Modelling of Hydrogen Dispersion with EFFECTS

How does atmospheric turbulence influences plumes – an example of a liquid hydrogen jet release

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ICHS 2023 International Conference on Hydrogen Safety

September 19-21, 2023

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Modelling of Hydrogen Dispersion with EFFECTS

- Introduction: Challenges in hydrogen dispersion modelling; scenario's for heavy gas and light gas releases
- Turbulence in the atmospheric boundary layer
- EFFECTS in a nutshell
- Liquid hydrogen jet releases: FFI/DNV 2020, Test 04 and 06: Comparison of experimental data
    - and simulations
    - Sensitivity of hydrogen dispersion behaviour with respect to variation in turbulence
- Summary and Recommendations

Challenges in hydrogen dispersion modelling

Dispersion modelling of heavy and light gas releases

Heavy gas: (hydrocarbons)

“straightforward”, plumes stay on ground, dispersion; damping of turbulence at interface plume/ABL

What is the worst case scenario?

- High wind speed: plume pushed downwind, low lateral spreading, high turbulence, shortest effect distances
- Zero wind speed: expanding “pancake”, huge area (not easy for simulations…)
- Low wind speed: plume pushed in downwind direction, longest effect distances at low turbulence levels (stable Pasquil classes) VDI 3783 correlates source term and wind velocity for maximum effect distances

Light/transitional gas (hydrogen, ammonia,…)

Gas might be heavy or light at release depending on storage condition (temperature, pressure)

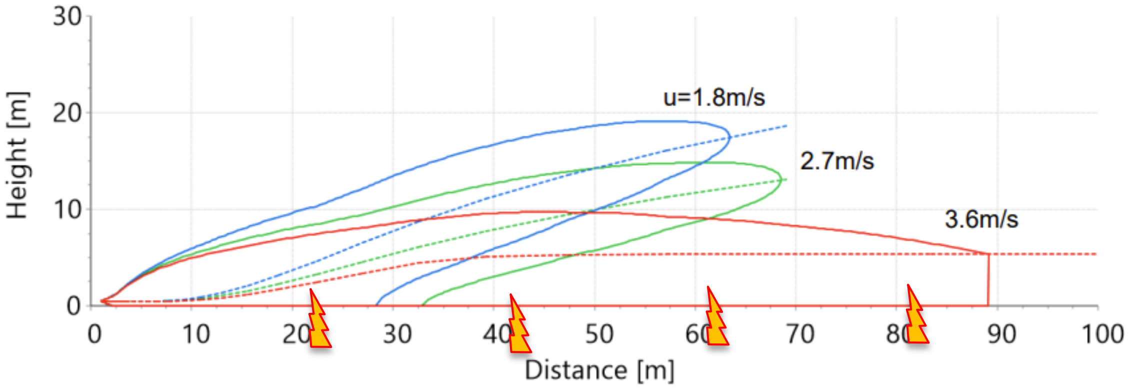
Light gas plumes might lift off directly after release at low wind speeds or stay grounded at higher wind speeds

What are relevant scenarios for QRA of hydrogen releases?

Grounded plumes: flammable mass is larger, usually

- ignition points and confinement areas are present

But when does a plume stay grounded?
Does my model predict this right?



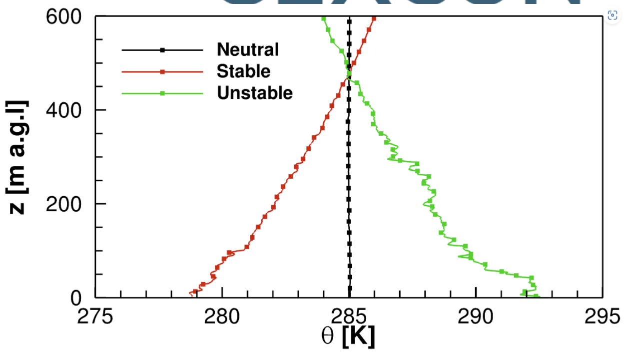
Turbulence in the Atmospheric Boundary layer (ABL)

Turbulent flow is irregular, quais-random, chaotic

Generated by mechanical, thermal or inertia effects (not only in atmospheric boundary layers!)

- mechanical: wind shear, surface friction, wakes of obstacles
- thermal: generated by buoyancy (plumes, thermals) and gravity
  - buoyancy accelerates parcels upwards or downwards (depending on density)

Simulations usually assume time averaged turbulence properties (integral models: Monin Obukhov theory for ABLs, RANS: Reynolds averaged Navier Stoke) > turbulent viscosity: eddies not resolved in time



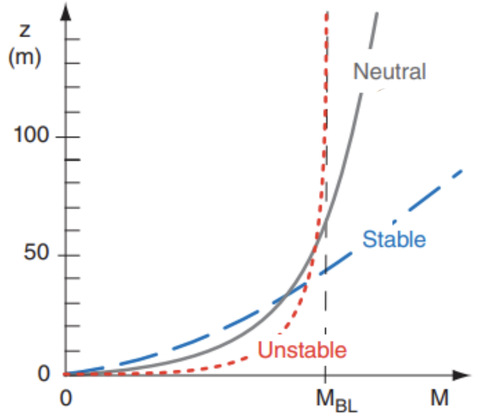
Temperature profiles in neutral, stable and unstable atmosphere

Letzgus et. Al.: Computational fluid dynamics studies on wind turbine interactions with the turbulent local flow field influenced by complex topography and thermal stratification. *Wind Energy Science*, 7(4), 1551-1573.

Neutral ABL (Pasquil D): No heat flux, only wind shear

Stable ABL (Pasquil E, F): ground is emitting radiation, ground is cooled > low turbulent viscosity (nighttime, very calm weather conditions)

Unstable ABL (Pasquil C, B, A):, solar radiation is heating the ground surface, large thermals can lift from the ground: high turbulent viscosity (daytime, sunny)



Wind profiles in neutral, stable and unstable atmosphere

Roland Stull. *Practical Meteorology: An Algebra-based Survey of Atmospheric Science.*

These principles also apply at the interfaces of plumes with the wind field: shear and buoyancy can lead to enhancement or damping of turbulence.

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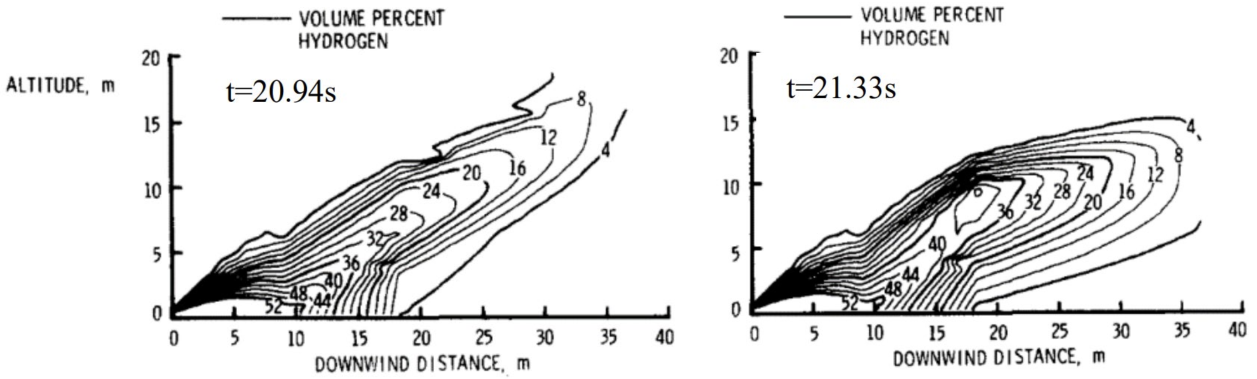
Observations: Turbulence?

NASA Whitesands (1983) 7 experiment, liquid hydrogen spill, pool evaporation

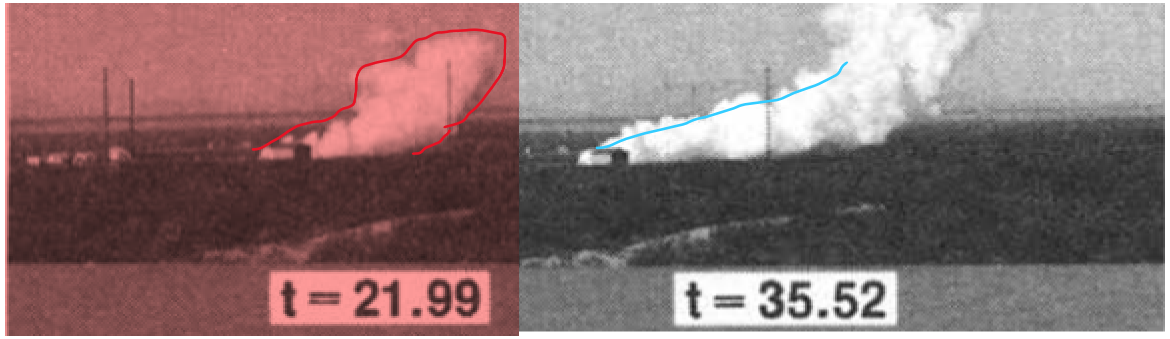
Test 6 showed first a lifting plume which "reattached" to the ground at later times possibly due to changes in the atmospheric boundary layer.

All other tests showed a clearly grounded or lifted plumes with stable trajectories.

Usually, simulations are based on steady state atmospheric conditions. How sensitive are simulations of lifting plumes to changing conditions?



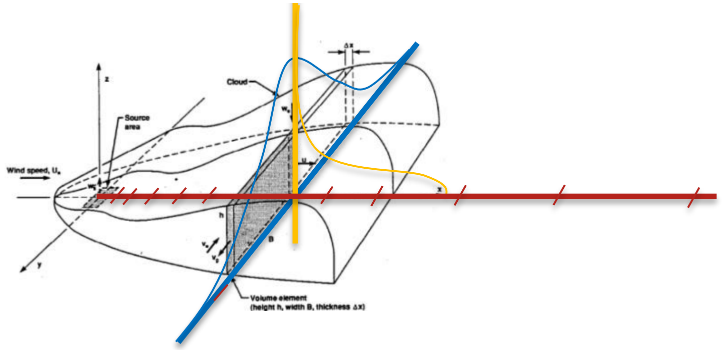
Test 4: NASA Test 6, instantaneous temperature deducted hydrogen concentrations at t=20.94s (left) and 21.33s (right)

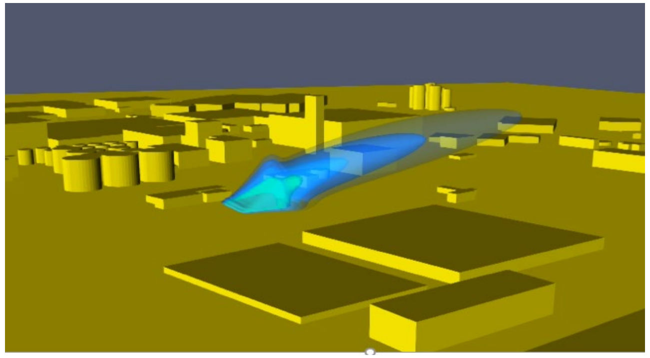


Witcofski, R.D., Chirivella, J.E., Experimental and analytical Analysis of the Mechanisms governing the Dispersion of Flammable clouds formed by Liquid Hydrogen Spills, Int. J. Hydrogen Energy, Vol. 9, No. 5, pp. 425-435, 1984

EFFECTS in a nutshell

- software for consequence modeling of loss of containment
- developed for external safety (originally by TNO)
- INTEGRAL MODEL; based on a 1d discretization of the plume center with functions for the lateral and vertical distributions
- conserving mass, momentum and energy and has additional equations to solve for the lateral and vertical distributions
- solving for two phase flow, phase change and heat transfer
- has been validated extensively for heavy and light gas releases for a wide range of substances including plume lift-off
- results are 3D; concentration distributions are available in the full domain
- runs very fast (within seconds)
- is part of RISKCURVES (QRA-tool) and the X-suite of Gexcon





EFFECTS Visualization of lifting plume (3D)

EFFECTS results visualized in Google Earth

Liquid hydrogen jet releases

FFI/DNV experiments

7 different tests, horizontal and vertical (downward) releases

Test 4 and 6 (horizontal jets, 25.4mm) have almost identical source terms (ca. 0.83kg/s) at different wind conditions (6.7 and 2.7m/s)

Concertation and temperature measurements at 30m, 50m and 100m arc at heights of 0.1m, 1m and 1.8m

Response time of concentration sensors <6s (90%)

Meteo data measured at 5m and 10m height

Obstacles (2 Containers, piping, camera holder) are neglected; wake of containers slightly influences slightly plume lateral position further downstream

Earlier comparison performed with FLACS (Hansen, 2022)

Figures from: Medina C.H., Allason D., Data Report: Outdoor leakage studies, Forsvarets forskningsinstitutt (FFI) Norwegian Defence Research Establishment, Report No.: 853182, Rev. 2, 2020

Liquid hydrogen jet releases

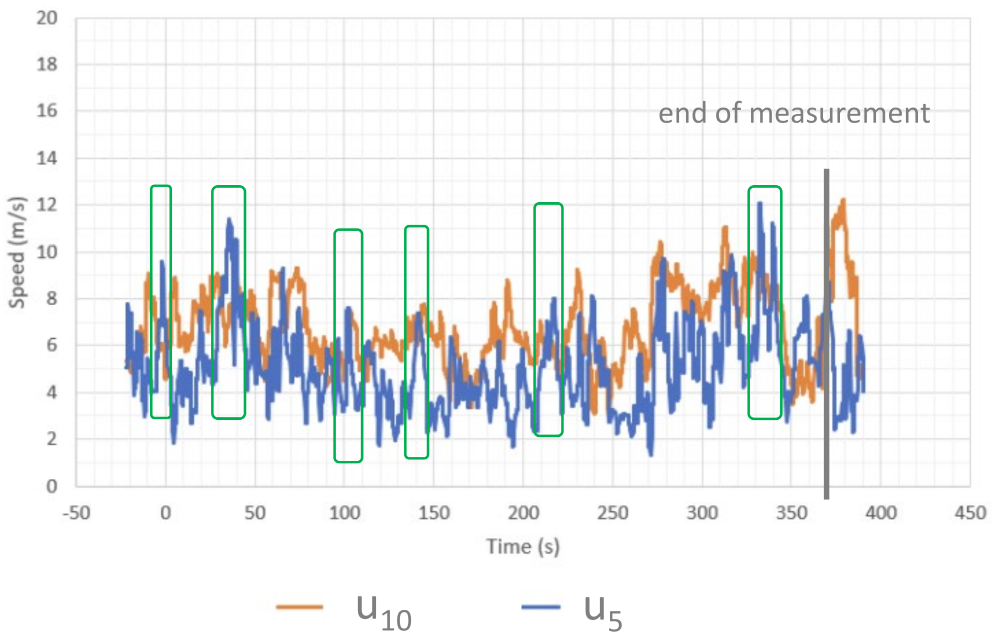
Ambient weather data, wind speed measurements

Strong, higher frequency fluctuations during Test 4 (“normal” turbulence?)

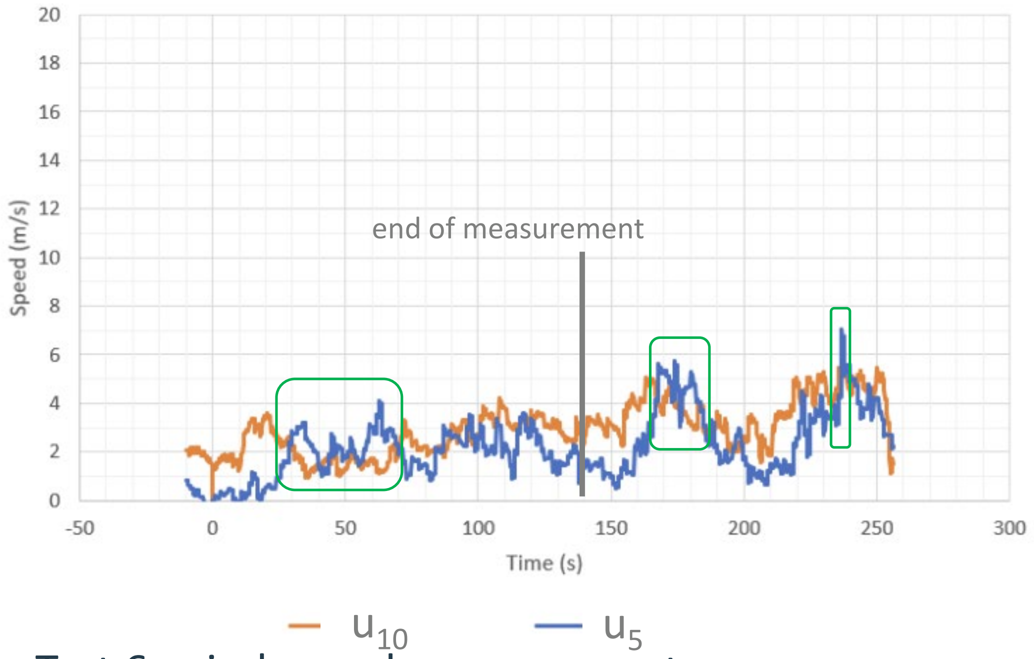
Lower frequency fluctuations during Test 4 (0.5-4m/s wind speed)

Wind direction change: +-10º, peaks +-25º

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



Test 4: Wind speed measurements



Test 6: wind speed measurements

Data from: Medina C.H., Allason D., Report No.: 853182, Rev. 2, 2020

Test 04 (wind speed 6.7m/s)

Experiment:

Correlated sensor reading at 3 distances

Sensor at 100m detects continuously concentrations during the experiment

Simulations:

Release from pressurized vessel, exit pressure ca 3bar,
airborne liquid fraction 70.5%, no rainout

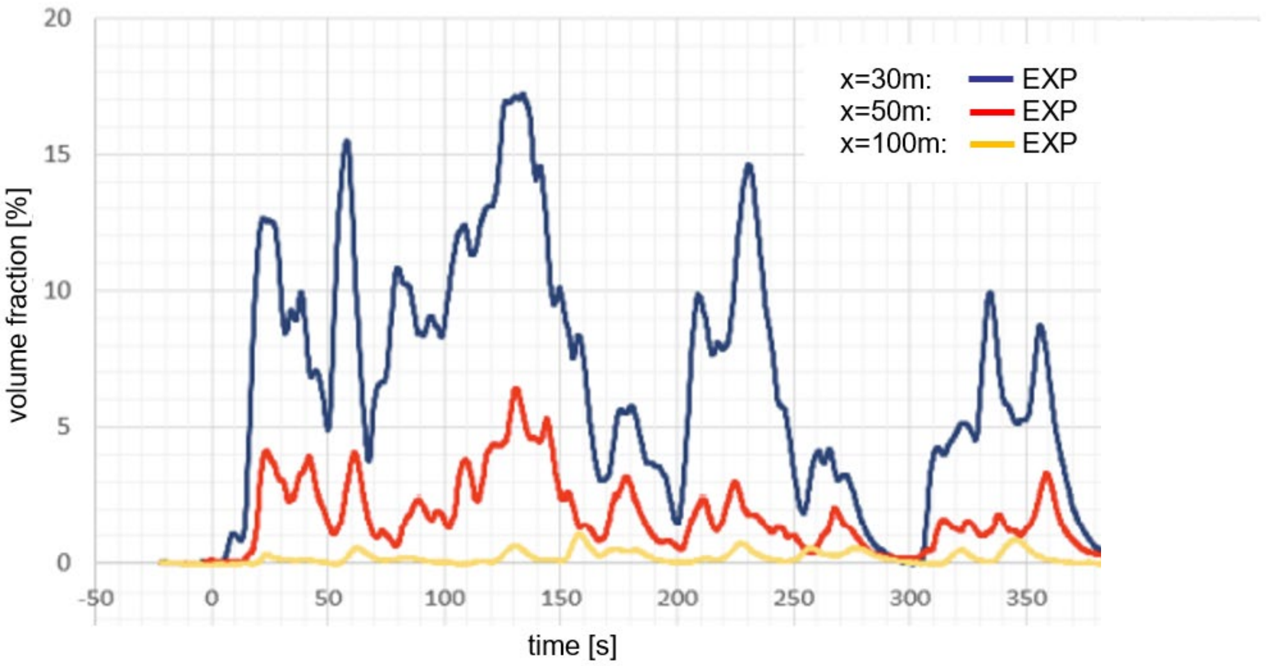
3 reference velocity (reference, high, low), increased turbulence (Pasquil C)

Reduced turbulence: Pasquil E (circles)

No plume lift off for all wind speeds and turbulence levels

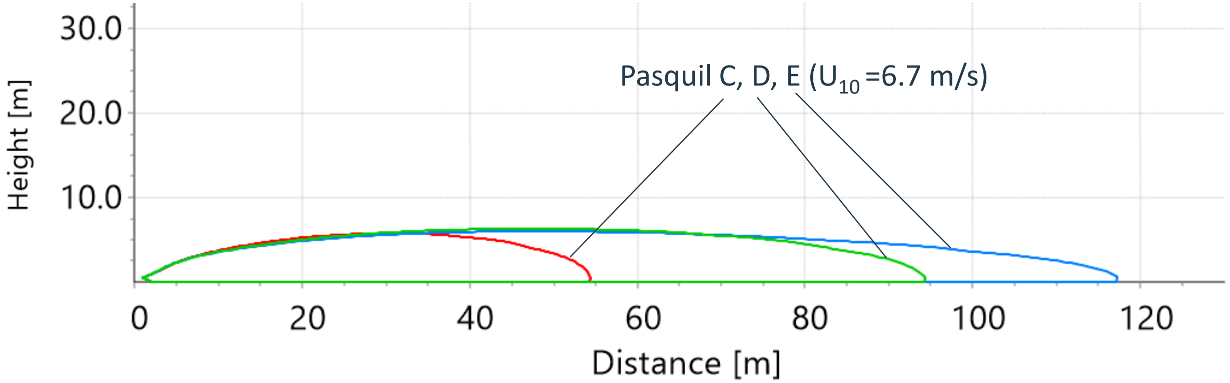
Reasonable agreement with concentration average data

Maximum values are underpredicted (integral model/CFD-RANS > LES)



Test 4: Comparison of maximum hydrogen concentrations during Test 6 (EXP*) compare with simulations from EFFECTS v12 (SIM): circels correspond to Pasquil E

*Exp data from: Medina C.H., Allason D., Report No.: 853182, Rev. 2, 2020



Test 4: Plume simulations, shown by concentration contour (2% v/v)

Test 06 (wind speed 2.7m/s)

Experiment:

Correlated sensor reading at 2 heights

Sensor at 100m does not detects concentrations

Simulations

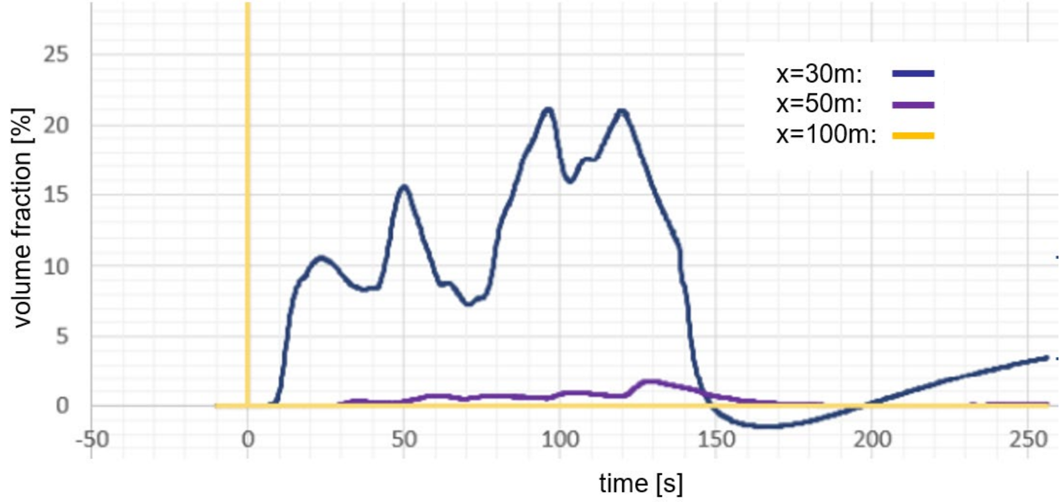
3 velocities (reference, high, low)

Variation of turbulence

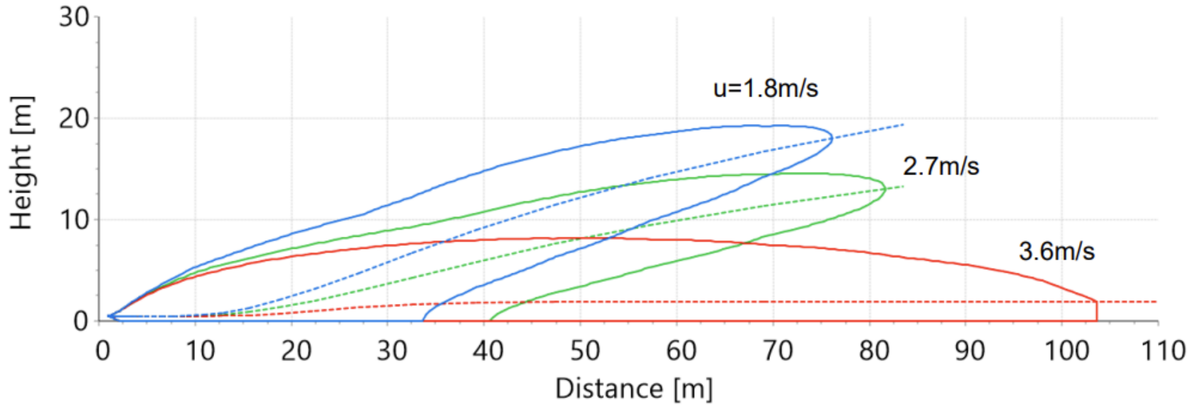
Variation of surfaces roughness length

Variation of heat flux from ground

Transition from lifted plumes to grounded plumes is observed withing the variation of wind speed (present during the experiment)



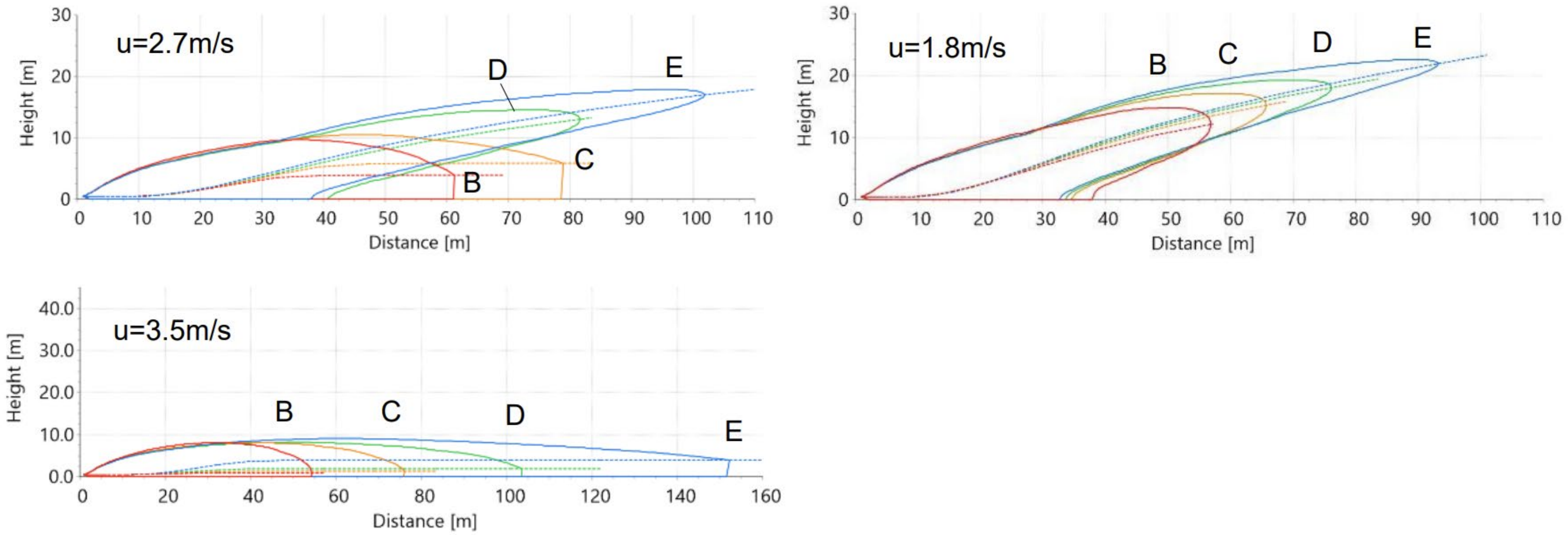
Test 4: Maximum hydrogen concentrations during Test 6 (EXP)*



Test 06: Plume simulations, shown by concentration contour (2% v/v)

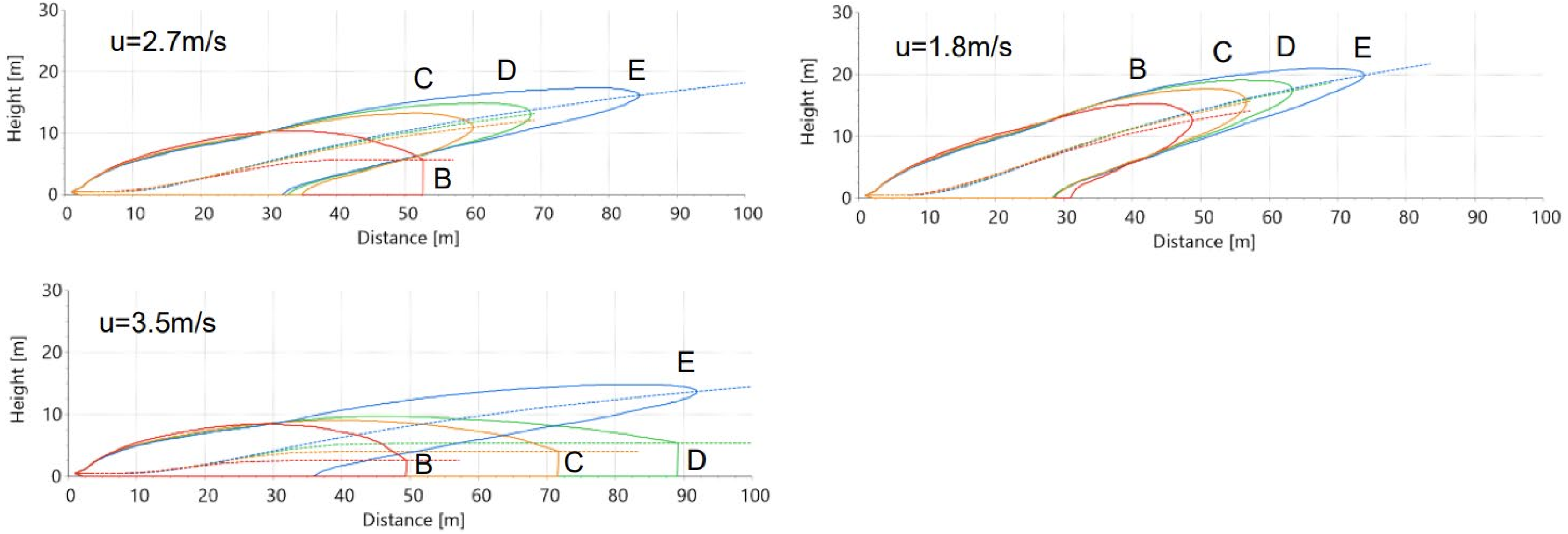
*Exp data from: Medina C.H., Allason D., Report No.: 853182, Rev. 2, 2020

Test 06 Variation of turbulence: weather stability class



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

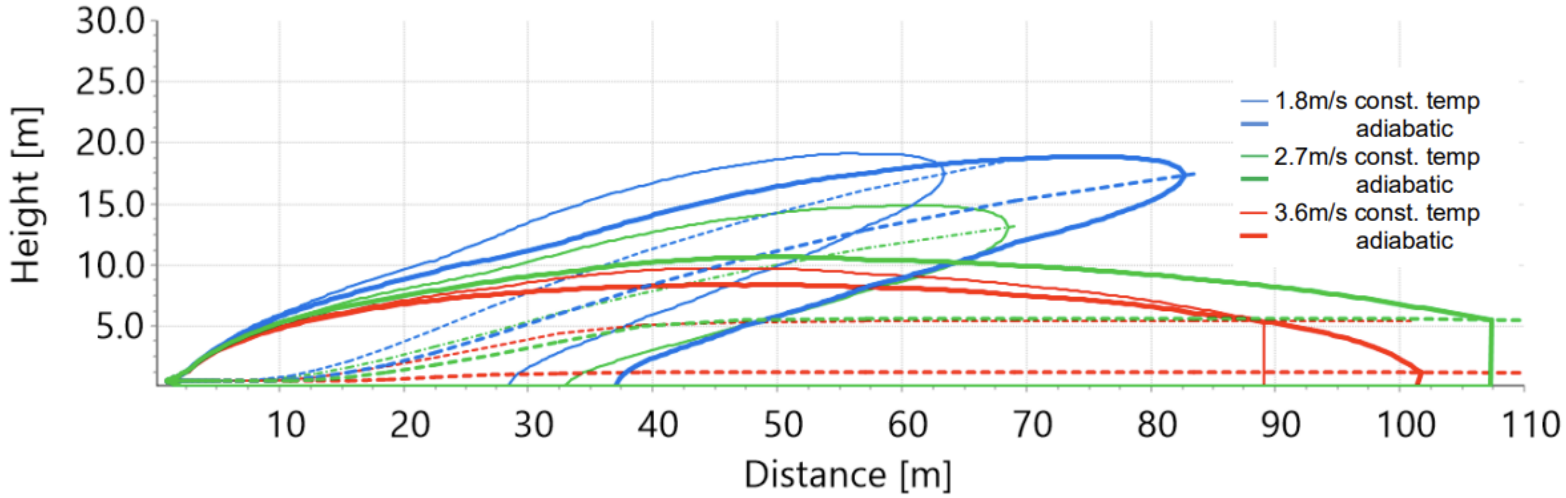
Test 06 Variation of turbulence: surface roughness length



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

Shorter effect distances, slightly more lifting plumes due to different velocity profile + turbulence level)

Test 06 Variation of heat transfer from ground



Test 6: 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)

Liquid hydrogen: very low temperatures results in high heat flux from ground > sensitive to plume rise
For 2-phase releases humidity of ambient air can also play a significant role

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Test 06 Results

Experiment:

Correlated sensor reading at 2 distances

Sensor at 100m detects does not concentrations during the experiment: lifted plume

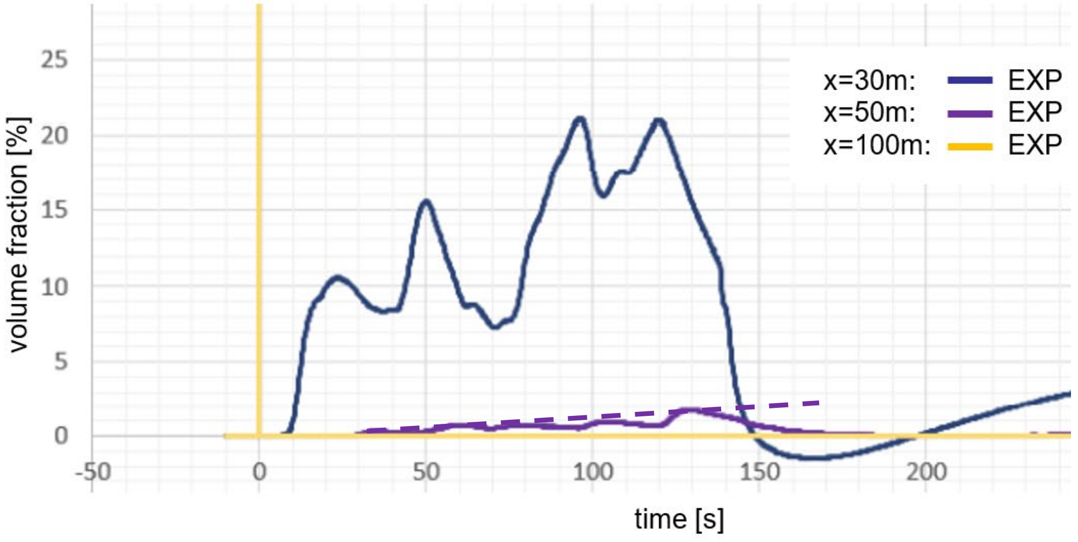
Simulation results including parameter variations of:

3 reference velocity (reference, high, low), increased turbulence (Pasquil C)

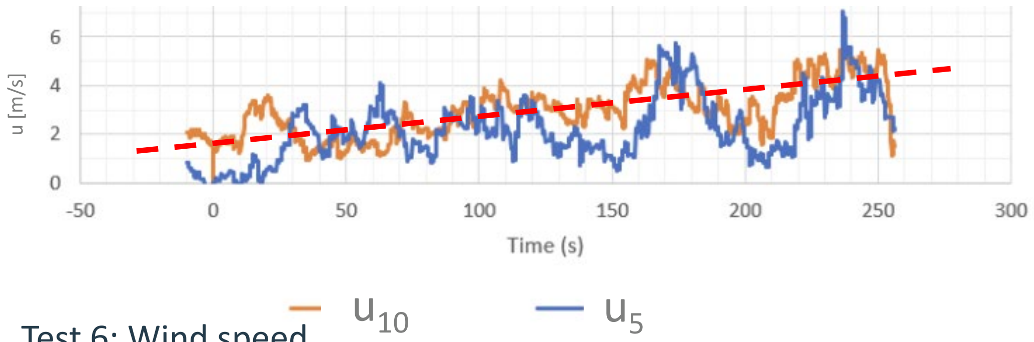
Reasonable agreement with concentration average data

Maximum values close to release are underpredicted (integral/CFD-RANS > LES)

Grounded plumes overpredict measured values



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



Test 6: Wind speed

Data from: Medina C.H., Allason D., Report No.: 853182, Rev. 2, 2020

Summary & Recommendations

- For light gas clouds, already moderate wind speeds can lead to fully grounded plumes (risk of ignition, confinements)
- For hydrogen releases, changing turbulence levels might have a significant impact on effect distances, flammable clouds and risk
- Assessing risk (QRA) should include an assessment of the effect of turbulence including uncertainties in turbulence due to atmospheric conditions
- Apart from the demonstrated variations other parameters might be applicable (ambient temperature, humidity, release term/scenario, storage condition…)
- Integral Models like EFFECTS can be applied to get an insight into the sensitivities for different scenarios with low effort in a short time

worst case **Heavy Gas** release ≠ worst case **Light Gas** release

Heavy Gas: low wind speed, stable atmospheric conditions (less mixing)

Light Gas: moderate wind, neutral or unstable atmospheric conditions (more mixing, grounded plumes)

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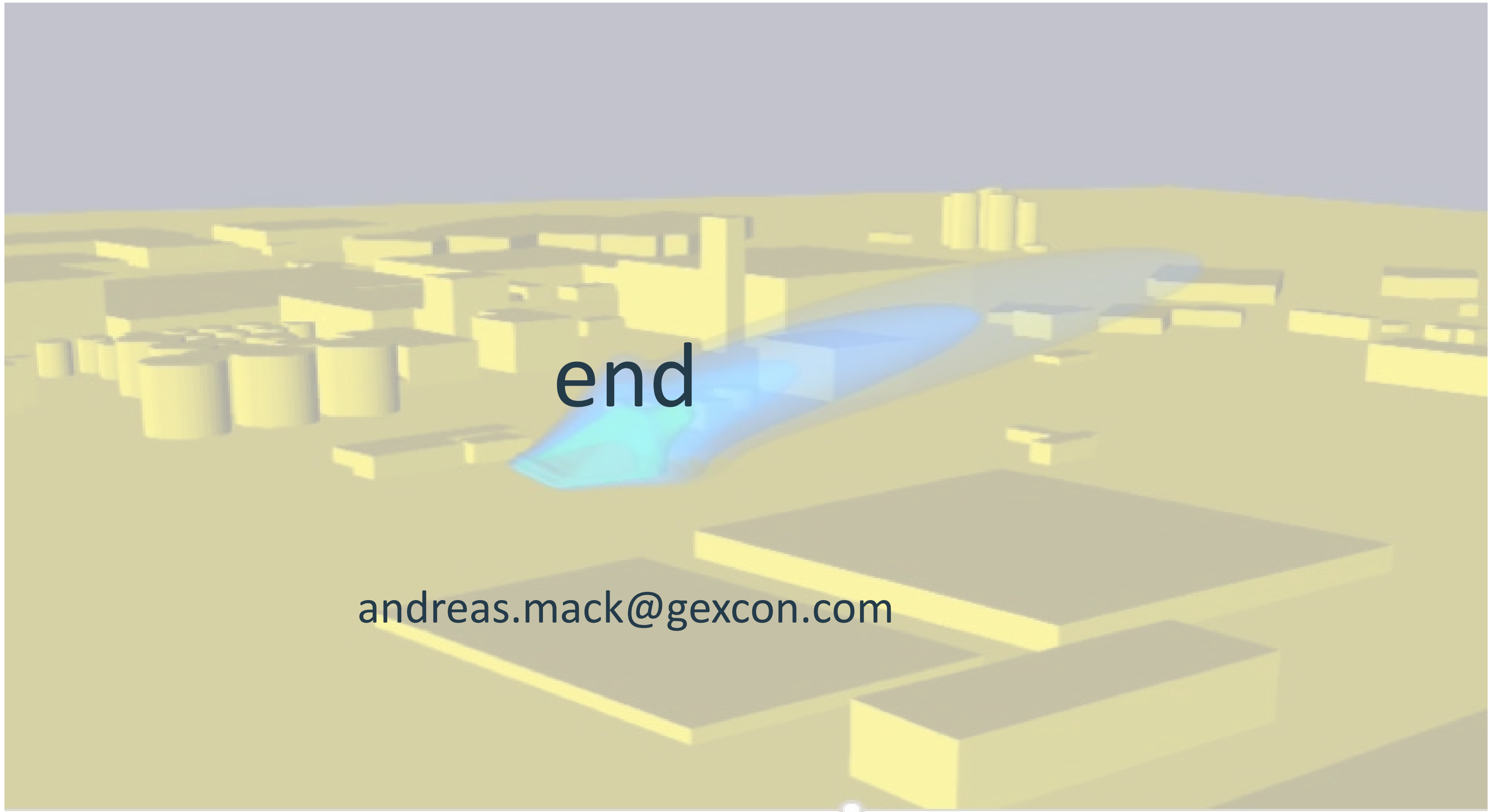

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EFFECTS Visualization of lifting plume (3D)