Unique design of the junction between a thick pressure vessel shell and a thinner hemispherical head

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Abstract: Considering the fact that the required thickness of a hemispherical head for pressure loading is only half of that necessary for a cylindrical shell, the authors have developed a proprietary junction of shell to hemispherical head where the head is thinner than the shell. In the past 5 years, more than 100 high-pressure vessels with such junctions have been manufactured and safely used in the People's Republic of China. Theoretical investigations as well as engineering applications show that such junctions are rational in structure, convenient in fabrication and low in cost. For example, for a vessel with an inner diameter of 1000 mm and design pressure of 31.4 MPa, using the new junction, the head weight is reduced by 54.3 and 27.4 per cent respectively in comparison with a forged flat head and a hemispherical head with equal thickness of shell. The larger the vessel, the greater the economic benefits it achieves. In this paper, the authors describe its basic structure, stress characteristics and the engineering design method for the unique junction.

Keywords: high-pressure vessel, reinforcing ring, hemispherical head

NOTATION

D_i	inner diameter of the vessel (mm)
H	height of the reinforcing ring (mm)
h	height of the inner cylindrical surface of the reinforcing ring (mm)
P	design pressure (MPa)
R_i	inner radius of the hemispherical head (mm)
R_{ho}	inner radius of the cylindrical surface of the reinforcing ring (mm)
R_o	outer radius of the reinforcing ring (mm)
β	angle of the tapered surface (degree)
δ_m	nominal thickness of the hemispherical head (mm)
δ_n	nominal thickness of the shell (mm)
Δ	the difference between the outer radius of the hemispherical head and the inner radius of the cylindrical surface of the reinforcing ring (mm)

The MS was received on 4 May 2001 and was accepted after revision for publication on 12 September 2001.
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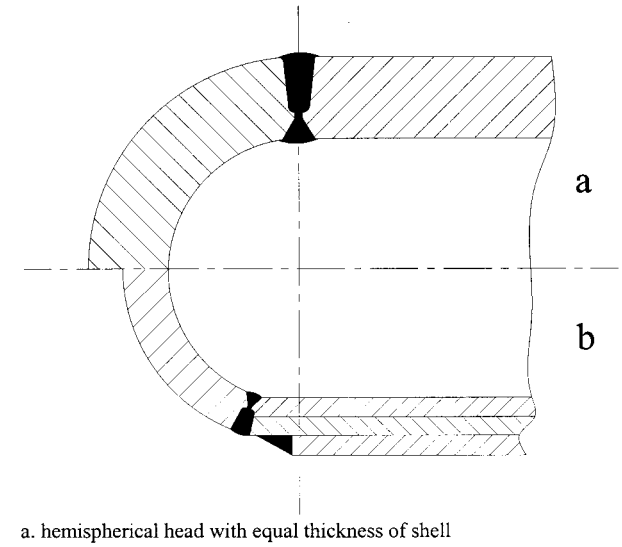
1 INTRODUCTION

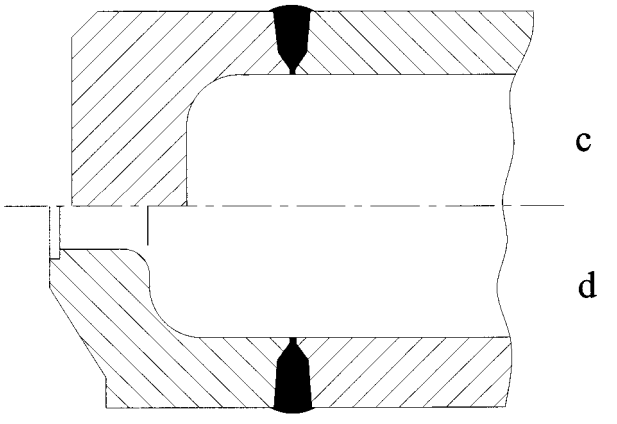
High-pressure vessels, such as ammonia converters, urea reactors and supercritical fluid extractors, etc., are widely used in chemical, oil refining, energy industries, and so on. Such vessels are key equipments in various processes and have potential hazards. Much attention has been paid to using them safely and to lowering their costs, with great progress being made in the last century. For example, the flat steel ribbon wound pressure vessel invented by Zhu not only greatly reduces the cost in fabrication but also creates a high reputation for safety [**1, 2**]. However, the majority of these vessels uses hemispherical heads with equal thickness of shell, partial spherical heads, forged flat heads, thinner hemispherical heads with layered or welded transition and forged compact heads, which are shown in Fig. 1. These heads are made from either thick steel plates or large forgings. They become more difficult to fabricate and cost more with the increase of inner diameter and/or operating pressure [**3**].

It is well known that the required hemispherical head thickness is only half that of a cylindrical shell under the same design condition with internal pressure. This suggests that the thickness of the hemispherical head can be less than that of the shell. Unfortunately, high



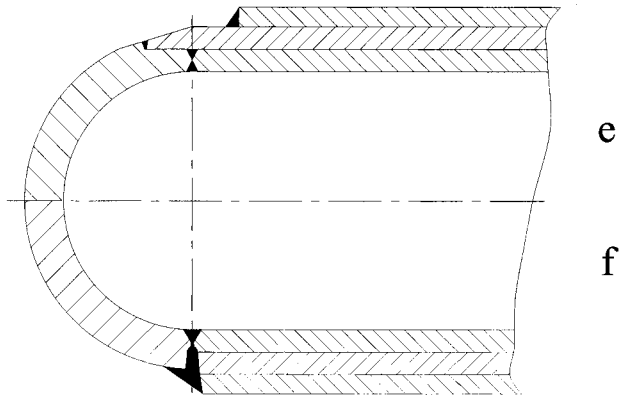
a. hemispherical head with equal thickness of shell

b. partial spherical head



c. forged flat head

d. forged compact head



e. thinner hemispherical head with layered transition

f. thinner hemispherical head with welded transition

Fig. 1 Currently available junctions of thick shell to head

stress concentration factors occur in the vicinity of the junction if they are directly welded together. In order to reduce local stress, transitions with a 3:1 taper minimum are adopted in many pressure vessel codes [**4**–**9**] and some proprietary junctions [**1**, **10**]. Depending on the attachment of the hemispherical head to the shell, it is shown in Fig. 1 that the transition may be made either in the hemispherical head section by adding weld metal or in the shell section by pre-cutting the end of the solid cylinder or by using a layered transition at the end for layered cylinders such as concentric wrapped shells or shrink-fit shells. For flat steel ribbon wound cylindrical shells, the hemispherical head thickness should be greater than that of the shell to weld ribbons at both ends [**1**].

In order to make full use of the advantage of a hemispherical head, the authors have devised a unique junction between a thick shell and a hemispherical head where the head is thinner than that of the shell by using a reinforcing ring outside the hemispherical head. This overcomes difficulties associated with making the tapered transitions currently available. In the past 5 years, more than 100 high-pressure vessels with such junctions have been constructed and used safely in the People's Republic of China. The maximum inner diameter of these vessels is 1600 mm, the minimum 600 mm and design pressure ranges from 10.0 to 31.4 MPa. Theoretical investigations as well as engineering practice show that the junction is rational in structure, convenient in fabrication, safe in use and low in cost. The weight of the head can be significantly reduced, and hence significant economy can be achieved by using the junction. The larger the vessel, the higher the pressure and the greater the economic benefits.

2 BASIC STRUCTURE

The unique junction between the thick shell and the thinner hemispherical head is shown in Fig. 2. When the shell is a solid shell, shrink-fit shell, spiral wrapped shell or coil wound shell, Fig. 2a should be used. There is a deep-groove, through-thickness butt weld between the shell and hemispherical head. If the shell is a flat steel ribbon wound cylindrical shell or concentric wrapped shell, Fig. 2b should be employed. In Fig. 2b, a step weld is used, which is more reliable than a deep-groove butt weld [**1**].

The reinforcing ring shown in Fig. 2c is clearance fitted at the cylindrical surface of the hemispherical head shown in Fig. 2d. They are in contact with each other on the tapered surface. There may be a small physical gap between them at the cylindrical surface, so that no associated stresses are produced during assembly. The main function of the reinforcing ring is to connect the shell to the hemispherical head and to eliminate the conventional transitions. The reinforcing ring is provided

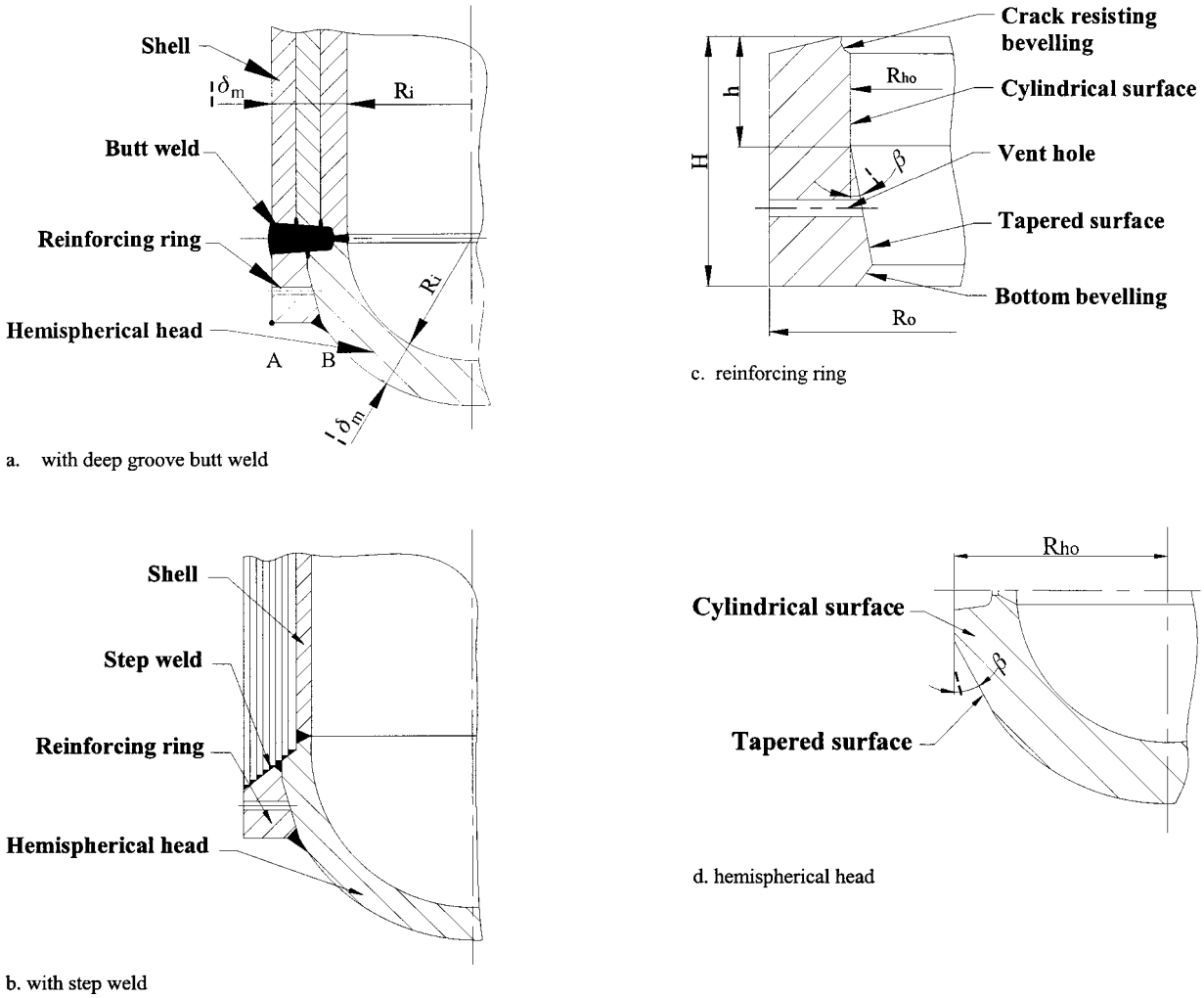


Fig. 2 Unique junction of thick shell to thinner hemispherical head

with at least two vent holes and its outside diameter equals that of the shell. The wall thickness of the hemispherical head is determined by its own requirement. In the case of very high pressures and larger diameters, layered hemispherical heads may be used. For vertical vessels, no additional support lugs or rings are needed, since the bottom of the reinforcing ring can be used as a supporting surface.

A typical manufacturing procedure for the new junction is as follows. Respectively, both cylindrical and tapered surfaces are machined at the outside surface of the hemispherical head formed from steel plate and the inside surface of the reinforcing ring made up of steel plate by rolling and welding. Both the reinforcing ring and hemispherical head have the same inclining angle β. They are assembled and welded at the bottom of the reinforcing ring, followed by weld inspection and machining crack-resisting bevelling and butt weld/step weld bevelling. The hemispherical head with a reinforcing ring has now been prepared for welding between the shell and head.

3 STRESS CHARACTERISTICS

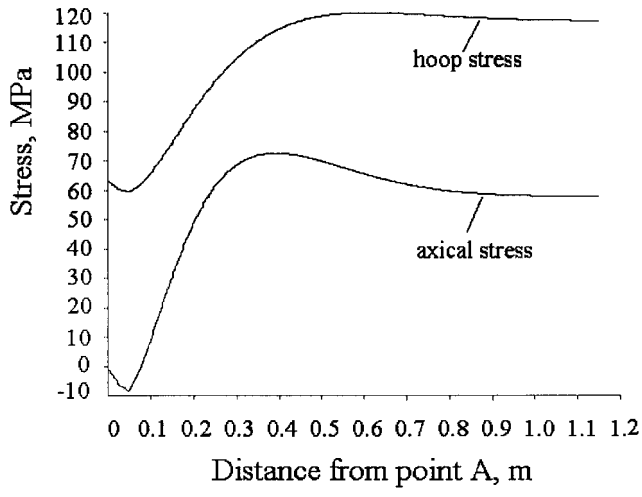
In order to reveal stress distributions near the junction and to develop an engineering design method, both theoretical analysis and experimental investigation have been conducted. Stress measurements were made at the outside surfaces of two flat steel ribbon wound vessels and one shrink-fit vessel with a design pressure of 31.4 MPa and internal diameters of 600, 800 and 1000 mm respectively [**11**]. Results showed that the reinforcing ring has a significant reinforcing effect on the shell.

A stress analysis model with finite element analysis has been developed by considering both the change in thickness of the formed hemispherical head and the effect of the possible physical gap at the interface between the hemispherical head and the reinforcing ring [**12**], which predicts stresses in good agreement with measured ones. For a shrink-fit high-pressure vessel (ammonia separator) with parameters given in Table 1, stress distributions at the outside and inside surfaces under design pressure are shown in Fig. 3.

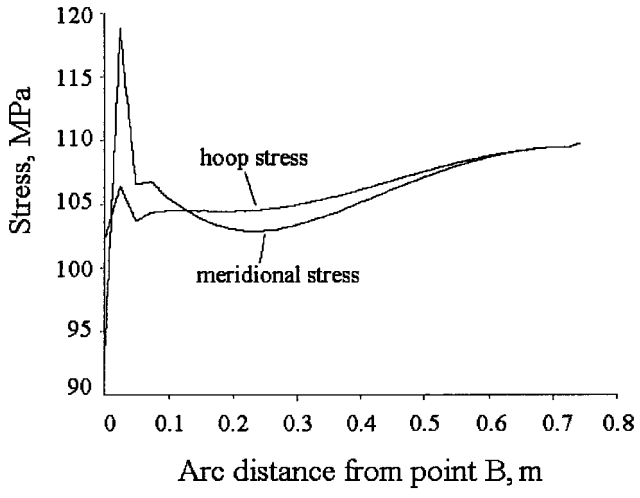
Table 1 Parameter of a calculated shrink-fit vessel

Design pressure, P (MPa)	Inner diameter of vessel, D_i (mm)	Nominal thickness of shell, δ_n (mm)	Nominal thickness of hemispherical head, δ_m (mm)	Height of reinforcing ring, H (mm)	Radius of inner cylindrical surface of reinforcing ring, R_{ho} (mm)	Angle of the tapered surface, β (deg)	Height of inner cylindrical surface of reinforcing ring, h (mm)
31.4	1005	120	70	150	567	10	60

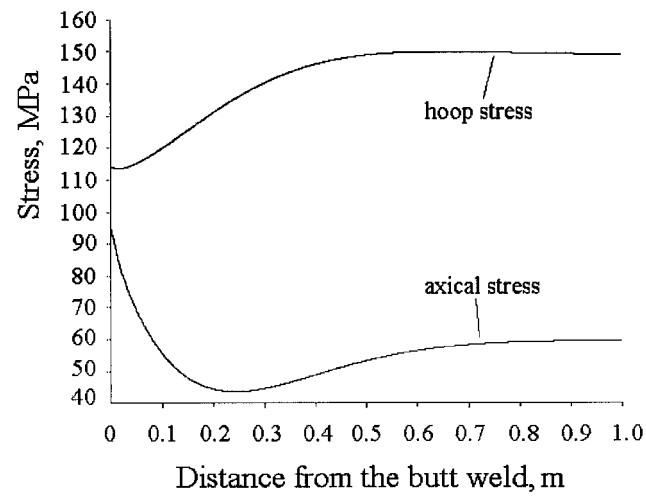
Some assumptions are as follows during stress calculations. According to the Chinese Pressure Vessel Standard GB150 [7] completed shrink-fit high-pressure vessels are subjected to post-weld heat treatment. The stresses produced in the shell due to shrink-fit are almost eliminated and negligible. Therefore, only stresses caused by internal pressure are considered. Furthermore, hoop strain measured at the midpoint between adjacent circumferential joints of the vessel showed that the gap between layers is very small. Perfect contact between layers is assumed in stress analysis. The materials of the shell, hemispherical head and reinforcing ring are 16MnR with Young's modulus of 2.0×10^5 MPa and Poisson's ratio of 0.27.



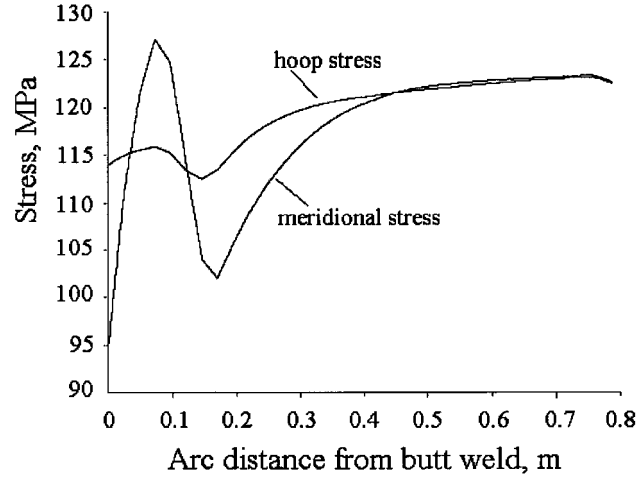
a. Outside surface of the shell



b. Outside surface of the hemisperical head



c. Inner surface of the shell



d. Inner surface of the hemispherical head

Fig. 3 Stress distributions near the junction

3.1 Stresses at outside surface

With an increase of the distance from point A shown in Fig. 2a, both axial and circumferential stresses at the outside surface (Fig. 3a) decrease, followed by an increase in these stresses until they approach the values predicted by the Lamé equation for a thick cylinder under internal pressure. Stresses in the shell at the vicinity of the weld joint are less than those far away from the butt weld, which implies no stress concentrations at the outside surface of the shell. At the outer surface of the hemispherical head (Fig. 3b, where point B is shown in Fig. 2a), both maximum hoop and meridional stresses locate near the interface between the bottom plane of the reinforcing ring and the hemispherical head. However, they are less than the maximum meridional stress at its inner surface. On the bottom plane of the reinforcing ring, stresses are very small.

3.2 Stress at inside surface

Under internal pressure, both axial and hoop stresses in the vicinity of the butt weld at the inner surface of shell (Fig. 3c) are less than hoop stress far from the weld, which also shows no stress concentrations. At the inner surface of the hemispherical head (Fig. 3d), with the increase of arc distance from the centre-line of the butt weld, there is almost no change in stress, while meridional stress reaches its maximum at the intersection circle between the bottom plane and inner surface of the hemispherical head. The meridional stress concentration factor is about 1.11.

3.3 Stress at the tip of gap

Numerical calculations with the same vessel dimensions, except for varying the radial clearance of the gap at the cylindrical surfaces between the reinforcing ring and hemispherical head (ranging from 0.5 to 3 mm), shows that the radial clearance has little influence on the stresses at the surface of the shell and head but has certain effects on the stress at the tip of the gap. Both ends of the gap are welded together and are able to transfer radial stress from the head to the ring. This might be the reason why the clearance of the gap within the above range has little effect on surface stresses.

At the tip of the gap there are tensile hoop stress, tensile axial stress and compressive radial stress. Compressive radial stress tends to close the gap under internal pressure. Since the tapered surface can share axial force with the welds, the possibility of failure caused by shear is very small. Detailed investigation on this problem is under way.

The allowable stresses of the material 16MnR of the shell and hemispherical head are 163 and 148 MPa respectively according to the Chinese Pressure Vessel Standard GB150 [**7**]. The maximum stress of the shell is 149.9 MPa and that of the hemispherical head is 127.1 MPa. Both of them are less than their allowable stresses so the vessel can be safely used.

The maximum stress intensity of the vessel is 280 MPa, which locates at the upper tip of the gap between the reinforcing ring and the hemispherical head. As the yield stress of the material is 285 MPa shakedown can be ensured.

4 ENGINEERING DESIGN METHOD

The nominal thicknesses of the hemispherical head and shell, δ_m and δ_n respectively, can be determined according to pressure vessel standards [**4**–**9**]. The outer radius of the reinforcing ring R_o should be equal to the outer radius of the shell, which is the sum of the inner radius R_i and the nominal thickness δ_n of the shell. In order to make the cylindrical and tapered surfaces, its inner radius at the cylindrical surface R_{ho} should be less than the outer radius of the hemispherical head by 5–10 mm. Thickness measurements indicate that thickness of the formed hemispherical head changes regularly, i.e. it becomes thicker at its junction and thinner at its crown. To reduce the thickness of the reinforcing ring, the radius of the hemispherical head at the cylindrical surface R_{ho} should be as large as possible, provided that the height of the cylindrical surface and the tapered surface can be ensured.

If a larger tapered angle β is employed, more material of the head should be cut during machining and the ring becomes thicker. However, if β is too small, the axial force transferred by the ring is almost carried by the welds.

If the ratio of H/D_i varies from 0.1 to 0.16 and the tapered angle β from 5 to 20°, numerical investigation shows that neither the ratio of H/D_i nor the tapered angle β have a significant effect on the maximum stress near the junction [**13**]. Obviously, the weight of the ring will increase as the ratio H/D_i increases. If the geometric parameters comply with the following requirements, stress calculations and measurements verified that enough strength can be ensured:

$$R_o = R_i + \delta_n$$

$$R_{ho} = R_i + \delta_m - \Delta$$

$$\Delta = 5\text{–}10 \text{ mm}$$

$$\beta = 5\text{–}20^\circ$$

$$H/D_i = 0.10\text{–}0.16$$

Table 2 Weight comparison of various heads

Head	Component material	Weight of component	Total weight (kg)
Unique junction of thick shell to thinner hemispherical head	16MnR	Hemispherical head, 1006 kg; reinforcing ring, 241 kg	1247
Hemispherical head with equal thickness of shell	16MnR	Hemispherical head, 1506 kg; web, 16 kg; support ring, 195 kg	1717
Forged flat head	20MnMo	Forged flat head, 2730 kg	2730

Obviously, stresses in the vicinity of the junction are caused by internal pressure and structural discontinuity. Since not all types of stresses or their combinations require the same safety factors in protection against failure, stress categories near the junction should be conducted to optimize the geometric parameters of the reinforcing ring. Such a study is under way.

5 ANALYSIS AND COMPARISON

5.1 Weight

Take a high-pressure vessel with an inner diameter of 1000 mm and design pressure of 31.4 MPa for example. Table 2 shows the weight comparison of the new structure compared with a forged flat head and a hemispherical head with equal thickness of cylinder. By using the new structure, the weight of the head is reduced by 54.3 per cent compared with the forged flat head and 27.4 per cent compared with the hemispherical head.

5.2 Fabrication

Obviously, the thicker the plate, the more difficult it is to construct the hemispherical head and to ensure its quality. Forged flat heads not only cost more but also need a complex forging facility. The thickness of the hemispherical head is reduced by using the new junction. It is therefore easier to fabricate.

6 CONCLUSION

1. The unique junction of the shell to a hemispherical head thinner than that of the shell is rational in structure, convenient in fabrication, safe in use and low in cost. The larger the vessel, the higher the design pressure and the greater the economic benefits.
2. The unique junction is applicable to all kinds of shell to thinner hemispherical head.
3. The proposed method for the hemispherical head and reinforcing ring may be used in the engineering design of high-pressure vessels.

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