Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Investigation on the temperature distribution and strength of flat steel ribbon wound cryogenic high-pressure vessel

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Received June 19, 2006; revision accepted Aug. 1, 2006

Abstract: By analyzing heat transfer on the wall of flat steel ribbon wound vessel (FSRWV), a numerical model of temperature distribution on the entire wall (including inner core wall, flat steel ribbons, outside cylinder of jacket and insulating layer) was established by the authors. With the model, the temperature distribution and the length change in the vessel walls and flat steel ribbons in low temperature are calculated and analyzed. The results show that the flat steel ribbon wound cryogenic high-pressure vessel is simpler in structure, safer and easier to manufacture than those of conventional ones.

Key words: Cryogenic high-pressure vessel, Flat steel ribbon wound vessel (FSRWV), Temperature distribution, Numerical simulation
doi:10.1631/jzus.2007.A0210 **Document code:** A **CLC number:** TB6; TK91

INTRODUCTION

Cryogenic high-pressure vessels are used to store liquid hydrogen and liquid oxygen, and are necessary equipments in the fields of chemical engineering, astronautic engineering and nuclear power plant, and so on. Safe operation of the vessel is always a concern of environmental protection. The inner pressure of the vessel can reach 40 MPa at temperature of 20 K; Therefore, the vessel requires high-performance wall material excellent in mechanical strength, plastic property, impact toughness, fracture toughness, fatigue strength, forgeability and hardenability (Zhou, 1998; Nichols, 1980; Lloyd and Edwin, 1959). However, with traditional procedure, it is difficult to manufacture the vessel with qualified materials for mostly the forge-welded or multi-layer reel-welded, and especially it is difficult to control quality of deep ring welding line and resulted in the risk of low-stress brittle fracturing.

In the 1960s, a new type of flat steel ribbon wound vessel (FSRWV) was developed in China, which is flexible in design, simple to manufacture, safe and wide application, and realtime monitoring. It can avoid the shortage of traditional craft requiring heavy-duty forge welding, thick wall reel-welding, and solid heat treatment, difficult to manufacture, expensive and unsafe. There have been many researches on FSRWV so far, but most of them were aimed only at the optimum design (Jiang, 2001; Zheng, 1997) or safety monitoring (Zheng *et al.*, 1998; 2006; Zhu, 1996; Chen and Jiang, 2004). Regarding the heat transfer, some researchers have calculated and analyzed the heat transfer and the rate of evaporation of the vessel under a steady heat flow (Chen and Zheng, 2001). To our best knowledge, no research has been reported so far on temperature distribution, changes in whole vessel wall performance, or in the dimension and stress of the flat steel ribbons. In this research, a hypothesis is made for the heat transfer. With a physical model, the temperature distribution and the length change of vessel walls and flat steel ribbons at low temperature can be calculated and analyzed.

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STRUCTURE OF VESSEL WALL

The FSRWV model structure (Fig.1) is designed for holding a pressure of 35 MPa at temperature of 20 K. The inner core is made of stainless steel having flat steel ribbons wound wrapped. The outside cylinder of jacket is made of mild carbon-steel alloy that can save liquid nitrogen when vessel is cooled, and insulate the heat when liquid nitrogen is discharged and evacuated. So, it is safe for the operator if vessel bursts.

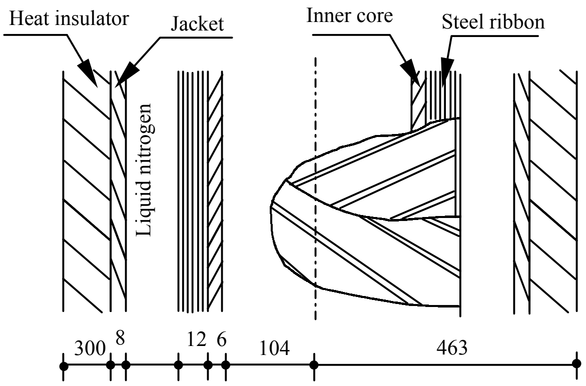

Fig.1 Sketch cross-section of the FSRWV system structure (unit: mm)

PHYSICAL MODEL OF THE VESSEL WALL

The inner core is 208 mm across with a 6 mm-thick wall, and the flat steel ribbon is 2 mm thick in 6 layers. The outer cylinder of the jacket is 8 mm thick in external diameter of 326 mm. The liquid nitrogen zone is between the flat steel ribbons and the outer cylinder. The whole system is wrapped with 300 mm-thick polyurethane foam for heat insulation.

The heat transfer of the vessel wall includes not only within the system including inner core, flat steel ribbons, outer cylinder and the heat insulator, but also between the heat insulator and environment. The heat transfer among other parts of the vessel is not discussed in this paper.

It is difficult to calculate exactly the heat transfer of the vessel wall for having various heat transfer forms. Therefore, simplifying the model would be a practical solution, supposing: (1) the vessel is an infinite cylinder and the heat transfer is a 1D radial form and the temperature gradient can be ignored; (2) the liquid nitrogen does not flow into the seams of the flat steel ribbons when the vessel is cooled; (3) all of the materials are homogeneous and isotropic.

Based on the above assumptions, the heat transfer can be termed as:

$$\rho c \frac{\partial T}{\partial \tau} = \lambda \left(\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right), \tag{1}$$

with a boundary condition of

$$-\lambda \frac{\partial T}{\partial r} = h(T_{\mathrm{w}} - T_{\mathrm{f}}), \tag{2}$$

where, ρ is the density, kg/m^3; c is the specific heat, J/(kg·K); τ is the time, s; r is the radius, m; T_{w} is the wall temperature, K; T_{f} is the fluid temperature, K; λ is the thermal conductivity, W/(m·K); h is the convection heat transfer coefficient, W/(m^2·K).

The external insulator of the vessel is made of polyurethane foam whose coefficient of heat conductivity is 0.027 (Xu, 1995). The heat transfer between the insulating layer and outside air is natural-convection, in the same boundary condition in Eq.(2).

When liquid nitrogen is charged into the liquid nitrogen zone, the temperature distribution of the whole vessel wall is an unsteady process, in which heat transfer happens among liquid nitrogen, flat steel ribbons and the outside cylinder. The heat transfer process changed with the temperature difference ΔT ($\Delta T=T_{\mathrm{w}}-T_{\mathrm{f}}$) between the liquid nitrogen and the wall: for example, when $\Delta T>100$ K, the film boiling heat transfer would happen; 5 K$<\Delta T<$100 K, the nucleate boiling heat transfer would happen; and $\Delta T<5$ K, natural-convection heat transfer would happen, in which nucleate boiling heat transfer is very intensive (Chen, 1989).

The expression of film boiling heat transfer is:

$$h = (13.38 - 15.53T_{\mathrm{r}} + 6.14T_{\mathrm{r}}^2 - 0.588T_{\mathrm{r}}^3) \times [(1.73/D + 207)]Pr^{0.25}, \tag{3}$$

where T_{r} is the reduced temperature; Pr is the Prandtl number; D is the length of liquid zone along the radius, m.

The form of a nucleate boiling heat transfer is:

$$h = Cq^{0.624}(\rho c_{\mathrm{p}} \lambda)^{0.117}, \tag{4}$$

where C is the boiling medium pressure dependent constant; q is the heat flux density, W/m^2; c_p is the constant-pressure specific heat, J/(kg·K); and the rest are the same as in Eq.(1) and Eq.(2).

The form of natural-convection heat transfer is:

$$q = h(T_f - T_w). \quad (5)$$

The heat transfer between the inner wall and the air is the same as that of the liquid nitrogen with flat steel ribbons and the external cylinder.

When liquid nitrogen is pumped out and the liquid nitrogen zone is evacuated, the nitrogen zone is regarded as an insulating zone, in which heat transfer is mainly by radiation while the conduction of rarefied air can be neglected (Chen, 1989). The radiation is shown by:

$$q_{1,2} = 5.67\varepsilon_s\left[(T_1/100)^4 - (T_2/100)^4\right], \quad (6)$$

where ε_s is the system emissivity factor; T_1 and T_2 are the temperatures of flat steel ribbons and of the external cylinder respectively.

$$\varepsilon_s = \frac{1}{1/\varepsilon_1 + (d_1/d_2)(1/\varepsilon_2 - 1)}, \quad (7)$$

where ε_1 is the emissivity factor of the outside flat steel ribbon; ε_2 is the emissivity factor of the cylinder; d_1 is the diameter of outside flat steel ribbon; and d_2 is inner diameter of flat steel ribbon.

NUMERICAL SIMULATION

When the physical model is established, the finite difference method is used to simulate the numerical calculation. The difference equations of inner node are established using central difference method and heat balance method for the third boundary condition.

A diagrammatic sketch of the whole vessel wall is showed in Fig.2.

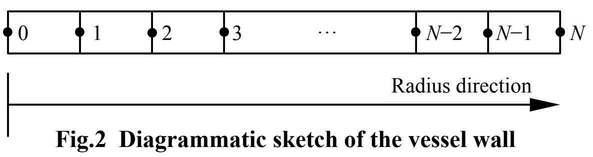

Fig.2 Diagrammatic sketch of the vessel wall

(1) The difference equation of inner wall and flat steel ribbons is

$$\lambda_1\left(\frac{T_{i+1}^{k+1} - 2T_i^{k+1} + T_{i-1}^{k+1}}{\Delta r^2} + \frac{1}{r}\frac{T_{i+1}^{k+1} - T_{i-1}^{k+1}}{2\Delta r}\right) = \rho_1 c_1 \frac{T_i^{k+1} - T_i^k}{\Delta\tau}. \quad (8)$$

Let $a=\rho_1 c_1/(\lambda_1\Delta\tau)$, $b=1/(\Delta r)^2$, $d=1/(2r\Delta r)$, substituting them into Eq.(8), we obtain

$$(b-d)T_{i-1}^{k+1} - (2b+a)T_i^{k+1} + (b+d)T_{i+1}^{k+1} = -aT_i^k. \quad (9)$$

When the vessel is cooled and the liquid nitrogen is discharged and evacuated, the heat transfer in liquid zone is by radiation in the form of Eq.(6).

(2) The equation of inner node boundary difference of the inner vessel wall is

$$\lambda_1\frac{T_0^{k+1} - T_1^{k+1}}{\Delta r} = h_1(T_{f1} - T_0^{k+1}), \quad (10)$$

where h_1 is the convection heat transfer coefficient of air in the inner wall, calculated with Eqs.(4)~(6); T_{f1} is the air temperature initially set at 300 K.

Let $d_1=\Delta r h_1/\lambda_1$, substituting it into Eq.(10), we obtain

$$(1+d_1)T_0^{k+1} - T_1^{k+1} = d_1 T_{f1}. \quad (11)$$

(3) The difference equation of outside boundary of flat steel ribbon is

$$\lambda_2\frac{T_{N-1}^{k+1} - T_N^{k+1}}{\Delta r} = h_2(T_N^{k+1} - T_{f2}), \quad (12)$$

where h_2 is the convection heat transfer coefficient of liquid nitrogen, which is calculated with Eqs.(4)~(6); T_{f2} is the temperature of liquid nitrogen.

Let $d_2=\Delta r h_2/\lambda_2$, substituting it into Eq.(12), we obtain

$$-T_{N-1}^{k+1} + (1+d_2)T_N^{k+1} = d_2 T_{f2}. \quad (13)$$

(4) The difference equation of the air in the inner vessel is

$$h_1(T_{f1}^{k+1}-T_0^{k+1})=\rho_3 c_3\frac{r_0}{2}\frac{T_{f1}^{k}-T_{f1}^{k+1}}{\Delta\tau}. \tag{14}$$

where r_0 is the inside radius of inner vessel wall.

Let $d_3=h_1$, $e_3=\rho_3c_3r_0/(2\Delta\tau)$, substituting them into Eq.(14), we obtain

$$(e_3+d_3)T_{f1}^{k+1}-d_3T_0^{k+1}=e_3T_{f1}^{k}. \tag{15}$$

After the difference Eqs.(9), (11), (13) and (15) are established, the results can then be obtained by computer programs.

RESULTS AND DISCUSSION

Analysis of the change in temperature of the vessel wall in cooling phase

In our model, the initial temperature is 300 K in the inner core wall and 77 K in the liquid nitrogen when liquid nitrogen is charged for cooling. After the liquid nitrogen is filled up, the temperature distribution of flat steel ribbons and inner core wall would change. Using simulated results, the tendency chart of all nodes is plotted (Fig.3), in which several curves from top to bottom represent the temperature changes in the inner core and six flat steel ribbons from inside out respectively. As the time goes, the temperature of all nodes become uniform, the temperature of outside nodes is more prone to stabilize than the inside ones. At last, the temperature of flat steel and inner vessel reached 77 K because the convection heat transfer coefficient of liquid nitrogen h_2 is greater than that of the inner air's h_1. Temperatures at a certain point are shown in Table 1.

Table 1 Temperatures at the end of seven-minute in cooling phase

Node	T (K)
Inner vessel	85.0
1st FSR	84.6
2nd FSR	83.2
3rd FSR	81.8
4th FSR	80.5
5th FSR	79.2
6th FSR	78.0

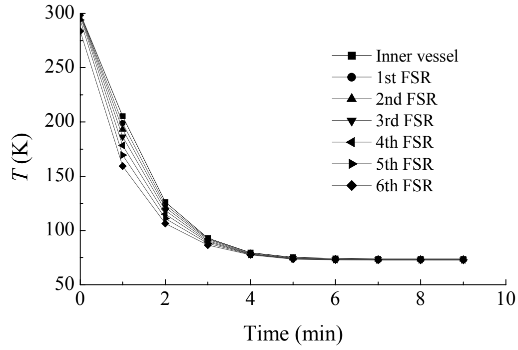

Fig.3 Temperature change of different nodes in cooling phase (FSR: flat steel ribbon)

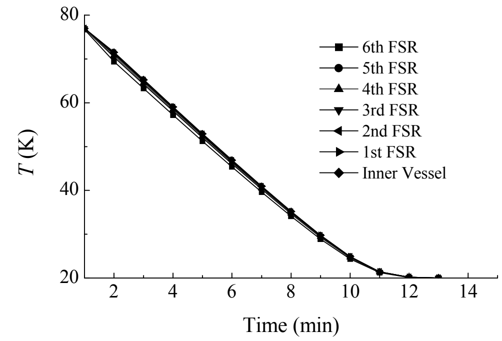

Fig.4 Temperature change of different nodes when charged with liquid hydrogen

The form of heat transfer in the flat steel ribbons is the same as the inner core under the second assumption mentioned above. The temperature of flat steel ribbons is also 77 K at last.

When liquid hydrogen is charged into the inner core, the tendency of temperature change (Fig.4) is analogous to those in different nodes in cooling phase (Fig.3), the temperatures of inner vessel wall and flat steel ribbons are 22 K at last.

The temperature distribution varies in different moments when temperature field of entire vessel wall (including inner core, outer cylinder of jacket and flat steel ribbons) stabilizes. The tendency of temperature change of the entire vessel wall is shown in Fig.5. The convection heat transfer coefficient h_2 is greater than h_1, and the temperature difference between liquid nitrogen and flat steel ribbons is greater than that of air and inner core at initial time, so heat transfer between liquid nitrogen and flat steel ribbons is more intense than that of air and inner vessel. However, the heat transfer change becomes gentle and temperature gap narrows down as time goes by. It is known that the temperature change of outside flat steel ribbons is bigger than that of inside ones during the stabilization;

in other words, the slope of right side of the curve is greater than that of the left one. The curve of temperature change turned to be straight (the bottom one in Fig.5), and the heat transferring from sharply to gently.

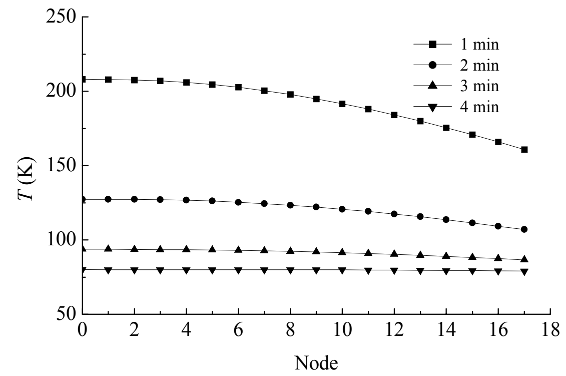

Fig.5 Temperature change in different minutes in cooling phase of cooling phase

Fig.6 indicates the temperature change of the vessel wall when liquid hydrogen is pumped into the inner core. Heat transfer between inner core wall and liquid hydrogen is more intensive than that inside the vessel wall. It is also shown in Fig.6 that the slop in left part of the temperature curves is steeper than that of the right part. When heat is being transferred, the temperature change would gradually slow down and turns to be stabilized at last.

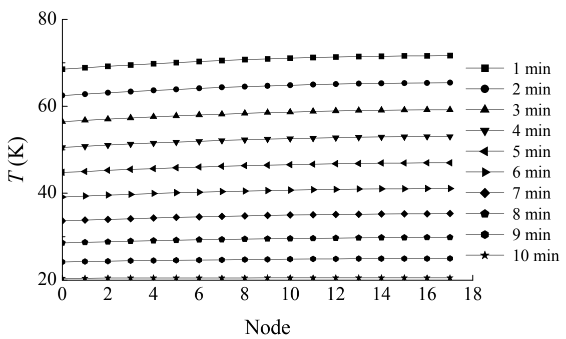

Fig.6 Temperature change in different minutes of liquid hydrogen filling

Length change of flat steel ribbons

The length of flat steel ribbons changes as temperature changes. The following equation depicted the change in the length Δl and the temperature T (Zhu and Zheng, 1995):

$$\Delta l = (-0.0002T^2 - 0.0403T + 31.641)\pi d \csc\alpha, \quad T \le 300\ \text{K}, \tag{16}$$

where α is the winding tilt angle of the flat steel ribbons; d is the loop diameter of inner vessel wall or flat steel ribbons, m.

With Eq.(16), the relative length change, l_R, in the temperature T is:

$$l_R = \Delta l / l = -0.0002T^2 - 0.0403T + 31.641, \quad T \le 300\ \text{K}. \tag{17}$$

In cooling phase, the length of six flat steel ribbons and inner core changes too (Fig.7). The more outside the flat steel ribbon, the greater the length change. Consequently, the temperature of all the flat steel ribbons would be even and the relative length change of each flat steel ribbon would tend to be the same. Eq.(17) explains this process. In Fig.7, the density of curves indicates that the length change of each flat steel ribbon is different. At the beginning of cooling, relative length change of outside flat steel ribbons is larger than that of the inside ones, resulting in tightening of the ribbons which would speed up the heat transfer. However, it would also intensify the ribbons stress, which can be avoided if the vessel is cooled by steps. At last the temperature of flat steel ribbons is balanced out, so does the relative length change.

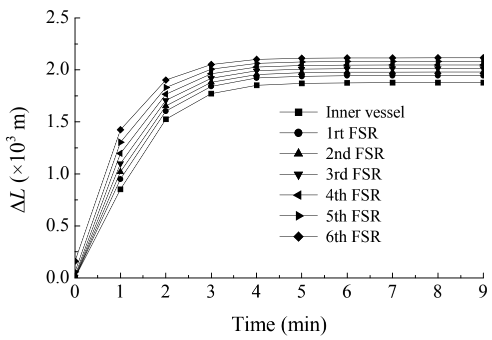

Fig.7 The change in the length of flat steel ribbons in cooling phase

When inner core is being filled with liquid hydrogen, the relative change in the lengths of inner vessel and flat steel ribbons (Fig.8) is kept consistently because the coefficient of thermal expansion of the flat steel ribbons is approximately a constant when temperature is below 80 K. As liquid hydrogen is charged into the inner core, layers of the flat steel ribbons would relax and loosen and the temperature difference between inside and outside of the vessel walls can reach 60 K.

In brief, the use of flat steel ribbons in the vessel system is safe. Being charged with liquid nitrogen or liquid hydrogen, the inner core would keep its tightness and strength; therefore no fracture would be resulted and the system would keep its original state once temperature distribution stabilized.

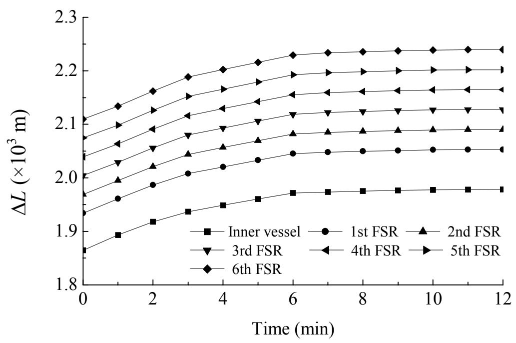

Fig.8 The change in the length of flat steel ribbons as the inner vessel is being filled with liquid hydrogen

CONCLUSION

By calculating and analyzing the heat transfer process in a new-type flat steel ribbon wound vessel wall, the authors concluded:

(1) The temperature in heat transfer in the system changes sharply at the beginning then gently until it stabilized. The process is similar to the one in the inner core when it is charged with liquid nitrogen or liquid hydrogen. The temperature of the whole system including the vessel and the liquid would reach balance.

(2) In cooling phase, the flat steel ribbons would tighten up which would favor the heat transfer. A small difference exists in pressure of the inner core when it is charged with liquid nitrogen or with liquid hydrogen for cooling. However, it does not impact the vessel in safety. And the influence can be compensated at last when the temperature of vessel wall goes steady.

(3) The performance of flat steel ribbons is good without risk of looseness or fracture. The relative change in length is the same for each flat steel ribbons and the system can remain its initial shape or state.

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