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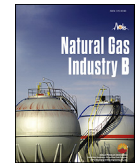

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Research article

A large LNG tank technology system “CGTank®” of CNOOC and its engineering application

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Abstract

LNG tanks are complex in design and building process and high in costs, so LNG tank technology is one of the most advanced ones in the field of energy, which has been monopolized by foreign companies for a long time. In order to work out LNG tank technology domestically, China National Offshore Oil Corporation (CNOOC for short), the largest LNG importer in China, develops a LNG tank technology system “CGTank®” successfully in reference to the design and construction experience of domestic and foreign companies, after years of scientific research in tackling difficult problems. This system presents four traits as follows. First, a set of calculation software is developed independently by CNOOC, and the tanks in all operating conditions are calculated after 3D hologram and multi-point contact model of fluid-solid coupling effect is built up. Second, earthquake effect research and inner tank check research are improved innovatively by means of response spectrum analysis after European standards are introduced. Third, it is put forward for the first time that the stress strength discrimination standard is based on the principal stress which is obtained by means of the maximum shearing failure theory. And fourth, a large LNG full-capacity tank technology package with completely independent intellectual property right is established. The “CGTank®” system was first applied in the Tianjin LNG demonstration project, which has passed all indicator tests and is now in operation smoothly. The project is provided with the core tank design technology by CNOOC Gas and Power Group and with the EPC by CNOOC Engineering Co., Ltd. The independent LNG tank technology can be applied in a wide scope and it is favorable for impelling domestic production of LNG industry completely.

Keywords: CNOOC; LNG; Receiving station; Full-capacity tank; CGTank®; Engineering application; Domestically produced; Tianjin LNG demonstration project

As the major storage of LNG converted under very low temperatures, LNG storage tanks would be produced through complicated processes with a high cost. The cost for designing and constructing a large full containment LNG tank may account for one third of the total cost for constructing a receiving terminal. LNG tank technology is one the sophisticated technologies in energy field, so computation, analysis and optimization of tank structures has always been a research focus.

As to the construction of receiving terminals in China, middle and large LNG tanks previously employed in LNG projects in Dapeng, Putian and Shanghai had all been contracted out to foreign companies for an engineering design. In recent years, China has made great progress in the art of LNG tank [1−4] and accomplished several EPC projects for LNG receiving terminals. China National Offshore Oil Corporation (hereinafter as CNOOC for short) imported 1411 × 10^4 t LNG in 2014, accounting for 70% of general LNG import in China. As the second largest LNG importer in the world, CNOOC is in an urgent need of the LNG tank techniques. After years of efforts, CNOOC has made great breakthroughs in LNG tank technology and created “CGTank®”, a proprietary brand of large full containment LNG tank with many patents, software

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copyrights and algorithms. "CGTank®" techniques have been applied to the construction of two full containment tanks of 3×10^4 m^3 for the phase-1 Tianjin LNG Project, CNOOC, during which several difficulties have been overcome. The first is low bearing pressure on the terrestrial foundation constituted by dredger fill in a short period. The second is the challenge from high earthquake accelerations (up to 7.875 m/s^2 locally, which was the highest at that time in China). The accomplishment of the phase-1 project is a landmark of independently designing and constructing LNG tanks by CNOOC with the aid of other domestic companies for the first time.

1. CGTank® systematized techniques

A project team supported by the R&D Center of CNOOC Gas and Power Group was organized in 2009 for technical researches on a large full containment LNG tank. The systematized techniques registered as CGTank® had been accomplished in 2013.

1.1. Basic theories

Classical mechanics (including solid mechanics, hydromechanics, plastoelasticity, kinetics, etc.) has formed the foundation for the analysis of the stress state for a tank structure. The point is how to link these basic theories with a practical design. In addition to theoretical studies, domestic and overseas specifications also provide a good reference for the analysis of regular structures in the tank so as to formulate and systemize practical expressions for computation.

1.2. Modeling and computation

Only theoretical calculation itself cannot handle the complicated structure of an LNG tank (Fig. 1). A common practice is to utilize common or self-developed finite element software in tank modeling and computation, which is detailed as follows.

Fig. 1. Model of a full containment LNG tank.

(1) Estimation of extreme operating conditions and load combinations;
(2) Simulation analysis and computation on each operating condition and load combination;
(3) Back calculation, validation and modification of the existing model.

1.3. Design by simulation

This part involves re-design of the accomplished projects and simulating design of the tank to be built, which is detailed as follows.

(1) Simulate accomplished domestic projects to validate the computational model and tailor the guidance documents.
(2) Complete the simulating design of the tank to be built in terms of its actual engineering conditions.
(3) Examine the construction drawing and evaluate the guidance documents.

2. Technical breakthroughs and innovations

The project team has made great efforts for years and is now capable of accomplishing structural calculations on pile foundation, cushion cap, outer container wall, concrete dome, inner container, anchoring system, low-temperature mantle ring, aluminum ceiling, lattice dome, TCP, etc. All operating conditions including normal running, hydraulic pressure test, pre-cooling, preheating, and SSE/OBE earthquake, could also be simulated. Their achievements are detailed as follows.

2.1. Self-developed software package

A self-developed software package for the optimum design of large full containment LNG tank and other systems including HAZOP specifically developed for storage tank have been patented [5,6] and could be used to significantly reduce computational workload and improve the security and credibility of tank design.

2.2. 3D holographic model and multi-point contact based finite element calculation

The operating conditions of a storage tank would be better simulated through the state-of-art finite element calculation for a holographic model which integrates fluid–solid coupling and multi-point contacts [7–10] (Fig. 2).

(1) Elements used to simulate a tank structure include solid element, shell element, beam element, spring element, smeared concrete bar element, discrete concrete bar

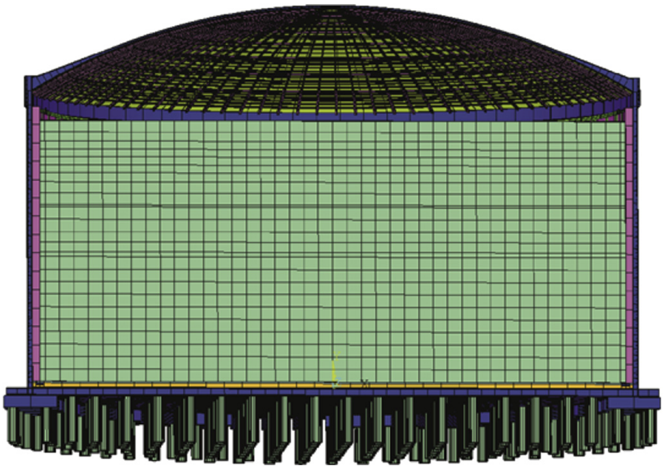

Fig. 2. Finite element model of a full containment LNG tank.

element, point contact element, surface contact element, target element, mass element, and fluid element.

(2) Tank contacts would be simulated by adopting several linkages including common node, multi-point constraint (MPC), and fluid-solid coupling.

(3) The operating conditions under various loads would be simulated, especially for serviceability limit state (SLS, with 12 portfolios) and ultimate limit state (ULS, with 26 portfolios), which involve static load, live load, pre-stressing load, wind load, hydraulic bearing load, positive-pressure load, negative-pressure load, temperature load, hydraulic pressure test load, snow load, leaking load, and earthquake load.

(4) The stress state throughout a tank would be better simulated based on a holographic model and the results could be used as the input to a local model.

2.3. Earthquake spectra

In terms of the response spectra designed for safe shutdown earthquake (SSE) and operation basis earthquake (OBE) in European Standard, the design and validation of pile foundation, outer tank and dome would be realized with the self-developed system for LNG tank optimum design so as to reduce risks.

2.4. Inner tank earthquake responses

Conventionally an international tank contractor would directly use earthquake parameters as basic load data for the design of an inner tank. We present a better solution for the first time by integrating in-situ earthquake measurements with soil shear wave velocities listed in European Standard to model earthquake spectra, which would then be input as the earthquake load. Response spectra would be calculated to analyze the impacts of earthquake-initiated LNG oscillation and shock on the inner tank and accordingly estimate oscillation amplitude. Finally empirical equations from different specifications would be used to check and correct the oscillation amplitude. This solution has been demonstrated to be feasible and could produce more accurate results for different inner tank structures [11–13].

2.5. Fatigue failures and life time under low-temperature stresses

Generally an international contractor would not conduct fatigue analysis on shell-to-bottom fillet welds and attachments at the bottom of an inner tank. Our innovative practice instead is to assess the life time of the key parts and the whole tank as per the stipulations in Specification for Unfired Fusion Welded Pressure Vessels (BSI PD 5500:2009) [14] and examine fatigue failures under low-temperature stresses of the key parts of the tank. We propose for the first time to use the principal stress worked out based on the maximum shearing failure theory to diagnose the intensity of stress [15].

3. Application of CGTank® to Tianjin LNG project, CNOOC

3.1. Project overview

The phase-1 Tianjin LNG Project was accomplished in eastern Nanjiang Port Area at Tianjin Port in Binhai Hi-Tech Industrial Development Area, Tianjin. The Earth's surface features arcuate accumulation landforms and is mainly composed of fine-grained sediments including clayey silts, silty clays and silts depositing since 5000–6000 years ago, which are the cause of poor geologic conditions such as low bearing pressure on foundation, large land subsidence, earthquake-induced saturated silty soil liquefaction, great water and soil corrosivity, and large earthquake acceleration.

In view of the above problems, Tianjin LNG Demonstration Project was technically supported by CNOOC Gas and Power Group for tank design and contracted out to CNOOC Engineering Co., Ltd. with an EPC contract. The Project was accomplished after two years of hard work.

3.2. Acceptance check and test after completion

Acceptance check and test were performed when the phase-1 project was finished.

(1) The systems for automatic control, safety check and emergency treatment functioned properly in the process of pre-cooling and liquid feeding debugging, indicating that the instrumental and process systems conform to the specifications and are safe and reliable.

(2) As per real-time monitoring by resistance temperature detectors (RTD) and fiber detectors, real-time temperature drop and liquid level change were homogeneous (lower than 5 °C/h) in the inner tank, indicating that model-based calculations were in line with engineering practice.

(3) Temperature difference of 10 °C between the inner side of the concrete outer tank and the environment during pre-cooling was reconciled with the simulation from finite element calculation, demonstrating the credibility of numerical simulation.
(4) The cold insulation system was tested to be qualified because neither frost nor dew was detected at the outer tank and tank bottom in the process of debugging and running.
(5) The tank structure was validated by small settlement monitored to be less than 5 mm that is in agreement with the design and differential settlement far less than 1/500 of the designed value in the hydrostatic test.
(6) The sealing and cold insulation were validated by the test of the evaporation rate of boil-off gas (BOG), which was 0.0564%/d, less than the designed 0.08%/d (for pure methane).

The completion and commissioning of the phase-1 project is a landmark in CNOOC LNG practice. This project gave CGTank® a stage show and also enhanced the core competency of CNOOC in LNG energy industry.

3.3. CGTank® technical improvement

Thanks to its engineering application, two additional functionalities, i.e. gravel pile reinforcement and over-length friction pile, and schedule optimization, were developed and added into CGTank®.

3.3.1. Gravel pile reinforcement and over-length friction pile

LNG site in Tianjin is a terrestrial area produced by hydraulic filling in a short period. The soil is not consolidated completely to sustain the storage tank. After comprehensive analyses and feasibility study, it was decided to reinforce the active zone of foundation with gravel piles and use over-length friction piles (55 m) as tank foundation. Two to three circles of gravel piles were built around the pile foundation in a quincuncial pattern so as to ensure the frictional force of the pile foundation and limit tank settlement resulting from foundation consolidation within the tolerance. This solution is superior to the common practices and could guarantee the bearing capacity and reduce the construction cost as well.

3.3.2. Schedule optimization for LNG tank construction

LNG tank construction is the major part in an LNG receiving terminal project. This time-consuming work involves a variety of operations for the inner and outer tanks (concrete pouring, inner tank welding, installation of intra-tank pipelines and devices, thermal insulation, etc.). Engineering and technical personnel made a thorough study of preceding LNG tank projects and compiled a research report dealing with the key techniques for LNG tank construction as well as schedule optimization and the management of cross operation [16–19]. As a result, the construction period was shortened by 3 months as compared with a traditional scheme.

4. Future development of CGTank®

The engineering application of CGTank® to Tianjin LNG Demonstration Project is of great importance to CNOOC technical development.

4.1. Application

In spite of its low proportion in primary energy in China, natural gas has been imported with increasing volume in recent years and LNG trading volume is also increasing. The configuration of LNG receiving terminals along coastal regions has been finished and there are a large number of LNG tanks being and to be built. The future application of CGTank® is very promising.

4.2. Future development

Due to fewer and fewer coastal areas and station sites available and complicated procedures for the approval to land use, storage capacity per unit area in an LNG receiving terminal has to be enlarged; in other words, the models in the near future would be large-scale and even supersized LNG tanks. The study of these tanks and their engineering application are extremely urgent.

4.3. LNG tank localization

4.3.1. Design by China

The engineering application of CGTank® has demonstrated the capacity of self-design of full containment LNG tank by CNOOC. From then on, the R&D center of CNOOC Gas and Power Group continued design review, preliminary design and technical support for several LNG receiving terminal projects being built to improve its self-developed techniques. LNG tank design could be completely fulfilled by domestic companies and engineers now.

4.3.2. Procurement by China

Domestic LNG undertakers would have more confidence to use home-made construction materials and equipment for cost reduction in view of the successful commissioning of Tianjin LNG Demonstration Project. Some major materials and equipment made in China have been utilized in the second LNG project (Guangxi LNG tank project) independently undertaken by CNOOC to weaken the dependence on high-end imports. In future LNG development, CNOOC would target full localization of LNG tank materials and equipment to promote the technical progress of associated industries.

4.3.3. Construction by China

Tianjin LNG Demonstration Project was undertaken by a domestic engineering company as the EPC contractor who integrated overseas EPC practice and national conditions in

China and has made a great improvement in EPC construction and supervision. Other domestic partners have also made great progress in LNG tank construction and project management. All of these companies are capable of constructing large LNG tanks independently. A hundred-percent localization in China would finally be realized in LNG tank construction.

5. Conclusions

The development and engineering application of CGTank® is a landmark of LNG tanks independently designed and constructed by CNOOC with the aid of other domestic companies for the first time. This success may be attributed to the following factors.

(1) Demand orientation. Increasing domestic demand for LNG is the driving force for constructing more LNG receiving terminals and developing our own techniques for LNG tank design and construction. CNOOC seized this opportunity to master these techniques and systemize them into CGTank® in a few years.
(2) Scientific research. Technical breakthrough is dependent on scientific research. CNOOC has always attached great importance to enterprise–college–research institute equality and cooperation so as to promote technical innovation and industrialized application.
(3) Engineering application. The final goal of scientific research is to master core techniques and put them into engineering application. Self-developed techniques would be perfected through application, modification, optimization and innovation. In this process, CNOOC used a strategy of small wins and careful validation. After its engineering application and testing, CGTank® would be employed in subsequent 16×10^4 m^3 and 22×10^4 m^3 LNG tank design and construction. It is planned to promote this system to international market.

The engineering application of CGTank® has greatly promoted CNOOC LNG practice and associated industries and produced remarkable economic and social benefits. The expansion of LNG industry and technical progress would definitely result in less investment and more efficiency for large LNG tank construction. CNOOC would continue the researches on supersized storage tanks and new techniques in LNG storage and collaborate with enterprises, colleges and research institutes in this industry to motivate LNG development.

Fund project

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References

[1] Wang Shanshan, Gao Tianxi, Wang Yonggang. Study of implementation of the 200000 m^3 LNG tank. Chem Eng Des 2014;24(4):30–4.
[2] Wang Bing, Chen Xuedong, Wang Guoping. New progress of large low temperature LNG storage tank design and construction technology. Nat Gas Ind 2010;30(5):108–12.
[3] Zheng Jianhua, Li Jinguang, Li Yanhui. Research on calculation model of full containment tank under the condition of seismic. Chem Eng Des 2012;22(2):11–4.
[4] Zheng Jianhua, Li Jinguang, Cheng Yanfen, Wu Haikun. Calculation of pre-stress scheme of full containment LNG outer tank. Pet Eng Constr 2010;38(6):49–52.
[5] Tang Lingli, Shan Tongwen, Zhang Chao, Zhong Xi, Chen Ruiying, Li Mu. A pile foundation construction method of a huge full containment LNG tank: China, 201210164709.6.2012-09-19.
[6] Tang Lingli, Shan Tongwen, Qu Changlong, Zhang Chao, Wang Chao, Pan Yinhui, et al. LNG storage tank safety monitoring with the methods of accident tree and HAZOP: China, 201210294821.1.2013-02-20.
[7] Zhang Chao. Application of LUSAS software in LNG storage tank finite element analysis and design. Hangzhou: Zhejiang University Press; 2014.
[8] Zhang Chao. Application of ANSYS software in LNG storage tank finite element analysis. Beijing: National Defense Industry Press; 2014.
[9] Chen Tuanhai, Zhang Chao, Yang Fan. Study on LNG tank filling nozzle stress based on fluid-solid coupling. Petrochem Equip Technol 2014;43(3):1–5.
[10] Song Kun. Large LNG storage tank liquid level control configuration optimization. China Pet Chem Stand Qual 2013;33(6):52–4.
[11] Chen Tuanhai, Zhang Chao, Yang Fan, Peng Yanjian, Li Mu. A height design method of LNG inner tank: China, 201410655776.2015-02-25.
[12] Yang Fan, Zhang Chao, Deng Qing. Selection of design scenario for inter tank stability of large-scale LNG tank. Oil Gas Storage Transp 2012;31(11):830–2.
[13] Yang Fan, Zhang Chao, Wang Chengshuo, Deng Qing. Analysis of design allowable stress in 9% Ni steel of liquefied natural gas storage tank. Petro-Chemical Equip Technol 2012;41(6):99–101.
[14] British Standards Institution. PD 5500 specification for unfired fusion welded pressure vessels. 4th ed. London: BSI; 2009.
[15] Yang Fan, Fu Chunyan, Zhang Chao, Chen Tuanhai. Calculation analysis on inner tank design life of large liquefied natural gas tank. Petro Chem Equip Technol 2014;43(6):46–9.
[16] Chen Hui. A feasible approach of shorten the construction period of full capacity large LNG tank. Pet Eng Constr 2012;38(5):24–8.
[17] Fu Zihang, Song Kun. The integrity of the LNG storage management and deconstruction. Oil Gas Storage Transp 2012;31(7):481–5.
[18] Fu Zihang, Shan Tongwen. Integrity management systems for large LNG tanks. Nat Gas Ind 2012;32(3):86–93.
[19] Zhong Xi. Research of gas rose roof in LNG storage tank construction. China Water Transp 2012;12(1):263–4.