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Optimization of Cryogenic Spill Protection Insulation Thickness

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Regarding to the cryogenic spill protection insulation design for the structural steel, the major concerns from design aspect are defining 1) Phase of spilled cryogenic hydrocarbon on the steel structure (i.e. liquid fraction) which affect the thickness of cryogenic spill protection (CSP) insulation, and 2) Extent of brittle fracture hazard area due to cryogenic hydrocarbon spill. However, there is no standardized approach defining these two points yet. Currently, the phase of spilled cryogenic hydrocarbon is assumed as liquid phase in order to set insulation thickness conservatively, and the extent of brittle fracture hazard area is assumed differently project by project.

This paper proposes to the engineering approach to determine 1) Phase of spilled cryogenic hydrocarbon on the steel structure which affect the thickness of CSP insulation, and 2) Extent of brittle fracture hazard area due to cryogenic hydrocarbon spill. Based on the principle of heat transfer phenomena for liquid, wet spray, and dry jet exposure on the steel structure, it is assumed that the significant temperature drop will occur due to latent heat of vaporization. Thus, this paper focuses on the wet spray phase of the cryogenic hydrocarbon spill on the vertical steel column, where cryogenic liquid film can be developed, rather than the dry jet phase.

In order to determine the adequate phase of cryogenic hydrocarbon spill to determine the thickness of cryogenic spill protection insulation for wet spray exposure on the vertical steel structure, experimental test is conducted based on the several flow rate of cryogenic wet spray and the accumulation of cryogenic liquid. Test results are evaluated against heat transfer calculation results. As a conclusion, the liquid nitrogen accumulation test is proposed as reasonable and enough conservative phase to determine the thickness of CSP insulation for vertical steel structure against the wet spray exposure. In addition, the heat transfer analysis is conducted to identify critical condition for steel structure rapidly causing brittle fracture which is demonstrated as liquid ratio in spilled cryogenic hydrocarbon, and decide the criteria of the cryogenic wet condition on the steel structure. Based on the defined criteria of the cryogenic wet condition, the traveling distance of spilled cryogenic liquid is calculated. The calculation method is evaluated by the experimental test using liquid nitrogen and concluded as reasonable and enough conservative side to use the calculation method.

1. Introduction

Passive Fire Protection (PFP) insulation is widely applied in the oil and gas industry for many years and the design criteria are indicated in international standards (e.g., API 2218, Fireproofing Practices in Petroleum and Petrochemical Processing Plant), company standards, etc. On the other hand, as modularized onshore LNG projects and floating LNG projects are increased, risk mitigation for cryogenic spill hazard to steel structures (i.e., brittle fracture) becomes one of the major interests in the industry. Potential risk mitigation measures for the cryogenic spill hazard to steel structures are the reducing leak sources (avoiding small bore connections and applying welding connection) and protect steel structures by active or passive ways (water spray or cryogenic spill protection insulation). Due to the limitation of applying welding connection from operation/maintenance view, the measure reducing the leak sources is not concrete solution. Because the passive type protection is inherently safer than active type protection, cryogenic spill protection insulation is considered as feasible and practicable solution in many projects.

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However, the approach of determining 1) Phase of spilled cryogenic hydrocarbon on the steel structure (i.e., liquid fraction) which affect the thickness of cryogenic spill protection (CSP) insulation, and 2) Extent of brittle fracture hazard area due to cryogenic hydrocarbon spill, has not been standardized as an international design standard. Currently, these design conditions are decided differently project by project. In many cases, the phase is assumed as liquid phase in order to determine the insulation thickness at conservative side and the liquid nitrogen immersion test is considered as conservative approach for the vertical column since the horizontal cryogenic jet spray will affect one side of structure. The extent of brittle fracture hazard area is commonly defined by risk analysis. However, the criteria of risk analysis have not been well established yet in view of cryogenic spill dispersion phenomenon and brittle fracture mechanism. In order to define the practical engineering approach, following two simulations and experimental test are conducted. Note that all analysis and experimental test is conducted by Liquid Nitrogen (LIN) considering the safety during the test, and that the temperature of LIN (-196°C) is close to the LNG (-162°C).

1.1 Phase of spilled cryogenic hydrocarbon on the steel structure

The required performance and thickness of CSP insulation material will be different with the phase of cryogenic hydrocarbon spill on the structure, i.e. liquid, wet spray and dry jet, and the affected area over steel volume. To define the adequate phase of spilled cryogenic hydrocarbon to determine the thickness of CSP insulation material against horizontal wet spray release case on the vertical structure component, the following steps are taken.

(a) Steel structure for this study is decided as vertical H-column, which are widely used in the facility
(b) The experimental test is conducted to measure the temperature drop affected by liquid nitrogen in various condition of phase (changing flow rate of wet jet, and liquid accumulation) to H-column
(c) Conduct heat transfer analysis to simulate the result of the test
(d) Propose the adequate phase of cryogenic spill to define the CSP thickness for vertical column against horizontal wet spray.

1.2 Extent of brittle fracture hazard area

From the steel structure integrity point, resistant time and lowest steel temperature should be considered in the design against the brittle fracture hazard. In general, carbon steel is considered to withstand up to -29°C. Thus, temperature drop speed to -29°C will be a key indicator. The temperature drop speed will be different by phase of cryogenic spill on the steel structure. Due to higher thermal conductivity and latent heat of vaporization, full liquid phase contact gives the most strict temperature drop. However, it is confirmed that the liquid contacting structure surface only contributes temperature drop of structure. Especially, wet spray horizontal release on vertical structure will give different temperature drop speed depending on liquid ratio. To define the extent of brittle fracture hazard area, the following steps are taken.

(a) Liquid ratio of wet spray giving same temperature drop with full liquid condition is estimated based on the heat transfer analysis.
(b) Wet spray dispersion calculation is conducted to simulate the distance giving the liquid ratio estimated in (a).
(c) The experimental test is conducted to measure the distance which cause significant temperature drop on the steel test plate
(d) Establish and propose the method to determine the extent of brittle fracture hazard area

2. Phase of spilled cryogenic hydrocarbon on the steel structure to define the CSP thickness

This section describes the method and result of the analysis and experimental trial test about the phase of spilled cryogenic hydrocarbon to define the CSP insulation thickness.

2.1 Method

<u>Theory</u>

PFP insulation thicknesses for steel structures are determined based on the fire condition (type, temperature, pressure, etc.), duration of fire, exposed surface area of steel structure, and Hp/A of steel structure (heat perimeter divided by cross sectional area). On the other hand, there are no defined approaches to define the thickness of CSP insulation against the cryogenic wet spray/liquid exposure. In the past, the steel structure with CSP insulation is immersed into the LIN to decide the thickness. However, it is widely known that the immersion condition into the LIN is very conservative compared with the actual cryogenic spill hazard in facilities. In many cases, cryogenic spill is occurred at flange or seal part of valve in the pressurized system. Therefore, the most common scenario of cryogenic hydrocarbon spill hazard is “directional wet spray”. Thus, the one side wet spray exposure on a vertical and horizontal steel structure, and also liquid accumulation on a deck floor should be considered as practical cryogenic spill hazard scenario to determine the CSP insulation thickness on the steel structure.

The liquid accumulation scenario can be defined as one specific condition, but the condition of wet spray exposure on the steel structure is different by the pressure, flow rate, and distance from the release location. However, based on the heat transfer theories, it can be assumed that if there is sufficient liquid droplets and wet condition is achieved on the steel structure, there are no differences from heat transfer point of view among the different flow rates of wet spray and the liquid accumulation condition. Once cryogenic liquid (LIN for this test) droplet reaches the surface of CSP insulation, the temperature of the surface of the CSP insulation drop immediately close to boiling point of LIN because the heat transfer due to boiling is much faster than the heat transfer of CSP insulation. After the temperature of the surface of the CSP insulation reaches boiling point of LIN, the heat flux is determined by thermal conductivity of the CSP insulation and its thickness. Hence, the boiling rate is determined by the thickness of CSP insulation, and excess LIN remains on the surface without boiling. So, temperature drop of the steel structure is assumed unrelated to the LIN conditions. Firstly, LIN wet spray discharge test and LIN accumulation test are conducted to verify the assumption. Then, establish simulation method and validate it by using the test results.

Experimental Trial Tests

3 tests have been conducted to justify the assumption in above. 2 tests (Test No. 2-1 and 2-2) are LIN wet spray discharge test by different flow rate on vertical steel column, and one test (Test No. 2-3) is LIN liquid accumulation on the horizontal steel structure. Refer to table 1 about the summary of 3 tests with images of the tests. The PITT-CHAR XP (PPG Protective & Marine Coatings) 12mm is applied as a CSP insulation material, and 1.2m length of standard UL 1709 H-column (W10X49) is used for all tests. Thermal insulation is applied on the structure surface of non-CSP insulation. The thermocouple is installed inside the test piece to measure the temperature of steel structure. The LIN discharge is continued up to the hitting point temperature reaches at below -29°C or 20 minutes whichever earlier. The temperature at the back side of the LIN discharge point is recorded every 1 minute during the test. Outside temperature is also recorded at the beginning of each test and the temperature drop is used for the discussions.

Simulation

The test scenario is modelled to simulate the experimental trial test condition. The simulation domain is 2-dimension, the boundary condition at wetted part is set as temperature-fixed boundary of boiling point of -196°C, and other portion is assumed as adiabatic boundary. The initial temperature of the steel structure and the CSP is set to 32°C. The physical properties are as shown in table 2.

Table 1: Test Scenario

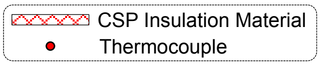
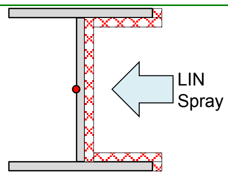
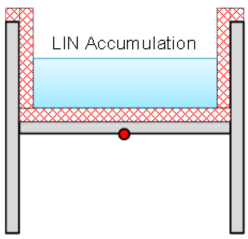
Test No.	LIN Condition Description	Flow Rate [g/s]	Section View of Test Condition 
2-1	Spray exposure on vertical web side of H-column	100	
2-2	Spray exposure on vertical web side of H-column	200 (2 nozzles)	
2-3	LIN accumulation on web side of horizontal H-column	N/A (Accumulation)	

Table 2: Physical properties

Carbon steel		
Density	7830	kg/m^3
Specific heat	461	J/kg K
Thermal conductivity	53	W/m K
Pitt-char XP		
Density	1100	Kg/m^3
Specific heat	1207.4	J/kg K (0°C)
	687.4	J/kg K (-100°C)
Thermal conductivity	0.244	W/m K

2.2 Result

The temperature of LIN spray hit point of each test is indicated in figure 1. It is found that the temperature drop trend is similar in test 2-1, test 2-2 and test 2-3. This result shows that if the LIN spray forms a liquid film on the steel structure and become a wet condition, the heat transfer from cryogenic spill to the steel structure is not different from the cryogenic liquid accumulation scenario. Based on these results, it is proposed that the phase of spilled cryogenic hydrocarbon to define the CSP insulation thickness should be one side cryogenic liquid accumulation, because if the cryogenic liquid wet spray exposure forms the film on the steel structure, there is no different effect from heat transfer point of view. And also the flow rate of the wet spray does not affect the heat transfer if the liquid film is formed.

Comparing to the simulation result, the beginning part of the test is different from the simulation result. This is because that the boundary conditions at wetted part are set as temperature-fixed boundary. It means that heat transfer coefficient is assumed as infinity. On the other hand, heat transfer coefficient is finite value in actual condition. The temperature-fixed boundary is conservative side assumption. Therefore, as a conclusion, it is proposed that the simulation can be used to define the thickness of CSP insulation, if the firmed physical property of the CSP insulation and steel structure is available.

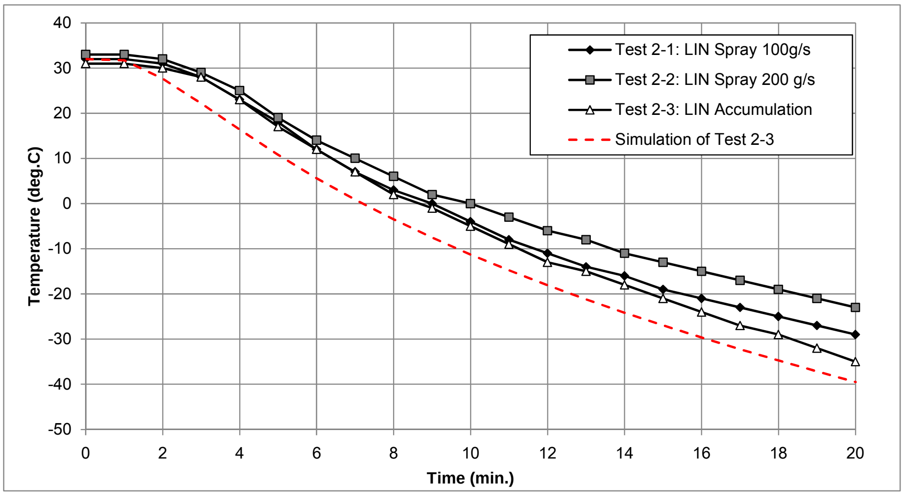


Figure 1: Temperature Record and Simulation Result

3. Extent of brittle fracture hazard area

This section describes the method and result of the analysis and experimental trial test about the extent of affected area of cryogenic liquid release.

3.1 Method

<u>Theory</u>

The heat transfer from cryogenic liquid to the steel structure is explained by the heat transfer from LIN to the surface of steel structure and from the surface of steel structure to the steel structure. Once the heat transfer reaches at the surface of steel structure, the steel start cooled and CSP insulation will be required to avoid brittle fracture. The important criteria to affect the heat transfer from LIN to the steel structure is whether LIN will reach as liquid or fully vaporised gas on the steel structure. In general, boiling heat transfer coefficient is much larger than gas heat transfer coefficient. Therefore, it is assumed that if LIN reaches the steel structure, the temperature drop of the steel structure is significant and if LIN is vaporised before reaching the steel structure, the temperature drop of the steel structure become much lower, and this distance is considered as the extent of brittle fracture hazard area from cryogenic hydrocarbon spill.

Simulation

To simulate the LIN liquid travel distance, the function of liquid fraction calculation in Phast developed by DNV GL is applied.

Experimental Trial Test

Test to ensure the simulation result is conducted as per the below method.

1) Condition of LIN wet spray is summarized in below.
- Inside tank pressure is maintained at 0.05 to 0.09Mpa
- LIN storage Temperature is around -189°C
- Nozzle size: 9.5mm
- Capacity of LN2: 121kg or 160Liter per tank
- Flow Rate: 100g/s
2) A small piece of steel (200mmX200mmX14mm) is set at selected distance from the LIN discharge nozzle
3) One thermocouple is set at the centre of the backside of test piece to measure the temperature
4) Record outside temperature at the beginning of the test
5) Start LIN discharge toward to the test piece.
6) Flow rate of LIN is kept at 100g/s during the test.
7) Record the test piece temperature at 1 minute interval during the test. Test is conducted for 15 minutes.
8) Define the LIN droplet travel distance from the recorded test piece temperature drop trend.

The result of simulation by Phast and the result by experimental trial test is compared and discussed.

3.2 Result

The simulation result is summarized in the Table 3. Based on the table-3, the LIN droplet distance is expected around 2,260mm.

Table 3: Summary of Simulation Result for LIN Droplet Travel Distance

Flow rate (g/s)	Nozzle Diameter (mm)	Downwind Distance (mm)	Liquid Fraction @ given distance	Liquid Mass @ given distance	Liquid Mass Rate [g/m2 s]
100	9.5	2,120	0.06	6	18.7
100	9.5	2,260	0.02	2	5.3

The experimental trial tests are conducted as per procedure in section 3.1 to verify the theory and simulation result. The temperature drop at 10 minutes after the LIN discharge of 4 test cases of different distance are summarized in Table 4. It is found that the temperature of test piece drops significantly between 2150 mm and 1900 mm. Both simulation result and experimental test result are indicated in Figure 2. As summarized in figure 2, it can be concluded that the simulation result is reasonably conservative against the experimental trial test result to define the cryogenic liquid droplet travel distance, the significant temperature drop point is considered as the border of liquid droplet travel on the test piece and form LIN liquid film. The variation of the wet spray pressure and difference of wind/atmosphere condition, etc can be a cause of the slightly longer estimate of liquid travel distance by simulation.

Table 4: Test Record _ Temperature Drop at 10minutes after LIN Discharge

Flow rate (g/s)	Nozzle Diameter (mm)	Distance (mm)	Temperature Drop at 10 minutes after LIN discharge (°C)
100	9.5	2400	-10
100	9.5	2150	-18
100	9.5	1900	-55
100	9.5	1400	-65

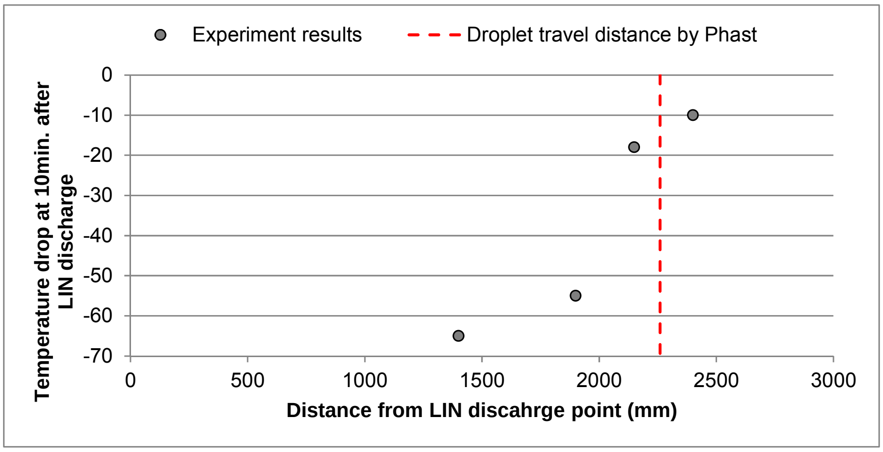


Figure 2 Summary of Simulation Result and Test Result

Based on the above, it is proposed that the following engineering method as reasonably conservative approach to define the extent of brittle fracture hazard area due to cryogenic hydrocarbon spill.

Step-1: Define the cryogenic liquid
Step-2: Define release hole size and flow rate of the cryogenic liquid spill
Step-3: Conduct calculation by Phast and define the cryogenic droplet travel distance
Step-4: Calculated distance can be considered as cryogenic release affected area, where CSP insulation should be considered.

4. Conclusion

The engineering approach to define the CSP insulation thickness and the extent of brittle fracture hazard area is proposed. These proposed methods are verified by the experimental trial test.

Phase of spilled cryogenic hydrocarbon on the steel structure

It is proposed that the one side cryogenic liquid accumulation scenario can be considered as the adequate phase of cryogenic liquid on the steel structure to define the CSP insulation thickness. The simulation based on heat transfer is conducted to compare with experimental trial tests. Based on the comparison with the experimental results, it is concluded that the simulation result is considered as reasonably conservative to apply during the design phase.

Extent of brittle fracture hazard area

It is proposed to simulate the cryogenic liquid droplet travel distance which will form the liquid film on the steel structure, and provide the significant heat transfer on the steel structure. The simulation can be conducted by Phast liquid fraction calculation. Based on the comparison with the experimental trial test, the simulation result is considered as reasonably conservative to apply during the design phase.

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