Study of temperature distribution of flat steel ribbon wound cryogenic high-pressure vessel

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By analyzing the heat transfer process of a flat steel ribbon wound vessel (FSRWV) wall, a temperature distribution model of the whole wall is established. Based on the model, the temperature distribution and the length change of vessel walls and flat steel ribbons at low temperature are calculated and analyzed by numerical method. The results show that the flat steel ribbon wound cryogenic high-pressure vessel is simple in structure, safe and easy to manufacture compared with the conventional cryogenic high-pressure vessel.

INTRODUCTION

Cryogenic high-pressure vessels that are used to store liquid hydrogen and liquid oxygen are important equipments in the fields of chemical engineering, astronautic engineering and nuclear power station etc. For the experimental research of astronautic engineering, the inner pressure of the vessel can reach 40 MPa and temperature 20K, so it requires much higher performance of the vessel wall material and it must satisfy some basic requirements such as high mechanical strength, well plastic property, high impact toughness value, high fracture toughness value, good fatigue strength, good forge ability and good harden ability etc. [1-3]. It is difficult for the conventional cryogenic high-pressure vessels to manufacture for that they are mostly forge-welded or multi-layer reel-welded. New type of FSRWV that initiated in China avoids the traditional technology shortcomings and has those merits.

There have been many researches on the flat steel ribbon wound vessel to date, but most of them have only aimed at optimum design [4-5] or safe monitor at ambient temperature [6-7]. Concerning the research of heat transfer, some researchers have calculated and analyzed the temperature difference of interfaces and the rate of evaporation under steady heat flow rate [8]. Up to now, research on temperature distribution, changes of the whole vessel wall and the dimension, stress change of the flat steel ribbons in very low temperatures has little presentation in literature. In this paper, a physical model for heat transfer of the vessel wall in very low temperatures is established under some reasonable hypotheses. Based on the model, the temperature distribution and the length change of vessel walls and flat steel ribbons at low temperature are calculated and analyzed. The results provide a basis for engineering design.

PHYSICAL MODEL AND NUMERICAL SIMULATION OF THE TEMPERATURE DISTRIBUTION

FSRWV model structure that is used in this research is showed in Fig.1. Its design pressure is 35MPa and the temperature is 20K.

This paper mainly discusses the heat transfer of the vessel wall. It is difficult to precisely calculate the heat transfer of the vessel wall, so it is necessary to hypothesize as follows to simplify the calculation: 1) the vessel is an infinite cylinder and the heat transfer is a one-dimensional radial form; 2) the liquid nitrogen isn't filtered into the seams of the flat steel ribbons when cooling the vessel; 3) all of the materials are isotropy.

Outside insulating material of the vessel is polyurethane foam, in which heat transfer is only by conduction and the coefficient of heat conductivity is 0.027[9]. Heat transfer between the insulating layer and outside air is natural-convection.

When liquid nitrogen is charged into liquid nitrogen zone, heat transfer happens between liquid nitrogen and flat steel ribbons and the jacket outside cylinder respectively. The heat transfer process is changed according to the temperature difference ΔT between the liquid nitrogen and the wall: when $\Delta T > 100K$, for example, the film boiling heat transfer will happen; $5K < \Delta T < 100K$, the nucleate boiling heat transfer will happen; $\Delta T < 5K$, the natural-convection heat transfer will happen, in which the nucleate boiling heat transfer is the most intense process [10]. The heat transfer between inner wall and air is the same as the liquid nitrogen with flat steel ribbons and jacket outside cylinder.

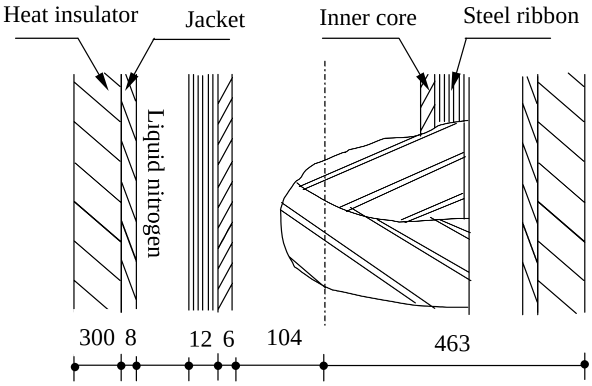

Fig.1. Sketch map of the FSRWV model structure

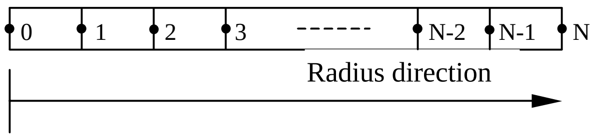

Fig.2. Diagrammatic sketch of vessel wall

When the liquid nitrogen is pumped out and the liquid nitrogen zone is vacuum-pumped, the zone is regarded as insulating-zone, in which the main heat transfer is radiation and the conduction of the rarefied air can be neglected [10].

According to the physical model, numerical simulation is calculated by using finite difference method. Difference equations of all nodes are established in terms of central difference method. The diagrammatic sketch of the nodes is showed in Fig.2.

RESULTS AND DISCUSSION

Analysis of temperature change of the vessel wall when cooling

To precool the vessel, liquid nitrogen is charged into the nitrogen zone, the temperature distribution of the wall is changed. Based on the results of simulating calculation, we get Fig.3. In the Fig., curves that are arranged from the top down represent temperature change of inner core and six flat steel ribbons from interior to exterior respectively. With the lapse of time, temperature of all nodes goes uniform, the temperature of outside nodes is more prone to stabilizing than the inside nodes and at last the temperature of flat steel and inner vessel reach 77K because the convection heat transfer coefficient of liquid nitrogen h_2 is much greater than that of the inner air h_1.

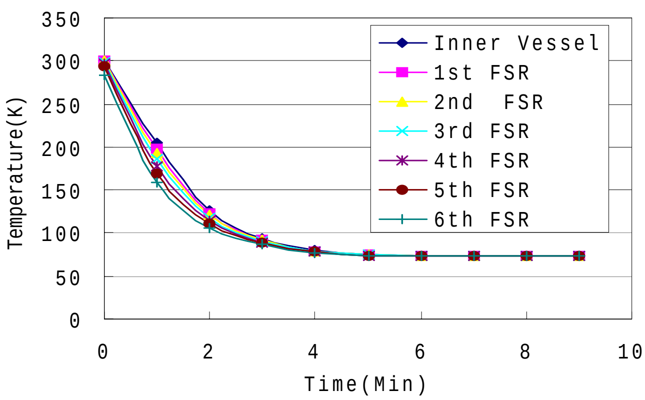

Fig.3.Temperature change of difference nodes when cooling

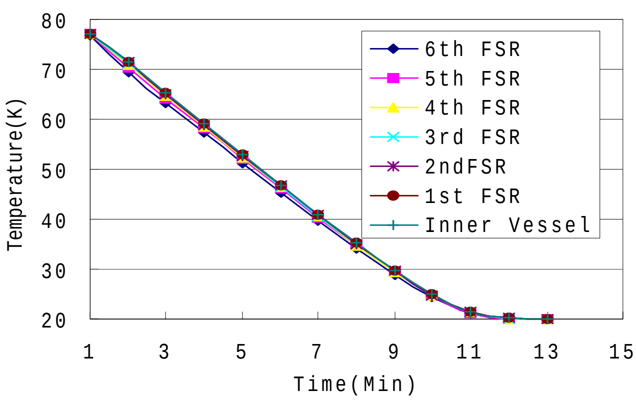

Fig. 4. Temperature change of different nodes when charged into liquid hydrogen

When the liquid hydrogen is charged into the inner core, the tendency chart of temperature change is showed in Fig.4 that is analogous with Fig.3, but the temperature of inner vessel wall and flat steel ribbons are 22K at last.

Temperature change tendency of all nodes at different time

The temperature distribution is different at different moment when the temperature field of whole vessel wall goes steady and the temperature change of all nodes is showed in Fig.5. Because here h_2 is greater than that of air h_1, the temperature difference between liquid nitrogen and flat steel ribbons is greater than that between air and inner core at initial time, heat transfer between liquid nitrogen and flat steel ribbons is more intense than that between air and inner vessel. But heat transfer goes gentleness with the temperature difference turn small with the lapse of time. It is known that the temperature change of outside flat steel ribbons is greater than that of inside flat steel ribbons at the process of going to steady (of right side slope of the curve is greater than that of left). The curve of temperature change turned into straight line that is also showed in Fig.5 bottom, which illustrates the fact that the heat transfer is changed from intensity to gentleness.

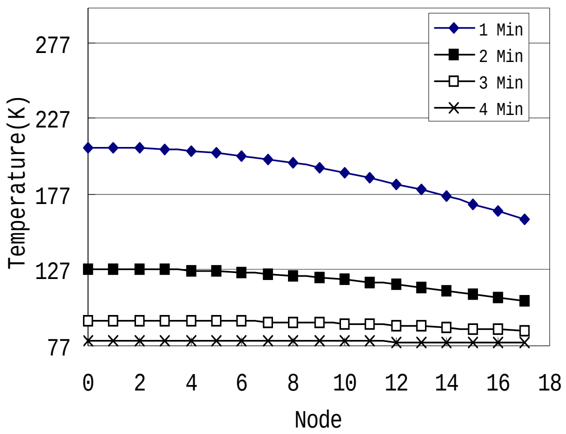

Fig.5. Temperature change of different nodes when cooling

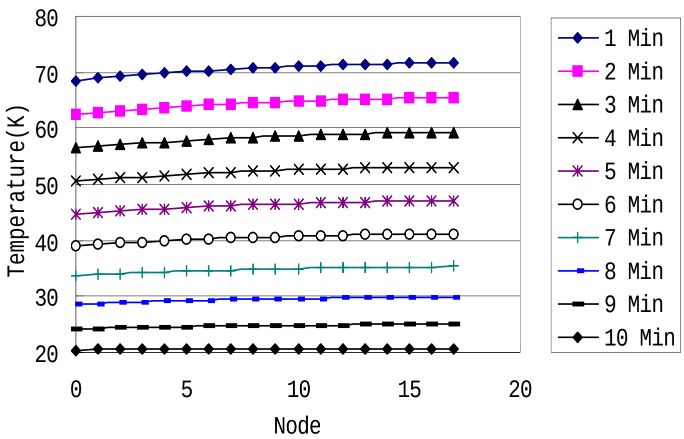

Fig. 6. Temperature change of different nodes when charged into liquid hydrogen

When the liquid hydrogen is charged into the vessel, temperature change of the vessel wall is showed in Fig.6. Since heat transfer between inner core wall and liquid hydrogen is more intense than that of inside of the vessel wall by conduction, the slop of curves at the left part is greater than that of the right part. With the heat transfer going on, temperature changes go to steady at last.

Length change of flat steel ribbons

The length of flat steel ribbons changes when temperature changes. When cooling the vessel, the length change of six flat steel ribbons and inner core is showed in Fig.7, from which we know that the length change of flat steel ribbons in outer layers is greater than that of flat steel ribbons in inner layers. But at last the relative length change of each flat steel ribbon is almost the same. According to the density of the curves we know that the length change of each flat steel ribbon is different. At the beginning of cooling, relative length change of the exterior flat steel ribbon is greater than that of the interior, which tightens the flat steel ribbons and enhances the heat transfer. But it also intensifies the stress of flat steel ribbons and it can be avoided if the vessel is cooled down slowly. At last the relative length change of each ribbon goes uniform.

When the liquid hydrogen is charged into inner core, the relative length change of inner vessel and flat steel ribbons showed in Fig.8 keeps uniform because the cryo-coefficient of thermal expansion of the flat steel ribbons is an approximate constant when the temperature is lower than 80K. At the mean time, the layers of flat steel ribbons have the loosening trend because the temperature difference between inside and outside vessel wall can reach 60K. The trend can be weakened for the initial stress and can be compensated rapidly when the internal pressure is created.

In brief, the flat steel ribbons are safe and they cannot get looseness or fractures when the inner core is charged into liquid nitrogen or liquid hydrogen. they keeps their designed state when the temperature distribution of vessel wall reach steady.

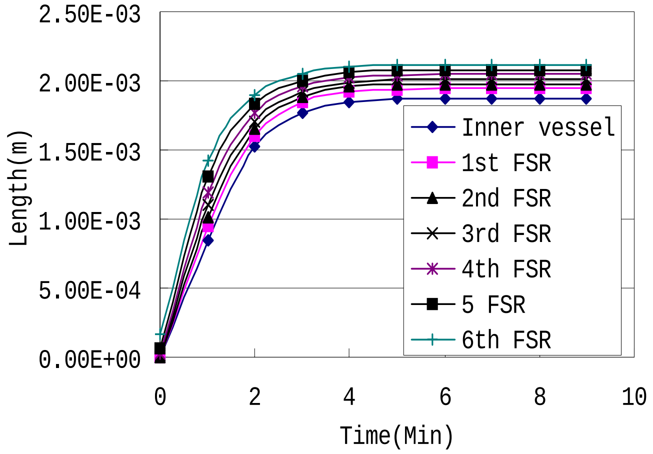

Fig.7. Length change of flat steel ribbons when cooling

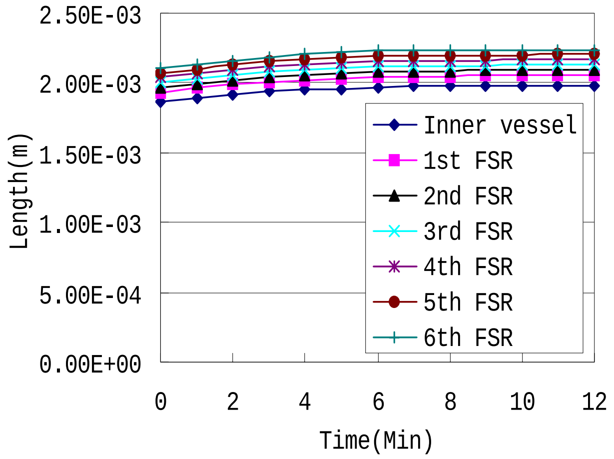

Fig.8. Length change of flat steel ribbons when charging liquid hydrogen into inner vessel

CONCLUSIONS

We get the following conclusions by calculating and analyzing the heat transfer process of the new-type flat steel ribbon wound vessel wall.

① Temperature change process that heat transfer undergoes intense to gentle is analogous when the inner core is charged into liquid nitrogen or liquid hydrogen, and the temperature of whole vessel is liquid nitrogen temperature or liquid hydrogen temperature.

② The process of cooling tightens the flat steel ribbons and is propitious to heat transfer. The inner pressure has some change when charged liquid nitrogen for cooling or charged liquid hydrogen into inner core, but it does not have influence upon the vessel and the change can be compensated when the temperature of vessel wall goes steady.

③ The flat steel ribbons do not have the risk of looseness or fracture, their relative length change is the same and they keep their designed state at the steady state.

REFERENCE

1. Zhou Y. Research and development of cryogenic vessel. Cryogenics (1998) 4 15-21(in Chinese)

2. Nichols R W. Developments in pressure technology, Materials and Fabrication, London, Applied Science Publishers Ltd, (1980)

3. Lloyd E B, Edwin H Y. Process Equipment Design. New York, John Wiley 8L Sons, Inc. (1959)

4. Jiang J L. Research on design of newly low temperature and high-pressure vessel wound by steel strip. Cryogenics (2001) 3 44-47(in Chinese)

5. Zheng C X. Optimal design method of flat ribbon wound pressure vessel. Petro-Chemical Equipment (1997) 1 14-19(in Chinese)

6. Zheng J Y, Xu P, Chen C, Investigation on bursting pressure of flat steel ribbon wound pressure vessels, International Journal of Pressure Vessels and Piping (1998) 75 581-587.

7. Zhu R L，Potential developments of pressure vessel technology by using thin inner core and flat steel ribbon winding techniques, International Journal of Pressure Vessels and Piping (1996) 65 7-11

8. Chen Z P, Zheng J Y. Analysis of heat transfer and calculation of evaporation rate of flat steel ribbon wound liquid hydrogen high-pressure vessel. Cryogenics (2001) 6 56-61

9. Xu L. Cryogenic Insulation Heat and Storage and Transportation technology, Beijing, China Machine Press (1995)

10. Chen G B. Cryogenic Insulation and Heat Transfer, Hangzhou, Zhejiang University Press (1989)