R&D of Large Stationary Hydrogen/CNG/HCNG Storage Vessels

Jinyang Zheng[1], Xianxin Liu[1], Ping Xu[2], Pengfei Liu[1], Chunhua Wei[3], Xiaoru Ye[3]

1. Institute of Process Equipment, Zhejiang University, Hangzhou, China
2. Institute of Applied Mechanics, Zhejiang University, Hangzhou, China
3. JUHUA Group Engineering Ltd, Quzhou, Zhejiang, China

Contents

Hydrogen

- **Hydrogen is considered to be the most potential energy carrier in the future.**
- **Hydrogen storage technology--*bottle neck* of hydrogen economy.**
  - Available hydrogen storage methods
    - **High-pressure hydrogen storage**
    - **Liquid hydrogen**
    - **Metal hydride**
    - **Physisorption of hydrogen (such as carbon nano tubes)**
    - **Storage via chemical reaction**
    - **……**

Hydrogen

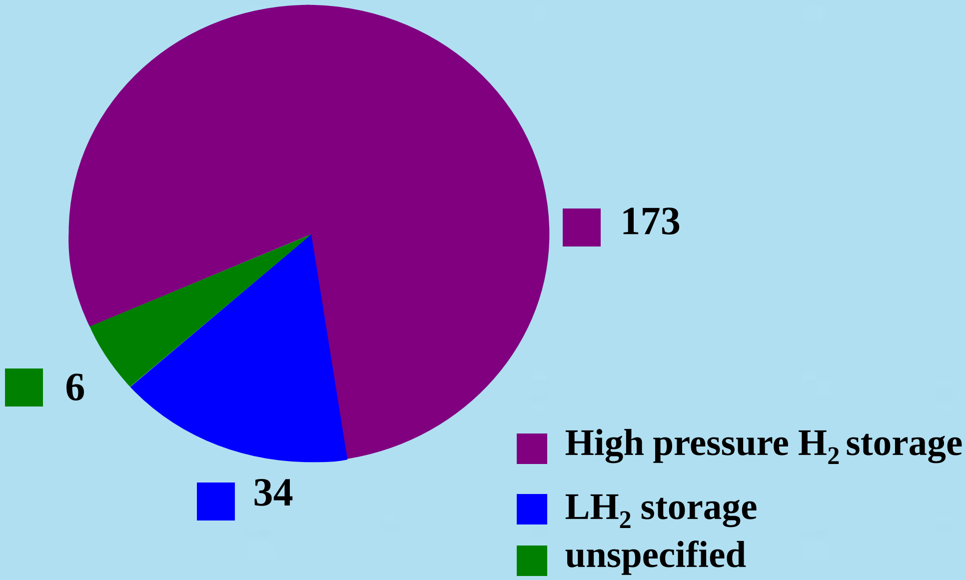
- **High-pressure hydrogen storage**

  -- Technical simplicity for Storage vessels

  -- Less energy required to compress H_2 than liquefy H_2

  -- Fast filling-releasing rate

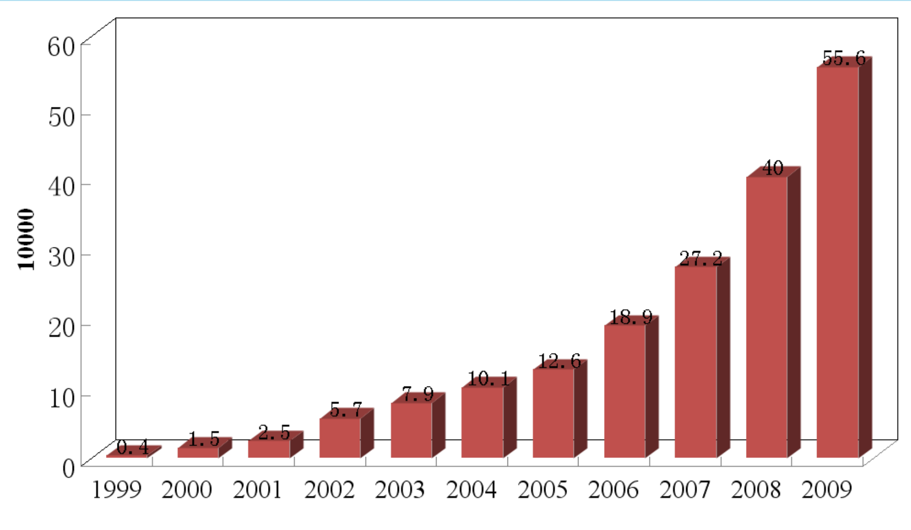
According to "FUEL CELLS 2000" (www.fuelcell.org), by November 2009, 202 hydrogen refueling stations have been built all over the world, more than 85% of them adopt high pressure hydrogen storage technology.



H_2 storage method for refueling stations

CNG

- Over the past decade, CNG vehicle has developed rapidly in China. The proportion of CNG taxis and buses in some cities (such as Chengdu, Chongqing, Lanzhou, Xi'an, et.al) has been over 90%.
- About 1,400 CNG refueling stations have been established in China.



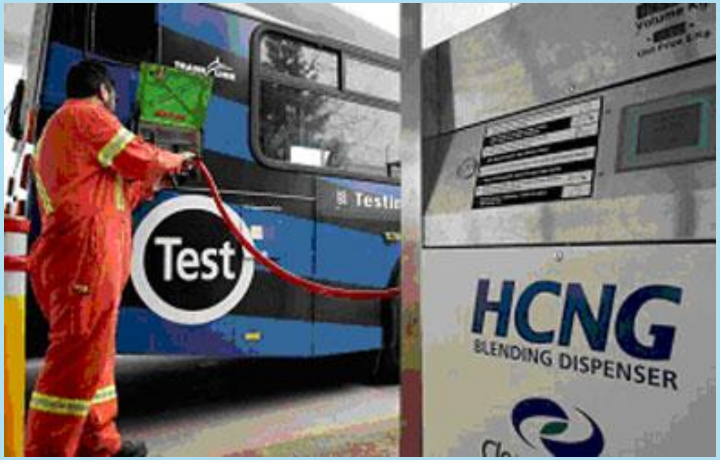
CNG vehicles development in China

CNG refueling station

HCNG

- Add hydrogen to natural gas makes it burn more cleanly (notably reducing smog-causing NO_X by 50%).
- HCNG represents a highly practical way for hydrogen usage, given that for HCNG blends, leakage and flammability risks are similar to those of regular CNG.

HCNG Bus development by Tsinghua



HCNG Refueling Station

Stationary Hydrogen/CNG/HCNG Storage Vessels

- Large stationary storage vessels are needed to achieve successive refueling for hydrogen/CNG/HCNG automobiles.
- Multi-vessel assemblies consist of several seamless high pressure gas vessels provide a way for bulk gas storage.

Higher Pressure

→

Larger Volume

Advantages:

--- No weld is needed;

--- Avoid weld defect

Disadvantages:

--- Volume of a single vessel is limited;

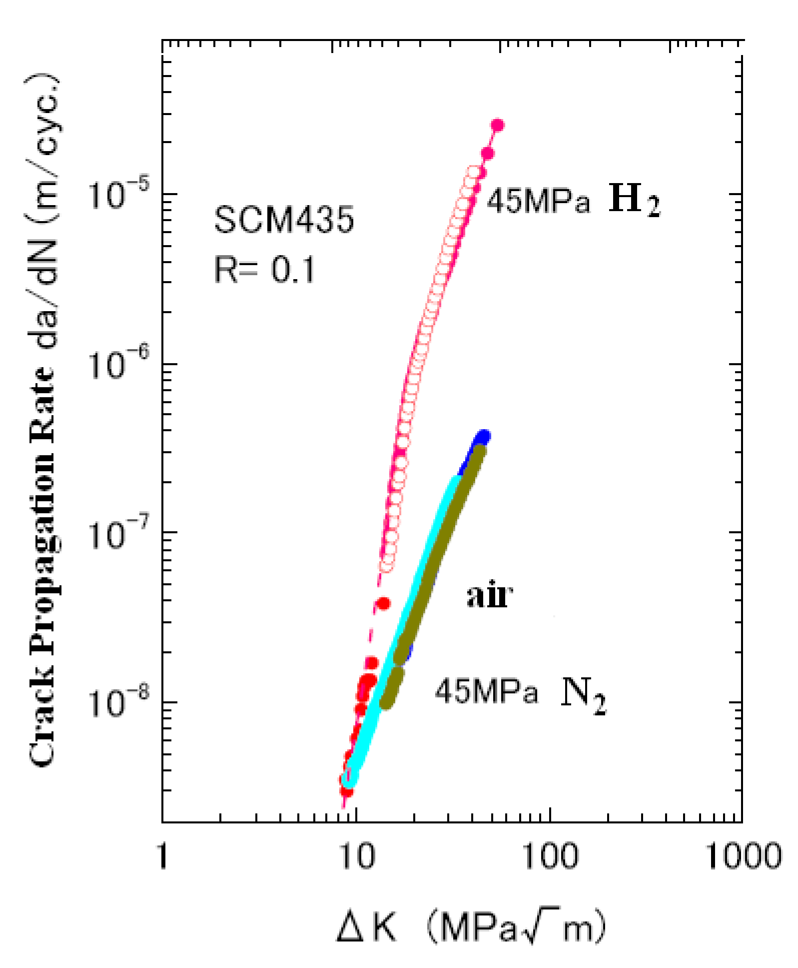
--- Difficult for online safety Monitoring;

--- Susceptible to hydrogen embrittlement.

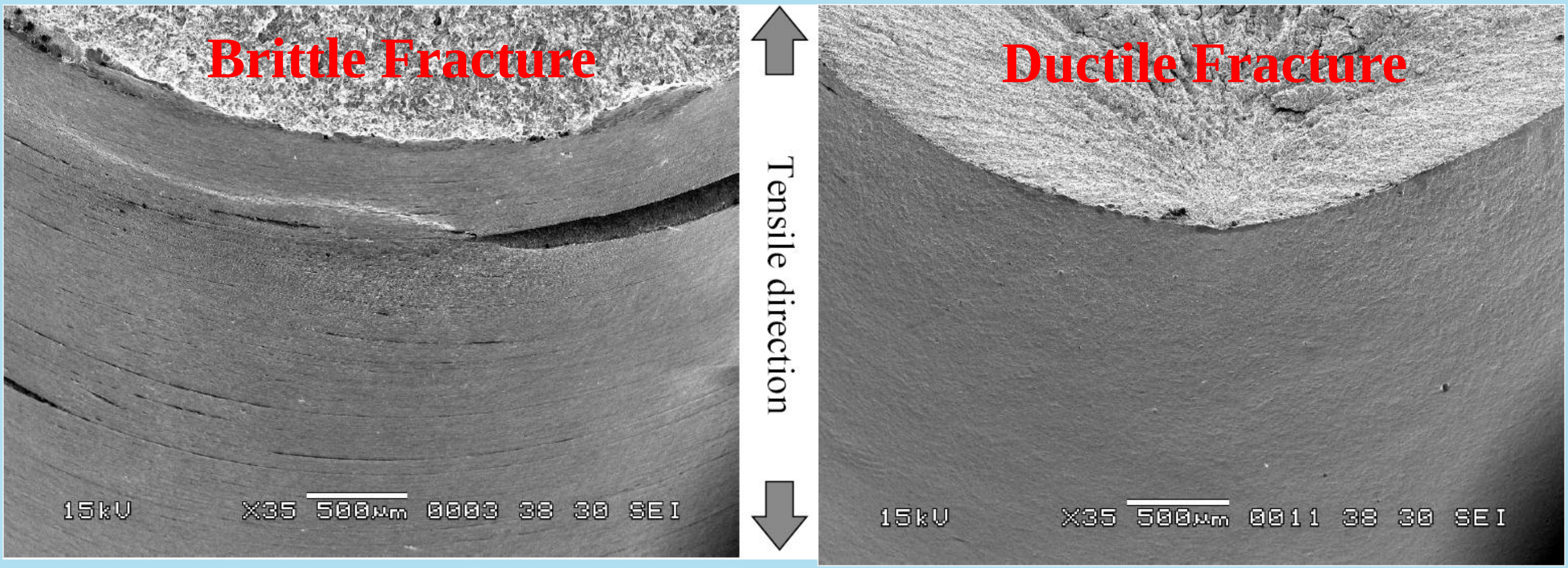
Hydrogen Embrittlement

Seamless high pressure gas vessels are made from high strength Cr-Mo steel, such as 34CrMo4 et al. which is of significant deterioration while storing high pressure hydrogen.

Take SCM435 (35CrMo) for example, compared with air or nitrogen, high pressure hydrogen accelerates crack propagation rate of the material and leads to brittle fracture.



Hydrogen Embrittlement

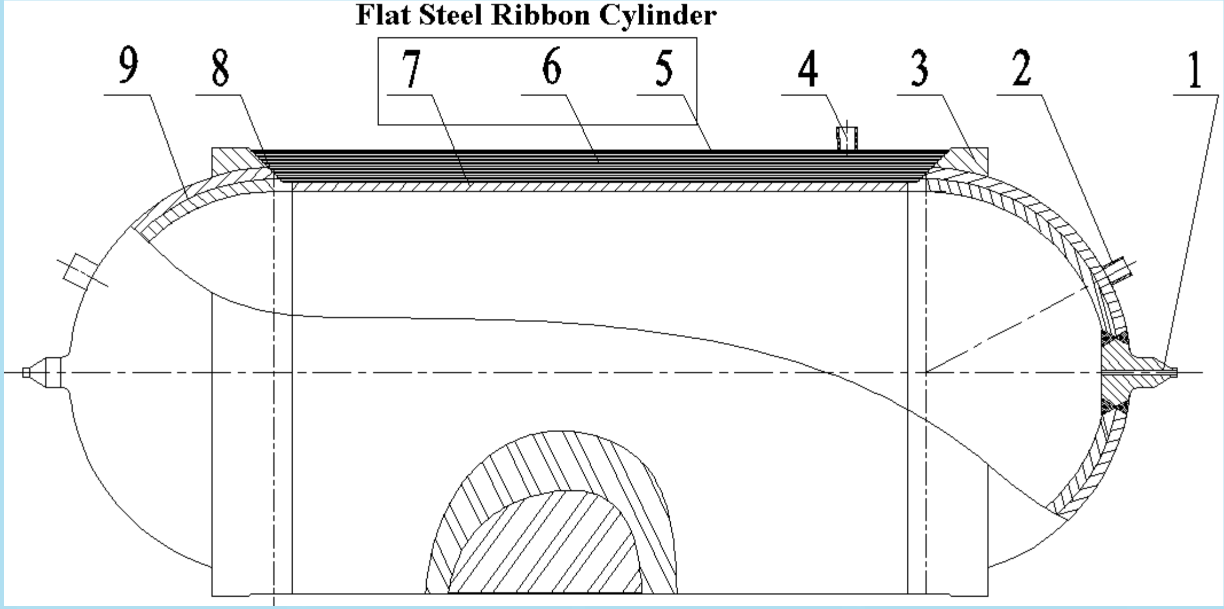


（45MPa H_2） （air）

Fracture surface of SCM435 specimens tested in 45MPa H_2 and air at room temperature

2. Structure ＆Characteristics

In order to solve the aforementioned problems, we have developed a type of large capacity multilayered storage vessel, named "Stationary flat steel ribbon wound vessel".



1. End nozzle; 2. Sensor nozzle; 3. Reinforcing ring; 4.Sensor nozzle 5. Protective shell; 6. Layered shell; 7. Inner shell; 8. Slant weld; 9. Double-layered hemispherical head

Structure — Flat Steel Ribbon Cylinder

- **Flat steel ribbon cylinder is one of the main pressure resistance parts, which consists of a thin inner shell, a layered shell and a protective shell.**

Flat steel ribbon cylinder

- Inner shell
  - **--steel sheet is rolled and welded into inner shell.**
  - **--usually 1/4~1/8 of the cylinder's total thickness.**
- Layered shell
  - **--Made from hot-rolling flat steel ribbons which are 80~160mm wide, 4~8mm thick.**
- Protective shell
  - **-- wrapped outside the layered shell to form a closed space for online safety monitoring.**

Structure — Heads and Reinforcing Ring

- **Double-layered hemispherical heads**

  --- Two layers nearly have the same thickness;

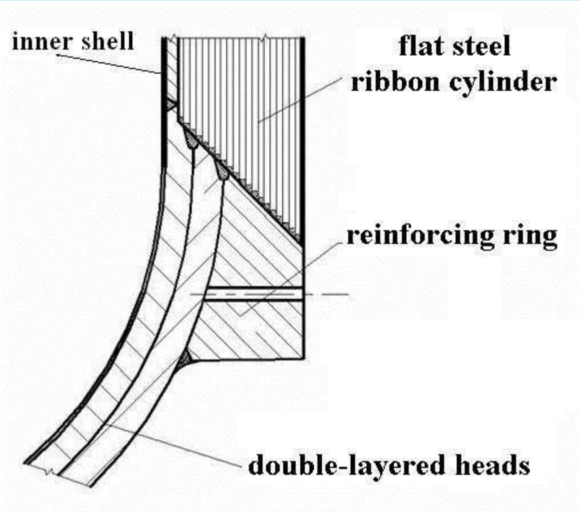
  --- At the operating pressure, the outer head can also withstand the operating pressure , even if the inner head leaks;

  --- Double-layered structure allows leakage monitoring.

- **Reinforcing rings**

  --- Steel forgings;

  --- Transition of head and cylinder with different thickness.



Characteristics

- **Feasible in Manufacturing Hydrogen Storage Vessels with High Parameters**
- **Burst Resistant or Self-protected**

  --The worst damage is always “ only leaking, but never burst”.
- **Random Dispersion of Defects or Cracks**

  --Ribbons and heads are joined by step weld instead of deep circumferential weld
- **Economical and Convenient for Manufacturing**
- **Feasible for Online Safety Monitoring**

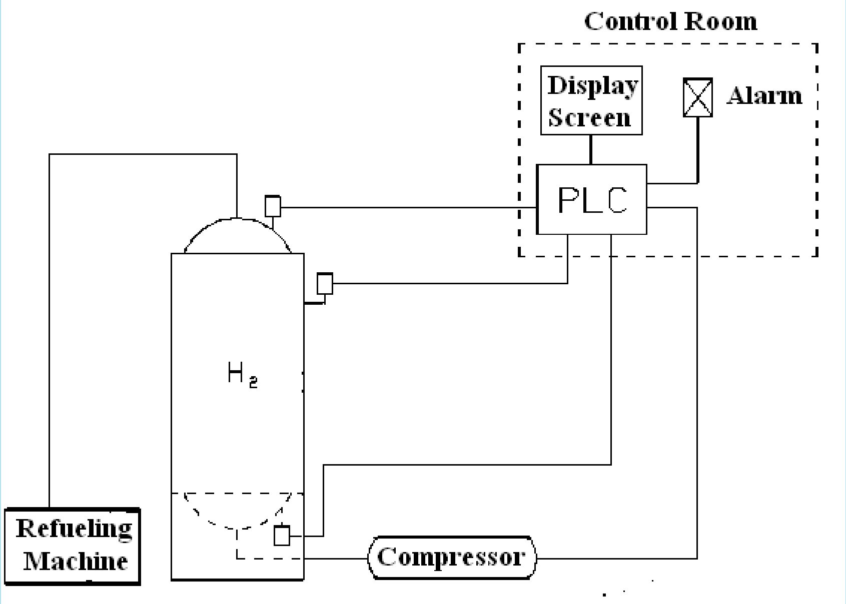
  --Layered structure and unique failure mode

Characteristics --Online Safety Monitoring

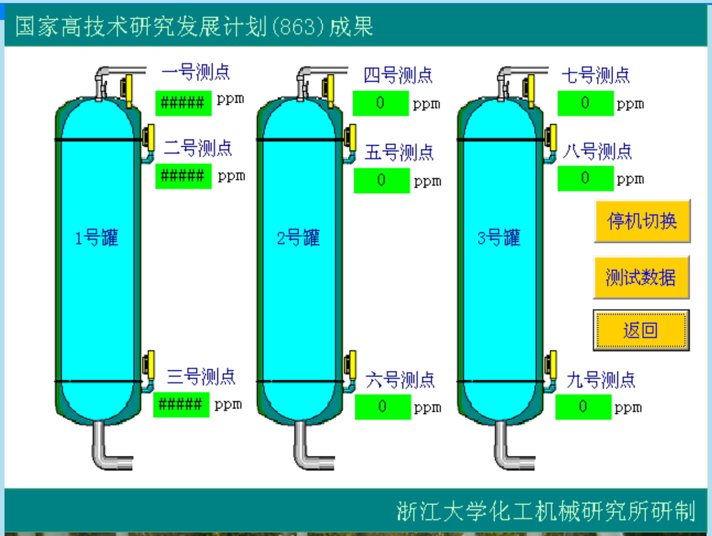
Function:

(1) Hydrogen leak detection and alarm;

(2) Automatically turn off the compressor.

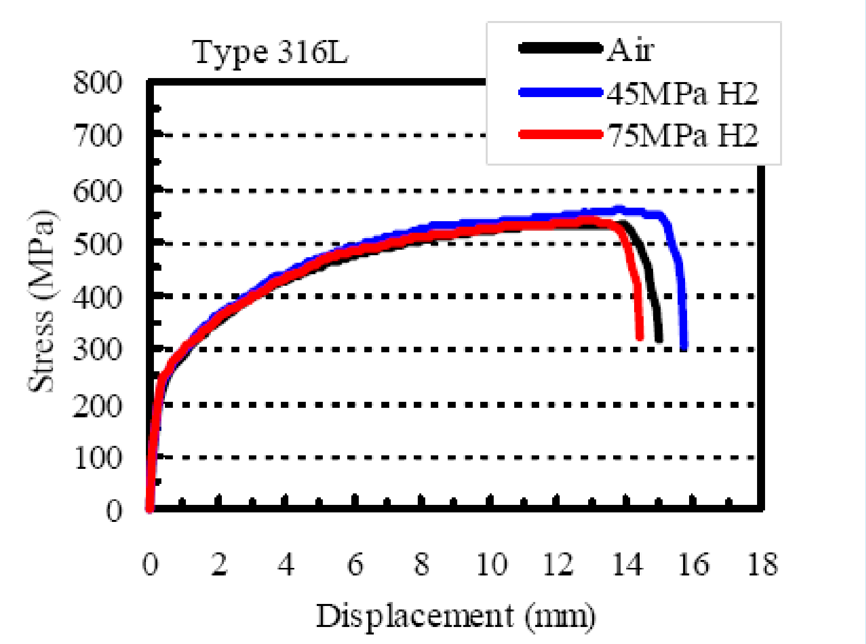


Monitoring Principles



3. Design ---- Material

- The layer that is directly in contact with hydrogen/HCNG uses materials having good compatibility with both gases, such as austenitic stainless steels.
- Other layers use ordinary high-pressure vessel steel.



Stress-displacement curves of Type 316L tested in 45MPa, 75MPa H_2 and air

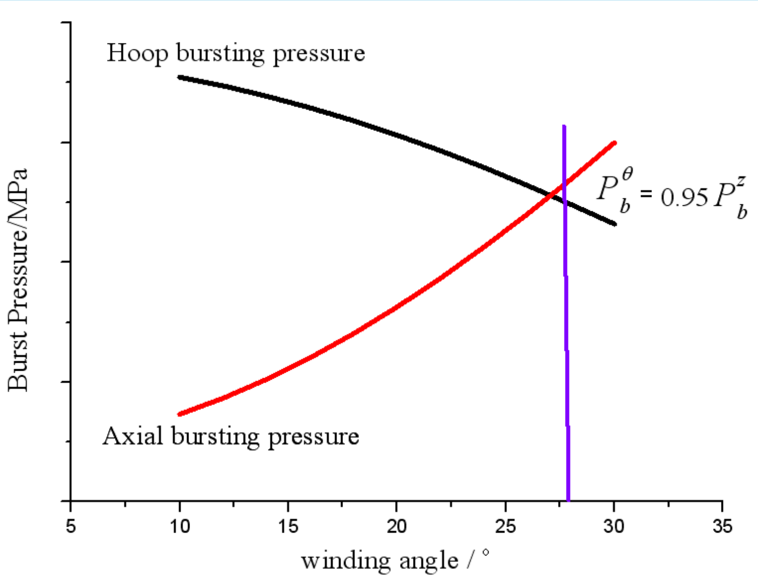
Strength Analysis ---- Uniform Strength Design

- **hoop bursting pressure**

$$p_b^\theta = \frac{2}{\sqrt{3}} R_{mi} \ln K_1 + R_{mw} \cos^2\alpha \ln K_2$$

- **axial bursting pressure**

$$p_b^z = \frac{K_1^2 - 1}{K_1^2} R_{mi} + R_{mw} (\sin^2\alpha + 0.125\cos^2\alpha)(K_2^2 - 1)$$



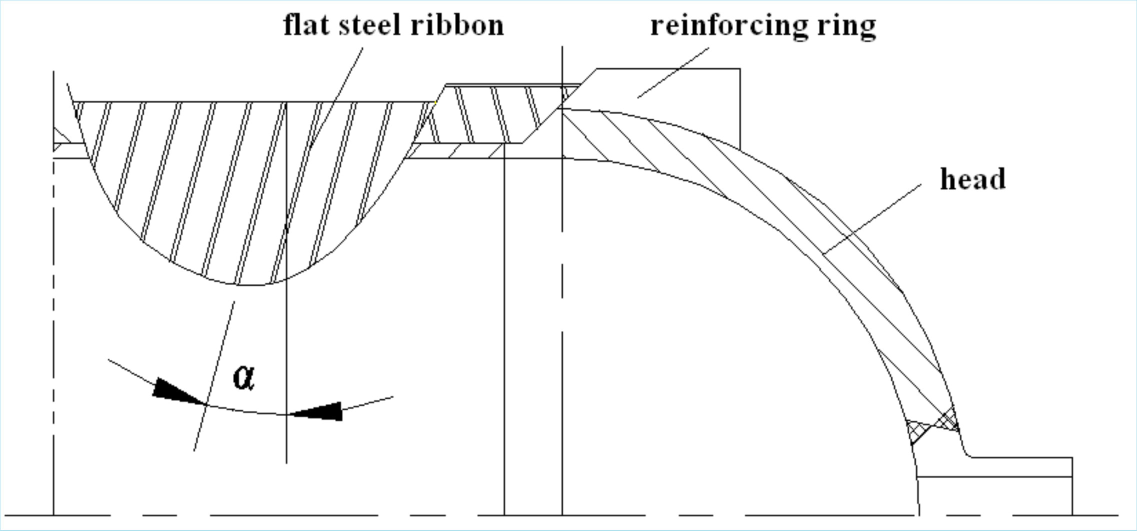
Considering that the axial strength is required to be slightly better than the hoop strength, it is stipulated that:

$$p_b^\theta = 0.95 p_b^z$$

Strength Analysis ---- Uniform Strength Design

The appropriate winding angle that can fulfill uniform strength design:

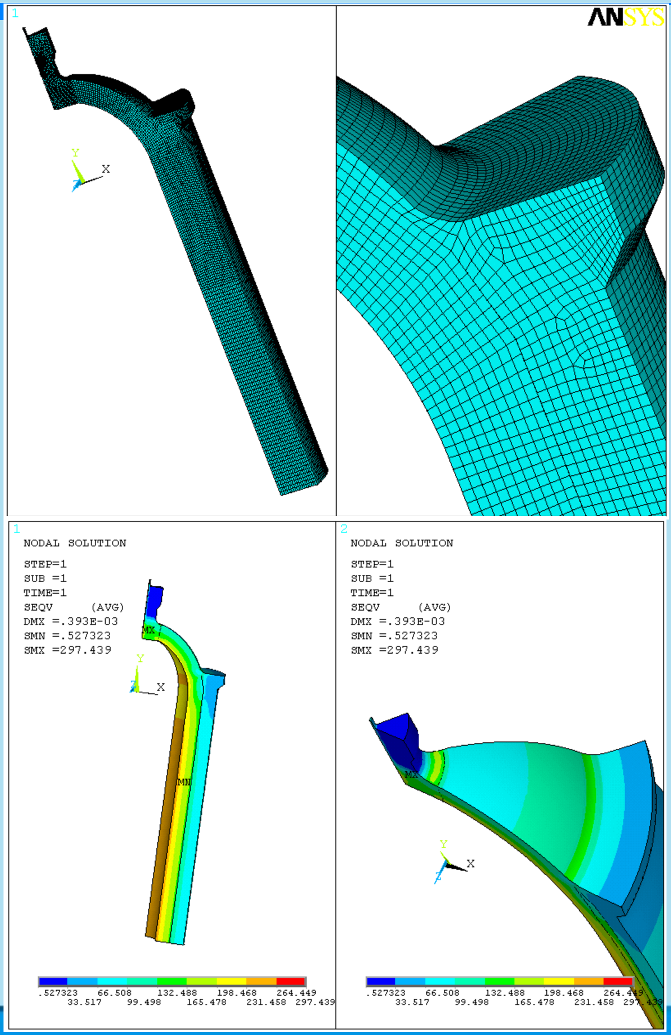
$$\alpha = \arccos\sqrt{\frac{0.95\left(K_2^2-1\right)R_{\mathrm{mw}}+R_{\mathrm{mi}}\left[0.95\left(K_1^2-1\right)/K_1^2-2\ln K_1/\sqrt{3}\right]}{R_{\mathrm{mw}}\left[\ln K_2+0.83125\left(K_2^2-1\right)\right]}}$$



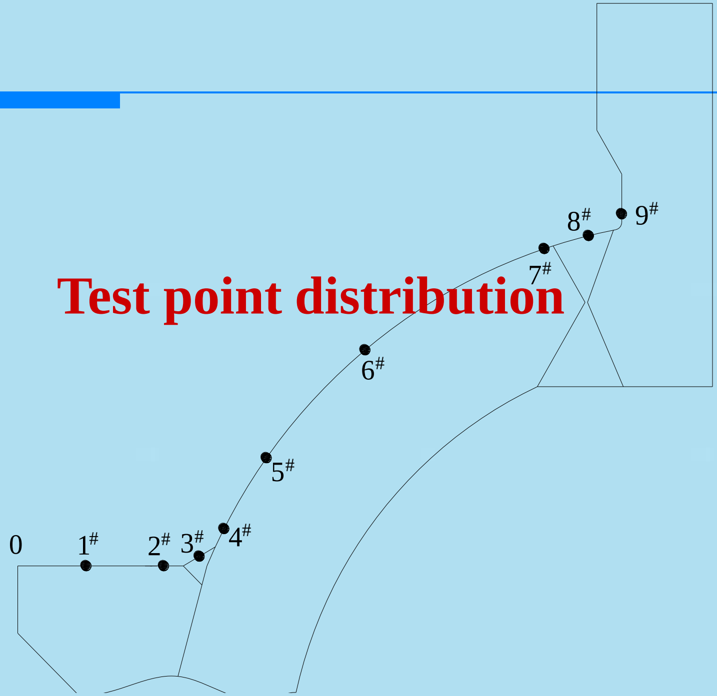
Strength Analysis ---- Finite Element Analysis（FEA）

To give a detail strength analysis for all parts (cylinder, heads, reinforcing rings, and end nozzles), a finite element analysis model has been established for this kind of vessel. The right figures show a 1/12 analysis model.

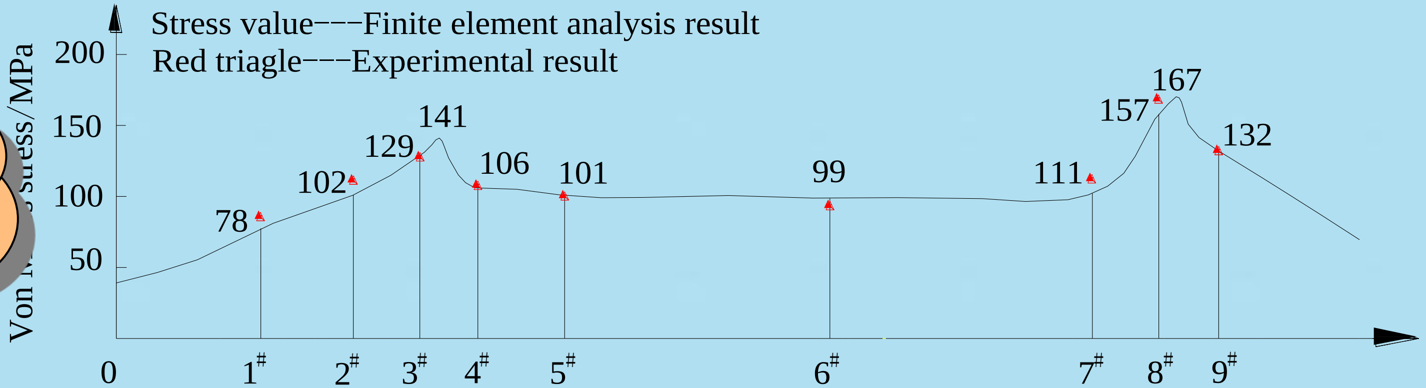
The validity of the model has been verified.



Strength Analysis ---- FEA Validation



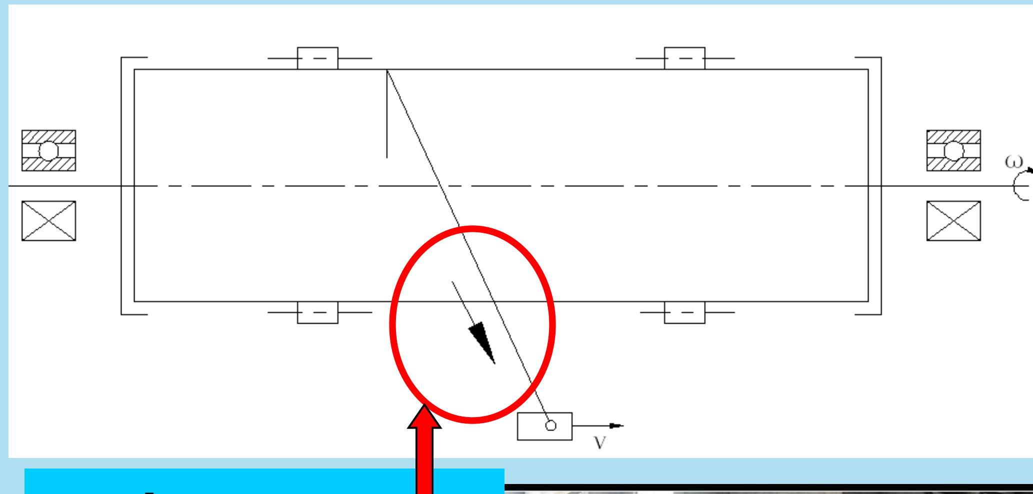
The maximum error is 10.7%



Optimal Stress Design ---- Uniform Shearing Stress along Thickness Direction

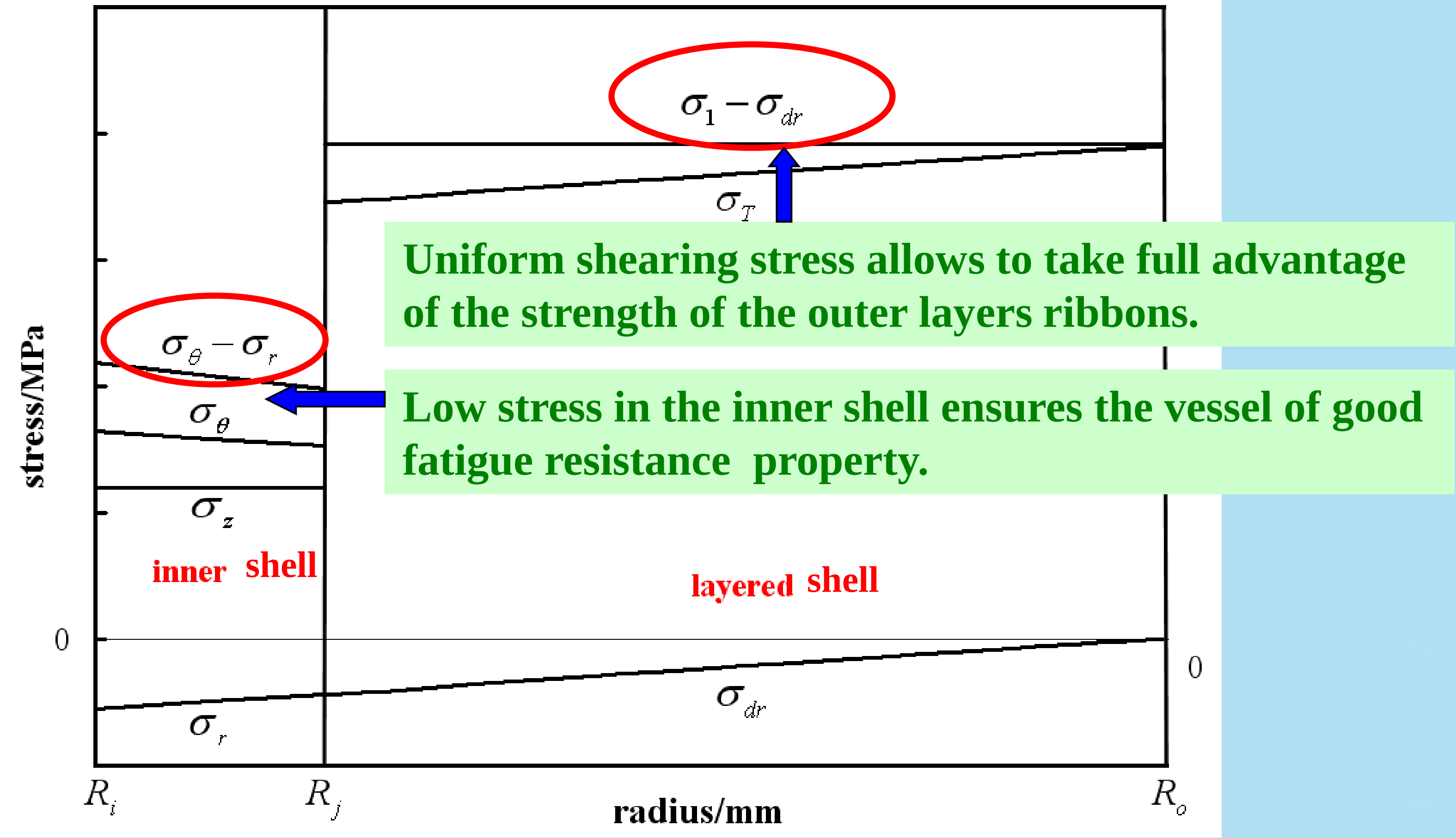
The stress state of this kind of vessel at working conditions is largely affected by the hoop and axial pre-stresses caused by the controllable winding pre-tension stress.

By giving well designed winding pre-tension stress, we can get the desired stress state.



winding pre-tension stress

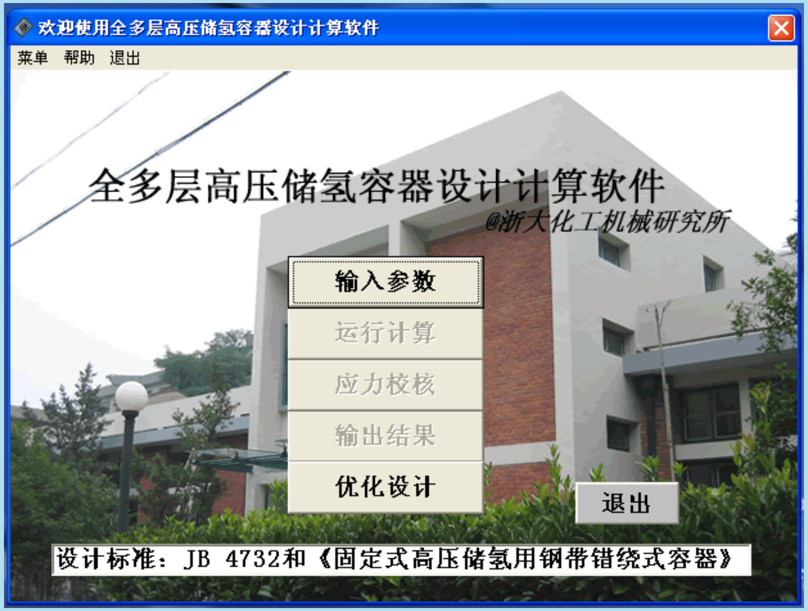
Optimal Stress Design ---- Uniform Shearing Stress along Thickness Direction

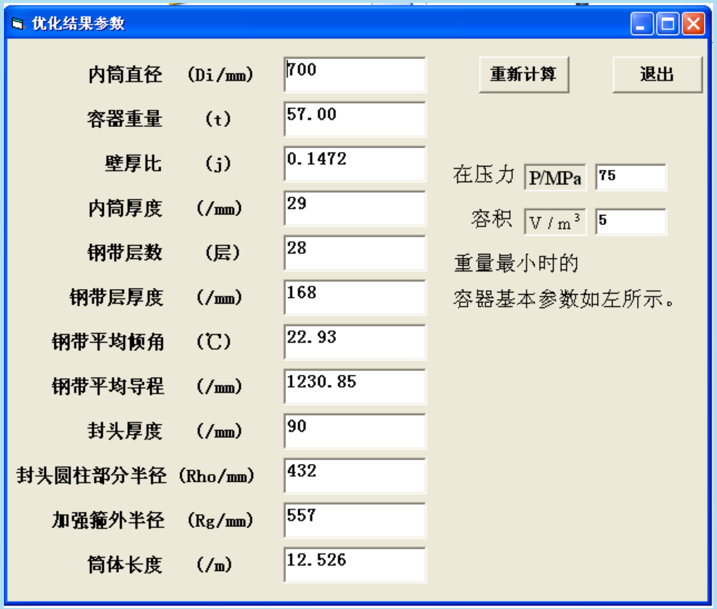


Typical stress distribution during working conditions

Minimum weight optimization software

To reduce the cost of material, a minimum weight optimization software has been developed. Once the required pressure and volume is given, the software presents the optimum structural parameters automatically.





4. Standardization-- History of related codes & standards

1 1969

Design Code of Steel Pressure Vessel for Petrochemical Industry of China

2 1980

Technical Conditions of Flat Steel Ribbon Pressure Vessel (JB1149-80)

3 1996

Division 1, Section VIII of ASME Case 2229 "Design of Layered Vessels Using Flat Ribbon Wound Cylindrical Shells "

4 1997

Division 2, Section VIII of ASME Case 2269 "Design of Layered Vessels Using Flat Ribbon Wound Cylindrical Shells"

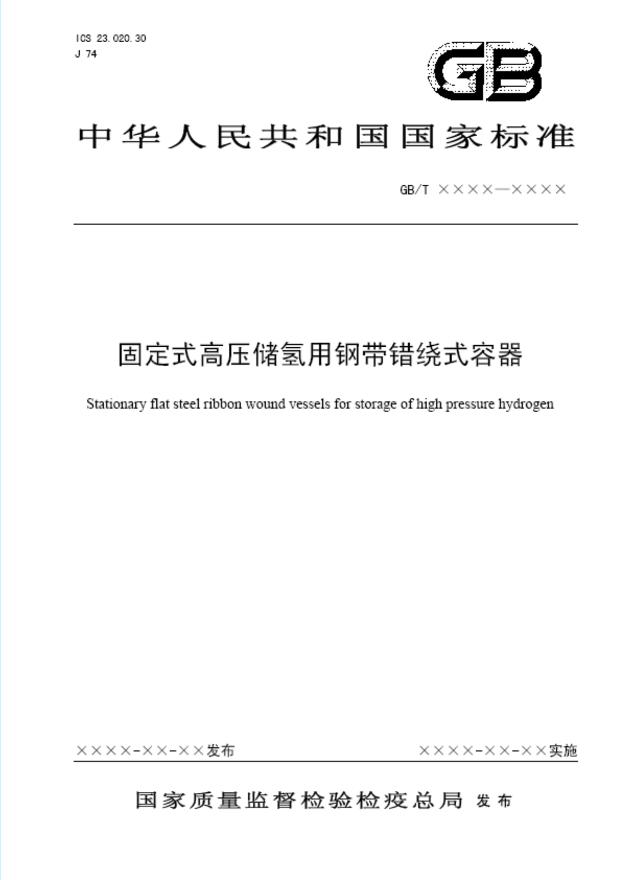
5 2005

Enterprise Standard on Multi-functional Full Multi-layered High Pressure Hydrogen Storage Vessel

6 2008

National Standard Named "Stationary Flat Steel Ribbon Wound Vessels for Storage of High Pressure Hydrogen" (Approval Stage)

4. Standardization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中华人民共和国国家标准

GB/T ××××—××××

固定式高压储氢用钢带错绕式容器

Stationary flat steel ribbon wound vessels for storage of high pressure hydrogen

××××-××-××发布　　××××-××-××实施

国家质量监督检验检疫总局 发布

Front cover of the standard

Scope ---- Design Pressure: 10MPa~100MPa

Temperature Scope: -40℃~80℃

Diameter: 300mm~1500 mm

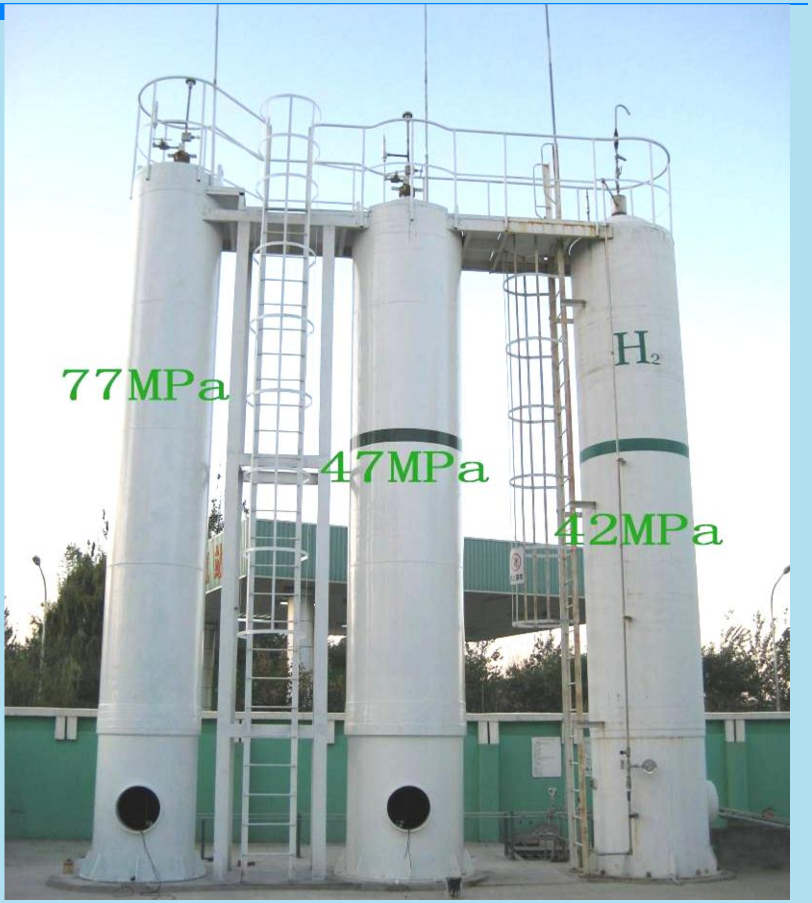
Review conference of the standard

5. Application Cases --Vessels in Hydrogen Refueling Station

Large stationary flat steel ribbon wound vessels for storage of high pressure hydrogen used in China.

Design parameters

	Design pressure /MPa	Volume /m^3	Inner diameter /mm
1	42	5	1000
2	47	5	1000
3	77	2.5	700



The world's largest 70MPa high pressure hydrogen storage vessel

Application Cases --Vessels for HCNG Refueling Station

Large stationary flat steel ribbon wound vessels for storage of HCNG used in China.

Design parameters

	Design pressure /MPa	Volume /m^3	Inner diameter /mm
1	27.5	10	1200
2	27.5	15	1200

Vessels used for the worlds largest HCNG refueling station in Shanxi, China

Application Cases -- Vessels in Process Industry

Large stationary flat steel ribbon wound vessels have also been widely used in process industry as pressure reservoir, ammonia synthesis converter, and methanol synthesis reactor for years.

We have developed 18 Dais large volume pressure reservoirs recently, whose design parameters can be seen in the table below. Now they are on active service in Zhejiang JINDUN, Holding Group Co., Ltd.

Design parameters

	Design pressure/MPa	Volume/m^3	Inner diameter /mm
1	33	9	1200

6. Conclusions

- Large stationary flat steel ribbon wound vessel is flexible in design, convenient in fabrication, safe in use, and easy in online safety monitoring.
- After years of effort, a mature optimal design method for large stationary flat steel ribbon wound vessel has been established.
- Large stationary flat steel ribbon wound vessel provides an economic and reliable method for bulk gas storage. It has been used to storage high pressure hydrogen in China successfully, and it shows a broad prospect in hydrogen/CNG/HCNG storage.

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- Taiyuan University of Technology
- Northwest Institute of Nuclear Technology

Contact

- http://www.zjupe.com
- Tel: 86-571-87952110
- Fax:86-571-87953393
- E-mail: jyzh@zju.edu.cn
- Address: Institute of Process Equipment, Zhejiang University, 38 Zheda Road, Hangzhou, P.R. China 310027

Thank you!