MODELLING OF HYDROGEN DISPERSION WITH EFFECTS

Mack, A., Boot, H.
Gexcon Netherlands BV, Princenhof Park 18, Driebergen, 3972 NG, The Netherlands
andreas.mack@gexcon.com

ABSTRACT

The paper shows the latest developments of Gexcon’s consequence modelling software EFFECTS with validation based on hydrogen experimental data for different storage conditions and scenarios, including liquid hydrogen two-phase jet releases. The effect of atmospheric turbulence on the dispersion and potential worst-case scenarios of hydrogen which are very different from heavy gas releases are discussed. Beside validation for gaseous hydrogen releases, a validation study for pressurised liquid hydrogen jet releases including a sensitivity analysis is performed and the results are compared with experimental data.

1. INTRODUCTION

Hydrogen from renewable energies will play a key role in the energy transition from the use of fossil fuels to renewable energies. Stored highly pressurized at several hundred bars at ambient temperature or under cryogenic temperature at ambient pressure, hydrogen will show different dispersion behavior when released accidentally. Therefore, consequences and risks must be addressed accurately in advance. Gexcon’s consequence modelling software EFFECTS is a numerical tool based on the integral method approach. The dispersion model in EFFECTS was originally developed for heavy gas dispersion. EFFECTS has recently been updated for the simulation of new energy carriers with the focus on hydrogen (included in v12 of the software tool). The dispersion model developed for v12 is based on one single model being able to handle the entire domain of heavy, neutral and light gas dispersion including the transition between the regimes. This is in particular relevant for the delayed ignition of hydrogen when released at cryogenic conditions which can undergo the entire dispersion domain from an evaporating pool of heavy gas to a strongly lifting plume. When stored at high pressure and released as a jet, the momentum is dominant, and hydrogen might be dispersed already within the momentum dominated region without showing light gas behavior. To accurately account for these effects, the dispersion model must take all relevant physical mechanisms into account. An updated dispersion model has been implemented in EFFECTS v12 and validated in particular for lighter than air releases like hydrogen. This model has been tested against numerous experimental results for a correct prediction of lifting plumes including liquid hydrogen pool releases [1]. In the present paper, simulation results for gaseous and liquid jet releases will be investigated and compared with experimental data.

2. VALIDATION OF GASEOUS HYDROGEN JET RELEASES

The dispersion model in EFFECTS v12 is also adapted for gaseous, highly under expanded jets for a wide range of substances and storage conditions and shows excellent agreement with a wide range of experimental data sets [2]. Here, additional validation data including cooled and unsteady (blow down) releases are discussed.

Pressurized hydrogen release experiments from a 1mm hole including storage temperatures of 80K and 293K from Veser [3] were compared with EFFETCS v12 simulations. Comparable to previous results in [2] the agreement of the simulations results of EFFECTS v12 with the experimental data set is excellent. For the underexpanded release from 29.9bar and a reservoir temperature of 80K the static temperature drops much further due to the expansion into the supersonic regime. Likewise, the agreement with the experimental data is good (Figure 1). Previous release EFFECTS v11 showed more conservative concentrations, slightly less than a factor of two above the experimental data.

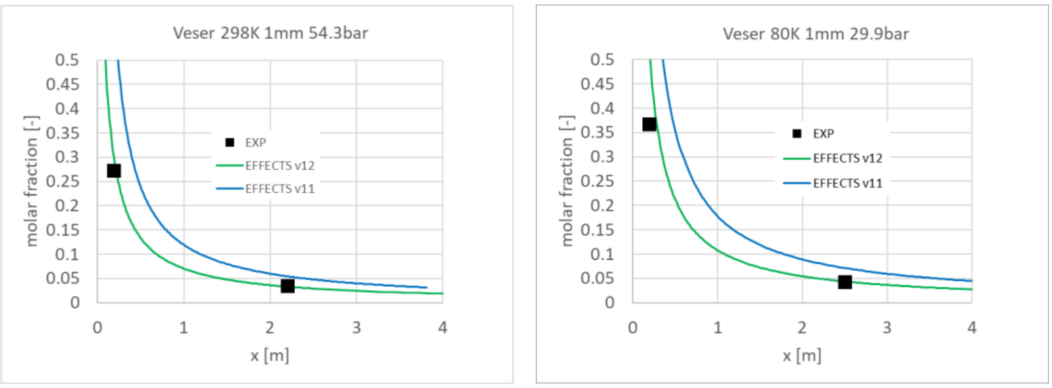

Figure 1: Hydrogen release experiment (Veser) at 298K, 54.3bar, 1mm hole (left) and 80K, 29.9bar, 1mm hole, (right); experimental data from [3], simulation with EFFECTS v12

Experiments are usually performed at constant release rates. Real life storage facilities have a certain volume; depending on the failure scenario (hole diameter) the pressure inside the vessel can drop rapidly leading to a decreasing mass flow rate over time. Tests were performed by Ruffin from a storage vessel of 5m^3 with hole diameters of 75 and 100mm at 40bar storage pressure resulting in short-term, massive releases [3]. The release durations of the blowdown to completely empty the vessel are approximately 3s for the 100mm hole and 6s for the 75mm hole. In EFECTS v12, comparable to other consequence modelling software's a representative mass flow rate is calculated which is then applied to the dispersion model as constant value. As can be seen in Figure 2, the representative release rates of 10990kg/s for the 75mm hole and 19540kg/s for the 100mm hole lead to minor overprediction of the experimental concentration distributions for EFFETCS v12 (compare Figure 2). EFFECTS v11 showed a strong overprediction of the concentrations of almost a factor two. Taking the complex, short duration release scenario into account, the agreement with the experimental dataset representing maximum concentration values can be considered as good. In addition, the concept of the representative release rate also leads to reasonable results for this kind of short term, highly under expanded hydrogen releases.

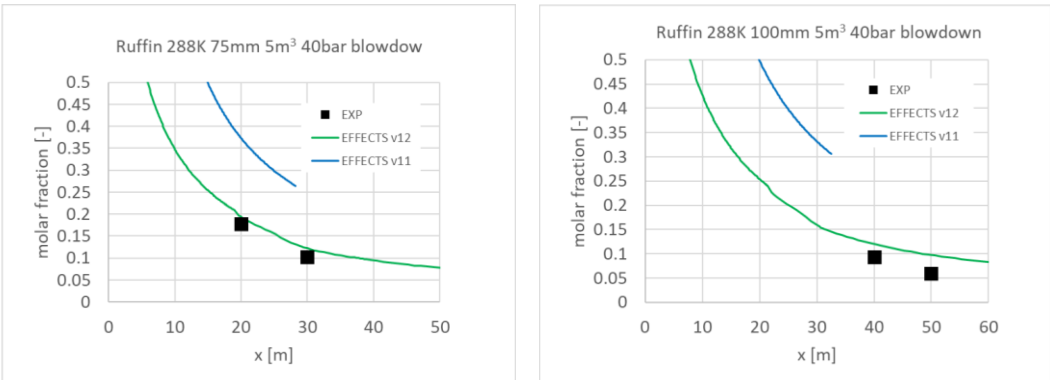

Figure 2: Hydrogen release experiment from a reservoir of 5m^3 (Ruffin), release at 298K, 40bar, 75mm hole, (left) and 288K, 40bar, 100mm hole (right); experimental data from [3], simulation with EFFECTS v12

Earlier validation of high-pressure hydrogen releases showed excellent agreement with the experimental data of Han also in the buoyancy dominated region [2]. Here, the experimental data set of Okabayashi (included in [3]) from a 1mm and 0.4mm hole at 400bar were rebuilt numerically. As can be seen in Figure 3, the agreement with the experimental data is excellent with a slight overprediction at some measurement locations; the improvement of the results from EFFECTS v12 compared with v11 is obvious.

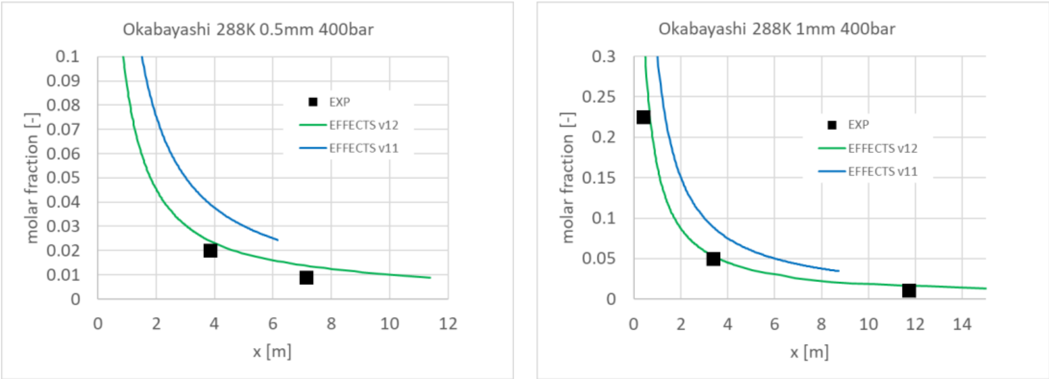

Figure 3: Hydrogen release experiment (Okabayashi) at 288K, 400bar, 0.5mm hole (left) and 288K, 400bar1mm hole, (right); experimental data from [3], simulation with EFFECTS v12

3. PHENOMENA IN LIGHT GAS LIFTING CLOUDS

In numerical simulations, usually steady state ambient conditions are assumed which are representative for the average wind condition. Contrary to heavy gas releases, light gas releases are much more affected since the cloud does not stay at the ground but might lift off. With changing meteorological conditions, clouds might be triggered to lift, stay grounded or show a transitional behaviour. Here, wind speed and turbulence play a major role. An increased wind speed usually pushes the cloud back to the ground. Higher turbulence, due to atmospheric stability but also upwind obstacles or sidewind increases the mixing and entrainment of ambient air, such that the buoyancy of the cloud can be significantly reduced. Especially in unstable weather conditions, where the atmospheric boundary layer is strongly turbulent and large scale vortical structures are present, the reduced buoyancy can lead to lower cloud trajectories or fully grounded plumes. The interaction of the released light gas with the atmospheric boundary layer creates turbulent structures at the shear layer; buoyant releases usually do not show smooth interfaces to the ambient air but are dominated by eddies form the cloud but also the atmospheric boundary layer.

For jet releases, the initial regime is momentum dominated with a strong shear layer due to a high velocity difference between released substance and the ambient air; the mixing is dominated by small vortices in the range of centimetres at high turbulence level. This can be identified as a relatively sharp interface with jet like behaviour in the experiments. Further downstream, at lower speeds, the mixing gets dominated by the buoyancy of the released substance. Usually, the eddies develop inside the gas cloud; eddy sizes are larger, in the order of centimetres to meters for a light gas. For heavy gases, due to stratification, the eddy sizes stay small and mixing is not enhanced but dampened due to the heavy gas. The mixing with ambient air defines the plume behaviour. For light gas releases the plume behaviour is positively buoyant, whereas for heavy gases is negatively buoyant. Depending on the release conditions, light gas releases at low temperatures or two-phase releases can also show negatively buoyant behaviour. Finally, at lower concentrations, the atmospheric boundary layer is dominating the dispersion process; at a later stage passive dispersion is observed. There, the turbulent structures of the atmospheric boundary layer are the main mixing drivers at eddy sizes in the order of 1-10m or more for unstable conditions.

Due to the different scales of dominating turbulent structures, the average meteorological conditions might not be representative for the simulation of light gas clouds. For unstable conditions, when large eddies dominate the ambient air, local wind speed, direction turbulence level can change significantly at relatively short time intervals. At sunny conditions, large eddies including locally increased wind velocities can “roll” over the ground or thermals lift off. In this case, the atmospheric turbulence where eddy sizes are a magnitude higher, dominates the dispersion process for a short time. This significantly increased mixing reduces the concentration and therefore also buoyancy and the plume is pushed to the ground.

By mixing the released gas with ambient air due to turbulence, heat transfer takes place. This includes the heat exchange between gases, evaporation of droplets and potential condensation of the released substance, and also water vapor which is present in the ambient air. In addition, heat transfer from the ground can change the buoyant behaviour of the clouds. This can play an important role for two-phase releases, which stay relatively cold until all droplets are evaporated or rainout might be present. If the ground is cooling down during the release, the heat transfer into the cloud is reduced and therefore also the positive buoyancy of light gas plumes. Light gas plumes might show less buoyant behaviour at longer release times. On the contrary, warm surfaces can increase the heat transfer into the plume.

During the NASA White Sands experiments in 1983 [4], instantaneous concentration distributions were derived from temperature sensors for Test 6 (compare Figure 4, left). As can be seen clearly, the plume trajectory changes within 0.4s from continuously lifting (Figure 4) to almost horizontal for a downwind distance larger than 20m (Figure 4 right, sensor time resolution was 0.2s). In addition, dilution takes place in vertical direction, where the contours are covering a wider vertical area. At the tip, the plume is displaced by approximately 7m in vertical direction which can hardly be due to the buoyancy of the plume but most probably due to large scale atmospheric turbulence. Prior and during the experiment, relatively strong changes (+/-25°) in the vertical wind component (elevation) were monitored whereas only eddies larger than 0.8m could be resolved [4]. Although these results should not be over interpreted, clearly highlight the possible interaction of flow phenomena in atmospheric boundary layers which increased complexity and sensitivity for buoyant plumes and increase awareness.

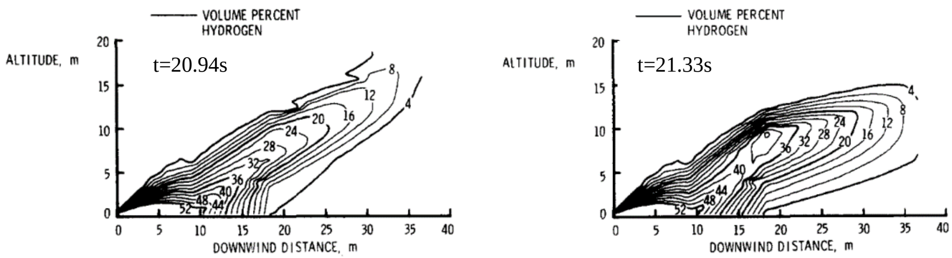

Figure 4: Temperature deducted hydrogen concentrations at t=20.94s (left) and 21.33s (right) for NASA Test 6 (taken from [4])

The explained mechanism in combination with the release conditions might lead to different plume trajectories and mixing behavior. Some conditions might be insensitive when the plume is very strongly lifting or grounded due to low buoyant behavior. For other conditions or ranges of wind speed and turbulence levels, the cloud behavior might be strongly sensitive. This is highly relevant for potentials effect distances and risks close to the ground. Sensitivity studies of the relevant parameters can be performed in order to get a full overview of possible consequences. Here, specific local conditions can have a strong influence like a hot climate at low average wind speeds, humidity, locations in open areas or highly turbulent wind fields.

4. VALIDATION OF LIQUID HYDROGEN JET RELEASES

The consequence modelling software EFFECTS v12 has been extensively validated for light gas lifting clouds for continuous and instantaneous ground, pool and jet releases. This includes also the NASA White Sands campaign [4] experimental dataset where different liquefied hydrogen pool releases result under different ambient wind conditions in a wide range of cloud behaviour from grounded to fully lifted which could be reproduced with EFFECTS v12 [1].

Apart from liquid hydrogen pool releases, validation with experimental data from liquid hydrogen jets releases are very relevant since the release is usually in the two-phase regime. Liquefied hydrogen can be released from pressurized tanks, where flashing, evaporation and rainout of droplets including strong heat transfer have an effect on the cloud dispersion behaviour. Also, liquefied hydrogen jet releases can feature grounded and lifting plumes depending on the conditions. Due to the low temperatures and high momentum, buoyancy effects usually occur further away from the release. As explained in the previous chapter, sensitivities on the plume trajectory and dispersion behaviour due to the atmospheric boundary layer, also apply for these releases.

Liquid hydrogen outdoor leakage studies releases were recently studied for the Norwegian Defence research Establishment (FFI) at the DNV test site Spadeadam. Extensive concentration and temperature measurement were performed for 7 different tests including horizontal and vertical (downward) jet releases at different wind conditions and release rates, compare [5] and [6]. For the present study, the horizontal releases Test 4 and Test 6 were selected since they were performed at almost identical release rated but different weather conditions. The release height is 0.5m. Test conditions are given in Table 1. The meteorological data is taken at 10m height. At three different arcs (30, 50 and 100m distance from the release) concentration measurement data is available at three different heights (0.1m, 1m and 1.8m). The sensor readings with the maximum concentration values are taken as representative values for the symmetry plane.

Due to the different wind conditions, the dispersion of the hydrogen cloud takes place close to the ground for Test 4 and shows a lift-off for Test 6. Cloud lift-off for Test 6 was also reported in the CFD simulations performed by Hansen [7].

For both tests, the wind speed and direction were fluctuating. Wind speed was measured at two heights (5m and 10m) and varied during the test by 20-30% with peaks up to 60-70%. Although the upper sensor average wind speed is higher than at the one at the lower sensor, temporarily the wind speed is higher at the lower sensor position. The wind direction changed by 10-15^o with peaks up to ±25^o. This shows that typical outdoor releases in atmospheric boundary layers are usually not taking place at steady state conditions but transient or fluctuating conditions. For the present study, the conditions at the upper sensor were taken.

Table 1. Release and weather conditions for Test 4 and Test 6 [5].

Test	Nozzle size [mm]	Mass flow rate [kg/s]	Wind velocity, mean and variation [m/s]	Temperature [^{o}C]
4	25.4	0.827	6.7±1.6	3.3
6	25.4	0.832	2.7±0.9	3.8

4.1 Liquid hydrogen release, Test 4

For Test 4, the time dependent concentration readings at the three measurement heights (0.1m, 1m and 1.8m) are reasonably correlated for all sensor positions and maximum concentrations were measured near the ground. This most probably means that the plume was grounded and did not lift. Plume meander in horizontal direction was present, leading to different sensor readings. The cloud widths were quite small for Test 4 and 6 and the lateral sensor distance large. In combination with the fluctuating wind direction only 2 sensors usually show relevant concentrations. As mentioned earlier, wind speed and direction were fluctuating during the experiment. No information about the stability of the atmospheric boundary layer is available, therefore Pasquil D was assumed. The surface roughness was set to 0.03m.

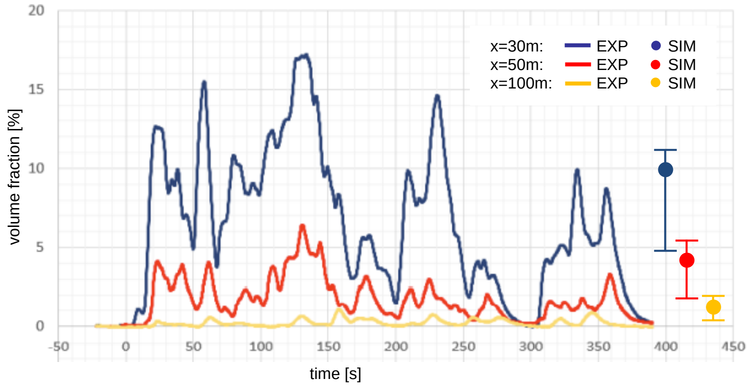

Figure 5: Comparison of maximum hydrogen concentrations during Test 4 (EXP) [6] compared with simulations from EFFECTS v12 (SIM)

The simulations were performed with EFFECTS v12. The release is modelled by a release from a vessel including friction from piping such that the mass flow rate matched the one from the experiment in a 25.4mm release diameter. The exit pressure is approximately 3 bar dropping slightly over the release which matches the data from the experiment. The liquid fraction is calculated at 70.5% after flashing and rainout whereas all droplets stay airborne, and no rainout is predicted. Besides the base values calculated with the three reference wind velocities and an averaging time of 200s (Figure 5, dots). This cloud averaging time is considered representative of taking the plume meander into account in a standard way. Parameter variations were performed for short averaging times (2s, representing maximum concentrations) and Pasquil class C which should mimic an increased turbulence level of the atmospheric boundary layer (Figure 5, error bars). As commonly known, the averaging time has a minor effect on the dispersion close to the release. Only the concentrations in lateral direction are less stretched and concentrations at the centerline increased due to shorter averaging times (+1% at x=30m). At larger distances, concentrations are also increased in the same order (+0.8% at x=100m). The variation of wind speed does not show significant effects (1% at 30m); the largest influence has the change of the atmospheric stability (up to -4%) (% at 30m and -0.5% at 100m), compare in Figure 5). Overall, the time averaged concentration values at the three distances are predicted well with a slight overprediction at x=100m. The peak values at the first arc (x=30m) of the experiment (17%) are not reached in the simulation (11%).

Strong fluctuations in the peak hydrogen concentration values have also been observed during other liquid hydrogen jet release experiments. Test 7 of the HSE experiment [8] is a comparable liquid hydrogen release from 0.86m (mass flow rate 0.07kg/s) in 3.07±0.82 m/s wind speed with fluctuating wind direction. High concentration fluctuations at the sensor locations are seen as consequence of the short-term fluctuations in the atmospheric conditions [8]. Peak values are up to a factor of 5-10 higher than the average values. These strong fluctuations are most likely also affected by the turbulence due to buoyancy in the cloud itself which is treated in a time averaged way in EFFECTS and are, therefore, not visible in the results. More research is needed to address the ratio of peak to average concentration for this relatively small-scale turbulence inside the plume by higher sophisticated models like CFD-LES methods.

Nevertheless, the simulation results with respect to the cloud trajectory are not sensitive to any of the parameter variations: the cloud stays grounded comparable to the experiment and the average concentrations agree well with the experimental data with a slight over prediction in the far field.

4.2 Liquid hydrogen release, Test 6

Test 6 was performed with almost identical source term of Test 4 whereas at reduced wind speed (see Table 1). Due to this, the cloud was more buoyant compared with Test 4 such that only the sensors at the first two arcs (x=30m and 50m) showed relevant concentrations levels. Therefore, at x=100m the cloud seems to be lifted off from the ground during the experiments. As mentioned earlier, this behavior was also observed in the CFD simulations of Hansen [7].

The simulations here were performed comparable to Test 4, including the variation of wind speed (1.8, 2.7 and 3.6m/s) and the variation of turbulence by additional calculation for a Pasquil stability class C. The cloud averaging time is kept at 2s and surface roughness is 0.03m.

The simulations show a strong influence of the wind speed on the cloud trajectory which is lifted for the lowest and medium wind speed and grounded for the highest one. It should be mentioned that the definition of "lifted" and "grounded" plumes is always up to certain interpretation. Comparing Figure 6 it can be seen that the plume trajectory (centerline) also shows a vertical displacement of approximately 2m for the highest wind speed; since the contour of interest (in this case 2% volume concentration) also reaches the ground at this distance the plume here is still considered as "grounded". Although the simulations are steady state computations it clearly demonstrates that the buoyant behaviour is sensitive to variations in the wind speed and might affect the dispersion of the cloud significantly. Therefore, also the concentrations at the measurement locations positioned close to the ground (0.1, 1 and 1.8m) will be

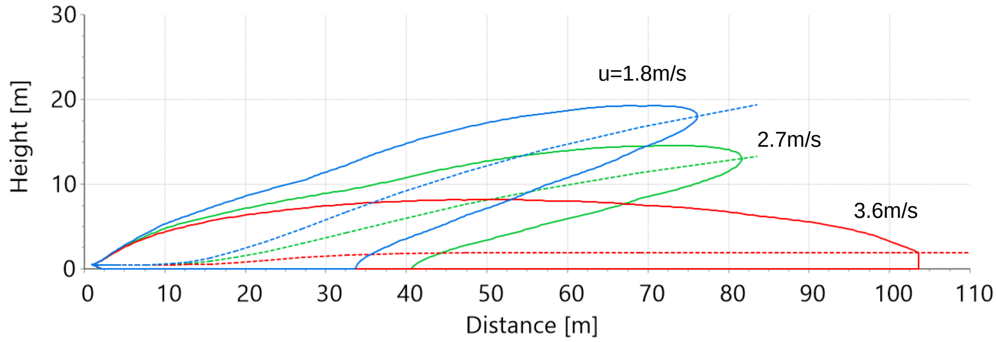

Figure 6: Simulations of Test 6 for different wind speeds; comparison of cloud dispersion behaviour shown by trajectory and plume contour (2% concentration v/v)

Sensitivity Analysis Test 6: Atmospheric stability

Additional simulations were performed to demonstrate the sensitivity on the stability of the atmospheric boundary layer for Pasquil class E, C and B (

Figure 7). The Pasquil classes C and B should mimic a temporarily increased turbulence level. For the lowest and highest wind speed, the cloud trajectory is not sensitive to the atmospheric stability, the cloud stays lifted (1.8m/s) or grounded (3.5m/s). Due to enhanced (C, B) or reduced turbulence (E) the effect distances are reduced or increased as expected. An additional effect on the trajectory is present since increased mixing reduces the buoyancy forces, and the cloud trajectories get closer to the ground moving from Pasquil class E to B.

For the reference wind speed (2.7m/s) the cloud effect distance and trajectory height are reduced from Pasquil class E to D when the cloud is still lifted. Increasing the atmospheric turbulence to Pasquil C, the buoyancy is reduced such that the cloud remains close to the ground. A further increase of turbulence (B) further reduces the effect distance and trajectory height. As can be seen clearly, the atmospheric stability can significantly change the dispersion behaviour and the consequences since the cloud remain close to the ground where possible ignition sources or confinement might be located.

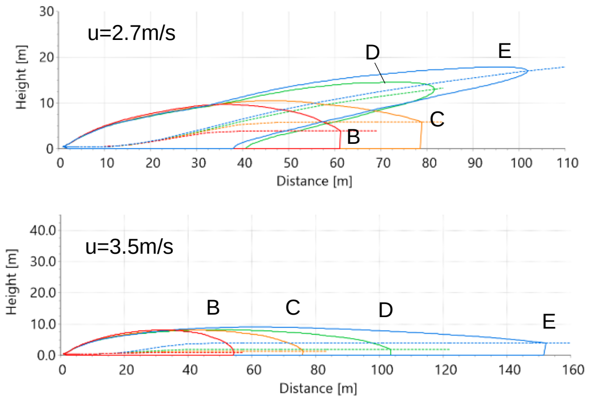

Figure 7: Simulations Test 6 for different atmospheric stabilities and wind speed of 2.7ms (a), 1.8m/s (b) and 3.5m/s (c); comparison of cloud dispersion behaviour shown by trajectory and plume contour (2% concentration v/v)

Sensitivity Analysis Test 6: Turbulence in wind profile

As commonly known the turbulence in the atmospheric boundary layer also changes with the terrain surface properties such as low vegetation or buildings. The surface roughness length defines the turbulence level, but also the shape of the wind profile. High surface roughness lengths reduce the wind speed close to the ground (below the wind speed reference height) more than for lower roughness heights. Since releases usually start in this area, turbulence level is increased and the local wind speed is decreased for higher surface roughness have an influence on the dispersion behaviour. Simulations were performed at an increased surface roughness length of 0.1m. The results are comparable to the previous calculations (surface roughness length 0.03m) whereas the trajectories are higher and effect distances are slightly reduced (compare Figure 8 and Figure 6). In addition, the clouds tend to stay longer lifted (compare Figure 9 and

Figure 7). The reduced effect distances can be explained by the increased turbulence level; since the clouds are developing from the ground the wind speed is reduced locally due to the increased surface roughness and clouds rise steeper. Therefore, increasing the surface roughness, the effect of the reduced wind speed seems to dominate over the effect of increased turbulence with respect to the plume trajectory.

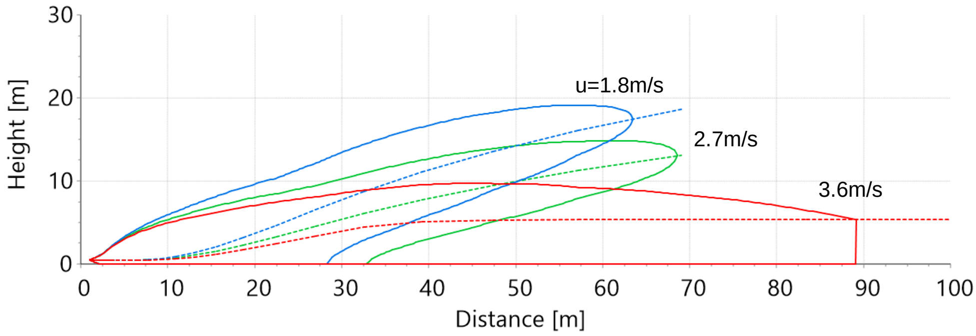

Figure 8: Simulations Test 6 (surface roughness length 0.1m) for different wind speeds; comparison of cloud dispersion behaviour shown by trajectory and plume contour (2% concentration v/v)

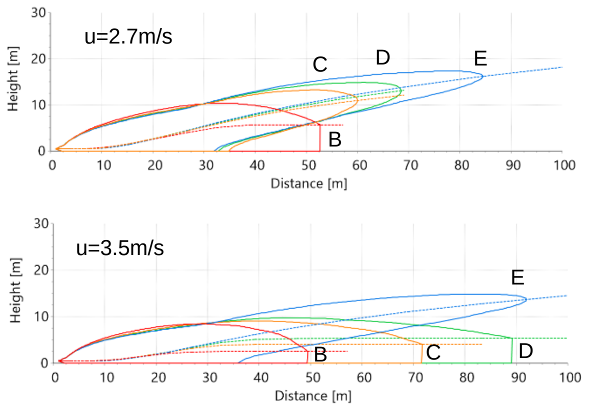

Figure 9: Simulations Test 6 (surface roughness length 0.1m) for different atmospheric stabilities and wind speed of 2.7ms (a), 1.8m/s (b) and 3.5m/s (c); comparison of cloud dispersion behaviour shown by trajectory and plume contour (2% concentration v/v)

Sensitivity Analysis Test 6: Ground heat transfer

Finally, the heat transfer from the ground plays an additional role. In particular for two-phase releases, the cloud can stay at low temperature for a long time until droplets have evaporated. The heat transfer from the ground can play a significant role since it can deliver a certain amount of heat for the evaporation of droplets. In EFFECTS v12, the air and ground temperature in the dispersion model are by default identical resulting in the maximization of the heat flux from the ground. The opposite situation might be representative for long release times: a zero-heat flux from the ground when the ground temperature has been decreased due to the presence of the cloud. This situation was investigated with a developer version of EFFECTS v12, the results are given in Figure 10 and compared with the results from Figure 8 for a zero heat flux (adiabatic) boundary condition (surface roughness length 0.1m). As can be seen clearly, trajectories are moving closer to the ground and get longer. Clouds will also stay grounded at lower wind speeds, compared with the simulations for the 2.7m/s wind speed where the cloud stays grounded when the heat transfer from the ground is set to zero. The adiabatic ground boundary condition shows the longest effect distance. This can be typical for plumes which are just grounded. Lower wind speeds would make them lift-off and entrain more ambient air. Higher wind speeds would increase the turbulence level and therefore also entrain more air. Both reduce the effect distance which can also be seen in Figure 10 but holds also for other scenarios.

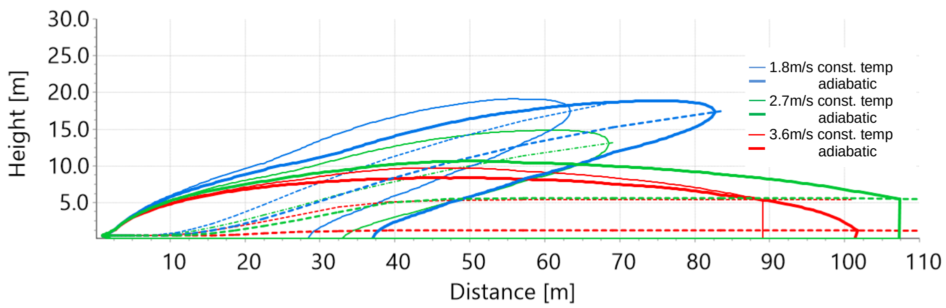

Figure 10: Simulations Test 6 with adiabatic and constant temperature boundary condition at the ground (surface roughness length 0.1m) for different wind speeds; comparison of cloud dispersion behaviour shown by trajectory and plume contour (2% concentration v/v)

In real releases the ground will be cooled down depending on the subsurface properties (heat capacity and conduction); at the beginning of the release (or for short release durations) a constant ground temperature is a good approximation since the ground needs time to be cooled. At a later point in time (or long release times) an adiabatic ground treatment might be more realistic since the ground will have been cooled. Nevertheless, a sensitivity analysis can give valuable insight into possible changes of the dispersion behaviour and therefore concentrations distributions.

Summary Test 6

Summarizing all data from the simulations of test 6 it can be concluded that sensitivities are present with respect to the plume trajectory and have a strong effect on the concentrations at the sensor positions. Therefore, results are given for the reference case at a wind speed of 2.7m/s (Figure 11, dots); the data of the variations of wind speed (1.8 and 3.6m/s), Pasquil stability (C) and adiabatic ground boundary condition are included in the error bars. The main effect for the variation of concentrations is obviously the plume trajectory which is grounded or lifted.

The average (14%) and maximum concentrations (22%) of the experiment at x=30m are underpredicted by the simulations (7.5% for the reference case and 10.5% for the highest concentration). At x=50m, the simulations for all cases show concentrations between 0.4% and 5.5% (experiment 0-2%). At x=100m, only grounded plumes show sensor readings up to 2.2%. Overall, the simulated cases give a reasonable overview of possible average concentration data present during the experiment. The predicted concentration range (error bars) are in reasonable agreement with the values observed during the experiment. In the farfield, a slight over prediction of the maximum range is observed due to the influence of the grounded plumes in the sensitivity study. Close to the release, the range is slightly underpredicted.

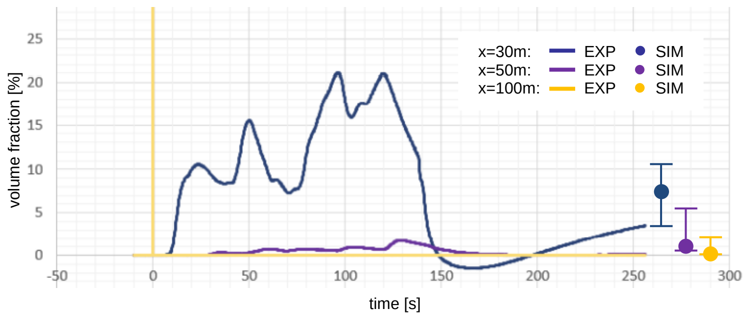

Figure 11: Comparison of maximum hydrogen concentrations during Test 6 (EXP) [6] compared with simulations from EFFECTS v12 (SIM)

4.3 Recommendations: sensitivity analysis and worst-case conditions

For the extrapolation to other releases, it should be kept in mind that the dispersion of lighter than air substances might be strongly affected by relatively minor changes in atmospheric conditions like the Pasquil stability class, turbulence, variation of wind speed and the release location (surface roughness, ground properties). Beside this many more sensitivities might be present, like a change in ambient temperature or the air humidity, in particular for two phase releases (not further shown here). As a result, clouds might stay close to the ground, slightly lift or fully lift-off which significantly impact on the concentrations being present.

Based on the present results, worst case scenarios for lighter than air substances differ a lot from the ones for heavy gas. Heavy gas worst case scenarios are at relatively low wind speed under stable atmospheric conditions (Pasquil E) at reduced mixing and entrainment conditions. Under these conditions, the heavy gas cloud is pushed in one direction without too much entrainment of ambient air and lateral spreading to create maximum effect distances. For lighter than air substances, as shown earlier, the situation is more complex. Since the plume trajectory is strongly depending on the mixing with ambient air and heat the transfer, worst case situations occur usually when the plume stays grounded where possible ignition sources or confinement locations are present. These situations depend strongly on the release term and atmospheric conditions and can occur at moderate wind speed and higher turbulence level (Pasquil classes D-B).

Therefore, it is strongly advised to perform a sensitivity analysis if a lifting of the cloud might be expected. The parameters must be chosen depending on the scenario, the location (confinements) and expected weather conditions. On the one hand, it might turn out that cloud topologies are relatively insensitive to any changes in conditions, like the present Test 4 where the cloud stays grounded for all conditions. The same applies for fully lifted clouds where buoyancy is the main physical driver. On the other hand, clouds might be in a regime where relatively small changes in conditions have a strong effect to either lift the plume or make it grounded like the previously discussed Test 6.

5. SUMMARY

The present research highlights validation exercises for gaseous hydrogen jet releases including low temperature storage, blowdown of vessel with release times in the order of seconds and high-pressure releases. For these conditions, EFFECTS v12 shows good agreement with the experimental data sets of concentration contours.

Further on, the effect of large-scale turbulent structures and temporarily changing atmospheric conditions like turbulence on the dispersion behaviour of lifting clouds has been described. For liquid hydrogen jet releases of the FFI Test 4 and 6, simulations have been performed including sensitivity studies for the plume dispersion behavior from lifted to grounded plume. The cloud trajectories are in agreement with the observed behaviour during the tests and earlier CFD solutions for test 4 and 6, whereas Test 4 is insensitive to plume lift and Test 6 showed a strong sensitivity on the atmospheric condition with respect to plume lift and concentration levels at the sensor positions. The overall agreement of the average concentrations is good when taking the results of a sensitivity analysis into account. Short term peak concentrations might be underpredicted, but average values of grounded and lifted plumes are within the calculated range of the sensitivity study.

REFERENCES

1. Mack, A., Ruiz-Pérez, S., Boot, H., Extension of the EFFECTS dispersion model for buoyant plume rise including lift-off, Mary Kay O'Connor Safety & Risk Conference, 2022, October 5-7, conference proceedings, Process Safety and Environmental Protection, 2023 (manuscript submitted for publication)
2. Mack, A., Boot, H., Improvement of the EFFECTS dispersion model for under expanded turbulent jets, AIDIC FEX23, 2023, October 8-11, Bologna, conference proceedings, 2023 (manuscript submitted for publication)
3. Molkov, V., Fundamentals of hydrogen safety engineering. Bookboon. com ISBN: 978-87, 2012
4. Witcofski, R.D., Chirivella, J.E., Experimental and analytical Analysis of the Mechanisms governing the Dispersion of Flammable clouds formed by Liquid Hydrogen Spills, Int. J. Hydrogen Energy, Vol. 9, No. 5, pp. 425-435, 1984
5. Aaneby J., Gjesdal T., Voie Ø., FFI Report 20/03101, Large scale leakage of liquid hydrogen (LH2) – tests related to bunkering and maritime use of liquid hydrogen, Norwegian Defence Research Establishment, Kjeller, Norway, 2021
6. Medina C.H., Allason D., Data Report: Outdoor leakage studies, Forsvarets forskningsinstitutt (FFI) Norwegian Defence Research Establishment, Report No.: 853182, Rev. 2, 2020
7. Hansen, O. R., & Hansen, E. S., CFD-modelling of large scale LH2 release experiments, Chemical Engineering Transactions, 90, 619-624, 2022
8. Giannissi, S. G., Venetsanos, A.G. et al., CFD modeling of hydrogen dispersion under cryogenic release conditions, International Journal of Hydrogen Energy, 39.28: 15851-15863, 2014