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On the Leakage Analysis of a Full Containment Tank Using a FEM

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Abstract: In this paper, the leakage safety of prestressed concrete structure including the insulation panels has been analyzed using a finite element analysis just after a collapse of 9% nickel inner tank. This FEM study shows that the outer tank may contain the leaked cryogenic liquid for the time being until the primary pump in the inner tank transports stored cryogenic liquids to the nearest LNG storage tank before the outer tank is demolished. This means that the total tank thickness from the insulation panel to the outer tank system safely may retain the leaked cryogenic fluids. The FE computed results indicate that the current structure in a full containment tank is obviously enough to securing the leak-proof safety of the tank system with two primary pumps.

Keywords: Leakage analysis FEM, inner tank, outer tank, insulation panel

1. Introduction

In recent years, the growing demand of a liquefied natural gas as pollution-free energy is one of the most important energy sources. Especially, several Asian countries have built an extra-large LNG storage tank up to 200,000 m^3 in service. The large LNG storage tank may increase the cost effectiveness, operation easiness, and productivity. And also it reduces the construction, operation and maintenance costs at the limited construction site near the crowed city. In these construction trends for a large-scale LNG tank, various kinds of advanced safety and control systems including the information technology are provided to guarantee the strict safety and increased productivity of LNG receiving terminal facility. The safety and control systems include safety device, sensors, instruments, safety structures, disaster prevention systems, and IT based management systems for a LNG receiving facility.

The extensive and advanced engineering studies on analysis, optimized design, construction, quality control, operation, and safety have been carried out by many receiving terminal suppliers for securing the safety of transportation and storage of the natural gas at any circumstances. Among the studies, a particular emphasis is given to the safety of the storage tank structures. Many tank designers are very interesting to know the leak-proof endurance of prestressed concrete structure at extremely low temperature −162°C because we did not experience such a disaster of the large scale storage tank. Thus, it is very important to insure the safety and reliability of an extra-large LNG storage tank.

This paper presents the leak-proof analysis of prestressed concrete outer tank including the insulation panels after a collapse of the inner tank. This study shows that the outer tank may contain the leaked cryogenic liquid for the time being until the primary pump in the inner tank transports stored cryogenic liquids to the nearest LNG storage tank before the outer tank is demolished. This is the primary goal of the current numerical investigation whether or not the tank system safely retains the leaked refrigerated fluids after the inner tank is collapsed.

2. FEM Analysis Scope

The full containment LNG tank is composed of the prestressed concrete as an outer wall and the 9% nickel inner tank with and without a dike depending on the regulations and design codes of the country. The prestressed concrete outer wall based on BS 7777 supports all the mechanical forces and thermal loads caused by the inner tank collapse. The inner tank stores −162°C cryogenic liquid with maximum safety devices and structures such as a corner protection wall, stiffener and top girder, optimized thickness of the inner tank, safety valve and primary pumps, insulation system, earthquake resistance design, condition monitoring system, etc.

The full containment LNG tank with a prestressed concrete/ 9% nickel model should be compromised with a cost and a safety of the tank system at the planning step. At the receiving terminal of 140,000 m^3, LNG storage tanks without a dike are to be built as an aboveground type based on the computed results of mechanical and thermal stresses caused by either transient or steady state conditions. The outer PC wall should be designed and constructed by the minimum residual compression zone of BS 7777 standard for a maximum safety. At the end, the composite material of the prestressed concrete with a residual compression zone should guarantee the safety of the LNG tank system when the inner tank is collapsed. The PC structure of the outer tank is very important as a dike role in a full containment tank.

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This study provides the fundamental design data for investigating the leak-proof safety of the full containment LNG storage tank based on the coupled thermal-mechanical analysis technique [1]. This may lead to reduce the construction cost without the loss of the safety of the large-scale LNG storage tank if the outer wall can support the mechanical and thermal loads, and protect the cryogenic liquid leakage due to an abrupt failure of the 9% nickel inner tank. In this study, the increased leak-proof capacity of the PC outer wall may guarantee the safety of the tank system and radically cut the construction cost and the space of the LNG storage tank. Therefore, a dike as a safety structure does not need any more because the prestressed concrete, several insulation layers, and other structures may delay or protect the leakage flow from the inner tank to the outside of the outer rank.

3. Design and Cyclic Loads

3.1. Strength Stability

It must be shown that the 9% nickel inner tank as a system will maintain its original shapes based on the stress and deformation of each part under cycling loads such as hydrostatic and gas pressures, mechanical-thermal loads, and seismic impact forces, etc. The outer tank which is constructed by the prestressed concrete must support any kinds of loads and protect the leakage, in which comes from the inner tank.

3.2. Leakage due to Inner Tank Collapse

The inner tank should not be fractured for any kinds of loads or abnormal operation conditions. For the maximum safety and reliability, the tank system should increase the safety factor, which is strongly related to the construction and operation costs. In the worst case, the inner tank may leak refrigerated liquids along the inner tank wall and the bottom of the tank even if it is very small. Thus, the insulation panels and the prestressed concrete structure included with the corner protection and vapor barrier should protect the leakage that comes from a collapse of the inner tank.

3.3. Cyclic Loads and their Effects

Cyclic loads that influence to the safety of the tank are likely to occur in cryogenic liquid pressures and thermal loads, as a result of the following operational conditions:

- Cool down to –162°C from the ambient temperature.
- Cycling effects of 9% nickel structure between liquid and gas temperature differences.
- Liquid pressures rise and fall.
- Warm up from liquid to ambient temperature.

Here, the thermal load is defined as the thermal stresses generated due to temperature gradients of the sidewall and base of the structure. The number of cycles is determined by considering the design life and working conditions of the LNG storage tank. The LNG tank must use suitable materials of high fatigue strength to protect the unexpected collapse and does not permit the leakage from the inside. But, in the case of the inner tank collapse by cyclic loads, the prestressed concrete structure must protect the leakage and sustain the loads for a while until the leak probability of the tank is kept at a low level. This means that the primary pump and other safety devices work simultaneously and effectively. The primary pump is submerged in the inner tank for pumping out the refrigerated liquid to the nearest storage tank when the inner tank is collapsed during a service.

4. FEM Analysis

The leak-proof analysis of LNG storage tanks must be carried out under various load conditions specific with suitable boundary conditions. A FE analysis using a cylindrical shell model is employed in the leak-proof investigation of the inner tank - insulation panel - outer tank layers. The boundary conditions of the sidewall structures in radial direction are determined from consideration of the hydrostatic pressure of a cryogenic liquid and thermal gradient loads.

The FEM model of the full containment storage tank as shown in Fig. 1 has been analyzed for determining the stabilized temperature distribution along the thickness of the tank walls. From the results, it may be understood and predicted the expected leakage retaining time due to a leaked cryogenic fluid from the inner tank. The retaining leakage time by the tank structures is very important design parameter for securing the leakage safety of the LNG tank system.

In this study, the large storage LNG tank of 140,000 m^3 has been analyzed as a simulation model to estimate the leakage retaining time after the inner tank is collapsed. The storage capacity of the full containment LNG storage tank is 140,000 m^3. The diameter of the inner tank is 59 m and the height of the tank is 30.7 m. The total thickness of the tank is approximately 2.05 m.

4.1. Assumptions

In this study, the following assumptions have been considered for a simple computation of the complex geometry of the LNG storage tank.

- Analyzed for only 10 degrees of the whole tank system as an axisymmetric model.
- The tank structure is assumed to be a leakage when two sides of the tank wall are arrived at the same cryogenic temperature of –162°C. This occurs when the leaked cryogenic fluid from an inner tank is only transported to the outside of the prestressed concrete structure. It may be explained as a leakage occurrence between two sides of the tank wall in design concepts and physical meanings. In other case, we can not say the leakage even though two sides of the tank is arrived at the same temperature of –162°C. But, two sides of the materials should be exposed to the same cryogenic temperature of –162°C at any circumstances for the leakage simulation as done in this study.
- The prestressed concrete is composed as a composite material with the residual compression zone. This means that the prestressed concrete has different density zones for the gas and liquid tightness and the special strength of the structure, which are related to the safety of the tank system.

The thickness and the density of the residual compression zone are influential design factors for checking leaked cryogenic fluids when the inner tank is suddenly collapsed.

- For the leakage and temperature analyses, the material is homogeneous and same properties at the same zone of the tank model. The material of the tank structures does not have any cracks, voids, and external particles in the matters even though the real case is a little different.

4.2. FEM Model and Boundary Conditions

Fig. 1 shows the general description of the LNG storage tank in radial direction. The inner tank is in direct contact with a cryogenic fluid of –162°C and the outer tank exposed to the air of 15°C as shown in Fig. 2. Insulation panels, corner protection, and vapor barrier between two tank walls are constructed for the safety and performance of the cryogenic tank system. In Fig. 2, W_1 denotes the standard density zone of 2,500 kg/m^3 for this study and W_2 is the residual compression zone with a high density compared with a standard density of the PC material.

The leakage retaining time and temperature distribution based on the thermo-mechanical coupled analyses were performed using a non-linear FEM program MARC [1]. Eight-node, isoparametric, three-dimensional brick elements with trilinear interpolation are simultaneously used in the finite element analysis. The finite element model was subdivided into 1,920 elements and 2,745 nodes for the prestressed concrete as shown in Fig. 2 and 3,120 elements and 4,270 nodes for the LNG tank system as shown in Fig. 3.

The boundary conditions of the tank system are shown in Fig. 3. The various forces which include a liquid pressure P_L by the LNG fluids, gas pressure P_G by the vaporized gas, and thermal loads by the refrigerated fluid and boil-off gas have been considered for the FE analysis in an inner tank. The outer prestressed concrete tank as shown in Fig. 2 has used the same boundary conditions of the inner tank and added vertical load

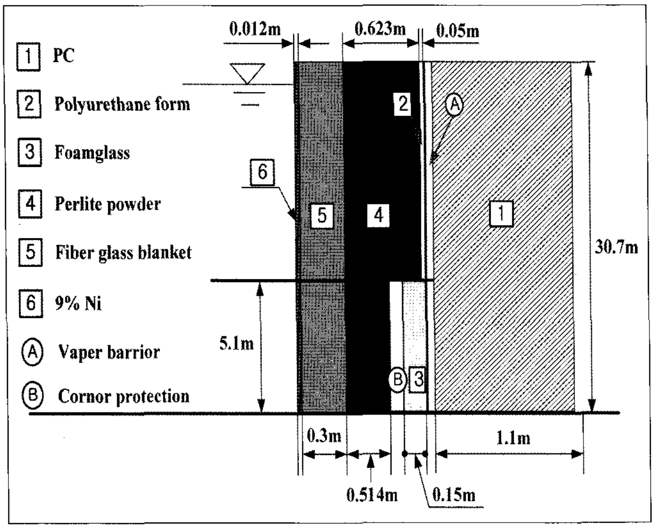

Fig. 1. Analysis model of the structure thickness between two tank walls in radial direction.

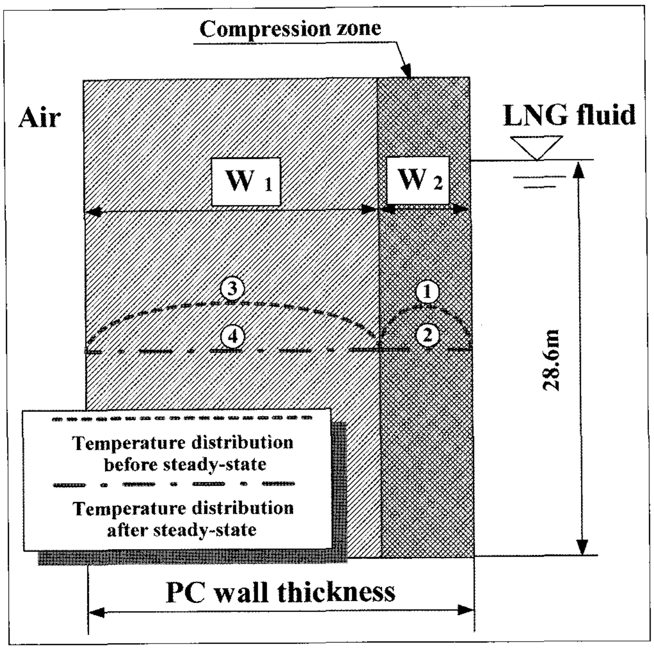

Fig. 2. Prestressed concrete with the residual compression zone that is in direct contact with leaked cryogenic fluids after the collapse of the inner tank.

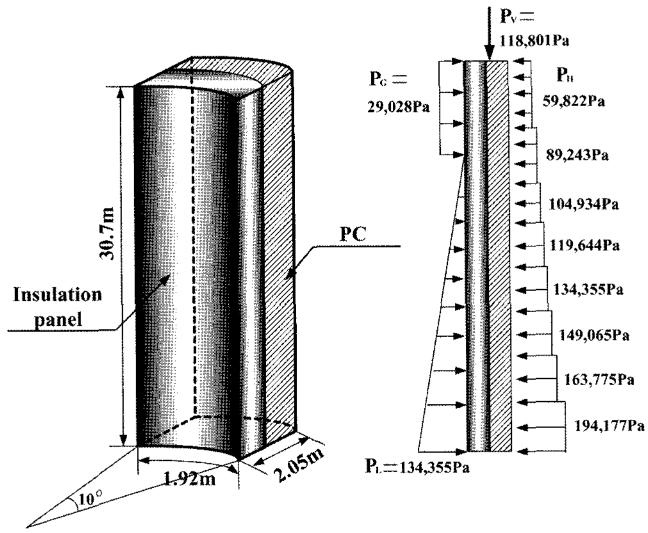

Fig. 3. Analysis model and boundary conditions of the LNG tank system.

P_V by the roof weight of the tank and the Hoop stress P_H in the circumferential direction on the assumption that the inner tank is collapsed. The hydrostatic pressure P_L depending on the LNG liquid height is varying in large because the capacity of the tank is so large as shown in Fig. 3.

The general dimensions of the tank are given in Fig. 1. The pressure as a function of the refrigerated height is very important for computing the mechanical behaviors and liquid tightness of the tank structures. The physical and thermal properties of LNG storage tank materials for the FEM analysis are given in Table 1.

Table 1. Physical and thermal properties of the tank materials

	Density, kg/m^3	Thermal conductivity, W/mK	Specific heat, J/kg · K
9% Ni	8000	16	510
Fiber glass blanket	16	0.03838	792
Perlite powder	760	0.0391	753.74
Foam glass	2180	0.05592	837.49
PUF	1190	0.0233	1465.6
Prestressed concrete	2500	2.326	837.21

5. Results and Discussion

The finite element method is used for investigating the temperature distribution and leakage retaining time of the tank system. This analysis concept for computing the retaining time of leaked fluids, which is calculated by the stabilized temperature distribution along the tank structure in radial direction, may explain the lifetime of the tank system due to the refrigerated fluid leaked from an inner tank.

The structure of the tank system is stabilized or equilibrated when two sides of the tank wall are arrived at the same cryogenic temperature of –162°C. This may be called as a leakage of the tank system in concept design. For the leakage analysis, two sides of the materials should exposed to the same cryogenic temperature of –162°C at any circumstances. But in the real case, we may not say that the leakage is occurred even though two sides of the tank are arrived at the same temperature of –162°C. It may be occurred when the leaked cryogenic fluid that comes from an inner tank is only exposed to the outside of the prestressed concrete.

Fig. 4 shows the cross sectional area of the LNG tank system, which is composed of an inner tank, insulation panel with fiber glass, perlite powder, foam glass and polyurethane form, and prestressed concrete structures in a series. In Fig. 4, the middle surface area of the tank is denoted as ABCD and the temperature distribution along the LNG tank is investigated as leak criteria.

At the perlite powder zone of the middle surface ABCD as shown in Fig. 4, the elapsed time for stabilizing the temperature from 15°C to –162°C has been presented as shown in Fig. 5. The computed results indicate that the elapsed time, which is converged from the initial atmospheric temperature 15°C to the cryogenic temperature –162°C, is strongly related to the leaked cryogenic fluids. In this figure, the stabilized temperature of –157°C at P point is equivalent to about 97% of the refrigerated temperature 162°C. It may be assumed that over 97% of the cryogenic temperature is already arrived at the leakage stage in the refrigerated fluid even though the cryogenic temperature –162°C is strictly explained as a perfect leakage. Thus, the point P as shown in Fig. 5 provides the interesting criteria of the leakage retaining time caused by the collapse of the inner tank.

The temperature gradients in radial direction may provide the basis of the leakage analysis of the tank system from the inside of insulation panels to the outside of the outer tank. The temperature distribution of the prestressed concrete outer tank at the cryogenic liquid heights of 14.3 m from the bottom of the tank is given in Fig. 6. This figure shows the progressive convergence from the initial air temperature 15°C to LNG cryogenic temperature 162°C between two side walls of the prestressed concrete. The leakage from the inside to the outside of the PC structure may be occurred depending on the equilibrium or stabilization of the temperature distribution in radial direction. In Fig. 6, the temperature of –157.3°C that is equivalent to 97% of the refrigerated temperature –162°C needs 4.8 days to arrive at the stabilized temperature gradient from the ambient temperature 15°C. As shown in Fig. 2, the dot line of ① and ③ denotes the partially stabilized temperature

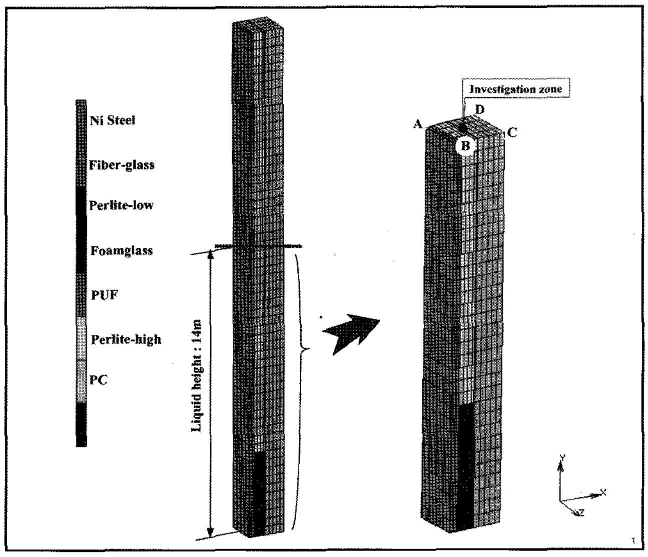

Fig. 4. LNG storage tank system that includes the inner tank, insulation materials, and outer tank structures and cross sectional area ABCD at the middle of the tank system.

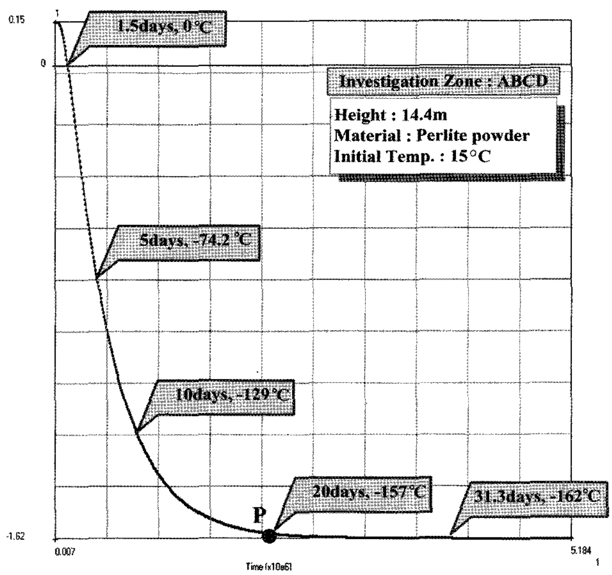

Fig. 5. Stabilized or equilibrated temperature profiles at the middle area ABCD of the LNG storage tank system.

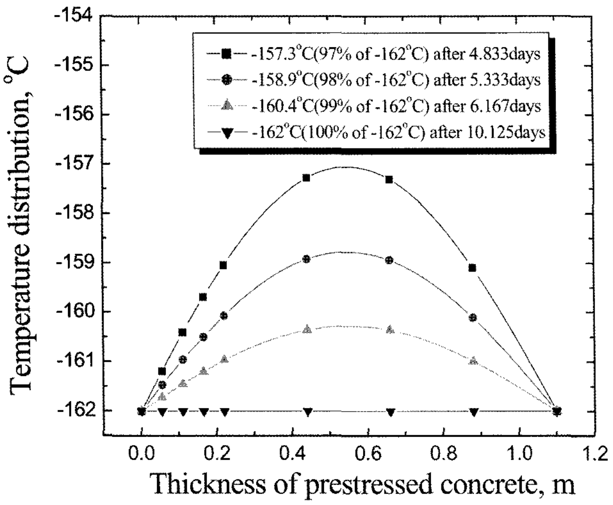

Fig. 6. Temperature distribution and leakage retaining time along the prestressed concrete with the residual compression zone of 10% for a high density of 4,000 kg/cm³.

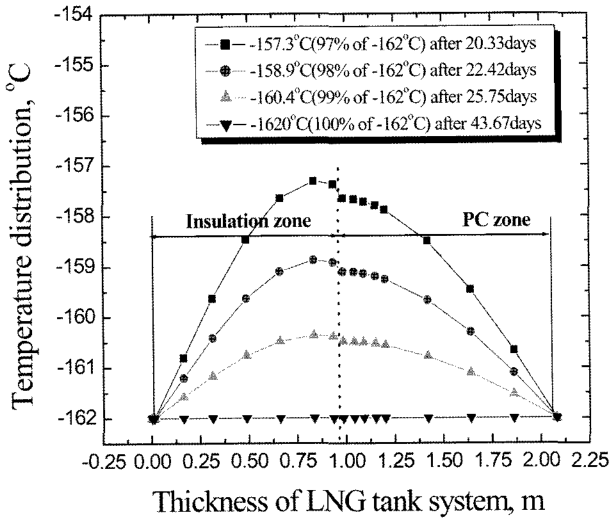

Fig. 7. Temperature distribution and leakage retaining time along the LNG tank system without the residual compression zone for a standard density of 2,500 kg/cm³.

distribution, which may be explained as a quasi-leakage of the leaked cryogenic fluid in the tank system. These retaining days, which need for retaining cryogenic fluids leaked from the inner tank, are not enough to guarantee the safety of the prestressed concrete structure with conventional two primary pumps in the inner tank. But the stabilization of the temperature from the initial air temperature 15°C to the refrigerated temperature –162°C needs 10 days as shown in Fig. 6. Here the 100% stabilization of the temperature gradient means that the prestressed concrete material is already equilibrated to –162°C. As shown in Fig. 2, the dash dot line of ② and ④ denotes the fully stabilized temperature distribution, which may be explained as a perfect leakage of the leaked cryogenic fluid in the tank system. Thus, ten days for the safety of the prestressed concrete structure are enough compared to that of the 97% stabilized temperature with two primary pumps.

In Fig. 7, the stabilized temperature distributions of the whole tank structure have been presented as a function of the tank thickness in radial direction. The computed results show the extended elapse time for a stabilization of the temperature compared to that of the equilibrated temperature, which is presented in Fig. 6. In Fig. 7, the stabilized temperature of –157.3°C (equivalent to 97% of the refrigerated temperature –162°C) needs 20 days to arrive at the stabilization from the ambient temperature to the cryogenic temperature as a function of the total thickness of the tank system. In the case of the whole tank system, these days that need for retaining leaked cryogenic fluids are enough to guarantee the safety of the LNG tank system with conventional two primary pumps in the inner tank. Even though we do not say the insulation panels can perfectly block the leakage flow of the cryogenic fluids in practical case, the result is very interesting for the LNG tank designers. To arrive at the refrigerated temperature –162°C of the tank system from the initial air temperature 15°C, the total thickness of the tank system needs 43 days even though the leakage retaining time is so long. The elapsed time of 43 days that retains the leaked cryogenic fluids by the tank system shows 4.3 times higher than that of the results 10 days, which is retained by the PC structure as shown in Fig. 6.

For a conventional storage capacity of 140,000 m³, the primary pump is usually installed two or three sets in the inner tank. For instance, the full containment tank of receiving terminal is installed two primary pumps, which are determined depending on the advanced technology of the tank system. The discharge capacity of the primary pump is 330 m³/hr per a tank for a receiving terminal. It may need 9 days to transport the total refrigerated liquids of 140,000 m³ to other LNG storage tank in an emergency. But if the corner protection of the 9% nickel steel plate with a height of 5 meters is considered as a safety structure, it needs approximately 7 days to transport the leaked cryogenic fluids to the nearest neighbor tank. The computed results indicate that the prestressed concrete cannot guarantee 7 to 9 days for a perfect safety of the tank system with the 97% stabilization of the temperature gradient. But if the total tank system is considered as a retarding structure of the leaked cryogenic fluid, the tank system should be guaranteed with conventional structures. In the full containment LNG storage tank, a dike does not need any more because prestressed concrete, several insulation layers, and other structures work as a substitute safety structure. These structures delay or protect the leakage flow from the inner tank to the outside of the outer rank.

In summery, the inner tank may leak stored cryogenic liquids through the inner tank wall and the bottom of the tank even if it is very small in service. To ensure the leakage safety of the inner tank, it is very important to detect a leak in the inner tank with several leak detection sensors, which are installed on the bottom of the annular space and on the first few meters of the tank wall. The increased leak of cryogenic liquids from the inner tank and the propagated crack of the 9% nickel steel plate may radically increase the probability of sudden failure of the inner tank. The corner protection and the insulation panels, which are composed by the polyurethane form, loose perlite and resilient glass blanket in part, should protect this catastrophe failure of the inner tank. As a final barrier, the prestressed concrete outer tank with a vapor barrier should retain leaked cryogenic liquids for a long period. At any circumstances, the outer PC tank constitutes an effective protection barrier against outer hazards but also ensures the liquid and gas tightness for a maximum safety of the LNG tank system. During containing leaked cryogenic liquids by the outer tank, the primary pump in the inner tank transports spilled cryogenic liquids to the nearest LNG storage tank. Thus, the LNG tank structures are kept at an outstanding level of the safety and reliability with combined effects of the outer tank system and primary pumps in the inner tank.

6. Conclusion

In this study, the fundamental analysis has been presented for investigating the leak-proof safety of the full containment LNG storage tank based on the FEM technique. The primary concern in the full containment tank is to evaluate the safety of the tank system without a dike even though most of the LNG storage tanks have been built based on the codes and regulations in their country.

The FE computed results indicate that the PC outer wall is expected to protect the LNG leakage for a limited period until a cryogenic liquid transferred to a neighbor LNG tank by a primary pump. The current LNG tank structure in a full containment tank is obviously enough to securing the leak-proof safety of the tank system with two primary pumps.

To guarantee the safety of the tank system, the full containment tank should be constructed based on the BS 7777 design concept and other regulations, which are recognized in the international LNG society. But, as the tank size is radically increasing, the safety of the tank system should be guaranteed with an increased density and thickness of the compression zone in the prestressed concrete tank, and high density of the insulation panel. In addition, the conventional safety structures such as top girder and several stiffeners in the inner tank may be changed to other structures for the maximum safety of the tank system. These advanced design concepts may guarantee the safety of effectiveness of extra large LNG storage tank system in future service.

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