Hydrogen Leak Detection: Atmospheric Dispersion and Sensor Placement

Mr Rakesh Paleja: Shell Research Limited
Ms Aarti Nagarajan: Shell India Markets Private Limited
Dr Matthew Jones: Shell Research B.V
Dr Philip Jonathan: Shell Research Limited

Agenda

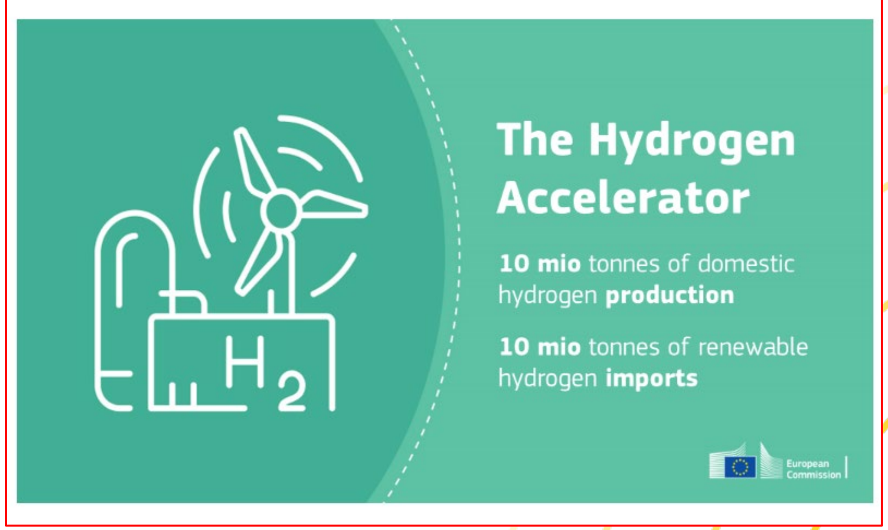
- Motivation
- Gaussian plume dispersion
- Sensor types
- Dispersion of hydrogen and sensor placement
- Conclusions and future work

Motivation

- Growing attention to Hydrogen (H_2) as an energy carrier and low carbon solution in energy transition to net zero
- Projected H_2 aspirations for some major economies*:
  EU: 10 million tonnes of production and imports by 2030
  UK: 5GW of production by 2030
  China: 35 million tonnes by 2025[1]
  India : 5 million tonnes by 20230[2]

- Due to small size H_2 may be more prone to leak
- Motivation:
  a)How does H_2 gas cloud disperse in the atmosphere?
  b)What are the sensor technologies and what is their suitability for H_2?
  c)How to spatially place sensors given the limitations of current technologies?
  d)What are the emerging R&D topics?

* Indicative aspirations in public domain



EU Hydrogen accelerator programme
https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en


UK Hydrogen Strategy

growing domestic and global markets. The UK Hydrogen Strategy sets out how we will drive progress in the 2020s, to deliver our 5GW production ambition by 2030 and position hydrogen to help meet our Sixth Carbon Budget and net zero commitments.

August 2021

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1175494/UK-Hydrogen-Strategy_web.pdf

Gaussian Plume Dispersion

- Advection diffusion equation[4]:

$$\frac{\partial C}{\partial t} = -\nabla.(C\vec{u}) + \nabla.(\boldsymbol{K}\nabla C) + S \text{ (Equation 1)}$$

- Under steady state condition, concentration profile given by[4]:

$$C(x,y,z) = \frac{1e^6 Q}{2\pi\sigma_y\sigma_z\rho u 3600}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\begin{array}{c}\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\\ \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\end{array}\right] \text{(Equation 2)}$$

C: Concentration, ppm,

Q: Leak rate, kg/h

$x, y, z,$: Distance in downwind, across wind and vertical direction, m

σ_y, σ_z: Horizontal and vertical standard deviations of emission distribution, m

u : Wind speed, m/s

ρ: Density, kg/m^3

h : Release height, m

Δh:Plume elevation from release height, m

H: Plume centre line distance from ground level

Gaussian plume dispersion

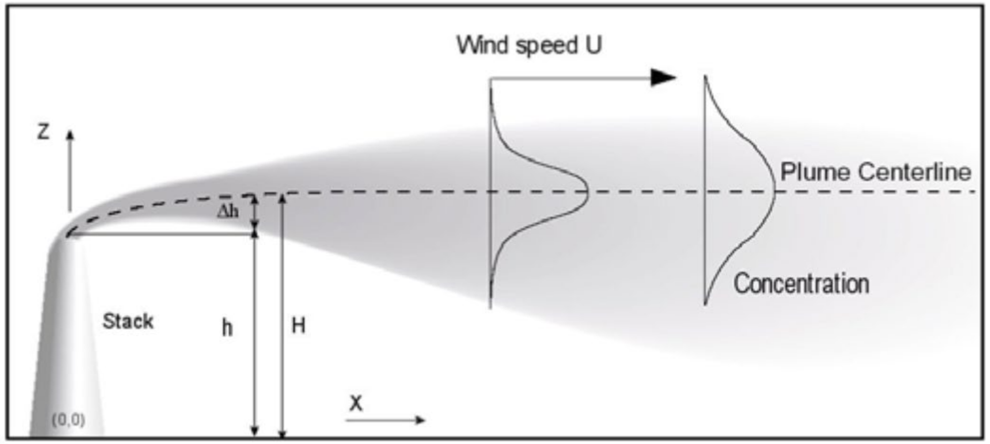


Image from https://www.researchgate.net/figure/Gaussian-plume-for-air-dispersion-model_fig1_267209805?vm=r

σ_y, σ_z and wind stability classes

- σ_y, σ_z linear function of downwind distance x and random shift in wind direction[4]
- Random shift expressed as standard deviation of wind angle θ_y, θ_z
- σ_y, σ_z specified as a function of x and θ_y, θ_z

  $\sigma_y(x) = x * tan(\theta_y) + w$ (Equation 3)

  $\sigma_z(x) = x * tan(\theta_z)$ (Equation 4)

- Generally for European locations, stability classes D and E are prevalent. Realistic u and θ_y, θ_z :

  u : 3- 9 m/s

  θ_y, θ_z : 3- 11^0

Pasquill Class[7]	θ, degrees[5]
A-Extremely unstable	25
B-Moderately unstable	20
C-Slightly unstable	15
D-Neutral	10
E-Slightly stable	5
F-Moderately stable	2.5
G-Extremely stable	1.7

Wind speed	Daytime incoming solar radiation			Night time cloud cover	
m/s	Strong	Moderate	Slight	>50%	<50%
<2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Class D applies with overcast skies at any windspeed during day or night[7]

Hydrogen Leak Detection : Sensor Types

Spot Sensors (e.g. Smoke detector)

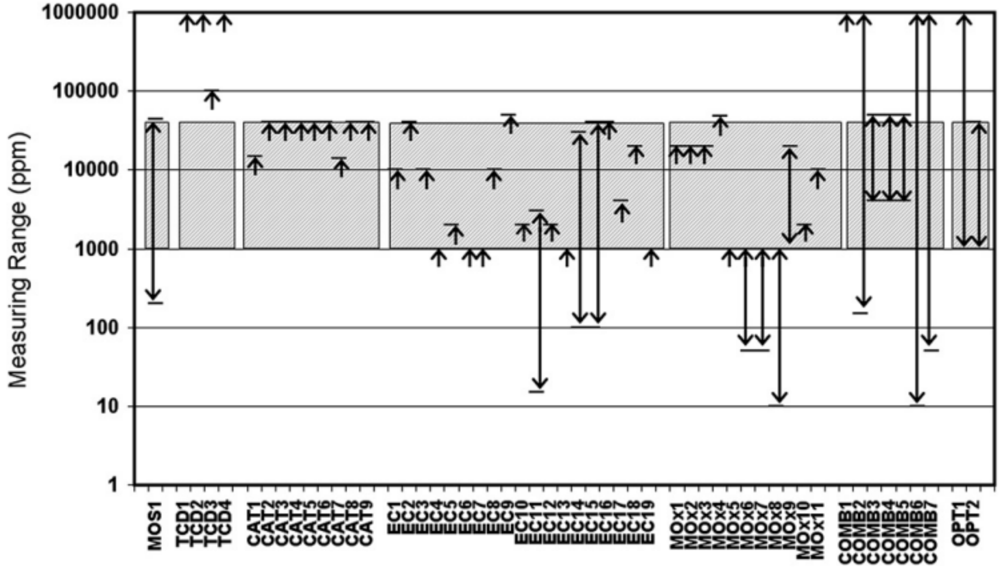
- H_2 has to come in contact with the sensor
- Commercially available
- Sensor will detect if

  -Concentration of H_2 is above the lower measuring range also called low detection limit (LDL)

  -H_2 comes in contact with the sensor

Wide Area Sensors (e.g. Human eye, IR camera)

- H_2 does not come in contact with the sensor
- Not commercially available



Measuring range of spot sensors[6]

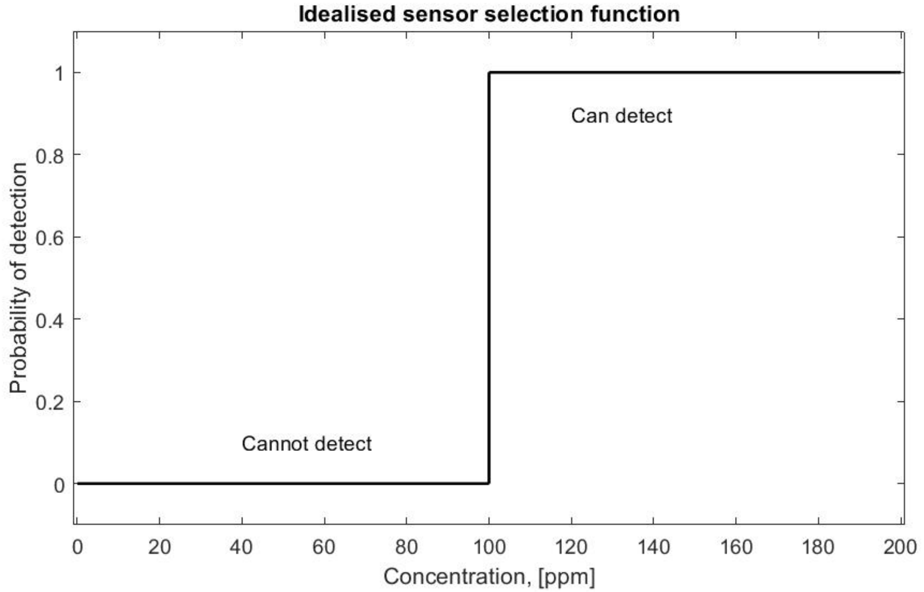
Most commercial spot sensors have LDL >=1000 ppm.

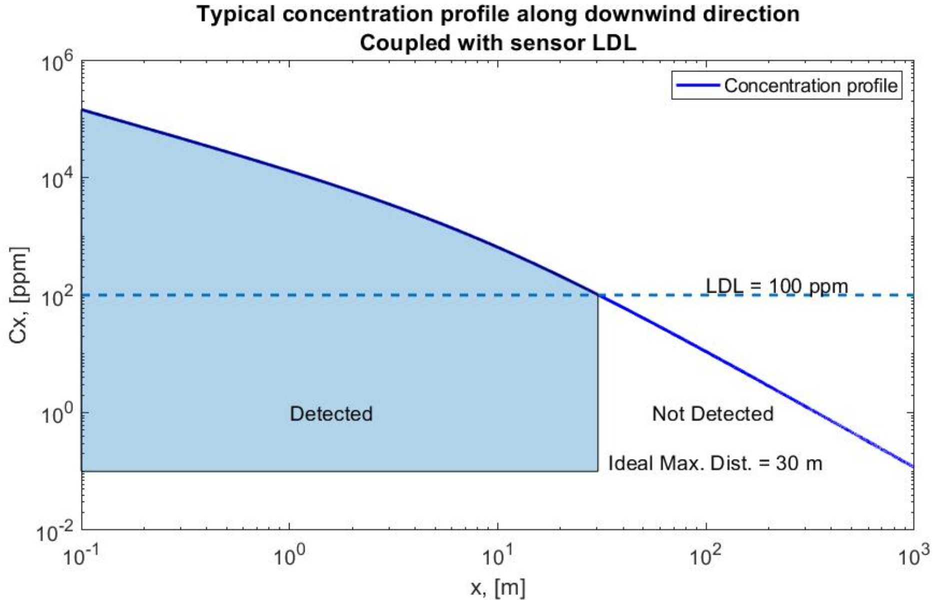
Few have LDL = 10-100 ppm

No commercial sensor with LDL = 1ppm

Combining sensor property with Gaussian Plume Dispersion in 1-D

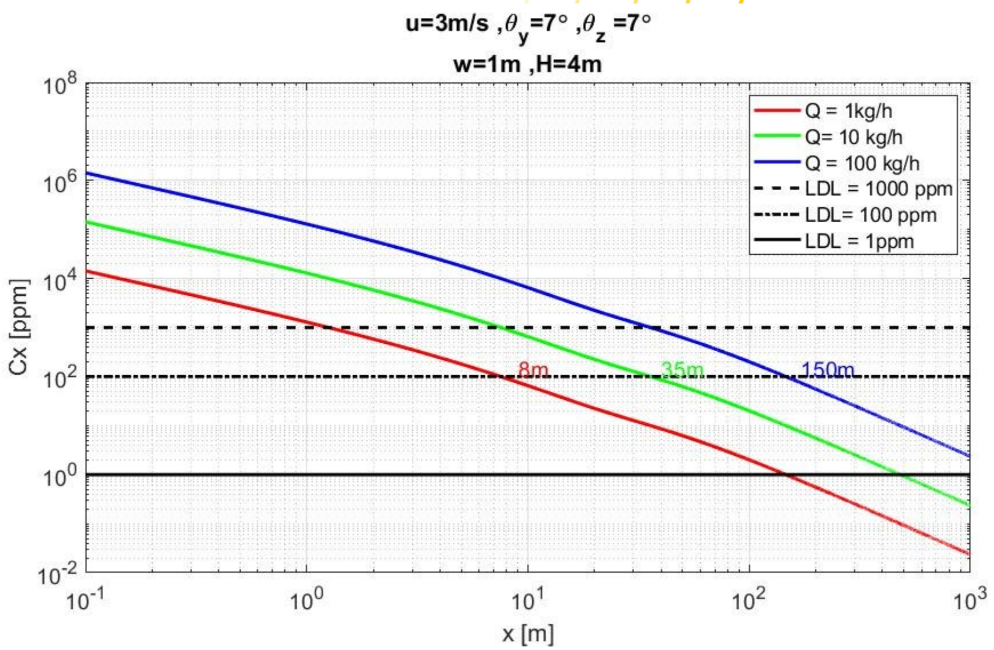
- Sensor selection function intrinsic property of the sensor and depends on its the lower detection limit (LDL)
- Pollutant concentration profile ($C_{(x,0,0)}$ or simply C_x) in downwind direction given by Equation 2 (Gaussian Plume dispersion)
- Combining the two provides useful information on sensor placement to detect a potential leak
- Distance at which the concentration is equal to LDL is the Maximum Distance from source at which the sensor can be placed
- Sensor place beyond Maximum Distance will lead to false negative alarm

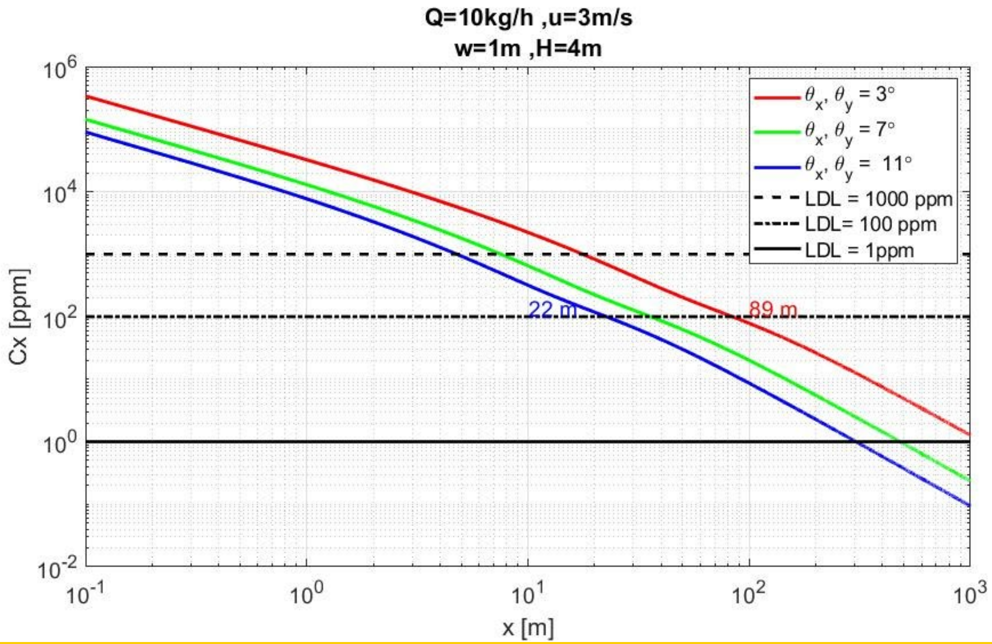


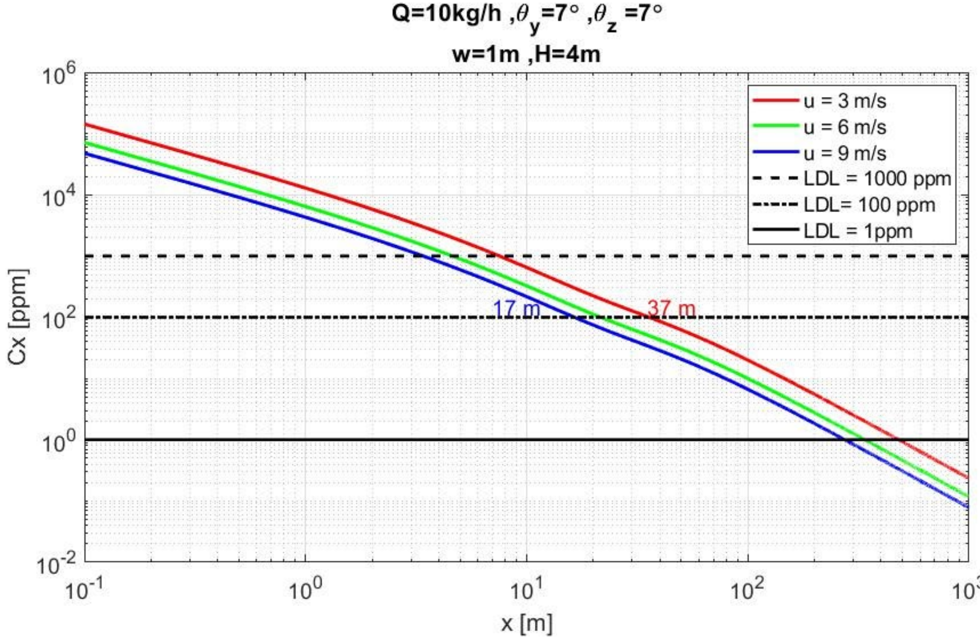


Impact of Q, u and θ on Maximum Distance in 1-D

- Realistic Q and u and θ for most prevalent wind stability class assumed in simulation
- H = 4m, open space. Potential leak sources are known
- C_x can be derived analytically but not the Max Distance
- Adverse wind conditions (high u and θ_y, θ_z) reduce Max Distance

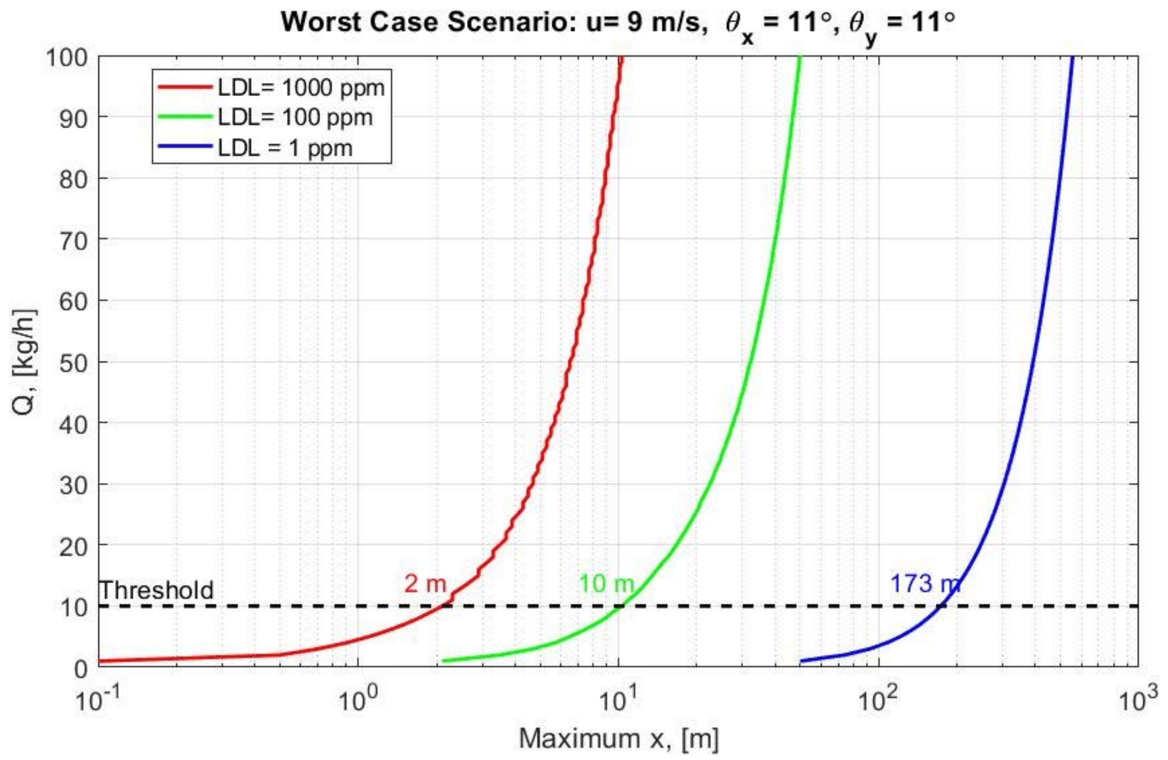






Sensor placement in 1-D: Threshold leak rate

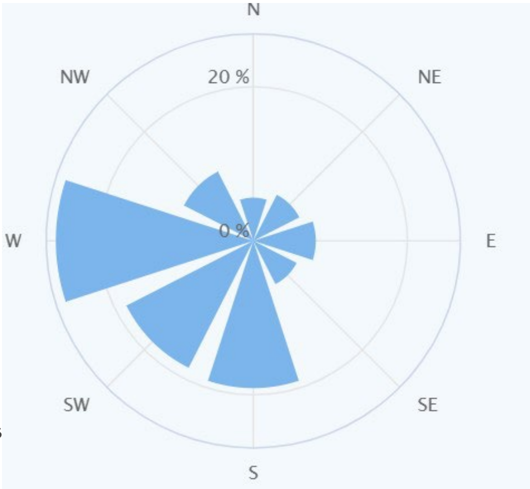
- All possible cases of Q considered for most adverse wind conditions (u = 10 m/s, θ_y, θ_z = 11^0) to determine conservative Maximum Distance
- Not all leaks can be detected by current technology
- A "threshold" leak rate can be used to understand sensor placement in downwind direction
- Sensor placement at Maximum Distance in downwind direction is a function of sensor's LDL, threshold leak rate and wind properties

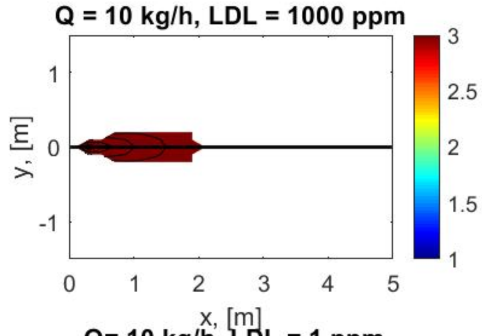


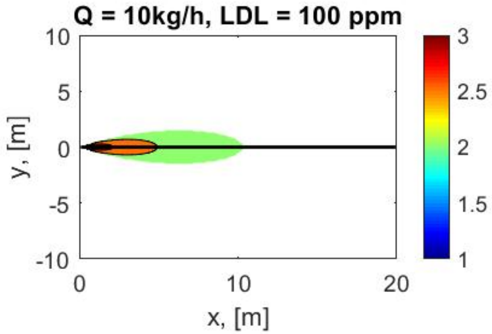
Dispersion in 2-D plane

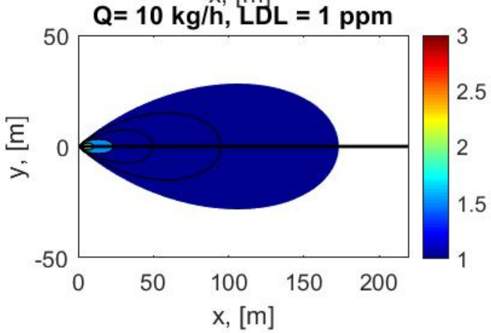
- Dispersion in 2-D plane for threshold rate coupled with sensor LDL determine co-ordinates in a plane
- Wind direction also changes over time
- A single sensor can lead to false negative (no alarm when there is a leak) with unfavourable wind direction
- Multiple sensors required to cover change in wind direction

Typical wind direction profile Manchester[8]

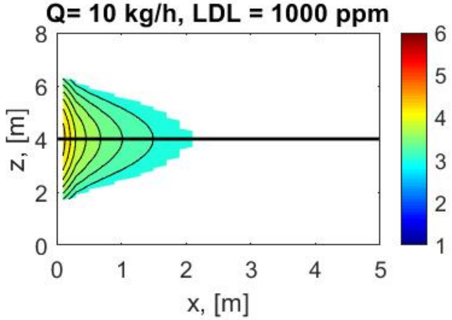


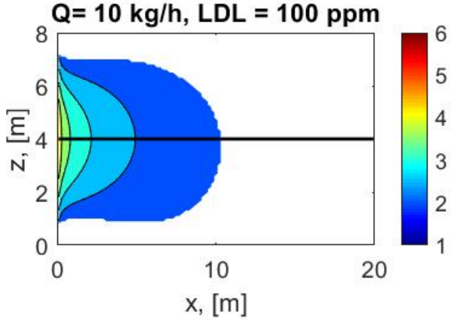


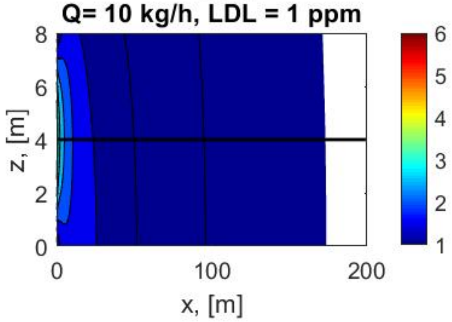




Colours show concentration (on log scale) above sensor's LDL.





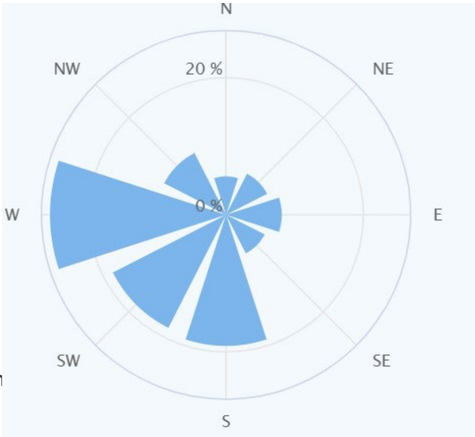


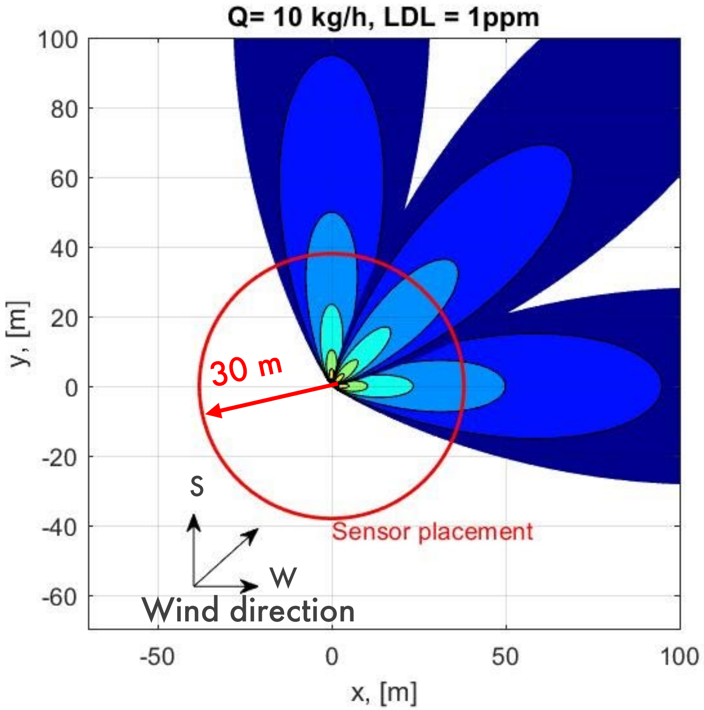
Colours show concentration (on log scale) above sensor's LDL.

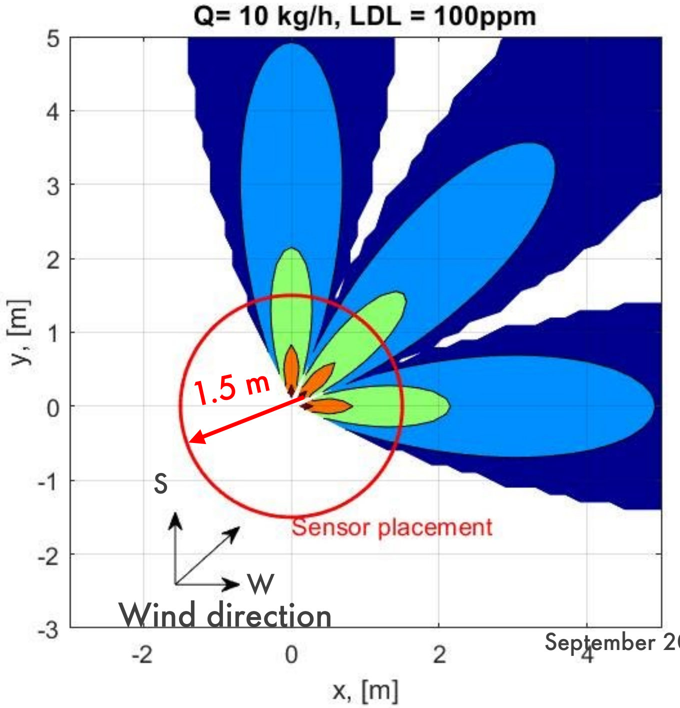
Sensor placement in 2-D (x-y) plane

- Historic wind direction data and sensor LDL useful for sensor placement in x-y plane and maximize probability of leak detection
- With three sensors limit, for prevalent wind directions, maximum distance is 30 m (1 ppm LDL) or 1.5 m (100 ppm)
- Sensor with 1000 ppm LDL not suitable to cover variation in wind direction
- Other factors such as permissible time between commencement of leak and detection play a role in number of sensors required

Typical wind direction profile Manchester[8]







Δh and approximate adjustment for 3-D sensor placement

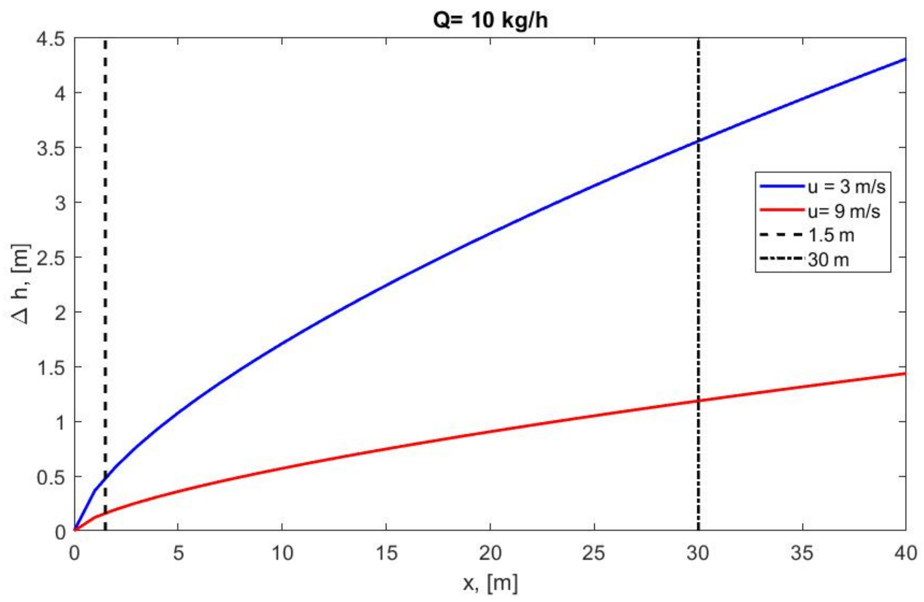
- $H = h + \Delta h$ (H = Centre line, h = release height, Δh = rise in centre line from release height)
- Buoyancy (F) and Advection (governed by u) counter each other to determine Δh, rise of plume from release height to h. Other factors* play a role
- Derivation of Δh [9] useful in determining lift in centre line and height , H at which sensors should be placed to maximise leak detection probability

  $F = Qg$ (Equation 5)

  $$\Delta h = \frac{1.6F^{0.33}x^{0.66}}{u} \text{ (Equation 6)}$$

- Units of measurement:

  F: m4/s3, Q:m3/s, g: m/s2
- Effective 3-D placement thus covered using dispersion properties and sensor LDL



* Other factors that determine Δh are release pressure & temperature, ambient temperature gradient in vertical direction, size of leak etc

Conclusions and future research areas

- It is possible to understand spot sensor placement in 3-D using Gaussian Plume dispersion and Sensor's Low Detection Limit (LDL) for open space application with potential leak sources known

- For wind conditions prevalent in Europe, sensors with lower LDL provide flexibility and additional degree of freedom in placement strategy

- Buoyancy is complex, needs to be fully understood

- R&D efforts to develop spot sensors with LDL ~1ppm will help to develop sustainable pathway for green hydrogen economy

- Development of appropriate wide area sensing technology can lead to significant reduction false negatives

References

1: Center for Strategic and International Studies. (2022). *China Unveils Its First Long Term Hydrogen Plan.* Retrieved from CSIS: https://www.csis.org/analysis/china-unveils-its-first-long-term-hydrogen-plan

2: Reuters. (2022). *India plans to produce 5 mln tonnes of green hydrogen by 2030.* Retrieved from https://www.reuters.com/business/energy/india-plans-produce-5-mln-tonnes-green-hydrogen-by-2030-2022-02-17/#:~:text=India%20will%20set%20up%20separate%20manufacturing%20zones%2C%20waive,to%20incentivise%20production%2C%20the%20federal%20power%20ministry%2

3: ARUP. (2023). *Five minutes guide to Hydrogen.* Retrieved from ARUP: https://www.arup.com/perspectives/publications/promotional-materials/section/five-minute-guide-to-hydrogen

4: Stockie, J. M. (2011). The Mathematics of Atmospheric Dispersion Modelling. *Society Of International Applied Mathematics*, 349-372. doi:10.1137/10080991X

5: NOAA Air Resource Laboratory (2023). *PG classes for fluctuations in wind direction and vertical temperature gradient.* Retrieved from https://www.ready.noaa.gov/READYpgclass.php

6: Brett, L. B. (2010). Identifying performance gaps in hydrogen safety sensor technology for automotive and stationary applications. *International Journal Of Hydrogen Energy*, 373-384.

7: Kahl, J. (2018). Atmospheric stability of characterisation using the Pasquill method. A critical evaluation. *Atmospheric Environment*, 196-209. doi:https://doi.org/10.1016/j.atmosenv.2018.05.058

8: Weather Archive (2023) *Weather archive in Manchester*. Retrieved from World Weather: https://world-weather.info/archive/united_kingdom/manchester_1/