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Effective Implementation of Inherently Safer Design during Design Phase of Modularized Onshore LNG Projects

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Onshore LNG Plant development projects start from the “Concept Definition” phase, where financial feasibility is first estimated and major conditions such as site location and development area extent are decided. Current industrial practice applies “risk” for the evaluation of design options once detailed design data is available. Due to the limited flexibility for “change” during the detailed design phase, safety measures tend towards the application of active safeguarding systems (such as automated depressuring by fire and gas detection). Consequently, it is difficult to apply ideal inherently safer design, e.g., separation distances, during the “Design” phase of a project.

Further, modularized LNG plants require large, complex structures (modules) to support LNG process equipment and to allow sea and land transportation. This results in excessive congestion and the existence of large voids under the module-deck, which are confined by large girders. As such, in the event of leakage, it is critical for plant safety to install adequate ventilation to reduce the accumulation of flammable gas and potential for subsequent explosions. In order to reduce the potential of such hazards, it is important to consider an inherently safer layout to enhance ventilation, e.g., direction or separation.

Implementation of an inherently safer layout during the early design phase requires a strategic approach, such as setting targets for accidental event sizes which avoid escalation events via the separation distance and/or pre-defining the separation distances themselves.

This paper proposes a strategy for the implementation of inherently safer design in the plant overall plot plan and pre-defined separation distances for modules within the process train, based on the evaluation of layout options in view of Air-Fin-Cooler induced air flow in modularized LNG plants by quantifying its effects as Air Change per Hour (ACH) and flammable gas cloud volumes through Computational Fluid Dynamics (CFD) analysis.

1. Introduction

It is common practice to apply inherently safer design (ISD) measures, e.g., separation distance, rather than to install active systems (fire water system), in order to prevent accident escalation. However, in the development of oil and gas facilities, the factors which greatly influence separation distance, such as site location and plant foot print, are decided during the Concept Definition phase which mainly focuses on financial considerations. As this early phase discusses only conceptual design conditions and does not define detailed design, safety aspects evaluated in this phase are normally limited to rough QRA (Quantitative Risk Assessment) and HAZID (Hazard Identification) studies in order to confirm the order of magnitude of process risk as described by Tanabe and Miyake (2012a). This paper discusses a strategic and practical approach to enhance inherently safer design applications for Onshore LNG Plants during the Concept Definition phase.

2. Onshore LNG development project

2.1 LNG plant

LNG plants are categorized in the midstream sector of the Oil and Gas business domain. Plants are built near shore (onshore) to receive natural gas from well heads (majority of the time from offshore) and export the LNG

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product by sea carrier. The development costs for LNG plants are higher than those for conventional oil and refinery plants (e.g. typically up to several billion for oil and refinery plants and more than 10 billion for LNG). However, due to depleting crude oil reserves and environmental aspects (lower impurities in natural gas), natural gas has been recognized as cleaner energy. LNG plants are commonly designed in accordance with onshore safety design practices, which are generally based on pool fires, however as the LNG process mainly consists of high pressure gas handling units, its safety features are similar to offshore plants, i.e., the major hazard is a gas jet fire. The safety design approach for onshore LNG plants should focus on its own specific hazards, such as gas jet fires, cryogenic spills, large vapour cloud and explosions.

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 minimized to protect sensitive environments, the modularization concept is being widely applied to onshore LNG liquefaction plants to reduce the volume of site work. If modularization is applied, the plant design features become similar to offshore plants.

Explosion hazards are higher when modularization is applied, due to the module structure elements, bracing and large voids under the module deck.

2.3 Development schedule

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

- *Concept Definition*: Based on well location 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)*: Basic design data (Basis of Design - BOD) and design philosophies are established in this phase.
- *FEED (Front End Engineering Design)*: Design philosophies are finalized, design data is established and the total investment cost is estimated for the Final Investment Decision (FID).
- *EPC (Engineering, Procurement and Construction)*: Detailed design is developed, equipment is purchased, plant is constructed and commissioned.

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

3. Proposed strategic ISD approach

3.1 Strategic ISD

For gas jet fire and explosion hazards, plant layout is the most effective measure (i.e., ISD measures) to reduce accident escalation. The greater the separation distance, the safer the design. However, it is not feasible nor practicable to provide greater separation distances for all areas in view of development cost and operability. It is therefore reasonable to provide greater distances only for selected areas in order to maximize the effect, and standard distances for other areas (for operability and maintainability). This does not necessarily mean to apply greater distances in the more hazardous areas, but between hazardous and non-hazardous areas. However, if only very small distances are available in hazardous areas, it leads to a higher possibility of accident escalation (e.g., initial small fire to large fire), and consequently, larger accident event severity. This is especially apparent in modular designs.

Thus, the Authors propose a strategic approach focusing on initiator event sizes leading to accident escalation. If a separation distance is defined such that accident escalation from small size jet fires (i.e., most frequent events) can be avoided, and can enhance ventilation thereby preventing large gas cloud formation within the LNG process train (most hazardous area in LNG plants), it can reduce the expected largest accident event sizes in the LNG process train and subsequently the required separation distance from the LNG process train to surrounding areas.

3.2 Rule of thumb for separation distances

The identification of appropriate inherent safety design measures and the criteria for its implementation should be based on a “rule of thumb” during the early phases of a project. When modularization is selected in the *Concept Definition* phase, the inherent safety design measures should also be discussed as explosion hazards are higher. The layout consideration to enhance ventilation, e.g., facility orientation and separation, is important in order to reduce the potential for flammable gas accumulation and subsequent explosions.

Many onshore base load LNG plants apply Air-Fin-Coolers (AFC) to provide the required duty for refrigerant cooling in LNG processes. In recent base load LNG plants, a very large number of AFCs [e.g., approx. 300

fans for a 4 – 5 MMTPA (Million Metric Ton Per Annum) production LNG plant] are mounted on the centre pipe rack in the process train. AFCs are process equipment items (not part of a safety system), hence are tripped in emergency situations, such as fire or gas leaks. However, since air flow rate through the AFCs is significant, forced ventilation is expected to reduce the amount of gas accumulated inside the trains. This study quantifies the effect of AFC ventilation through CFD analysis and evaluates design measures to enhance this effect.

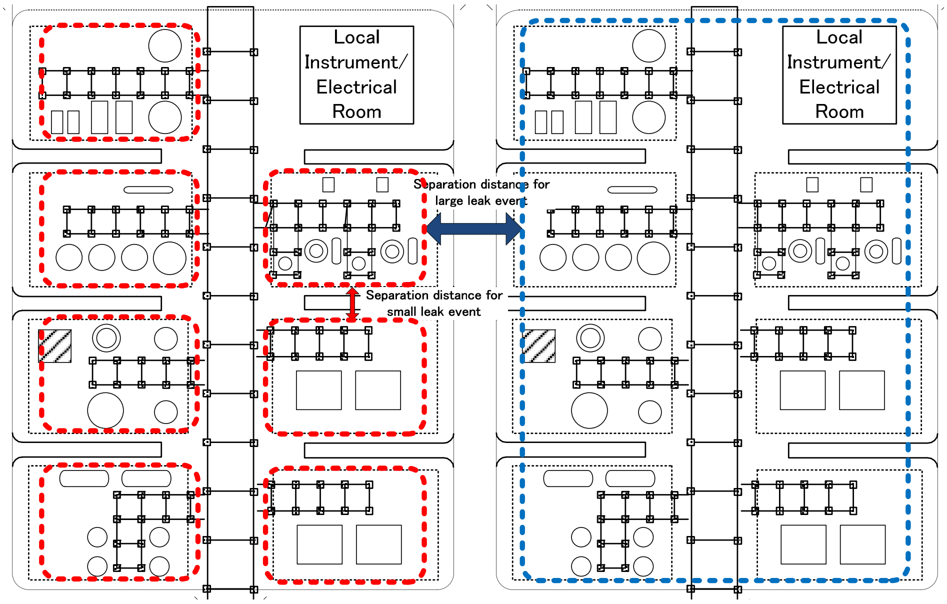


Figure 1: Simplified LNG Process Flow

4. Effective separation distance for ventilation

The CFD analysis was conducted by MMI Engineering, UK. CFX (ANSYS) software was used for this study due to the large number of source terms and required mesh size. The basic design data of an LNG plant of 4 MMTPA capacity (recent typical base load LNG single train capacity) was applied to identify inherent safety design options.

- AFC mounted height on the centre pipe rack: 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 pipe rack: 336 m (Length) x 32 m (Width) x 23.4 m (Height)

The following were the major model and case assumptions used in the study.

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

The following cases were considered as run cases in the study.

- AFC-on and AFC-off

Module separation distances of 8m, 15m and 25m

4.1 Air change per hour (previous work)

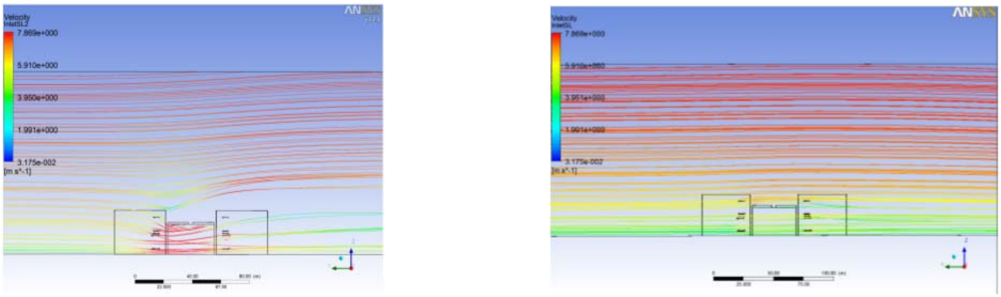
The increase in ventilation due to AFC forced air flow was evaluated based on the increase of Air Changes per Hour (ACH) compared to that for natural ventilation. It was found that AFC ventilation air flow significantly increases ACH in the LNG train due to an increase in the vertical air flow component (Table 1 and Figure 2). Full details of the study are provided by Tanabe and Miyake (2012b).

4.2 Flammable gas volume

Further to the evaluation of ACH, a flammable gas dispersion study was also performed to quantify its effects. The gas dispersion study evaluated for jet gas release toward the gaps, which may reduce the ventilation effect in the gaps. Two gas release cases, 3kg/s and 50kg/s, were modelled which was equivalent to releases from 2 inch and 8 inch holes respectively, based on high pressure propane refrigerant system process conditions. The gas release point and direction is shown in Figure 3.

Table 1: Separation Distance by AFC-on

Wind Condition	Area	%Increase in ACH due to AFC-on		
		Whole Module	Above Deck	Below Deck
Perpendicular Wind	NE	34	36	150
	NW	36	37	127
	N-GAP	37	39	179
Parallel Wind	GAP12	7	5	36
	GAP23	25	24	45
	GAP34	41	40	45



AFC-on

AFC-off

Figure 2: Mode Geometry

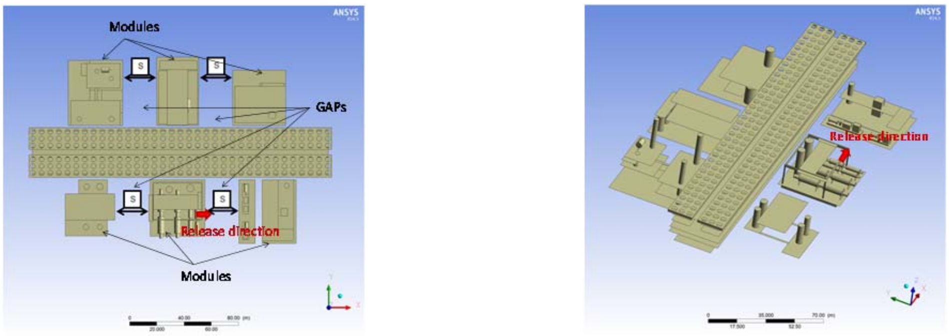


Figure 3: Model Geometry and Gas Release Point

4.3 CFD Model and equations

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

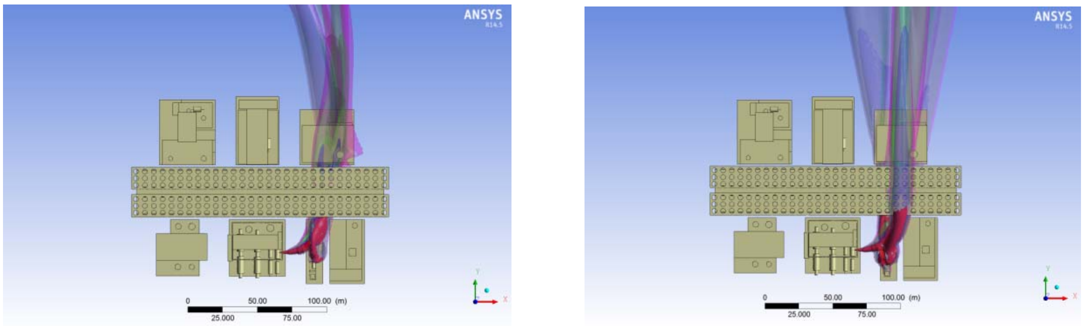
The equations used in the CFD model are shown in Table 1. Large equipment was modelled using the geometrical characteristic of individual pieces of equipment. The loss term due to small pieces of equipment was established as a friction factor only. Module congestion was represented by applying non-unity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

5. Results and discussions

The results of the gas dispersion study are shown in Figures 4 and 5. Figure 4 shows iso-contours for 100% LFL (red), 50% LFL (blue), 20% LFL (green) and 10% LFL (pink). It demonstrates that the AFC-on case reduces gas cloud volumes compared to the AFC-off case. Figure 5 summarizes the gas cloud volumes for AFC-on and AFC-off cases against module separation distances. It clearly demonstrates that a smaller SD case has larger gas cloud, and the larger the SD, the smaller the resultant gas cloud formation. The gas cloud size for AFC-on and AFC-off cases converge at a separation distance of 15m (15mSD), hence a 15m SD is considered effective for both AFC-on and AFC-off cases.

Table 2: Equations

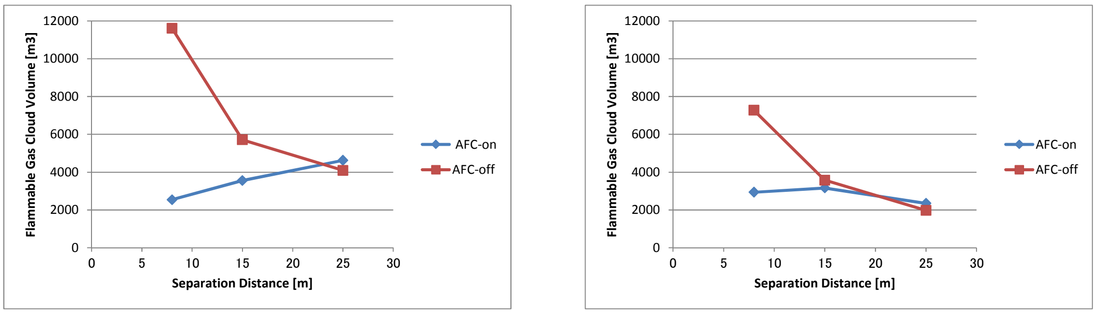
Terms	Equations	Remarks
Turbulence	k-ε	Based on eddy-viscosity concept
Energy	CFX thermal energy equation	Simplified equation suitable for low Mach number flows of compressible gases
Steady/ Transient	Steady state simulations	Convergence criteria of 1e-5 was used
Continuity and Momentum	Porosity equal 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.



AFC-on

AFC-off

Figure 4: AFC-on & AFC-off 50kg/s 15mSD Perpendicular Wind



Parallel Wind

Perpendicular Wind

Figure 5: Comparison for 50kg/s Release Cases

6. Recommended design option (Rule of Thumb)

Although the number of cases studied in the ventilation and gas dispersion study was limited, the following design approaches have been identified as possible safety design measures, optimizing the use of AFC-on ventilation for onshore modularized LNG plants, which can be applied during the *Concept Definition* phase.

- A separation distance of 15m should be considered as the minimum requirement (Table 3). With a separation distance of 15m, the expected worst credible escalation scenario can be mitigated (Table 4). Where plant development site area is limited, using the 15m SD and worst credible event size (50mm release events) must be considered to optimize layout.
- 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 and suitable for hazardous area classification Zone-2 operation to minimize ignition probability.

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. However, as a modularized approach increases congestion of the plant and creates large voids under the module deck, which are confined by large girders, it is recommended that as a “rule of thumb” the proposed measures specified above should be seriously considered regardless of any adverse effects in other design aspects.

Table 3: 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
15m	All cases	Enhancing natural ventilation in safety gaps and reducing potential forming larger gas cloud over safety gaps	AFC Ventilation/Gas Dispersion Study	-
8 m	Module/ Perpendicular orientation	Forced Ventilation for AFC (Perpendicular)	AFC Ventilation/Gas Dispersion Study	E.g., small capacity single train LNG plant

Table 4: Separation Distances for LNG Train to Surrounding Area

Separation Distance	Selection Condition	Basis
30 m	Code & Standard Minimum Requirement	NFPA 59A
50 m	50mm hole size (gas phase)	Jet fire and explosion blast overpressure study (MEM) by PHAST
70 m	50mm hole size (2-phase)	
100 m	100mm hole size (gas phase)	
125 m	100mm hole size (2-phase)	

7. Conclusion

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

The proposed approach is a “rule of thumb” based on conceptual information when a 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 a project. The authors believe that applying this approach to enhance inherently safer design will contribute to the improvement of design safety in onshore LNG plant projects.

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