CFD BASED CONSEQUENCE ASSESSMENT FOR AN NH3 FUELED SHIP

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Abstract

A safety assessment is performed within the Apollo EU project in order to demonstrate that the risk level associated with the considered ammonia fueled vessel is at an acceptable level, and not higher than for a conventional diesel-fueled vessel. The consequence assessment study is performed using the ADREA-HF CFD tool. The examined accidental conditions were defined through a HAZID exercise and cover offshore ship operation as well as ship bunkering procedures. The entire ship's geometry is included through CAD files. The contribution presents selected results of the performed CFD dispersion simulations. Validation of the CFD tool is also presented against pre-existing NH3 large scale dispersion experiments.

1 INTRODUCTION

Ammonia is widely accepted as a potential marine fuel, but due to its toxicity safety studies are needed to analyze the associated risk in case of accidental releases. For earlier related work on the subject see [1, 2, 3].

As part of the Apollo EU project (https://apollo-project.eu/), the supply vessel Viking Energy—owned by Eidesvik and under contract with Equinor—will be converted to run on ammonia as fuel. The objective of this work is to simulate the three-dimensional (3D) dispersion of ammonia for various accidental scenarios identified in a dedicated HAZID exercise and to characterize the toxic ammonia clouds formed in the atmosphere after a release.

DNV Rules for Ships Part 6 Chapter 2 Section 14 [9.2.2.17] [4] requires that the definition of a toxic ammonia gas concentration shall not exceed 300 ppm and that the ammonia gas concentration at mustering stations and lifesaving appliances and access to such stations and appliances shall not exceed 25 ppm, unless suitable mitigating measures have been agreed with the flag administration. Those limits are thus assumed in this study, to direct the design and dispersion analysis efforts towards securing that those limits are observed in the locations of interest.

The 300 ppm exposure limit also corresponds to the exposure limit derived from NIOSH IDLH (Immediately Dangerous to Life or Health) standards, representing the maximum concentration from which a person could escape within 30 minutes without experiencing escape-impairing symptoms or irreversible health effects. This threshold is based on tolerance studies showing 300-500 ppm exposure for 30-60 minutes as the maximum short-term tolerance.

The 25 ppm exposure limit represents the established occupational standard across multiple international bodies: NIOSH REL (Recommended Exposure Limit) for 8-hour time-weighted average, ACGIH TLV (Threshold Limit Value), and UK HSE workplace exposure limits. The European SCOEL (Scientific Committee on Occupational Exposure Limits) established similar thresholds for occupational ammonia exposure evaluation.

In comparison the AIHA Emergency Response Planning Guidelines provide a three-tier system: ERPG-1 at 25 ppm (maximum airborne concentration below which nearly all individuals could be exposed for up to one hour without experiencing effects), ERPG-2 at 150 ppm (serious or irreversible adverse health effects), and ERPG-3 at 750 ppm (life-threatening health effects). Similarly, AEGLs (Acute Exposure Guideline Levels) are another effect discretization system, where exposure time and concentration are considered simultaneously. AEGL-1 is independent of exposure time and has 30 ppm assigned to it. AEGL-2 ranges from 220 ppm for 10 and 30 minutes down to 110 ppm for 4 and 8 hours. AEGL-3, the highest category is assigned for 2700 ppm in case of 10 minutes all the way down to 390 for 8 h exposure. The new IMO Guidelines MSC.1/Circ.1687: "Interim Guidelines for the Safety of Ships Using Ammonia as Fuel" concentrate on 25 ppm, 110 ppm and 220 ppm levels, apparently corresponding mostly to the AEGL scale.

2 SCENARIOS

From the five scenarios identified in the HAZID for further CFD analysis and briefly described below only scenarios 1 and 3 will be further analyzed in this contribution.

Scenario 1 concerns release of ammonia from the ship's vent mast in the event of a fire load in the tank hold space. This fire load is expected to cause the ammonia contained in the tank to evaporate, thus increasing the pressure and causing the opening of the pressure relief valve and the venting of the ammonia to the vent mast, from where it disperses freely. The adopted release conditions for this scenario are shown in Table 1. The release location is shown in Figure 1.

The vent mast scenario was selected as this is the one being most often discussed as a first one during the design process. Its importance is related to the much-needed flexibility in locating the aerodynamically remote vent mast – a challenging task for a small vessel. Vent mast releases potentially present also a considerable risk in case of operation near an offshore installation. The overall mass released in this scenario is large and distributed over considerable time length, hence potentially having some implications on vessel – far field surroundings interactions.

Scenario 2 concerns leakage of ammonia in the tank connection space (TCS). In this case, liquid ammonia will leak onto the TCS floor, evaporate and be transported outside by the TCS ventilation exhaust.

Scenario 3 concerns the leakage of pressurized ammonia from a flange in the bunkering station (BS). Liquid ammonia is assumed to leak from the bunkering hose flange (8-bolt DN100) into the drip tray located at the floor, where it evaporates. It then exits the bunkering station from the opening for the hoses and the ventilation opening. The ventilation operates in extraction mode. The release location and conditions for this scenario are shown in Figure 1 and Table 1 respectively.

Bunker station scenario was established as the most demanding one, with its rapid release in relative closeness to the vital parts of the ship as openings to the enclosed spaces, ventilation intakes, muster stations, etc. In addition, the frequency of carrying the bunkering, possibility of an error/accident makes the risk considerable.

Scenario 4 has to do with the ammonia slip from the engine exhaust. Under normal operation, there is an expected leak of ammonia along with the engine exhaust products.

Scenario 5 concerns the study of internal ammonia dispersion in the engine room in the event of an explosion in the crankcase of the engine. The atmosphere inside a crankcase of a medium-sized marine engine is a complex combination of gases including ammonia. The explosion inside the crankcase causes the explosion valves to open.

Table 1: Release conditions for the various scenarios (provided by Breeze [5])

Scenario	T (K)	Pressure (barg)	Diameter (m)	Mass flow rate (kg/s)	Density (kg/m^3)	Velocity (m/s)
1	388.5	0.0	0.167	1.2	0.534	102.77
3	268.15	10.0	0.0156	4.19	645.1	34.0

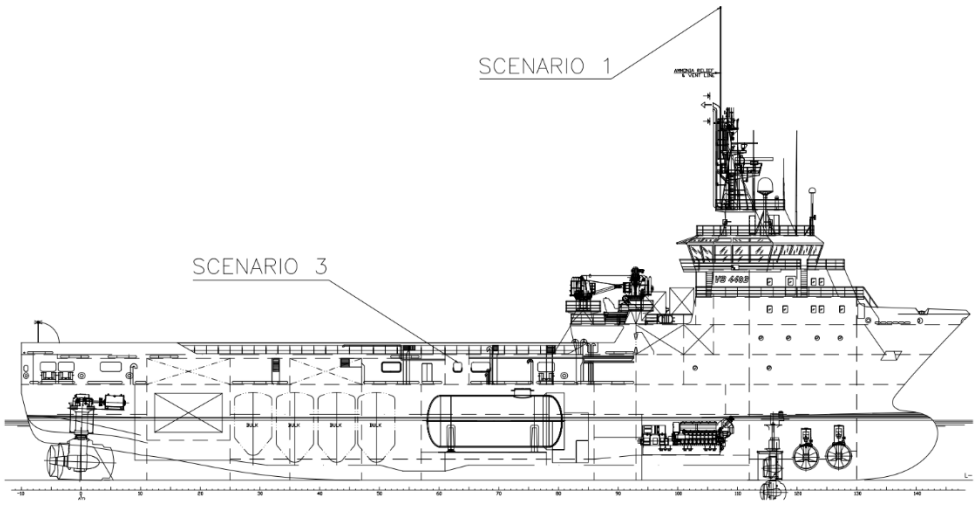


Figure 1: Drawing of Viking Energy showing the outlets for scenarios 1 and 3 (provided by Breeze)

3 SAFETY ASSESSMENT METHODOLOGY

The simulations were performed using the ADREA-HF CFD code [6]. ADREA-HF code is a fully implicit, 3D transient pressure solver, that uses the control volume discretization method and which handles irregular geometry with structured Cartesian grids through the porosity approach.

The code solves the equations of continuity, species transport, momentum and enthalpy for a multi-phase mixture. The mixture is assumed to be ideal and the different phases to share the same pressure, temperature and velocity (HEM approach). A PH-flasher (implementing Raoult's equilibrium phase change approach) is used to obtain phase distribution knowing mixture enthalpy, pressure and mixture components total mass fractions, see [7]. Turbulence is modelled through the standard k-ε model with buoyancy terms included. Standard wall functions are used near solid boundaries.

The external simulations shown herein were performed in three steps: a) First the 1d steady state profile of approaching far field wind flow and turbulence (k and ε) is calculated, such that the velocity magnitude at 10 m matches the preset target value. b) In the second step the 3d steady state wind field over the ship is calculated using the previous 1d profiles (from the first step) as initialization and as boundary conditions at the inflow planes. c) The third step comprises of the 3d NH_3 dispersion calculation, which is initialized from the previous 3d steady state wind calculation and also uses the previous step to provide inflow boundary conditions at the inflow planes.

3.1 Validation against FLADIS-15

During the FLADIS campaign [8] large scale NH_3 release and dispersion experiments were performed in open space and flat terrain. From the performed experiments results of ADREA-HF validation against test FLADIS 15 is shown here. Other CFD validation work against the same test can be found in [9]. The ambient conditions are shown in Table 2. The release was horizontal from a height of 1.5 m, with conditions as shown in Table 3. Given the under-expanded conditions at the nozzle, a fictitious nozzle approach was applied here to model the NH_3 source. The model uses mass, momentum and total enthalpy preservation to bridge the gap between nozzle and fictitious nozzle.

Table 2: FLADIS-15 ambient conditions

Parameter	Value
Average wind speed at 10m (m/s)	5.9
Wind direction relative to ideal (°)	-7
Ambient pressure (mbar)	1019
Ambient temperature (°C)	17
Relative Humidity (%)	60

Table 3: FLADIS-15 Conditions at nozzle and fictitious nozzle

Parameter	Nozzle	Fictitious nozzle
Velocity (m/s)		67.40
Temperature (°C)	18	-33.4
Pressure (bar)	7.7	1.02
Mixture density (kg/m^3)		5.25
Quality of mixture (%)	0.0	16.50
diameter (mm)	6.3	42.88
Void fraction (%)	0.0	99.36
Mass flow rate (kg/s)	0.51	0.51

In order to reproduce the experimentally measured NH_3 mass flow rate history, see Figure 2, the source velocity in the simulations was adapted accordingly with the rest of the conditions in Table 3 kept constant. Figure 3 shows predicted versus experimental NH_3 concentration histories at various distances from the source. The intercomparison is considered to be in reasonable agreement.

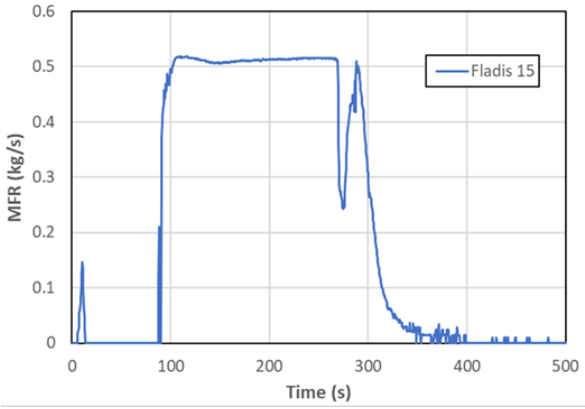
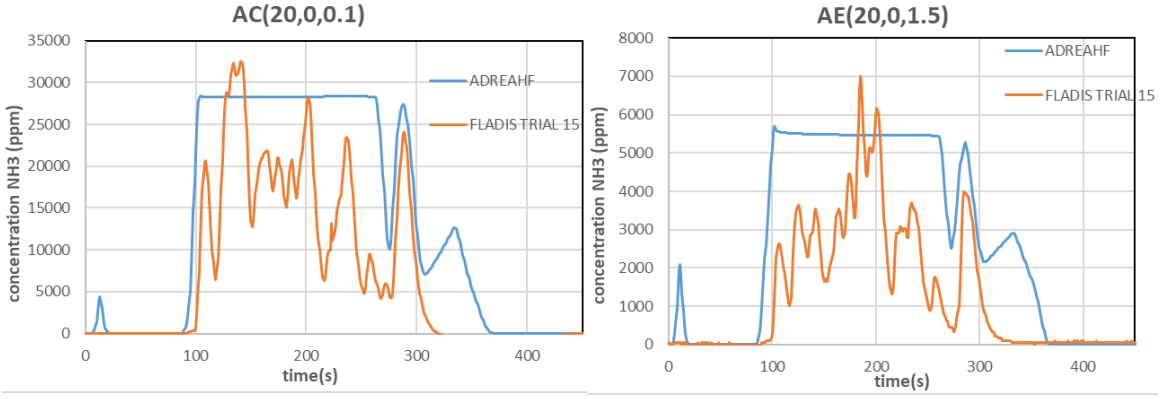


Figure 2: FLADIS-15 Measured experimental mass flow rate history provided as input to the CFD



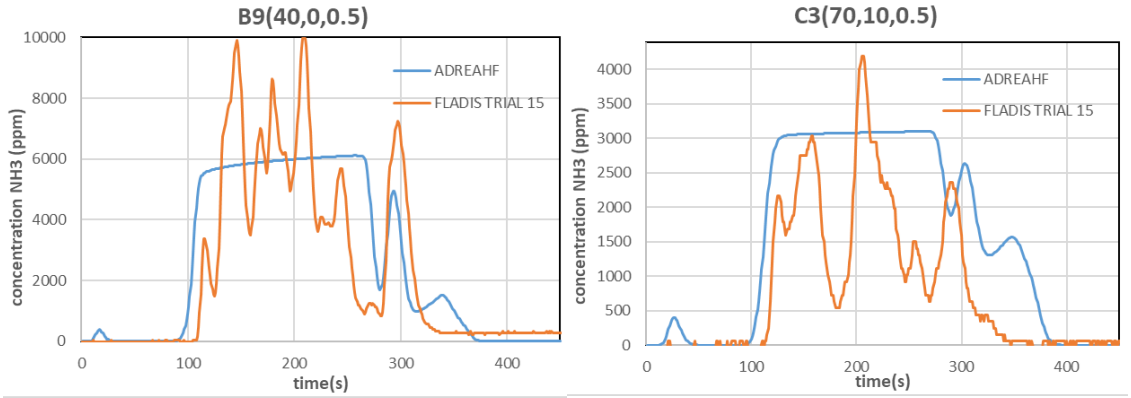


Figure 3. FLADIS-15 Predicted versus experimental NH_3 concentration histories at various distances from the source

3.2 Validation against INERIS test-4

Large scale NH_3 release and dispersion experiments were performed in open space and flat terrain by INERIS [10]. From the performed experiments test-4 is selected here for validation. The experimental conditions are shown in Table 4. It can be observed that the mass flow rate of NH_3 is much larger than in case of the FLADIS experiments.

Table 4: INERIS test-4 Experimental conditions

Nozzle Diameter (mm)	50.8
Mean Discharge (kg/s)	4.2
Test Duration (s)	600
Tank pressure (bar)	5.8
Ambient Temperature (ºC)	12.5
Wind speed at 7m height (m/s)	3.0
Wind angle at 7m height (º)	-6.5
Relative Humidity (%)	82

Figure 4 shows the predicted maximum NH_3 concentration at 1 m height and various distances from the source, compared against the experimental data. The conditions at the nozzle were assumed expanded (ambient pressure). A parametric study was performed regarding the liquid mass fraction at the source. This was determined either through isentropic or isenthalpic expansion from 5.8 bars measured before the nozzle or by selecting some even higher values (cases VF01, VF02) as shown in Table 5 below.

Table 5. Source conditions in the simulations performed for the vapor quality parametric study.

Case	Velocity (m/s)	Density (kg/m^3)	Pressure (Pa)	Temperature (K)	Vapor volume fraction	Liquid mass fraction
Isentropic	302.96	6.83	101325	239.63	0.99124	0.8747
Isenthalpic	328.97	6.29	101325	239.63	0.99203	0.8635
VF01	186.76	14.50	101325	239.63	0.985	0.9231
VF02	142.86	11.09	101325	239.63	0.98	0.9414

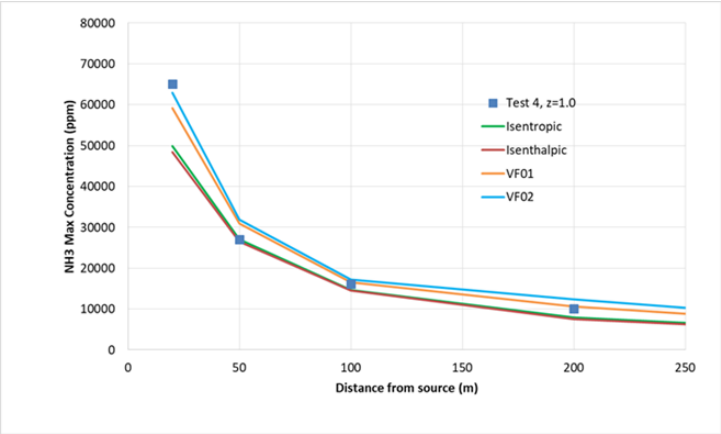


Figure 4. INERIS test-4. Predicted versus experimental NH_3 maximum concentration at 1 m height and at various distances from the source. Effect of release conditions (see Table 5).

4 CFD SIMULATION RESULTS AND DISCUSSION

4.1 Scenario-1

CFD simulations for scenario-1 were performed for various wind speeds and directions. Release conditions were as given in Table 1. Figure 5, Figure 6 and Figure 7 below show the predicted 25 and 300 ppm NH_3 clouds for 2m/s wind and directions 0, 90 and 180 degrees. The shown clouds are in general buoyant and not affected by flow recirculation near the ship. The releases considered in scenario-1 do not lead to any risk of exposure of personnel onboard the ship. The effect of increasing wind speed was found to be a reduction of the size (volume) of the 25 and 300 ppm NH_3 clouds.

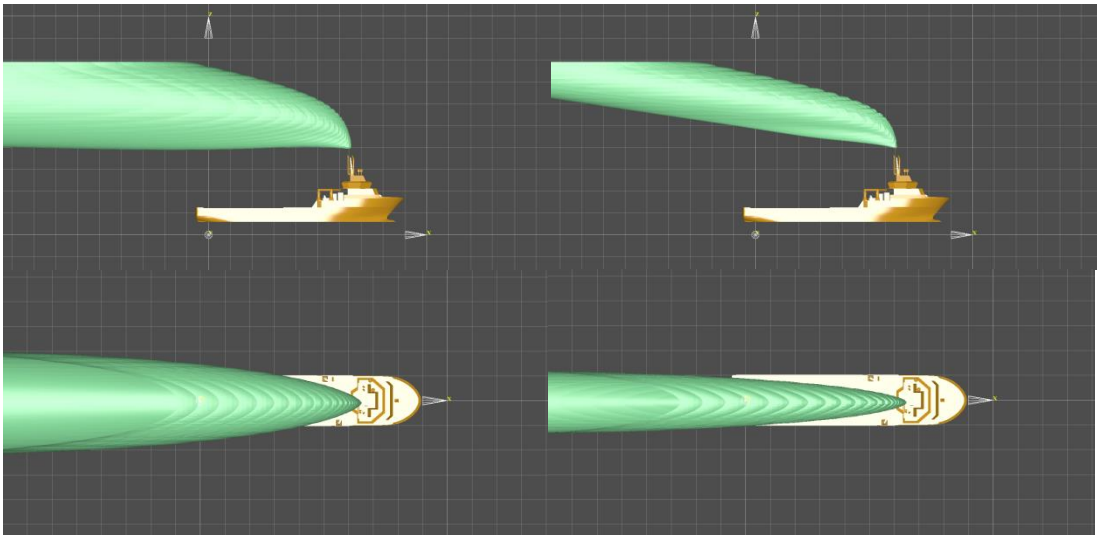


Figure 5. 0°, 2 m/s: 25 ppm (left) and 300 ppm (right) NH_3 isosurfaces. (Graphical grid 10 ×10m)

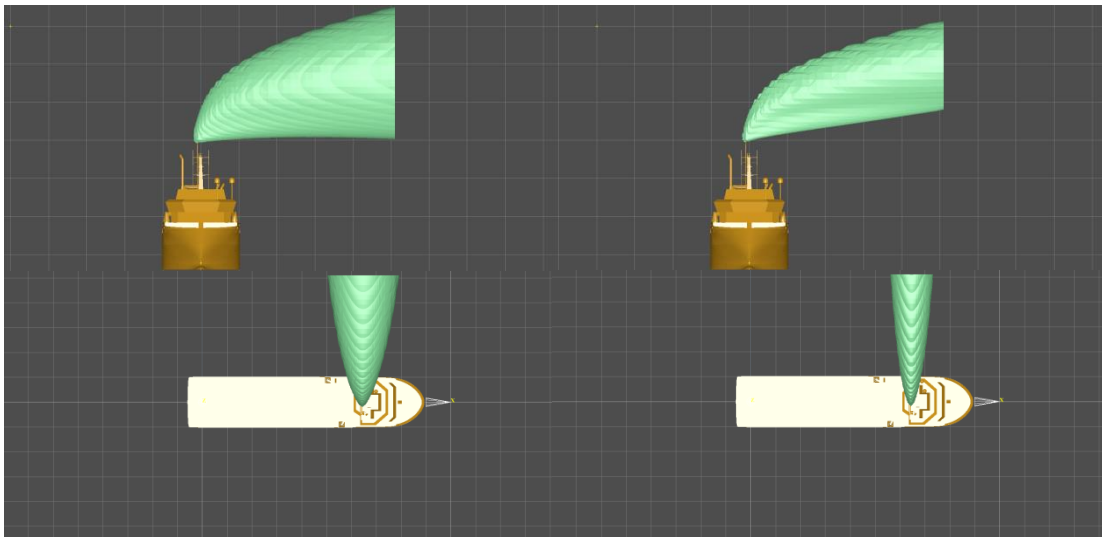


Figure 6. 90°, 2 m/s: 25 ppm (left) and 300 ppm (right) NH_3 isosurfaces. (Graphical grid 10 ×10m)

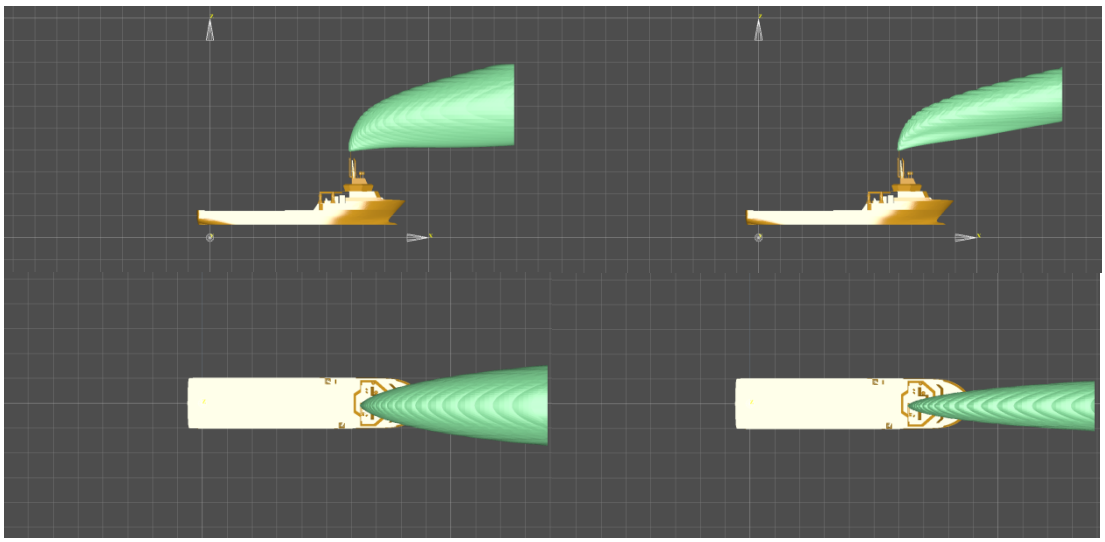


Figure 7. 180°, 2 m/s: 25 ppm (left) and 300 ppm (right) NH_3 isosurfaces. (Graphical grid 10 ×10m)

4.2 Scenario-3

CFD simulations were first performed for the NH_3 release into the BS enclosure space in order to establish the source boundary conditions for the external dispersion problem to be simulated next. The geometry and part of the grid that was used in the internal modelling of the NH_3 leaks is shown in Figure 8. The dimensions of the enclosure in the model are 2.4 m x 1.19 m x 3 m in the X, Y and Z directions respectively. The enclosure dimension in the Y direction was reduced by 15% with respect to the original 1.4 m in order to account for the volume of piping present inside the bunkering station enclosure. Before the release simulation started, the flow inside the ventilated BS enclosure was simulated until a steady state was reached. The release conditions are shown in Table 1.

Simulations were performed for both the 60 and 21 seconds. The 21 s correspond to the case of an automatic emergency shutdown and the 60 s for manual shutdown if the former did not work or not available at bunkering facility. The 60 s were estimated considering that there is permanent presence of an operator.

Figure 9 presents the calculated parameters at the hose opening (space averaged) as function of time for a release period of 21 sec. These were used as boundary conditions for the external CFD problem. It can be observed that long after the end of the release there is two-phase ammonia remaining inside the BS enclosure, which is slowly evaporating.

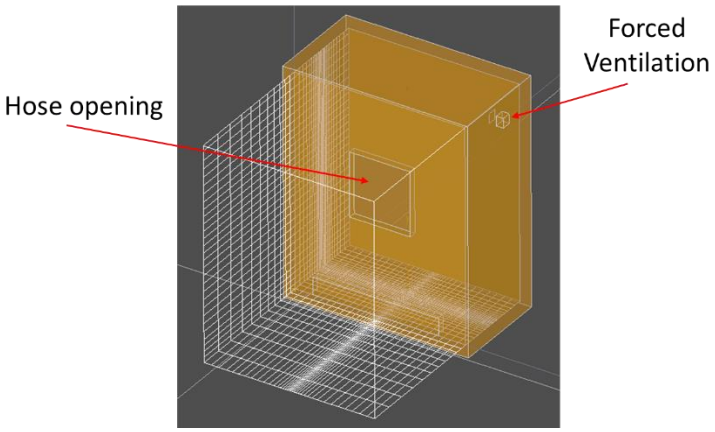


Figure 8. Geometry and grid used in the internal modelling of the NH_3 leak in the bunkering station.

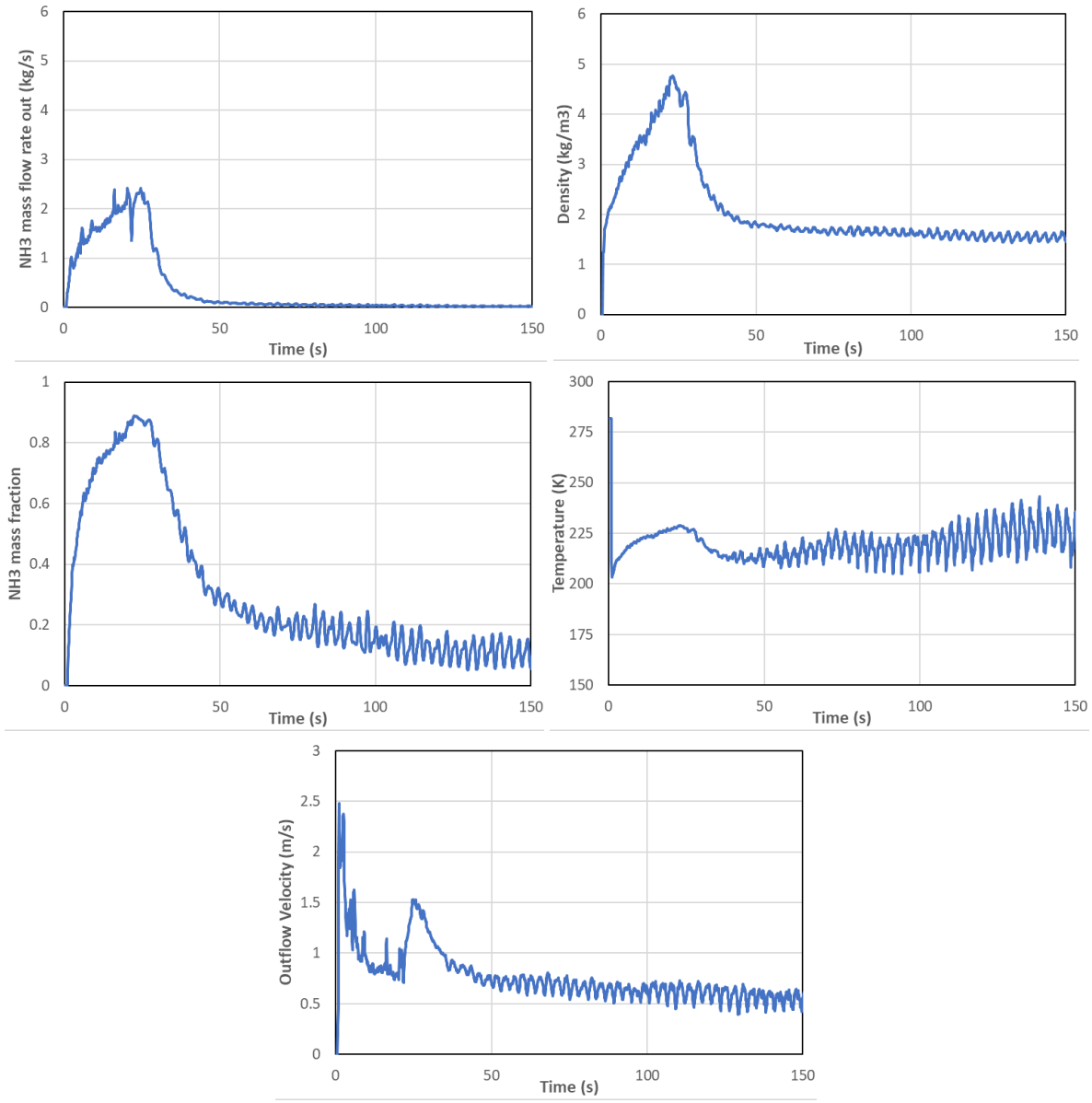


Figure 9. Calculated parameters at the hose opening for a release time of 21 s: NH_3 mass flow rate, density, NH_3 mass fraction, temperature and velocity.

The external simulations included the pier. It is assumed vertically located 2m below the floor of the bunkering station and horizontally approximately 1.8 m from the ship's starboard side, see Figure 10

below. The CFD simulations shown here were performed assuming an ambient wind of 270 degrees, 2 m/s at 10 m height from sea. Figure 11 and Figure 12 show the predicted 300 and 25 ppm NH_3 clouds assuming 21 seconds release time. From the figures one can evaluate the zones affected on the ship as well as an indication of the distances travelled by the respective clouds on the pier. Figure 13 shows the predicted 25 and 300 ppm NH_3 cloud volumes as function of time from start of release. For both concentrations maximum volume values are shown to be reduced by half when the NH_3 release duration is reduced from 60 to 21 seconds. In general scenario-3 was found to be the most critical in terms of consequences.

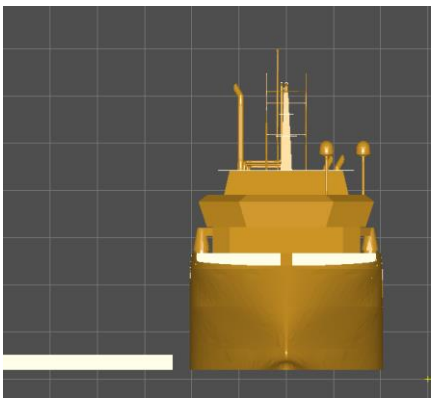
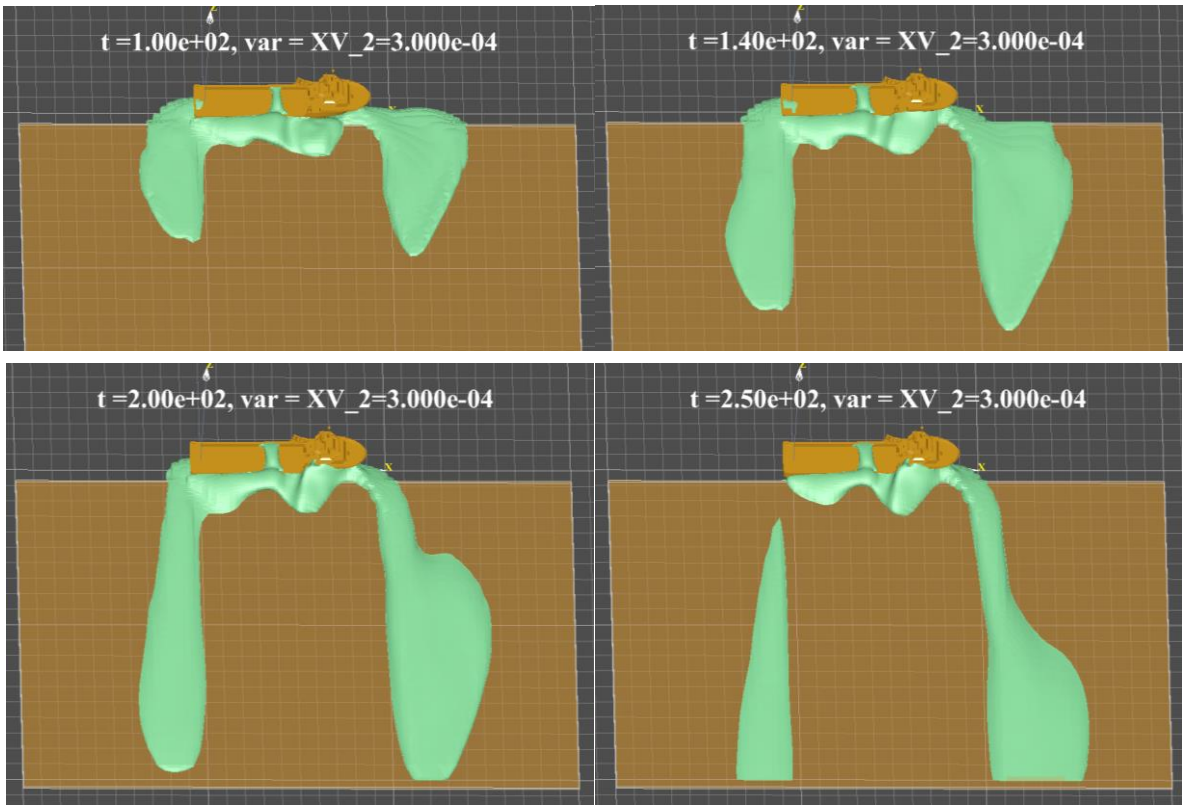


Figure 10. Front view of Viking Energy including the pier (each grid box shown is 5×5 m)



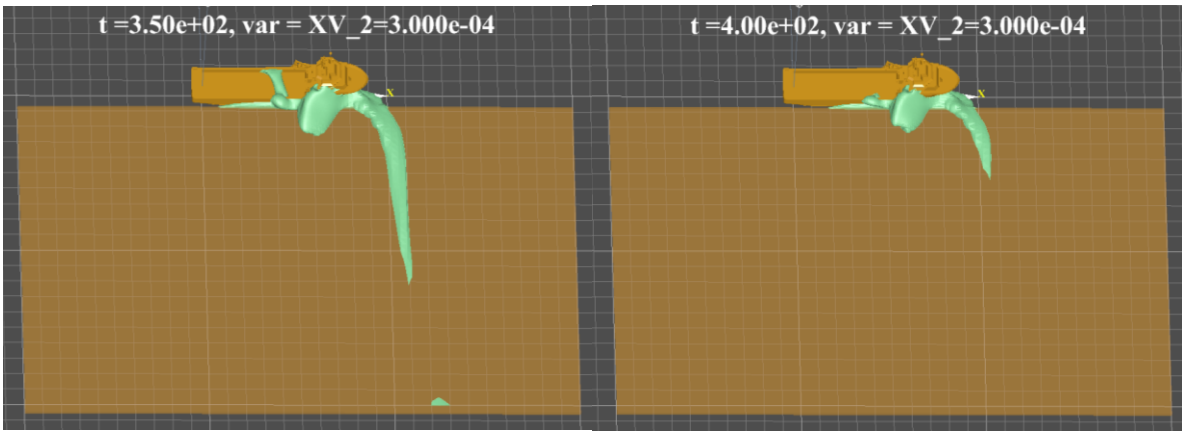


Figure 11. 21 seconds release time, 270 degrees, 2 m/s wind. Predicted 300 ppm NH3 isosurfaces at various times from start of release (each grid box shown is 10×10 m)

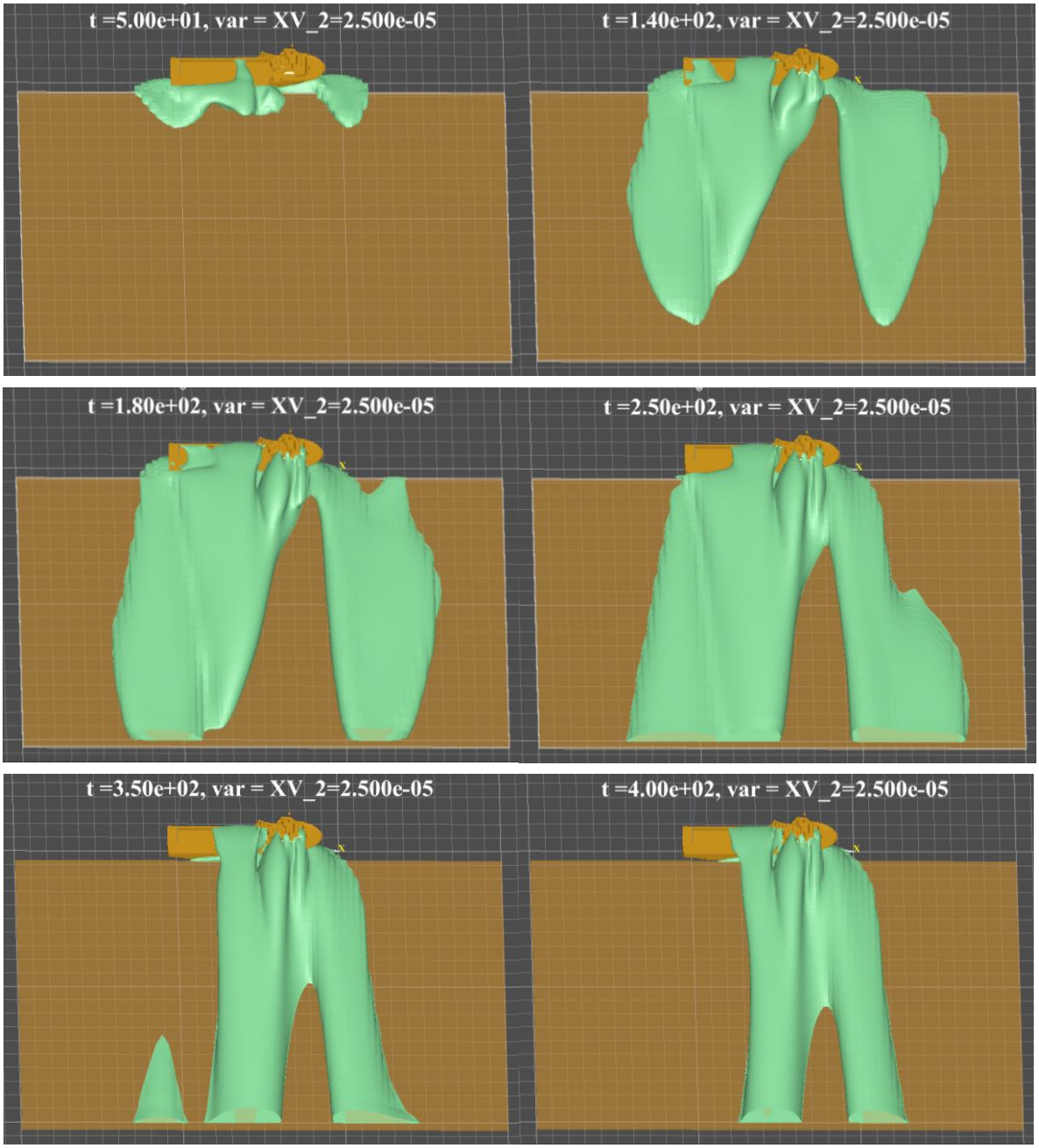


Figure 12. 21 seconds release time, 270 degrees, 2 m/s wind. Predicted 25 ppm NH_3 isosurfaces at various times from start of release

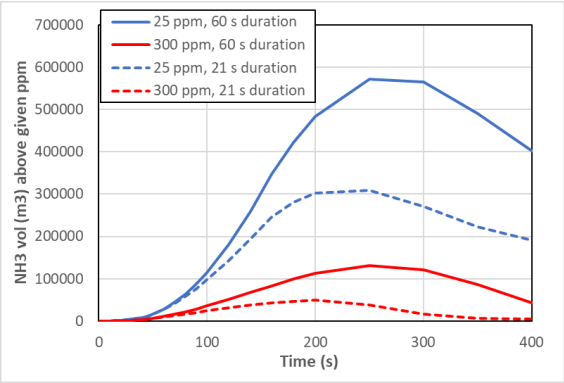


Figure 13. 270 degrees, 2m/s wind. Predicted volume history of 25 ppm and 300 ppm NH_3 clouds. Effect of NH_3 release duration (21 or 60 seconds).

5 CONCLUSIONS

A CFD consequence assessment study was preformed for an NH_3 fueled ship, using the ADREA-HF CFD code.

Validation of the ADREA-HF code against the FLADIS-15 and the INERIS-4 NH_3 large scale release experiments was first performed and the results were found to be in reasonable agreement with the experiments.

From the accidental scenarios identified in the HAZID exercise, two scenarios were addressed in this contribution: Scenario-1 including release from the vent mast of the ship due to fire in the tank holding space and Scenario-3 involving release inside the bunkering station enclosure and subsequent release out of the ship through the hose opening.

- Scenario-1 was found to not expose any area of the ship to ammonia for all wind speeds and directions considered. The higher the wind speed the smaller the 25 and 300 ppm clouds were found.

- Scenario-3 was found to be the most critical in terms of consequences. It was shown that the consequences of the release/exposure of ship and surroundings will be significantly reduced if the duration of the release time can be reduced.

6 ACKNOWLEDGEMENTS

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