한국태양에너지학회
THE KOREAN SOLAR ENERGY SOCIETY
추계학술발표대회 논문집

Numerical study on Comparison of Self-Pressurization Behavior of Liquid Nitrogen Cryostat for Umbilical Cord Blood Storage System Design

M. I. Mahfud, K. E. Phil *

Graduate School of dept. of Refrigeration and Air Conditioning Eng., Pukyong National University
**Department of Refrigeration and Air Conditioning Engineering, Pukyong National University*

Abstract

Since cryogens are stored at very low temperatures, the cryogenic storage systems are quite sensitive to heat leaks. Even though the vessel operated under sealed condition with vacuum insulation and reflective coatings are used, the heat leakage into the vessel is still unavoidable. Therefore, this paper concerns with numerical study of self-pressurization used to analysis the optimum design with the variation volume fraction, effect of heat flux and storage pressure of liquid nitrogen. The result shows that as the volume fraction increases, the pressure rise reduces and the relatively at atmosphere pressure is better than the higher one. In addition, higher heat flux leads the pressure rise increases faster than low one. The additional of heat pipe system to reduce the pressure rise rate also has been done. By this comparison, the optimum design for storage umbilical cord blood can be selected.

Keywords: *numerical, self-pressurization, umbilical cord blood.*

1. Introduction

In recent years, umbilical cord blood which contains both hematopoietic stem cell and pluripotent mesenchymal cells has been used in treatment of leukemia, cancer, genetic disease and inborn error of metabolism. Over 7000 umbilical cord transplants have taken place worldwide [1]. Umbilical cord blood that stored under cryopreservation does not have deterioration in the quality of the cells after ten years and have performed as well as new ones.

Since cryogens are stored at very low temperatures (far away from environment), cryogenic storage systems are quite sensitive to heat leaks. The heat leakage of the vessel can affect the performance in the process of non-losses (holdup-pressure) storage. On the one hand, the internal energy of the system increase causes the temperature to raise. Therefore, the saturation pressure rise. With the temperature rising, the volume of the liquid expands, that causes the space for the gaseous phase reduce. The volume of the liquid nitrogen is incompressible , so the pressure in the vessel rises rapidly.

This change is different for various volume fractions of liquid nitrogen.

Vacuum vessel that created first time by James Dewar in 1892 is base Cryogenic storage system. In early 1960 multilayer insulation was introduced and until now, a lot of researches have been trying to reduce the heat losses for cryogenic storage system. The research conducted by Khemis et al. [2] presented an experimental investigation of heat transfer in a cryostat without lateral insulation and considering radiation mode. Son et al. [3] presented a study on fluid flow and heat transfer of liquid hydrogen in a zero boil-off cryogenic storage tank in a microgravity environment with heat pipe-pump system. Li et al. [4] analyzed effects of liquid volume fraction, temperature and work pressure in cryogenic vessels on the pressure rise rates in cryogenic vessels experimentally for liquid oxygen, liquid helium and liquid hydrogen. Boukeffa et al. [5] presented an experiment, theoretical and numerical analysis concerning heat transfer between the vapor and the cryostat neck obtain by liquid nitrogen cryostat.

Because of liquefaction costs, safety considerations and the low heat of vaporization, special high-high performance insulations are required to reduce the evaporation rate of cryogenic liquid in storage vessels. Furthermore, even the vessel operated under sealed condition with vacuum insulation and reflective coating are used, the heat leakage into the vessel will always exist. When heat leaks into the tank, it will be carried to the liquid-vapor interface by conduction and natural convection causing vaporization, which in a closed tank will result in a pressure rise.

In this paper, the comparison of self-pressurization behavior of liquid nitrogen cryostat with the variation of volume fraction, storage pressure and the affect of heat flux amount will be analyzed by means of the numerical method. The addition of heat pipe also will analysed to reduce the pressure rise rate. By this way, the optimum design can be selected.

2. Physical model

A cryogenic storage tank (cryostat) that designed for cord blood banking is a vessel that made by dewar or vacuum flask. This required vessel should be able to hold liquid nitrogen in a liquid state with minimal boil off.

In this study, the basic cryostat for umbilical cord blood storage system is modeled by a cylindrical tank of stainless steel material with inner shell diameter of 1124 mm and outer shell diameter of 1236 mm, the overall height is about 1246 mm with the depth of 1180 mm. the thickness of inner shell and outer shell are 3 mm. the capacity of 1171 l.

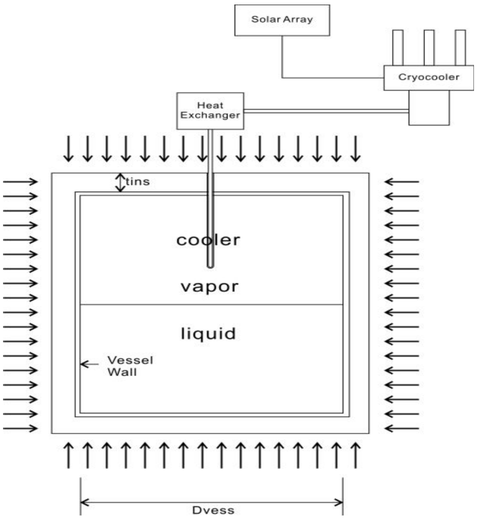

Figure 1. Model of cryogenics vessel subjected to heat leakage.

Liquid nitrogen has ability to maintain temperature far below the freezing point of water makes it extremely useful in a wide range of application, primarily as an open-cycle refrigerant, including the cryopreservation of blood, reproductive cells (sperm and egg), and other biological samples and materials.

All of the cryogenic liquids have a relatively low heat of vaporization. For example, at a pressure of 1atm the heat of vaporization for liquid nitrogen is 199.3kJ/kg. Conversely, the heat of vaporization for water at 1 atm is 2257kJ/kg.

3. Mathematical model

Because the geometry of the vessel and the boundary condition, it is allow making it simpler, tank model can be attained by neglecting the three dimension of cylindrical vessel with the rectangular section. With the uniform heat flux induce to all section of wall due to poor insulation. The fluid assumed initially is at the rest, where;

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

The system is closed system, no fluid flow into or out of the vessel. Where,

$$\frac{d}{dt}(\rho_v V_v)+\frac{d}{dt}(\rho_l V_l)=0$$

The multiphase mixture model used is generated by Fluent code which the vapor is assumed to behave like an ideal gas and the developed mathematical model for liquid nitrogen domain consists of conservation of mass, momentum, energy equation with density dependent temperature. The continuity equation for mixture model is given by [6];

$$\frac{\partial}{\partial t}(\rho_m)+\nabla.(\rho_m\vec{v}_m)=0$$

Where $\vec{v}_m$ is the mass averaged velocity and ρ_m is mixture density

The momentum equation for the mixture can be obtain by summing the individual momentum equation both phase. It can be express as:

$$\frac{\partial}{\partial t}(\rho_m\vec{v}_m)+\nabla.(\rho_m\vec{v}_m\vec{v}_m)=-\nabla p+\nabla.[\mu_m(\nabla\vec{v}_m+\nabla\vec{v}_m^T)]+\rho m\vec{g}+\vec{F}+\nabla.(\textstyle\sum_{k=1}^{2}\alpha_k\rho_k\vec{v}_{dr,k}\vec{v}_{dr,k})$$

Where p is pressure, α_k is volume fraction of phase *k*, $\overline{F}$ is body force, μ_m is viscosity of the mixture, $\vec{v}_{dr,k}$ is the drive velocity of secondary phase *k*.

From the continuity equation for secondary phase *p*, the volume fraction equation for secondary phase *p* can obtained:

$$\frac{\partial}{\partial t}(\alpha_p\rho_p)+\nabla\cdot(\alpha_p\rho_p\vec{v}_m)=-\nabla\cdot(\alpha_p\rho_p\vec{v}_{dr,p})+\textstyle\sum_{q=1}^{n}(\dot{m}_{qp}-\dot{m}_{pq})$$

As a result of heat addition into the liquid and vapor phases, the internal energy of both phases is increased and consequently, the tank pressure is also rised. If the liquid and vapor are sufficiently well mixed to ensure homogeneity within the system, the tank pressure will rise at the rate predicted by the first law of thermodynamics.

Heat transfer is governed by the multiphase energy equations, which generalize the single phase energy equations. The multiphase energy equation for the mixture takes in the following form;

$$\frac{\partial}{\partial t}\sum_{k=1}^{2}(\alpha_k \rho_k E_k) + \nabla\cdot\sum_{k=1}^{2}(\alpha_k \vec{v}_k(\rho_k E_k + p)) = \nabla\cdot(k_{eff}\nabla T + S_E)$$

Where E_k is the total energy for phase k, k_{eff} is effective conductivity and S_E is heat source.

4. Results and Discussion

The predicted pressure rise for three different mesh densities is shown in figure 2. Since the solution is nearly identical as the number of computational cells increase, a grid of 1444 cells is selected as a suitable compromise between accuracy and computational efficiency.

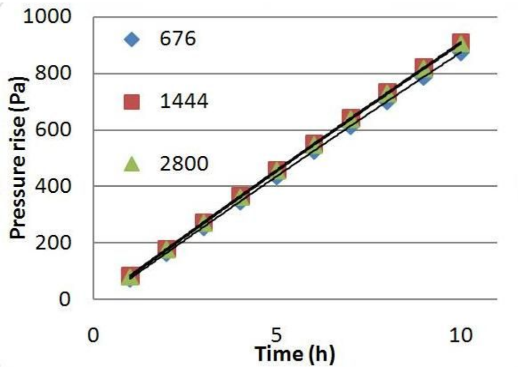

Figure 2. Comparison pressure rise for different mesh densities.

As a result of heat addition in the vessel, the inside temperature of the tank is increased. The increasing temperature both for liquid nitrogen and air are caused by the expansion of the volume of both fluids. Because the liquid nitrogen is incompressible, it reduces the space for the air, so the pressure in the vessel increases rapidly. These changes are different for various volume fraction of liquid nitrogen.

Figure 3 shows the effect of different fill level for cryogenic storage system on pressure rise inside the vessel with same heat flux. In this comparison heat flux with 10 W/m^2 used. The 10 % volume fraction have fastest pressure rise compared with higher fill level. However, as the volume fraction increases the pressure rise inside the vessel is decreased. In addition, with higher amount of liquid nitrogen the rise of internal energy is lower. The higher amount of liquid nitrogen means higher heat capacity. So, with the same of heat flux but with different amount of heat flux the expansion of liquid nitrogen is different. Because smaller amount of liquid nitrogen that fill the vessel smaller heat capacity, the smaller of volume fraction had larger pressure rise with the same heat flux.

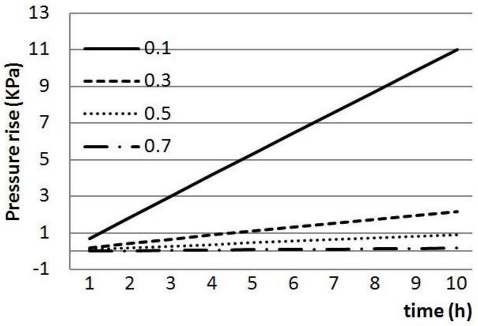

Figure 3. Comparison pressure rise with different volume fraction.

Figure 4 shows the effect of initial storage pressure on the pressure rise inside the vessel. From the figure, the initial storage pressure with atmosphere pressure has the best solution for pressure rise compared with the higher one.

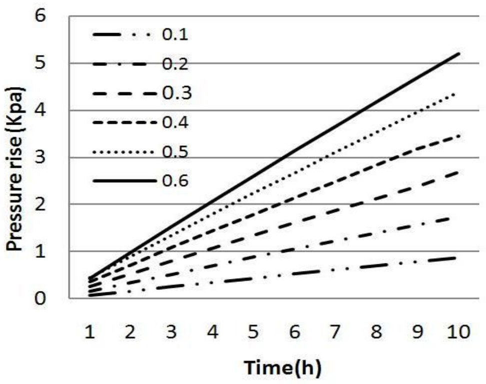

Figure 4. Comparison pressure rise with different storage pressure (MPa).

Difference temperature environment and the thermal conductivity coefficient of the insulate material resulting the different heat flux quantity in the storage system.

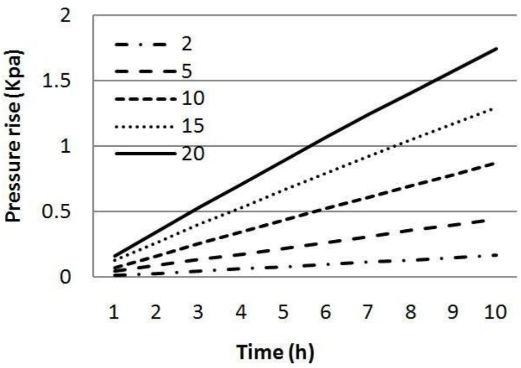

Figure 5. Comparison pressure rise with different heat flux (W/m^2).

Figure 5 shows the measured pressure rise as a function of time for 2, 5, 10, 15 and 20 heat flux level. As a result of heat flux into the liquid phase of nitrogen and air, the internal energy of both phases are increased and consequently the pressure is rised. the pressure rise rate increased with increasing heat flux.

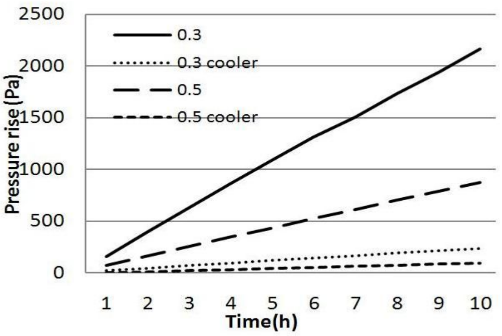

Figure 6. The effect of cooler on pressure rise rate.

The additional of cooler to reduce the pressure rise rate also have been done. When the cryogenic storage system equipped with cooler that maintain at 70 ^{o}K, the pressure rise rate inside the vessel reduced significantly. Figure 6 presents the histories of pressure rise rate comparison of original cryostat and the addition of cooler for volume fraction 0.3 and 0.5.

5. Conclusion

The fill levels (volume fraction) of liquid nitrogen, pressure storage and amount of heat flux on the storage system for umbilical cord blood have a significant effect for self pressurization. High volume fraction was best selection compared with the small one with the neglecting the weight of the total system.

Smaller heat flux has advantage with slower self-pressurization. Atmosphere pressure is selected for the system due to the performance of system is better than higher one. The effect of cooler on pressure rise rate that build with heat pipe also have been done. The result shows that the additional heat pipe can increase the performance of storage vessel design.

References

[1] CIGNA HealthCare Coverage Position. Umbilical Cord Blood Banking; 2007

[2] O. Khemis, M. Boumaza, M. Ait Ali, M. X Francois, Experiment analysis of heat transfer in a cryogenic tank without lateral insulation, Applied thermal engineering 23(2003) 2107-2117

[3] Ho Son H, Rahman MM. Three-dimensional analysis for liquid hydrogen in a cryogenic storage tank with heat pipe-pump system. Cryogenics (2007)

[4] Li Zhaoli, Xu Lie, Sun Heng, Xiao Youming, Zhang Jie. Investigation on performances of non-loss storage for cryogenic liquefied gas. Cryogenics 44(2004) 357-362

[5] Boukeffa D, Boumaza M, Francois MX, Pellerin S. Experimental and numerical analysis of heat losses in a liquid nitrogen cryogenic. Applied thermal engineering 21 (2001) 967-975

[6] Ansys Fluent Theory Guide. Ansys, Inc; 2009