Dispersion Modelling for Explosion Risk Analysis

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The understanding of the explosion hazards on fixed and floating offshore facilities is required to be able to demonstrate that risks are ALARP (As Low As Reasonably Practicable). It is becoming increasingly common to adopt a risk based approach whereby overpressures are calculated across a range of frequencies. Such an approach is typically referred to as an Explosion Risk Analysis (ERA).

In order to understand the explosion hazards, one of the key aspects is to calculate the range of potential gas cloud sizes that can arise from an accidental release from the different inventories present. This is achieved by conducting dispersion analysis using either empirical or CFD (Computational Fluid Dynamics) methods which are not well validated.

The scope of this paper is as follows;

- Validate the use of CFD for calculating cloud sizes by comparing the results with experimental data.
- Validate the Frozen Cloud concept.

Keywords: Explosion Risk Analysis, CFD, Frozen Cloud, Dispersion

1.0 Introduction

The understanding of the explosion hazards on fixed and floating offshore facilities is paramount to ensure that the risks are ALARP (As Low As Reasonably Practicable). It is becoming increasingly common that in order to understand the explosion hazards a risk based approach is taken whereby overpressures are calculated across a range of frequencies; this is typically referred to as an Explosion Risk Analysis (ERA).

In order to understand the explosion hazards one of the key aspects is to calculate the range of potential gas cloud sizes that can arise from an accidental release from the inventories on a facility. This is achieved by conducting dispersion analysis using either empirical or CFD (Computational Fluid Dynamics) methods. CFD techniques are becoming common practice in a wide range of industries to solve complex engineering problems. CFD is used extensively in process safety to calculate hazard ranges for flammable and toxic materials, heat flux levels for fires, explosion overpressures and for calculating cloud sizes and ventilation rates.

The first objective of this paper is to validate the use of CFD for dispersion modelling in ERA by comparing CFD results to the data available from the Joint industry Project (JIP) titled Gas Build up from High Pressure Natural Gas Releases in Naturally Ventilated Offshore Module (Shell Global Solutions and BG Technology 1999). This validation is performed using the CFD code FLACS as it is designed specifically for use in the oil and gas industry and despite initially being tailored to modelling explosions has now been extended to consider ventilation and dispersion. FLACS is a well-established CFD code that has been used extensively in support of Safety Cases, and has been the subject of several critiques by the Health & Safety Laboratory (Ledin 2002, Gant et al 2010). Previous work has compared FLACS to the same JIP experimental data (Savvides et al 2001) but this did not present detailed result or information on grid sensitivities. This was raised in a critique of FLACS (Gant et al 2010) and is addressed as part of this work.

The dispersion analysis can potentially be the most time consuming and costly part of the analysis because in order to understand the full range of potential cloud sizes calculations have to be performed considering variations across the following parameters:

- Release Rate;
- Release direction;
- Release location;
- Wind speed and direction.

It is not practical to consider all permutations of these parameters as this leads to an impractical number of simulations. Methodologies have been developed to reduce the permutations that are analysed with CFD, and where possible to develop correlations to interpolate between known points. The Frozen Cloud concept is one such methodology that is employed but limited information is available on its validation or applicability (acknowledged by the HSE at http://www.hse.gov.uk/offshore/strategy/disperse.htm). Therefore the second objective of this paper is to assess the validity the Frozen Cloud concept and the results of JIP experiments have been used as a basis for the validation.

2.0 1999 JIP Experimental Set-Up

The experimental results considered are those associated with the JIP titled Gas Build up from High Pressure Natural Gas Releases in Naturally Ventilated Offshore Module (Shell Global Solutions and BG Technology 1999). This work considered a number of gas releases based on varying the following parameters:

- Release rate;
- Release location and direction;

  Three different release locations were used in the experiments. Release location 1 and 2 were on the ground floor and release location 2 was on the mezzanine deck.
- Wind speed;
- Wind direction;

  For configuration A and B the prevailing wind directions were from the east and west respectively and for configuration C it was from the west. The wind direction is reported in degrees with zero being a wind from the east (see Figure 1 for orientation of north)
- Geometric configuration (A, B and C);

The geometric configurations that are referred to above (A, B and C) correspond to different configurations of the walls as described below.

- Configuration A had walls to the north and south;
- Configuration B had walls to the north and south with partial blockage to the east and west;
- Configuration C had walls to the south and west that effectively made an L.

The configurations are illustrated in Figure 1.

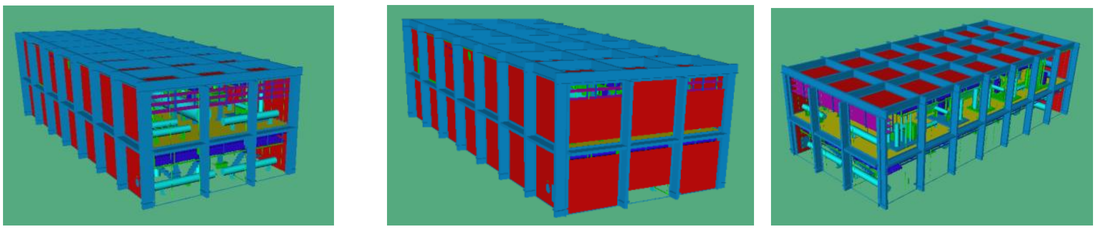

Figure 1. Geometric Configurations A, B and C

Experiments were carried out for the three configurations; 32 for A, 14 for B and 18 for C. This work only considers configurations A and C. For each of the experiments the concentration was recorded at 192 positions across 4 elevations as illustrated in Figure 2.

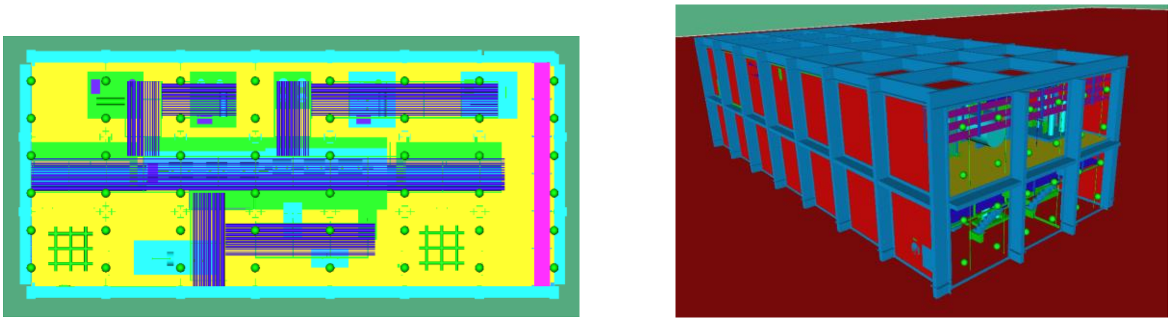

Figure 2. Monitor Locations

In the 1999 JIP the volume concentration at each of the 192 points was recorded. For each experiment this work tabulated the data and converted into volume fill data (in m^3) by assuming that each monitor point corresponded to a volume equal to the spacing between the points. The volume reported is based on concentrations greater than 5% (referred to as Above Lower Flammable Limit (ALFL) here after) and between 5% and 15% (referred to as between Lower and Upper Flammable Limits (LFL-UFL)); these values are chosen as 5% and 15% to correspond to the lower and upper flammable limits for methane which is the main component of gaseous process streams seen in the oil and gas industry.

3.0 CFD Set-Up

CFD solves equations for mass, momentum, heat transfer and turbulence which are collectively known as the Navier-Stokes equations. In order to solve the Navier-Stokes equations it is necessary to model rather than resolve the turbulence as the time scales and length scales associated with solving it explicitly are prohibitive for industrial applications and are only possible using Direct Numerical Simulation (DNS). FLACS models turbulence using the k-ε model. This is a type of 'eddy viscosity model', in which turbulence is considered as small eddies that are continuously forming and dissipating on smaller and smaller orders of magnitude. The model is defined by two equations that define respectively the turbulent kinetic energy, k, and the rate of dissipation of this energy, ε. This type of model is commonly used in industry as it offers a good compromise between numerical efficiency and computational accuracy. The equations are solved within a 3D domain which comprises a large number of control volumes, or cells. Within this domain is a representation of the 3D geometry of interest and large geometric objects are directly resolved into the computational grid, whereas sub grid-scale objects are modelled as a source of turbulence and drag.

A number of CFD dispersion calculations have been performed and the calculated cloud sizes compared against the experimental data to validate its use. When conducting CFD analysis it is best practice to run a grid sensitivity with different sized control volumes to check that a grid independent solution is being obtained; this was done considering grid sizes of 0.25m, 0.5m and 1m respectively. The initial grid sensitivity study was conducted for experiment A12 and based on the results an additional 5 experiments were simulated for configuration A and 2 for C. The scenarios were chosen to capture a range of the different parameters studied (e.g. release position, release orientation, mass flow rate, wind speed and direction). Details of the scenarios simulated are given in Table 1.

Test Number	Release Position	Release Orientation	Measured Mass Flow Rate (kg/s)	Wind Speed (m/s)	Wind Direction
A02	R2	west	8.67	6.4	24
A30	R1	east	5.05	3.2	176
A15	R2	Down	9.08	4.3	3
A12	R1	V.Up	5.13	2.1	2
A31	R1	east	0.99	3.4	183
A27	R3	south	1.01	2.95	181
C12	R2	south	5	3.4	171
C17	R3	east	9.03	8.6	175

Table 1. Dispersion Validation Cases

4.0 CFD Dispersion Results

4.1 CFD Configuration A

Figure 3 shows the results of the grid sensitivity conducted for A12. This shows there is limited variance between the results for the different grids with the closest match to the experimental data being seen for the 0.25m grid. Based on the results in Figure 3 it was considered that the incremental benefit of using a 0.25m grid was not worth the computational expense therefore the 0.5m grid was used for all subsequent simulations.

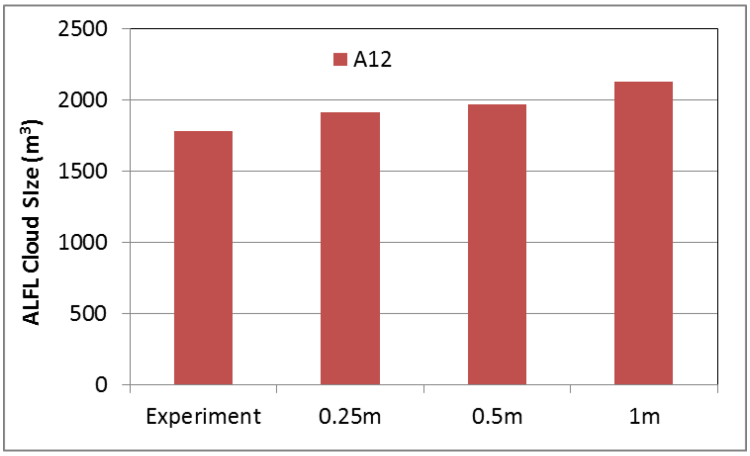

Figure 3. A12 Grid Sensitivity

Figure 4 and Table 2 present the dispersion validation results for configuration A and Figure 5 to Figure 9 present a visual comparison between the experimental and CFD cloud sizes. No error bars are given in the experimental report therefore lines showing +/- a factor of 1.5 on measured volumes are presented as reasonable error bounds.

The results show there is a good correlation both in terms of the size and location of the clouds. The exceptions are experiments A30 and A31 where the cloud size is over predicted. For both of these experiments the release immediately impinged on a vessel and Figure 6 and Figure 9 show that for the experiments the cloud was confined to the lower levels of the module whereas for the CFD results the release is directed both above and below the vessel as the release impinges in the centre and is deflected. The experimental report gives the coordinates of the release but there is conflicting information given on the height of the vessel; if the vessel was actually higher than that modelled in the CFD it is expected that this would explain the discrepancies in the results. It is noted that only slight variations in release height / direction in this scenario could result in significant differences to experimental results.

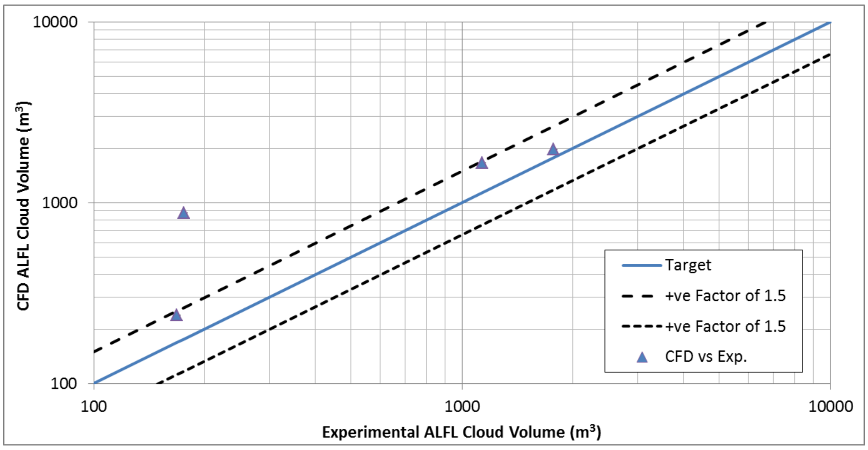

Figure 4. Configuration A Dispersion Validation Results

	CFD ALFL Cloud Size (m^3)	Experimental ALFL Cloud Size (m^3)
A02	240	152
A30	880	176
A15	1656	1088
A12	1968	1776
A31	96	0
A27	0	0

Table 2. Configuration A Dispersion Validation Results

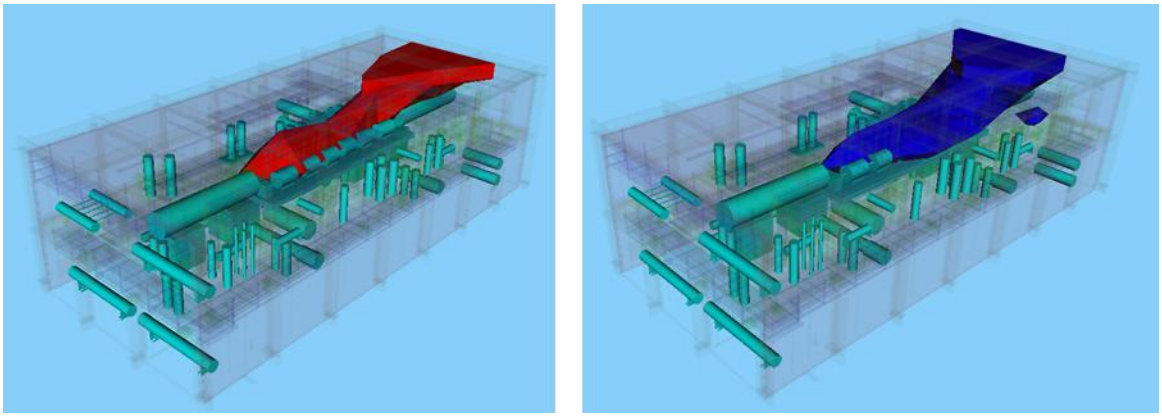

Figure 5. A02 – Experiment on the Left (Red), CFD on the Right (Blue)

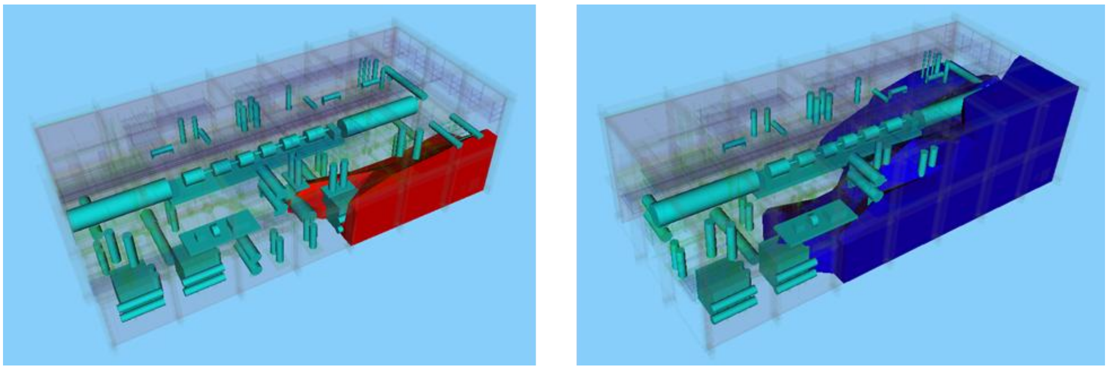

Figure 6. A30 – Experiment on the Left (Red), CFD on the Right (Blue)

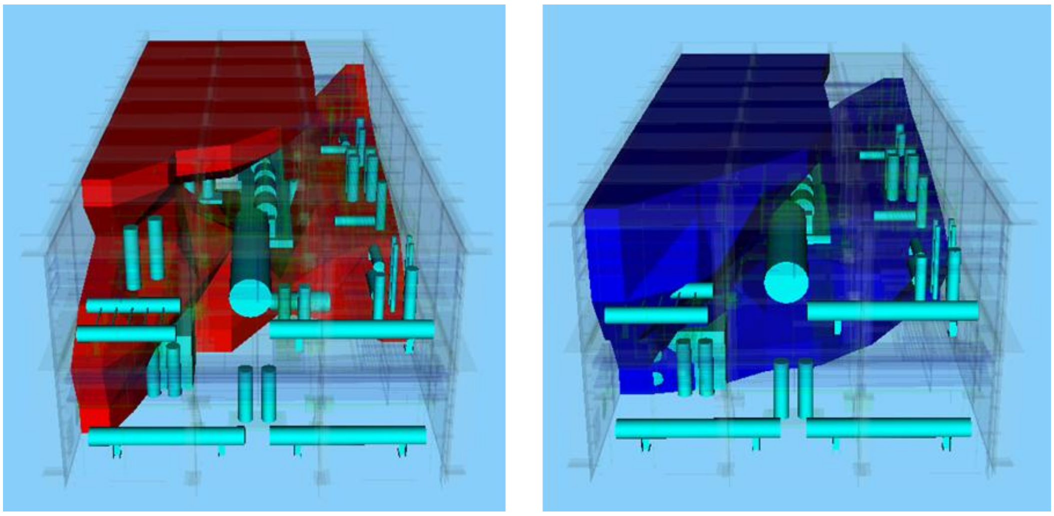

Figure 7. A15– Experiment on the Left (Red), CFD on the Right (Blue)

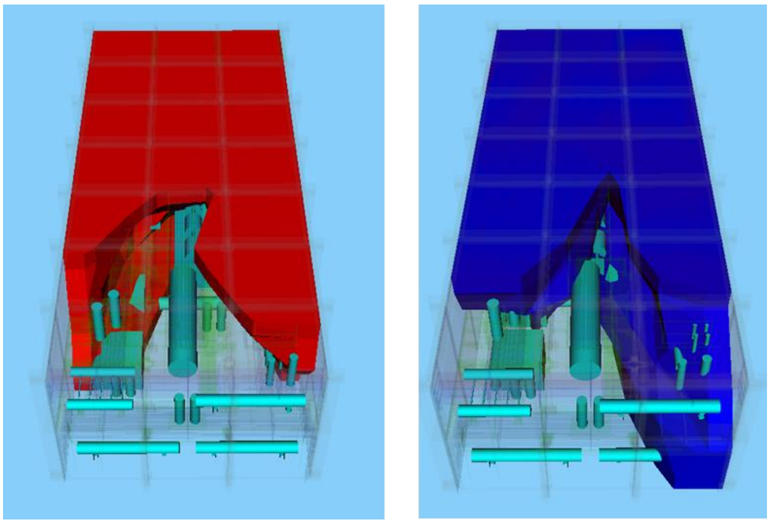

Figure 8. A12– Experiment on the Left (Red), CFD on the Right (Blue)

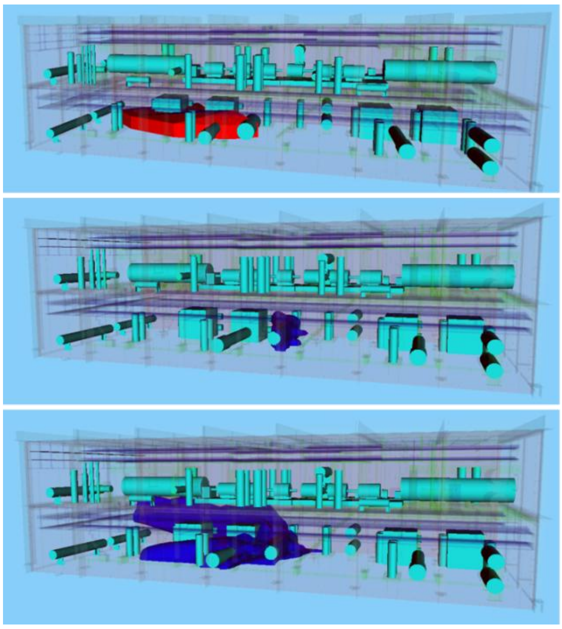

Figure 9. A31 – Experimental Results in Red and CFD in Blue

4.2 CFD Configuration C

Figure 10 and Table 3 present the dispersion validation results for configuration C and Figure 11 to Figure 14 present a visual comparison between the experimental and CFD cloud sizes. There is good agreement for C12 but the cloud size for C17 is under predicted by a factor of approximately 4. To understand how the gas cloud forms for C17 in the CFD analysis, Figure 13 shows a 2D cut plane of velocity vectors through the release location; this shows that although the release is directed out of the module the flow pattern set up by the interaction with the wind and geometry act to blow gas back in the opposite direction to the release. A sensitivity analysis was run where the upper bound wind speed (based on the experimental error reported) was used and the region to the north and west of the module was resolved with more grid cells to see if this lead to more gas being blown back into the module. The results are shown in Figure 14. Although there is still a significant discrepancy between the experimental result and the CFD the cloud size has increased from 560m^3 to 792m^3 using the higher wind speed and grid resolution but is still a factor of 3 below the experiments. Consequently further interrogation of the results was carried out and the impact of concentration of the cloud volume was investigated. This showed that when a volume of 4% was used the experimental and CFD cloud sizes were 2096m^3 and 1888m^3 respectively. These results are much more comparable and show that in the experimental work there were large portions of the module just below 5% and hence presents a possible explanation of the discrepancy between the results. This highlights how sensitive the cited cloud size can be to the value of LFL chosen and suggests that a sensitivity study on cloud sizes should be conducted with a lower value of LFL to understand the impact on the results.

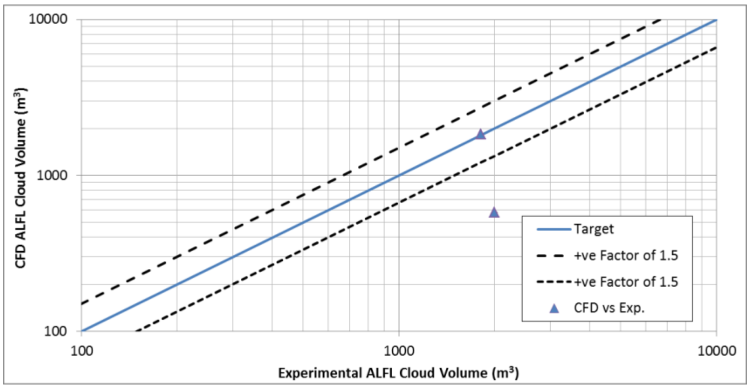

Figure 10. Configuration C Dispersion Validation Results

	CFD ALFL Cloud Size (m^3)	Experimental ALFL Cloud Size (m^3)
C12	1840	1816
C17	576	2000

Table 3. Configuration C Dispersion Validation Results

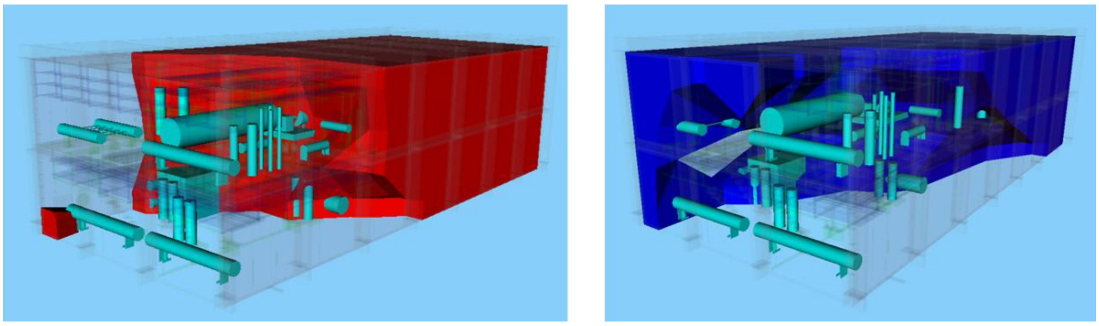

Figure 11. C12 – Experimental Results in Red and CFD in Blue (ALFL)

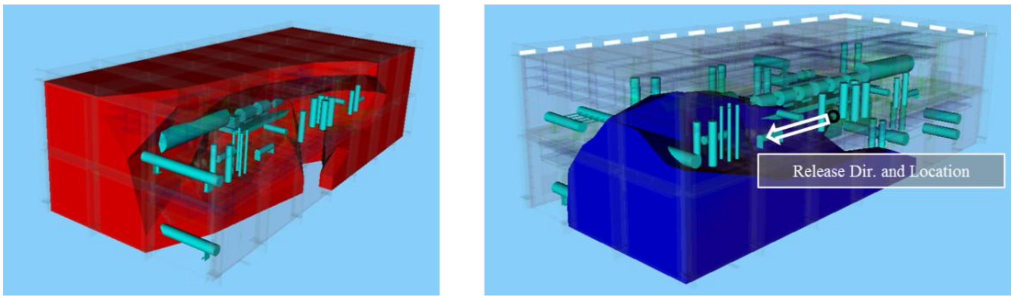

Figure 12. C17 – Experimental Results in Red and CFD in Blue (ALFL)

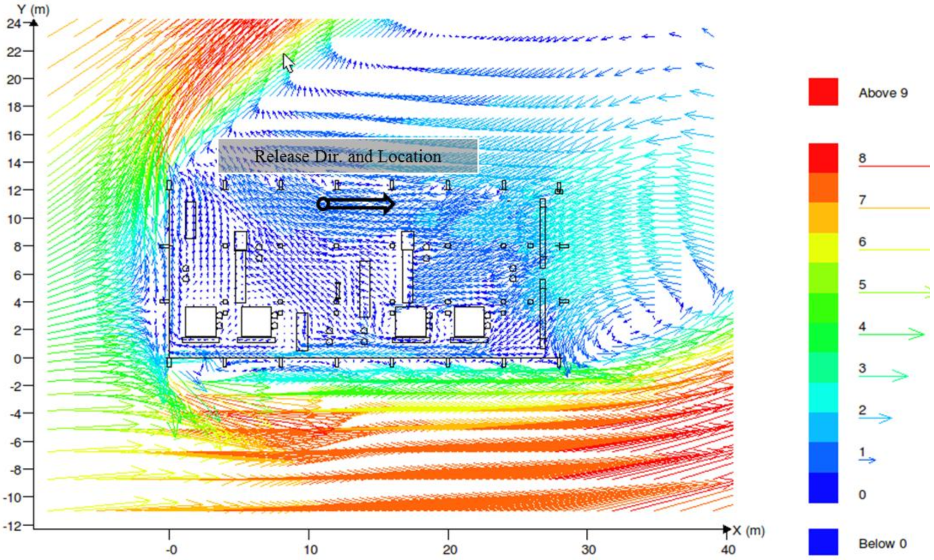

Figure 13. C17 – Velocity Vectors

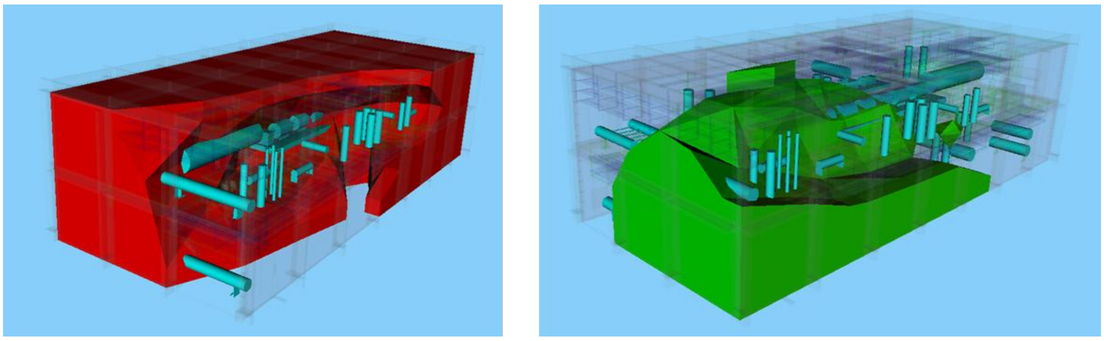

Figure 14. C17 – Experimental Results in Red and CFD in Green using 10.5m/s Wind and Refined Grid in Wake of the Module (ALFL)

5.0 Frozen Cloud Concept

The Frozen Cloud concept is based on the assumption that the concentration at any point is proportional to the mass flow rate divided by the ventilation rate. Therefore, assuming that all other parameters remain the same (e.g. release location, wind direction, release direction) the results of a case with a given mass flow rate and ventilation rate can be used to calculate concentrations at points, and therefore cloud sizes, at other mass flow rates and ventilation rates. In simple terms the Frozen Cloud concept would assert that if the mass flow rate doubled and the ventilation doubled then the concentration and hence cloud size would remain the same. If this method is valid, it can be used to significantly reduce the number of CFD dispersion analyses required for performing an ERA. There is limited data and guidance available in literature on the applicability of the Frozen Cloud concept with the only guidance being that extrapolation from known results should limit the Mix Factor (Equation 1) to between 0.5 and 2 (Gexcon 2013). The Mix Factor is defined as follows:

$$Mix\ Factor = {}^{m_1 V_2}\!/_{m_2 V_1} \qquad \{1\}$$

Where:

m_1 m_2 Mass flow rate for scenario 1 and 2

V_1 V_2 Ventilation rate for scenario 1 and 2

In order to validate the Frozen Cloud concept, and assess the extents to which results can be used for extrapolation, experiments with similar parameters (e.g. release location, wind direction, release direction) have been grouped together. For Configuration A the following groups of experiments have been investigated:

- Case 1: westerly release, location 1, wind from the east (3 experiments, A25, A24, A22);
- Case 2: easterly release, location 1, wind from the west (2 experiments, A31, A30);
- Case 3: easterly release, location 1, wind from the east (6 experiments, A06, A21, A20, A05, A19, A04);
- Case 4: Upward release, location 1, wind from the west (3 experiments, A34, A33, A32);
- Case 5: Upward release, location 1, wind from the east (6 experiments, A18, A13, A17, A16, A12, A11);
- Case 6: Westerly release, location 2, wind from the east (3 experiments, A01, A02, A03);
- Case 7; Southerly release, location 3, wind from the east (3 experiments, A09, A08, A07).

For Configuration C the following groups have been investigated:

- Case 8: easterly release, location 1, wind from the west (3 experiments, C07, C06, C05);
- Case 9: Upwards release, location 1 wind from the west (2 experiments, C10, C15);
- Case 10: southerly release, location 2, wind from the west (5 experiments, C13, C09, C12, C08, C14);
- Case 11: westerly release, location 2, wind from the west (3 experiments, C03, C02, C04);
- Case 12: easterly release, location 3, wind from the west (2 experiments, C18, C17).

For each case the results for each experiment have been used to calculate the cloud size for other experiments in that group based on the Frozen Cloud concept.

5.1 Frozen Cloud Results

For each case (i.e. grouped set of experiments) the experimental cloud sizes are plotted against the ratio of mass flow rate to ventilation rate; this is shown as the blue line on the top graph of Figure 15. On the same graph the cloud sizes calculated using the Frozen Cloud concept are also plotted in red; for a given experiment these are calculated based on the results of the other experiments for that case (i.e. there will be n-1 points per experiment, where n is the total number of experiments grouped together in a given case). The cloud sizes from the Frozen Cloud concept are calculated from the Mix Factor for each experiment. To give an appreciation of how results vary with Mix Factor for each experiment, graphs are also plotted showing Mix Factor on the x-axis and cloud size on the y-axis. The experimental results are shown in red and the cloud sizes calculated using the Frozen Cloud concept in blue; these are the bottom two graphs in Figure 15.

5.1.1 Frozen Cloud Configuration A

The results from the cases of most interest for Configuration A are shown in Figure 15 to Figure 18. For Configuration A cases 1 and 6 both show reasonable agreement between the experimental data and Frozen Cloud calculations with only one case being poorly predicted (Experiment A02). This is despite some cases having a Mix Factor outside the recommended range of 0.5 to 2. In addition for all the experiments at least one of the data points is calculated to be larger than the experimental data; therefore based on the assumption that, if conducting an ERA and using the Frozen Cloud concept that the largest value would be used, then the results would be conservative. Cases 3 and 5 show a much greater variation in the cloud sizes calculated using the Frozen Cloud concept. This is to be expected to a certain extent due to the greater range of

Mix Factors as the dataset is larger but the range of results calculated still show the degree of variance associated with this method. The results for case 5 show a clear trend where by as the Mix Factor approaches 1 the predictions tend to improve. For case 3 this is not the case and for some experiments it can be seen that Mix Factors outside the recommended range (0.5 to 2) sometimes produce better predictions.

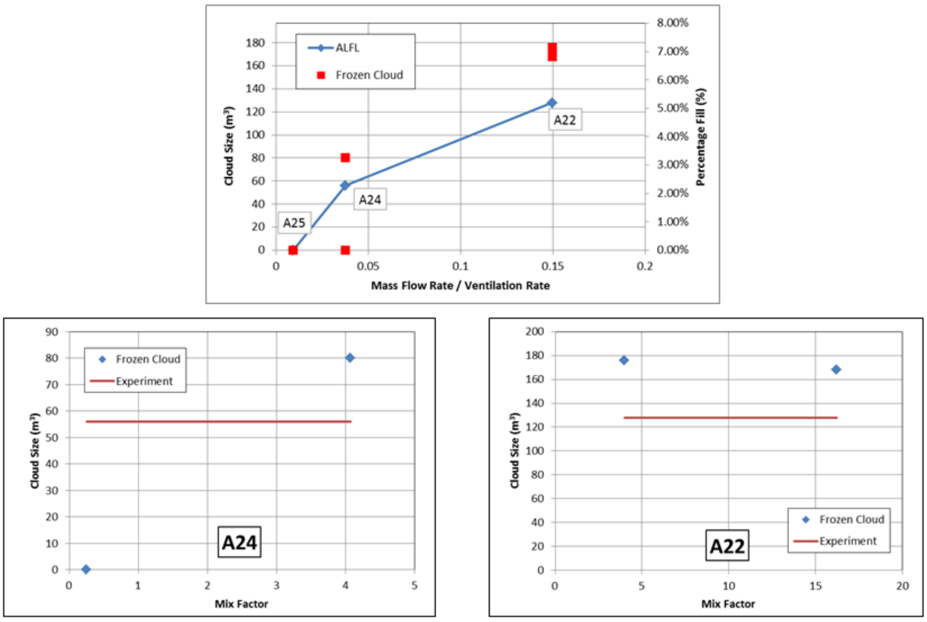

Figure 15. Configuration A – Case 1 (westerly release, location 1, wind from the east)

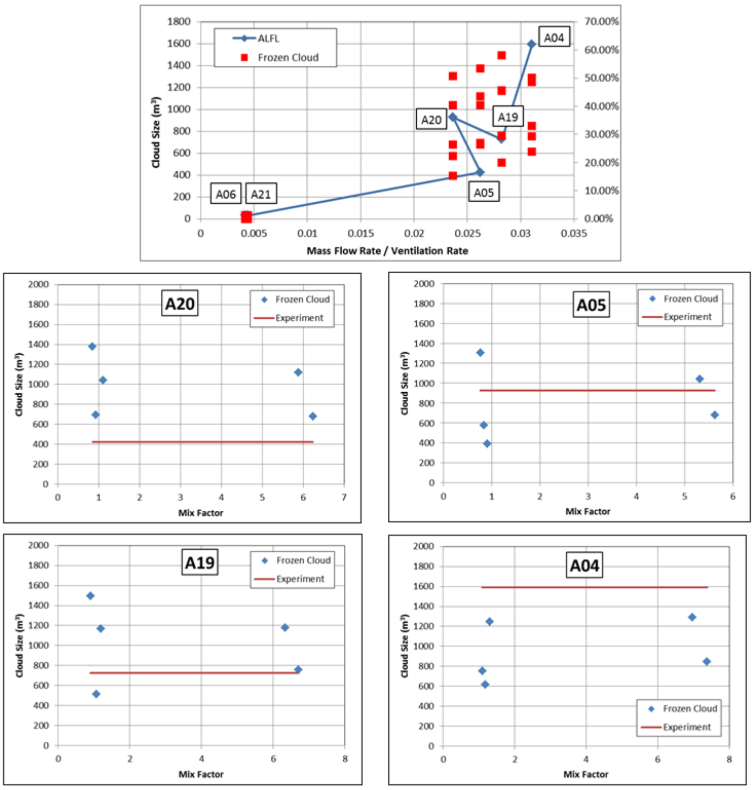

Figure 16. Configuration A – Case 3 (easterly release, location 1, wind from the east)

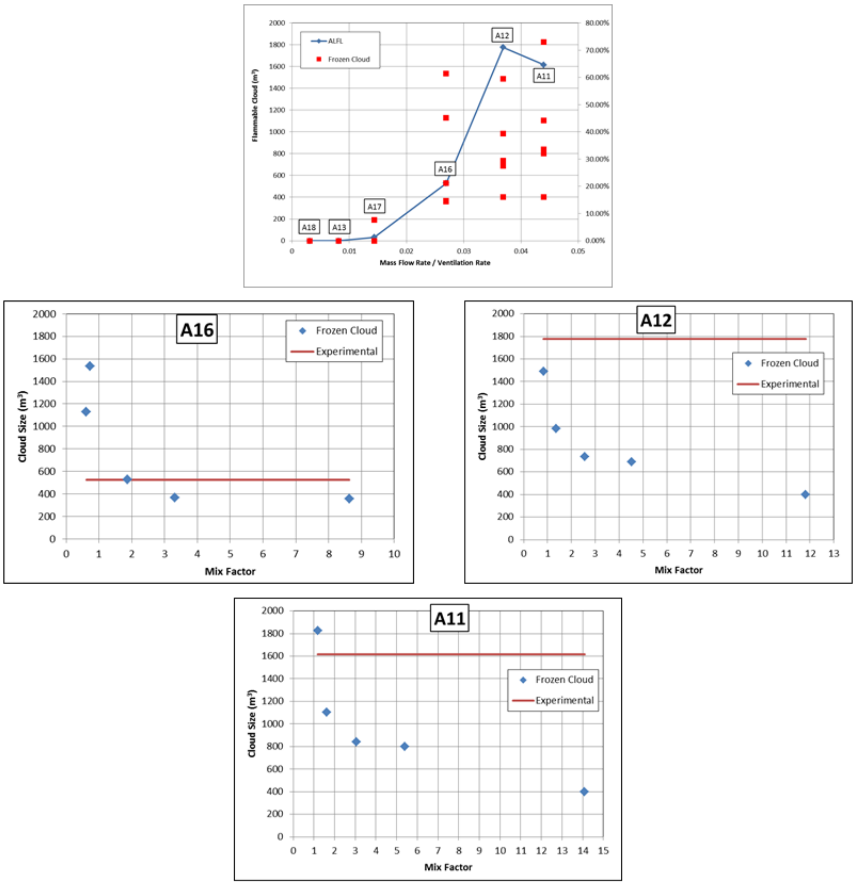

Figure 17. Configuration A – Case 5 (Upward release, location 1, wind from the west)

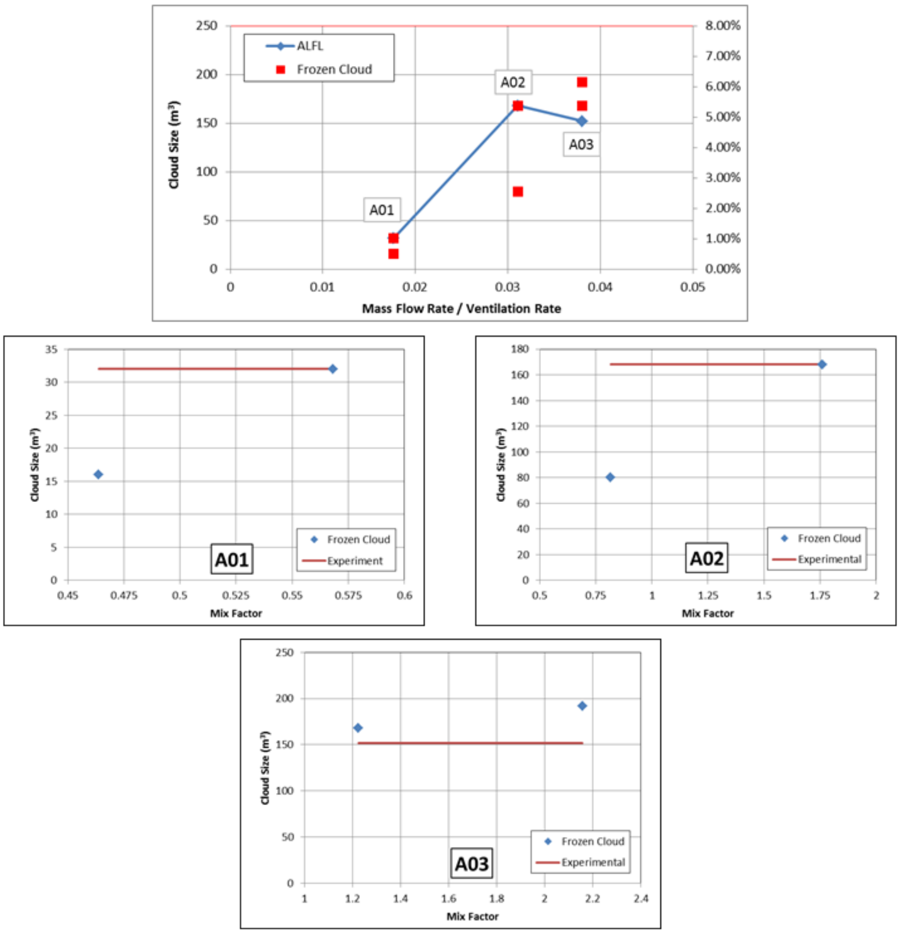

Figure 18. Configuration A – Case 6 (Westerly release, location 2, wind from the east)

5.1.2 Configuration C

The results from the cases of most interest for Configuration A are shown in Figure 19 and Figure 20. For Configuration C, case 10 shows the best agreement of any of the cases studied with a similar trend to case 5 with Mix Factors closer to 1 tending to give better predictions. Case 11 does not predict the experimental values as accurately and, like with case 3, in some instances Mix Factors outside the recommended range give better prediction.

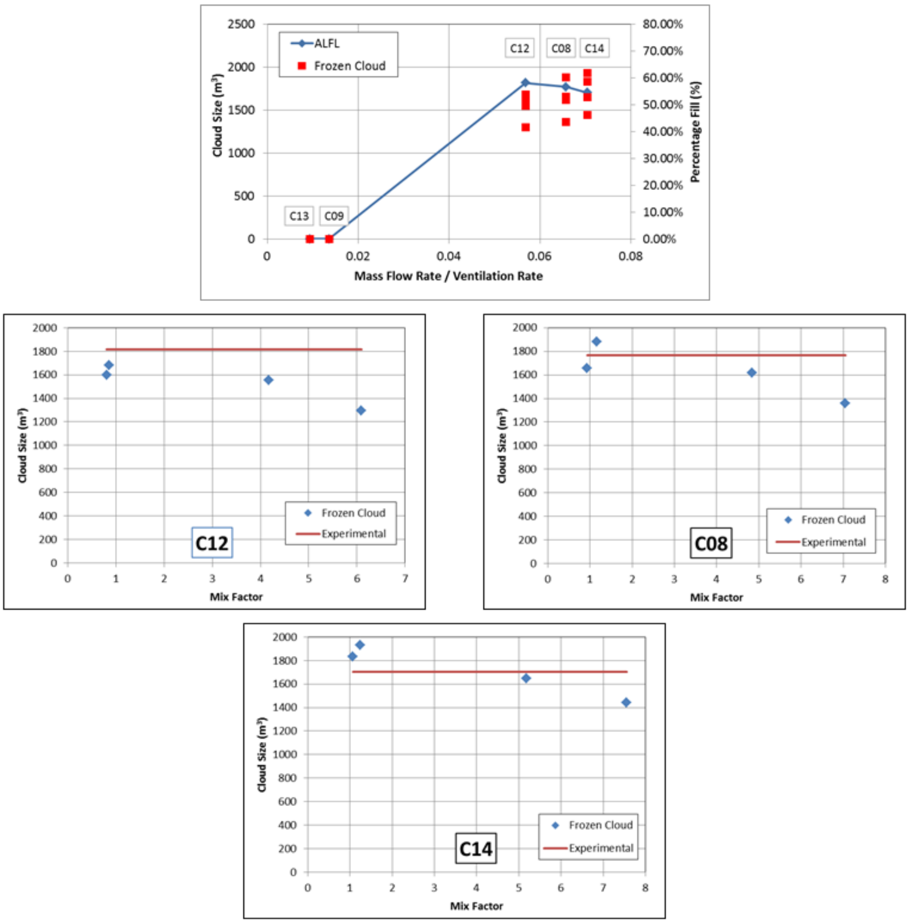

Figure 19. Configuration C – Case 10 (southerly release, location 2, wind from the west)

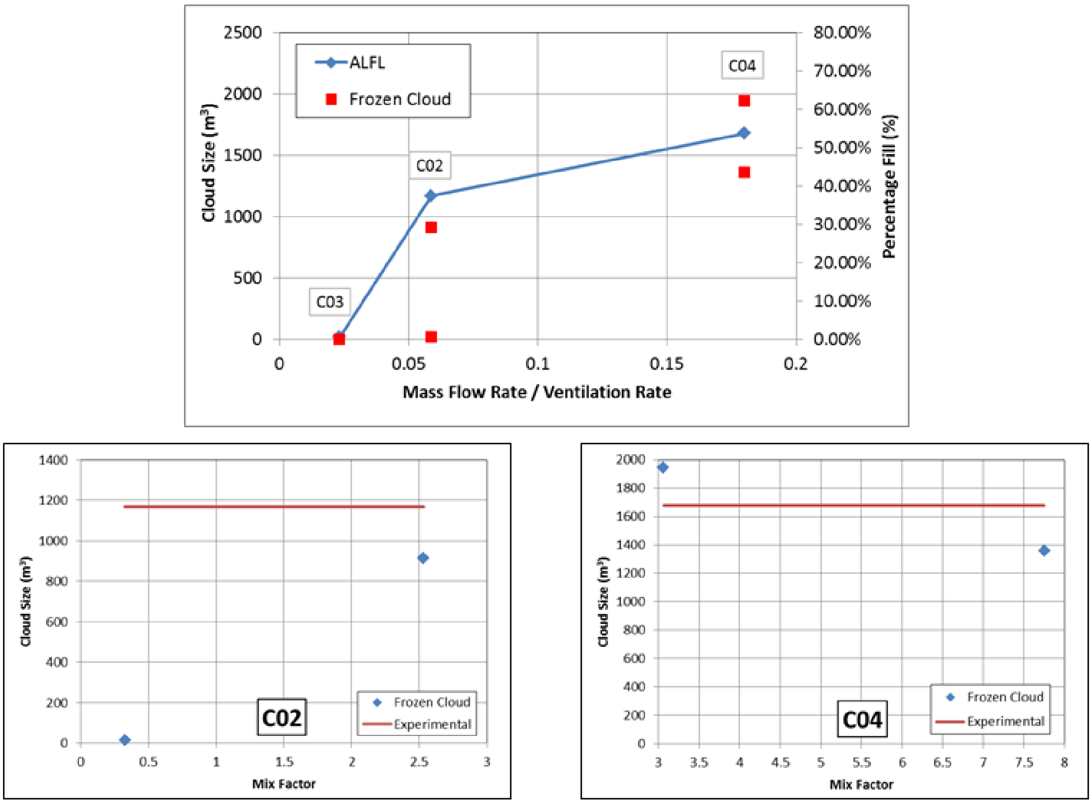

Figure 20. Configuration C – Case 11 (westerly release, location 2, wind from the west)

5.2 Frozen Cloud Summary

The results of this exercise have shown that the Frozen Cloud concept is a method that gives results that are 'physical' (i.e. calculated volumes do not exceed the module volume) but there is a large degree of variance in the predicted clouds and different trends are seen depending on the parameters studied. It is recommended that if the Frozen Cloud concept is to be used in an ERA then an initial CFD verification exercise should be carried out for different groups of parameters to check the Frozen Cloud concept is appropriate i.e. a number of CFD calculations should be carried out and the ability of the Frozen Cloud concept to predict the results of one CFD analysis based on the results of others should be verified.

It is acknowledged that the experimental data used as a basis of this validation exercise is limited and that there is some variation in the wind directions that are assumed to be fixed when grouping experiments; this has the potential to affect the results and conclusion here. It is the intention of the author to extend this study in the future by considering additional cases using CFD as this work has shown that this has given reasonable matches to experimental data; this will also enable a finer resolution in terms of points as concentrations can be monitored at every point in the domain rather than just at monitor locations used in an experiment.

6.0 Conclusions

The conclusions of the dispersion validation work were:

- The grid sensitivity study showed limited variance between the results for the different control volume sizes used.
- Configuration A showed good agreement between the CFD and experimental results except when the release impinged on a vessel. The experimental data presents conflicting information on the location of the vessel and could explain the discrepancy as the exact impingement location will significantly affect the flow regime.
- For Configuration C, C12 showed good agreement with the experimental data but C17 was over predicted. The over prediction was because in the experiment there were significant portions of the module only just below the 5% concentration which meant they were not counted as contributing to the cloud volume.When a value of 4% was used the results compared much more favourably. This highlights the sensitivity of designated cloud size to the chosen LFL value and it is recommended that this should be considered when conducting an ERA.

The conclusions of the Frozen Cloud concept validation work were:

- The Frozen Cloud concept leads to a large degree of variance in the predicted cloud sizes and different trends tend to be seen depending on the parameters studied.
- The Frozen Cloud concept tends to perform better when the Mix Factor is closer to unity but in some instances better predictions are seen with high values of Mix Factor.
- It is recommended that if the Frozen Cloud concept is to be used in an ERA then an initial CFD verification exercise should be carried out for different groups of parameters to check the Frozen Cloud concept is appropriate.
- The data used for the basis of this validation is limited therefore it is recommended that this work is extended by considering additional cases in CFD as this work has shown that this is a valid method for calculating gas cloud sizes.

7.0 References

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