First Workshop ARENHA project:
"Introduction to novel technologies related to ammonia-based energy storage"

Direct use of ammonia for mobility (ICE)

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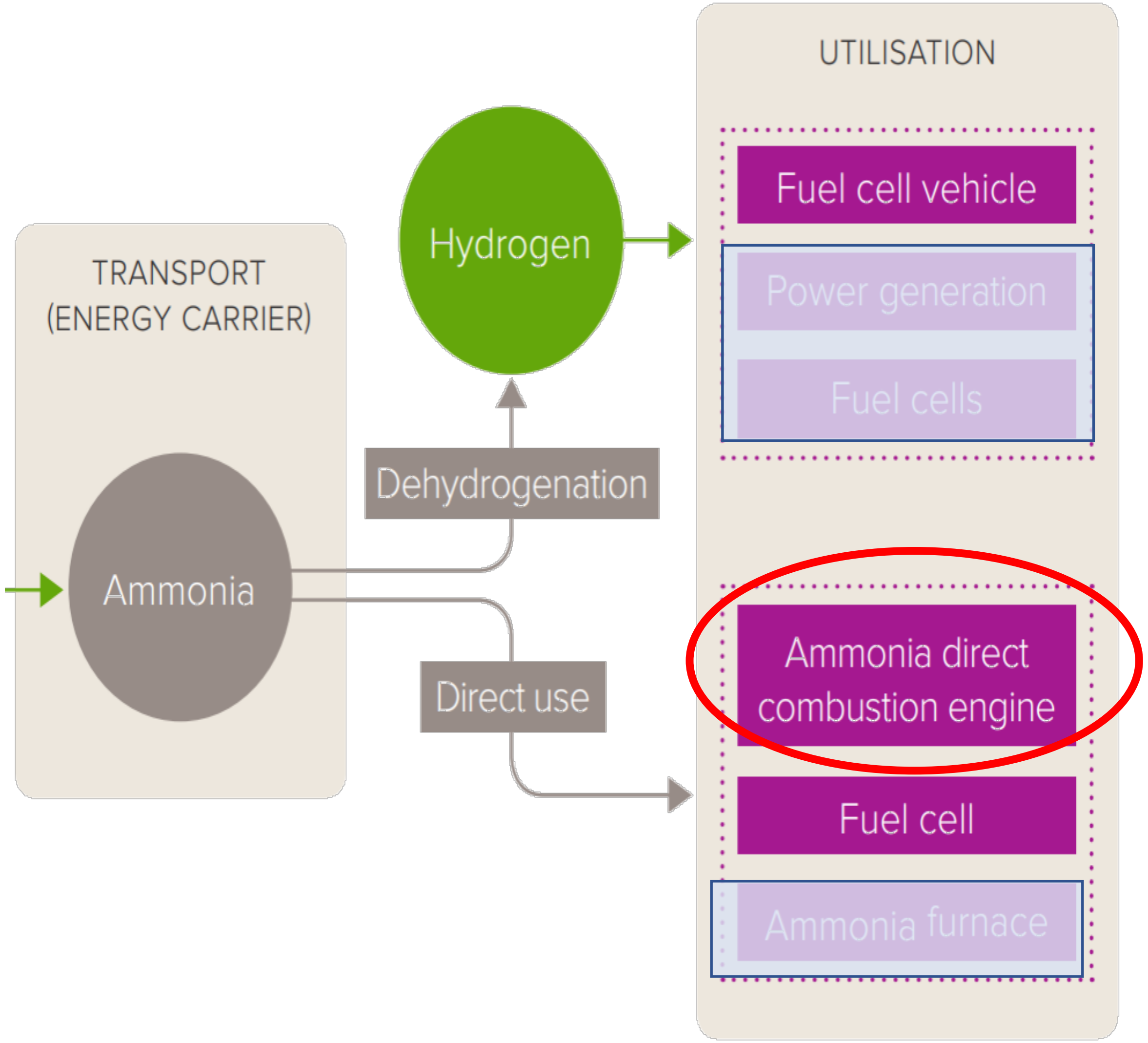
1. How extract the energy content in ammonia ?

3 solutions

- ❑ To decompose ammonia by means of new optimized reformers to recover hydrogen
- ❑ To use ammonia directly
  - ❑ in fuel cells
  - ❑ In combustion systems such as turbines or internal combustion engines.



1. NH_3 as fuel for vehicles = an old story

2013
Marangoni Toyota GT-86 Eco-Explorer,

60s : theoretical studies, ‘Research Engine’ CFR studies (USA)

2012-2015 :

KIER, Korea

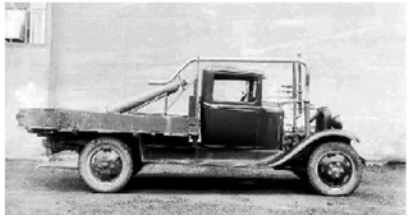
Dual Fuel
gasoline or Diesel

until 80% NH_3

2007-2012 :
Michigan University

50%NH_3/Gasoline

3 800 km



1940s

Belgium

NH_3/Coal gas

10 000 miles

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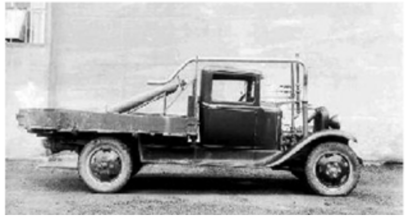

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2013
Università di Pisa
H_2 reformer

2020
Hydrofuel Project
(Ontario Univ.)

2018-2021
C-Free Run project, Hydrogen Engine Center (Iowa) Ford 460 (9.4 l/ CR 13.5) max RPM 2500
Start and stop engine on hydrogen, when warm run on 85-90% ammonia and 10-15% hydrogen

ACTIVATE
norvegian project, Silesian University project 2022-2024

1. Global ammonia combustion characteristics

	Hydrogen	Methane	Methanol	Gasoline	Diesel Fuel	Ammonia	consequences
Low Heating Value (MJ/kg)	120	49	19.9	44	45	18,6	Compensated by air/fuel ratio
Air/Fuel ratio at stoichiometry (kg/kg)	34.2	17.65	6.46	14.6	14.6	6.06	High fuel consumption
Flammability limit in air (vol.%)	4.5-75	5-15	6.7-36	1.3-7.6	1-6	15-30	Low risk
Laminar flame speed (cm/s)	210	38	40	~40		7	Difficult propagation
Auto-ignition Temperature(°C)	537	595	465	275	225	651	Difficult ignition
Octane Number (-)	>120	120	109	88-98		>120	Low knock occurency ?
Adiabatic flame temperature (°C)	2519	2326	2228	2392		2107	Colder flame
Quenching distance (mm)	0.64	2		3	7	7	Lower heat wall loss

1. Main results in engine tests

Combustion and Performances in SI engines		
Minimum H_2 for combustion stability	**Efficiency**	**Output energy**
Between 5-10% in vol	Higher for ER>=1	Less than gasoline at low and partial load
Amount needed decreases with load increase (full load: 0%)	Higher than gasoline	Increase with CR or boosted pressure
slight effect of engine speed	Decrease with H_2 increase	

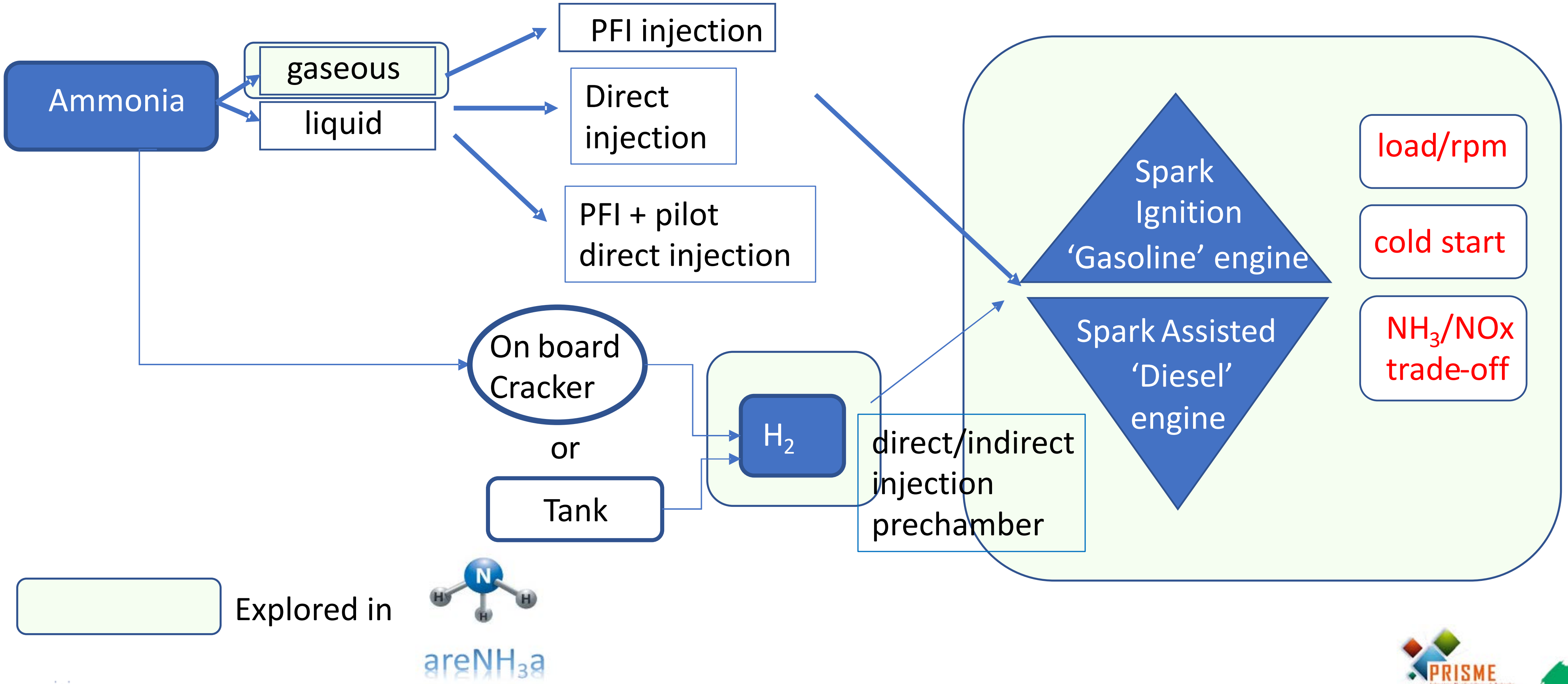
But only from 2000 to 4000 rpm in small engine

Pollutant Emissions before any aftertreatment device				
	ER decrease (lean)	**ER increase (rich)**	**H_2 increase**	**Load**
NOx (ppm)	++ maximum > gasoline	--	+	slight increase but no universal trend
Unburnt NH_3	--	++	-- But H_2 at exhaust	no universal trend

1. Best possibilities to use ammonia only in ICE

Difficulties to auto-ignite NH3 :

- spark ignition mode : optimum



2. Impact of engine architecture

- Objectives : assessment of combustion stability, efficiency, pollutants for pure NH_3
  - Identification of H_2 requirement
  - Specificity of 'cold start' conditions (650 rpm)
  - Identification of limits and tradeoffs (NOx versus NH_3)

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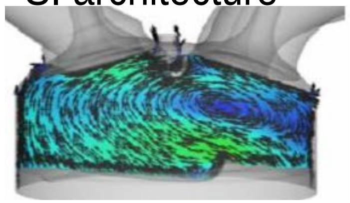
- Objectives : assessment of combustion stability, efficiency, pollutants for pure NH_3
    - Identification of H_2 requirement
    - Specificity of 'cold start' conditions (650 rpm)
    - Identification of limits and tradeoffs (NOX versus NH_3)
- Different engines designs :
    - 2 standard engine : gasoline and diesel (but in single cylinder mode) :
        - SI engine = 'current' EP6
            - regular Compression Ratio
        - SA Diesel engine = 'current' DV6 + spark plug instead of fuel injector
            - High Compression ratio : better for Ignition and Flame propagation
    - 1 research large stroke engine SI
        - SI engine with high CR

SI architecture



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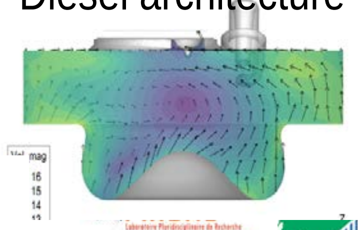
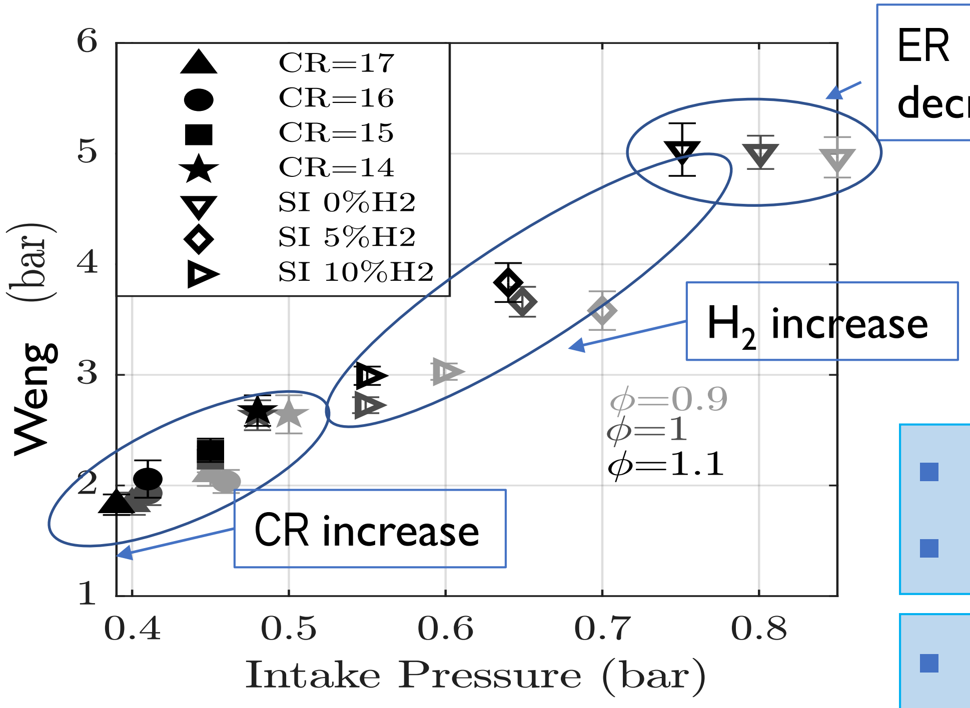
Diesel architecture



2. Impact of engine architecture

❑ Solution : Increase the CR to reach 'cold start' conditions



Engine speed :1000 rpm

Engine Type	Gasoline engine PSA EP6DT	Diesel engine 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

- Possible to run without H_2 even with standard SI
- But impossible to reach stable conditions without H_2

- Good improvement of NH_3 combustion with CR increase despite of flow field
- No H_2 needs
- Extension of low load limits
  - lower limit with slightly rich

2. Impact of engine architecture

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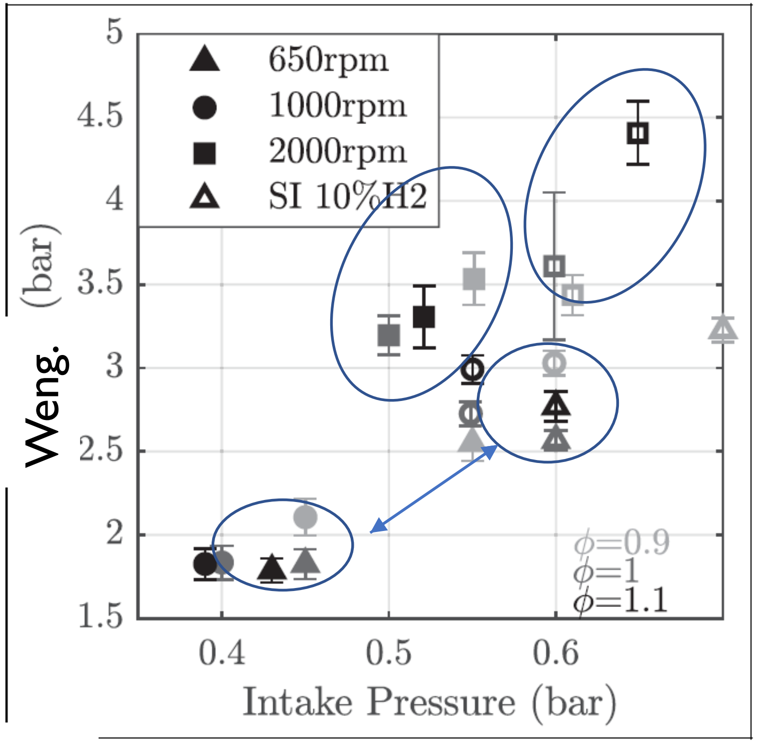
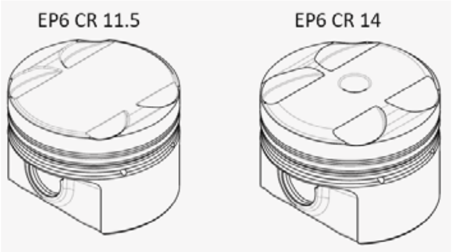
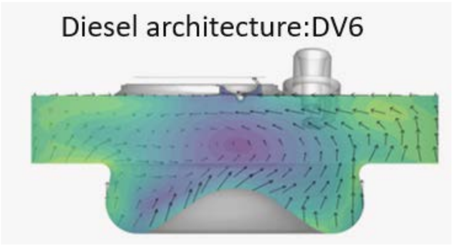


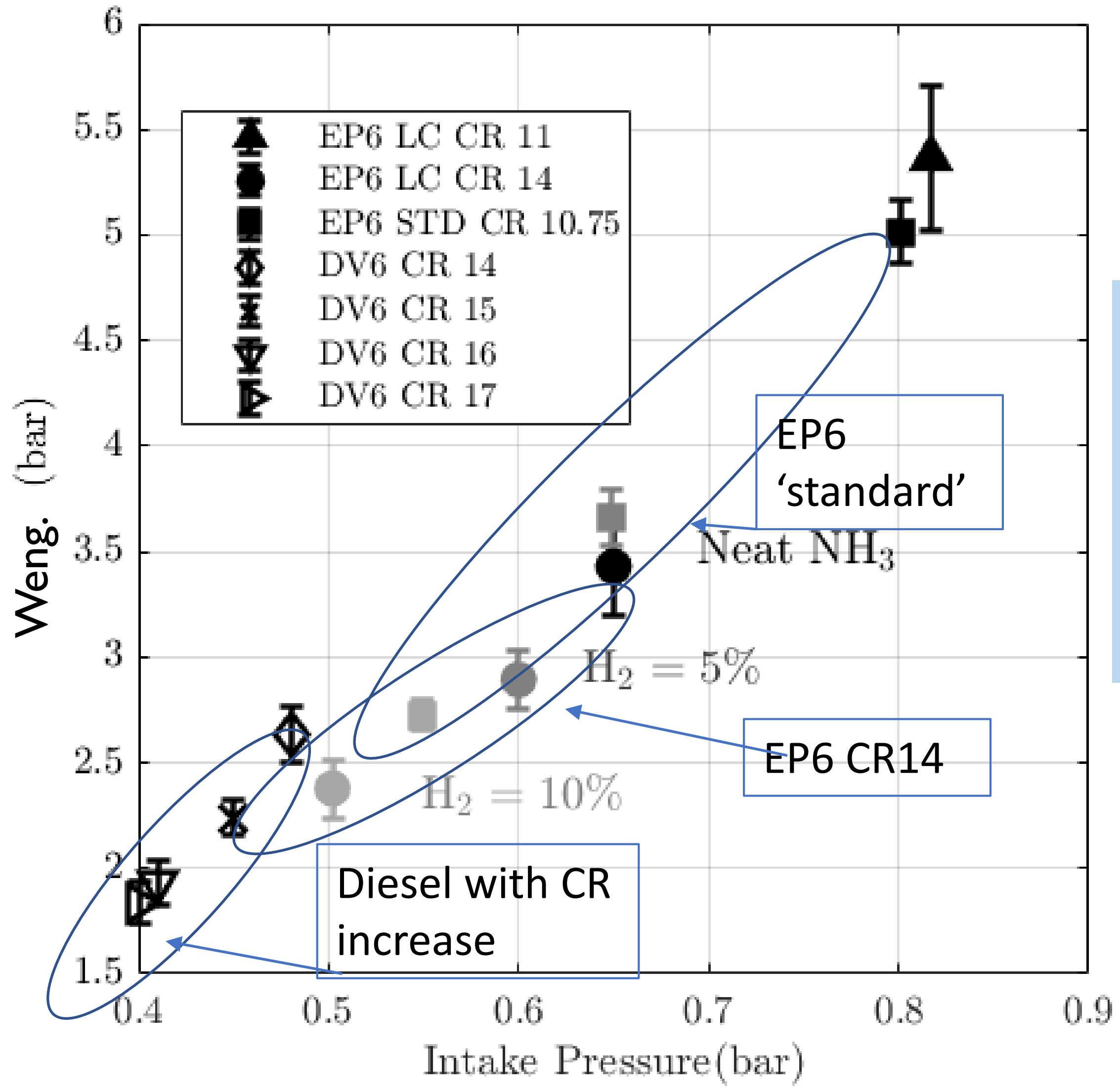
Figure 12. Minimum IMEP versus minimum intake pressure for three engine speeds – CR = 17:1, Tin = 50°C. Previous data in SI engine with 10% H_2.

- Extension of low load limits
  - lower limit with slightly rich
  - 1.7 b IMEP (as Koike et al. with Reformer)
  - CR 17, 650 rpm
  - Even at 2000 rpm, stability and limit improvement

2. Impact of engine architecture





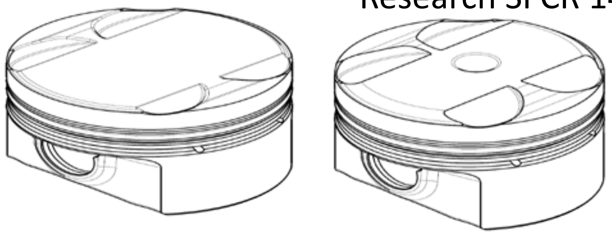


Example at 650 rpm :

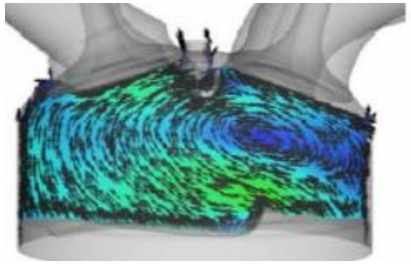
- H_2 required with for research SI engine even at CR14 !
- Lowest IMEP in SAD engine, even without H_2

3. Consequence on emissions

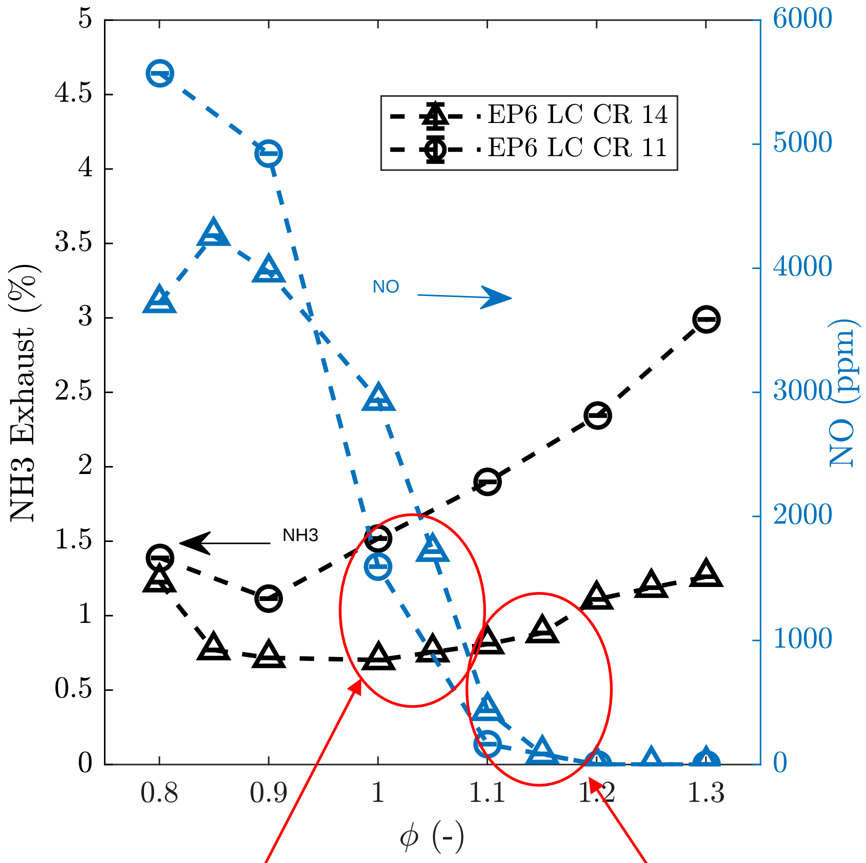
Research SI CR 11.5 Research SI CR 14



4 valves, 0.4 l



1000 rpm, intake pressure = 1 bar, IMEP = 8 b, NH_3 only



optimised window ?

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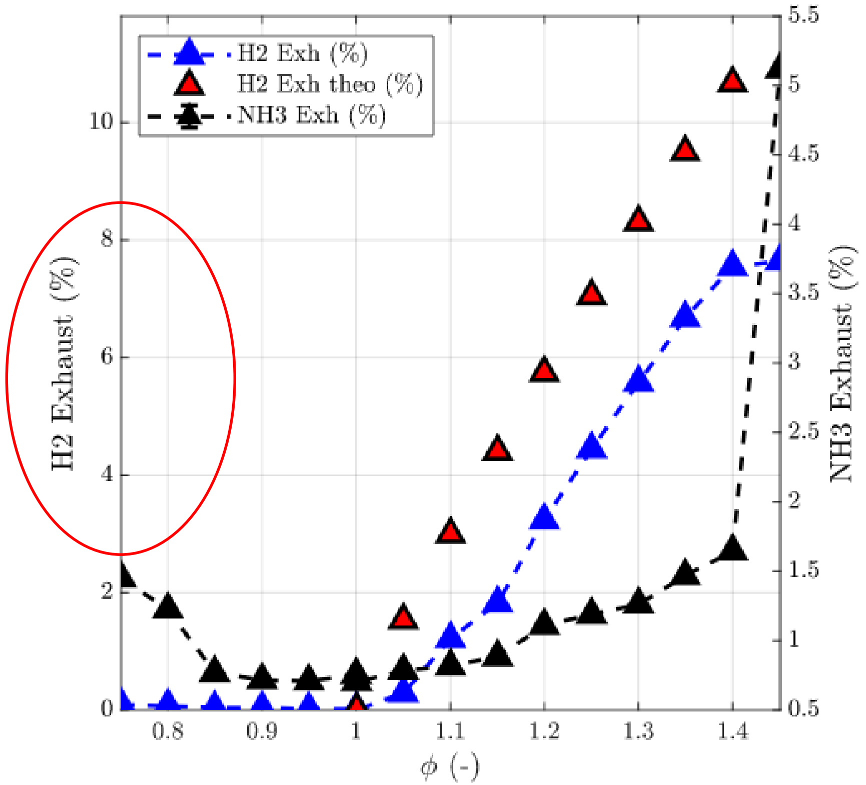

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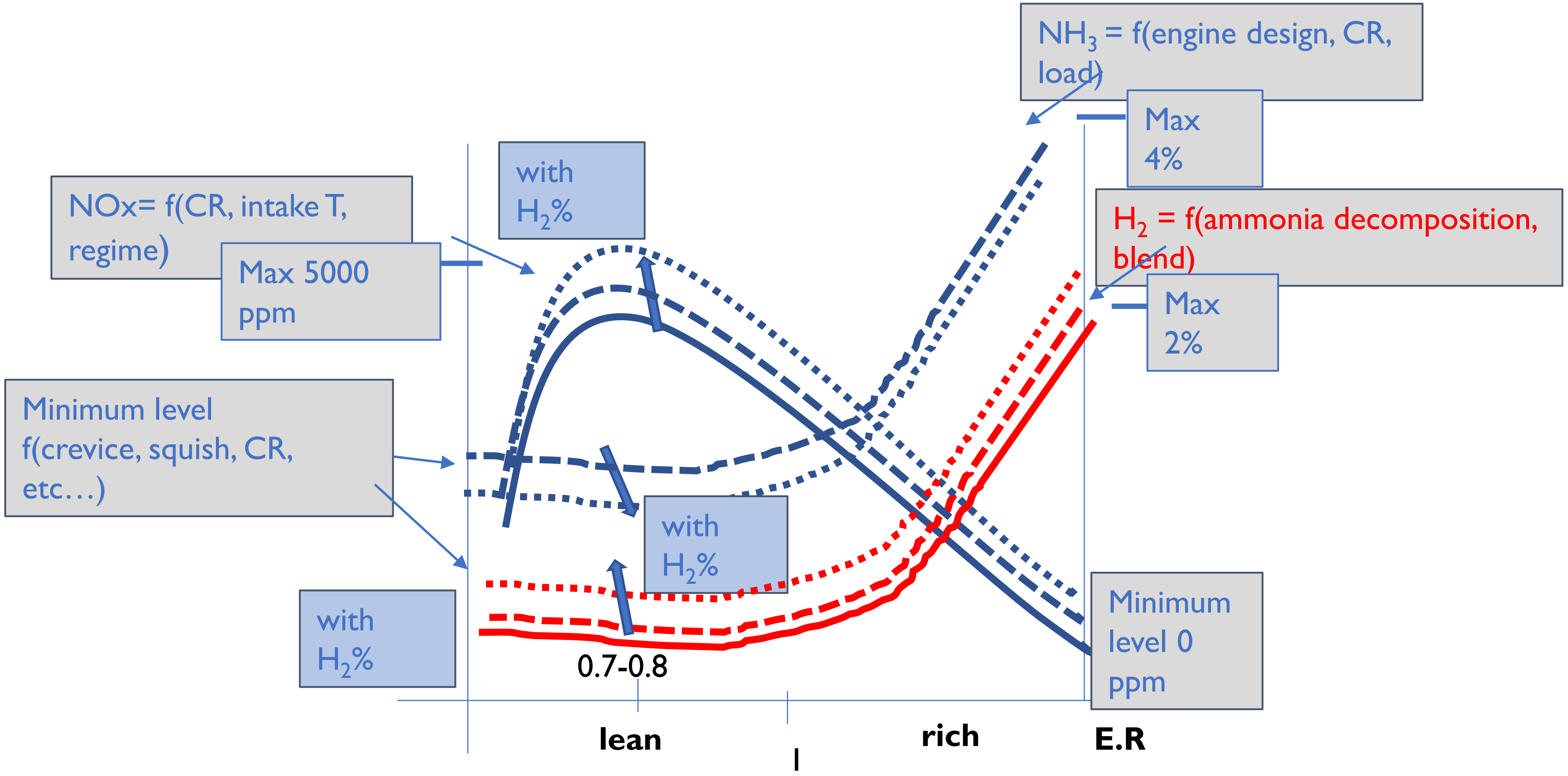


3. Consequence on emissions

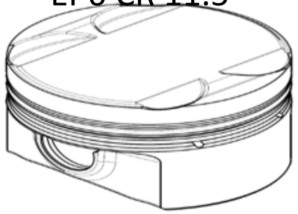
NH_3 = f(engine design, CR, load)

Max

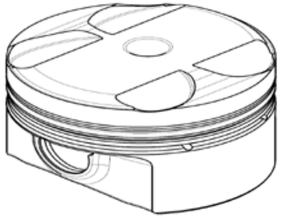
- **NO_x**
  - Minimum for **rich mixture**, Maximum around 0.7-0.8 until 5000 ppm !
  - Increase with H_2 addition
- **NH_3**
  - Minimum for **lean mixture/stoichiometry, max can be 4%**
  - **Function of engine design !**
  - **H_2 emissions due to 'in situ' decomposition of NH_3**

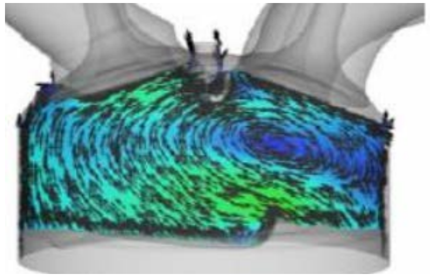
3. Consequence on emissions : nitrogen specie

EP6 CR 11.5



EP6 CR 14





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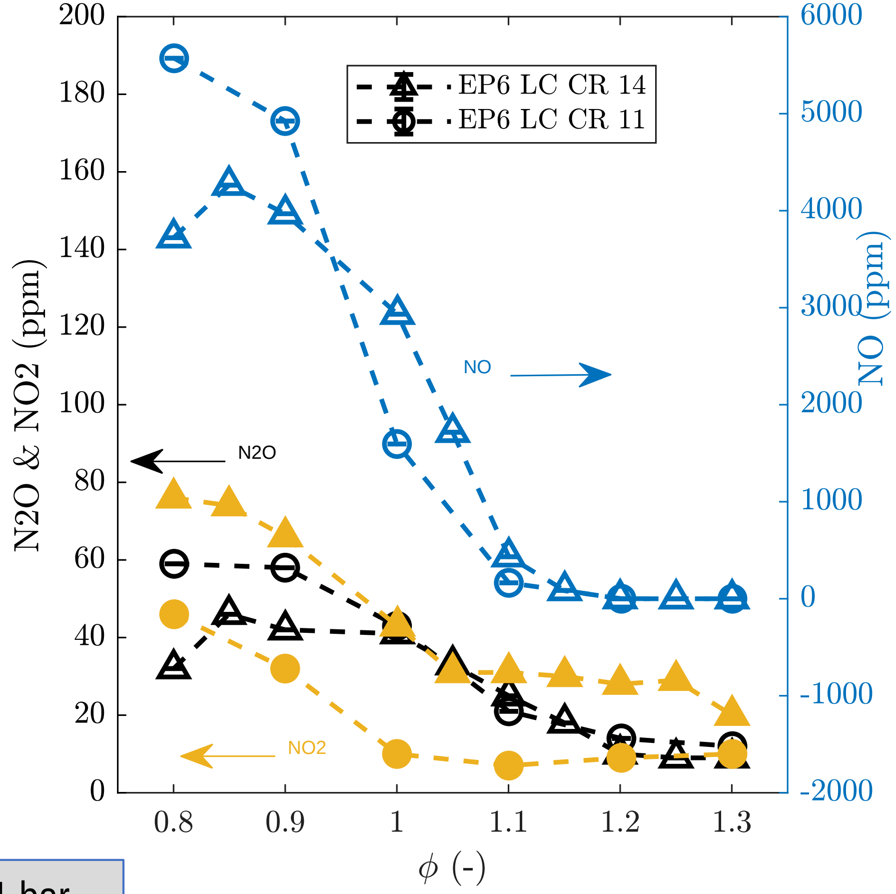
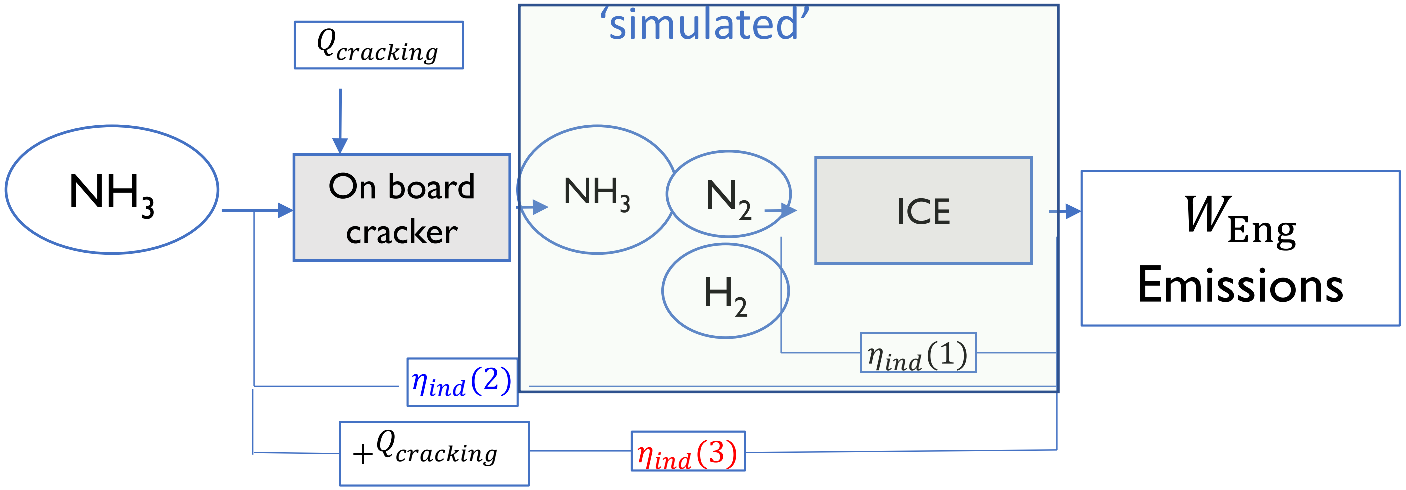
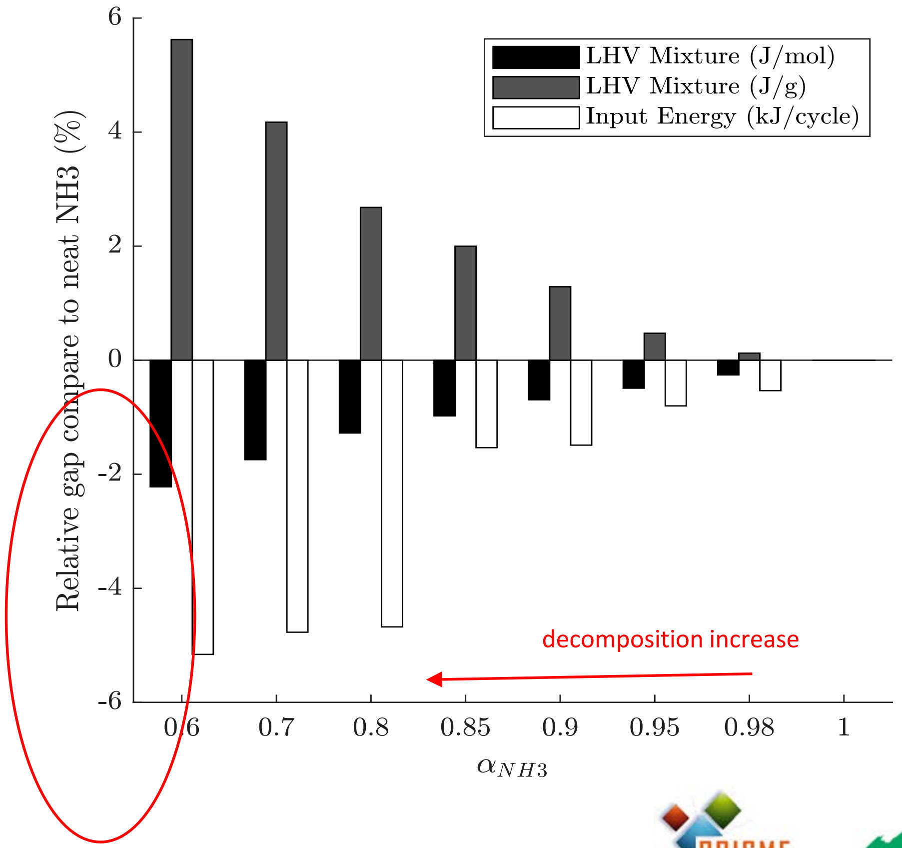


- **NO_2 & N_2O :**
  - Max for lean, min for rich
- **NO_2**
  - <<< NO
  - Function of CR ?
- **N_2O**
  - Max ≈ 100 ppm
  - BUT ≈ 1.5% CO_2 for GWImpact
  - No real link with CR

4. Ammonia on-board cracking : what benefits ?

$$\alpha NH_3 + (1-\alpha)\left(\frac{3}{2}H_2 + \frac{1}{2}N_2\right) + \frac{3}{4}(O_2 + 3.78N_2) \rightarrow \frac{3}{2}H_2O + \left(\frac{1}{2} + \frac{3}{4} * 3.78\right)N_2$$





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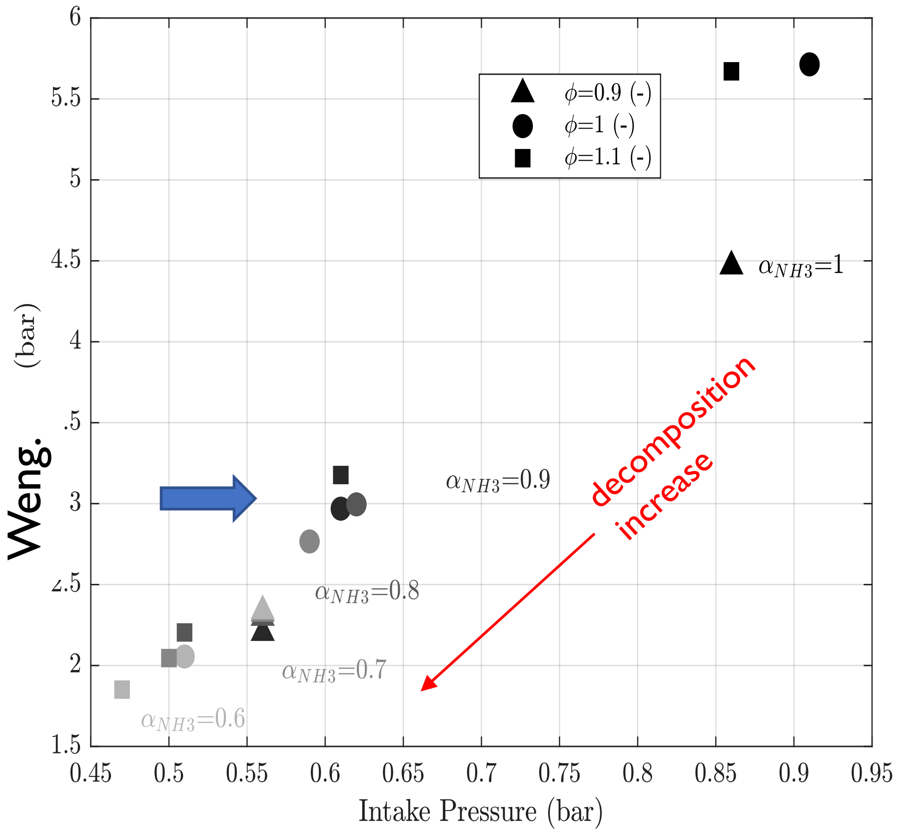

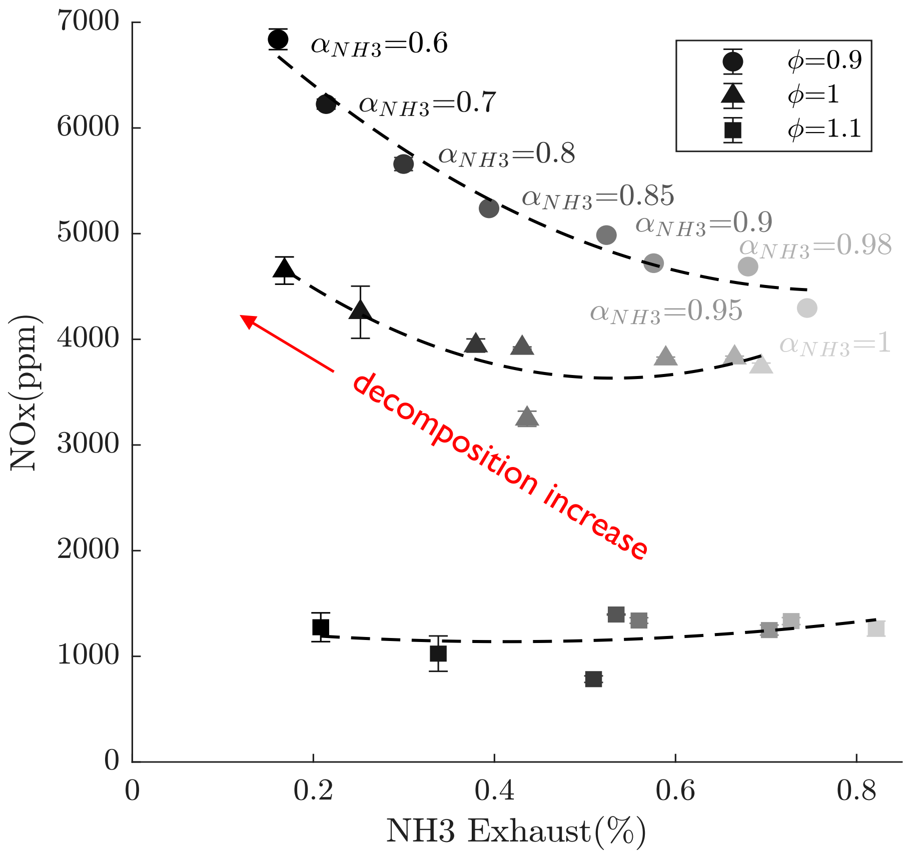

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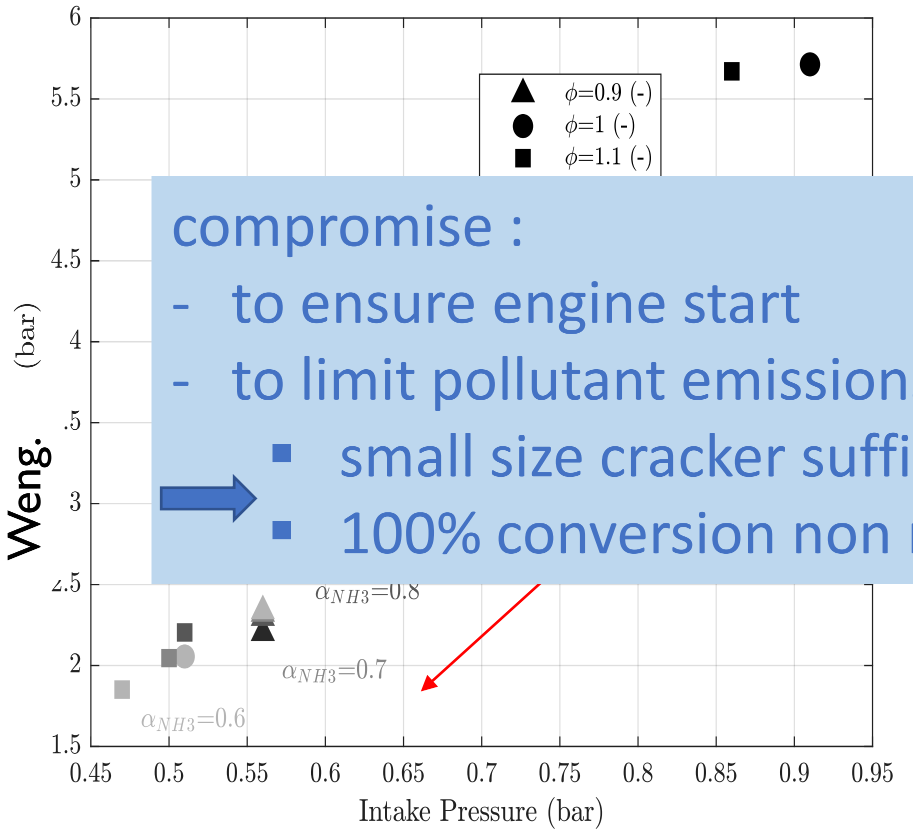
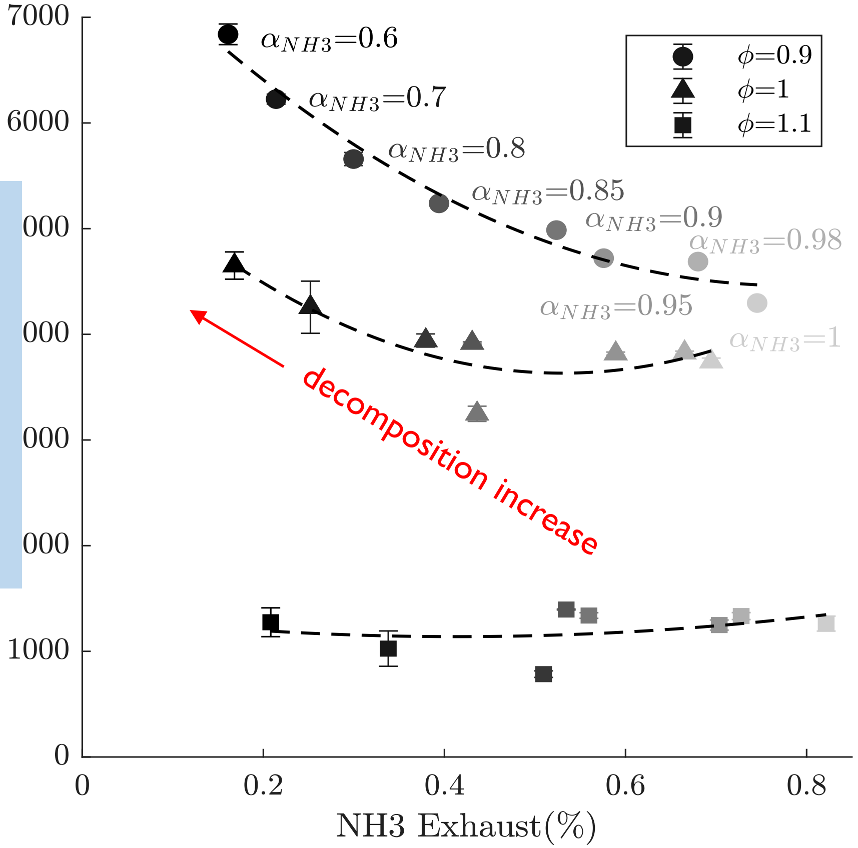


compromise :
- to ensure engine start
- to limit pollutant emissions
  - small size cracker sufficient,
  - 100% conversion non needed



5. Conclusions and perspective

Direct use of ammonia in ICE

- GOOD NEWS : YES IT IS POSSIBLE !
- In standard Gas ne engine :
  - small conte
    - even with
  - means of 'sm
- In standard Dies
  - addition of sp
  - more unburn

Direct use of ammonia for mobility (ICE)

First Workshop ARENHA project, ENGIE Lab CRIGEN, 07-04-2022

Thank you for your attention

Website project: https://arenha.eu/

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J. Bouriot, S. Houillé, C. Dumand, P. Brequigny, B. Raitiere, A. Mercier,