Ammonia light duty-engines : main issues

Christine Mounaïm-Rousselle

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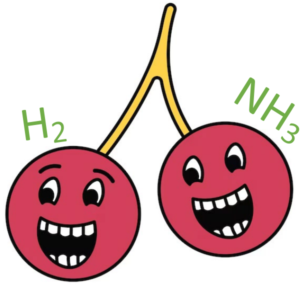
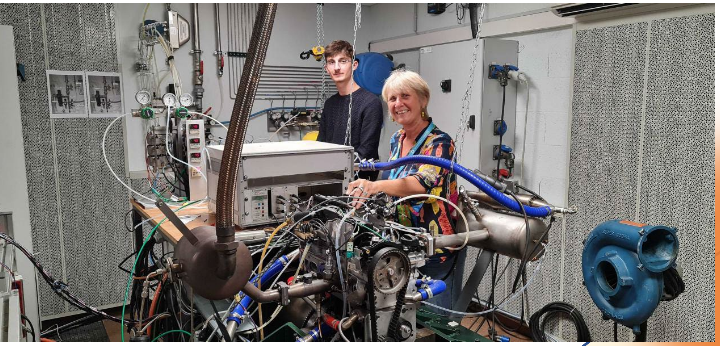
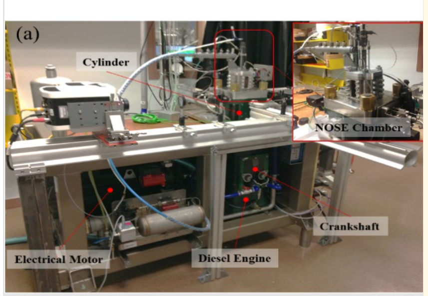
Since 2017
Ammonia as a zero-carbon fuel topic

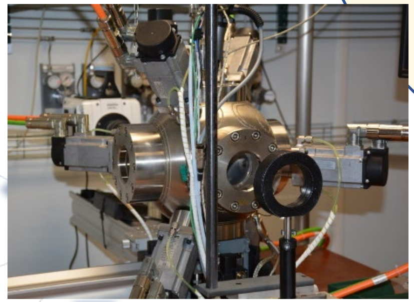


Thanks to all : Pierre Bréquigny, Camille Hespel, Fabrice Foucher, Bruno Moreau, Seif Zitouni, Caneon Curien, Adrien Mercier, Charles Lhuillier, Ricardo Rabello, Ronan Pelé, Noé Monier, Florian Hurault, Richard Samson, Anthony Dupuy, Anthony Desclaux, ….

From fundamental to application



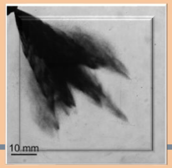




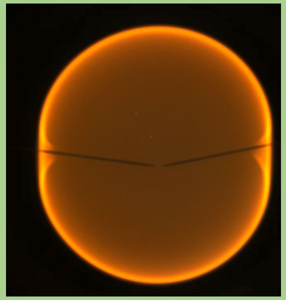
Rapid Compression Machines

Auto Ignition Delays (P, T, Equivalence ratio, species)

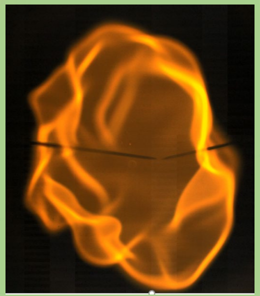
HP, HT vessels
For spray studies



Penetration length, spray angle, vaporisation rate, mixture fraction

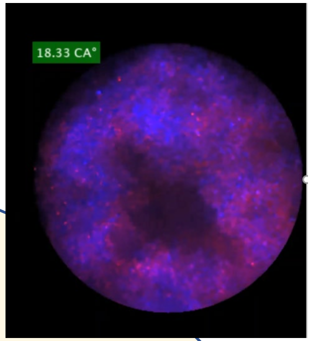


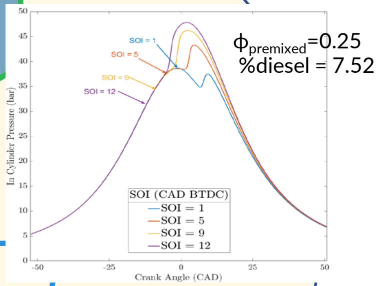
HP, HT vessels
For combustion studies



Fundamental data
laminar and turbulent burning velocities

4 stroke Single cylinder engines
Optical or all metal





Mixture, combustion, pollutant

ENGINE APPLICATIONS

Improvement of combustion modeling : kinetics, turbulence-flame interaction


Ammonia: Fuel vs. Hydrogen Carrier
NH3 or H2
Ammonia on route to fuel
Carbon-neutral ammonia could be a
by Alex Scott
AUGUST 12, 2020 | APPEARED IN
CMA CGM
Green ammonia for electrical power
AMMONIA
BOCIMAR
NH3 205.000 DWT Dry Bulk Carrier
China's GAC Unveils World's First Ammonia Car Engine
The low carbon alternative fuel is already used in shipping
GAC said its engine can burn ammonia efficiently and safely
Japanese Projects Achieve Stable Combustion on Ammonia-Fueled Engines
THIS IS INSANE!
Toyota CEO: "Our New Ammonia Engine Will Bankrupt The Entire EV Industry!"
Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon
By Robert F. Service | Jul. 12, 2018 , 2:00 PM
EMSA
By Julian Atchison
Ammonigy's "Ammonia Fuel Refineme
A chemical traditionally used in the fertiliser industry, ammonia is now also entering the realm of energy as a way to store and transport hydrogen, or as an alternative transport fuel

RESEARCH GAPS FOR CLEAN AND EFFICIENT NH_3 ENGINE

Challenges	Impacts	Research needs (Experiments & modeling)
Hard to ignite	Cold start Need ignition strategy/promoter	(Auto-) Ignition properties of NH_3 blends & related chemical kinetics
Narrow flammability	Stability/operability problems	Extinction and stability characteristics of NH_3 blends
Slow flame propagation	Stability/operability problems Depleted thermal efficiency	Flame propagation characteristics & chemical kinetics of NH_3 blends
Fuel-bound nitrogen	Pollutant emissions	Chemistry and physics of low-emission combustion modes

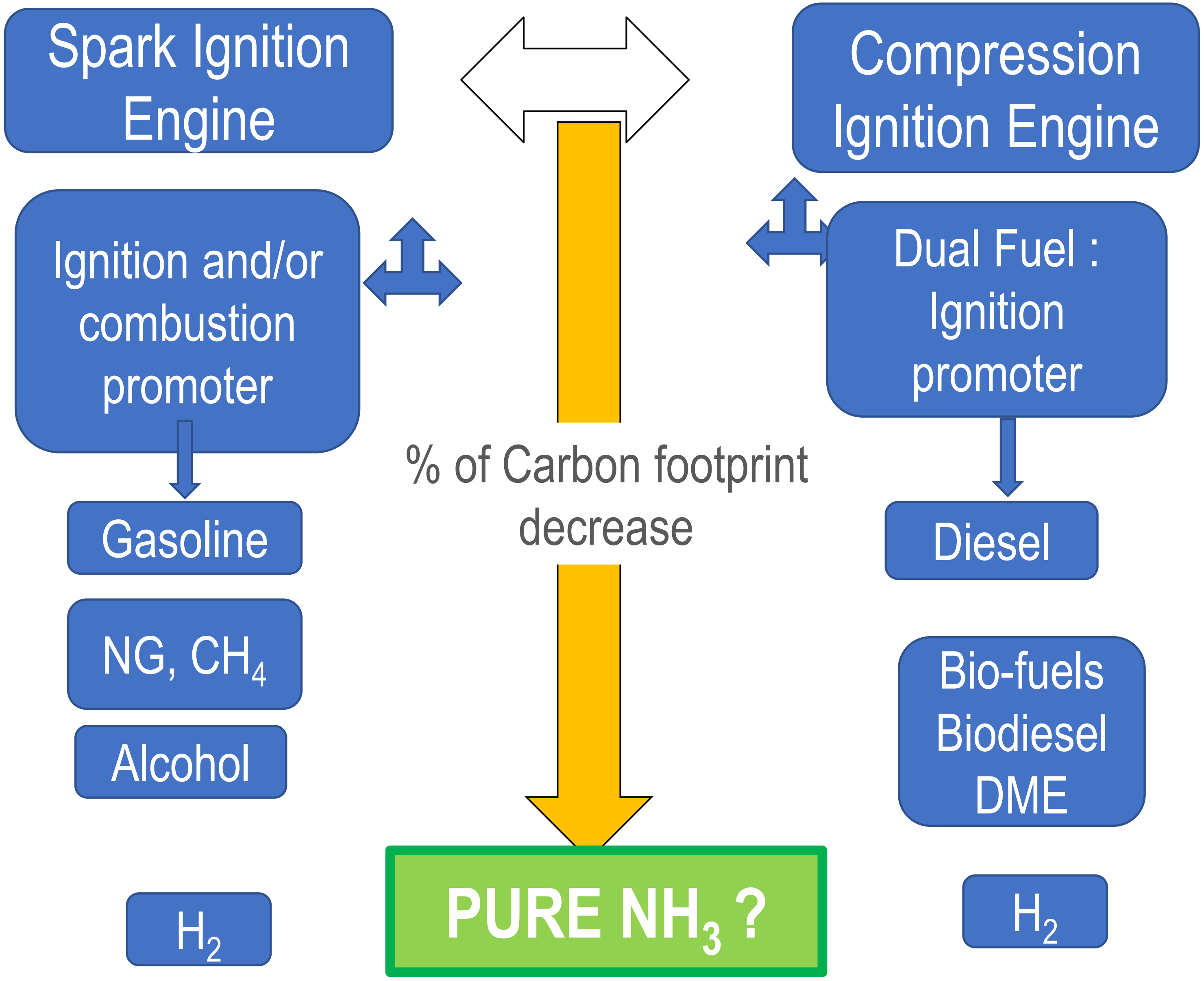
AMMONIA COMBUSTION CHARACTERISTICS

- No appropriate combustion properties for piston engines ?

	Hydrogen	CH_4	Gasoline	Methanol	Ammonia
Stoichiometric air/fuel ratio (mol./mol.)	2.38	**9.52**	59.5	7.74	**3.57**
Stoichiometric air/fuel ratio (kg/kg)	34.3	**17.2**	15	6.97	**6.06**
Heat Energy (MJ/kg fuel)	119.9	50	44.4	19.94	18.8
Energy (MJ/kg air)	3.5	2.9	2.8	3.3	3.1
Flammability limits in air (vol.%)	4.5-75	5-17	1.3-7.6	7.9-26	15-30
Auto-ignition temperature (°C)	537	595	>225	440	651
Research octane number (-)	>120	120	0	>120	>120
Adiabatic flame temperature (°C)	2110	1950	2030	1880	1880
Laminar burning velocity (cm/s) (ER=1)	210	38	40	45-50	7

- similar energy input (by air charge)
- Good to limit knock occurence: high Compression Ratio or turbocharging conditions
- Lower flame temperature = Lower thermal NOx but fuel NOx, N_2O emissions

CASE OF NH_3 AS FUEL FOR ICE



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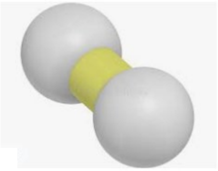
How improve ammonia combustion in ICE

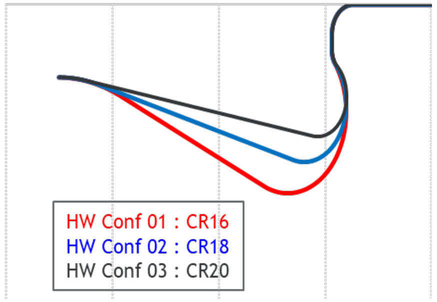
Reactive fuel addition



H2

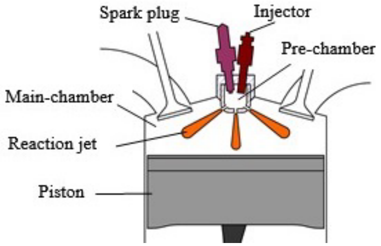
Biofuels (diesel, dme, additive)

CR increase



Ignition Improvement ?

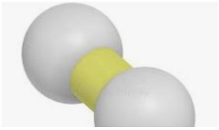
High energy igniter



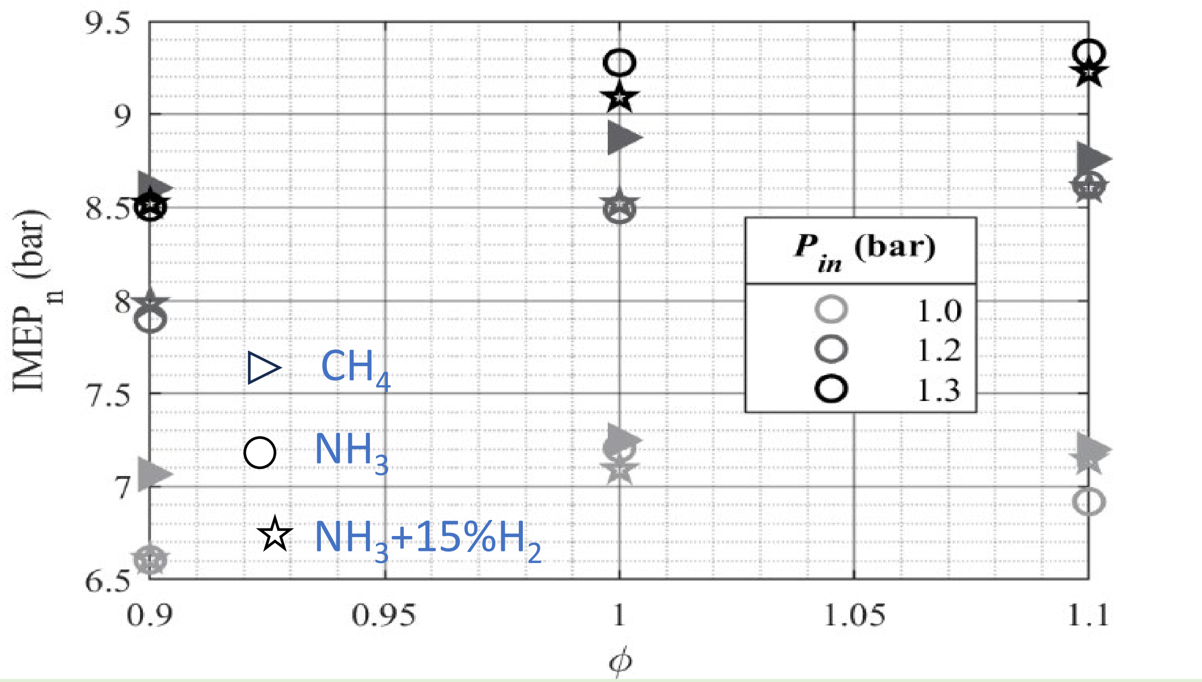
Prechamber igniter

How improve ammonia combustion in ICE

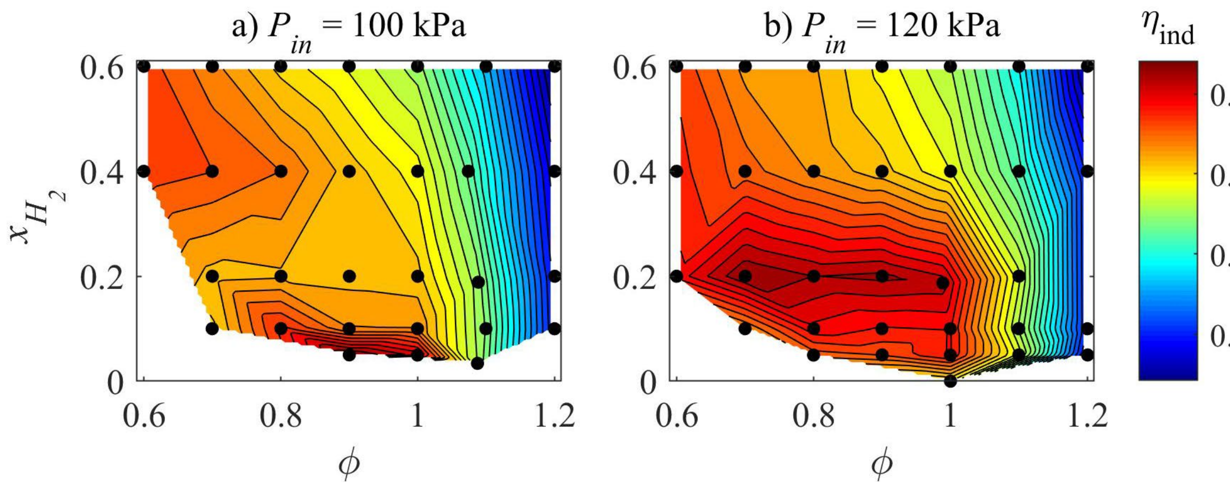
H$_2$ addition



Citation: Lhuillier, C., BREQUIGNY, P., Contino, F., and Rousselle, C., "Combustion Characteristics of Ammonia in a Modern Spark-Ignition Engine," SAE Technical Paper 2019-24-0237, 2019, https://doi.org/10.4271/2019-24-0237.



$$\eta_{ind} = \frac{IMEP_n}{FuelMEP}$$

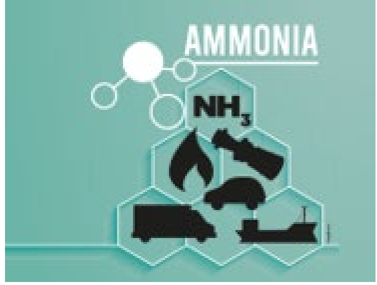


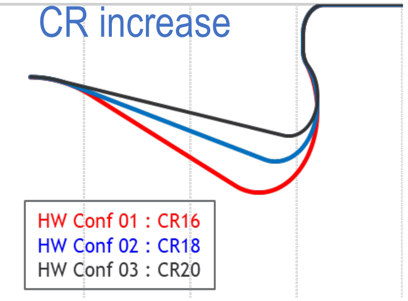
- Pure NH$_3$ possible
- Not real difference between IMEP with H$_2$ or not
- Maximum work obtained for 1<φ<1.1
- Example at φ = 1.1 and Pintake = 1.2 b : similar IMEP than CH$_4$!
- But not possible at low load and various regime

Highest efficiencies :

- lean mixtures (no excess fuel)
- $5\% \leq x_{H_2} \leq 20\%$
- $\eta_{ind} \lesssim 40\ \%$ → comparable with conventional fue

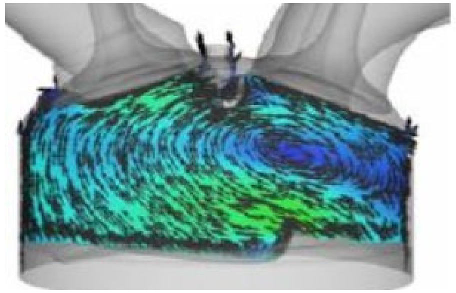
How improve ammonia combustion in ICE





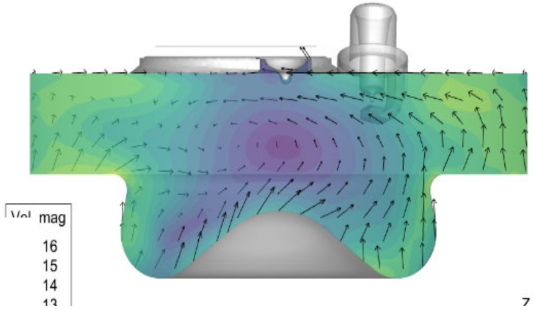
- ❑ Easy way : Compression Ignition engine with Spark Plug !
  - ❑ Retrofit 'current' Diesel engine (less expensive …)
  - ❑ High Compression ratio : better for Ignition and Flame propagation

SI architecture



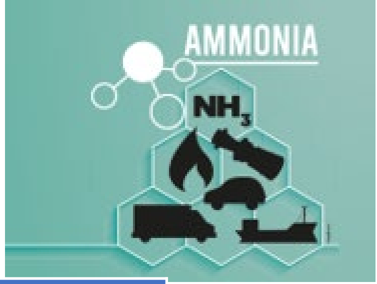
TKE+ Turbulent vortices

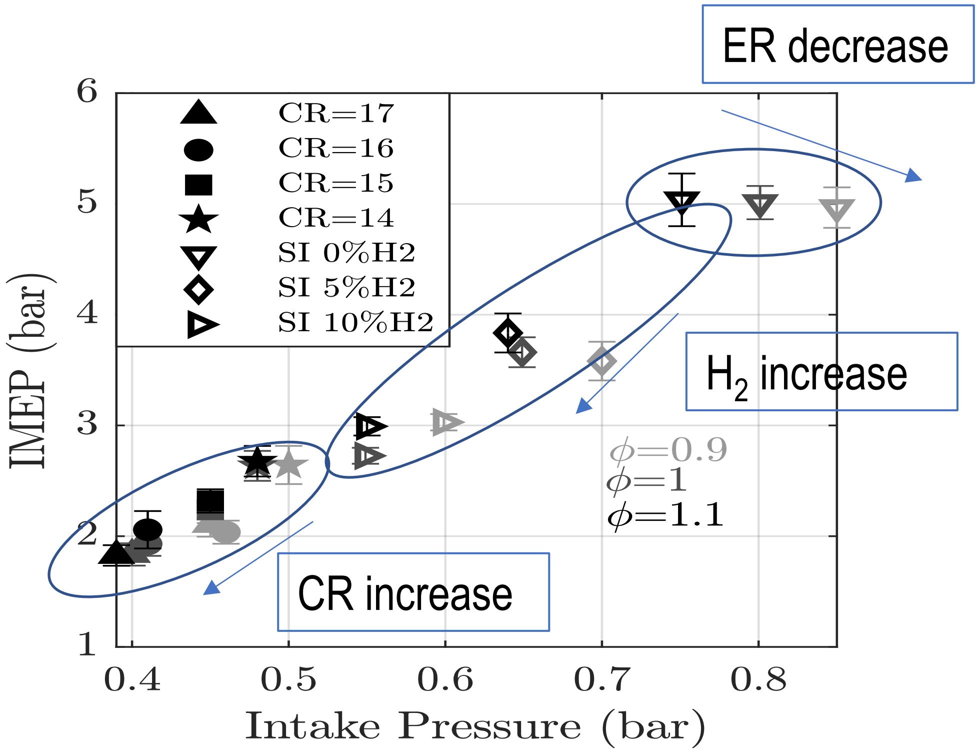
Diesel architecture



- ❑ But
  - ❑ No turbulence ? Only strong swirl motion ?
  - ❑ 'classical piston bowl : unburnt ammonia ?

Another solution : increase the CR





Engine speed :1000 rpm

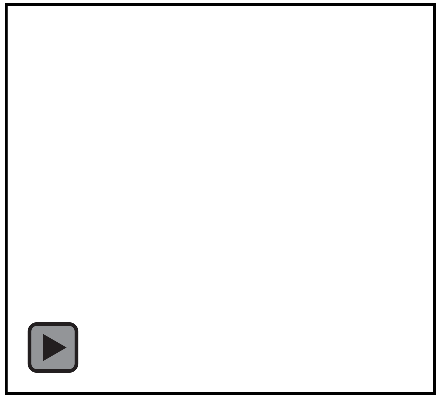
Engine Type	Current PSA EP6DT	SAD PSA DV6
Displacement Volume V_{cyl}	400 cm^3	400 cm^3
Compression Ratio	10.5	14 to 17
Valves	4	2
Tumble ratio	2.4	
Swirl ratio		2

- Good improvement of NH_3 combustion with CR increase despite of flow field
- No H_2 needs
- Extension of low load limits
  - 1.7 b IMEP (as Koike et al. with Reformer)
  - CR 17, 650 rpm,
  - lower limit with slightly rich

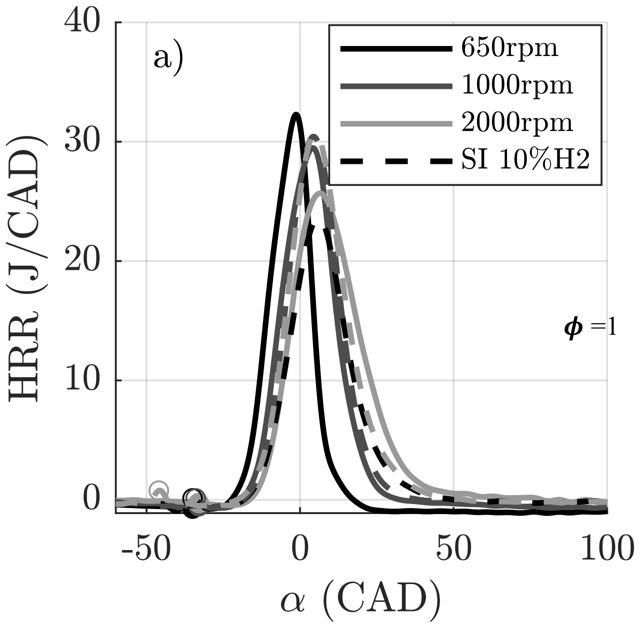
Christine Mounaïm-Rousselle, Adrien Mercier, Pierre Brequigny, Clément Dumand, Jean Bouriot, et al.. Performance of ammonia fuel in a spark assisted compression Ignition engine. *International Journal of Engine Research*, 2021, pp.146808742110387. ⟨10.1177/14680874211038726⟩. ⟨hal-03519268⟩

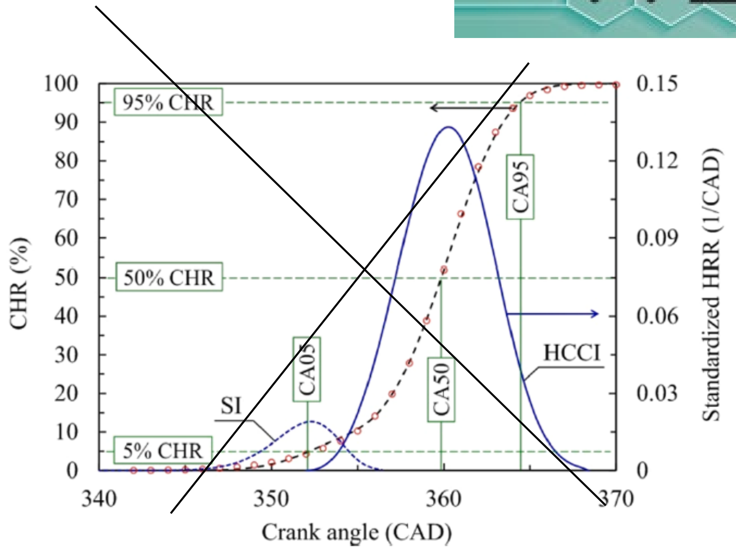
FLAME DEVELOPMENT : SPARK ASSISTED DIESEL ENGINE VERSUS SI

Spark plug location



-40 CAD to 27 CAD ATDC



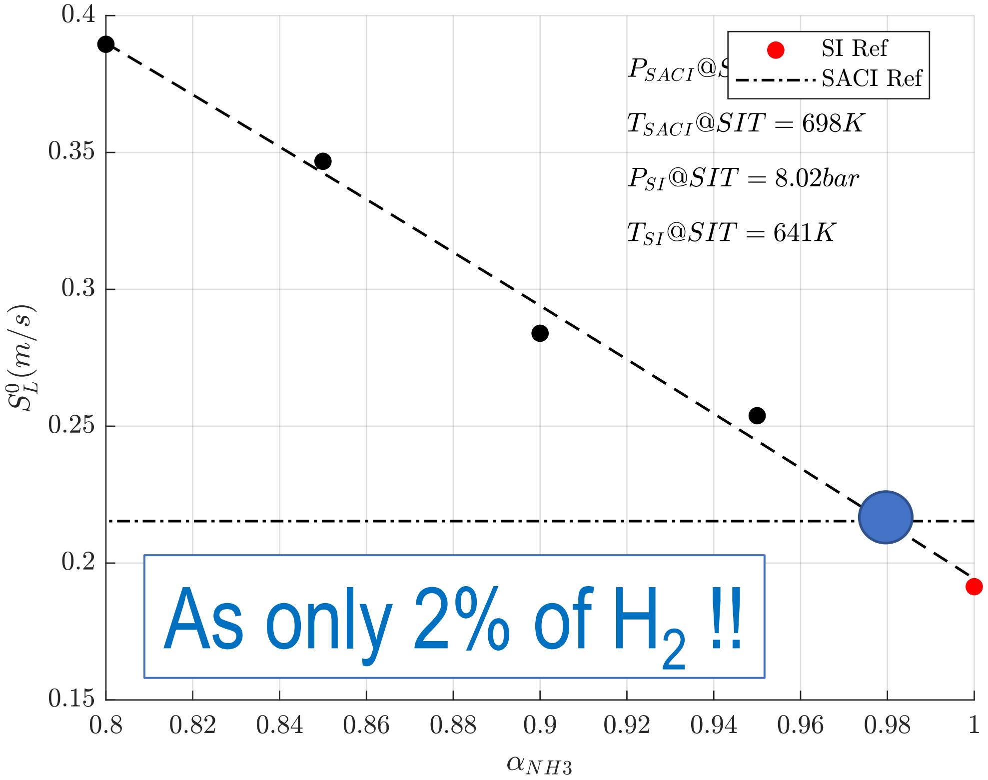


- Spark Assisted Diesel engine combustion mode :
  - Without H_2
  - Not 2 identified phases of HRR
- Faster first phase than SI engine
  - Pressure effect ?
  - FULLY PREMIXED PROPAGATION ‘without turbulence’ ?

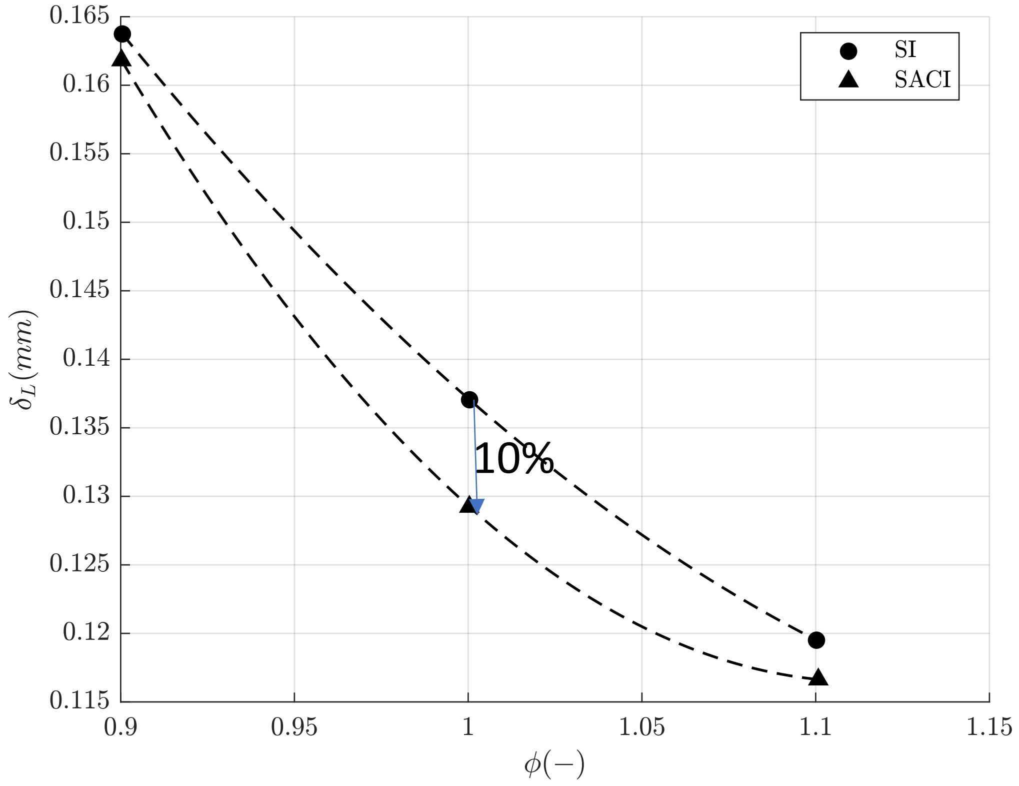
PREMIXED TURBULENT FLAMES

SI engine to 'SI' Diesel engine :

	SI	SA Diesel engine
P (Spark Timing)	8 b	12 b
T (Spark Timing)	640K	698 K

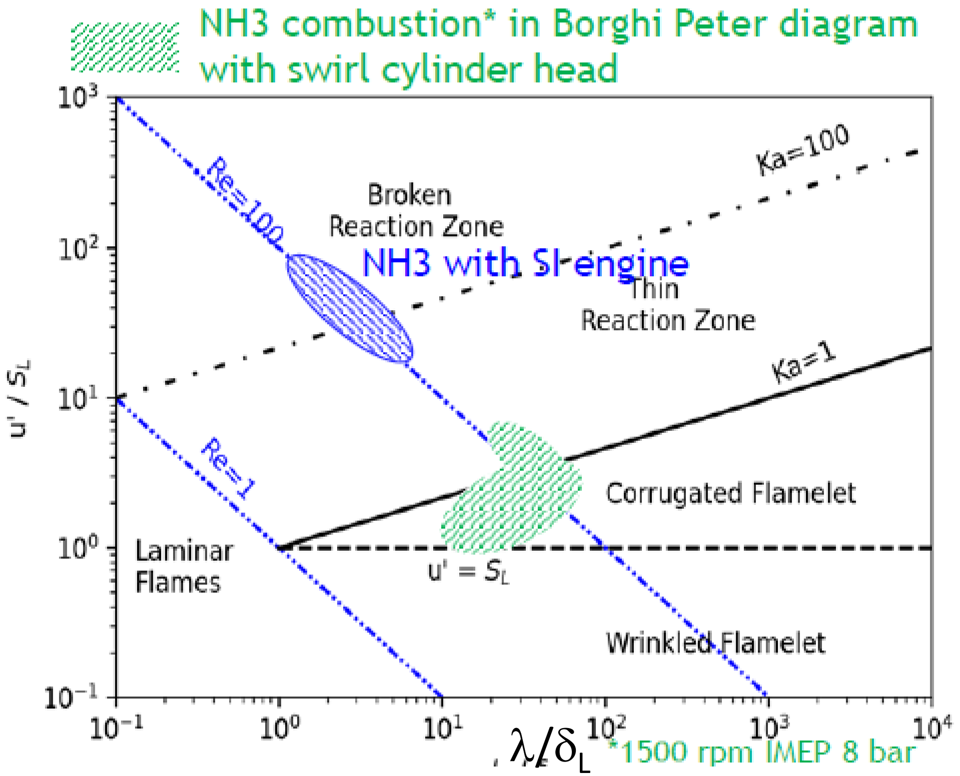


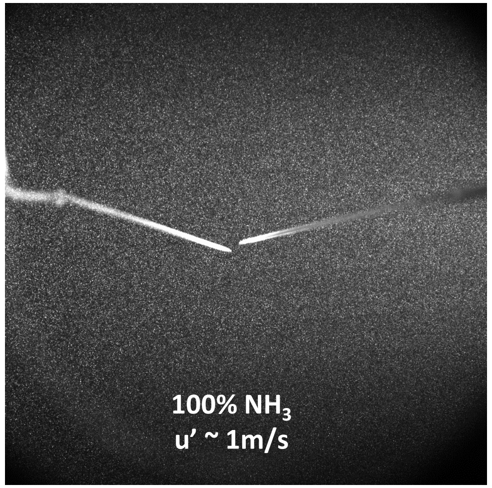
α=%NH_3/NH_3+H_2



Correlation from Lhuillier, C., Brequigny, P., Lamoureux, N., Contino, F., Mounaïm-Rousselle, C., Fuel 263, p.116653, 2020

AMMONIA – turbulence interaction : strongly different





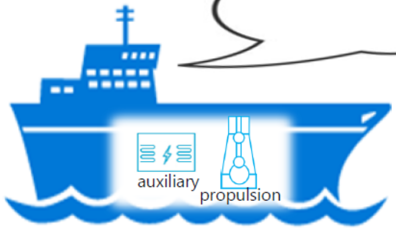
- ➢Very different turbulent-flame interaction
- ➢What best flow field for ammonia combustion in ICE ?

Main questions : pollutant emissions for ammonia engine

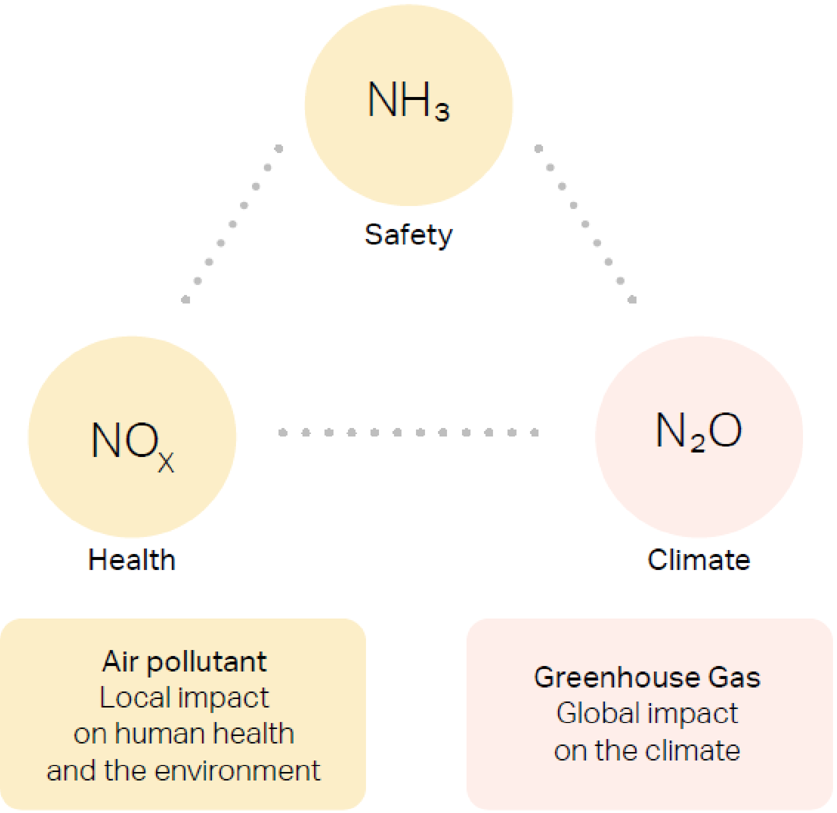
Combustion exhaust gases from ammonia fueled engine will include …

NH_3 : Strong pungent smell, highly toxic to human body
NO_x : Photochemical smog, acid rain, air pollution
N_2O : GHG about 300 times more potent than CO_2, ozone depleting gas

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \ (+ NH_3 + NOx + N_2O)$$



Ammonia combustion emission risk triangle



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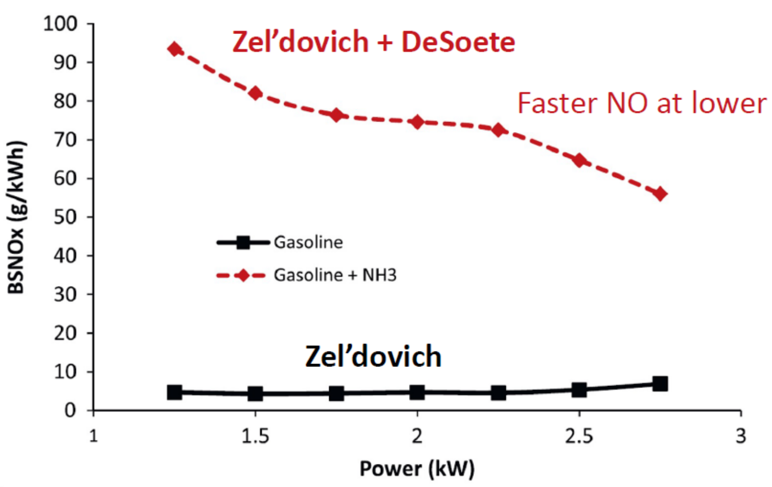
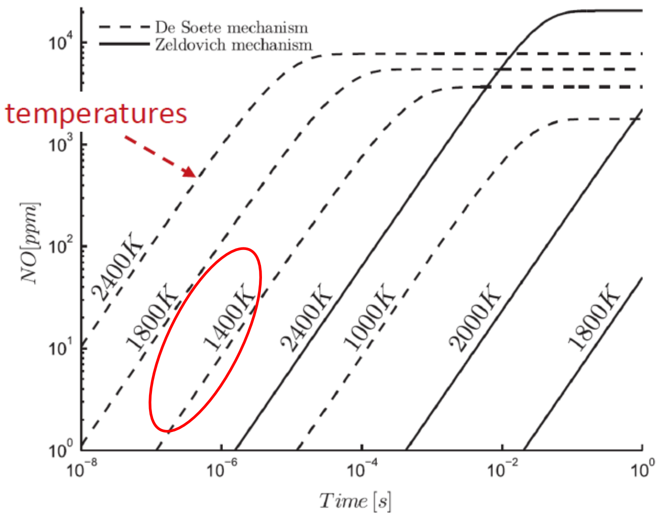
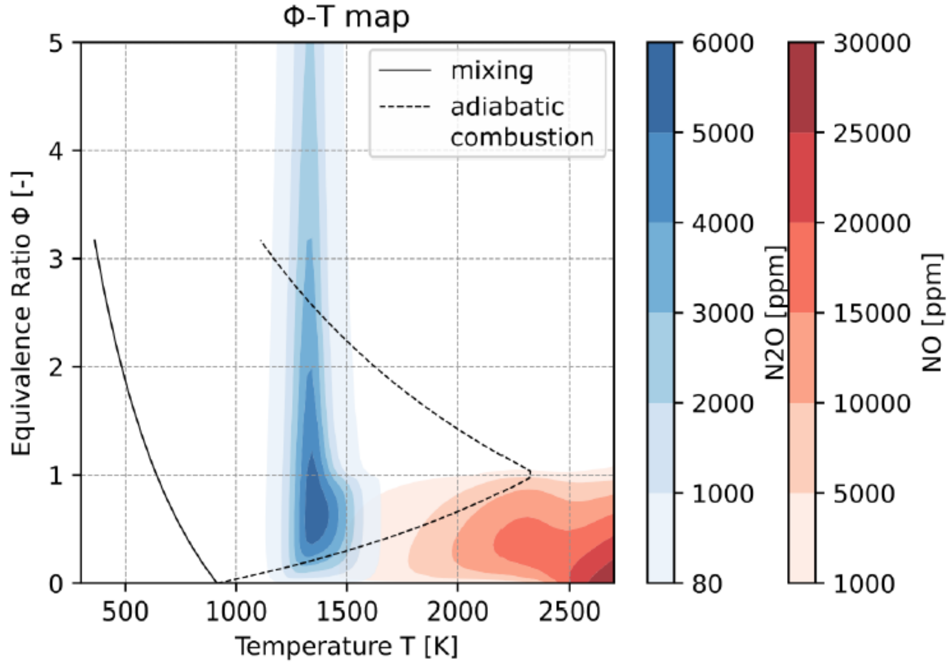
Thermal Nox versus Fuel NOx



Ryu, K., Zacharakis-Jutz, G. E., & Kong, S. C. (2014). Effects of gaseous ammonia direct injection on performance characteristics of a spark-ignition engine. *Applied energy*, *116*, 206-215.



Westlye, F. R., Ivarsson, A., & Schramm, J. (2013). Experimental investigation of nitrogen-based emissions from an ammonia fueled SI-engine. *Fuel*, *111*, 239-247.



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NO : T>1500 K, PHI < 1
N2O : T< 1500 , ALL PHI

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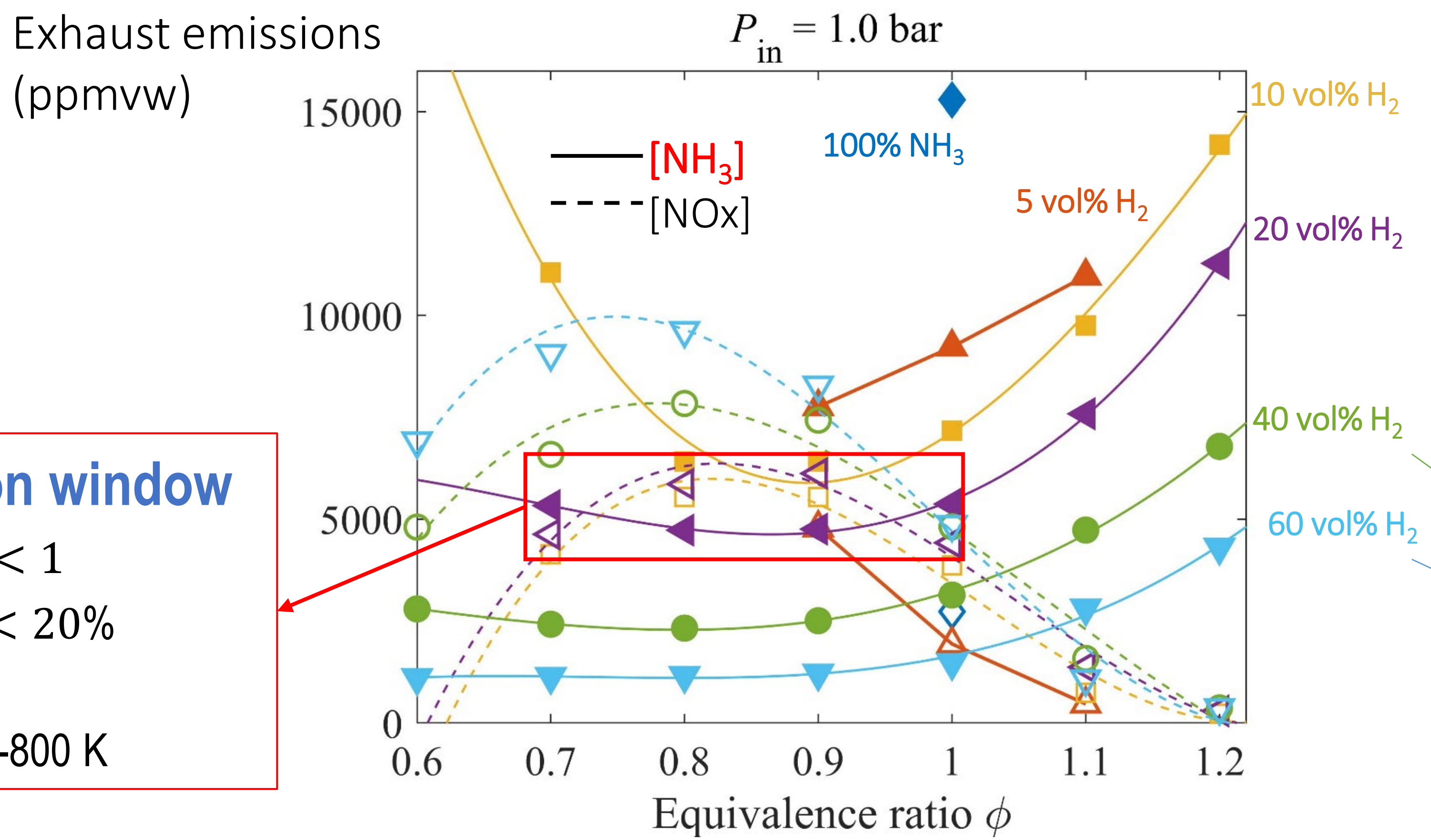
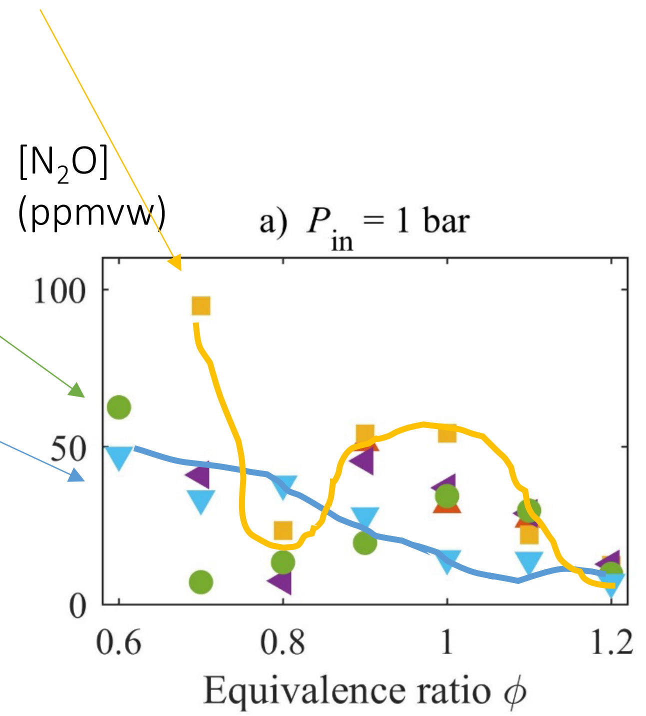
EFFECT ON H2 ON EMISSIONS

Citation: Lhuillier, C., BREQUIGNY, P., Contino, F., and Rousselle, C., "Combustion Characteristics of Ammonia in a Modern Spark-Ignition Engine," SAE Technical Paper 2019-24-0237, 2019, https://doi.org/10.4271/2019-24-0237.





"Low" emission window

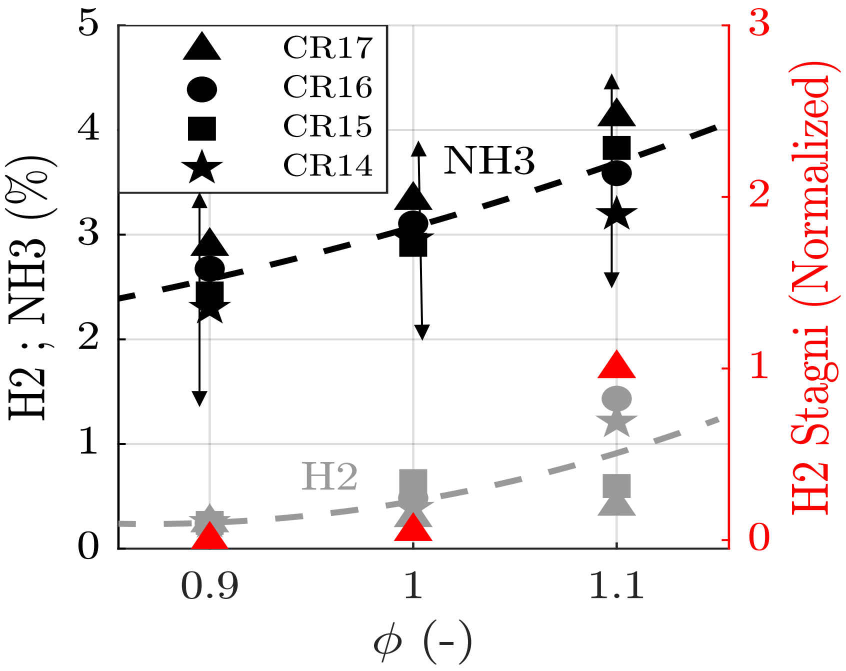
$0.7 < \phi < 1$

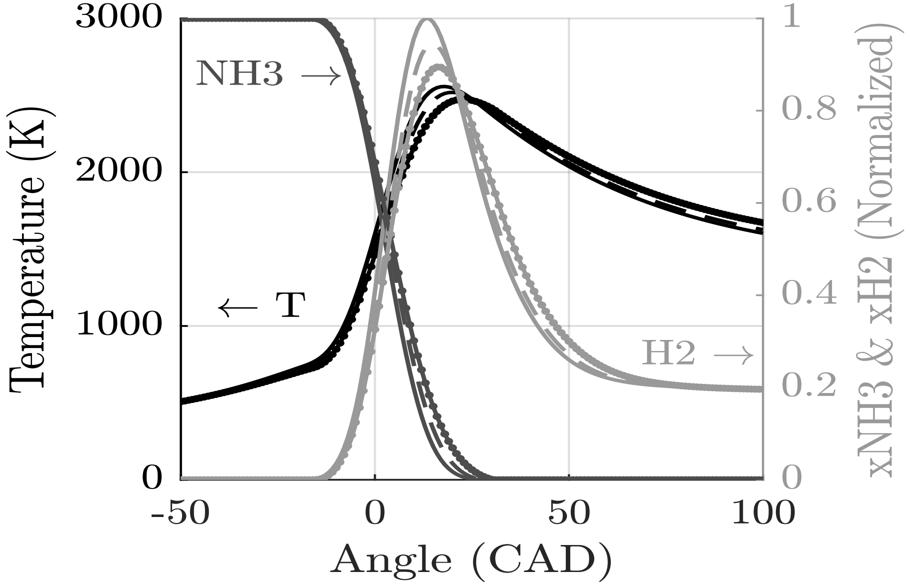
$5\% < x_{H_2} < 20\%$

$T_{exhaust}$ = 700-800 K

H2 = one parameter to reach $\frac{NOx}{NH_3} \sim 1$ (SCR/SNCR) for post-treatment !

ONLY AMMONIA ?





Stagni et al. 2020,
OD SI engine modelling CHEMKIN ANSYS

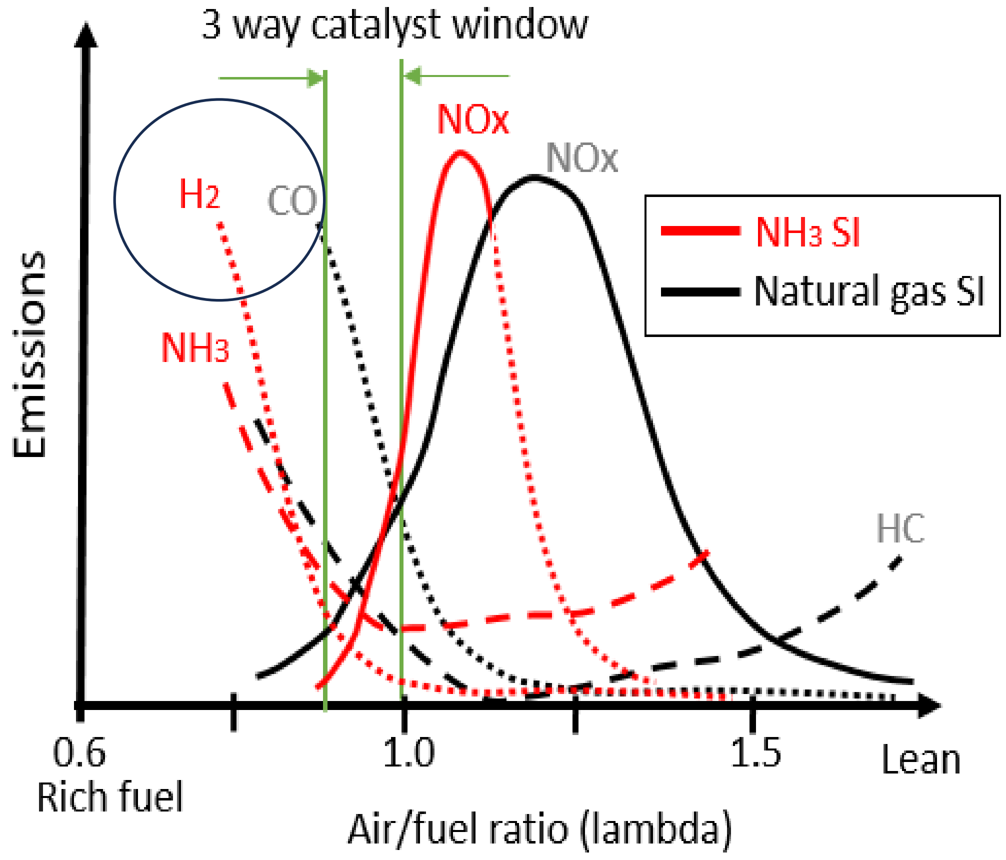
$$\alpha_{NH3} + (1-\alpha)\left(\frac{3}{2}H_2 + \frac{1}{2}N_2\right)$$

- SACI combustion mode :
  - HT/HP = in situ NH_3 decomposition in H_2
  - For Phi>1

Last important question : what emissions for ammonia engine

Premixed ammonia SI engine

- Similar trends as usual SI engine



- **NH_3**
  - Minimum for lean mixture/stoichiometry
  - max : 4%
  - Function of engine design ! Crevice trap !
  - H_2 emissions due to 'in situ' cracking of NH_3
- **NO_X**
  - Minimum for **rich mixture**,
    Maximum around 0.7-0.8 until 5000 ppm !
  - Increase with H_2 addition

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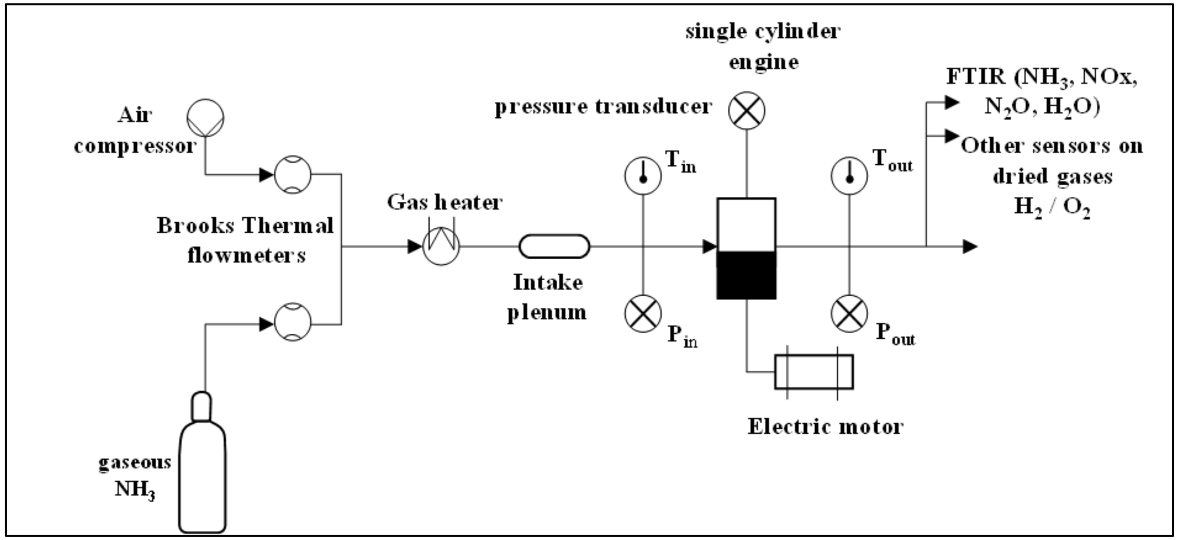
Comparison between Spark Ignition and Pilot Reactive fuel ignition

Caneon Kurien and Christine Mounaïm-Rousselle, Comparative study on the effect of premixed equivalence ratio on engine characteristics of ammonia fuelled engine under DieSEL PIlot IGNITION vs SPARK IGNITION combustion mode, ICEF2024-140740, Proceedings of the ASME 2024, The Westin Riverwalk, San Antonio, TX, USA

- Same engine with premixed gaseous NH_3/air intake
  - no injector
- 2 configurations :
  - Original CRI Bosch injector
  - Spark plug

Engine	DW10
Displaced Volume [cm^3]	499.4
Stroke [mm]	88
Bore [mm]	85
Compression ratio [-]	16.4:1
Number of valves [-]	4
Swirl ratio (50 CAD BTDC)	2.0
Bowl type (baseline)	Re-entrant

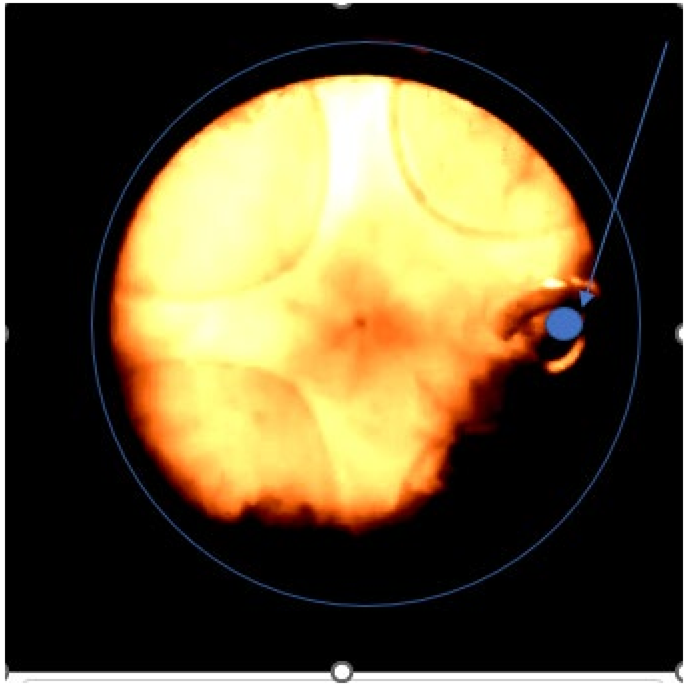
Parameters	CI Mode	SI mode
Fuel	NH3 + diesel	100% NH3
Diesel energy share	Less than 5%	-----
Ignition	Diesel pilot injection	Spark
Injection duration	550 µs	-----
Charge duration	-----	2000 µs
$\Phi_{premixed}$ (NH_3 + air)	0.80 – 1.25	0.80 – 1.25
Engine speed	1000 rpm	1000 rpm
Intake pressure	1 bar	1 bar
Intake temperature	80°C	80°C



Ammonia flame propagation in ICE

- CR = 16, PSA_DW10 0.5 l, 1000 rpm,
- Intake pressure =0.9 bar Tintake =35°C

-40 CAD to 27 CAD ATDC



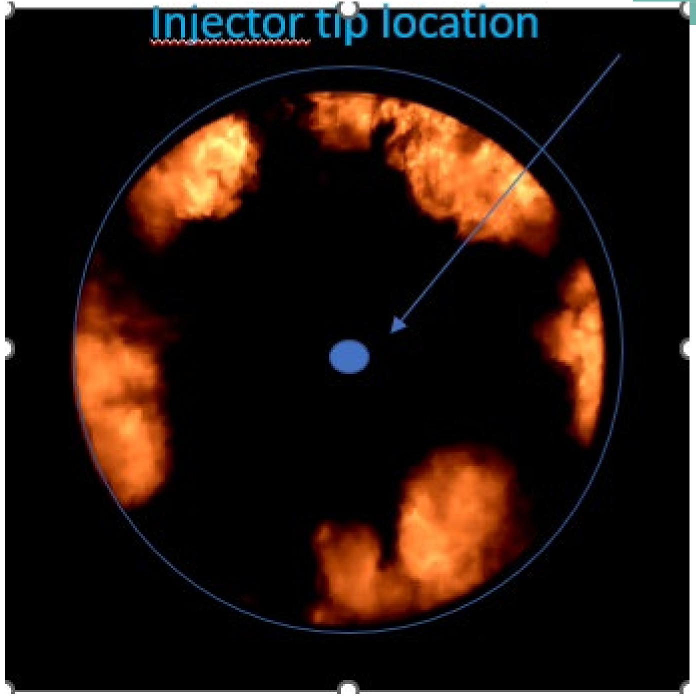
Spark Assisted Ignition

Spark timing : -40 CAD

ER NH3 = 0.9

IMPE = 6.7 b

-10 CAD to 57 CAD ATDC



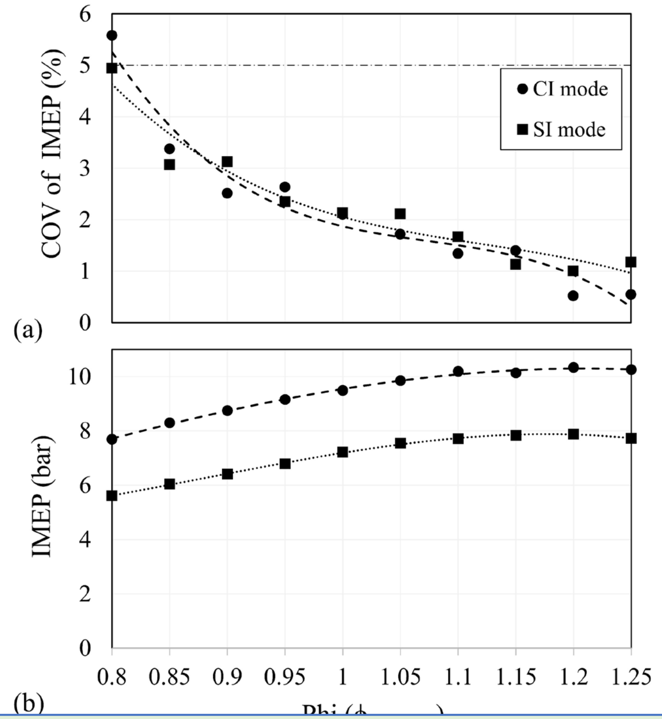
Decane spray ignition

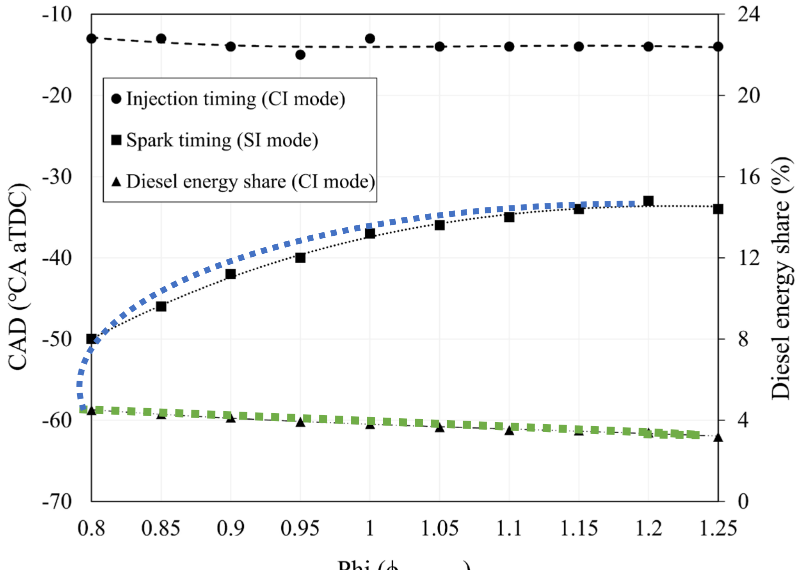
- SoI -22 CAD before Top dead Center
- **%decane/fuel (vol.)=11% in Energy input**
- **ER NH3 = 0.9, E.R. total = 1.07,**
- **IMEP = 7.4 b**

Comparison between Spark Ignition and Pilot Reactive fuel ignition

1) Decane injection
- duration = constant for all conditions
- injection timings adjusted to minimise cyclic variabilities (COVIMEP)
- **4.5% to 3.2% with premixed equivalence ratio**

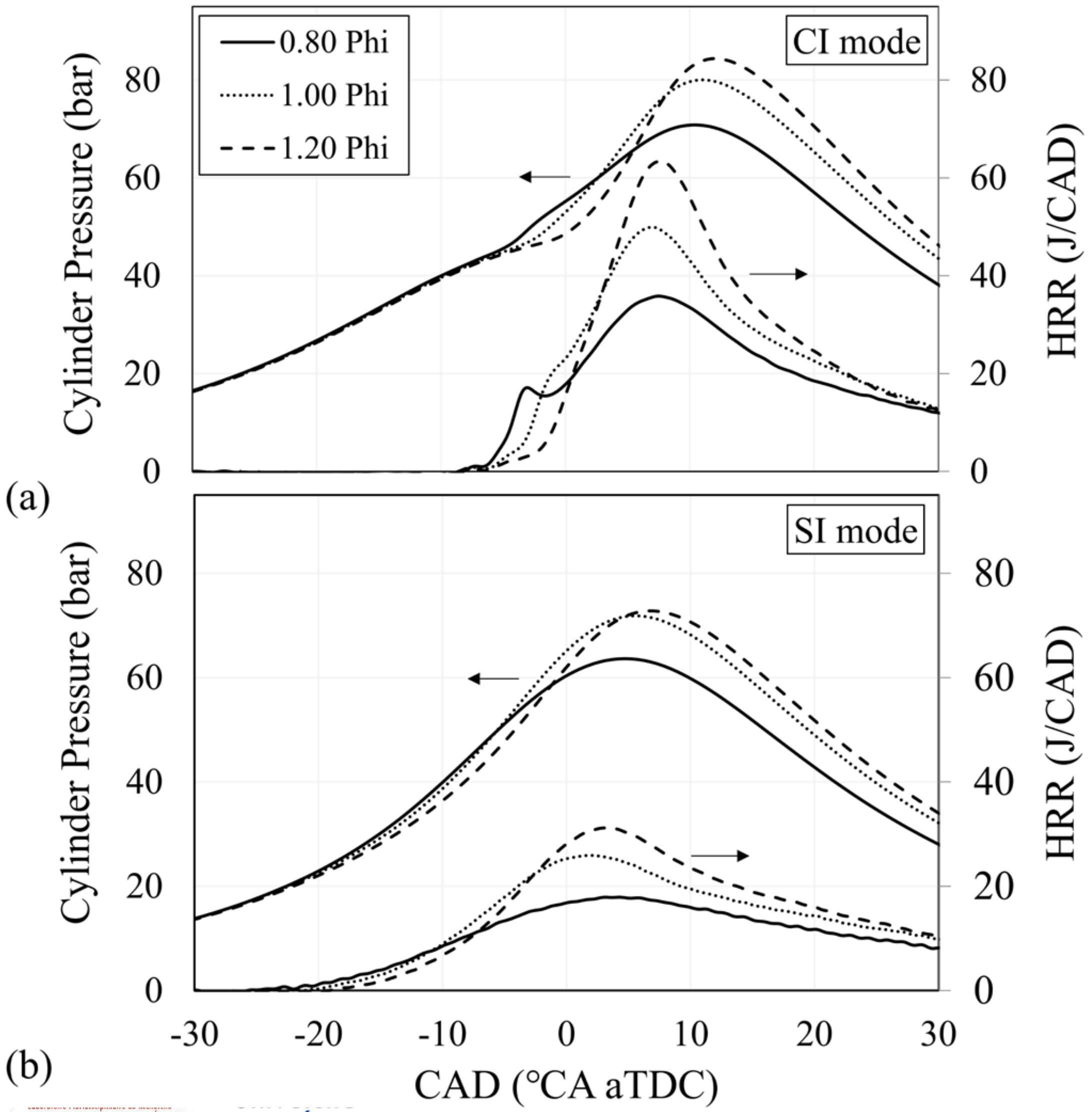
2) Spark timing :
- sweep to to minimise cyclic variabilities (COVIMEP)
  - larger spark advance required at lean operating conditions due to lower laminar flame speed
  - near-stoichiometric rich conditions, no significant adjustement needed





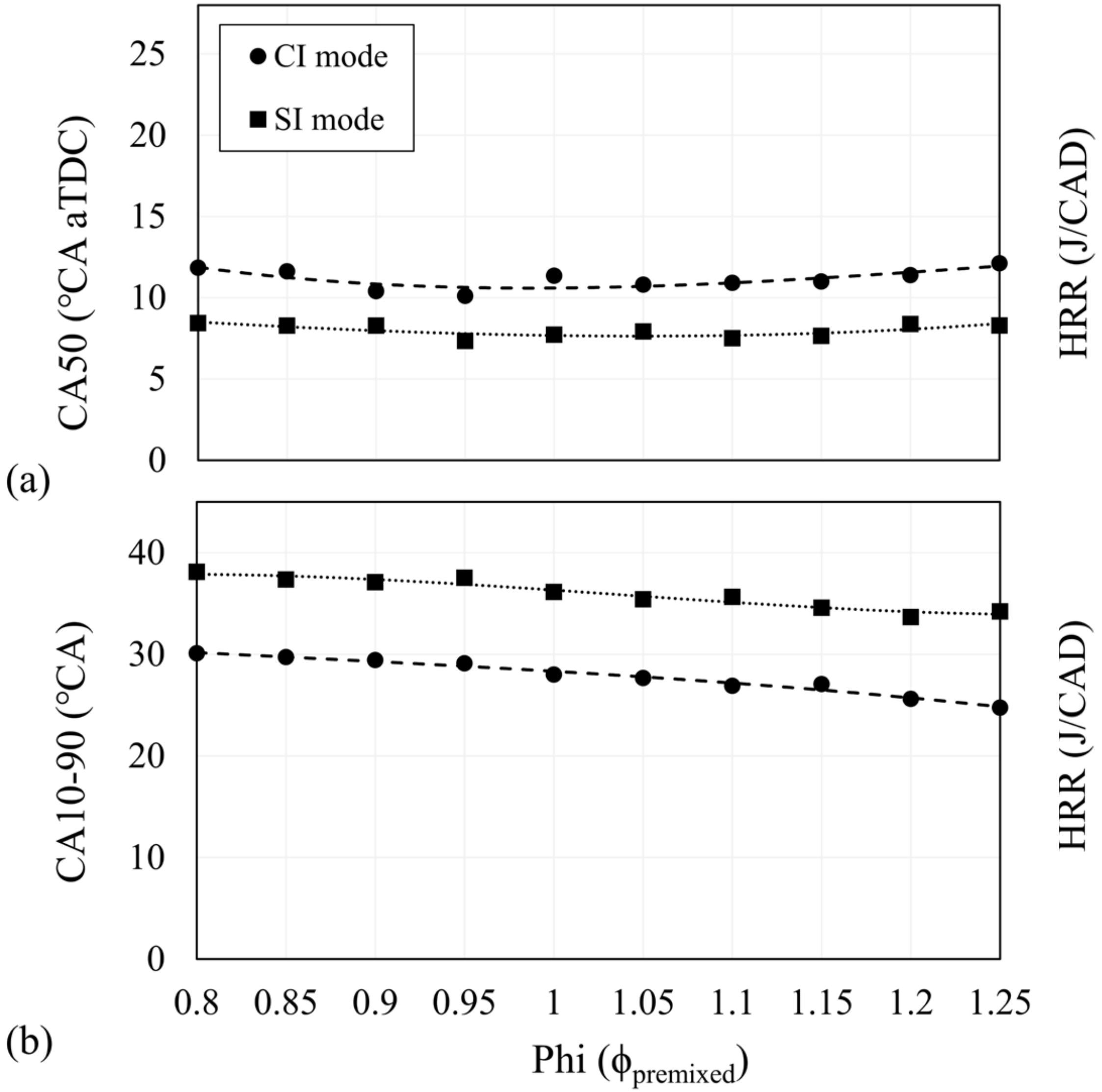
- ➢ Higher load for Pilot Reactive Fuel Ign.
  - ▪ not only due to Diesel fraction
  - ▪ better combustion efficiency ?
- ➢ Longer combustion duration for SI
  - ▪ strong enhancement by diesel comb. ?
    - ▪ Increase the number of high reactivity zones
    - ▪ multi-point ignition
  - ▪ Or enhancement of local turbulence ?

Comparison between Spark Ignition and Pilot Reactive fuel ignition



- MAx pressure + Max HRR ↑
  - ↑ with Premixed Phi
- Pp and PHRR CI > SI mode.
- 2 combustion phases in CI :
  - mode premixed + diffusion phases for $\varphi_{premixed}$ = 0.8
  - Not for the other Phi : combustion development = SI mode.
- ID for $\varphi_{premixed}$ = 1.2 >> due to the retarding influence of ammonia on the ignition

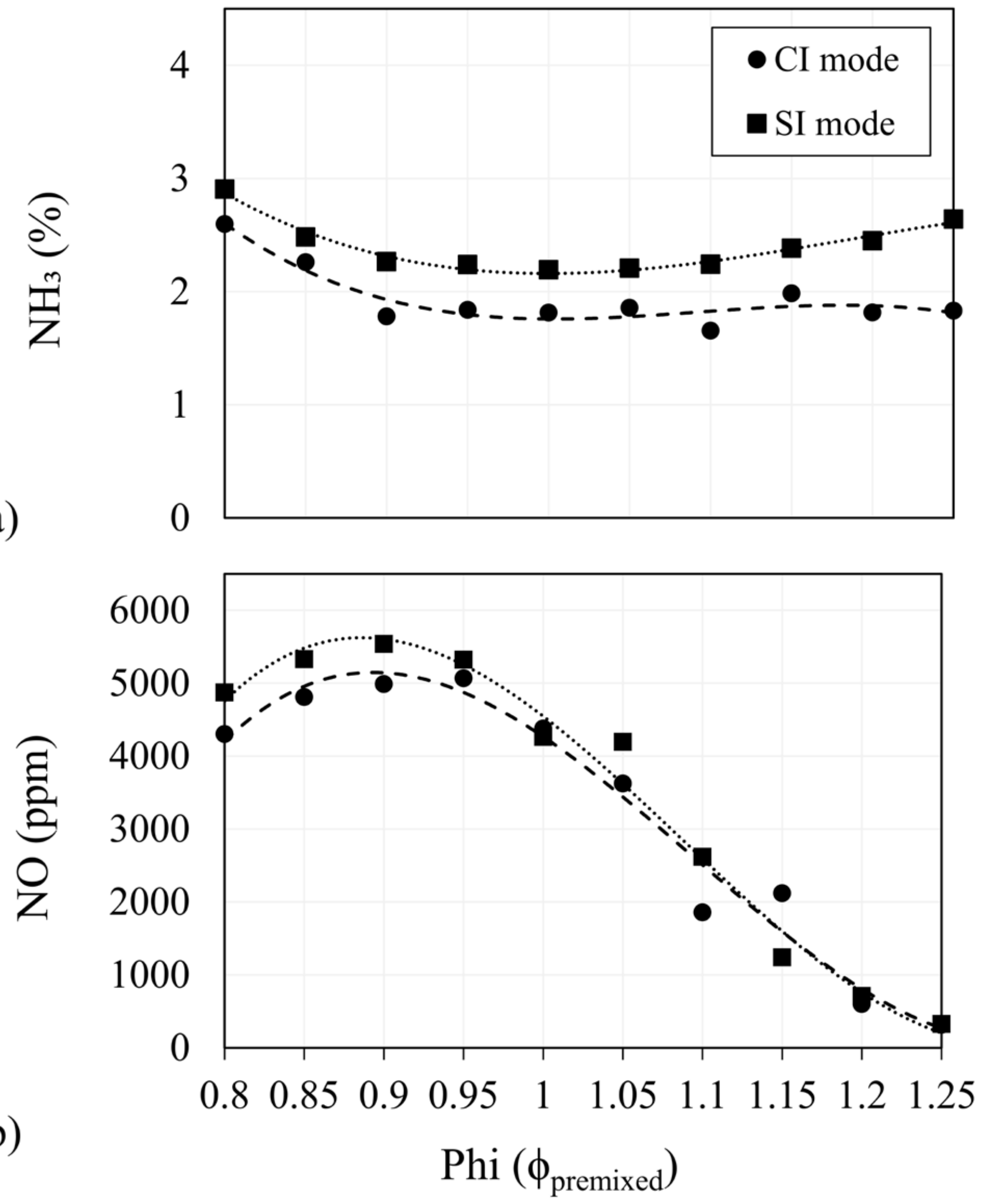
Comparison between Spark Ignition and Pilot Reactive fuel ignition

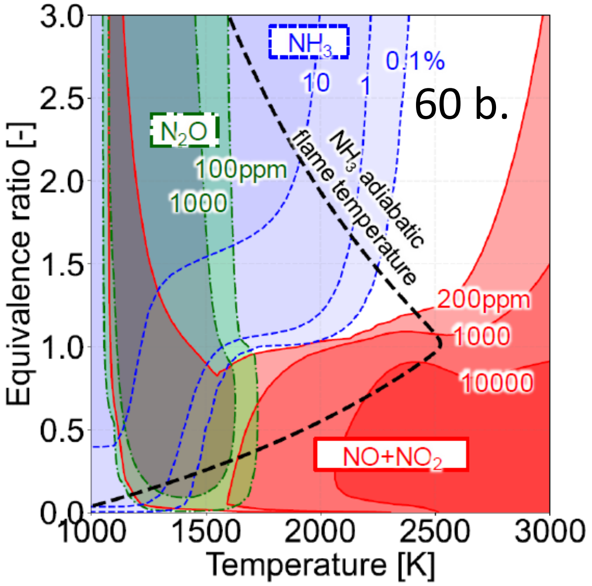


- Similar phasing of the combustion (CA50 = crank angle where % of fuel is burnt)
- Longer combustion duration with SI
  - PRFI : more efficient combustion
  - Lower fuel consumption !

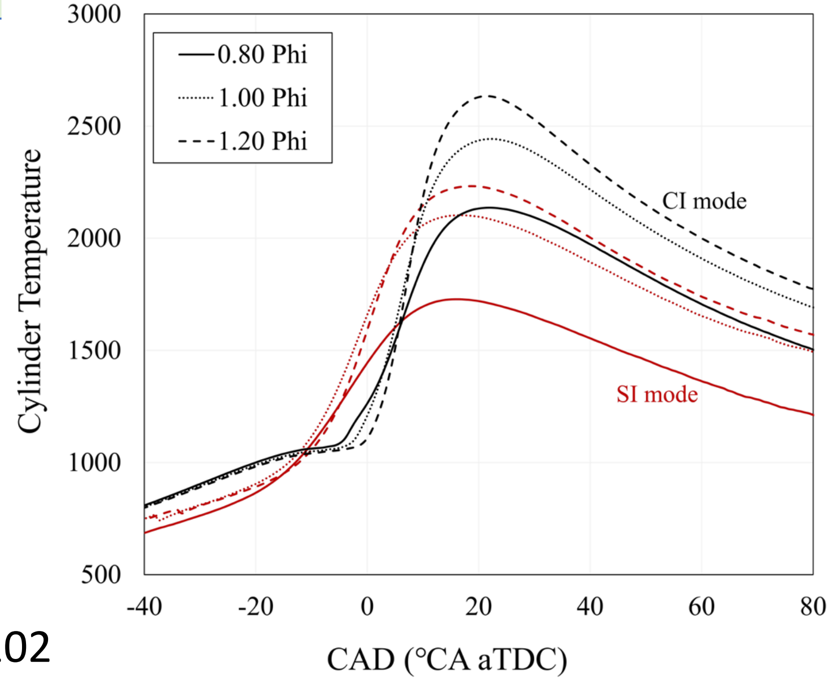
Last important question : emissions

- NH_3
  - Similar order of magnitude : due to crevice and piston design
  - Slightly lower with CI
- NO_X
  - Higher Peak with SI
  - Max around 0.85 – 0.9

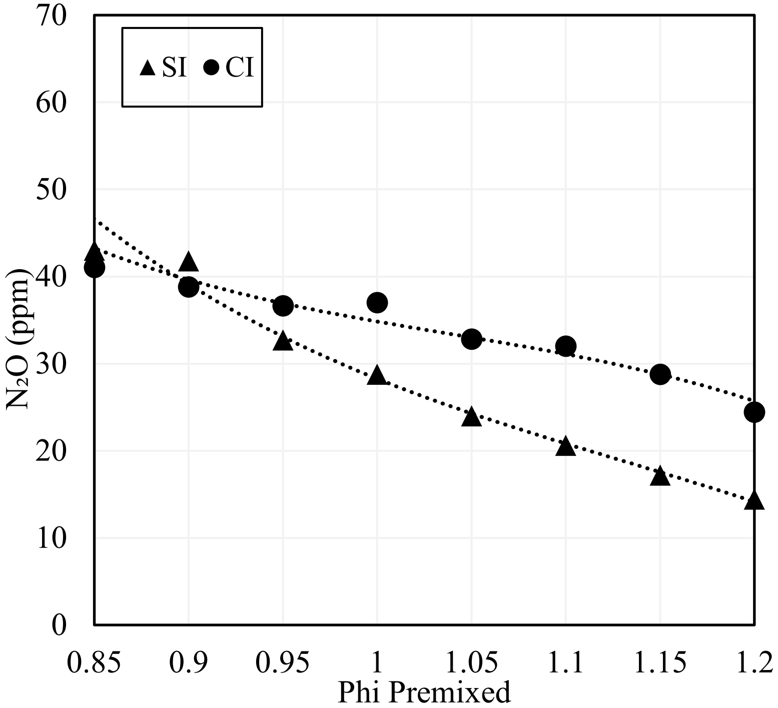


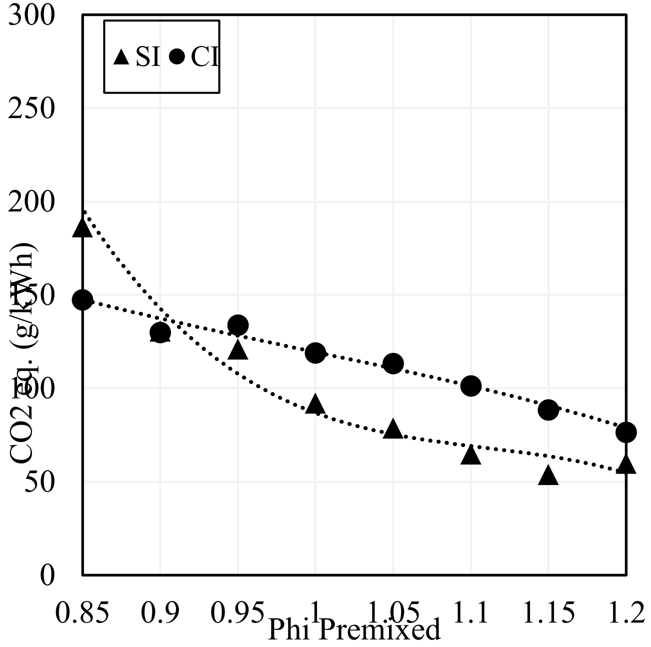


Hiraoka et al., SAE 2023-32-0102

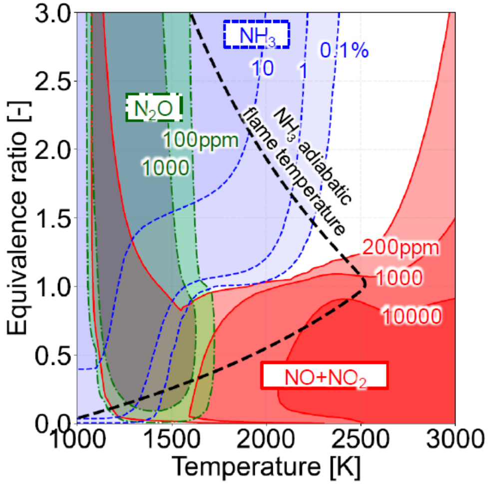


Last important question : emissions





- Global Warming Impact equivalent
  - N_2O = 265 *CO_2 GWI at 100 years !
  - Same order of magnitude between both ignitions for lean mixture and Decane
  - Lower from ER >= 1 for SI
  - CO2 equivalent remains higher for CI with pilot injection



PRISME Laboratoire Pluridisciplinaire de Recherche Ingénierie des Systèmes, Mécanique, Énergétique

Université d'ORLÉANS

Ammonia fuel : a lot of scientific challenges

Challenges	Impact & requirements on practical combustion systems	Knowledge gaps requiring new research
Difficult ignition	Problems at cold start Improved ignition system or combustion promoter (SI, GT) High CR (CI)	Autoignition behavior of NH_3 under elevated conditions, and in blends Related chemical kinetic modeling
Narrow flammability	Stability/extinction problems Operability	Flame-stretch and extinction behavior of pure and blended NH_3
Low reactivity & slow flame propagation	Low combustion efficiency Depleted thermal efficiency Stability Combustion promoter Improved aerodynamics Improved thermodynamic conditions	Experiments in practical systems for phenomenological understanding and validation of models LBV measurement under elevated conditions and in blends Chemical kinetic modeling with combustion promoters Investigation and modeling on flame-turbulence interactions and stretch effects Investigation and modeling on thermal effects
Fuel-bound nitrogen	Potential high N_2O, NOx and NH_3 exhaust emissions	Chemical kinetic modeling Investigation and modeling of low-emission combustion modes
High latent heat of vapor.	Challenging direct injection Power penalty	Optimization of system design for premixed combustion

Lhuillier, phd thesis, Univ. Orléans, Dec. 2020

Best Possibilities to use ammonia (>95% !) in ICE ?

Ammonia

gaseous

liquid

Cracker

$H_2 + N_2$

Reactive fuel

Bio fuel

Pilot injection

Spark Ignition engine

Compression ignition engine