Detailed Fire Scenario Assessment by CFD Simulation: Pool Fire Under Air-Cooled Heat Exchanger in Modularized LNG Plant

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Modularization is one of the approaches to compress the LNG project cost by reducing the site construction works where it is extremely severe. For the modularized LNG plants, ACHE (Air-Cooled Heat Exchanger) is mounted across the multiple modules and in some cases, process equipment is located beneath ACHE. While various international standards do not recommend the installation of the fire potential equipment beneath ACHE to avoid any escalation of the fire incident. This paper presents the approach to assess the fire scenario and pool fire behavior under such equipment installation based on the CFD simulation by FLACS Fire. The simulation result showed 150-200% increase in the flame size of the pool fire beneath ACHE due to the air flow into the ACHE, which resulted in higher heat radiation at the adjacent modules. Furthermore, as the ACHE acted as an obstacle for the high temperature plume above the pool fire, the plume at 500°C dispersed horizontally along the ACHE to the adjacent module. It was also indicated that there was a threshold pool diameter. Namely no difference was observed in the flame behavior due to the air flow into the ACHE for the pool fire with a small pool diameter. As per the results, the following safety engineering approaches for the modularized LNG plant should be considered: Credible fire scenario and accidental spill control, Executive actions upon gas/fire detection, Safety distance, Fire mitigation and Escape route arrangement.

Key Words: CFD, FLACS Fire, Simulation, Air-Cooled Hear Exchanger, Module, Modularized LNG, Liquefaction

1. Introduction

Modularization is one of the key approaches to compress the LNG project cost where site construction works are extremely severe. It is a construction method to pre-fabricate the modules at the fabrication yard (such as shipbuilding yard), transport to the plant development site and install (Hook-up) the modules at the site. As the capability of the natural gas wellhead development increases, the number of LNG project development at remote areas where it is difficult to secure the work force and the construction unit price at the site is expensive. For such LNG projects, the application of the modularization could be unavoidable and have a cost advantage compared to the conventional stick-build LNG project.

LNG liquefaction process requires removing the heat as a part of refrigerant cycles and ACHE (Air-Cooled Heat Exchanger) is usually applied as a cooler for onshore LNG plants. ACHE consists of fan, plenum, tube bundle and supporting structure as shown in Figure 1. For the induced draft type ACHE, the tube bundle is located below ACHE fan. Therefore, in case of the large pool fire under ACHE, the tube bundle can be exposed to the fire.

As the required heat duty is huge for the recent large scale LNG plant, ACHE is normally mounted on the central pipe rack of the LNG liquefaction process train. For the modularized LNG plants, ACHE is mounted across the multiple modules. In some cases, due to the constraint of the equipment layout within a compacted module, process equipment is located beneath ACHE.

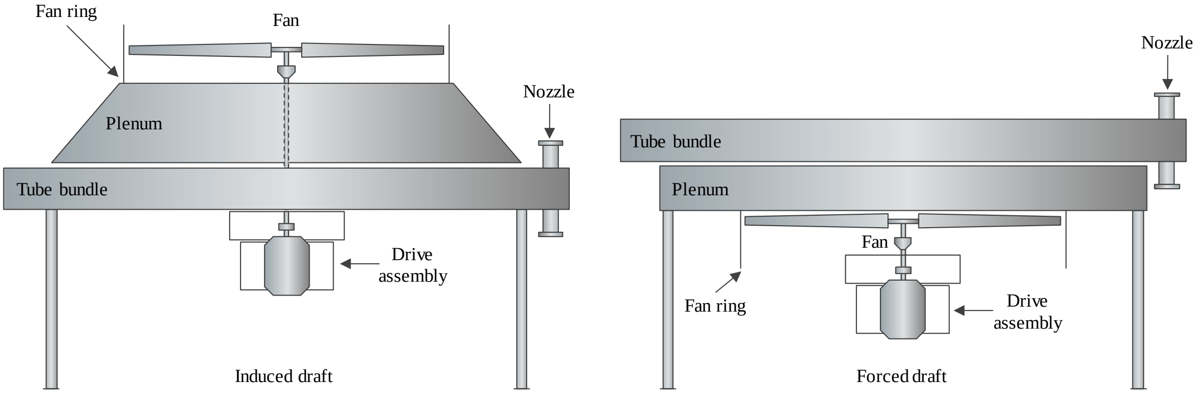


Figure 1 Typical components of ACHE (Air-Cooled Heat Exchanger)

It is commonly known that the fire hazard escalates under an upward current. Considering the effect of a fire event when it has occurred, various international standards and good engineering practices describe the equipment layout considerations, especially for the fire potential equipment, such as rotary equipment handling flammable fluid (Pumps and Compressors), and ACHE as summarized in

Table 1. These considerations recommend ensuring a certain safety distance between the fire potential equipment and the pipe rack on which the ACHE mounted, and not to install the fire potential equipment beneath the pipe rack as an escalation of the pool fire event can happen due to the ACHE induced air flow.

Table 1 Standards and guidelines for ACHE and other equipment layout

Standard/Guideline	Section	Considerations
PIP PNE00003 [1]	11.4.4	Air cooled heat exchangers may be located on the top level of pipe racks provided that the pumps are located in accordance with Section 11.5.5 (11.5.5: For location of pumps relative to pipe racks pumps should be located such that the wet end is located outside the pipe rack and the driver should not extend more than 0.76 m (2 ft-6 in) inside the center line of the pipe rack column).
GE GAP 2.5.2 [2]	Intra-Unit Spacing	Do not group pumps and compressors handling flammable products in one single area. Do not locate them under pipe racks, air cooled heat exchangers and vessels. Orient pump and driver axes perpendicular to pipe racks or other equipment to minimize fire exposure in case of a pump seal failure. Separate high pressure charge pumps from any other major process equipment and other pumps by at least 25 ft (7.5 m).
CCPS Siting and Layout of Facilities [3]	6.8.7	Updraft air-cooled heat exchangers draw air through the cooler and may also draw the heat and fire in the same direction. The additional heat input to the cooler from the fire can cause high temperature and overpressure of other equipment. Additionally, the metallurgy that makes the fins appropriate for heat transfer also makes them highly susceptible to damage from heat. Do not locate vessels or pumps containing flammable or combustible liquids beneath air-cooled heat exchangers., Do not locate heat exchangers containing flammables or combustibles that are heated above their autoignition temperature beneath air-cooled heat exchangers. Do not locate multiple flanges and valves, such as in control stations, under air-cooled heat exchangers. Separate air-cooled heat exchangers from ignition sources such as fired heaters.
API 521 [4]	4.4.13.2.8.5	The air cooler should not be located above equipment containing or transporting large amounts of flammable liquids. Equipment in this classification includes pumps, heat exchangers, surge drums, reboilers, and accumulators, but rack piping can be normally excluded.
API 2001 [5]	5.6.6.3	Rotating equipment, such as pumps and compressors, is more susceptible to accidental releases than most other equipment. Therefore, from a fire protection standpoint, it is preferable to locate this type of equipment away from ignition sources. Pumps handling hydrocarbons should be carefully located, avoiding areas below pipe alleys, major vessels, air coolers, and other critical equipment. Where this cannot be avoided, consideration of fixed fire protection systems is appropriate (see API 2030). Additional spacing should be given to mechanical equipment handling flammable liquids near or above their autoignition temperature and fixed protection considered.
API 2218 [6]	5.1.3.3	When air cooled exchangers are located above vessels or equipment that contain flammable materials, fireproofing should be considered for the structural supports located within a 20 ft to 40 ft (6 m to 12 m) horizontal radius of such vessels or equipment, regardless of height

Figure 2 is quoted from API 2218 [6], which indicates the recommended fireproofing application extent for the pipe rack supporting ACHE. Fire scenario envelope in API 2218 is considered as 6 m to 12 m from a fire potential equipment. In addition to this basic concept, in case ACHE is mounted on the pipe rack, fireproofing is recommended for all structural supports regardless of the heights. It means that a potential escalation of the pool fire is considered behind this recommendation.

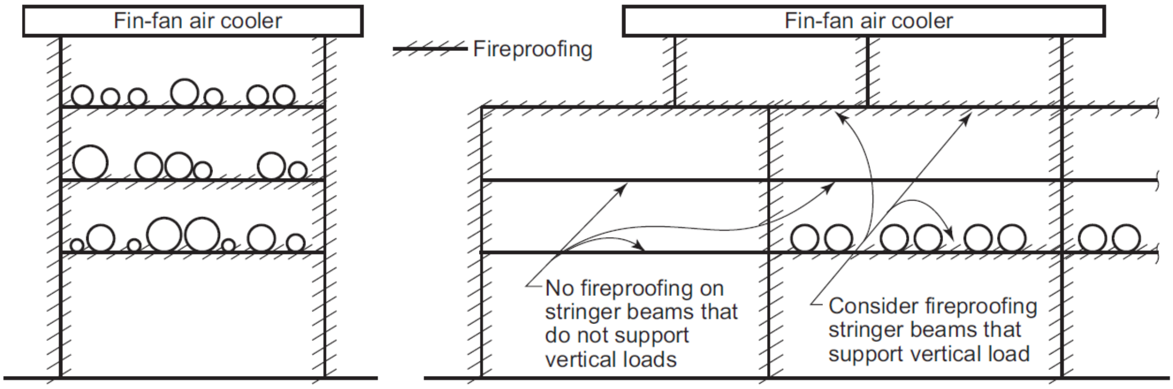


Figure 2 Fireproofing extent for pipe rack supporting fin-fan air coolers in a fire scenario area [6]

For the flammable gas leakage scenario under ACHE, Tanabe and Miyake [7] evaluated a complex air flow under ACHE for the modularized LNG plant by CFD (Computational Fluid Dynamics). It showed that the induced air flow due to ACHE contributed to the increase of ACH (Air Change per Hour) within congested LNG process modules. Tanabe [8] conducted further evaluation by the flammable gas dispersion study with the various safety distances between the modules and it showed the most effective reduction of the flammable gas accumulation with 15 m safety distance in case of the leakage as ACHE acted as a ventilator. Therefore, it was concluded that ACHE induced air flow is an effective mitigation of the explosion risk within congested LNG process modules and ACHE fans should be kept running even in emergency conditions with 15 m safety distance.

On the other hand, the fire scenario under ACHE has not yet evaluated in detail. Figure 3 shows the schematic of pool fire under ACHE. The induced air flow toward ACHE just above the pool fire leads to the increase of flame dimension. Also, the flame tilts toward the adjacent module due to the induced air flow toward ACHE mounted on it. In addition, the flame reaches ACHE and the flame would be oriented horizontally toward the adjacent modules. As a result, more severe pool fire consequence is expected.

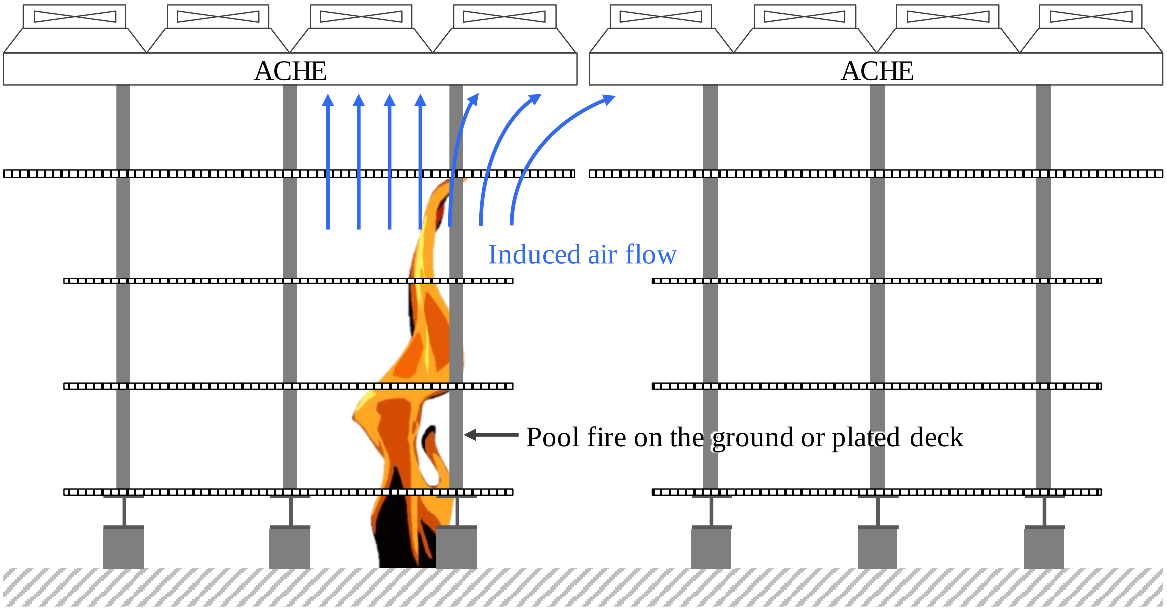


Figure 3 Schematic of pool fire under ACHE

As mentioned above, the modularization is adopted to the LNG projects where site construction works are extremely severe. Due to the equipment layout constraint within a compacted module, process equipment is located beneath ACHE, which is not a recommended layout in various international standards and good engineering practices considering the escalation of the pool fire under ACHE as a general guideline. However, few reports are available on the pool fire behaviour under ACHE complex induced air flow, although detailed behaviour must be different depending on various conditions (e.g., pool fire size, air flow speed, level of congestion). This paper focuses on the detailed pool fire scenario under ACHE and clarifies the pool fire behaviour considering the induced air flow and blockage effect by ACHE using CFD fire simulation. The result of the detailed fire scenario assessment is reported. Based on the result, the key factors for the safety engineering approach of the modularized LNG plant are identified.

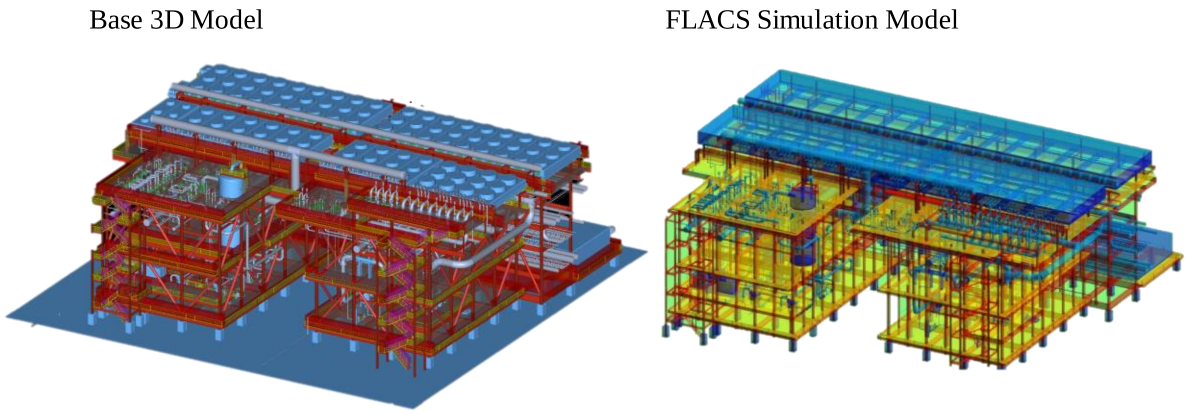
2. Study methodology and basis

2.1. Software

FLACS Fire Ver 10.8.1, which is specialized CFD package for fire modelling, was used for the simulation to evaluate detailed fire behaviour inside a congested geometry.

2.2. Simulation model

Simulation model consists of two process modules of the LNG liquefaction process. The dimension of one module is 40 m, 68 m for the width and depth, and 34 m for the height. The safety distance between those modules is 15 m. Base 3D model is not based on the real project but based on the modularized LNG concept developed by JGC internally for study purpose. The base 3D model includes the concrete foundations, steel structures, floors, buildings, ACHE housings mounted on the pipe rack, major equipment and large bore piping but not include the instrument and electrical cables, small bore piping. The base 3D model was converted to DGN format and imported to FLACS Fire as shown in Figure 4.


Base 3D Model

FLACS Simulation Model

Figure 4 Typical modularized LNG module base 3D model and imported FLACS Fire Simulation model

2.3. Simulation setting and parameters

FIRE simulation model was selected in FLACS Fire. Simulation duration was set to 120 seconds. It has been confirmed using FLACS Fire that within 120 seconds, the pool fire behaviour becomes stable and there is no additional value to conduct longer simulation.

Stationary pool fire with fixed pool diameter was used. To avoid the fuel run-out and loss of flame, the fuel mass was set at 999999 kg, which does not affect the pool geometry. The source of pool fire was assumed to be Propane which is often used as a refrigerant in the liquefaction processes. Pool diameter was varied for each simulation case.

ACHE and ACHE induced air flow were modelled by FAN leak which assigns a fixed momentum to the air. Z direction porosity of ACHE was varied for each simulation case.

Detailed settings are described in Table 2, Table 3 and Table 4.

Table 2 General simulation setting summary

Parameter	Value	Remarks
Simulation model	FIRE	Eddy dissipation concept was applied for the combustion modelling.
CFLC [-]	5 or 10	Courant-Friedrich-Levy number based on sound velocity The value was selected depending on the stability of the simulation.
CFLV [-]	0.5 or 1	Courant-Friedrich-Levy number based on fluid flow velocity The value was selected depending on the stability of the simulation.
Simulation duration [s]	120	-
Wind velocity [m/s]	0	No wind was assumed to evaluate the effect of ACHE induced air flow.

Parameter	Value	Remarks
Ambient temperature [ºC]	30	-
Wind direction	N/A	N/A

Table 3 Pool fire setting summary

Parameter	Value	Remarks
Pool fire model	PM1	Stationary pool fire with fixed pool diameter was used.
Fuel mass [kg]	999999	999999 kg was selected to avoid the fuel run-out.
Fuel composition [-]	C_3H_8 100%	-
Pool diameter [m]	2, 10 and 20	-
Ignition time [s]	0.5	0.5 second delay was to generate enough flammable gas cloud.

Table 4 ACHE FAN leak setting summary

Parameter	Value	Remarks
Leak model	FAN leak	Induced air flow was modelled by FAN leak assigning a fixed momentum to the air.
Dimension [m/bay]	4.3 ×15.3	Dimension was based on the ACHE datasheet for the real project.
No. of bay	69	No. of bay was based on the real project.
Air flow [m/s/bay]	6.8	Air flow was based on the ACHE datasheet for the real project.
ACHE porosity [%]	0, 10 and 100	Only Z direction porosity was defined.

2.4. Simulation cases

Simulation cases are summarized in Case No. 05 was conducted to identify the pool diameter threshold leading to the escalation of the fire event under ACHE induced air flow. The result of the simulation was compared to Case No. 01 to see the difference in the pool fire behaviour between large (10 m) and small (2 m) diameter pool under ACHE. ACHE porosity was assumed to be 100% (No blockage) to separate the ACHE induced air flow effect from the blockage effect by ACHE.

Table 5. To purely evaluate the basic pool fire behaviour under the ACHE and the flame blockage effect, no atmospheric wind condition was modelled for all simulation cases as the base 3D model represents less congestion compared to the As-build 3D model and the ambient wind directly hits the flame without being obstructed by the module components such as piping, cable trays and auxiliary equipment.

Case No. 01 and 02 were conducted to evaluate the pool fire behaviour under ACHE induced air flow. 10 m diameter pool fire was simulated with ACHE in operation and ACHE stand-by condition. ACHE porosity was assumed to be 100% (No blockage) to separate the ACHE induced air flow effect from the blockage effect by ACHE.

Case No. 02, 03 and 04 were conducted to evaluate the flame blockage effect by ACHE as an obstacle. In this simulation, induced draft type ACHE was assumed. ACHE consists of fans and tube bundles which provides physical blockage to fire flame and/or high temperature air plume. Here, the plate object was installed at ACHE tube bundle elevation and Z direction porosity of the object was varied from 0% (Full blockage) to 100% (No blockage) with the fixed pool diameter. The temperature at the tube bundle elevation was monitored. As the simulation, which contains FAN leak (ACHE in operation) with 0-99% porosity object simultaneously, did not converge, to simplify the simulation model, ACHE was assumed to be Stand-by condition.

Case No. 05 was conducted to identify the pool diameter threshold leading to the escalation of the fire event under ACHE induced air flow. The result of the simulation was compared to Case No. 01 to see the difference in the pool fire behaviour between large (10 m) and small (2 m) diameter pool under ACHE. ACHE porosity was assumed to be 100% (No blockage) to separate the ACHE induced air flow effect from the blockage effect by ACHE.

Table 5 Simulation case summary

Case No.	Purpose of cases	ACHE running status	ACHE porosity [%]	Pool diameter [m]	Comparison and discussion		
01	Base case	In operation	100	10	3.1	-	3.3
02	Sensitivity for ACHE induced air flow	**Stand-by**	100	10	3.1	3.2	-
03	Sensitivity for ACHE physical blockage effect on pool fire	**Stand-by**	**10**	10	-	3.2	-
04	Sensitivity for ACHE physical blockage effect on fire and/or high temperature air plume	**Stand-by**	**0**	10	-	3.2	-
05	Sensitivity for flame size against pool fire escalation under ACHE induced air flow	In operation	100	**2**	-	-	3.3

Result 3.1: Pool fire behaviour exposed to ACHE induced air flow

Result 3.2: Pool fire blockage due to ACHE

Result 3.3: Pool diameter threshold for the escalation

2.5. Grid setting

The Simulation volume was defined as 310 m, 300 m for X, Y direction respectively and 120 m for Z direction. Two modules and the concerned pool fire were within the core domain with the fine grid (Cubic: 0.5 m in each X, Y and Z directions). As shown in Figure 5, outside of the core domain, the grid was stretched with a factor of 1.2 towards the boundaries, to conserve simulation time and computer memory.

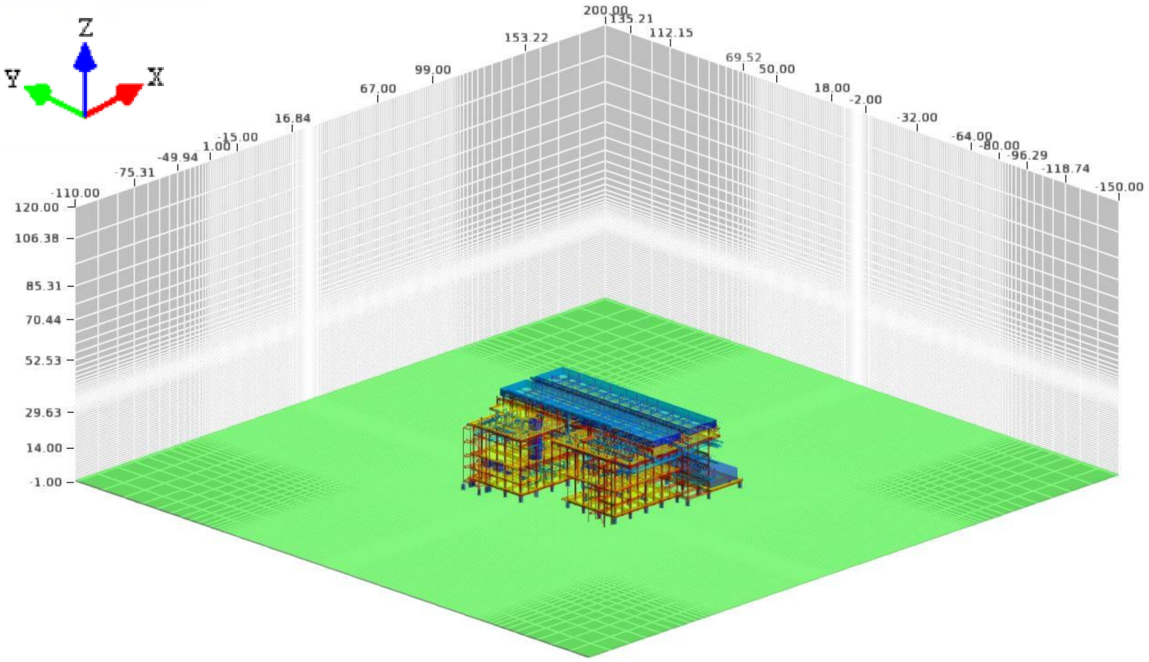


Figure 5 Simulation grid setting of FLACS Fire

2.6. Monitoring Point

The monitoring points were put every 5 meters around the pool fire across two modules covering from 1st deck to 3rd deck. Examples are indicated at the allow tips in Figure 6. Temperature (T [°C]) and Radiation (Q [W/m^2]) were obtained from these monitoring points to monitor the behaviour of the pool fire.

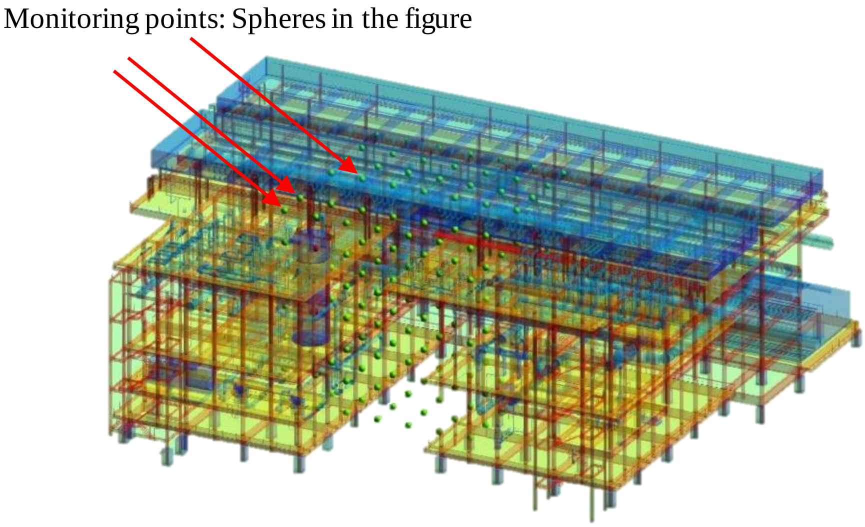


Figure 6 Monitoring point locations around pool fire under ACHE

3. Results

3.1. Pool fire behaviour exposed to ACHE induced air flow

CFD simulation results of the pool fire with and without ACHE induced air flow are shown as Figure 7. Whereas the high temperature plume above 500ºC was below ACHE elevation (34 m) in case of ACHE stand-by, it extended above ACHE elevation in case of ACHE in operation. Due to the induced air flow to the adjacent module ACHE, the temperature contour tilted toward the adjacent module.

Radiation contour and its trend at the adjacent module are shown as Figure 8. The radiation trends were obtained from the monitoring points located at 1st deck and 2nd deck of the adjacent module which has 15 m safety distance from one module. The radiation at 1st deck and 2nd deck of the adjacent module from 10 m diameter pool fire was less than 10 kW/m^2 in case of ACHE stand-by. On the other hand, the radiation at the same location was increased significantly in case of ACHE in operation and the radiation varies from 20 kW/m^2 to 45 kW/m^2.

Based on these results, it can be inferred that the escalation of the pool fire due to ACHE induced air flow was observed. ACHE induced air flow caused not only advection of the high temperature plume extensively but also 150-200% growth of the flame dimension. As the flame dimension was increased and it tilted due to the induced air flow to the adjacent module, the radiation was increase increased significantly.

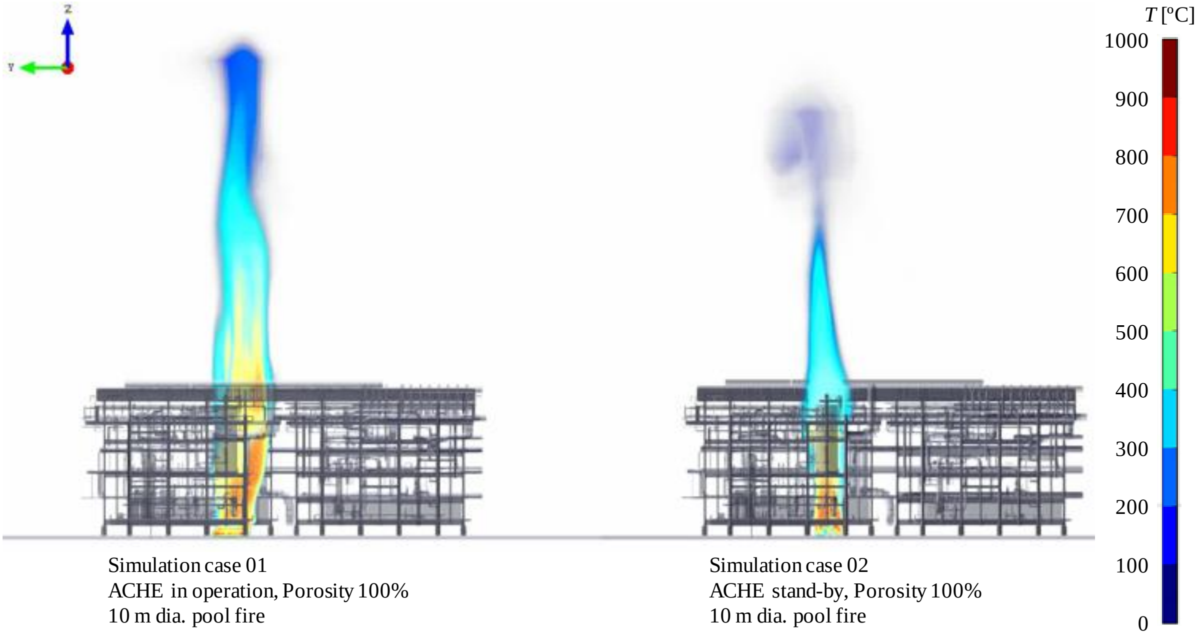


Figure 7 Temperature contour of 10 m diameter pool fire with ACHE in operation and ACHE stand-by

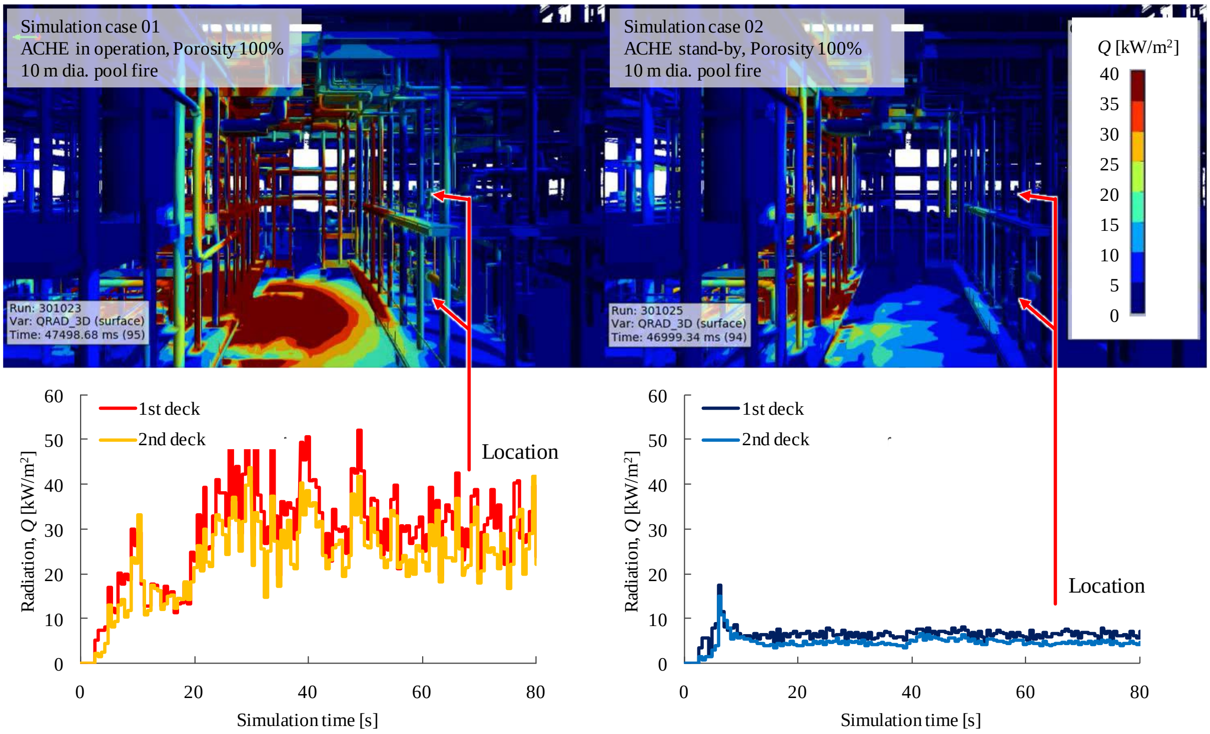


Figure 8 Radiation contour and trend comparison of 10 m diameter pool fire

3.2. Pool fire blockage due to ACHE

Temperature contours of the different porosity setting of ACHEs from Simulation case 02, 03 and 04 are shown as Figure 9. Temperature contour at ACHE tube bundle elevation (34 m) cut plane is shown as Figure 10. Note that ACHE was not in operation due to the limitation by the stability of the simulation as described in Section 2.4, and thus, pool fire flame itself does not reach to ACHE elevation as per the result in Section 3.1.

While, the increase of the radiation at the adjacent module ACHE platform was not observed. Figure 11 shows the radiation contour and trend for each simulation cases. The radiation trend was obtained from the monitoring points located at the ACHE platforms (3rd deck). Although the peak radiations were observed due to the fluctuation of the flame, the radiation values were constantly low. The effect on the radiation might be observed if the blockage effect could be simulated with ACHE induced air flow (i.e., larger pool fire flame which reaches to ACHE).

However, as shown in Figure 9, because of the presence of ACHE as an obstacle, the high temperature plume is blocked and drifted toward the adjacent module along ACHE.

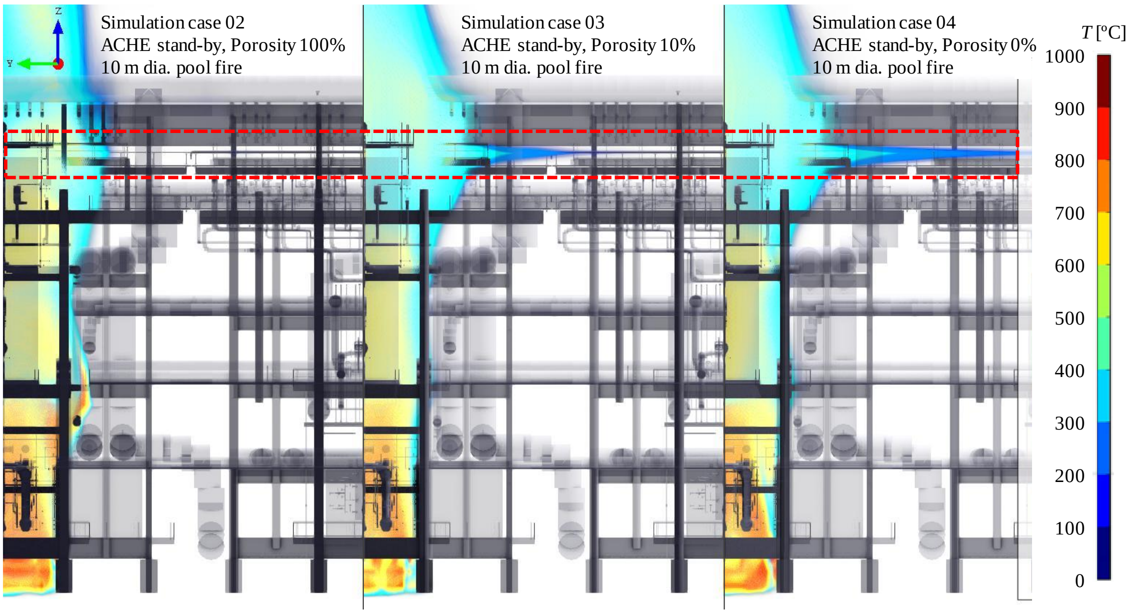


Figure 9 Blockage effect of 10 m diameter pool fire due to ACHE as an obstacle

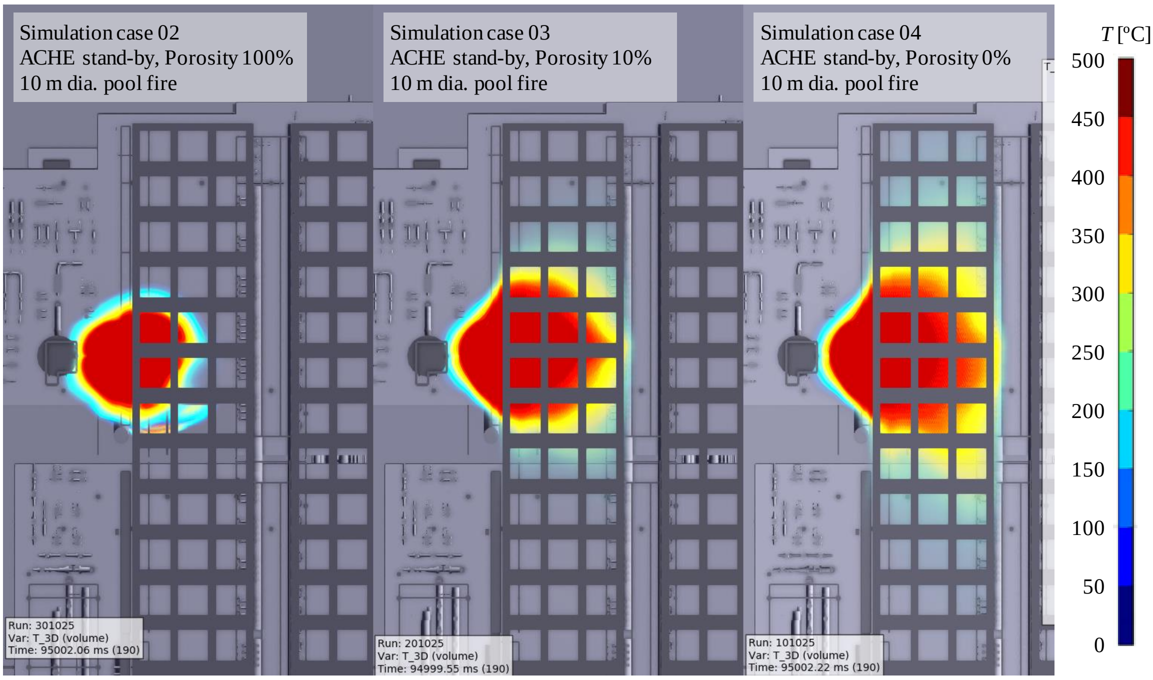


Figure 10 500°C high temperature plume extent at ACHE tube bundle elevation due to 10 m diameter pool fire

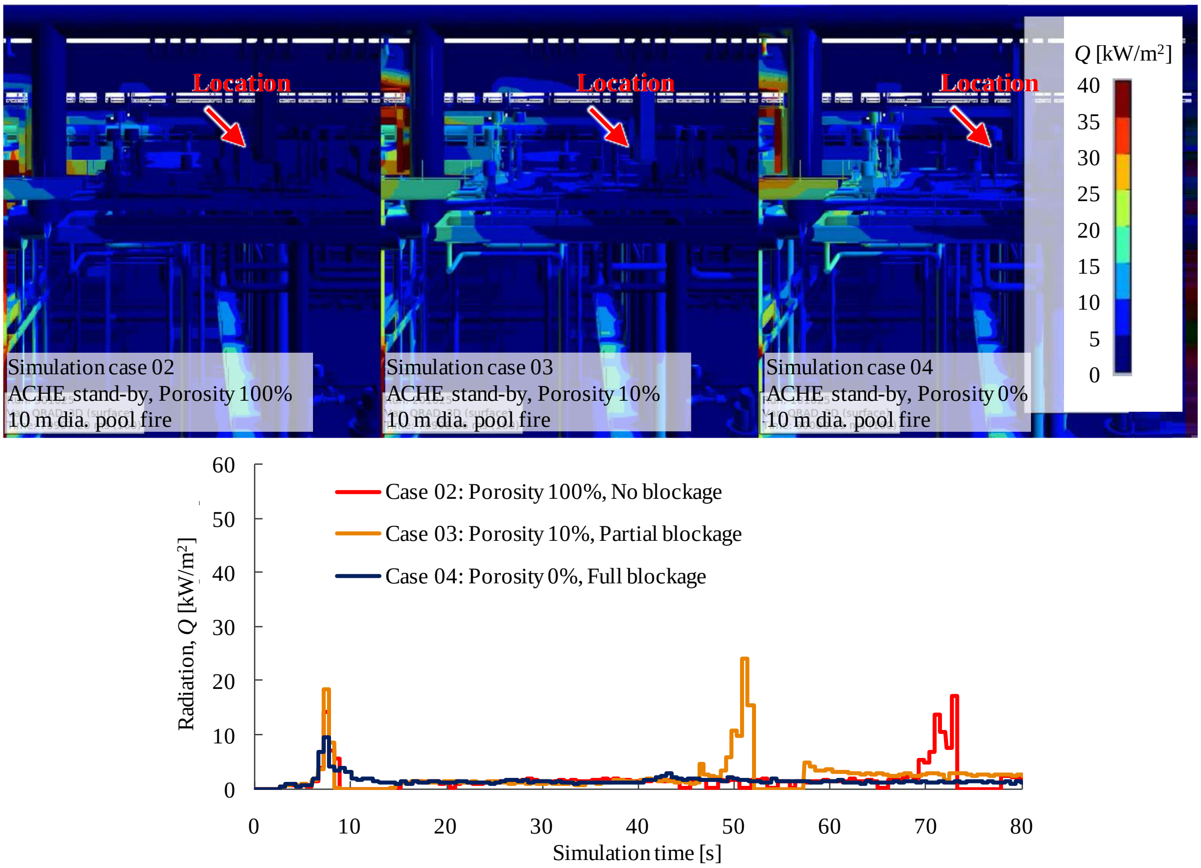
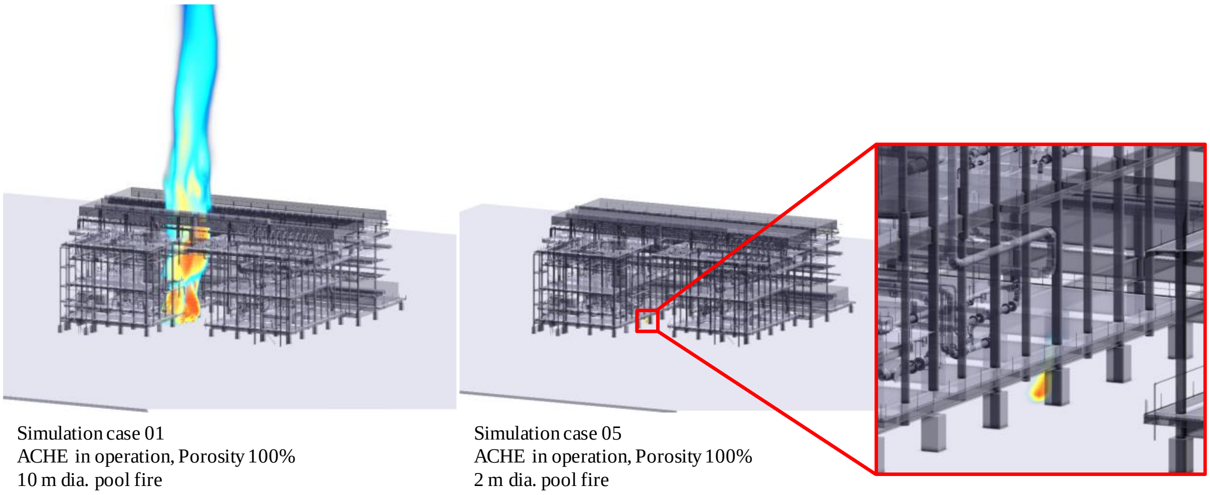


Figure 11 Radiation trend at ACHE platform level by 10 m diameter pool fire

3.3. Pool diameter threshold for the escalation

Temperature contour comparison with 2 m diameter pool fire is shown as Figure 12. Both simulations were conducted with ACHE in operation. Contrary to the 10 m diameter pool fire behaviour, no escalation of 2 m diameter pool fire was observed. Therefore, it can be inferred that ACHE induced air flow does not affect the localized small pool fire. There would be a threshold pool diameter which escalates in combination with ACHE induced air flow.


Simulation case 01
ACHE in operation, Porosity 100%
10 m dia. pool fire

Simulation case 05
ACHE in operation, Porosity 100%
2 m dia. pool fire

Figure 12 Temperature contour comparison with a small diameter pool fire during ACHE in operation

4. Engineering approaches

As per the results, it was observed that a pool fire is escalated by ACHE induced air flow. Where layout locating potential leak sources of flammable fluids under ACHE is inevitable due to project limitation, engineering approaches to reduce the risk of pool fire escalation and/or high temperature air plume become important. The following safety engineering approaches should be considered during the engineering phase.

i. Credible fire scenario and accidental spill control

Credible pool fire scenario and pool diameter under ACHE should be investigated based on the equipment layout and the process information. As described in Section 3.3, there would be a threshold pool diameter which escalates in combination with ACHE induced air flow. If large release of the liquid hydrocarbon is expected, possibility of the pool fire escalation is not negligible. Potential leak sources should be eliminated as much as possible to reduce the potential leak size in case of a risk-based fire scenario assessment (e.g., Application of welding joints instead of flanged joints).

Accidental spill control design should be implemented to prevent a formation of the large diameter pool in case of the leakage from the process equipment. In addition, to avoid the flammable liquid accumulation on the process modules, the 1st deck of the module should be a grating. It also contributes to the reduction of the opportunity of the flammable gas accumulation in the large void under the module and the confinement of the module, which reduces the explosion risk and the blast over pressure against the module.

ii. Executive actions upon gas/fire detection

ACHE fans should be kept running even upon the gas detection. As Tanabe [8] reported, ACHE induced air flow can contributes to the increase of ACH (Air Change per Hour) within congested modules and reduction of the flammable gas accumulation because it acts as a ventilator. However, once the flammable pool is ignited, as the escalation of the pool fire event, in terms of the radiation and high temperature plume, is expected, ACHE fans should be stopped upon fire detection under the ACHE. Therefore, the automatic shutdown logic of ACHE upon fire detection is recommended.

iii. Safety distance

Following the fire scenario assessment mentioned above, the safety distance between modules should be reviewed. The increase of the radiation at the adjacent module was described in Section 3.1. In this simulation, it was assumed that there were no blockage effects by ACHE and ACHE caused only to the growth of the flame dimension due to ACHE induced air flow, which was conservative assumption. In the actual situation, the radiation would be less than this simulation as the growth of the flame is hindered by ACHE as an obstacle.

iv. Fire mitigation

The adequate firefighting equipment should be installed against the credible fire scenarios. The fireproofing is also effective to mitigate the escalated pool fire effect on the module structures. The application height of the fireproofing should be determined based on the credible fire scenarios.

v. Escape route arrangement

Although the module is compacted and the equipment layout degree of freedom is limited, escape routes should be clearly defined and considered during 3D model development. Those escape routes should be free from obstacles to ensure the operator safety during escaping.

5. Conclusions

The detailed pool fire scenario assessment under ACHE was conducted by using CFD simulation. The results showed that due to ACHE induced air flow, the flame dimension was increased in 150-200% and the radiation at the adjacent module was also increased. At the same time, as ACHE acted as an obstacle, the high temperature plume orientation was changed toward the adjacent module. However, for 10 m diameter pool fire, the radiation increases due to this blockage effect. Furthermore, it was found that there is a threshold pool diameter which escalates in combination with ACHE induced air flow. Based on the simulation results, five safety engineering approaches were proposed which should be considered against this pool fire scenario as follows.

i. Credible fire scenario and accidental spill control

ii. Executive actions upon gas/fire detection

iii. Safety distance

iv. Fire mitigation

v. Escape route arrangement

6. Reference

[1] Process Industry Practice Piping, "PIP PNE00003 Process Unit and Offsites Layout Guide," 2013.

[2] Global Asset Protection Services, “GAP.2.5.2 Oil and Chemical Plant Layout and Spacing,” 2015.

[3] Center for Chemical Process Safety, “Guidelines for Siting and Layout of Facilities,” 2003.

[4] American Petroleum Institute, “API Standard 521 Pressure-relieving and Depressuring Systems,” 2014.

[5] American Petroleum Institute, “API Standard 2001 Fire Protection in Refineries,” 2019.

[6] American Petroleum Institute, “API Standard 2218 Fireproofing Practices in Petroleum and Petrochemical Processing Plants,” 2013.

[7] M. Tanabe and A. Miyake, “Forced Ventilation Effect by Air-Fin-Cooler in Modularized Onshore LNG Plant,” *Process Safety and Environmental Protection,* no. 91, pp. 351-366, 2013.

[8] M. Tanabe, “Forced Ventilation Effect by Air-Fin-Cooler on Flammable Gas Cloud Dispersion,” *Process Safety and Environmental Protection,* no. 98, pp. 82-92, 2015.