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Inherent Safety Design Considering Forced Ventilation Effect by Air-Fin-Cooler in Modularized Onshore LNG Plant

Masayuki Tanabe[a], Atsumi Miyake*[b],

[a]JGC Corporation, 2-3-1, Minato Mirai, Nishi-ku, Yokohama 220-6001, Japan
[b]Yokohama National University, Hodogaya-ku, Yokohama 240-8501, Japan
tanabe.masayuki@jgc.co.jp

Onshore LNG Plant development project starts from *Concept Definition* phase, where financial feasibility is estimated and major conditions, such as site location and development area extent. It becomes difficult to set ideal inherent safety design, e.g., separation distance, in this phase due to unavailability of design data and priority on financial feasibility. Further, the LNG plant modularized approach requires large, complex structures (modules) for supporting the LNG process equipment and for allowing sea and land transportation. This results in additional congestion of the plant and large voids under module-deck, which are confined by large girders. Thus, in case of leaks, the proper ventilation to reduce the accumulation of gas is critical for the safety. Therefore, the inherently safe layout consideration to enhance ventilation is important in order to reduce potential of flammable gas accumulation and subsequent explosion, e.g., orientation and separation distance.

Many base load onshore LNG plants use large number of Air-Fin-Coolers normally mounted on the center pipe rack of the LNG process train. This paper evaluates the Air-Fin-Cooler induced air flow in modularized LNG plants to quantify the effect as Air Change per Hour (ACH) using Computational Fluid Dynamics (CFD) analysis. The results of this evaluation show that the ventilation of the Air-Fin-Cooler induced air flow is influenced by the process train orientation. Further, a moderate increase is observed in specific design conditions or areas, such as shorter separation distances between modules. Based on the results of this evaluation, the inherent safety design measures, which should be taken into consideration in the *Concept Definition* phase, are proposed to optimize the use of Air-Fin-Cooler, such as train orientation against prevailing wind direction and separation distance between modules.

1. Introduction

It is common practice to select inherent safety design measure, e.g., separation distance, rather than active system (fire water system), in order to prevent accident escalation. However, in the development of oil and gas facilities, the requirements which greatly influence the separation distance, such as site location and plant foot print, are decided at the *Concept Definition* phase which mainly focuses on financial considerations. Since this early phase discusses only conceptual design conditions and does not define detailed design, safety aspects evaluated in this phase are normally limited to coarse QRA (Quantitative Risk Assessment) and HAZID in order to confirm the order of magnitude of process risk as described by Tanabe and Miyake (2012a). This paper discusses the approach for enhancing the inherent safety design application to Onshore LNG Plants at the *Concept Definition* phase.

2. Onshore LNG Development Project

2.1 LNG Plant

An LNG plant is categorized as midstream in the business domain. It is built near shore (onshore) to receive natural gas from well heads (majority of the times from offshore) and export the LNG product by sea carrier. Recently, the number of LNG plant development projects is increasing. The development costs for LNG plants are higher than the one for oil and refinery plants (e.g. typically up to several billion

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for oil and refinery plants and more than 10 billion for LNG). However, due to the reduction of crude oil reserves and environmental aspects (lower impurity in natural gas), natural gas has been recognized as cleaner energy. Further, the natural gas/LNG is now very attractive as alternative energy source to nuclear power in Japan. LNG plants are commonly designed based on onshore safety design practices, but as the LNG process mainly consists of high pressure gas handling units (Figure-1), the safety features are similar to the offshore plants, i.e., major hazard is gas jet fire. However, the deterministic approach for conventional onshore plants, which is applied to LNG plants, is generally based on pool fire. LNG Safety is discussed in many papers (Tugnoli et al., 2010 and Cozzani et al., 2011).The safety design approach for onshore LNG plant should consider its specific hazards, such as gas jet fire, cryogenic spill, large vapor cloud, and explosion hazard.

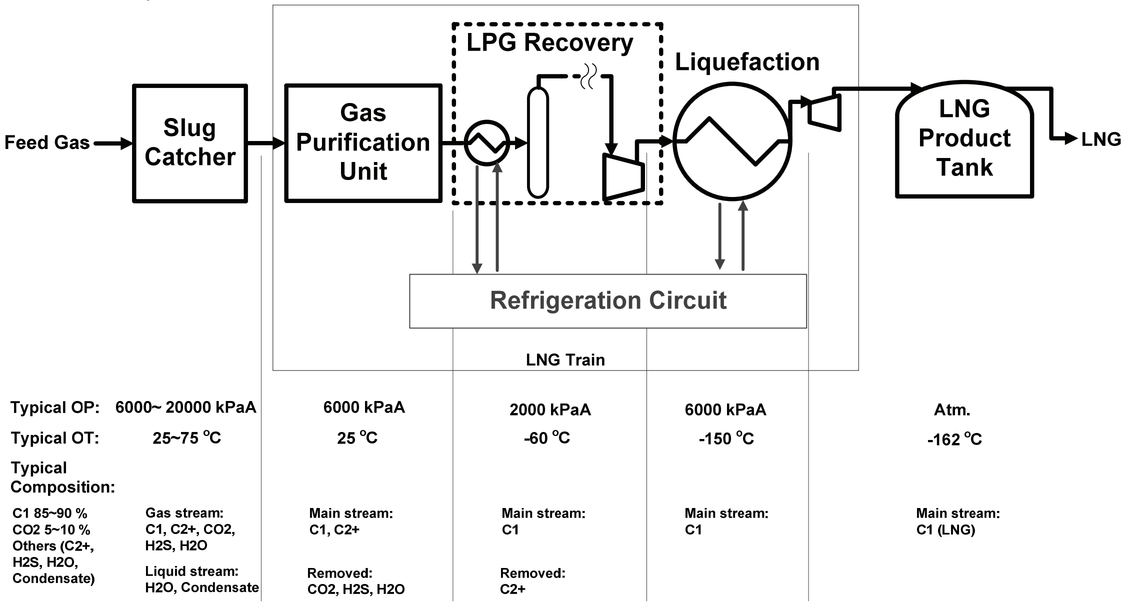


Figure 1: Simplified LNG Process Flow

2.2 Modularization Concept

Recently, due to the increasing number of developments in remote locations where labour mobilization is difficult and/or site construction is to be minimized to protect sensitive environments, the modularization concept is being widely applied to onshore LNG liquefaction plant to reduce work volume at the site. If modularization is applied, the plant design features become similar to offshore plants.

The explosion hazard becomes higher when modularized concept is applied, due to the module structure elements and bracing and large voids under module deck.

2.3 Development Schedule

The typical schedule of an onshore LNG plant development can be divided in four major phases which are *Concept Definition*, *Pre-FEED*, *FEED* and *EPC*.

- *Concept Definition*: Based on location of well and feed gas characteristics, the overall development concept, such as product, capacity, onshore or offshore, location of the onshore plant, and its economic feasibility are studied and defined in this phase.
- *Pre-FEED (Pre- Front End Engineering Design)*: The basic design data (Basis of Design - BOD) and the design philosophies are established in this phase.
- *FEED (Front End Engineering Design)*: The design philosophies are finalized, the design data is established and the total investment cost is estimated for the Final Investment Decision (FID).
- *EPC (Engineering, Procurement and Construction)*: The detailed design is developed, equipment is purchased, and the plant is constructed and commissioned.

The facility/equipment orientation and separation for better ventilation should be identified in the early stage of the project, as changes in layout become difficult in the later stage. However, at the early stage of the project, there are difficulties in setting these measures due to limitation of available design data.

3. Proposed Inherent Safety Design Approach for Modularized Onshore LNG Plant

The identification of the appropriate inherent safety and the setting of the criteria for its implementation should be done by “rule of thumb” during the early phase of the project. When modularized concept is selected in the *Concept Definition* phase, the inherent safety design measures should be also discussed since the explosion hazard becomes higher when modularized concept is applied. The layout consideration to enhance ventilation is important in order to reduce potential of flammable gas accumulation and subsequent explosion, e.g., facility orientation and separation.

Many onshore base load LNG plants apply Air-Fin-Cooler (AFC) to provide required duty for refrigerant cooling in LNG process. In recent base load LNG plants, a very large number of AFCs [e.g., approx. 300 fans for 4 – 5 MMTPA (Million Metric Ton Per Annum) production LNG plant] is mounted on the center pipe rack in the process train. Because AFCs are process equipment (not safety system), they are tripped in emergency conditions, such as fire and gas leak. However, since air flow rate through AFC is not negligible, the reduction of the amount of gas accumulation due to the forced ventilation inside the trains is expected. This effect for outdoor facilities has not been quantified for use in design safety before, although ventilation study inside enclosed area was done by Palazzi et al. (2010). This study quantifies the ventilation effect by AFC using CFD analysis and evaluates design measures to enhance the effect.

4. CFD Model

The basic design data of an LNG plant of 4 MMTPA capacity (recent typical base load LNG single train capacity) is used in this study identifying inherent safety design options. The full detail of the study was provided by Tanabe and Miyake (2012b):

- AFC mounted height on the center piperack: 23.4 m
- Total induced air flow rate by AFCs: 22620 m^3/s
- Size of LNG process train: 400 m (Length) x 250 m (Width)
- Size of module: 40 m (Width) x 40 m (Length) x 17 m (Height) including module deck height of 4 m (below deck).
- Size of AFC mounted piperack: 336 m (Length) x 32 m (Width) x 23.4 m (Height)

4.1 Air change per hour

The increase in ventilation due to the AFC forced air flow is evaluated based on the increase of Air Changes per Hour (ACH) compared to that for natural ventilation, used as a datum.

The Air Change per Hour (ACH) is calculated based on the following formula:

$$Q_a = V_{mod} \cdot R/_{3600} \tag{1}$$

Where

Q_a : Air flow rate (m^3/s)

V_{mod} : Free module volume (m^3)

R : Air change rate per hour

Since the ACH calculation is simply related to free volume in the area and air flow rate passing through the area, it is important to correctly identify the detailed air flow inside the area. Therefore, CFD analysis has been used. The air flow passing through the “target” volume (i.e., under the 1st floor deck, above 1st floor deck and gap between modules) is measured for each face of the volume under consideration, which means that the ACH is calculated based on the air flow through each face in order to simulate the detailed air flow streams.

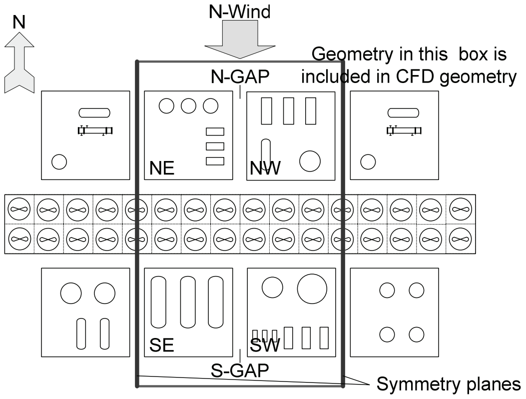
4.2 CFD analysis model

The CFD analysis was conducted by MMI Engineering, UK. CFX (ANSYS) is used for this study due to large number of source terms and required mesh size. The AFC ventilation is evaluated in terms of ACH by Formula (1). The air flow passing through the “target” volume (e.g., under the 1st floor deck, above 1st floor deck and gap between modules) is measured for each face of the volume under consideration, which means that the ACH is calculated based on the air flow through each face in order to simulate the detailed air flow streams. The following are the major model and cases assumptions used for this study.

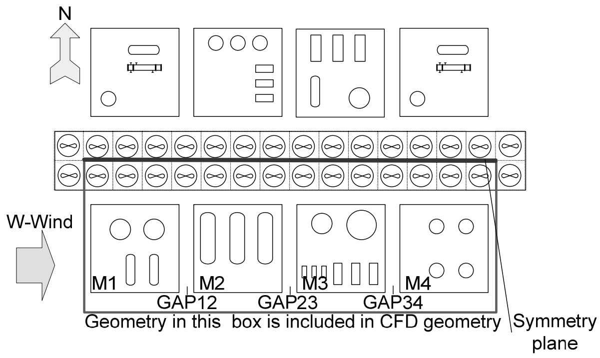
- Atmospheric temperature: 300.15 K
- Atmospheric stability class: D (neutral condition)
- Atmospheric wind speed 5 m/s, 10 m/s

N-Wind model and W-Wind model

In order to keep the computational grid to a practical size, only the central part of the LNG train is included in the computational model as illustrated in Figure 2.



a) N-Wind



b) W-Wind

Figure 2: N-Wind model and W-Wind Model

4.3 Model geometry and boundary

For the N wind simulations, the east and west domain boundaries are symmetry planes. The North boundary is located approximately 260 m upstream of the North modules; the South boundary is located approximately 260 m downstream of the South modules. The domain length in the N-S direction is 650 m. The top boundary of the domain is located approximately 140 m above the ground level.

For the W wind simulations, the north boundary is a symmetry plane. This is located half way between the two banks of AFCs. The West boundary is located 250 m upstream of the first AFCs. The East boundary is located 300 m downstream of the final AFCs, so the width of the domain varies with module separation. As for the N wind simulations, the top boundary of the domain is located approximately 140 m above the ground level.

4.4 AFC Model

In the CFD model, only AFC fans included in the CFD geometry are modelled. The raised temperatures are set at AFC outlet. The AFCs are treated as isothermal. The inlets to the AFCs are defined as domain outlets with no constraint on temperature. The outlets from the AFCs are defined as domain inlets, with the air entering the domain constrained to have the temperature defined by the actual design information. The temperature is applied uniformly across the boundary.

4.5 Equations

The equations used in the CFD model are shown in Table 1. The large equipment is modelled using the geometrical characteristic of the individual pieces of equipment. The loss term due to small pieces of equipment is established as a friction factor only. Module congestion is represented by applying non-unity porosity and a flow resistance source term for the momentum equation based on the Modified Porosity Distributed Resistance (MPDR) model, which Vianna (2009) provided the detailed explanation.

Table 1: Equations

Terms	Equations	Remarks
Turbulence	k-ε	Based on eddy-viscosity concept
Energy	CFX thermal energy equation	Simplified equation suitable for low Mach number flows of compressible gases
Steady/ Transient	Steady state simulations	Convergence criteria of 1e-5 was used
Continuity and Momentum	Porosity equal to unity: CFX full porous model Porosity less than unity: Modified Porosity Distributed Resistance (MPDR) model	-
Flow resistance	Porosity Distributed Resistance (PDR) method	Since wetted area is different for each congested region, and friction factor is different for each congested region and coordinate direction, a different value of flow resistance is specified for each congested region and coordinate direction.

4.6 Results

The results are summarized in Tables 2 and 3.

The results showed that the increases in ACH in modules due to AFC-on and train orientation were more than 80 % in the case of perpendicular wind direction to the process train axis (N-Wind) and more than 30 % in the case of parallel wind direction to the process train axis (W-Wind). Especially, the increase in ACH in the upwind gap was significant (more than 170 %) in the case of perpendicular wind direction to the process train axis (N-Wind). The increases in ACH due to the separation distances between modules vary significantly. The increase in ACH in the gaps with shorter separation distance (ACH with 8 m separation) between modules was observed to be 25 % for N-Wind and 250 % for W-Wind (increase over ACH with 25 m separation at 5 m/s wind). However, the increased ACH in the W-Wind case was mainly due to the "channel effect". Crosswind flow in W-Wind case, which prevents flammable gas accumulation in the gaps, was increased when separation distance between modules is increased.

Overall, the increase of the ACH is mainly due to the AFC-on and train orientation. The separation distance and the deck materials have moderate impact (increase) on the ACH in specific conditions or areas.

Table 2: AFC-on vs AFC-off

Wind Cond.	Area	ACH				%Increase in ACH due to AFC-on	
		AFC-on		AFC-off			
		Above Deck	Below Deck	Above Deck	Below Deck	Above Deck	Below Deck
N-wind 5m/s	NE	690	856	507	342	36	150
	NW	694	787	507	348	37	127
	SE	607	732	500	402	21	82
	SW	590	728	495	392	19	86
	N-GAP	722	1048	518	375	39	179
	S-GAP	634	828	509	424	25	95
W-wind 5m/s	M1	538	531	505	361	6	47
	M2	654	631	482	356	36	78
	M3	735	651	450	365	63	78
	M4	767	650	435	348	77	87
	GAP12	2568	2329	2438	1717	5	36
	GAP23	2809	2409	2269	1657	24	45
	GAP34	2968	2360	2125	1627	40	45

Table 3: Separation Distance

Wind Cond.	Area	ACH					
		Above Deck			Below Deck		
		8m SD	15m SD	25m SD	8m SD	15m SD	25m SD
N-wind 5m/s	NE	690	700	692	856	811	779
	NW	694	694	693	787	765	770
	SE	607	620	607	732	701	664
	SW	590	608	593	728	680	664
	N-GAP	722	716	702	1048	920	831
	S-GAP	634	646	614	828	713	682
W-wind 5m/s	M1	538	557	577	531	535	564
	M2	654	694	726	631	621	634
	M3	735	750	786	651	625	682
	M4	767	776	780	650	636	673
	GAP12	2568	1436	960	2329	1319	850
	GAP23	2809	1608	1092	2409	1361	957
	GAP34	2968	1731	1150	2360	1403	939

4.7 Recommended design option enhancing ventilation

The following design approaches are identified as possible safety design measures, optimizing the use of AFC-on ventilation for onshore modularized LNG plant, which can be considered in the *Concept Definition* phase.

- The LNG train axis should be perpendicular to the prevailing wind direction to increase ACH in the gaps and below deck, and the AFC fans should be kept running even in emergency conditions to reduce the amount of flammable gas accumulation, although normally AFC fan motors are stopped upon emergency shutdown condition. This recommendation is based on the fact that the fan motors are normally explosion proof type suitable for the hazardous area classification Zone-2 operation to minimize the ignition probability.

- If the probability of the prevailing wind direction is very high, it is worthwhile to consider using shorter separation distance between modules to further increase the ACH. However, considering the hazards due to shorter separation distances, as most common event is a jet fire as presented by Tanebe and Miyake (2011), a separation distance of 15 m should be considered as the minimum requirement (Refer to Table 4).

These design measures shall be carefully evaluated from other aspects (such as adverse effect by reducing the separation distance, hot air circulation, operation/maintenance aspects) based on specific design conditions. Since the modularized approach increases congestion of the plant and creates large voids under the module deck, which are confined by large girders, we believe that as “rule of thumb” the proposed measures specified above should be seriously considered even if there may be adverse effects in other design aspects.

Table 4: Separation Distances for Module (40 ~ 50m width)

Separation Distance	Selection Condition	Purpose	Source	Remarks
25 m	Populated area	Explosion Overpressure Mitigation	Van Den Berg and Versloot, 2003	-
20 m	Populated area	Jet Fire (LPG 2-Phase @ 20 kPaA)	Tanabe and Miyake, 2011	Jet flame length @ 12 mm hole Calculation by PHAST - Larger flame due to 2-phase release.
15 m	All cases	Jet Fire (Natural Gas @ 60 kPaA)	Tanabe and Miyake, 2011	Jet flame length @ 12 mm hole Calculation by PHAST
25 m	Module/ Parallel orientation	Forced Ventilation for AFC (Parallel)	AFC Ventilation Study	-
8 m	Module/ Perpendicular orientation	Forced Ventilation for AFC (Perpendicular)	AFC Ventilation Study	-

5. Conclusion

This paper proposes the approach for enhancing inherent safety design in onshore LNG plant project by defining the required inherent safety design measures in the project *Concept Definition* phase. The inherent safety design measures presented in this paper were established based on the proposed safety concepts and case study results using actual LNG plant design data.

The proposed approach is a “rule of thumb” approach based on the conceptual information when the modularized approach is considered in the concept definition phase. This approach can be applied in the early phases of the project because it allows a better and thorough use of the limited information available at this stage of the project. The authors believe that enhancing this approach will contribute to the improvement of the design safety in onshore LNG plant projects.

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