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Analysis of a Cryogenic System for Cord Blood Banking

Bin Zhang[1] · Eunpil Kim†

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Abstract : The application of a cryogenic storage system is growing fast in different kinds of fields including to keep umbilical cord blood. Umbilical cord blood stem plays an important role in the treatment of a blood and immune system related genetic diseases, cancers and blood disorders. This study gives the optimal cryogenic system for cord blood banking. Three-dimensional models are employed and finite element method is used to do structure analyses of all designed models. The results shows model 3 have a good structure properties, and model 4 shows the best structure property as its maximum is 92.9 MPa. The other is too dangerous or infeasible to support load condition that allowed by STS 304. The results can be used in the design of these kinds of systems to obtain good predictions of trends over a wide range of design alternatives and operating conditions.

Key words : Cryogenic Engineering, Modeling, Liquid Nitrogen, Umbilical Cord Blood

1. Introduction

Cord blood stem cells are used in the treatment of over 40 life-threatening diseases, and play an important role in the treatment of blood and immune system related genetic diseases, cancers and blood disorders. In laboratory experiments it has been shown that cord blood stem cells can differentiate into a number of different cell types, which could give rise to future potential new therapeutic uses[1]. Cryogenic engineering has been used in these banks in order to storage umbilical cord blood cells. This is necessary because conventional techniques of storage permit effective preservation of whole blood for only 21 days. Fast freezing and maintenance at liquid nitrogen temperature, on the other hand, result in successful long-term storage of blood[2]. A cord blood bank is a facility which stores umbilical cord blood for future use. The advantages of the banking of umbilical cord blood have been discussed in the paper of Sozeos and Joseph[3]. Implications of umbilical cord cell banking has been presented by Jennifer Gunning[4], in which the potential future use of cord blood stem cells has been discussed.

The purpose of this study is to design an optimal cryogenic tank for banking of umbilical cord blood. A base model of the cryogenic will be first built and analyzed. In order to make the banking security, one of the most important thing will be tested to prevent the tank from pressure collapse. The results will be used to

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† Corresponding author (Pukyong National University, Division of Mechanical Engineering, E-mail:ekim@pknu.ac.kr, Tel: 051-629-6182)

1 Pukyong National University, Graduate school of Refrigeration and Air Conditioning

design optimal cryogenic tanks for banking of umbilical cord blood.

2. Modeling

A cryogenic tank is a vessel, similar in construction to a vacuum flask used to maintain cold cryogenic temperature. Cryogenic tanks are designed to bank the umbilical cord blood units. This requires the cryogenic tanks should be able to hold liquid nitrogen in a liquid state with minimal boil off (evaporation rate). Cryostats are manufactured with two vessels, one inside the other. These designed in this study are built with an outer evacuated vessel, and an inner liquid nitrogen vessel. For the umbilical cord blood storage, liquid nitrogen is used in the cryogenic tank to storage the blood in a long-term.

The out vessel can keep its contents cooler than the environment by interposing an evacuated region to provide thermal insulation. Using vacuum as an insulator avoids heat transfer by conduction and convection. A reflective coating is applied to the outer surface of the vessel to minimize the heat loss by radiation. Figure 1 shows the top and front view of the out vessel. In the front view, we can see the vacuum region between thin walls. The outer diameter of the vessel is 1,236 mm and the inner diameter is 1,124 mm. The overall height is about 1,330 mm when the depth is about 1,180 mm.

Both of the out shell body wall and the inner shell body wall are 3.0 mm in thickness. Between the two shells, there is the vacuum region with a thickness of 50 mm. The wall on the two sides of the vacuum region will afford pressures, and this is the region where pressure collapse is most likely to happen.

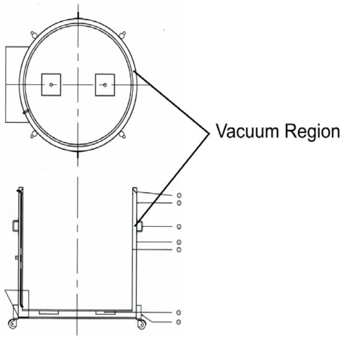
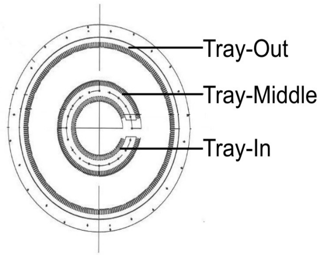
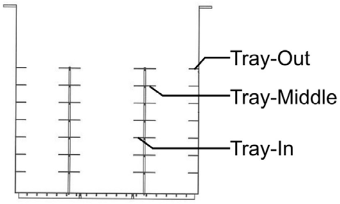


Figure 1: Schematic of the outer vessel



a) top view



b) front view

Figure 2: Schematic of the inner vessel

The inner vessel contains several round racks hich is located on three concentric trays, as shown in the Figure 2. Generally, three trays, racks and bottom support make up the inner vessel.

For the structure analysis, the following factors have been analyzed: dead weight of the cryogenic tank, weight of the liquid nitrogen loaded on the inner vessel, pressures on the thin walls, and the weight of full filled canisters located on racks. For the dead weight, an acceleration of 9.8 m/s^2 is added to the whole tank to analyze the effects of the gravity. The load of liquid nitrogen is assumed that about 520 *l* liquid nitrogen is loaded in the inner vessel. This load is added on the bottom surface of the inner vessel.

For an optimal cryogenic tank designing for banking of umbilical cord blood units, six models have been designed. An optimal cryogenic should meet the structure strength requires and be manufactured by less material. The first designed cryogenic tank model has a thickness of 3.0 mm for the vessel wall, thicknesses of 3.0 mm for the tray-in, tray-mid and tray-out, and a thickness of 2.0 mm for the rib of bottom support. Other five models are designed based on the first model. Table 1 shows the difference of each model in thickness in details.

For each analytical factor, numerical analysis has been done using CATIA by FEM. The governing equations for the analysis is shown user's manual[5]. For an FEM analysis, the model is meshed as a 3-D property with triangle elements. The governing for calculating stress is used as the following equation.

$$\varepsilon = \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad (1)$$

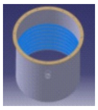
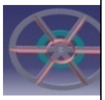
where $\frac{\partial u}{\partial x}$ and $\frac{\partial v}{\partial y}$ are two partial derivatives. Element stresses at Gauss points are the product of the Comportment law and the strain deformation as follows:

$$\sigma = D \bullet \varepsilon \qquad (2)$$

where σ is element stress.

D is the Comportment law which is computed as a function of the following parameters. v is the Poisson Ratio. E is the Young's Modulus, and ε is the strain deformation computed according to the displacement.

Table 1: Specifications of analyzed models

Model	Thickness (mm)				
	Vessel Wall	Tray-in	Tray -mid	Tray-out	Bottom Rib
1	3.0	3.0	3.0	3.0	2.0
2	2.0	2.0	2.0	2.0	2.0
3	2.0	3.0	3.0	2.0	2.0
4	2.0	2.0	2.0	2.0	3.0
5	1.5	1.5	1.5	1.5	1.5
6	1.5	1.5	1.5	1.5	2.0
					

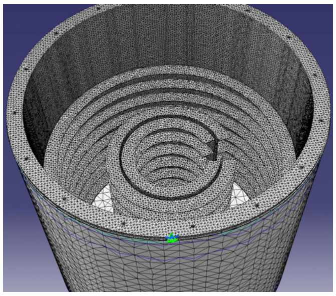
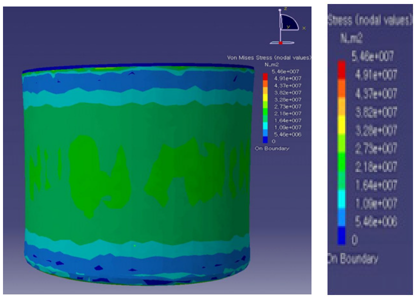


Figure 3: Refined mesh for the model 1

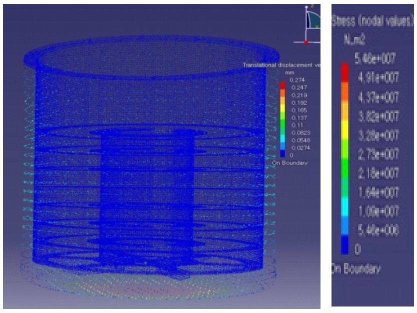
Figure 3 shows the results of the sampled mesh. Some parts such as the support and racks have been refined in mesh.

3. Results and discussion

In each analytical factor for the structure analysis mentioned before, the influences caused by internal and external pressures on thin wall of the tank is shown in Figure 4.



a) Von Mises Stress



b) translational displacement

Figure 4: Influences of internal pressure and external pressure

Table 2 shows the maximum values of Von Mises stress and translational displacement caused by each analytical factor for the first model. For the first model, the dead weight makes a maximum Von Mises stress of 1.44e+007 N/m^2, a maximum translational displacement of 0.150 mm, and the storage of 520 *l* liquid nitrogen makes a maximum Von Mises stress of 3.04e+006 N/m^2 and a maximum translational displacement of 0.027 mm. Internal and external pressures make a maximum Von Mises stress of 5.46e+007 N/m^2 and a translational displacement of 0.274 mm. We can see that the pressures give a largest influence to the model. This is because of the vacuum layer existing between the outer shell wall and the inner shell wall of the outer vessel. In fact, pressure collapse could happen if the internal pressure exceeds the limitation.

Among the three racks, the canisters loaded on the rack-mid give the largest stress, which is as high as 7.32e+007 N/m^2. We can also see the rack-mid has the largest displacement. This is because the rack-mid has a highest ratio of load to area which means the density of distributed force is the biggest on the rack-mid. The loads on rack-mid also cause the largest translational displacement to the whole model. The largest translational displacement caused by loads on rack-mid is 0.809 mm.

After analyses of factors have been done one by one, the combined analyses of all factors have been taken out for each model. Thus the stress distribution of the whole model can be calculated out. The values of maximum Von Mises stress and maximum translational displacement have been recorded, and then compared to the max allowable stress of STS 304.

From these comparisons, the feasible designs can be found out. Since a cryogenic tank works under severe conditions, for example, the temperature in the tank can be as low as -196℃

when the temperature of the environment outside can be around 0℃, the max allowable stress of 137 MPa has been chosen to the STS 304 according to ASME BPVC 2004 [6].

Table 2: Maximum value of Von Mises stress and translational displacement

Analytical Factors		Distribution Location	Analysis Results	
			Von Mises Stress (N/m2)	Translational Displacement (mm)
Dead Weight	545kg (empty)	whole model	1.44e+007	0.150
Liquid Nitrogen	520 l	bottom of the inner vessel	3.04e+006	0.027
Pressure	1 atm	thin walls of the outer vessel	5.46e+007	0.274
Storage Capacity	70 canisters	rack-in	2.94e+007	0.303
	148 canisters	rack-mid	7.32e+007	0.809
	270 canisters	rack-out	1.27e+006	0.005

Table 3 shows that for all models, the maximum Von Mises stress happen at the ribs of the bottom support, which means, if the maximum Von Mises exceeds the maximum allowable stress, ribs of the bottom support will break first. The maximum allowable stress of STS 304 is 137 *MPa*.

From the analysis results of the six models, we can find out that model 2 and 5 are infeasible. And model 6 is also not feasible as the maximum Von Mises stress of 135 MPa is too close to the maximum allowable stress.

Table 3: Results of statics structure analyses for 6 models

Model	Max Von Mises Stress	Max Displacement	Conclusions
1	108 MPa	1.10 mm	Feasible
2	298 MPa	1.43 mm	Infeasible
3	128 MPa	1.37 mm	Feasible
4	92.9 MPa	1.28 mm	Feasible
5	219 MPa	1.72 mm	Infeasible
6	135 MPa	1.61 mm	Dangerous

The left three models are feasible. Cryogenic tanks can be manufactured following these three models. Among these feasible models, model 4 shows the best structure property as its maximum is 92.9 MPa, which is much smaller than the others. It is the most safety on in all of designs.

Among these factors, the load of canisters on the rack-mid gives the whole structure a largest stress of 7.32e+007 N/m^2, which is mainly afford by the bottom support for the inner vessel. The load of canisters on the rack-mid gives the whole structure a largest translational displacement of 0.809, which occurs at the break position of the top racks of rack-mid. Internal and external pressures give a big influence to the thin walls, as there is a vacuum region between the inner shelland the out one. When the internal pressure is out of control and increases rapidly, the collapse of the cryogenic tank will happen.

We can find out that in model 2 and model 5, the designs are not feasible, because the maximum stress exceeds the maximum allowable stress of the material. Pressure collapse happens. In model 6, the designed model is dangerous, because the maximum stress is very closed to the maximum allowable stress of the material. This can be improved if we increase the thickness of the bottom rid. But it still has a larger maximum translational displacement compare to other feasible models.

4. Conclusions

In the paper, there are seven main factors have been analyzed. They are dead weight of the cryogenic tank, the storage capacity of liquid nitrogen, the internal and external pressures, three different loads on three different racks, respectively. Six models have been suggested. The results shows model 3 have a good structure properties, and model 4 shows the best structure property as its maximum is 92.9 MPa. The other is too dangerous or infeasible to support load condition that allowed by STS 304.

The results can be used in the design of these systems to obtain good predictions of trends over a wide range of design alternatives and operating conditions.

Acknowledgements

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Author Profile

Eunpil Kim

Professor, School of Engineering, Pukyong National University. Ph.D. in Mechanical Engeering, University of Pittsburgh, 1995.

Bin Zhang

Graduate Student, Department of Refrigeration and Air Conditioning. Pukyong National University.