

Modelling of releases of flashing liquids around buildings

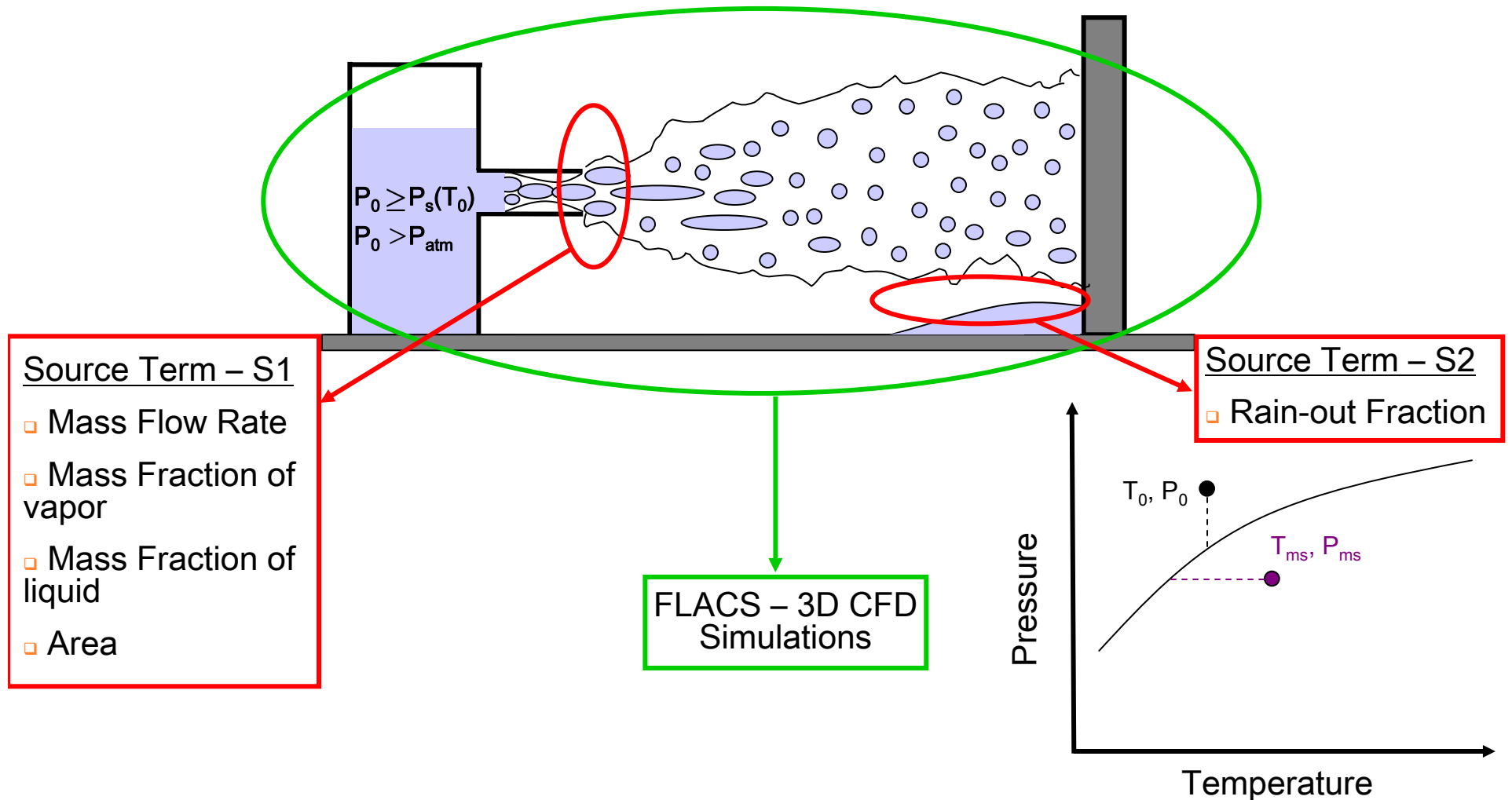
Mathieu Ichard, Olav Hansen and Jens Melheim
GexCon AS

89th AMS Annual Meeting
Eighth Symposium on the Urban Environment
11-15 January 2009, Phoenix, Arizona, USA

Scope of the work

Objective:

3D-computations and hazard prediction of flashing releases in realistic environment.



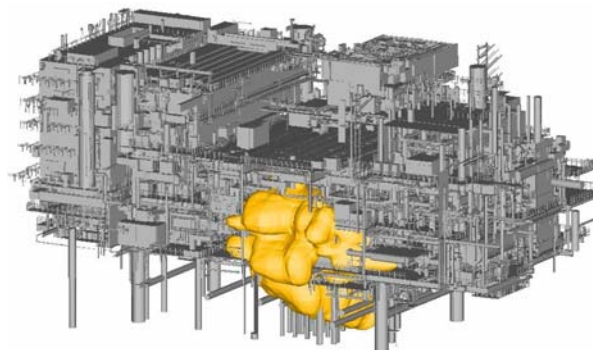
Overview

- Motivations
- Presentation of the FLIE INERIS experiments – Flashing Liquids in Industrial Environments (FLIE)
 - Validation of the mass flow rate computations
 - Droplets diameters for propane and butane
 - Validation of rain-out predictions
- Computation of the source terms
 - Computation and validation for the source term S1
 - Computation and validation for the source term S2
- FLACS – 3D simulations of impinging flashing releases
 - Two-phase model and concepts in FLACS
 - Evaporation and temperature validation
 - Simulation of a flashing impinging jet of butane

Motivations

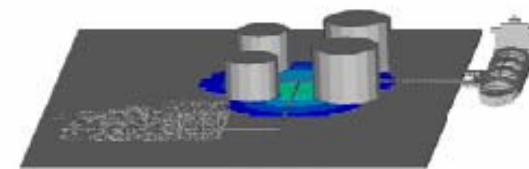
CFD and flashing modeling:

- FLACS CFD code initially developed for explosion safety on oil rigs. Powerful tool also for gas dispersion (flammable & toxic)
- Few dispersion computer models can handle the flashing phenomenon

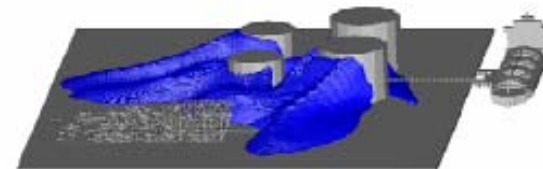


Flashing jets in the FLACS CFD code - Status:

- Utility program FLASH
- Predict the characteristics of a pseudo-source where all the liquid in the two-phase jet has evaporated: Area, temperature, velocity, rain-out fraction
- Can only handle free flashing jets – no obstacle in the near field of the release
- Computations in the 3D-CFD code FLACS start at the pseudo-source position \Rightarrow problems in highly congested areas



LNG spill, pool spread (top) and evaporation (below)



FLIE INERIS experiments

Overview:

- Performed in France from March to October 2004 (Bonnet, 2005, *INERIS report No. 41508*)
- 94 flashing jet releases of propane and butane
- Propane and butane were stored as sub-cooled liquid ($\frac{P_0}{P_s(T_0)} = [1.02 ; 5.0]$)

Measurements:

- Measurement of rain-out for free jets and impinging jets
- Measurement of droplets characteristics with PDA (Phase Doppler Anemometer)
- Measurement of the temperature along the jet axis and on the obstacle in case of impinging jet

Example of dataset:

<u>Date:</u>	23.03.2004
<u>Specie:</u>	propane
<u>Pressure in the tank (bar):</u>	8.1
<u>Temperature in the tank (C):</u>	9.0
<u>Pressure 10 cm before exit (bar):</u>	8.1
<u>Liquid temperature 10 cm before exit (C):</u>	17.0
<u>Diameter of circular opening (mm):</u>	2.0
<u>Dimensions of rectangular opening (x mm ; z mm):</u>	--
<u>Mass Flow Rate (kg/s):</u>	0.044
<u>Ambient Temperature (C):</u>	10.2
<u>Humidity:</u>	87.0



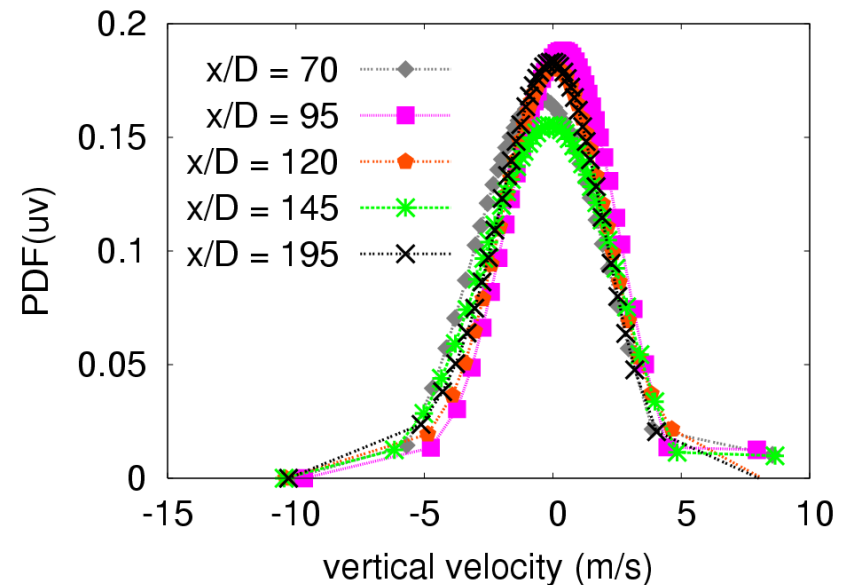
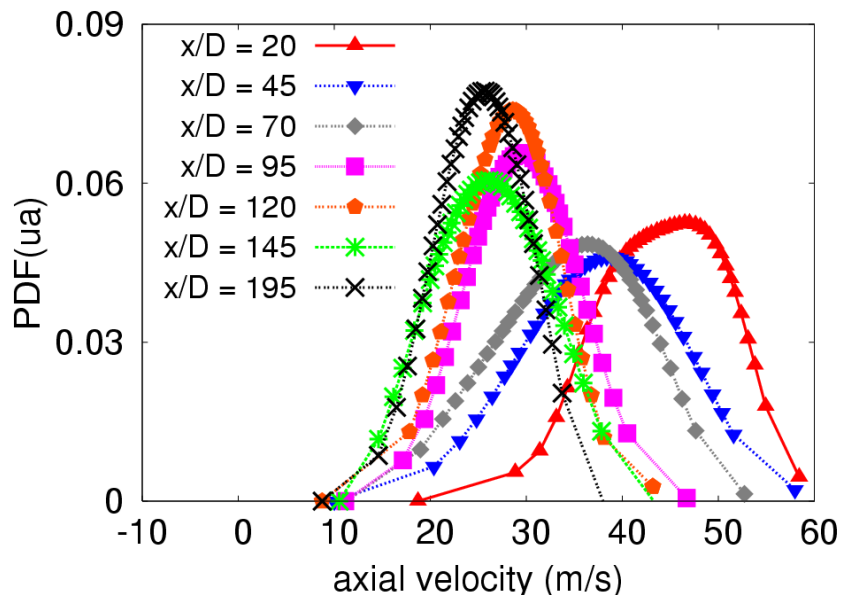
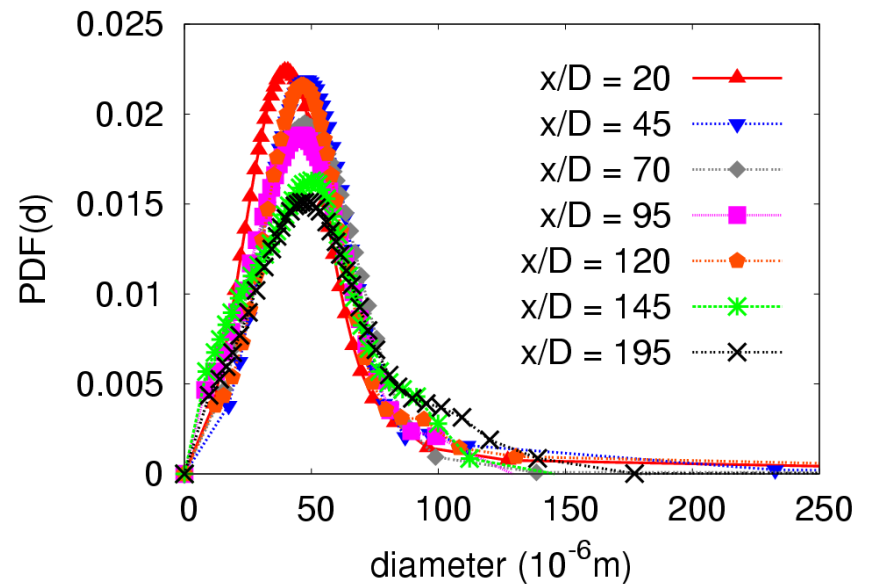
Flashing impinging jet from the INERIS test series report

FLIE INERIS experiments

Example of droplets distributions

Parameters of the test:

Date:	23.03.2004
Specie:	propane
Pressure in the tank (bar):	8.1
Temperature in the tank (C):	9.0
Pressure 10 cm before exit (bar):	8.1
Liquid temperature 10 cm before exit (C):	17.0
Diameter of circular opening (mm):	2.0
Dimensions of rectangular opening (x mm ; z mm):	--
Mass Flow Rate (kg/s):	0.044
Ambient Temperature (C):	10.2
Humidity:	87.0



Computation of the source term – S1

Computation of the mass flow rate at the exit orifice

- Assume the temperature and the pressure (T_0 and P_0) of the liquid in the storage vessel are known
- Assume a high degree of sub-cooling in the storage tank so that the material is in the liquid phase at the exit orifice.
- Compute the mass flow rate at the orifice from the following expression:

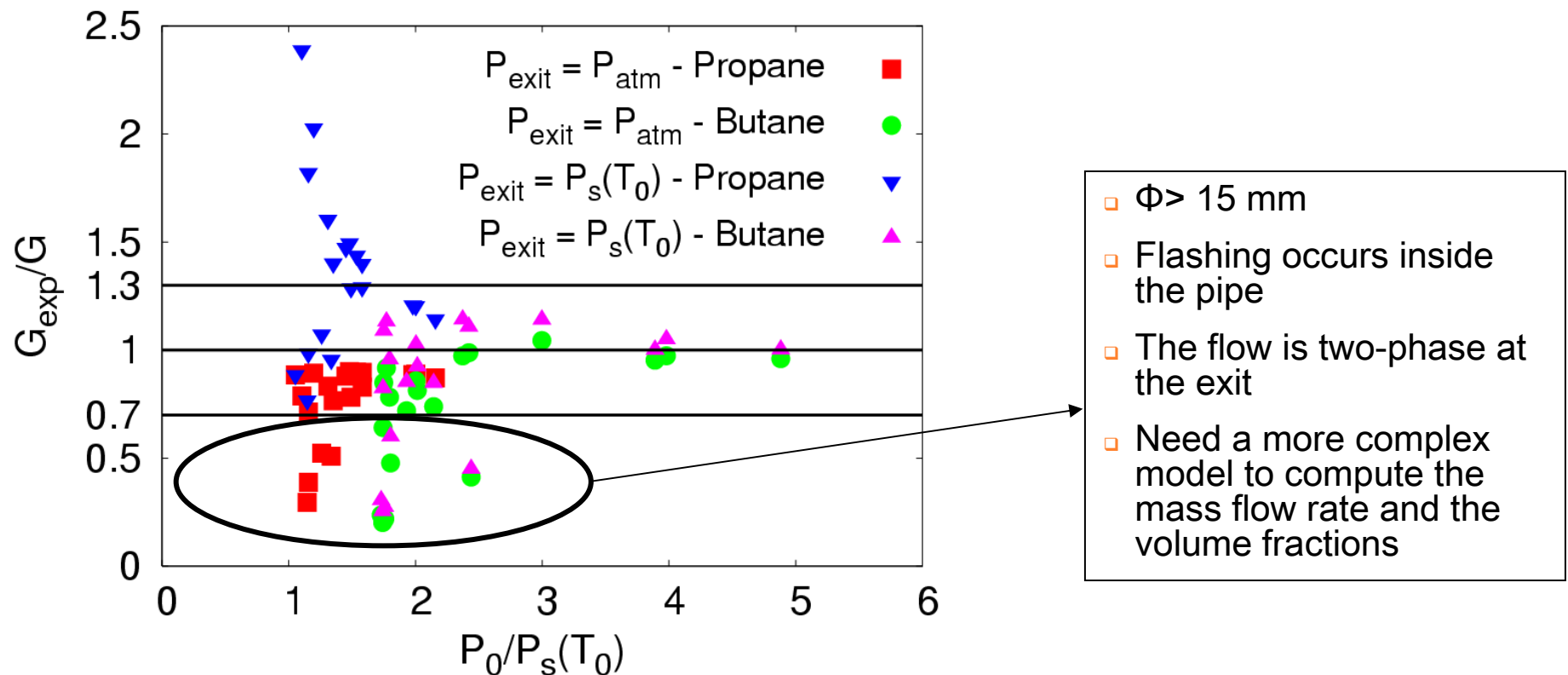
$$G = C_D \sqrt{2\rho_{l_0} (P_0 - P_e)} \quad C_D = 0.62 \quad [G] = \frac{\text{kg}}{\text{m}^2 \text{s}}$$

- How to estimate P_e , the pressure at the exit ?
 - $P_e = P_{\text{atm}}$
 - $P_e = P_s(T_0)$

Computation of the source term – S1

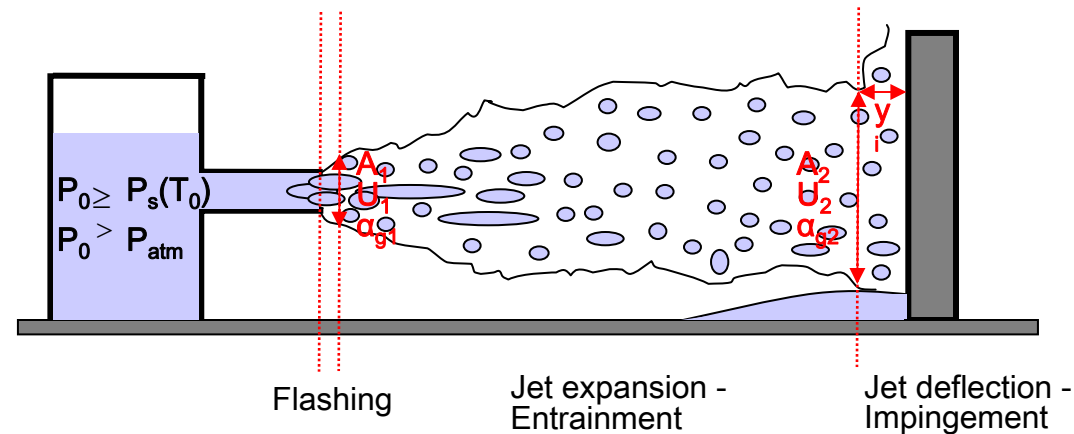
Comparison with the INERIS experiments

- Release geometry: adiabatic pipe of 50 mm diameter, 30 m in length was used to link the bottom part of the storage tank (liquid phase) to the release point.
- Predictions of the mass flow rate for circular openings (diameters of 2, 5, 10, 15, 20 and 25 mm) and different degree of sub-cooling



Computation of the source terms – S2

Computation of the fraction of released mass that rains-out after jet impingement



- Estimate the area, A_1 , and the bulk velocity of the jet, U_1 , and mass fraction x_{g1} , after flashing

$$x_g = \frac{c_p^1 (T_e - T_{nbp})}{L} \quad U_1 = U_e \quad A_1 = \frac{G}{\rho_{m1} U_1}$$

- Estimate the bulk velocity of the jet, U_2 , at the deflection position

$$\rho_{1m} A_1 U_1^2 = \rho_{2m} A_{2m} U_2^2 + \rho_a (A_2 - A_{2m}) U_2^2 \quad U_2 = \frac{G}{\rho_{2m} A_{2m}} \Rightarrow (\text{Fluke et al., 1983}) \quad y_i \Rightarrow (\text{Giralt et al., 1977})$$

- Estimate the critical droplet diameter, d_c , and the rain-out fraction f

$$d_c = \left(\frac{18 St_c \tau \mu_{2g}}{\rho_d} \right)^{0.5} \quad \tau = \frac{D_2}{U_2} \quad \Rightarrow \quad f = (1 - F_m(d_c)) (1 - x_g)$$

Computation of the source terms – S2

Computation of the fraction of released mass that rains-out after jet impingement

- ▣ Critical droplet diameter is given by:

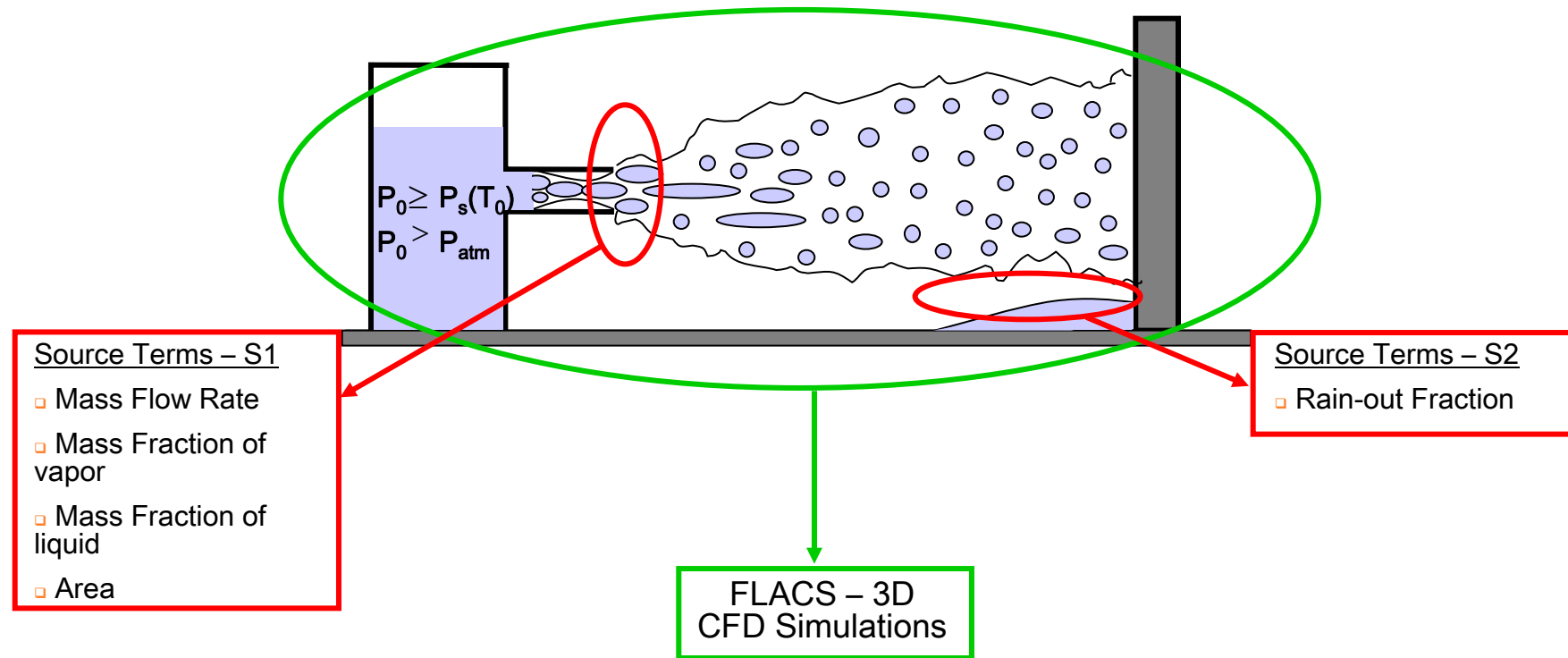
$$d_c = \left(\frac{18St_c \tau_f \mu_{2g}}{\rho_d} \right)^{0.5} \quad \tau_f = \frac{D_2}{U_2}$$
- ▣ Stokes number: $St = \frac{\tau_d}{\tau_f}$
 - $St \ll 1$ the droplet is able to respond to changes in flow velocity
 - $St \gg 1$ the droplet is not affected by changes in flow velocity
- ▣ Value for the critical Stokes Number, St_c : in the range 10 - 100 => (*Tang et al., 1992*)
- ▣ From comparison with experimental observations, St_c is set to 70

Specie	$P_0/P_s(T_0)$	Distance (m)	Rain-out		
			Data	Predictions	
				MFR_{exp}	MFR_{comp}
Propane	1.02	0.83	11%-12%	13%	18%
Butane	2.0	1.6	31%-39%	25%	33%
Butane	1.78	1.6	31%-39%	22%	26%
Butane	5.0	1.6	40%-50%	45%	46%
Butane	3.0	1.6	36%-45%	49%	48%
Butane	2.12	0.83	40%-50%	64%	75%

Comparison with experimental data for a circular orifice of diameter 10 mm (MFR = Mass Flow Rate at the exit orifice)

FLACS – 3D Simulations

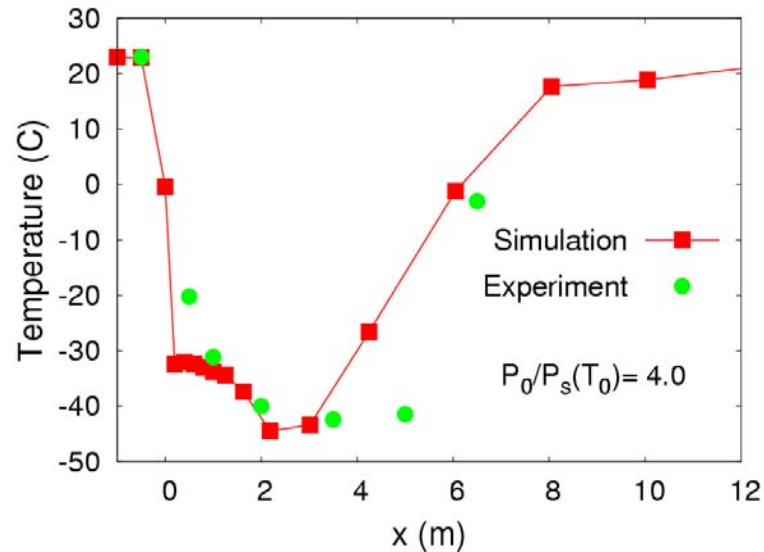
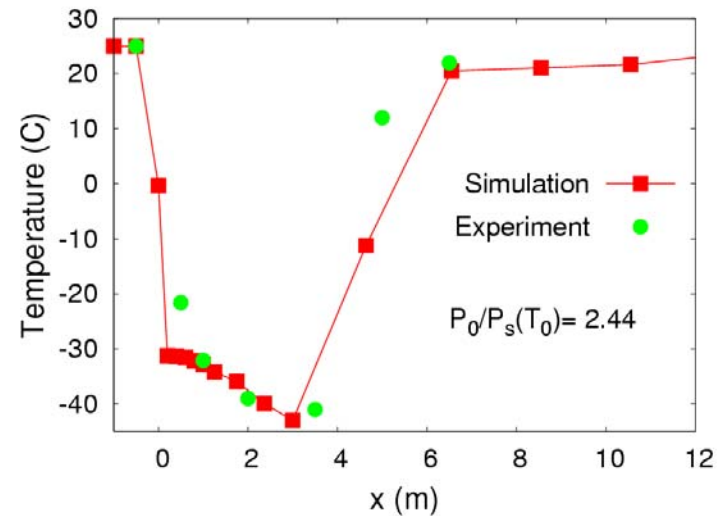
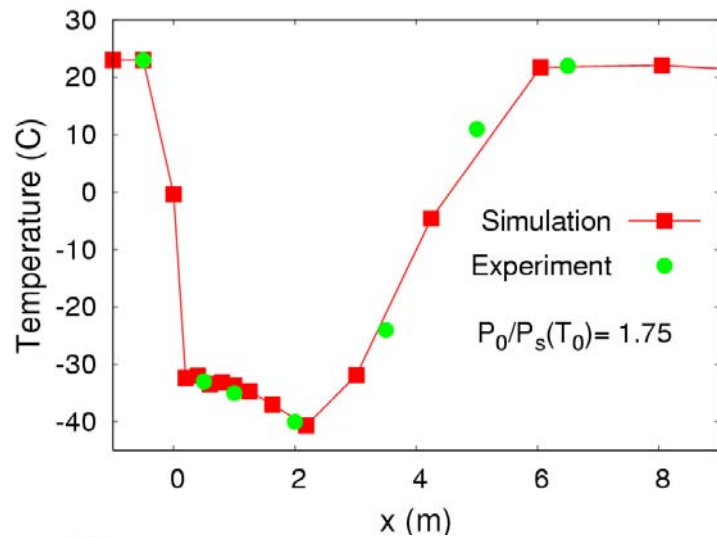
Modeling a two-phase jet in the CFD code FLACS



- Mixture of dry air, chemical droplets and chemical vapor
- Homogeneous equilibrium model:
 - assume thermodynamic equilibrium
 - assume droplets are homogeneously statistically distributed both spatially and in size
- Evaporation of the chemical droplets

FLACS – 3D Simulations

Simulation of a flashing butane release with FLACS (free jet) – Temperature comparisons



Test B1 – $P_0/P_s(T_0) = 1.75$

- MFR = 0.81 kg/s – error 15 %
- $T_{amb} = 23\text{ °C}$

Test B2 – $P_0/P_s(T_0) = 2.44$

- MFR = 1.03 kg/s – error 2 %
- $T_{amb} = 25\text{ °C}$

Test B3 – $P_0/P_s(T_0) = 4.0$

- MFR = 1.37 kg/s – error 3 %
- $T_{amb} = 23\text{ °C}$

FLACS – 3D Simulations

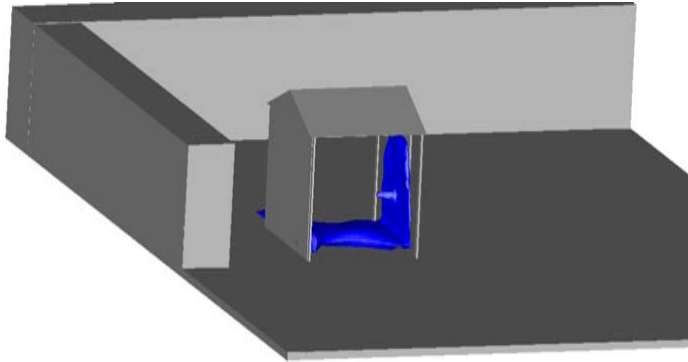
FLACS setup for the simulation of impinging flashing jets of butane

- Parameters of the tests:
 - $P_0 = 1.75 \times P_s(T_0)$
 - Circular opening with a diameter of 10 mm
 - $T_{amb} = 23 \text{ }^\circ\text{C}$
 - Velocity is 3 m/s at a height of 10 m and the stability class is neutral

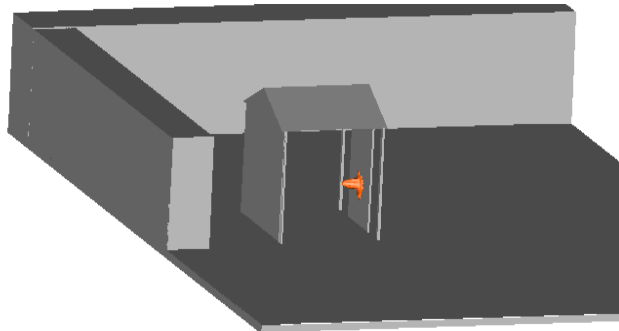
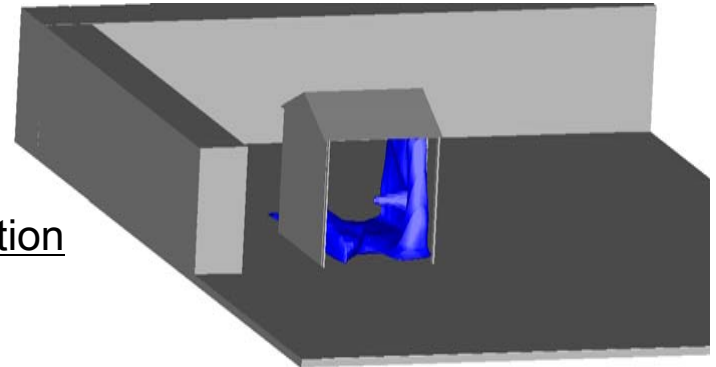
- Predicted mass flow rate at the exit: 0.86 kg/s – Measured mass flow rate at the exit: 0.7 kg/s
- Volume fraction of vapor after flashing: 0.977
- Test 1: wall is located 0.83 m from release point – 67 % of the released mass rains-out
- Test 2: wall is located 1.6 m from release point – 26 % of the released mass rains-out
- The liquid that rains-out forms a pool on the ground. Spreading and evaporation of the pool is handled in FLACS

FLACS – 3D Simulations

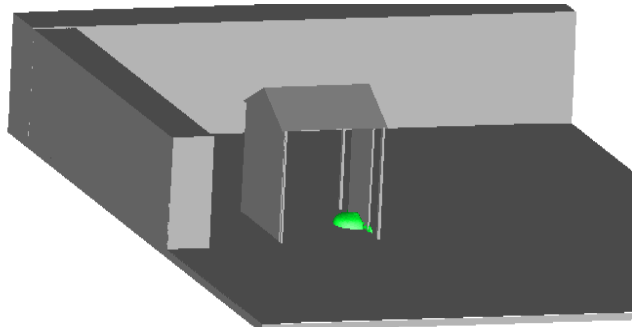
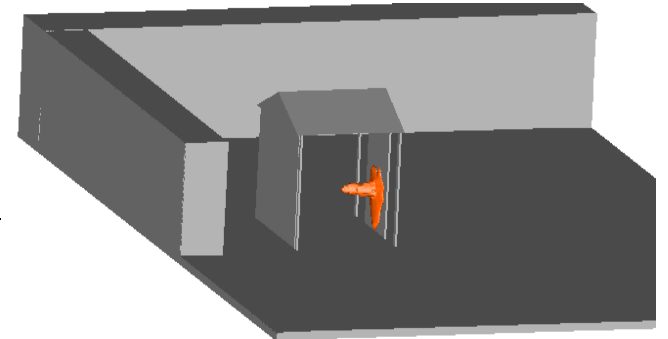
FLACS results for impinging flashing jets



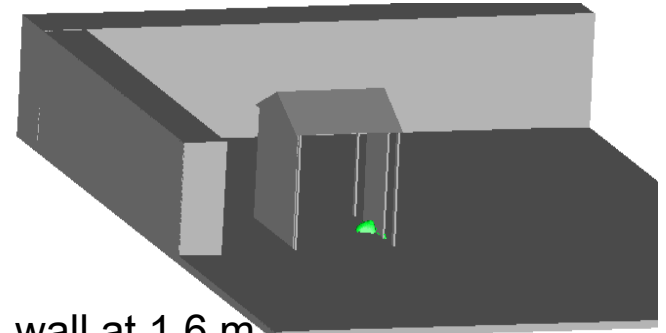
Vapor Volume Fraction
3.5 % contour



Liquid Volume Fraction
2.0 10⁻⁵ % contour



Pool Depth
1 mm to 1 cm



Test 1: wall at 0.83 m

Test 2: wall at 1.6 m

Conclusion

- An approach to handle flashing jets in complex environments has been presented
- INERIS large scale experiments on impinging flashing jets of propane and butane have been discussed
- A model for the prediction of the mass flow rate (source term S1) has been presented and results have been compared with experimental observations:
 - Accuracy improves when the degree of sub-cooling increases
 - Occurrence of flashing inside the pipe does depend on the release geometry
- A model for the prediction of the percentage of liquid that rains-out due to jet impingement (source term S2) has been presented:
 - Predictions have been compared with experimental observations
 - Butane gives the largest amount of rain-out
 - Rain-out increases when the degree of sub-cooling increases and when the distance to impingement decreases
 - Predictions could be improved with a more complex model: droplet interaction with the wall
- Simulations of free flashing jets of propane and butane have been presented:
 - The homogeneous equilibrium model has been implemented in the CFD FLACS code
 - Comparisons with experimental data of the temperature field show good agreements
- Future work: validation of concentrations downstream, include humidity, Lagrange Models

Thank you for your attention

Questions ?

Mathieu Ichard, GexCon AS R&D, Bergen, Norway, mathieu@gexcon.com

Jens Melheim, GexCon AS R&D, Bergen, Norway, jens@gexcon.com

Olav R. Hansen, GexCon US, Bethesda, Maryland, USA, olav@gexcon.com

cmr Gexcon

