Liquid spill hazard investigated for LNG tanks

This article is the latest in a series and covers the fundamental and decisive aspects of the complex load case spill

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The rules and requirements of the load case liquid spill are described and most of the codes, regulations and specifications are derived from BS 7777.

In BS 7777, abnormal load cases are under the following preconditions:

"The outer tank should be designed and constructed in such a manner that it contains the maximum liquid contained in the inner tank, assuming that the annular space between the shells is filled gradually.

"The outer tank is intended to be capable both of containing the refrigerated liquid and of controlled venting of the vapour resulting from product leakage after a credible event."

Part 3 of BS 7777 calls for a concrete tank where:

"Under the maximum design loading conditions including the liquid and the temperature loading due to inner tank leakage, the minimum residual average compression stress of 1 N/mm2 should be provided in the principal directions and further the compression zone is adequate to maintain the liquid tightness."

Further recommendations and more specific requirements are given only in Owners' specifications.

Information with regard to the time-dependant sequence of events is not given in standards. Proof of compliance with the specification depends therefore entirely on the designer.

In this paper, the fundamental and decisive aspects of the load case, liquid spill are discussed and the consequences shown.

Assumptions for modeling

Describing the load case liquid spill is a matter of great complexity due mainly to the unclear description of the time-dependant sequence of events.

The events during leakage of the inner tank with rising liquid level in the annular space between inner tank and outer tank and the simultaneous cooling down of outer tank concrete have to be broken down into manageable stages.

The question regarding the impermeability of concrete tank wall under rising spill level is another main aspect of this paper.

As a possibility for idealization, a time-dependant step-wise analysis of the main components can be considered, the monolithic connection between wall with bottom slab and the wall section around the assumed liquid spill level. The wall section can be of different thickness in case of a tapered wall.

The results of unsteady state investigations are used to determine the acting loads and are used to create a stationary model for liquid spill events at different stages.

Time-dependant considerations

For a better understanding of the load case liquid spill, the time dependant events, leakage and cool down of the concrete wall are described in more detail using a typical tank with a volume of 160,000m³ LNG, 39.0m inner tank radius and a 1.0m annular space with perlite insulation.

On the assumption that the available pore volume within the perlite is 25%, the LNG liquid level will decrease by approximately 45cm in the inner tank and a quantity of 2150m³ LNG will leak into the annular space. If the pore volume were 50%, the level would decrease by 90cm and 4300m³ LNG would flow into the annular space.

Assuming an average discharge of 1 l/sec, the time to fill the annular space is 25 days in the first case.

One main consideration is the duration of the cooling down process of the entire wall section. This is assumed to be finished when the temperature gradient within the wall is nearly linear.

With the use of an FE-model the unsteady state cooling down was investigated. The results are shown in figure 1 and figure 2.

The figures show the temperature gradients within a concrete wall of 80cm thickness at different times

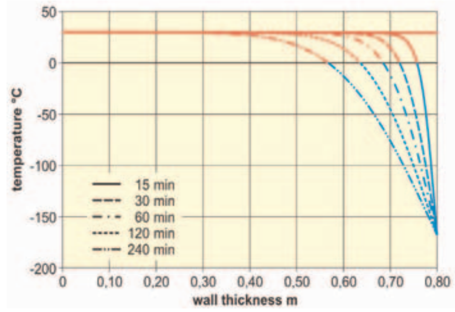

Figure 1: Temperature in the wall at 15, 30, 60, 120 and 240 minutes

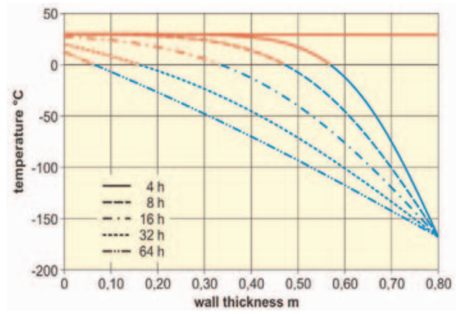

Figure 2: Temperature in the wall at 4, 8, 16, 32 and 64 hours

whereby an outer ambient temperature of + 30°C was assumed. The surface heat transfer coefficient at the outside of concrete wall was taken into account with 1/a = 0.04m2K/W. The inside of concrete wall is assumed to cool down at t = 0 from +29°C to –168°C.

Figure 1 shows the temperature gradients within the first 240 minutes and Figure 2, the temperature gradients from four hours to 64 hours. It is noted that the expansion of the cool temperature within the section by a defined distance requires a doubling of the elapsed time.

For an 8cm thick concrete wall the temperature gradient is approximately linear after three days and the state can be described as steady. For a 60cm thick concrete wall this state is reached after approximately two days.

Isotherms in discontinuity zones

This chapter describes the influence of a given liquid level on the isotherms for varying wall thickness.

The area of the tank wall directly in contact with the LNG shows a regular arrangement of isotherms. The temperature distribution within the concrete wall can be assumed to be linear. Temperature change between inside and outside takes place within the concrete wall only.

Above the LNG liquid level the pattern of isotherms is irregular. This area shall be called "discontinuity zone" in the following. Above the discontinuity zone the arrangement of isotherms is again regular. It can be stated that the main temperature change occurs within the insulation above the liquid spill level.

Figures 3, 4 and 5 show the isotherms in the discontinuity zone above the liquid spill level for concrete walls of 60cm, 80cm and 100cm thickness.

The general arrangement of isotherms is similar for the different wall thicknesses. It is noted that the height of the discontinuity zone is approximately 1.5 times the wall thickness, for an 80cm wall the discontinuity zone is approximately 1.20m high.

Another irregular zone is the area below the top of thermal corner protection (TCP). A typical arrangement is shown in figure 6. The described approximation is also valid for this area and the discontinuity zone is approximately 1.5 times the wall thickness.

Figure 7 shows that this effect occurs above the liquid spill level as well as below the top of the TCP.

Temperature loading of the wall

In order to apply a static loading to the tank structure the temperature has to be divided into a constant component (temperature change) and a linear component (temperature gradient).

In the undisturbed areas above and below the discontinuity zones the temperature values from a steady-state temperature calculation can be used.

The height of the discontinuity zone in the calculation is consistent with the results of section 4.

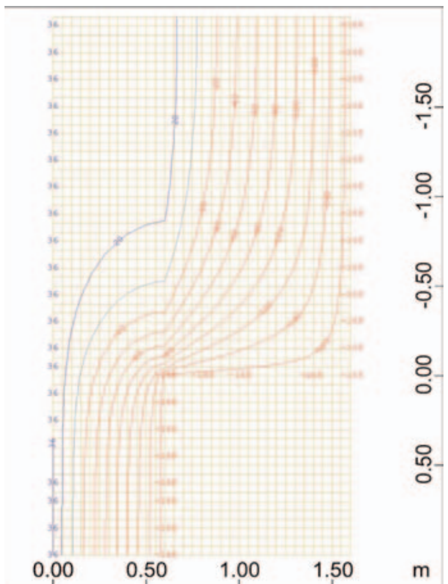

Figure 3: Discontinuity zone at 60cm wall

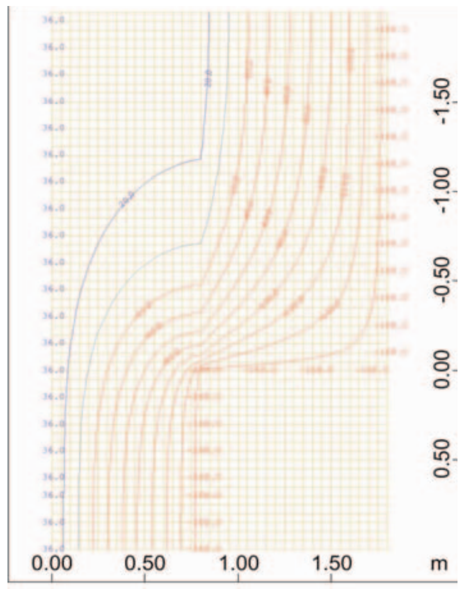

Figure 4: Discontinuity zone at 80cm wall

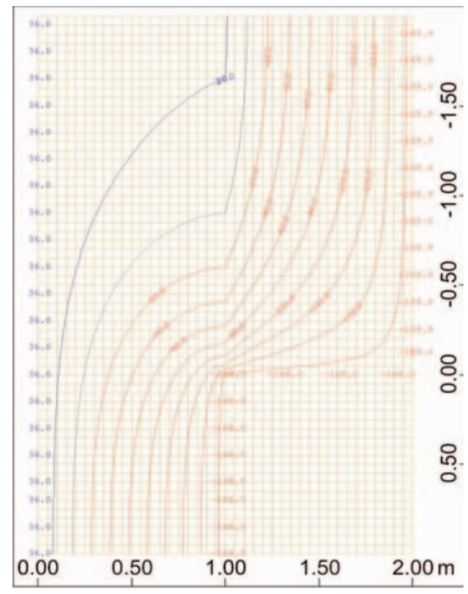

Figure 5: Discontinuity zone at 100cm wall

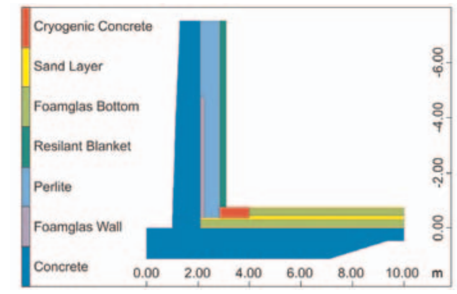

Figure 6: Wall to slab connection and thermal corner protection TCP

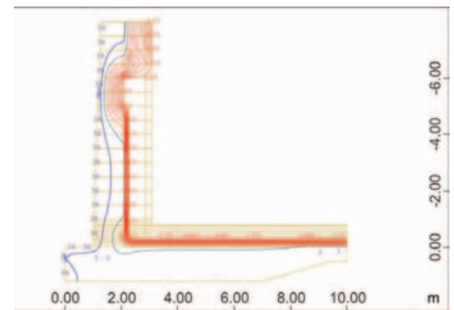

Figure 7: Isothermal curves in the wall to slab connection and thermal corner protection

Stress regime in the tank wall

The bottom slab and the adjacent wall section are protected against strain caused by temperature by the secondary 9% Ni steel layer and the thermal corner protection. Therefore only the tank wall is subjected to spill loading.

In the investigation of the wall, the single load cases dead load, horizontal and vertical prestressing, overpressure, liquid pressure and the temperature effect with temperature change and temperature gradient are considered.

The liquid pressure from liquid spill levels 6.0m, 8.0m, 11.5m, 15.4m, 19.25m, 23.1m, 26.95m, 30.8m and 34.65m are examined.

The resulting bending moment distribution in a vertical section in the outer concrete tank wall is shown in the figures 8, 9 and 10. For clarity, figure 8 shows only the lower spill levels. Figure 9 shows the upper spill levels and in figure 10 all levels are included.

The lowest spill level investigated is level +6.0m and results in a maximum bending moment at level + 5.0m at the top of the TCP. At spill level +8.0m, the maximum bending moment occurs at +6.0m. This hysteresis or lag of the maximum moment continues with the maximum moment in the concrete wall at level +8.0m with the spill level at +11.5m. The development from the bottom of the wall to the maximum value is nearly linear.

From this value the bending moment decreases with rising spill level, but only at a third of the rate in the lower section.

The development of bending moments in the lower part of wall is characterised by irregularity whereas the development in the upper part is more regular.

Spill level +23.10m, +26.95m, +30.80m and +34.65m produce approximately up to level + 15.0m a nearly identical bending moment. In the area above, caused by the discontinuity of the ring beam and roof, the course of bending moment is different but the magnitude of the moment is similar.

It can be concluded that for dimensioning of reinforcement in the upper part of wall it is sufficient to investigate the maximum spill level and to increase the amount of reinforcement by some 5%.

Rising compression zone

Figure 11 shows the development of the compression zone for an 80cm wall with rising LNG spill level for load cases as mentioned under section 6. It is demonstrated, that the required compression zone depth required by most specifications of at least 8cm or 10% of the wall thickness is maintained.

The minimum average compressive stress and dimension of the compression zone is well in excess of that generally specified.

Of significant interest is also the stress condition at zero moment. The calculation results show that the change of signs takes place 3m to 4m above the spill level.

The resulting concrete stress at the outer wall face for spill level +11.50m which generates the maximum moment is shown in figure 12. Approximately 3m above the spill level the minimum compression value is 2N/mm2 with an average value of 1N/mm2.

Wall with varying thickness

The results and relations represented in section 6 and 7 were derived on a system with constant wall thickness.

Comparative calculations for a tapered wall (40% lower part of the wall is tapered from 1.10m to 0.60m, 60% upper part of the wall has a constant thickness of 0,60m) show a significant reduction of the bending moment in the reduced wall thickness section from approximately 1400kNm/m to -900kNm/m.

The reason for this decrease is the dominant load case temperature gradient, which is proportional to the square of the wall thickness.

The reduction of the bending moments results in a reduction of the required reinforcement. A change of the concrete stresses is not recognizable, as the section modulus also reduces. The concrete stress values and their location above the spill level stay in the same range.

Cryogenic reinforcement

The load case liquid spill requires cryogenic reinforcement at the wall inner face. The boundary between cryogenic and non-cryogenic reinforcement is often the subject of discussion. The aim of the following section is to clarify this.

Cryogenic reinforcement is necessary in those areas, where the temperature is below -20°C (BS 7777). In the upper part of the wall this requirement ceases to be valid in the discontinuity zone above the maximum liquid level (compare figures 3 to 5) as the temperature is above -20°C. Generally, this takes place in the last concrete section of the wall just below the ring beam.

Cryogenic reinforcement is required in vertical direction over the entire height. In horizontal direction a different arrangement is possible, with non-cryogenic reinforcement starting 0.5m to 0.6m above the maximum spill level.

Figure 7 represents the temperature conditions at the lower part of the wall and the connection to the bottom slab. This area is influenced by the thermal corner protection. The primary function of the TCP is to reduce the temperature loading in the area of constraint and in addition to prevent low temperature expansion far below the TCP top.

The course of the isotherms shows that below level +4.0m the temperature is above -20.0°C. Therefore, starter bars for wall reinforcement are not required to be cryogenic. Figure 7 determines the height where cryogenic reinforcement is required in horizontal direction, which is approximately 1.0m to 1.5m below the top of the TCP. ■

References

/1/ BS 7777: Flat-bottomed, vertical, cylindrical storage tanks for low temperature services; Part 1: Guide to the general provisions applying for design, construction, installation and operation. BSI Standards, 1993.

/2/ BS 7777: Flat-bottomed, vertical, cylindrical storage tanks for low temperature services; Part 3: Recommendations for the design and construction of pre-stressed and reinforced concrete tanks and tank foundations, and for the design and installation of tank insulation, tank liners and tank coatings. BSI Standards, 1993.