450	325.234	360	passed
475	318.365	350	passed
500	331.003	340	passed
525	321.004	332	passed
550	318.337	324	passed
575	313.73	318	passed
600	308.631	312	passed

6. Conclusions

It may be unsafe for large scale spherical tanks during the whole-body heat treatment because of heavy weight, great difficulty of error control during manufacturing and setting and larger expansive capacity when heated. The adjustment scheme of column bases during heat treatment was developed for a 10000 m^3 spherical tank in this paper, which could provide a reference for other large scale spherical tanks.

Acknowledgements

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