Demystifying mist explosion hazards

Stephanie El - Zahlanieh, Idalba Souza Dos Santos, Hugo Tostain,
Alexis Vignes, Olivier Dufaud, Simon Gant

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- Mist Generation and Characterization
- Ignition and Explosion Severity
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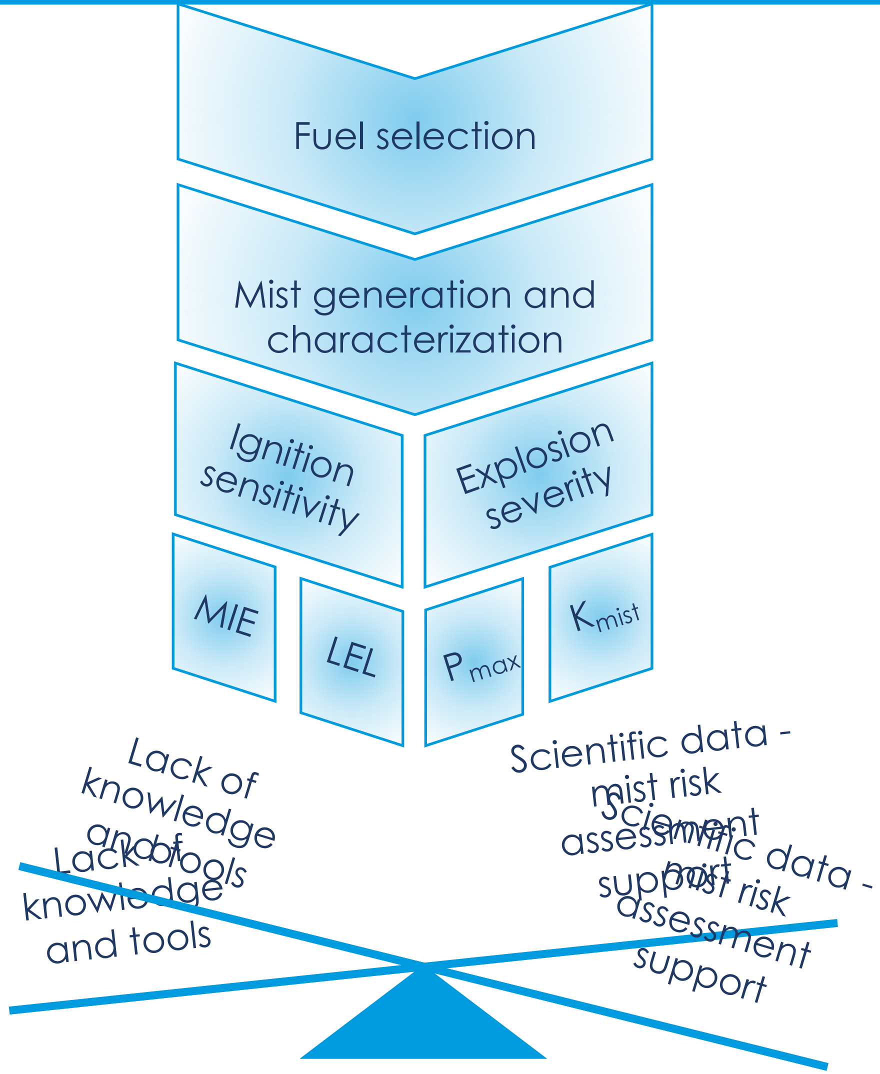
Introduction

- Whilst hazardous area classification of flammable gases and dusts is well established in ATEX, DSEAR, and EPS directives, the classification of aerosols is less clear
- When aerosolized, liquids can ignite and give rise to explosions at temperatures well below their flashpoint
- Santon (2007) review: 20 explosions, 29 fatalities
- Lees et al. (2019): 25 reported mist incidents over 2 year period on UK offshore platforms

The necessity to acquire full knowledge and ability in order to classify hazardous mist explosive areas



Fuel selection

Mist generation and characterization

Ignition sensitivity

Explosion severity

MIE

LEL

P_{max}

K_{mist}

Lack of knowledge and tools

Lack of knowledge and tools

Scientific data - mist risk assessment support

Scientific data - mist risk assessment support

Fuel Selection

Fuel Selection

	Diesel	**Biodiesel B100**	**Light Fuel Oil**
Flashpoint (°C)	> 55	> 300	> 55
Density ($kg.m^{-3}$)	150 - 380	> 350	150 - 380
Kinematic viscosity ($mm^2.s^{-1}$)	2 – 4.5 @ 40 °C	65 @ 20 °C	< 7 @ 40 °C
Surface tension ($kg.s^{-2}$)	0.0275	0.0312	0.025
HSE release class	Release Class I More volatile / Less atomizing	Release Class III/IV Less volatile / Less atomizing	Release Class I More volatile / Less atomizing

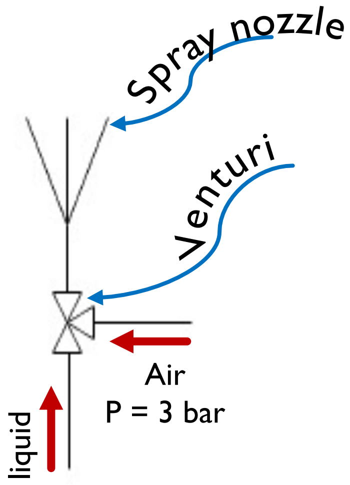
Mist Generation and Characterisation

Mist Generation and Characterization

Generation

Venturi-based twin-fluid injection system

- Control of the temperature and pressure of the liquid reservoir
- Variation of the air injection pressure, injection time, nozzle air and fluid cap
- Control of the DSD, average concentration, fuel/air ratio



	Diesel	LFO	Biodiesel
Mass flow rate ($g.s^{-1}$)	0.31	0.32	0.24

Mist Generation and Characterization

Characterization

Droplet Size Distribution (DSD)

- In-situ laser diffraction sensor
- Time evolution of the DSD
- Mean and representative diameters such as d_{10}, d_{50}, d_{90}, and SMD
- Optical concentration

Turbulence level

- Particle Image Velocimetry (PIV)
- Nd:YAG laser, $\lambda = 532$ nm
- PIVlab 2.45
- Horizontal and vertical fluctuations ➔ root-mean-square velocity v_{rms}

DSD of diesel mists under atmospheric condition at $P_{inj} = 3$ bar

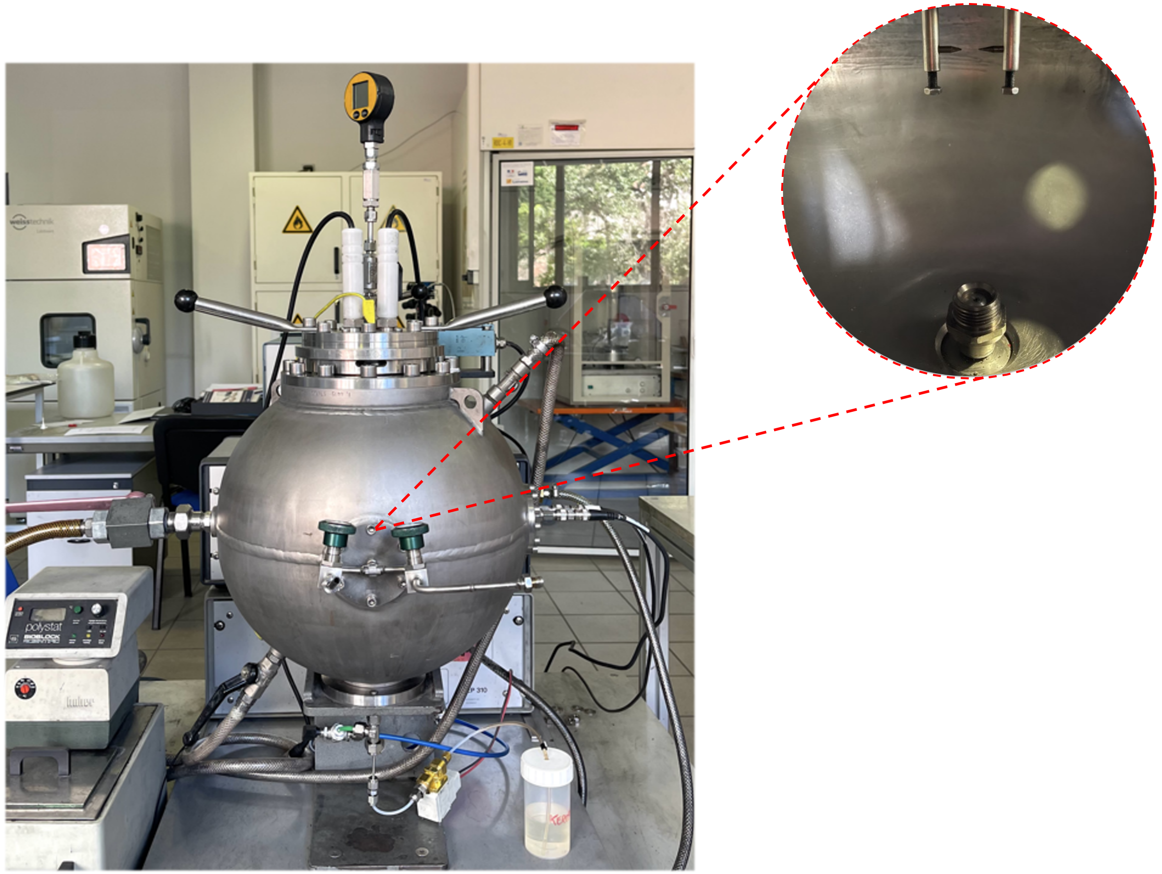
D_{10} (µm)	SMD (µm)	D_{50} (µm)	D_{90} (µm)
7.8	9.5	9.7	11.9

PIV results of diesel mists under atmospheric condition at $P_{inj} = 3$ bar

t_v (ms)	3	60	200	400	600	800	1000
V_{rms} (m/s)	1.78	0.9	0.68	0.59	0.46	0.29	0.28

Ignition Sensitivity and Explosion Severity

Ignition and Explosion Severity



- ✓ Modification of the standard 20 L sphere
- ✓ Installation of the mist generation system
- ✓ Control of inlet flowrates as well as the liquid / air ratio by 2 electronic valves
- ✓ Partial vacuuming of the sphere before injection
- ✓ Control of the system as well as the data acquisition
- ✓ Control of the sphere’s temperature by a water jacket
- ✓ Use of 100 J chemical ignitors or spark ignition
- ✓ Result: the explosion overpressure P_{ex}, the explosion rate of pressure rise dP/dt_{ex}, the lower explosive limit LEL, and the minimum ignition energy MIE

Ignition and Explosion Severity

Influence of the ignition delay time

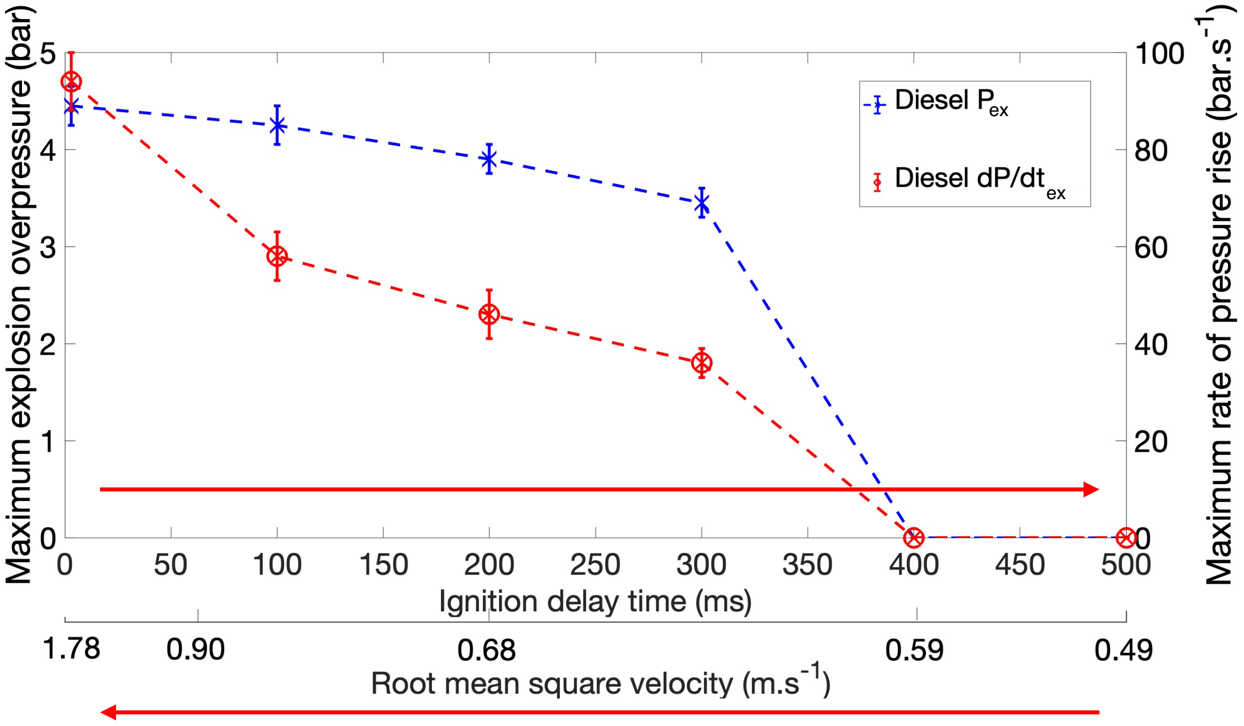
Diesel

100 J ignitors

T_{sphere} = 40 °C

T_{tank} = 25 °C

- P_{ex} and dP/dt_{ex} decrease as t_v increases
  - ➔ Sedimentation and decrease of average mist concentration
  - ➔ Decrease of the root-mean square velocity
  - ➔ A more noticeable decrease of dP/dt_{ex} showing the influence of the turbulence level on the flame propagation and the kinetics of the combustion reaction



Influence of the ignition delay time t_v on both P_{ex} and dP/dt_{ex} at T = 40 ° C and diesel mist concentration of 123 g.m^{-3}

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Ignition and Explosion Severity

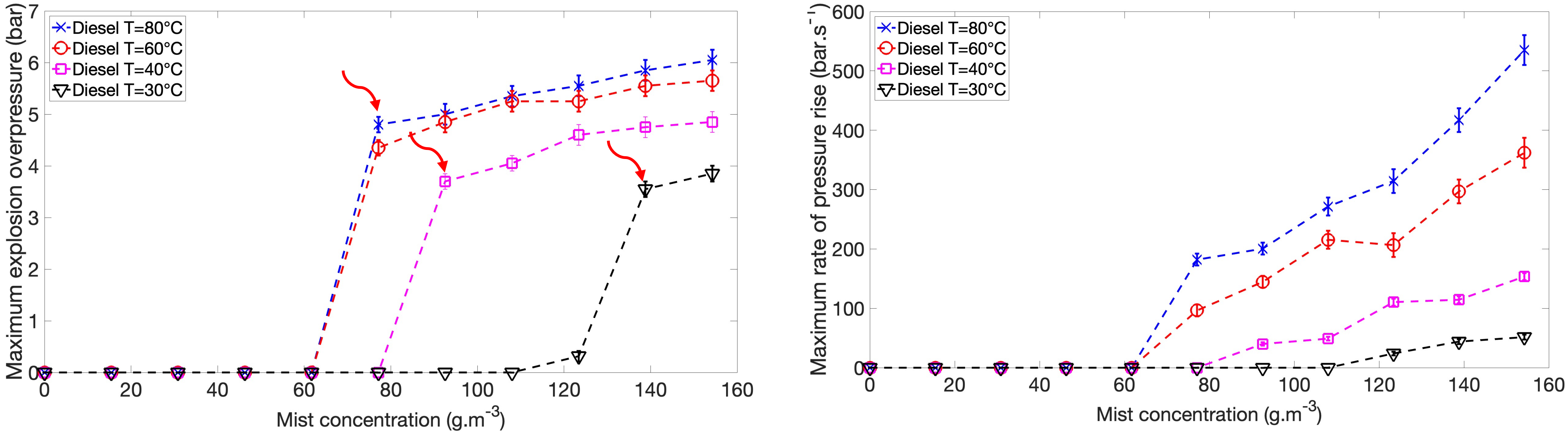
Influence of the initial sphere temperature

Diesel

100 J ignitors

T_{sphere} = 30, 40, 60, 80 °C

T_{tank} = 25 °C



Influence of the initial sphere temperature and diesel mist concentration on both P_{ex} and dP/dt_{ex}

- Increase in fuel vapour phase ➔ decrease in LEL
- Noticeable influence on dP/dt_{ex} ➔ influence on the combustion reaction kinetics and the growth of the initial flame kernel

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Ignition and Explosion Severity

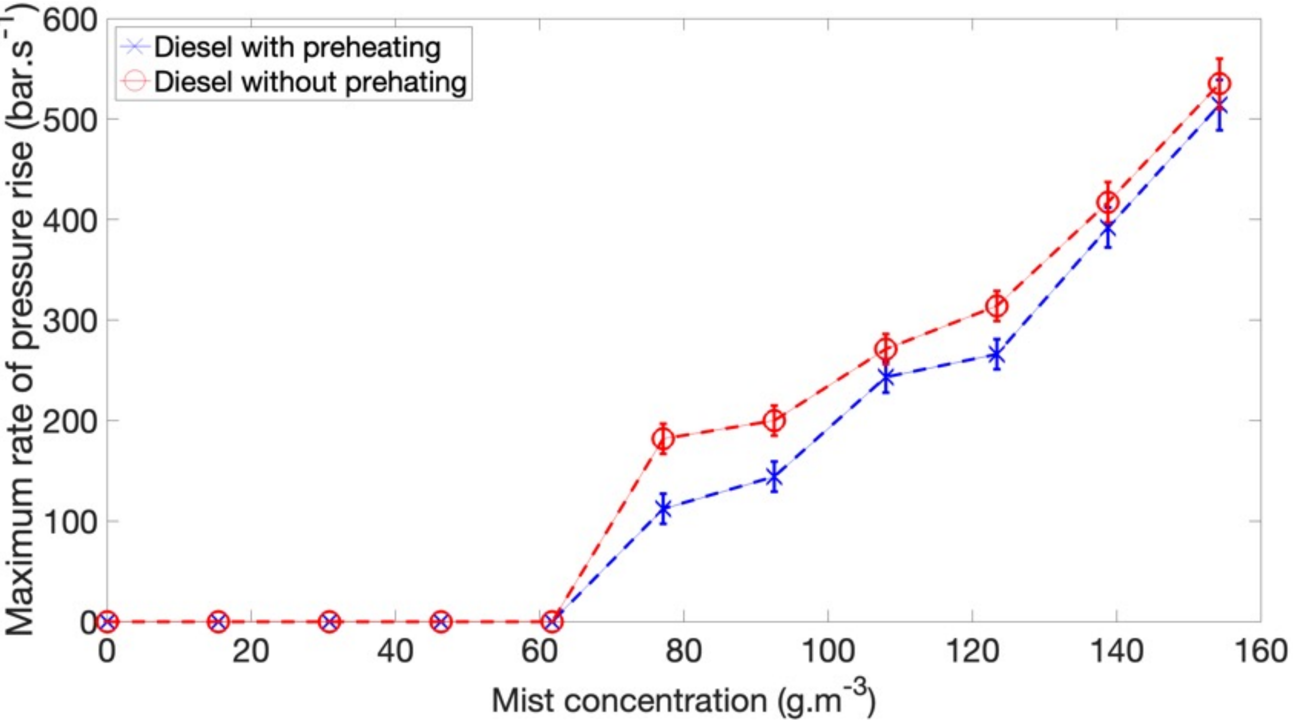
Influence of the initial sphere temperature

Diesel

100 J ignitors

T_{sphere} = 80 °C

T_{tank} = 80 °C

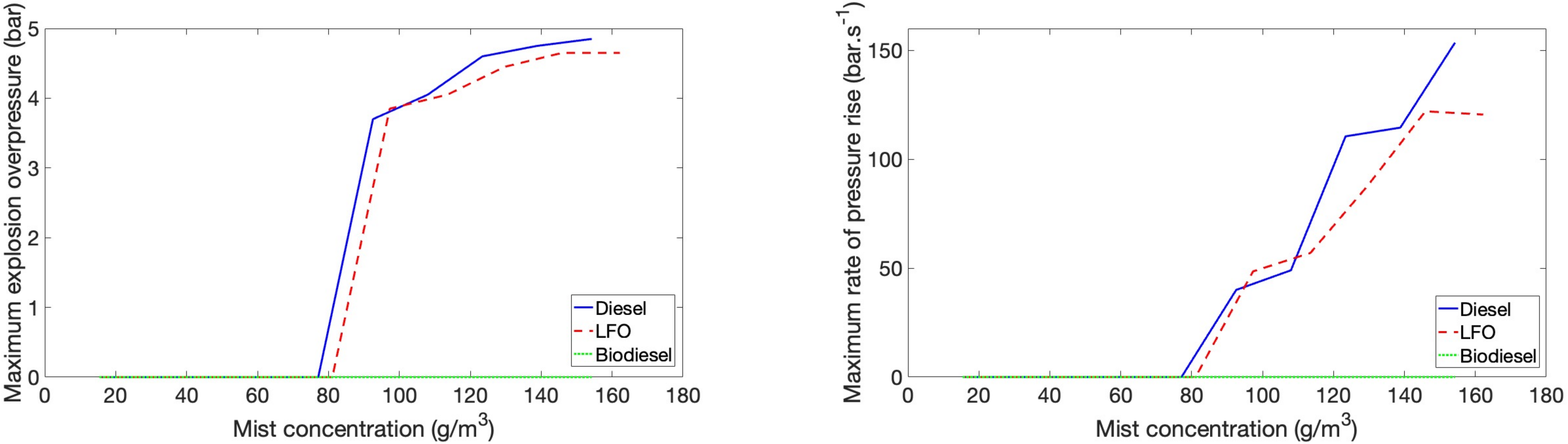


Influence of the diesel mist concentration on P_{ex} and dP/dt_{ex} with and without preheating the fuel before injection, T_{sphere} = 80 ° C

- Diesel fuel was preheated to T = 80 °C in a metallic reservoir
- Preheating the diesel fuel did not have a significant effect on the explosion severity but did affect the heating time of the droplets
- Further characterization tests should be carried out to assess the influence of the fluid properties

Ignition and Explosion Severity

Three-Fuel Comparison



Comparison of the explosivity of diesel, LFO, and biodiesel at T = 40 ° C

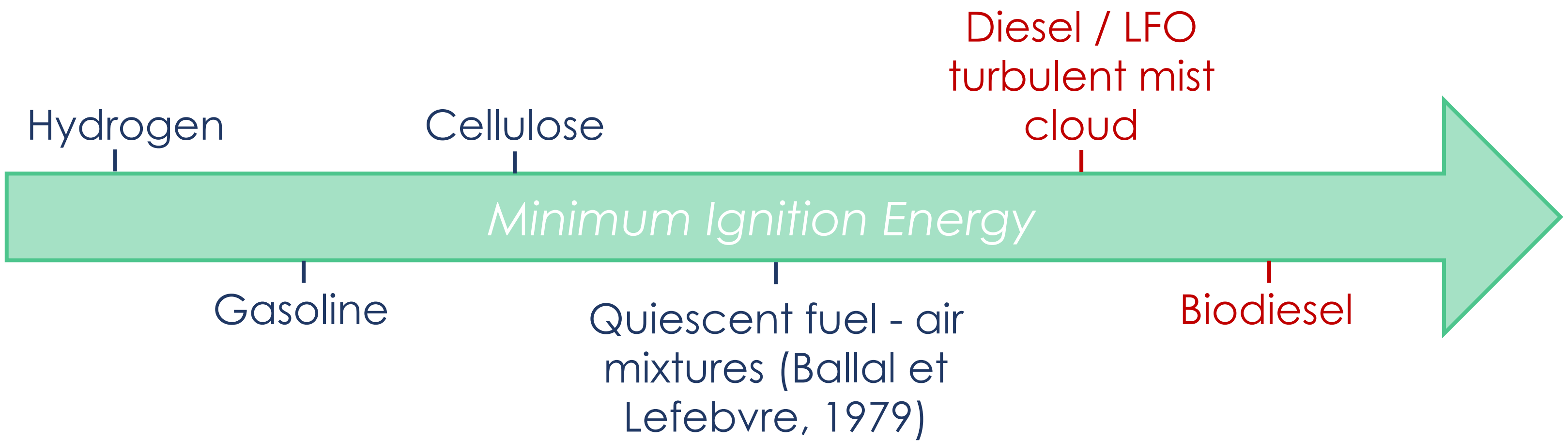
- Different explosivity behaviours depending on the liquid properties and ambient conditions

  ➔ Potential to develop different testing protocols based on liquid properties providing incident prevention and protection means

Ignition and Explosion Severity

Minimum Ignition Energy & Lower Explosive Limit

	LEL$_{T\,=\,30\,^{\circ}C}$	LEL$_{T\,=\,40\,^{\circ}C}$	LEL$_{T\,=\,60\,^{\circ}C}$	LEL$_{T\,=\,80\,^{\circ}C}$
Diesel	123.4	92.5	77.1	77.1
LFO	-	97.3	97.3	81.1
Biodiesel	-	-	103	91



Minimum Ignition Energy

Hydrogen

Gasoline

Cellulose

Quiescent fuel - air mixtures (Ballal et Lefebvre, 1979)

Diesel / LFO turbulent mist cloud

Biodiesel

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Evaporation Model

Evaporation Model

- The d²-law: a simplified model of droplet evaporation

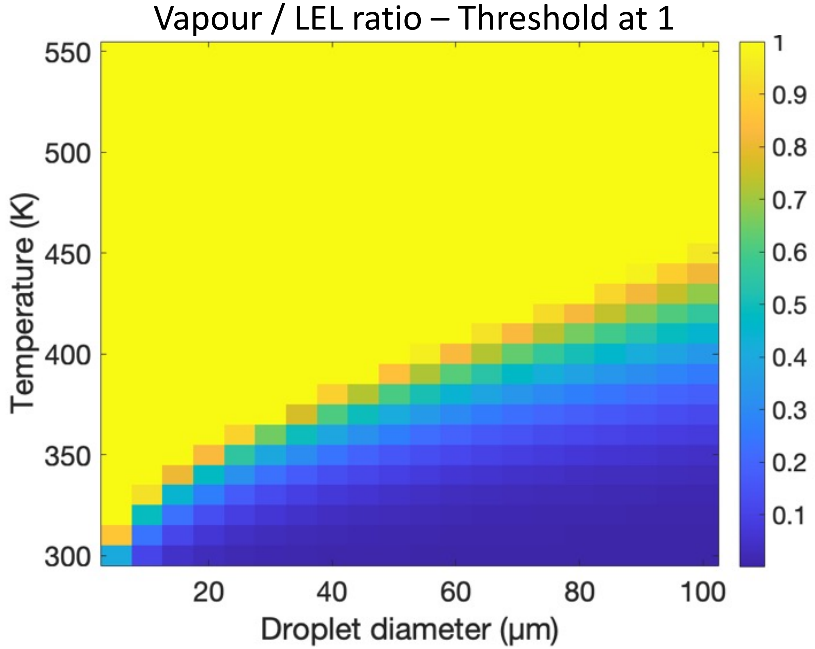
$$d^2 = d_0^2 - Kt$$

- Turbulent mist cloud:

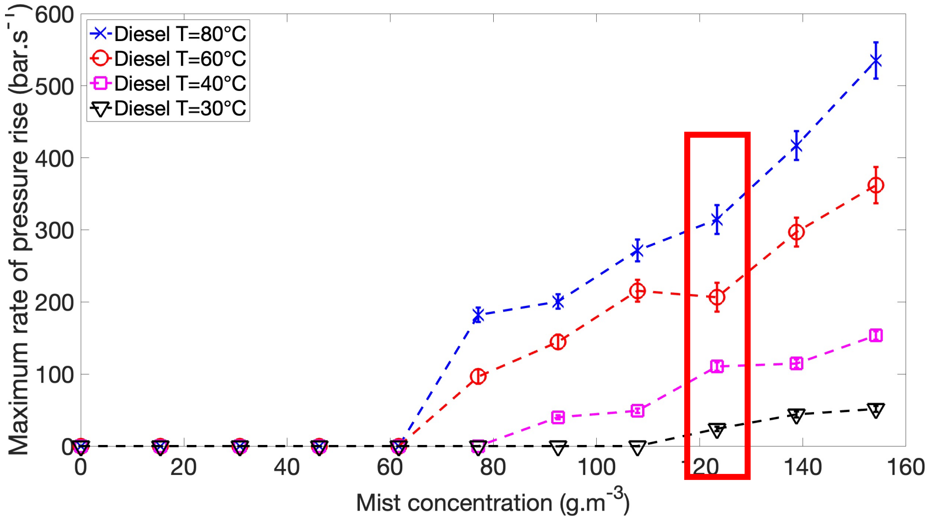
$$K = 8D\frac{\rho}{\rho_l}\ln(1 + B_T)\left(1 + 0.0276Re^{\frac{1}{2}}Sc^{\frac{1}{3}}\right)$$

- Heat transfer Spalding number with combustion:

$$B_T = \frac{C_{p,v}(T_\infty - T_d) + \frac{Q}{s}Y_{Ox,\infty}}{L_v}$$



The vapour/LEL ratio (the threshold value is set at 1) as a function of the initial temperature and droplet size for a 2.5 g diesel mist cloud (125 g.m⁻³) with a 3 ms ignition delay time



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Dimensionless Numbers and Liquid Classification

Dimensionless Numbers & Liquid Classification

Reynolds number	**Ohnesorge number**	**Spalding number**	**Stanton number**	**Nusselt number**
Liquid density	Liquid viscosity	T_{liquid}	Convection coefficient	Convection coefficient
Liquid viscosity	Surface tension	T_{sphere}	Heat capacity	Thermal conductivity
SMD	Orifice diameter	Heat capacity	Air density	SMD
Turbulence		Heat of vaporization		

Injection pressure

Air viscosity

Vapour fraction

Flow rate

DSD

Initial pressure

Flash point

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Dimensionless Numbers & Liquid Classification

Reynolds number	**Ohnesorge number**	**Spalding number**	**Stanton number**	**Nusselt number**
$Re = \frac{\rho_L d_0 U}{\mu_L}$	$Oh = \frac{\mu_L}{\sqrt{\rho_L \sigma d}}$	$B_T = \frac{C_{p,v}(T_\infty - T_d)}{L_v}$	$Sta = \frac{h}{\rho_{air} U C_p}$	$Nu = \frac{hd}{\lambda}$

- The presence of various dimensionless numbers and correlations allowing to study the influence of different parameters on the DSD, the flammability, and the explosivity of hydrocarbon mists
- Potential to develop new test protocols based on combining ignition and explosion risk (using dimensionless numbers) with HSE classification system

Conclusion

- ✓ The lack of knowledge present in the field of mist hazards was addressed by providing new scientific data to support mist risk assessment
- ✓ The strong influence of the initial operating conditions (specifically the initial temperature and turbulence level) on the safety parameters of hydrocarbon mists was demonstrated
- ✓ MIE values were shown to be in the range of 200 – 350 mJ for diesel mists at $T = 40$ °C
- ✓ LEL values of about 92 and 97 g/m^{-3} for diesel and light fuel oil mists respectively were found
- ✓ Possibility to characterize the ignition sensitivity and explosion severity of hydrocarbon mists with only one set-up

THANK YOU!

Contact Information:
Stephanie El – Zahlanieh
stephanie.el-zahlanieh@univ-lorraine.fr
https://www.linkedin.com/in/stephanie-el-zahlanieh-420689144/

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