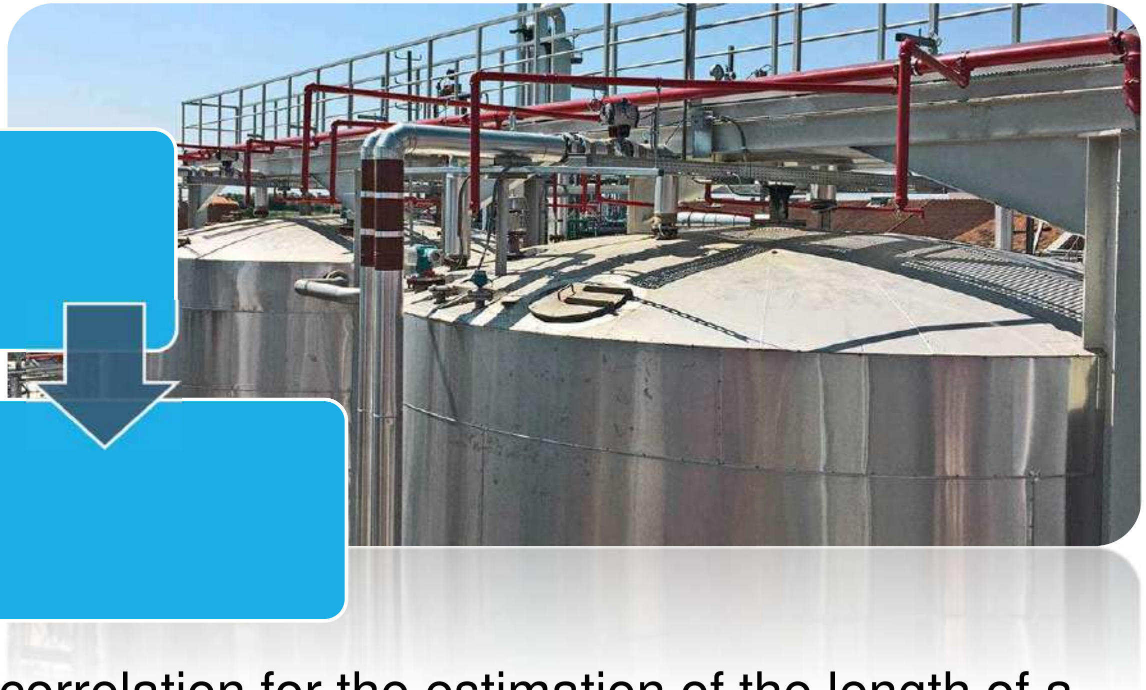
Security aspects related to critical installations:
quantitative analysis of accident scenarios

Valentina Busini

PRESENTATION OUTLINE

- Context 
- Definition of representative case studies 
- Results of the simulations 

CONTEXT



Handling of gas at high pressures

Intrinsecally hazardous situation

For example: by using the simpler correlation for the estimation of the length of a jet fire:

$$\frac{L_j}{d_j} = \frac{15}{C_T}\sqrt{\frac{MW_a}{MW_f}}$$

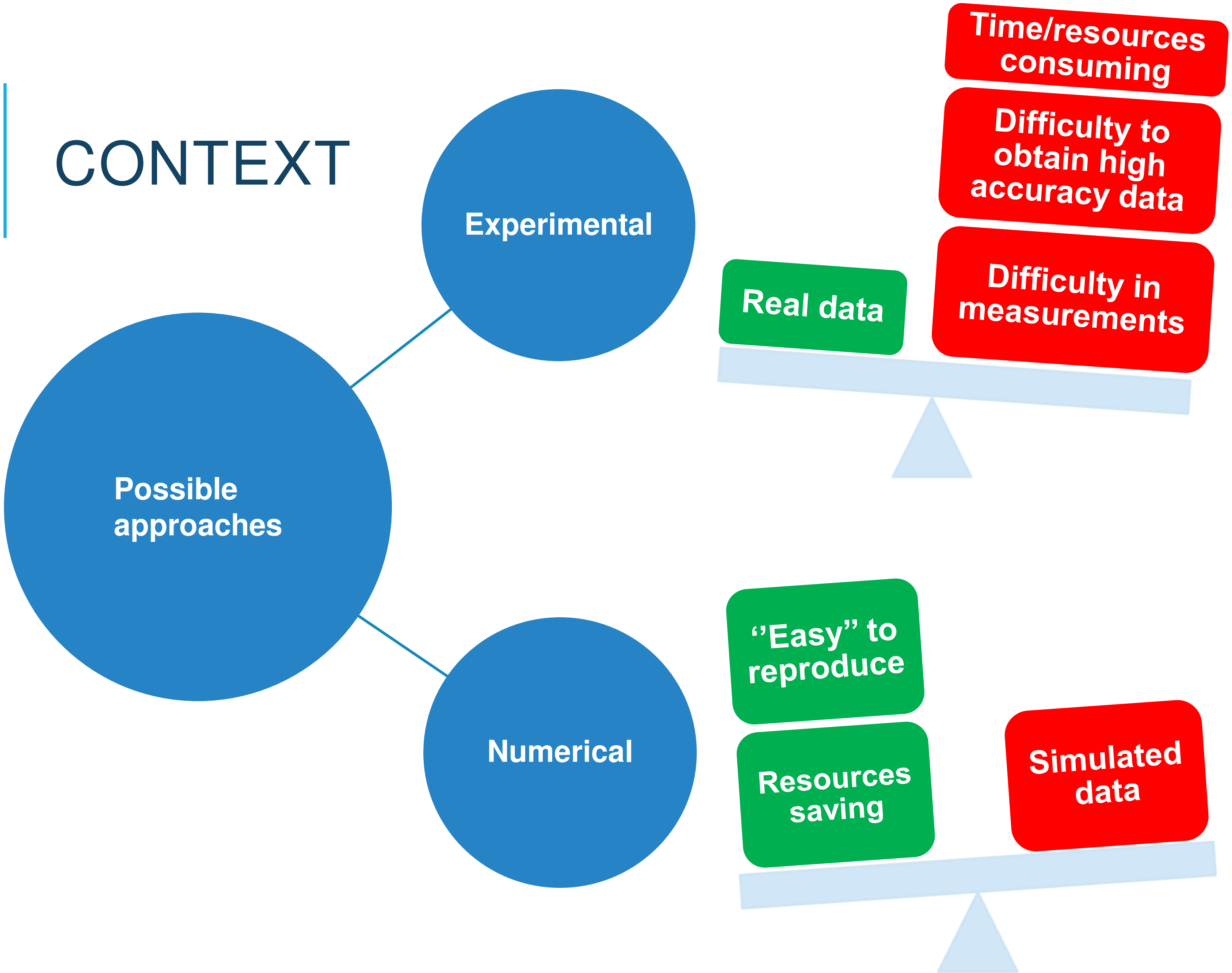
Considering propane as fuel (C_T 0.038), for a jet diameter of 1'' the length is 8 m.

CONTEXT

Small calibre bullet => loss of containment + HP gas + flammable substance + ignition

Scenarios with relevant consequences and domino effects

CONTEXT


Possible approaches
Experimental
Numerical
Time/resources consuming
Difficulty to obtain high accuracy data
Difficulty in measurements
Real data
"Easy" to reproduce
Resources saving
Simulated data

CONTEXT

Possible approaches

Experimental

Numerical

Algebric correlations

Integral models

«The presence of an obstacle **influences the flow field** produced by the interaction of an unintended release and such an obstacle»

Bénard et al., 2016.

CFD models → **Takes into account all kinds of obstacles**

AIM AND PROPOSED APPROACH

A general criterion for the jet impinging an obstacle: when CFD analysis can be avoided and when not?

Through a systematic approach, results of CFD simulations can be used to derive such a criterion: CFD simulations are the starting point

CFD STRATEGY

High pressure jet would require compressible simulations which are time consuming

Thus, the equivalent diameter approach has been used

Assuming an isentropic transformation and an ideal gas

$$\left(\frac{D_{\mathrm{ps}}}{D}\right)^2 = C_D \left(\frac{P_1}{P_3}\right)\left(\frac{T_3}{T_1}\right)^{0.5}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

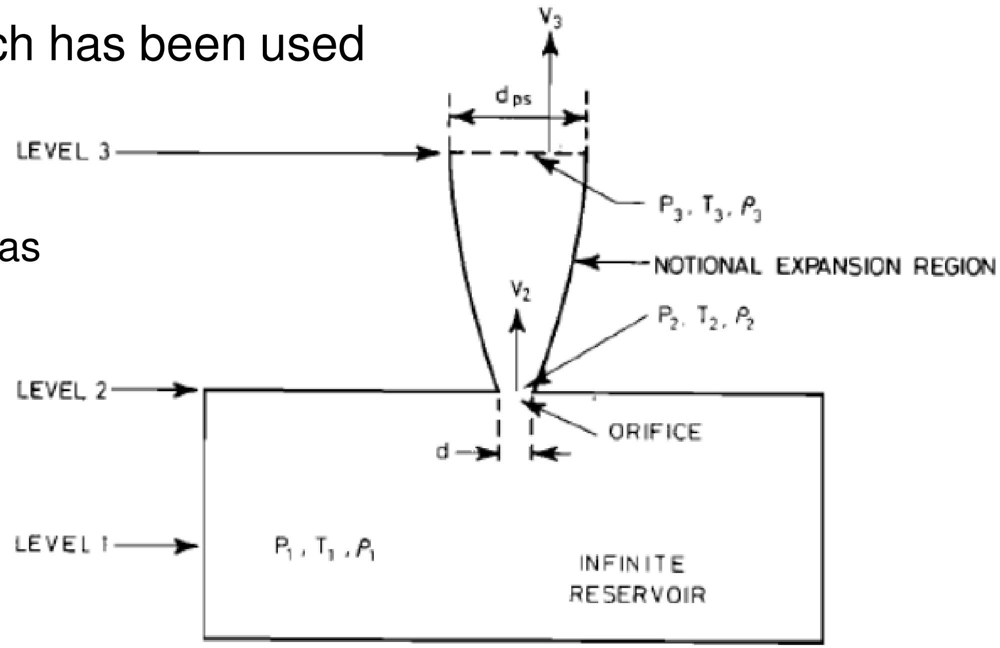


Figure 1: Zoning of an under-expanded jet

Birch et al. (1984)

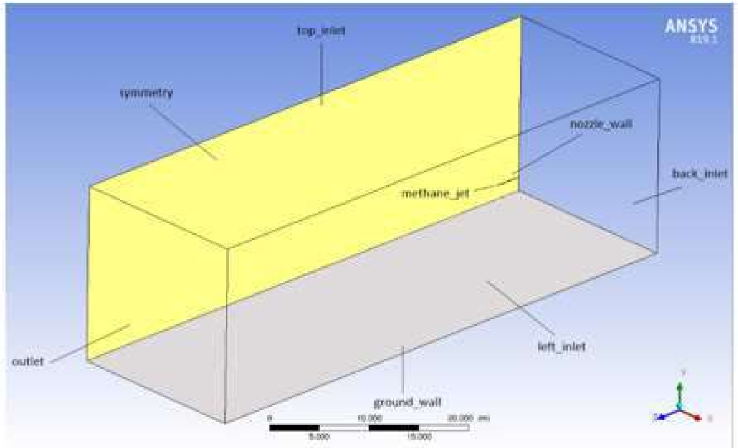
CFD MODEL DESCRIPTION

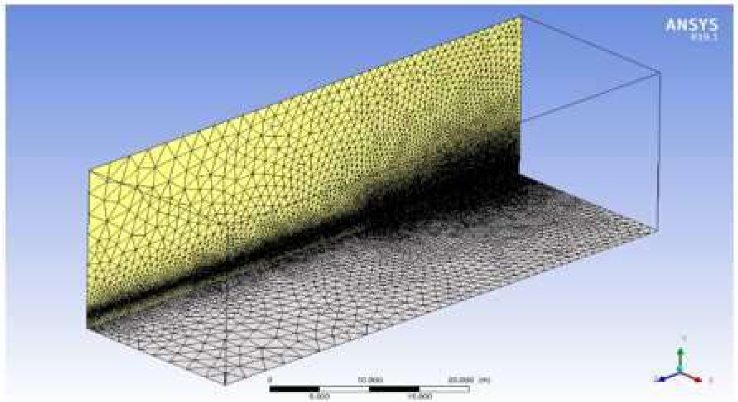
Geometry
- Box computational domain properly sized
- Vertical symmetry plane in correpondence of the jet axis
- Line body feature along jet axis

Mesh
- Body of influence mesh strategy
    - Refined mesh along the jet axis
    - Refined mesh around the ostacles
- Full unstructured tetrahedral ($X \cdot 10^6$ cells)

Numerical Solver (Fluent 19.1)
- Steady state simulations
- Pressure-based solver
- RANS – k-ω SST

✓ CFD results validated
✓ CFD results grid independent

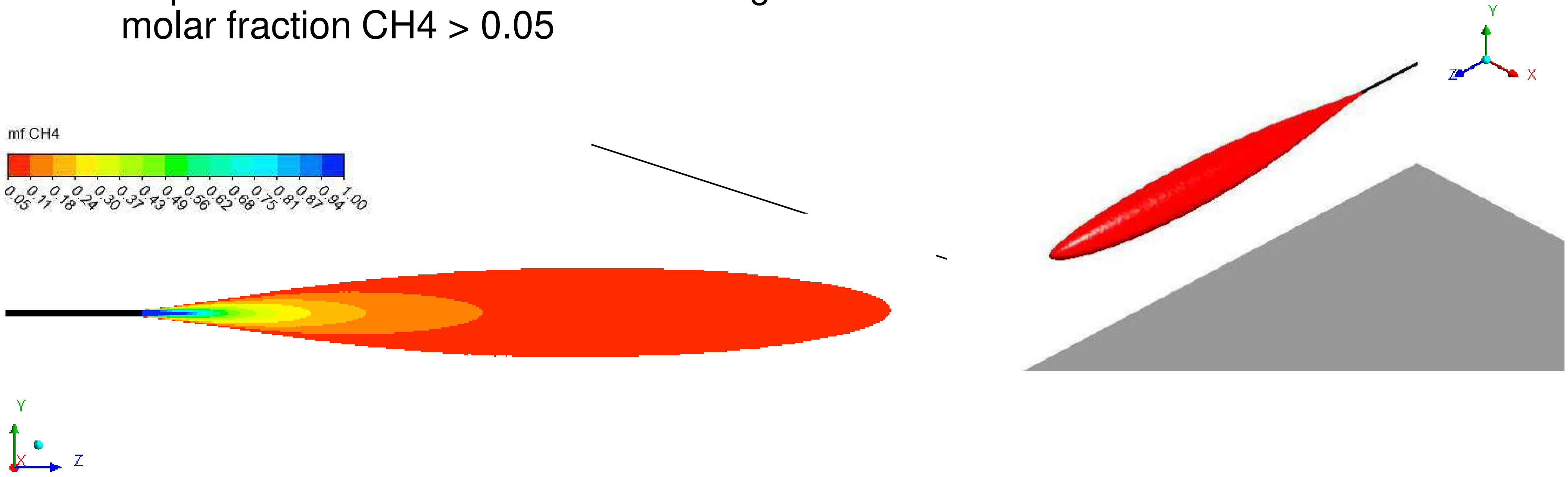




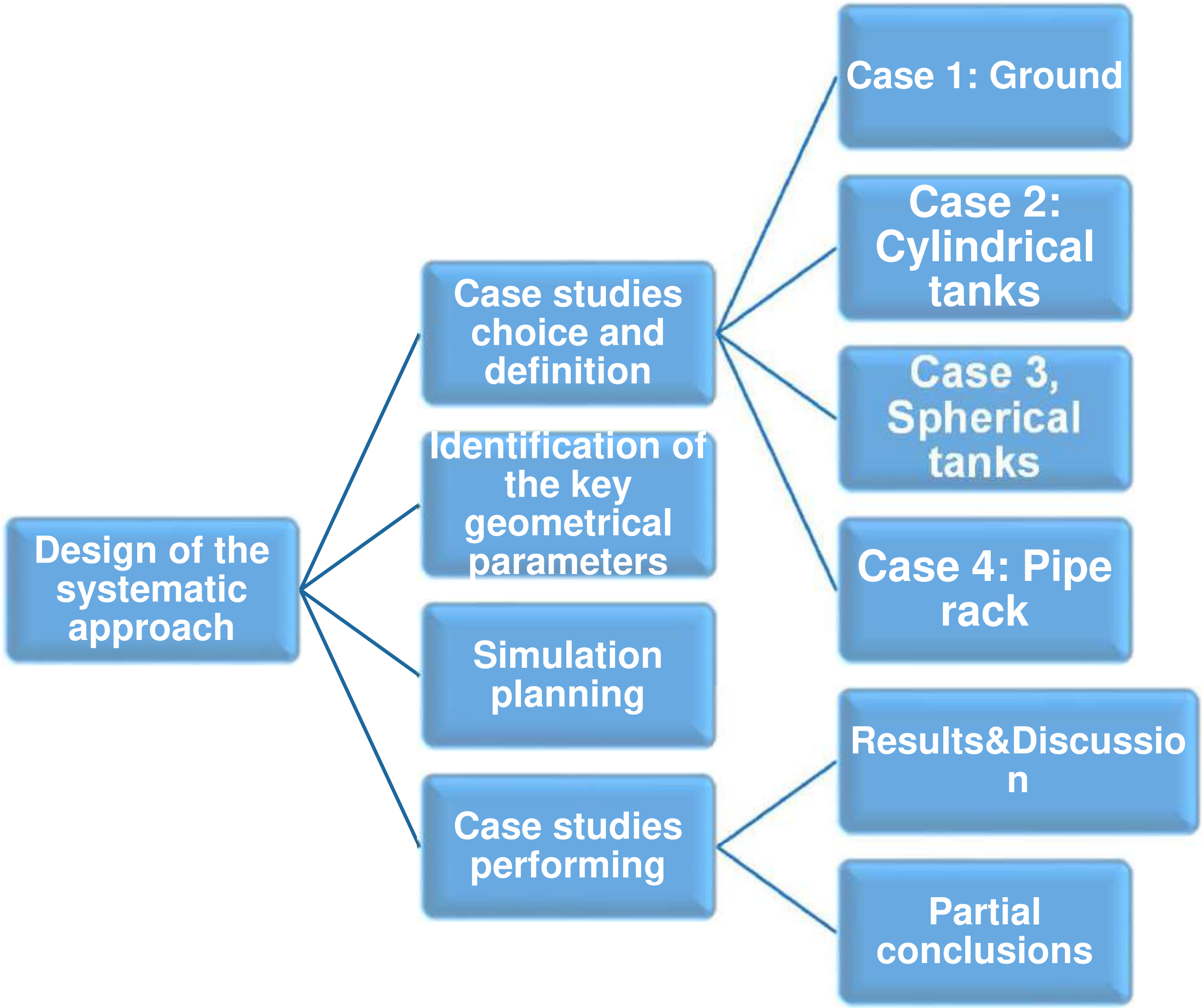
RESULTS REPRESENTATION

Isosurface constructed considering molar fraction = 0.05 (e.g., LFL of methane), no simulation of the flame!

Represents the surface area enclosing the volume of fluid for which the molar fraction $CH_4 > 0.05$

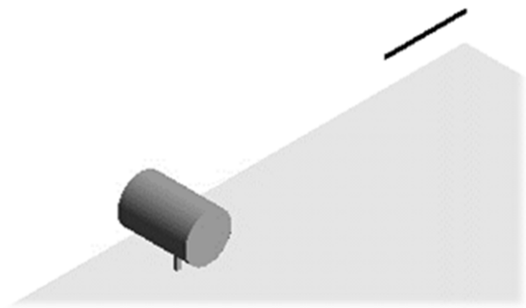


CFD WORK PLAN

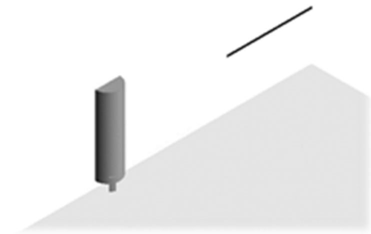


CASE STUDIES

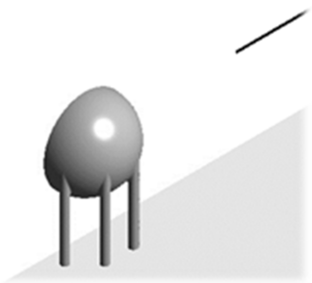
Colombini et al., J. Loss Prev. Process Ind., 2020



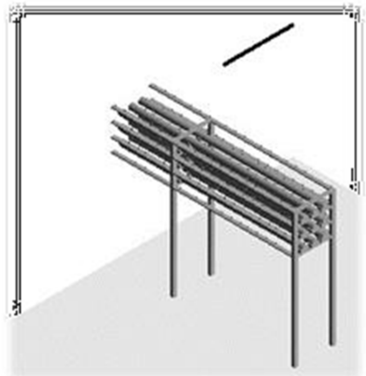
Colombini and Busini, Chem. Engineer. Trans., 2019
Colombini and Busini, ESREL Proceedings, 2019
Colombini et al., J. Loss Prev. Process Ind., 2022



Colombini and Busini, ESREL Proceedings, 2019
Colombini et al., J. Loss Prev. Process Ind., 2022



Colombini et al., J. Loss Prev. Process Ind., 2022b

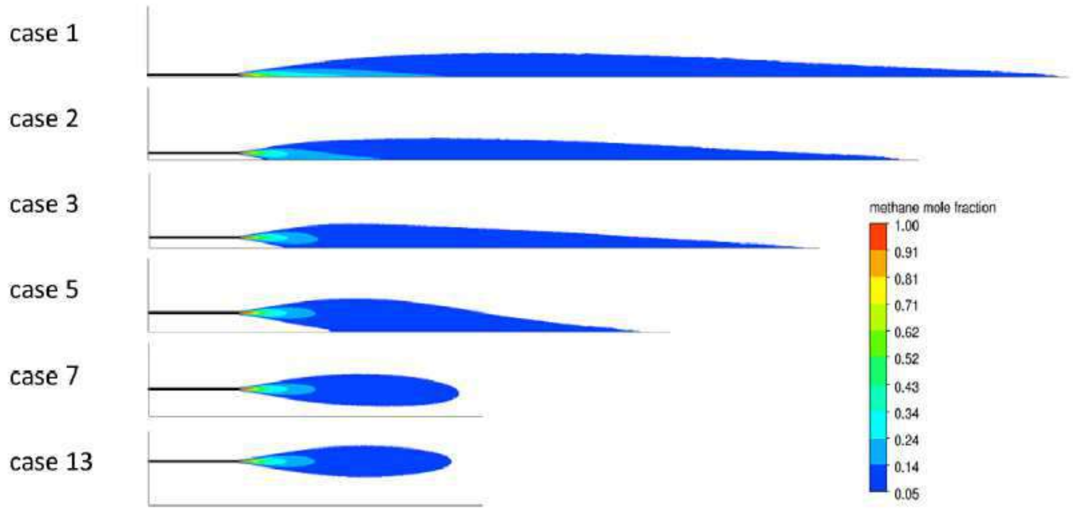


Colombini et al., J. Loss Prev. Process Ind., 2021

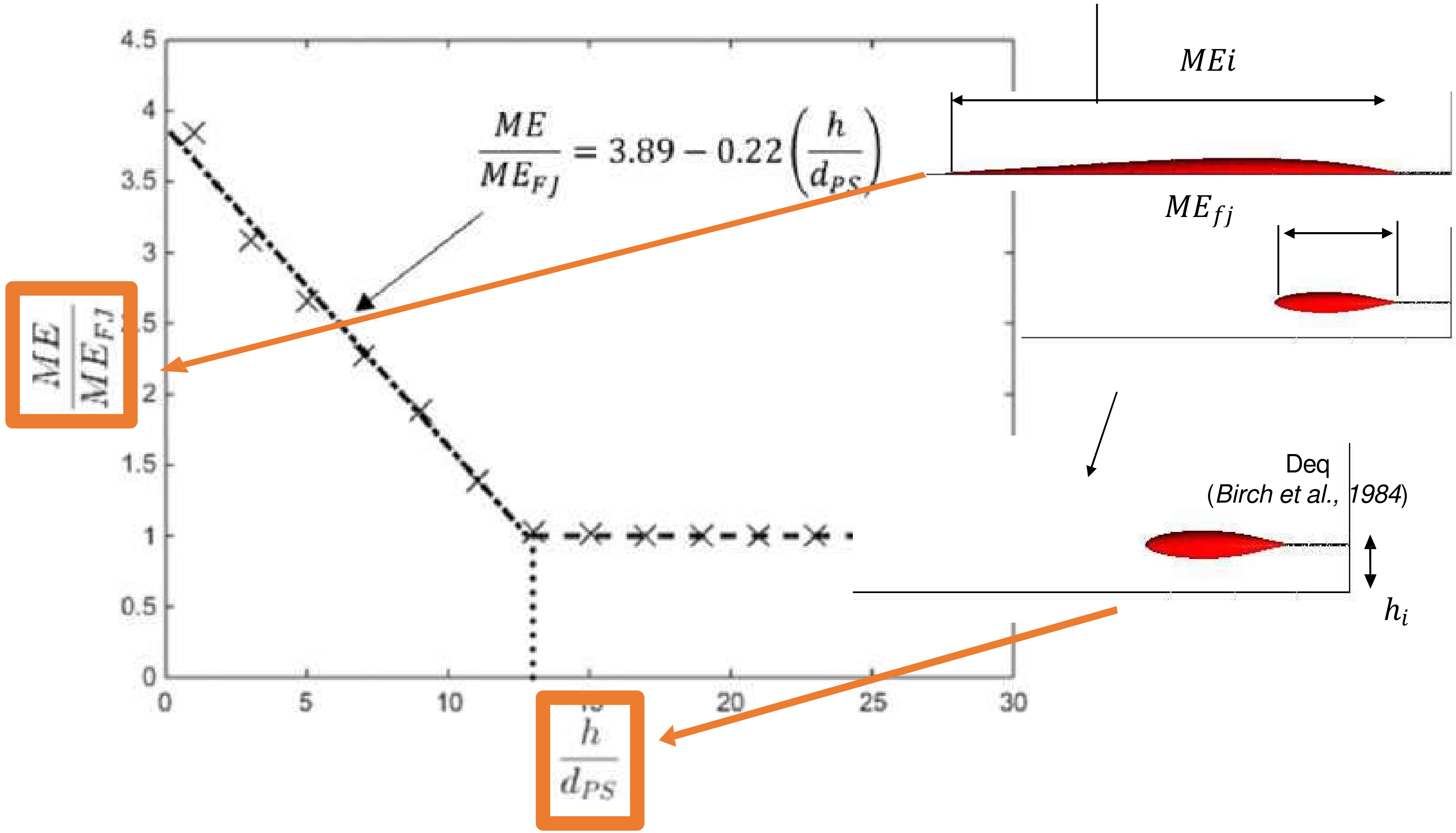
CASE STUDY 1: GROUND

- source:
- 1”=>D_{ps} 0.145m
- 65 bar_a
- 278.15 K

- Obstacle:
- ground
- 1 – 60 h/Dps (namely 13 cases, from 14.5 cm to 4.3 m).



CORRELATION FROM SIMULATIONS



VALIDATION WITH OTHER CASES

Specifics and simulations settings.

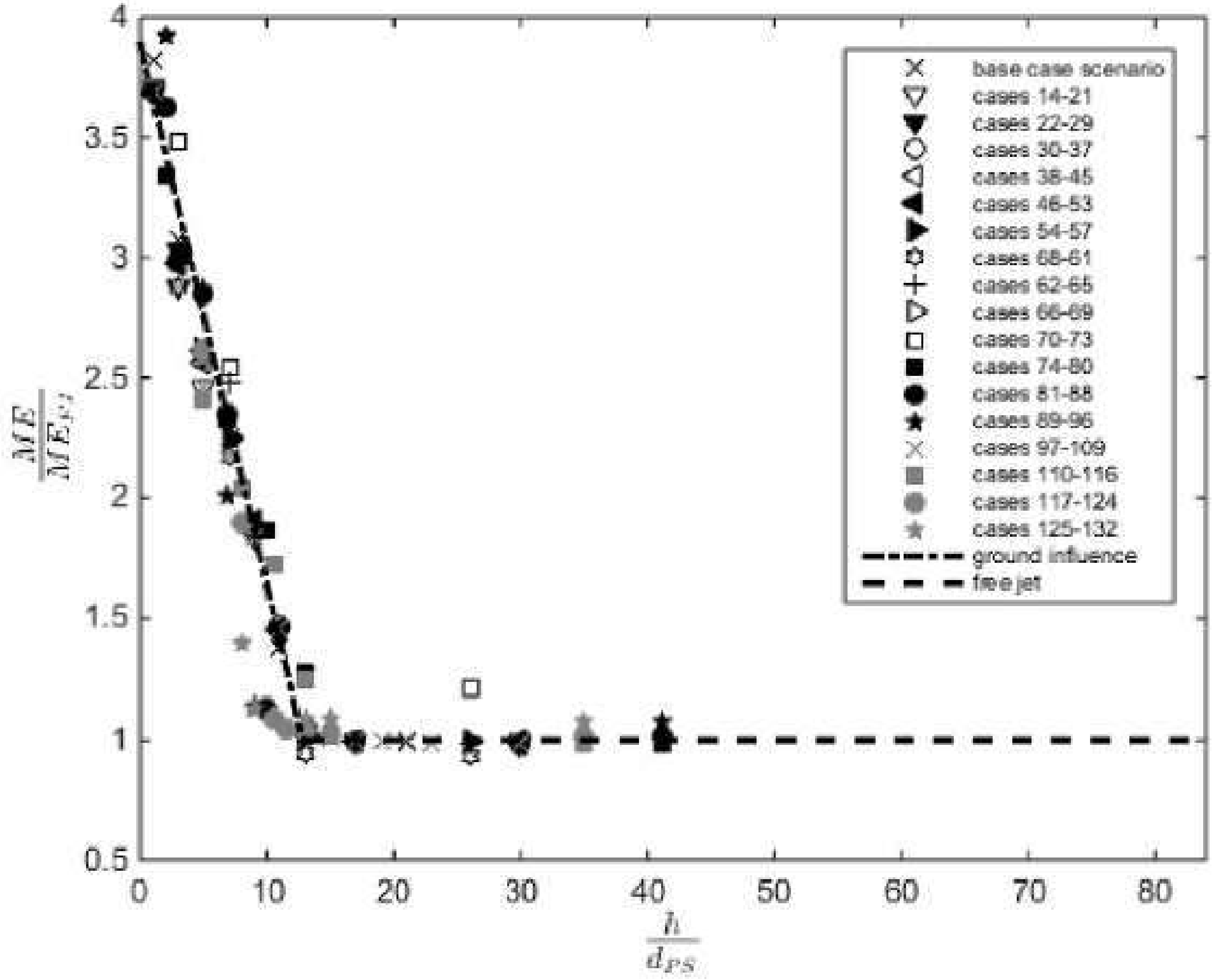
case	p [bara]	T [K]	d [m]	d_{pg} model	v_z [m/s]	T_{amb} [K]	h [m]	
14–21	2.5	278	0.0254	Birch et al. (1984)	profile	300	0.028, 0.085, 0.143, 0.257, 0.314, 0.371, 0.486, 0.858	Fig. 6a
22–29	32.5	278	0.0254	Birch et al. (1984)	profile	300	0.103, 0.309, 0.515, 0.927, 1.134, 1.340, 1.752, 3.09	
30–37	130	278	0.0254	Birch et al. (1984)	profile	300	0.206, 0.618, 1.03, 1.855, 2.268, 2.680, 3.505, 6.186	
38–45	65	278	0.0127	Birch et al. (1984)	profile	300	0.073, 0.218, 0.364, 0.656, 0.802, 0.947, 1.239, 2.187	Fig. 6b
46–53	65	278	0.0381	Birch et al. (1984)	profile	300	0.218, 0.656, 1.093, 1.968, 2.405, 2.843, 3.717, 6.56	
54–57	20	278	0.0381	Birch et al. (1984)	profile	300	0.363, 0.849, 1.576, 3.153	Fig. 6c
58–61	30	278	0.01907	Birch et al. (1984)	profile	300	0.223, 0.520, 0.967, 1.934	
62–65	85	278	0.0127	Birch et al. (1984)	profile	300	0.250, 0.583, 1.084, 2.168	
66–69	120	278	0.0127	Birch et al. (1984)	profile	300	0.297, 0.693, 1.288, 2.576	
70–73	120	278	0.0381	Birch et al. (1984)	profile	300	0.891, 2.080, 3.863, 7.727	
74–80	65	278	0.0254	Birch et al. (1984)	1	300	0.3, 0.729, 1, 1.458, 1.895, 2.187	Fig. 6d
81–88	65	278	0.0254	Birch et al. (1984)	10	300	0.3, 0.729, 1, 1.458, 1.676, 1.895, 2.187, 6	
89–96	65	278	0.0254	Birch et al. (1984)	20	300	0.3, 0.729, 1, 1.312, 1.458, 1.895, 2.187, 6	
97–109	2.5	278	0.0254	Birch et al. (1984)	profile	300	0.028, 0.085, 0.143, 0.200, 0.257, 0.314, 0.371, 0.429, 0.486, 0.553, 0.6, 0.657, 0.858	Fig. 6e
110–116	2.5	278	0.0254	Birch et al. (1984)	1	300	0.143, 0.228, 0.3, 0.371, 0.429, 1, 6	
117–124	2.5	278	0.0254	Birch et al. (1984)	10	300	0.143, 0.228, 0.3, 0.328, 0.371, 0.429, 1, 6	
125–132	2.5	278	0.0254	Birch et al. (1984)	20	300	0.143, 0.228 0.257, 0.3, 0.371, 0.429, 1, 6	
133–144	65	278	0.0254	Ewan and Moodie (1986)	profile	300	0.137, 0.412, 0.687, 1.236, 1.511, 1.786, 1.923, 2.061, 2.198, 2.335, 4.122	Fig. 6f
145–161	65	278	0.0254	Yuceil and Otugen (2002)	profile	300	0.085, 0.255, 0.425, 0.765, 0.935, 1.105, 1.19, 1.275, 1.36, 1.445, 1.53, 1.615, 1.7, 1.87, 2.04, 2.55, 3.4	
162–177	101	293	0.00635	FLACS embedded model	Not specified	293	0.029, 0.088, 0.206, 0.368, 0.481, 0.794, 1.011, 1.615, 2.03, 2.551, 3.197, 4, 6, 8, 10, free jet	From Benard et al. (2016)
178–195	251	293	0.00635	FLACS embedded model	Not specified	293	0.048, 0.143, 0.238, 0.333, 0.591, 0.769, 0.989, 1.263, 1.60, 2.025, 2.548, 3.197, 4, 5, 6, 8, 10, free jet	
196–213	401	293	0.00635	FLACS embedded model	Not specified	293	0.059, 0.176, 0.294, 0.412, 0.559, 0.74, 0.964, 1.242, 1.586 2.012, 2.539, 3.191, 4, 5, 6, 8, 10, free jet	
214–232	551	293	0.00635	FLACS embedded model	Not specified	293	0.069, 0.207, 0.345, 0.483, 0.621, 0.795, 1.011, 1.28, 1.614 2.031, 2.549, 3.195, 4, 5, 6, 7, 8, 10, free jet	
233–252	701	293	0.00635	FLACS embedded model	Not specified	293	0.077, 0.231, 0.385, 0.538, 0.72, 0.949, 1.231, 1.58, 2.01, 2.5, 3.195, 4, 5, 6, 7, 8, 9, 10, 11, free jet	

2.5 bar < p < 700 bar

6.3 mm < d < 38 mm

1 m/s < v_{WIND} < 20 m/s

RESULTS



base case scenario
cases 14-21
cases 22-29
cases 30-37
cases 38-45
cases 46-53
cases 54-57
cases 58-61
cases 62-65
cases 66-69
cases 70-73
cases 74-80
cases 81-88
cases 89-96
cases 97-109
cases 110-116
cases 117-124
cases 125-132
ground influence
free jet
$\frac{ME}{ME_{FJ}}$
$\frac{h}{d_{PS}}$

METHODOLOGY

1. From the accidental release characteristics, estimate the d_{PS} value using the Birch et al. (1984) model:

$$d_{PS} = d\sqrt{C_D\left(\frac{p}{p_{amb}}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{2(\gamma-1)}}}$$

2. Estimate the ME_{FJ} value using the Chen and Rodi (1980) model:

$$ME_{FJ} = \frac{kd_{PS}}{LFL}\left(\frac{\rho_a}{\rho_g}\right)^{\frac{1}{2}}$$

3. If $h/d_{PS} > 13$, ME_{FJ} provides directly the order of magnitude of ME
4. If $h/d_{PS} < 13$, the order of magnitude of ME can be estimated as

$$ME = ME_{FJ}\left(3.89 - 0.22\frac{h}{d_{PS}}\right)$$

SENSITIVITY TO DISCHARGED MATERIAL

None of them investigated and directly compared how the ground influences HP jets of different substances

↓

SCOPE OF WORK

↓

HP jet & ***Methane***
Propane
Hydrogen & ***ground***

Benard et al., 2007
Houf et al., 2011
Pontiggia et al., 2014
Benard et al., 2016
Colombini and Busini, 2019a
Colombini and Busini, 2019b
Colombini et al., 2020a
Colombini et al., 2020b
...

Methane, Propane, Hydrogen, Silane, ...

CH_4

p = 65 bar
T = 278 K
d = 25.4 mm
LFL = 5 %
PM = 16 kg/kmol

C_3H_8

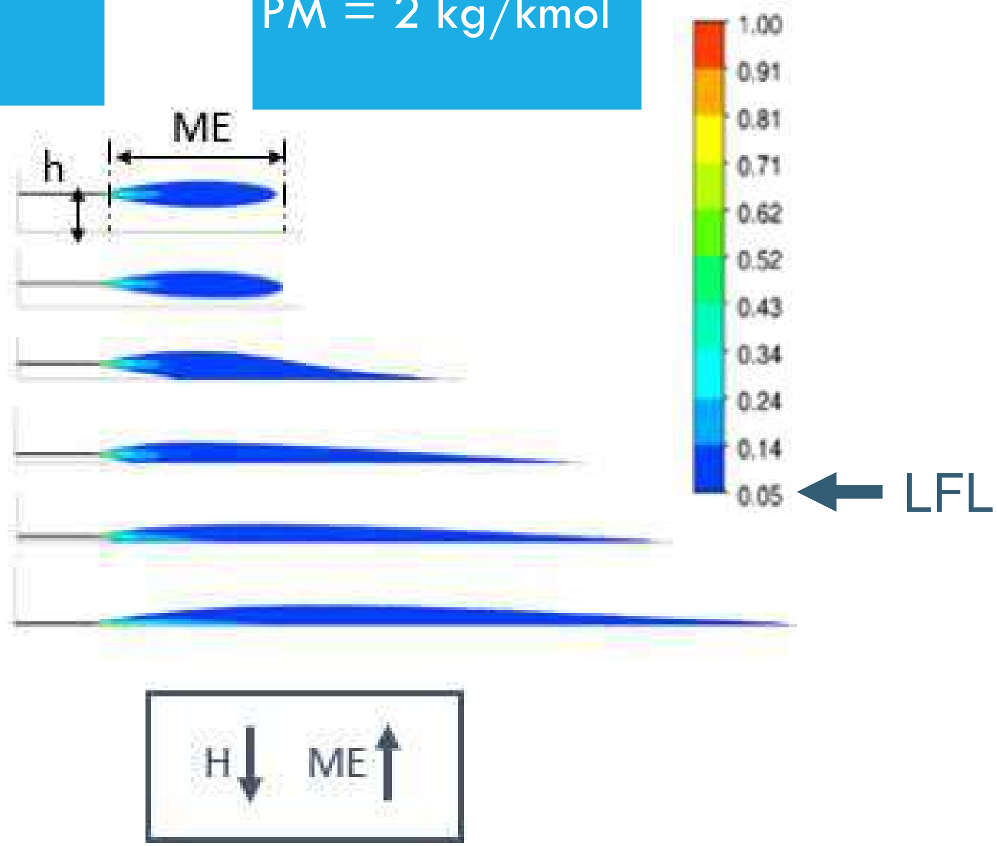
p = 8 bar
T = 278 K
d = 25.4 mm
LFL = 2.1 %
PM = 44 kg/kmol

H_2

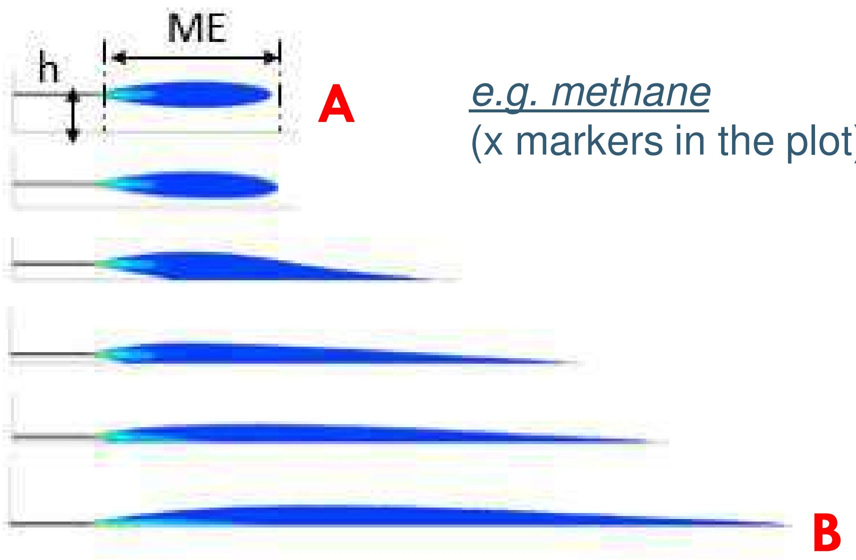
p = 101 bar
T = 293 K
d = 6.35 mm
LFL = 4 %
PM = 2 kg/kmol

For the three substances H have been varied between free jet condition and impinging condition

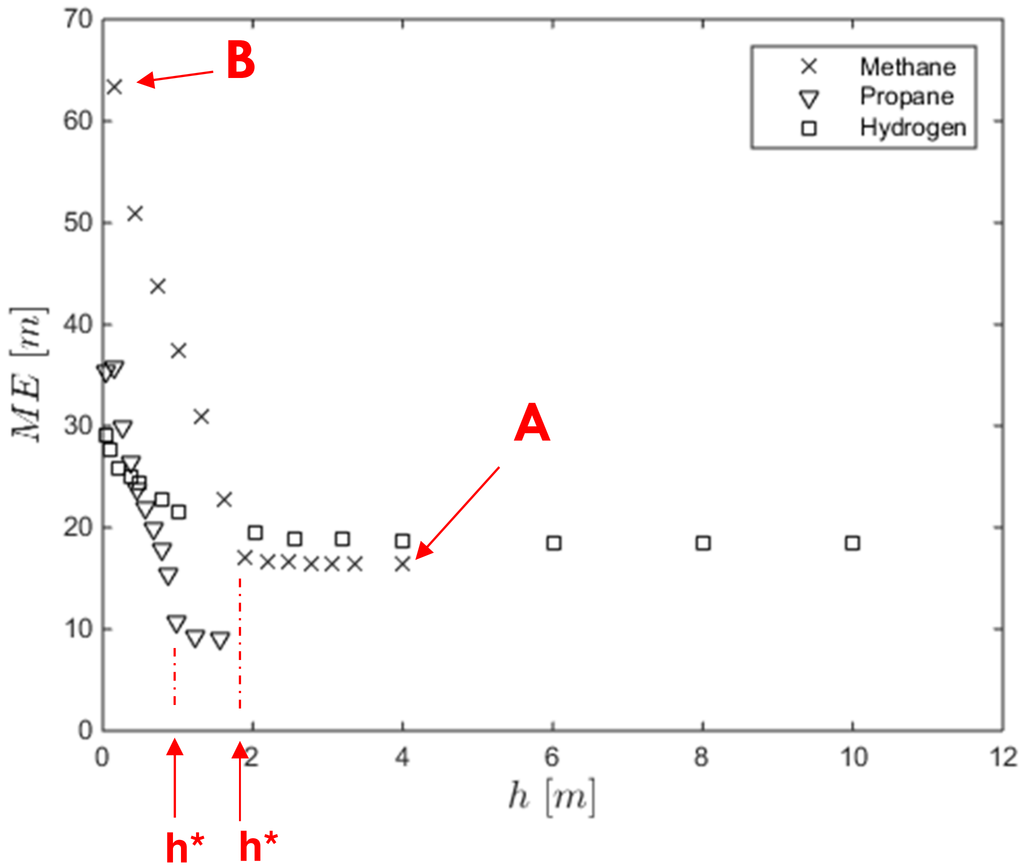
ME (Maximum axially Extent) of the LFL cloud has been recorded for each H evaluated



DISCUSSION



e.g. methane
(x markers in the plot)



h* can be identified such that

- If h > h* → ME is costant = ME_{FJ}, different for each of the compounds considered
- If h < h* → ME increases, accordingly to the physics of the jet development (Coanda effect, Miozzi et al. (2010))

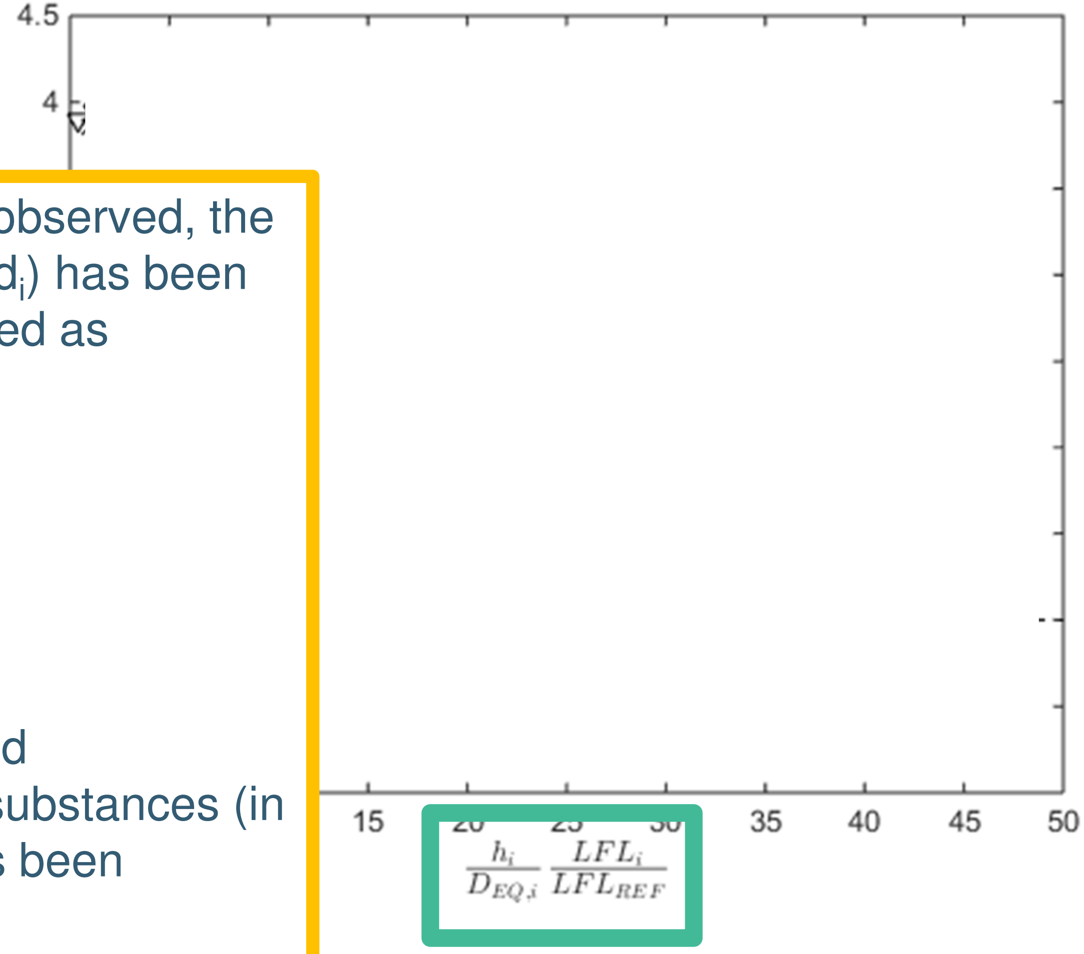
DISCUSSION

However,

- different upstream pressures (65 bar for methane, 8 bar for propane and 701 bar for hydrogen)
- different accidental source diameters (25 mm for methane and propane, 6.3 mm for hydrogen)
- different LFL values (5% for methane, 2.1% for propane, 4% for hydrogen)

<u>do not allow any kind of comparison based on only the substance considered</u>

IN SEARCH OF A NEW SPACE TO FIND A GENERAL CORRELATION



To offset the effect of different concentrations observed, the x axis (already offset with respect to p_i, T_i and d_i) has been multiplied for a dimensionless coefficient defined as

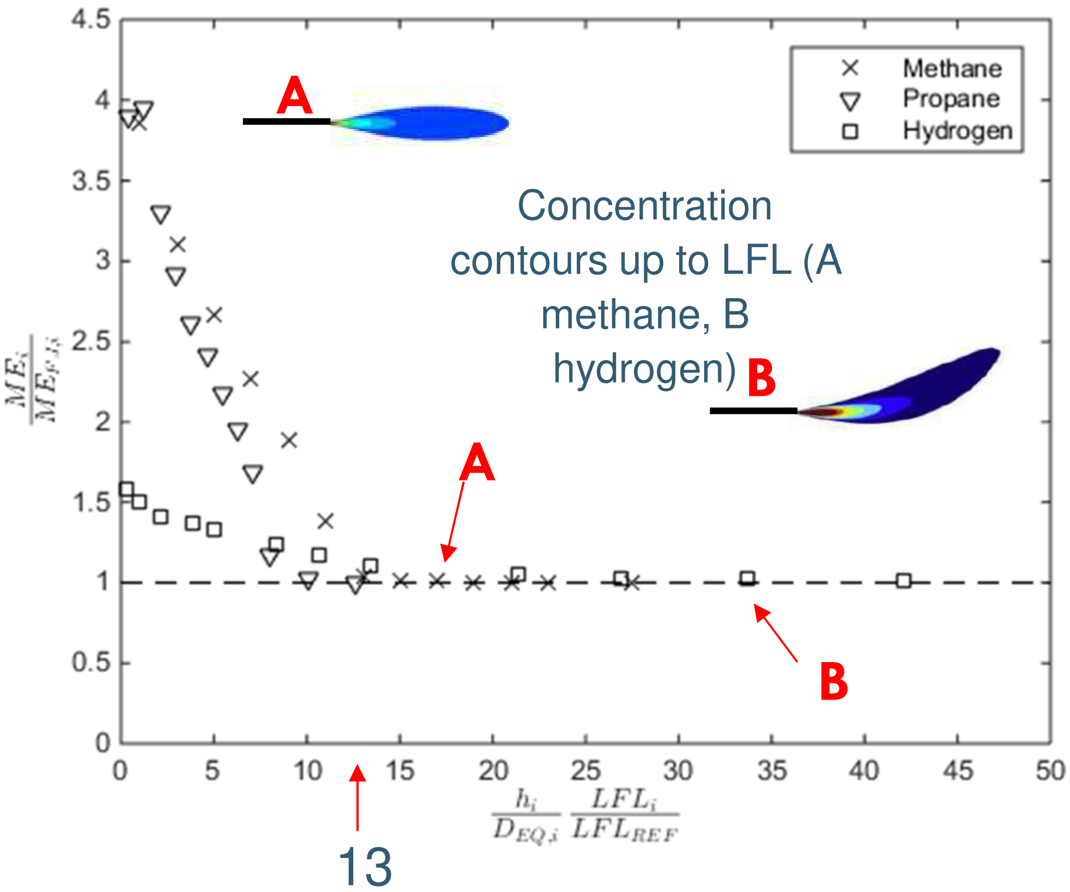
$$\frac{LFL_i}{LFL_{REF}}$$

Where:

- LFL_i is the LFL of each of the i-th compound
- LFL_{REF} is the LFL of one of the compared substances (in this case, for example, LFL of methane has been considered as reference)

DISCUSSION

- If the compound is heavier or similar to air, ground influence is practically similar (propane and methane)
- If compound is lighter than air, ground influence is different (less effect) (hydrogen)
- But, by order of magnitude, results show more or less same dimensionless critical height = 13 (i.e., when ground influence starts / ends)

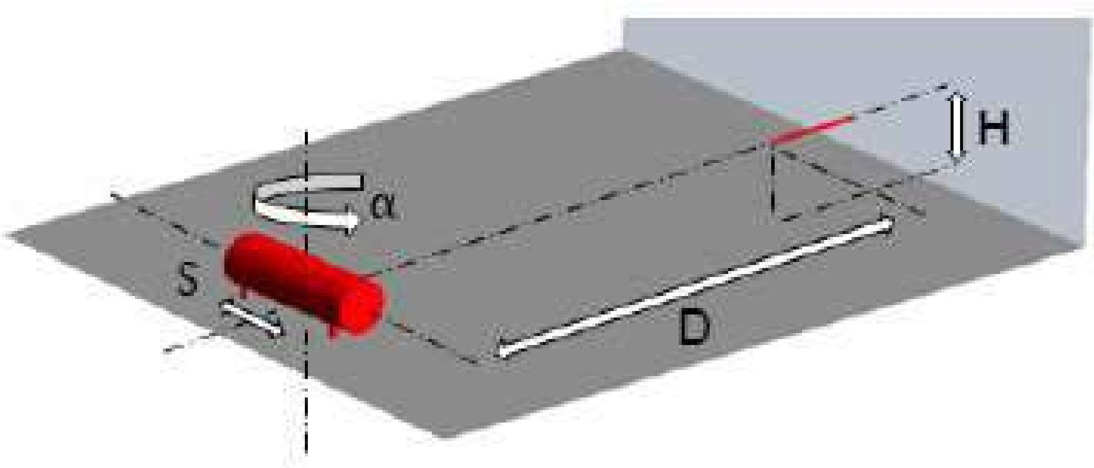


PARTIAL CONCLUSION -1-

- A general correlation has been found for ground influence on HP jets
- By order of magnitude all the results achieved show the same dimensionless critical height

Broadly speaking, the ground effect is to increase the damage area (Coanda effect). The results indicate that **for compounds heavier than, or similar to, air a larger increase of the hazardous distance should be expected with respect to the case of considering lighter compounds.**

CASE 2: CYLINDRICAL TANKS, KEY GEOMETRICAL PARAMETERS



- Distance of the obstacle from the jet orifice (D)
- Height of the orifice above ground (H)
- Tank diameter (Do)
- Rotation (α) of the tank with respect to the jet axis (results do not shown)
- Displacement (S) of the tank with respect to the jet axis (results do not shown)

Colombini and Busini, Chem. Engineer. Trans., 2019
Colombini and Busini, ESREL Proceedings, 2019

SIMULATION PLANNING

Values of the characteristics defining the cases simulated and results achieved for the horizontal obstacle case. Subscript x indicates the concentration level observed: x = L means c = 3.5%, x = M means c = 5.3% (LFL) and x = H means c = 10%.

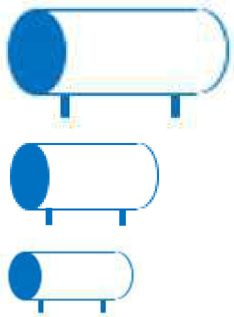
Run	p [bar]	d [m]	d_{ps} [m]	H_N [m]	D_O [m]	L_O [m]	D [m]	ME [m]		
								x = L	x = M	x = H
1_x	65	0.0254	0.146	6	2	11	2.93	13.7	9.4	5.45
2_x	65	0.0254	0.146	6	2	11	4.87	15.7	11.25	6.9
3_x	65	0.0254	0.146	6	2	11	6.81	18.25	13.3	8.15
4_x	65	0.0254	0.146	6	2	11	8.75	20.8	15.05	8.95
5_x	65	0.0254	0.146	6	2	11	10.68	23.3	16.45	8.45
6_x	65	0.0254	0.146	6	2	11	12.62	25.1	17.15	8.45
7_x	65	0.0254	0.146	6	2	11	14.56	26.4	17.15	8.45
8_x	65	0.0254	0.146	6	2	11	16.5	27.05	17.6	8.45
9_x	65	0.0254	0.146	6	3	11	3.43	12.6	8.7	5.05
10_x	65	0.0254	0.146	6	3	11	5.37	14.15	10.1	6.15
11_x	65	0.0254	0.146	6	3	11	7.312	16.7	12.15	7.5
12_x	65	0.0254	0.146	6	3	11	9.25	18.75	13.55	8.5
13_x	65	0.0254	0.146	6	3	11	11.18	19.9	14.25	8.45
14_x	65	0.0254	0.146	6	3	11	13.12	21.4	15.45	8.45
15_x	65	0.0254	0.146	6	3	11	15.06	22.8	16.2	8.45
16_x	65	0.0254	0.146	10	4.5	20	4.18	13.45	8.6	4.9
17_x	65	0.0254	0.146	10	4.5	20	6.12	14.25	9.8	5.9
18_x	65	0.0254	0.146	10	4.5	20	8.06	15.85	11.2	7.1
19_x	65	0.0254	0.146	10	4.5	20	10	16.65	12.65	8.3
20_x	65	0.0254	0.146	10	4.5	20	11.93	18.85	14.1	8.45
21_x	65	0.0254	0.146	10	4.5	20	13.87	20.4	15.1	8.45
22_x	65	0.0254	0.146	10	4.5	20	15.81	21.8	15.9	8.45
23_x	65	0.0254	0.146	10	4.5	20	17.75	22.0	16.5	8.45
24_x	65	0.0254	0.146	10	7.5	20	5.68	12.4	9.35	4
25_x	65	0.0254	0.146	10	7.5	20	7.62	13.15	9.45	5.1
26_x	65	0.0254	0.146	10	7.5	20	9.56	14.5	10.3	6.6
27_x	65	0.0254	0.146	10	7.5	20	11.5	16.2	11.4	8.1
28_x	65	0.0254	0.146	10	7.5	20	13.43	17.6	12.7	8.45
29_x	65	0.0254	0.146	10	7.5	20	15.37	18.9	13.9	8.45
30_x	65	0.0254	0.146	10	7.5	20	17.31	20	15.1	8.45
31_x	195	0.0254	0.252	10	3	20	3.43	21.8	13.6	7.6
32_x	195	0.0254	0.252	10	3	20	5.37	22.8	15.8	9.5
33_x	195	0.0254	0.252	10	3	20	7.31	25.2	18	11.1
34_x	195	0.0254	0.252	10	3	20	9.25	27.8	20.1	12.35
35_x	195	0.0254	0.252	10	3	20	11.18	30.7	22.3	13.45
36_x	195	0.0254	0.252	10	3	20	13.12	33.3	24.1	14.5
37_x	195	0.0254	0.252	10	3	20	15.06	36.1	25.8	14.8
38_x	260	0.0254	0.291	10	3	20	3.43	23.4	15.6	8.8
39_x	260	0.0254	0.291	10	3	20	5.37	26	17.9	10.65
40_x	260	0.0254	0.291	10	3	20	7.31	28.4	20	12.4
41_x	260	0.0254	0.291	10	3	20	9.25	31.4	22.4	13.9
42_x	260	0.0254	0.291	10	3	20	11.18	34.4	24.7	15.2
43_x	260	0.0254	0.291	10	3	20	13.12	37.4	26.9	16.2
44_x	260	0.0254	0.291	10	3	20	15.06	40.5	28.9	16.8
45_x	455	0.0254	0.385	10	3	20	3.43	32.35	20.5	10.4
46_x	455	0.0254	0.385	10	3	20	5.37	33.7	22.8	13.15
47_x	455	0.0254	0.385	10	3	20	7.31	36.5	25	15.2
48_x	455	0.0254	0.385	10	3	20	9.25	40.1	27.8	17.1
49_x	455	0.0254	0.385	10	3	20	11.18	43.7	30.5	19
50_x	455	0.0254	0.385	10	3	20	13.12	47.4	33.3	20.5
51_x	455	0.0254	0.385	10	3	20	15.06	51.4	36	21.8
52_x	650	0.0254	0.461	10	3	20	3.43	52.7	24	13.9
53_x	650	0.0254	0.461	10	3	20	5.37	38.7	25.9	14.9
54_x	650	0.0254	0.461	10	3	20	7.31	42.5	28.9	17.2
55_x	650	0.0254	0.461	10	3	20	9.25	47	32.1	19.5
56_x	650	0.0254	0.461	10	3	20	11.18	51	35.3	21.6
57_x	650	0.0254	0.461	10	3	20	13.12	55.5	38.8	23.6
58_x	650	0.0254	0.461	10	3	20	15.06	59.8	41.6	25.2

65 CASES

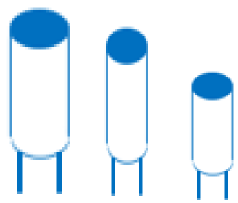
The influence of the cylindrical obstacle was investigated varying:

- the distance between the methane HP source and the obstacle (D);
- The height of the source above ground (HN);
- the methane storage pressure (p),
- the obstacle diameter (DO),
- the observed methane concentration in air (c) and
- the obstacle orientation (horizontal or vertical).

GEOMETRY

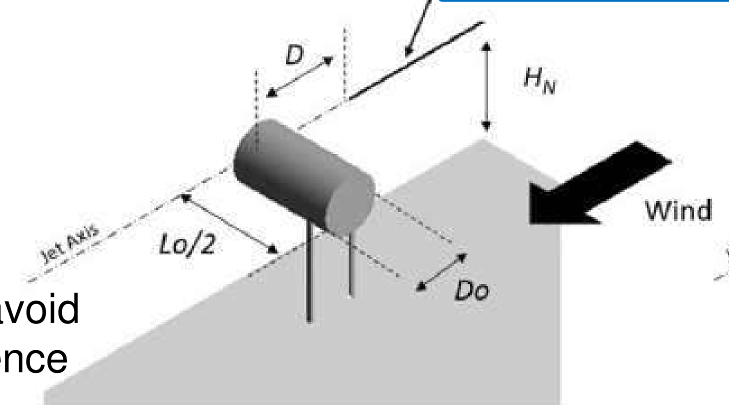


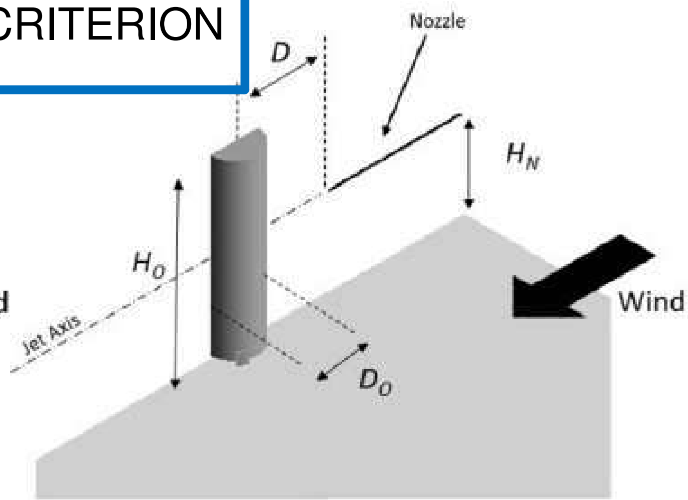
58 simulaitons



7 simulaitons

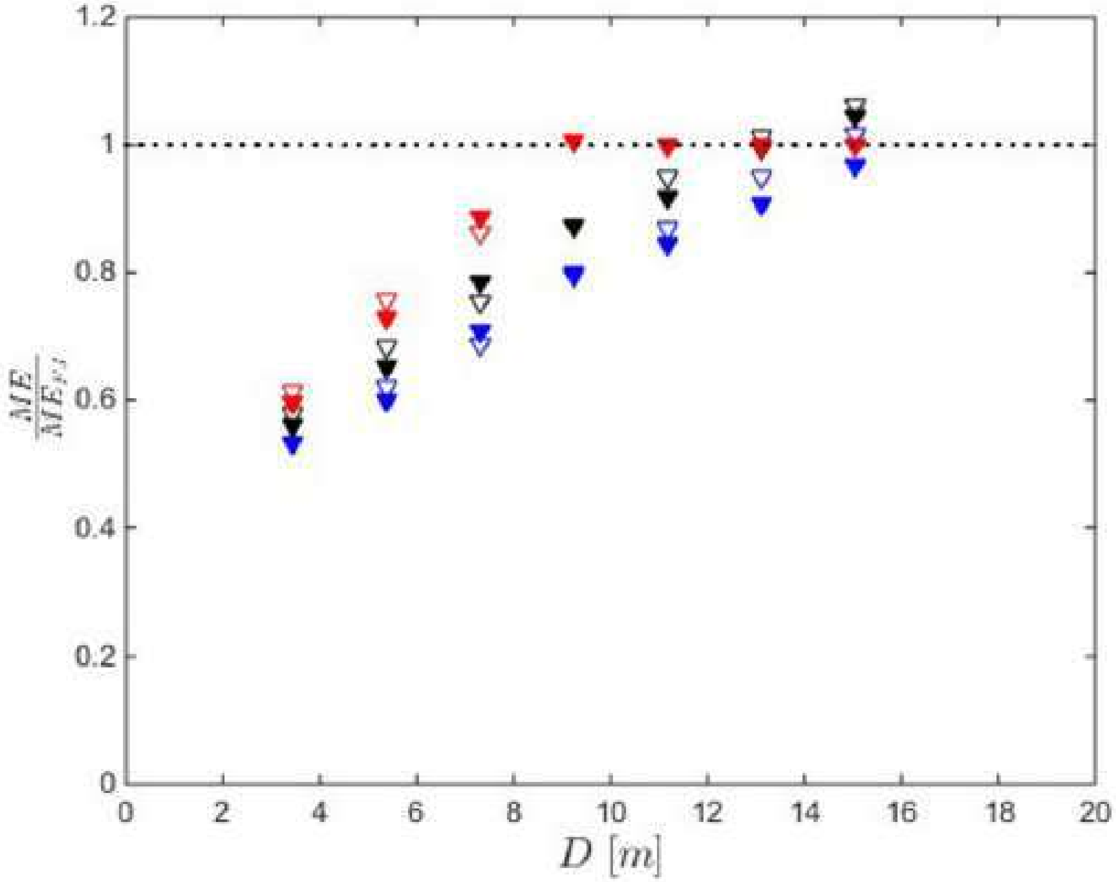
GENERAL CRITERION





Elevated to avoid
ground influence

RESULTS



Distance of the obstacles from nozzle

Empty markers refer to vertical cylindrical obstacle while filled markers refer to horizontal cylindrical obstacle.

blue is for the low level (c = 3.5%),

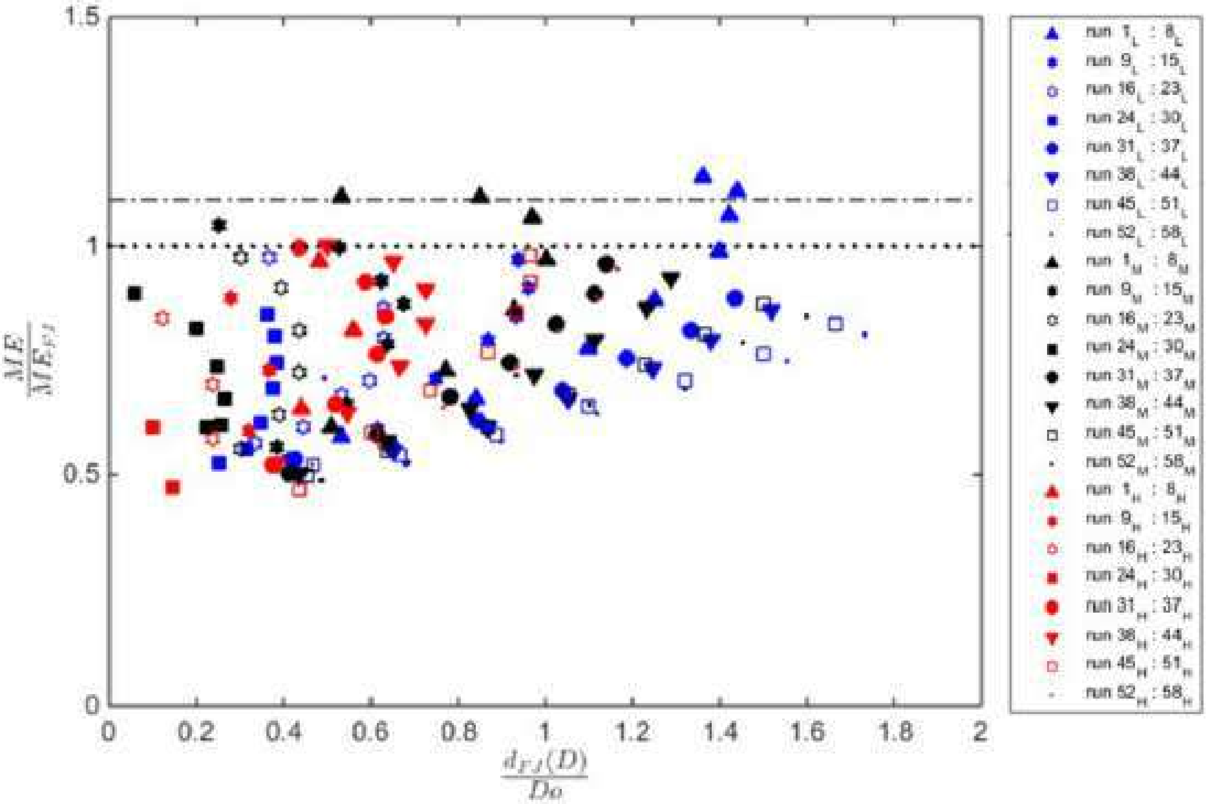
black is for the mean level (c = 5.3%)

red is for the high level (c = 10%).

The dotted line identifies when ME/ME_{FJ} = 1

The obstacle orientation does not introduce any relevant effect in the jet development

RESULTS , CHANGING THE SPACE



blue is for the low level (c = 3.5%),

black is for the mean level (c = 5.3%)

red is for the high level (c = 10%).

The dotted line identifies when ME/MEFJ = 1, while the dash dotted line when ME/MEFJ = 1.1.

The jet length is always lower than the maximum extent of the correspondent free jet and, only in few cases; the ME exceeds that of the free jet for no more than about 10%

Ratio between the radial dimension of the free jet cloud evaluated in correspondence of the cylindrical obstacle centre position ($d_{FJ}(D)$) and the obstacle diameter (Do)

METHODOLOGY

1. Estimate D_{PS} from Birch correlation
2. Using the concentration decay model of Chen and Rodi (1980) and source information, compute MEFJ
3. Coupling the models of Chen and Rodi (1980) and Cushman-Roisin (2020), estimate dFJ(D):

$$d_{FJ}(D) = 2 \cdot \sqrt{-\frac{D^2}{50} \cdot \ln\left(\frac{\bar{c}}{c_{ax}\left(D\right)}\right)}$$

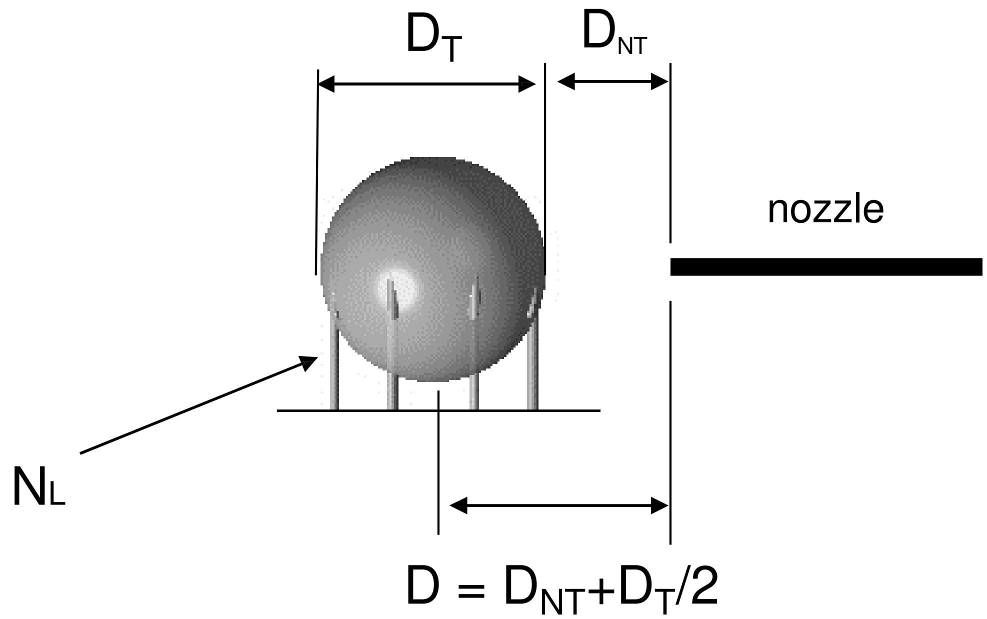
$$c_{ax}\left(D\right) = \frac{k d_{PS}}{D}\left(\frac{\rho_{amb}}{\rho_{PS}}\right)^{\frac{1}{2}}$$

4. If $d_{FJ}(D)/D_O < 1.8$, ME can be roughly considered equal to MEFJ since the maximum underestimation is expected to be lower than about 10%. If $d_{FJ}(D)/D_O \geq 1.8$, the results are outside the parameters window investigated, and thus the procedure expires its validity

PARTIAL CONCLUSION -2-

- the cylindrical obstacle (be it oriented horizontally or vertically) has the effect of decreasing the jet maximum extent instead of increasing it;
- At most, the impinging jet results to have similar length of the free jet case;
- Within the parameters window considered, the simple methodology proposed can be used to quickly estimate, by order of magnitude, the hazardous area extent subsequent to the accidental release in the jet axis direction (which is, in principle, the worst-case direction);

CASE 3: SPHERICAL TANK, KEY GEOMETRICAL PARAMETERS



- Distance of the obstacle from the jet orifice (D)
- Height of the orifice above ground (H)
- Tank diameter (D_T)
- Number of legs

SIMULATION PLANNING

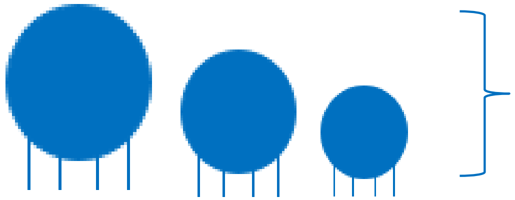
Run	p [bar]	d [m]	d_{PS} [m]	D_T [m]	D_{NT} [m]	D_L [m]	ME [m]		
							x = L	x = M	x = H
1	65	0.0254	0.1458	2	1.9375	0.1	27	16.7	8.7
2	65	0.0254	0.1458	2	3.875	0.1	32.8	20.5	8.4
3	65	0.0254	0.1458	2	5.8125	0.1	34.8	22.2	8.3
4	65	0.0254	0.1458	2	7.75	0.1	34	21.3	8.5
5	65	0.0254	0.1458	2	9.6875	0.1	33.2	20.4	8.4
6	65	0.0254	0.1458	2	11.625	0.1	32.6	18.8	8.4
7	65	0.0254	0.1458	2	13.5625	0.1	31.7	16.8	8.4
8	65	0.0254	0.1458	2	15.5	0.1	30.9	15.9	8.4
9	65	0.0254	0.1458	3	1.9375	0.15	25.3	16.9	7.2
10	65	0.0254	0.1458	3	3.875	0.15	28.6	17.7	6.3
11	65	0.0254	0.1458	3	5.8125	0.15	32.5	18.8	6.6
12	65	0.0254	0.1458	3	7.75	0.15	33.4	18.3	8.3
13	65	0.0254	0.1458	3	9.6875	0.15	32.9	17.3	8.4
14	65	0.0254	0.1458	3	11.625	0.15	32.2	15.8	8.4
15	65	0.0254	0.1458	3	13.5625	0.15	31.1	16.0	8.4
16	65	0.0254	0.1458	3	15.5	0.15	29.6	15.9	8.4
17	65	0.0254	0.1458	4.5	1.9375	0.23	26	17.3	5.1
18	65	0.0254	0.1458	4.5	3.875	0.23	25.6	14.1	6.4
19	65	0.0254	0.1458	4.5	5.8125	0.23	24.2	12.4	7.3
20	65	0.0254	0.1458	4.5	7.75	0.23	24.4	12.3	8
21	65	0.0254	0.1458	4.5	9.6875	0.23	26.5	13.8	8.4
22	65	0.0254	0.1458	4.5	11.625	0.23	26.3	14.8	8.4
23	65	0.0254	0.1458	4.5	13.5625	0.23	24.9	15.2	8.4
24	65	0.0254	0.1458	4.5	15.5	0.23	24.2	15.7	8.4
25	65	0.0254	0.1458	6	1.9375	0.23	27.6	16.0	5.2
26	65	0.0254	0.1458	6	3.875	0.23	23.3	11.1	6.0
27	65	0.0254	0.1458	6	5.8125	0.23	21.8	11	7
28	65	0.0254	0.1458	6	7.75	0.23	20	12.4	7.9
29	65	0.0254	0.1458	6	9.6875	0.23	19.4	13.5	8.4
30	65	0.0254	0.1458	6	11.625	0.23	19.1	14.3	8.4
31	65	0.0254	0.1458	6	13.5625	0.23	19.5	15	8.4
32	65	0.0254	0.1458	6	15.5	0.23	20.9	15.7	8.4
33	65	0.0254	0.1458	7.5	1.9375	0.39	24.1	10.8	5.05
34	65	0.0254	0.1458	7.5	3.875	0.39	19.7	9.87	5.76
35	65	0.0254	0.1458	7.5	5.8125	0.39	18.4	11.1	6.7
36	65	0.0254	0.1458	7.5	7.75	0.39	17.3	12.3	7.9
37	65	0.0254	0.1458	7.5	9.6875	0.39	17.2	13.3	8.4
38	65	0.0254	0.1458	7.5	11.625	0.39	18.4	14.1	8.4
39	65	0.0254	0.1458	7.5	13.5625	0.39	19.6	14.7	8.4
40	65	0.0254	0.1458	7.5	15.5	0.39	21	15.7	8.4
41	65	0.0254	0.1458	10	1.9375	0.68	20	10.8	3.7
42	65	0.0254	0.1458	10	3.875	0.68	16.6	9.5	4.2
43	65	0.0254	0.1458	10	5.8125	0.68	15.4	10	5.3
44	65	0.0254	0.1458	10	7.75	0.68	15.2	10.9	6.9
45	65	0.0254	0.1458	10	9.6875	0.68	16.3	11.6	8.6
46	65	0.0254	0.1458	10	11.625	0.68	17.6	12.6	8.4
47	65	0.0254	0.1458	10	13.5625	0.68	18.7	13.6	8.4
48	65	0.0254	0.1458	10	15.5	0.68	19.3	14.8	8.4
49	130	0.0254	0.2062	3	1.9375	0.15	36.6	23.7	12.2
50	130	0.0254	0.2062	3	3.875	0.15	42.3	25.8	11.6
51	130	0.0254	0.2062	3	5.8125	0.15	44.4	27.8	10.7
52	130	0.0254	0.2062	3	7.75	0.15	48.2	30.3	11.1
53	130	0.0254	0.2062	3	9.6875	0.15	48.6	30.7	12
54	130	0.0254	0.2062	3	11.625	0.15	48.1	29.7	12.1
55	130	0.0254	0.2062	3	13.5625	0.15	48	28.8	11.9
56	130	0.0254	0.2062	3	15.5	0.15	46.6	27.0	11.9
57	195	0.0254	0.2526	3	1.9375	0.15	-	28.3	14.7
58	195	0.0254	0.2526	3	3.875	0.15	-	32.7	16
59	195	0.0254	0.2526	3	5.8125	0.15	58.5	36.8	17.3
60	195	0.0254	0.2526	3	7.75	0.15	58.8	37.8	16.5
61	195	0.0254	0.2526	3	9.6875	0.15	59.4	38.7	16.1
62	195	0.0254	0.2526	3	11.625	0.15	59	38.3	15
63	195	0.0254	0.2526	3	13.5625	0.15	58.7	37.7	15.1
64	195	0.0254	0.2526	3	15.5	0.15	57.5	36.4	14.5
65	260	0.0254	0.2916	3	1.9375	0.15	-	-	16.4
66	260	0.0254	0.2916	3	3.875	0.15	-	38.7	18.9
67	260	0.0254	0.2916	3	5.8125	0.15	69.2	42	21.4
68	260	0.0254	0.2916	3	7.75	0.15	68	44.1	21.2
69	260	0.0254	0.2916	3	9.6875	0.15	68.2	44.6	21
70	260	0.0254	0.2916	3	11.625	0.15	67.4	44.4	19.6
71	260	0.0254	0.2916	3	13.5625	0.15	66.7	43.6	18
72	260	0.0254	0.2916	3	15.5	0.15	65.8	43	17.7
73	455	0.0254	0.3858	3	1.9375	0.15	-	-	21.6
74	455	0.0254	0.3858	3	3.875	0.15	-	-	23.7
75	455	0.0254	0.3858	3	5.8125	0.15	88.7	55	28.7
76	455	0.0254	0.3858	3	7.75	0.15	87.2	56.7	29.8
77	455	0.0254	0.3858	3	9.6875	0.15	87.8	58.3	30.9
78	455	0.0254	0.3858	3	11.625	0.15	86.5	58	30.5
79	455	0.0254	0.3858	3	13.5625	0.15	85.5	57.6	29.3
80	455	0.0254	0.3858	3	15.5	0.15	84.6	57	28.1
81	650	0.0254	0.4611	3	1.9375	0.15	-	-	25.5
82	650	0.0254	0.4611	3	3.875	0.15	-	-	27.85
83	650	0.0254	0.4611	3	5.8125	0.15	105.7	63.5	32.4
84	650	0.0254	0.4611	3	7.75	0.15	102.8	67.2	36.2
85	650	0.0254	0.4611	3	9.6875	0.15	101.7	67.9	37.2
86	650	0.0254	0.4611	3	11.625	0.15	101	68.1	37.2
87	650	0.0254	0.4611	3	13.5625	0.15	99.7	67.6	36.65
88	650	0.0254	0.4611	3	15.5	0.15	98.7	67	35.8

88 CASES

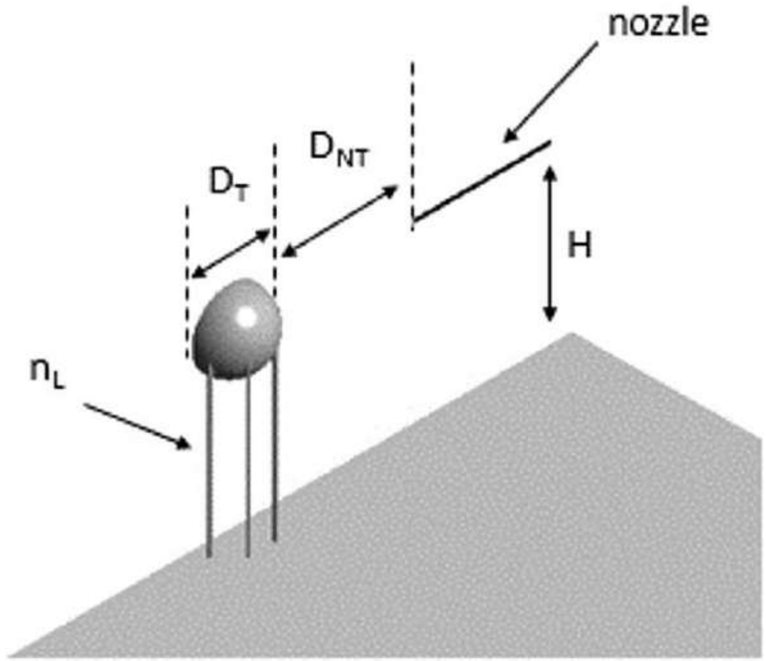
The influence of the spherical obstacle was investigated varying:

- the distance between the methane HP source and the obstacle (D_{NT});
- the methane storage pressure (p) (from 65 to 650 bar;
- the obstacle diameter (D_T),
- the observed methane concentration in air (c);

GEOMETRY

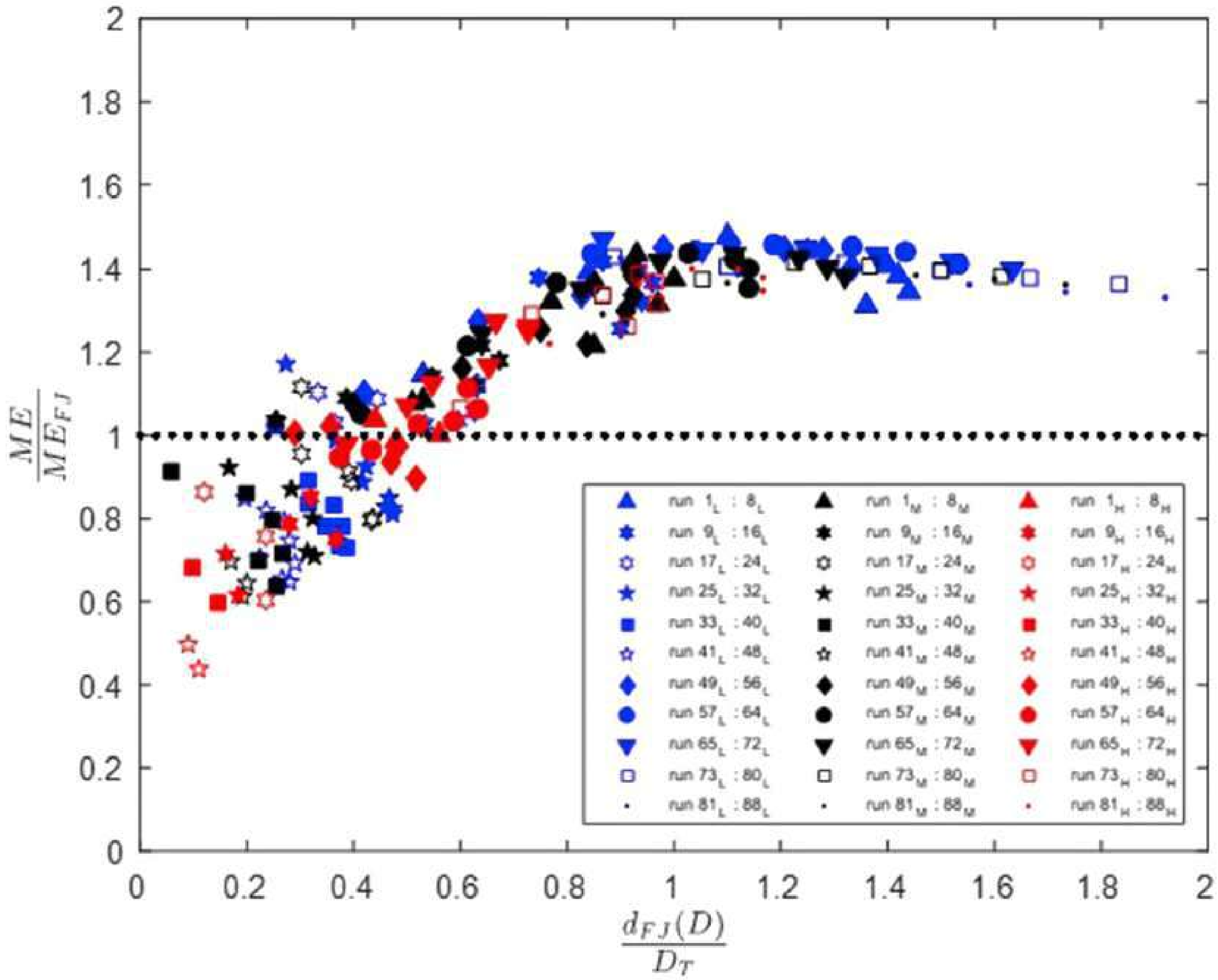


(24 + n) simulaitons



Elevated to avoid
ground influence

RESULTS



blue is for the low level (c = 3.5%),
black is for the mean level (c = 5.3%)
red is for the high level (c = 10%).
The dotted line identifies when $ME/ME_{FJ} = 1$.

Ratio between the radial dimension of the free jet cloud evaluated in correspondence of the cylindrical obstacle centre position ($d_{FJ}(D)$) and the obstacle diameter (D_T)

METHODOLOGY

1. Estimate D_{PS} from Birch correlation
2. Using the concentration decay model of Chen and Rodi (1980) and source information, compute ME_{FJ}
3. Coupling the models of Chen and Rodi (1980) and Cushman-Roisin (2020), estimate dFJ(D):

$$d_{FJ}(D) = 2 \cdot \sqrt{-\frac{D^2}{50} \cdot \ln\left(\frac{\bar{c}}{c_{ax}\left(D\right)}\right)}$$

$$c_{ax}\left(D\right) = \frac{k d_{PS}}{D}\left(\frac{\rho_{amb}}{\rho_{PS}}\right)^{\frac{1}{2}}$$

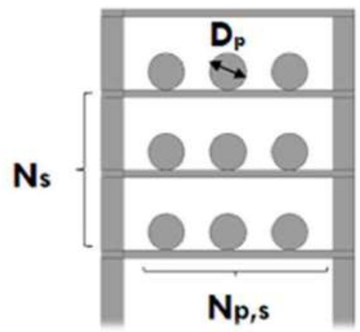
4. If $d_{FJ}(D)/D_T < 0.5$, ME_{FJ} provides a conservative order of magnitude of ME

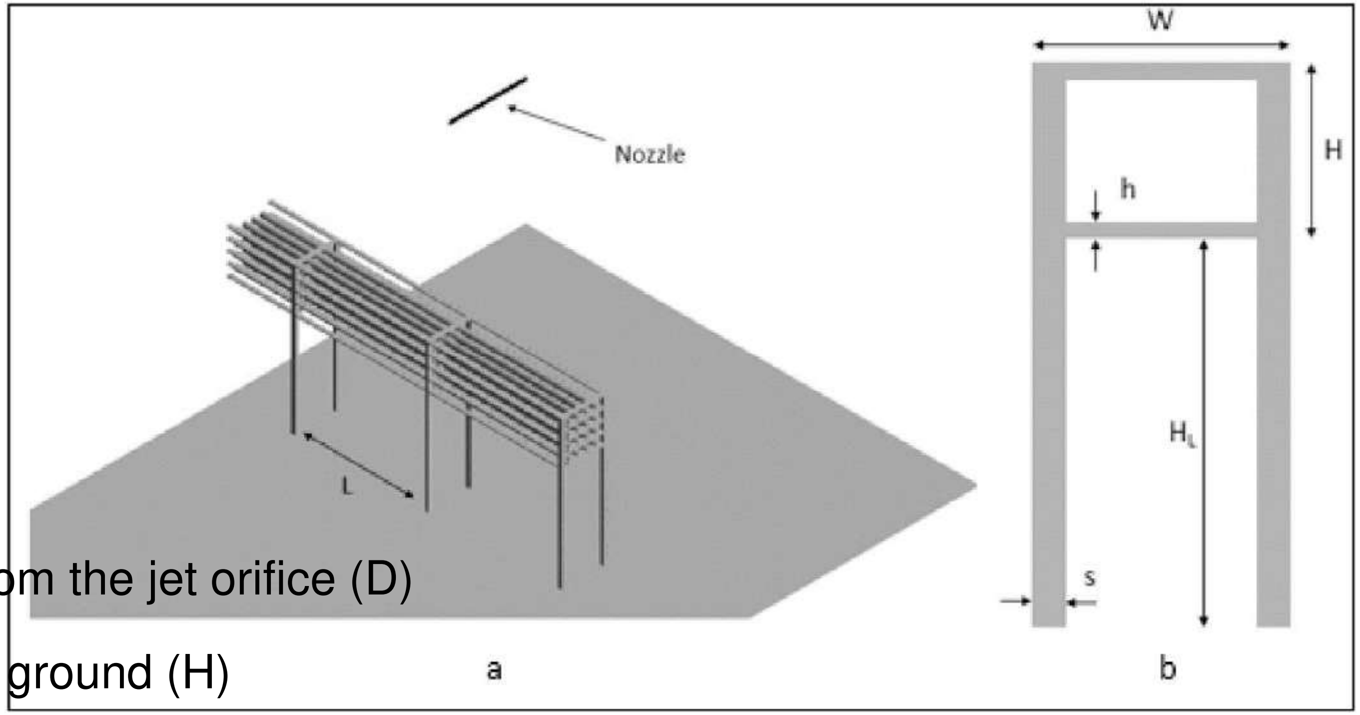
   If $d_{FJ}(D)/D_T \geq 0.5$, a conservative order of magnitude of ME can be estimated as 1.5 ME_{FJ}

PARTIAL CONCLUSION -3-

- the spherical obstacle either decreases or increases the ME of the jet cloud with respect to the free jet.
- As main outcome of practical importance, this work provides a brief by-hand procedure that, only based on known scenario information (or information that can be recovered by applying analytical literature models), allows estimating the maximum extent of the unignited high-pressure jet when interacting with a spherical obstacle.
- This procedure can be used as an order of magnitude estimation for a first attempt consequence calculation within QRA analysis.

CASE 4: PIPE RACK, KEY GEOMETRICAL PARAMETERS





- Distance of the obstacle from the jet orifice (D)
- Height of the orifice above ground (H)
- Pipe diameter (D_P): 15-37 mm
- Number of stack. N_S: 2-6
- Number of pipe per stack, $N_{p,S}$: 2-5

SIMULATION PLANNING

Run	d_p [m]	n_{PS}	n_s	Run	d_p [m]	n_{ps}	n_s
1	15.19	2	3	20	25	4	3
2	21.48	2	3	21	26.31	4	3
3	25	2	3	22	15.19	5	3
4	26.31	2	3	23	21.48	5	3
5	30.38	2	3	24	25	5	3
6	33.97	2	3	25	15.19	3	4
7	37.21	2	3	26	21.48	3	4
8	15.19	3	3	27	25	3	4
9	17.54	3	3	28	15.19	4	4
10	21.48	3	3	29	21.48	4	4
11	24.81	3	3	30	28	4	4
12	25	3	3	31	15.19	3	5
13	26.31	3	3	32	21.48	3	5
14	27.74	3	3	33	25	3	5
15	30.38	3	3	34	15.19	4	5
16	15.19						
17	18.61						
18	21.48						
19	24.02						

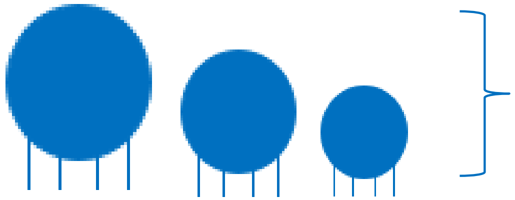
Run	p [bar]	d [m]	D [m]	α [°]	c [%]
39	32.5	0.0254	7.68	90	5.3
40	130	0.0254	7.68	90	5.3
41	65	0.0127	7.68	90	5.3
42	65	0.0508	7.68	90	5.3
43	65	0.0254	3.84	90	5.3
44	65	0.0254	5.76	90	5.3
45	65	0.0254	9.6	90	5.3
46	65	0.0254	11.52	90	5.3
47	65	0.0254	13.44	90	5.3
48	65	0.0254	15.36	90	5.3
49	65	0.0254	7.68	112.5	5.3
50	65	0.0254	7.68	135	5.3
51–88	65	0.0254	7.68	90	2.65
89–126	65	0.0254	7.68	90	10

19 CASES to find the correlation, from 20 to 126 to validate

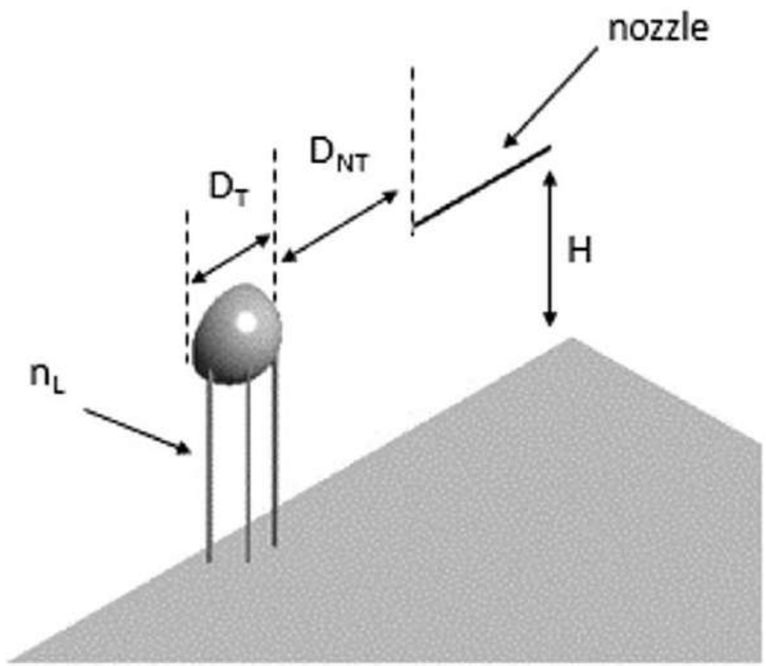
The influence of the pipe rack was investigated varying:

- The number of pipe per shelf (n_{pS});
- The number of shelves Ns;
- the methane storage pressure (p) (from 32.5 to 130 bar;
- the pipe diameter (d_P),
- the observed methane concentration in air (c);

GEOMETRY



(24 + n) simulaitons



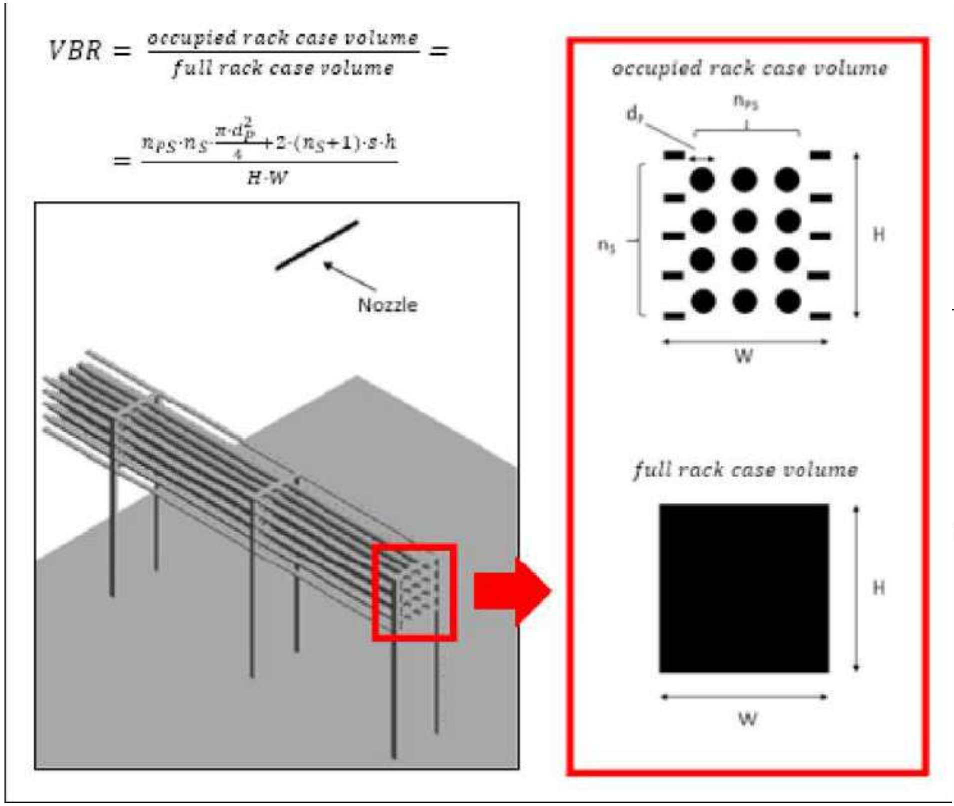
Elevated to avoid
ground influence

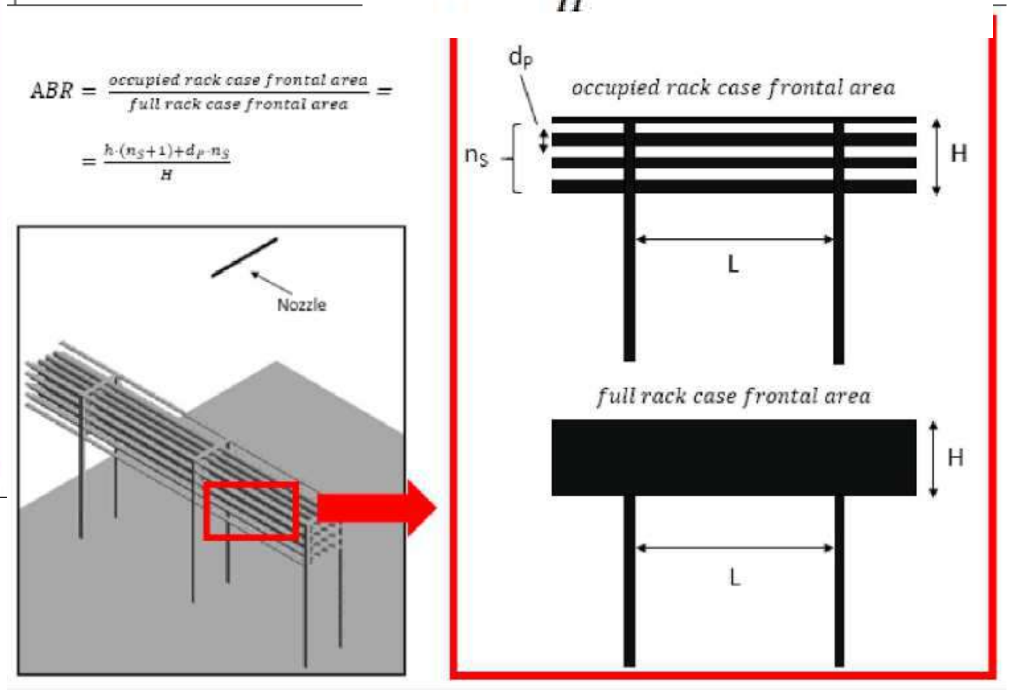
DEFINITION OF THE SPACE

$$VBR = \frac{n_{PS} \cdot n_S \cdot \frac{\pi \cdot d_P^2}{4} + 2 \cdot (n_S + 1) \cdot s \cdot h}{H \cdot W}$$

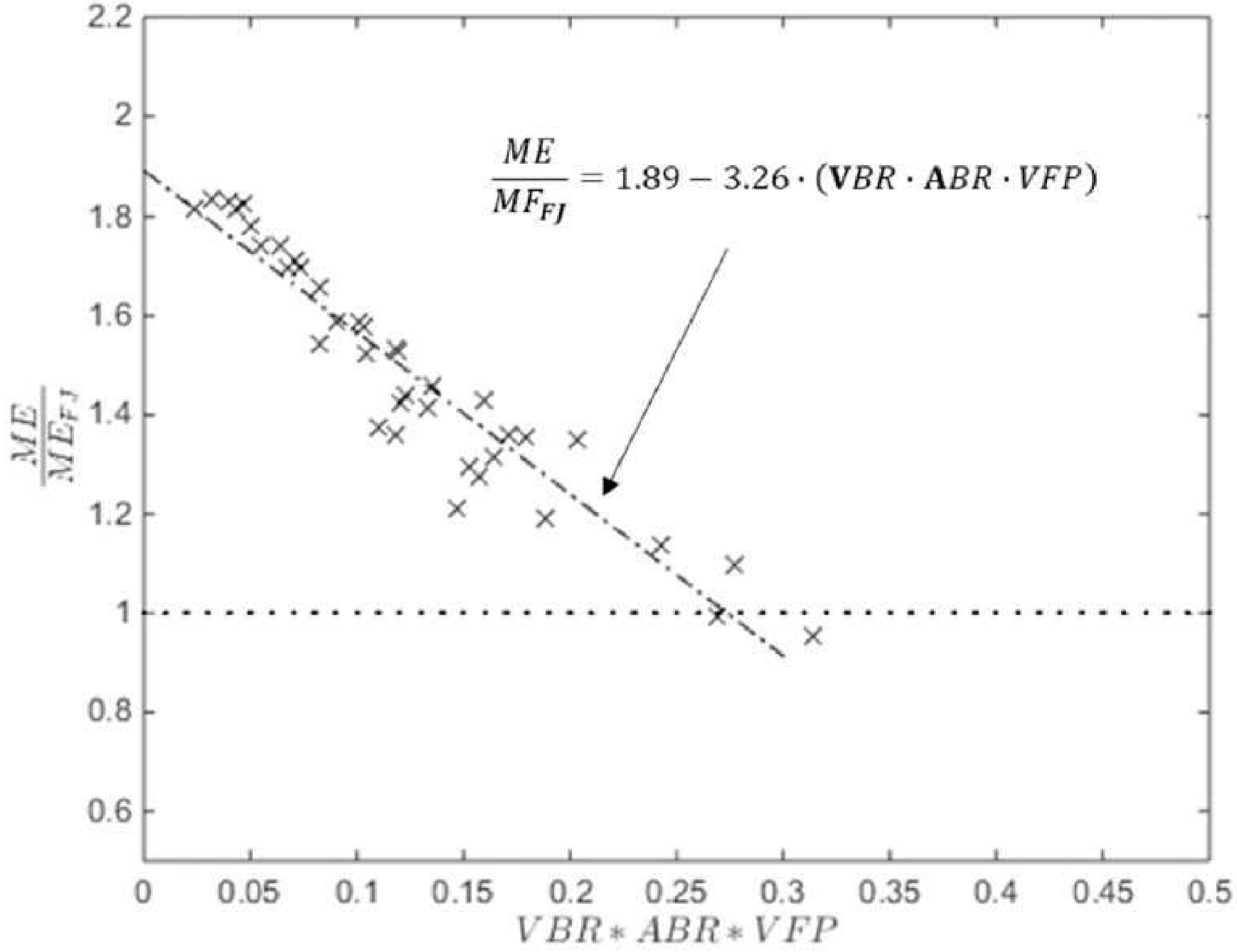
$$ABR = \frac{h \cdot (n_S + 1) + d_P \cdot n_S}{H}$$

$$VFP = \frac{d_{FJ}(D)}{H}$$

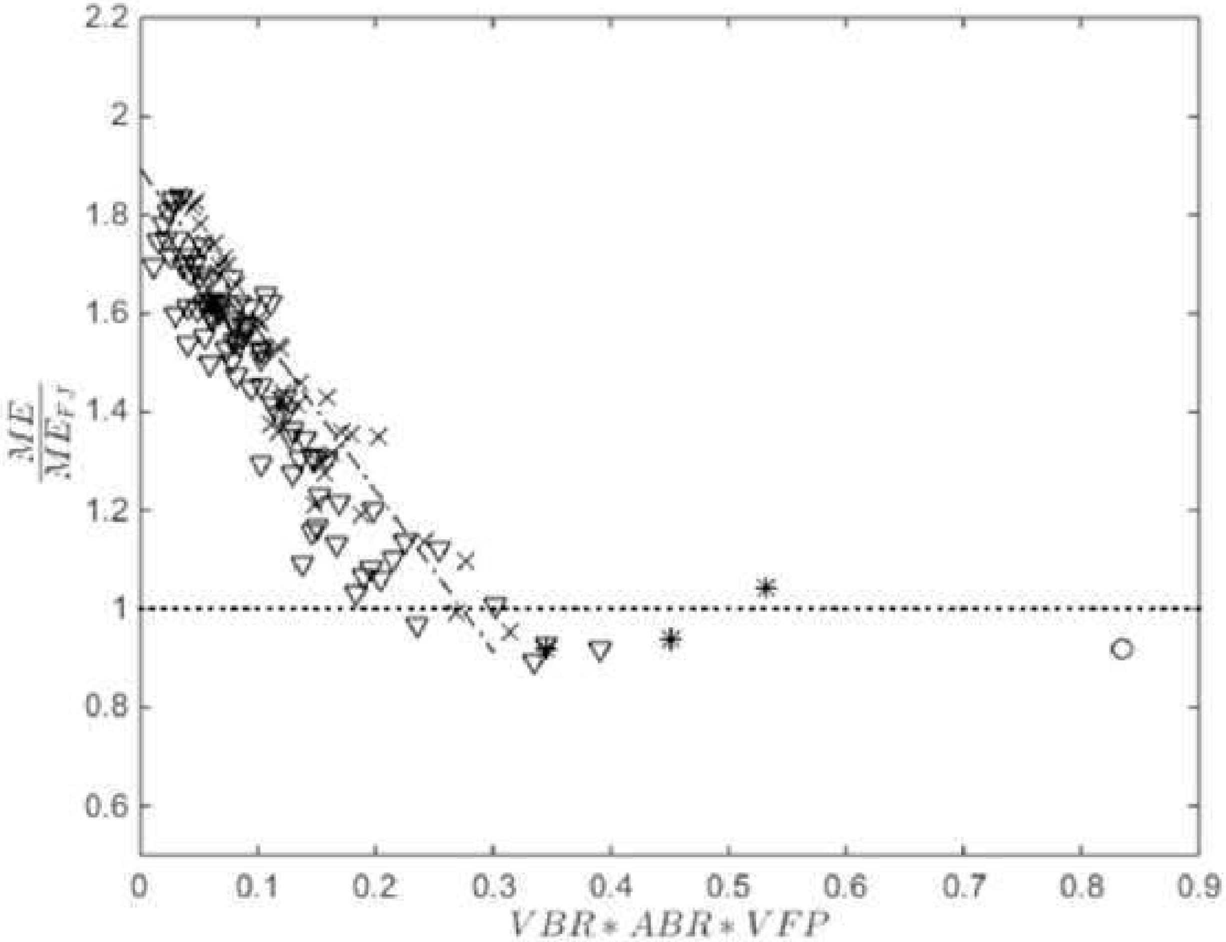




CORRELATION FROM SIMULATIONS



RESULTS



The dotted line identifies when $ME/ME_{FJ} = 1$.

METHODOLOGY

1. Estimate D_{PS} from Birch correlation
2. Using the concentration decay model of Chen and Rodi (1980) and source information, compute ME_{FJ}
3. Coupling the models of Chen and Rodi (1980) and Cushman-Roisin (2020), estimate $d_{FJ}(D)$:
4. From both the obstacle and source characteristics, estimate VBR, ABR, and VFP values
5. If VBR·ABR·VFP >0.3, ME_{FJ} provides the order of magnitude of ME.

   If VBR·ABR·VFP <0.3, the order of magnitude of ME can be estimated

   As:

$$\frac{ME}{MF_{FJ}} = 1.89 - 3.26 \cdot (VBR \cdot ABR \cdot VFP)$$

PARTIAL CONCLUSION -4-

- Scenario involving the impingement of a pipe rack has been deeply investigated through a CFD-based model
- The presence of a rack either enhance (for VBR·ABR·VFP lower than about 0.3) or does not influence (for VBR·ABR·VFP larger than about 0.3) the ME of the flammable jet with respect to the free jet.
- As practical tool for daily risk assessment activities, a by hand procedure allowing the estimation of the maximum axial extent of jet cloud has been proposed

CONCLUSIONS

- The influence of different types of industrial barriers has been extensively analyzed
- The limits of influence of each type of obstacle on the jet have been defined
- Engineering correlations of practical use which, in risk assessment, allow to easily and quickly determine the extension of the damage area (ME LFL) in the presence of an obstacle have been derived

Thank you for your kind attention!