KAUST Research Conference

Near Zero-Carbon Combustion Technology

21-23, June, 2021

Ammonia as a fuel For Internal Combustion Engine

Prof Christine Mounaïm-Rousselle

University of Orléans

Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon

Ammonia flagged as green shipping fuel of the future

Ammonia as renewable fuel for the maritime industry

Green Car Congress

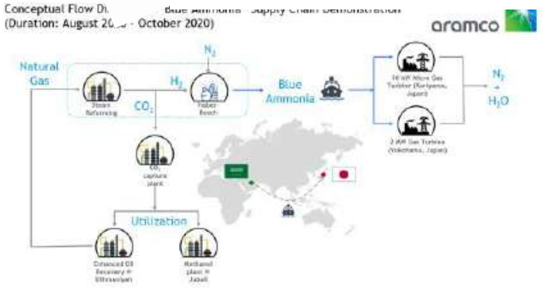
Monash team proposes roadmap to renewable ammonia economy; 3 generations of technology

Green Ammonia can replace fossil fuel storage at scale

Can Ammonia be the ...

Oxford University Looks To Power Aircraft With Ammonia

ammonia as the fuel of the future



PETROCHEMICALS

Is ammonia the fuel of the...

Industry sees the agricultural chemical as a convenient and sustainable means to transport hydrogen and save carbon dioxide emissions

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

UNIVERSITE D'ORLEANS

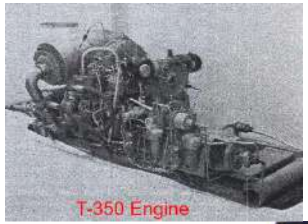
Thanks to some co-workers

P. Bréquigny, R. Rabello, A. Mercier, U Orléans,

C. Lhuillier (UORL/UCL), F. Contino, UC Louvain

AMMONIA AS FUEL FOR TRANSPORTATION : A 'BRIEF' HISTORY

1940
Belgium
NH_3/Coal gas = 'syngas'
10 000 miles



1960-1966
US Army
Rocket record

2007-2012 :
Michigan University
50%NH_3/Gasoline
3 800 km

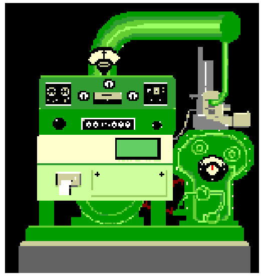
2012-2015 :
KIER, Korea
Dual Fuel
NH_3/Gasoline
10L/100km
until 70% NH_3

Marangoni Toyota GT-86
Eco-Explorer, 2013

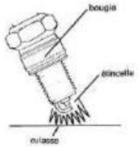
Hydrofuel Project-2020

C-Free Run project,
Hydrogen Engine Center
(Iowa), 2018-2021

SOME RECENT EXAMPLES : SPARK IGNITION ENGINE



CFR
Gas PFI
Gaseous direct injection

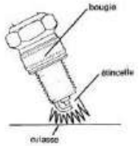


Iowa university, DTU, …

NH_3+Gasoline

2012-2013

Twin Lombardini (2 cyl./0,25 l)
Gas PFI
LPG injector



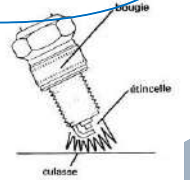
Pisa University

NH_3+H_2

Range Extender

Frigo et al. IJHE 2012

GM engine (4 cyl/0.6 l)
Gas PFI
Direct gas Inj
EMULSION

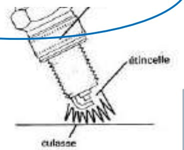


Texas university

Gasoline+ethanol (max30%)+NH_3 (17%)

(Haputhanthri et al. ASME 2017)

Heavy duty
6 cyl./1.8l
Premixed PFI – CR 10.5



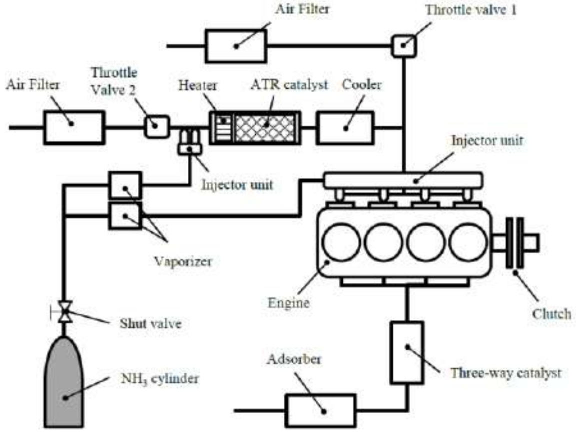
KIMM

Natural Gas + NH_3 (50%)

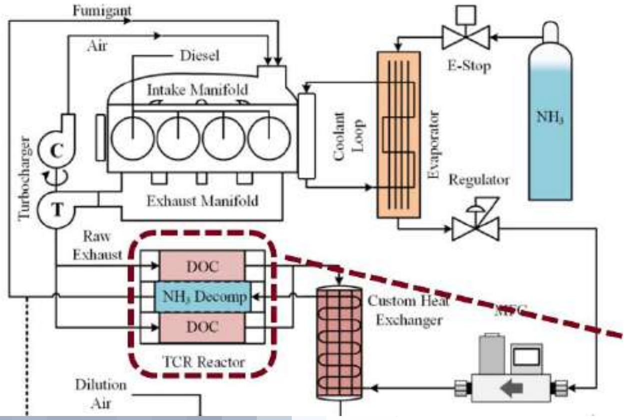
(Oh et al. FUEL 2021)

4 cyl./0.9l
Gaseous PFI – CR 9

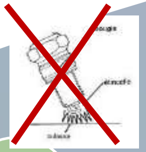
Toyota
NH_3 + H_2 Thermal Reformer
cold start + SCR catalyst
(Koike et al. IJHE 2021)



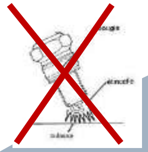
Some reseach examples : Compression Ignition Engine



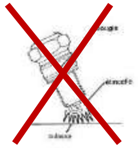
John Deere,
4 cyl. (1.125l)
CR 17



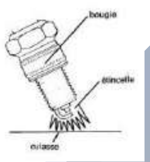
Single cylinder research
HCCI engine (0.5l)
Gas fully premixed



3 cyl.CI engine
CR 17.5 (0.54l)



Yammar Engine (0.3 l)
Liquid premixture GDI (200 b)



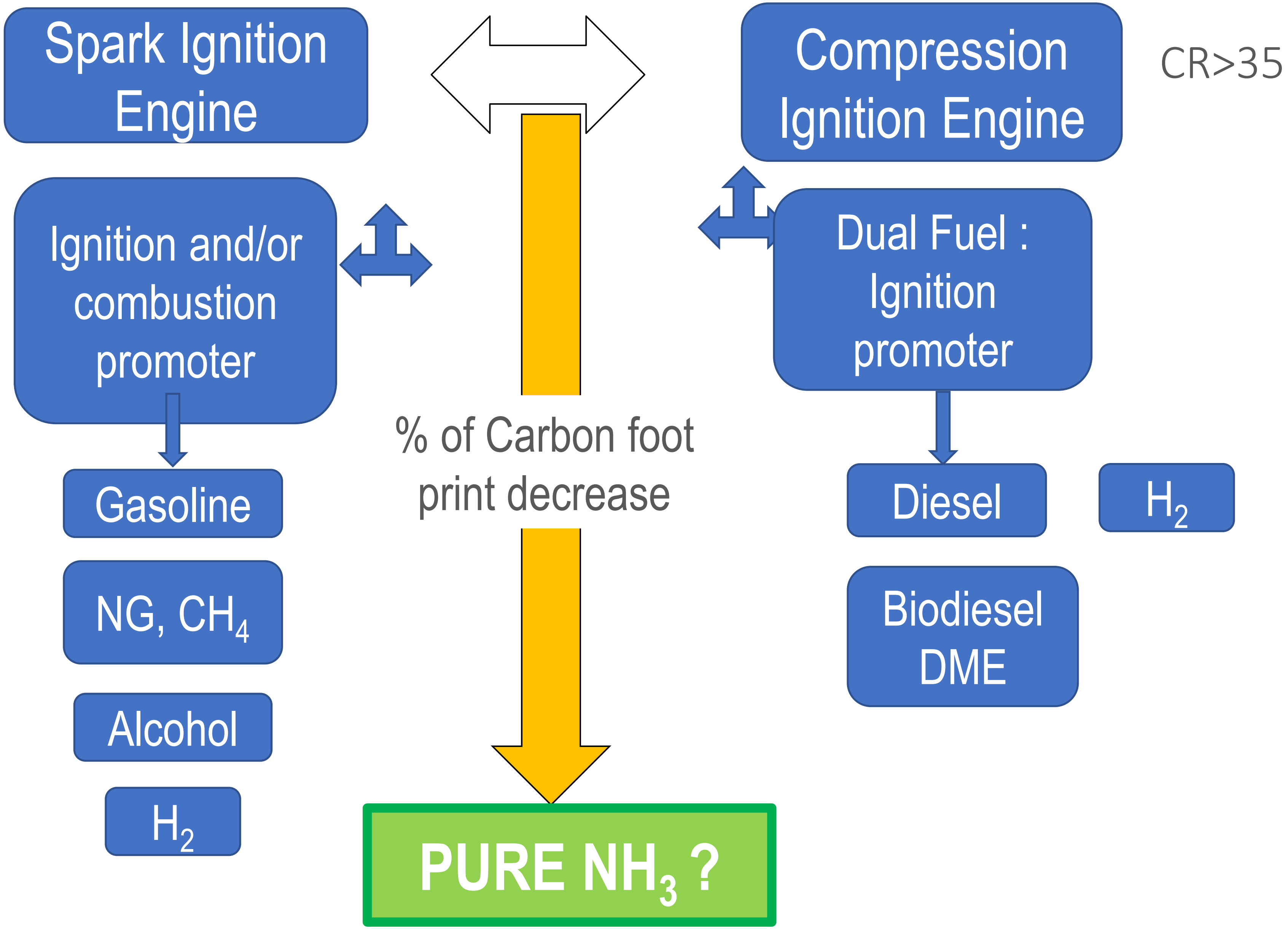
Iowa Energy Center
DUAL FUEL
Premixed DME(min 40%) /NH3
Ryu et al. 2014

KIER
Diesel (Min 62%)/NH3
DUAL FUEL
Woo, NH3 conference, 2014

Louvain-VRIJE – Université d'Orléans
HCCI
NH3+H2
Pochet et al., PROCI 2018

T.E. Murphy Engine Research Lab (Minneapolis) Diesel (45% in Energy)/NH3
Thermal Chemical Recuperation
- seed with H_2
Northrop et al. NH3 event 2021

NH_3 AS FUEL FOR POWERTRAIN



RELEVANCE OF SPARK-IGNITION (SI) ENGINE FOR NH_3

Properties of **ammonia** VS **gasoline**

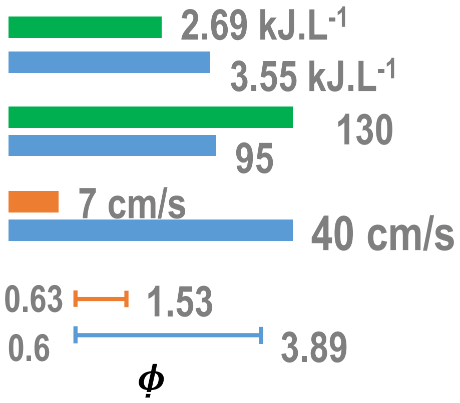
Carbon-free

Energy content (stoichiometric mixture)

Octane number (RON)

Laminar burning velocity
ϕ = 1, 298 K, 1 atm

Flammability limits



Fuel-bound nitrogen content

- No CO_2, CO nor PM emissions
- Good energy density
- Potential for high compression ratios (CR)
- Combustion promoter (H_2…) to boost performance and ensure stability ??
- **NOx and NH_3** mitigation strategy required for pollutants

MAIN RESULTS FROM PREVIOUS SI ENGINE STUDIES

For zero–carbon footprint : how ignite ammonia-air mixture,

How obtain complete combustion without any use of conventional fuels ?

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	

Frigo et al. : from 2000 to 4000 rpm (small engine)

Pollutant Emissions before any aftertreatment device

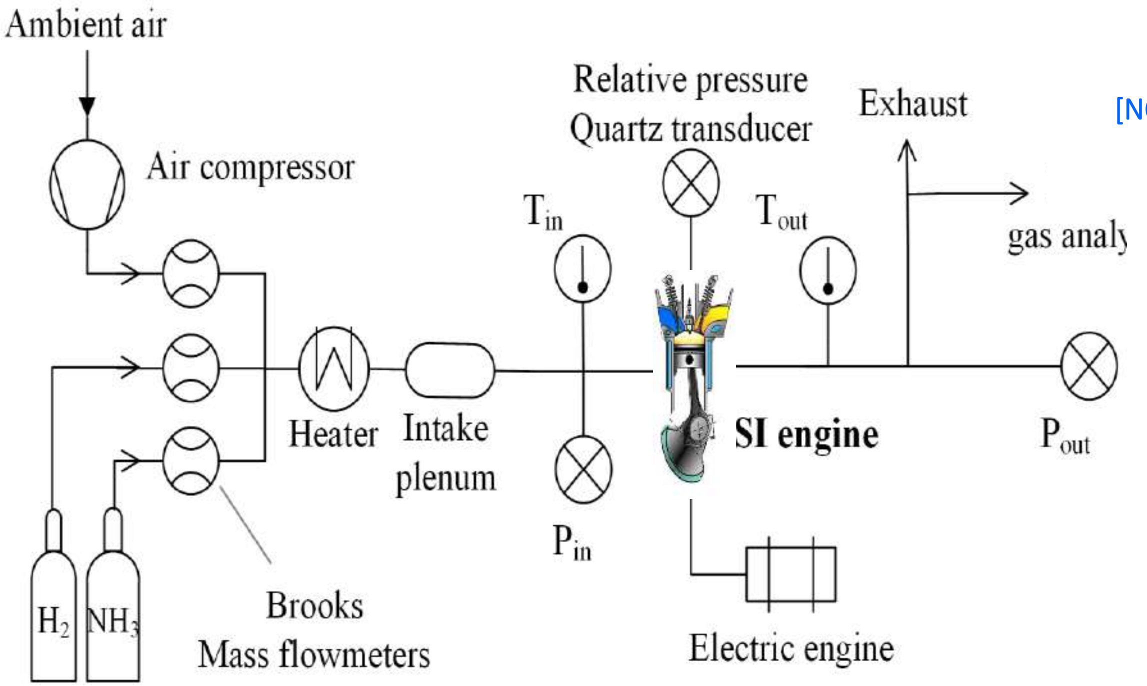
	ER decrease (lean)	**ER increase (rich)**	**H_2 increase**	**Load**
NOx (ppm)	++ maximum > gasoline	--	+	slight increase but no universal trend
Unburnt NH_3	--	++	-- H_2 at exhaust	no universal trend

Mounaïm-Rousselle C., Brequigny P. (2020) Ammonia as Fuel for Low-Carbon Spark-Ignition Engines of Tomorrow's Passenger Cars. *Front. Mech. Eng.* 6:70. doi: 10.3389/fmech.2020.00070

Some recent Highlights of combustion process in Single-cylinder engines

- ‘CURRENT’ ENGINE
  - no optimisation of piston/chamber design
  - no optimisation of ignition device
  - fully premixed NH_3/air (+minimum H_2)
    - to avoid injection process impact

SI Single Cylinder Engine



[H_2O], [NH_3],
[NO], [NO_2], [N_2O]
@ 180 °C (wet)
FTIR

[O_2], *Paramagnetic*
[H_2], *Thermal conductivity analyser*
@ 50°C, Dry gases

Piston geometry (GDI)

Engine Characteristics	
Engine Type	Current PSA EP6DT
Bore	77 mm
Stroke	85 mm
Connecting Rod Length	138.5 mm
Displacement Volume V_{cyl}	395.81 cm^3
Compression Ratio	10.5

MINIMUN OPERATING LIMITS WITH PURE AMMONIA

❑ Engine speed effect - stable conditions ($s_{IMEP} \leq 5\%$)

		650 rpm			1000 rpm			1500 rpm			2000 rpm		
		%H2											
Φ	Pin (bar)	0%	5%	10%	0%	5%	10%	0%	5%	10%	0%	5%	10%
0.9	<=0,65						X			X			X
	0,8-0,85		X	X	X	X	X		X	X			X
	1		X	X	X	X	X	X	X	X		X	X

- impossible to ignite at low and high rpm without H_2
- difficult at low load
- possible 'sometimes' to ignite with NH_3 only at naturally aspirated conditions

*optimized ignition timing (around 40-35 CAD BTDC)

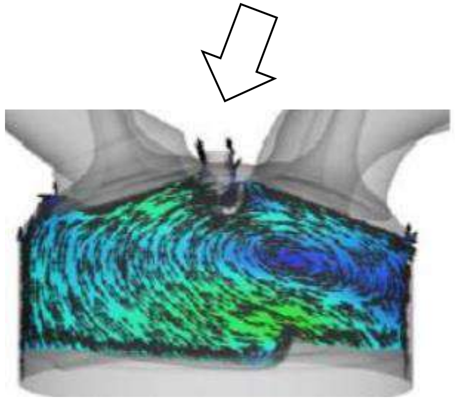
https://arenha.eu/

Mounaïm-Rousselle et al., submitted Energies

- Solution : Increase the CR
  - Diesel Engine with Spark Ignition

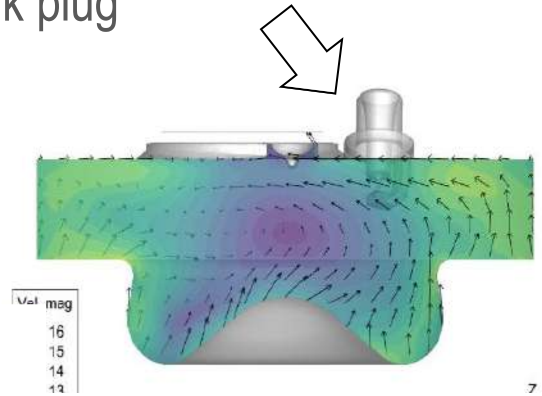
Engine Type	Current PSA EP6DT	SACI PSA DV6
Displacement Volume V_{cyl}	400 cm^3	400 cm^3
Compression Ratio	10.5	14 to 17
Valves	4	2
Tumble ratio	2.4	
Swirl ratio		2

*No optimization of ignition system or location



SI

Spark plug



SACI

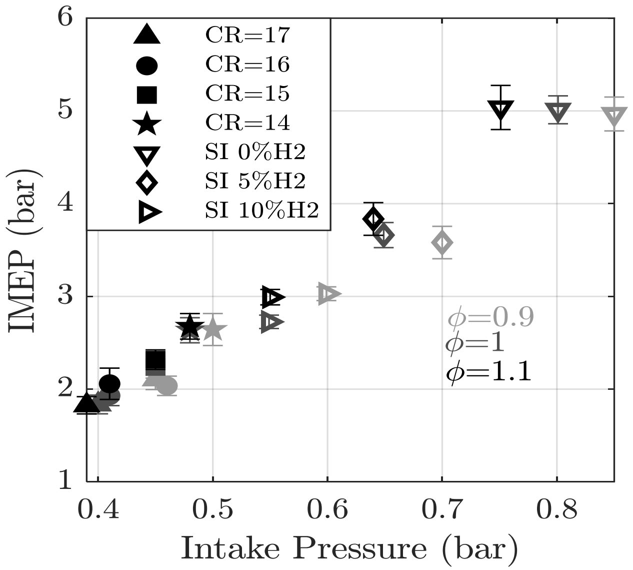
https://arenha.eu/

Mounaïm-Rousselle et al., submitted IJER

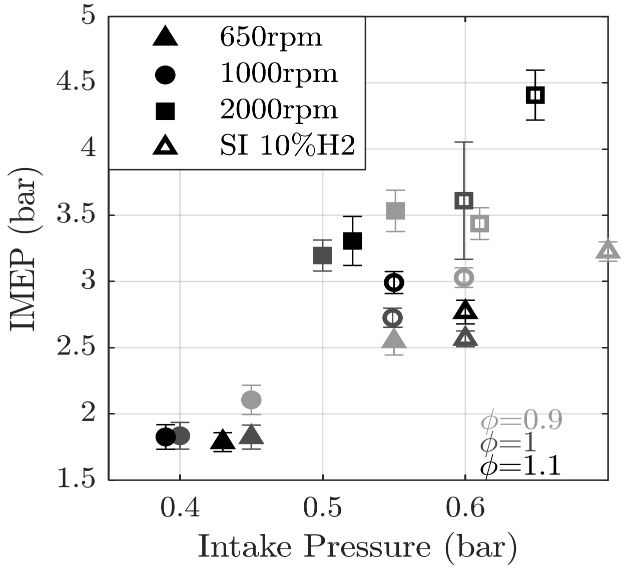
Extension of 'Low' Operating limit

❑ Increase of CR :

➢ SACI versus SI engine



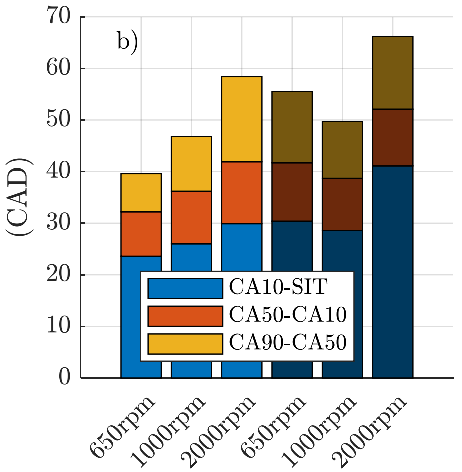
Engine speed :1000 rpm



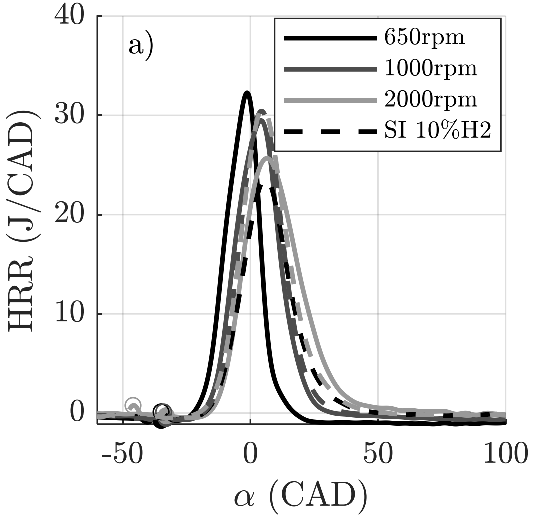
SACI CR: 17, SI :CR=10.5

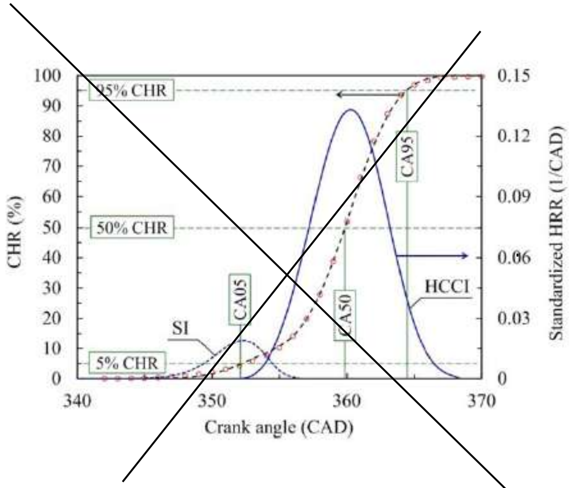
- Good improvement of NH_3 combustion with CR increase despite of flow field
- No H_2 needs
- Extension of low load limits
  - 1.7 b IMEP (as Koike et al. with Reformer)
  - CR 17, 650 rpm,
  - lower limit with slightly rich

FLAME DEVELOPMENT : SACI VERSUS SI



ϕ =1

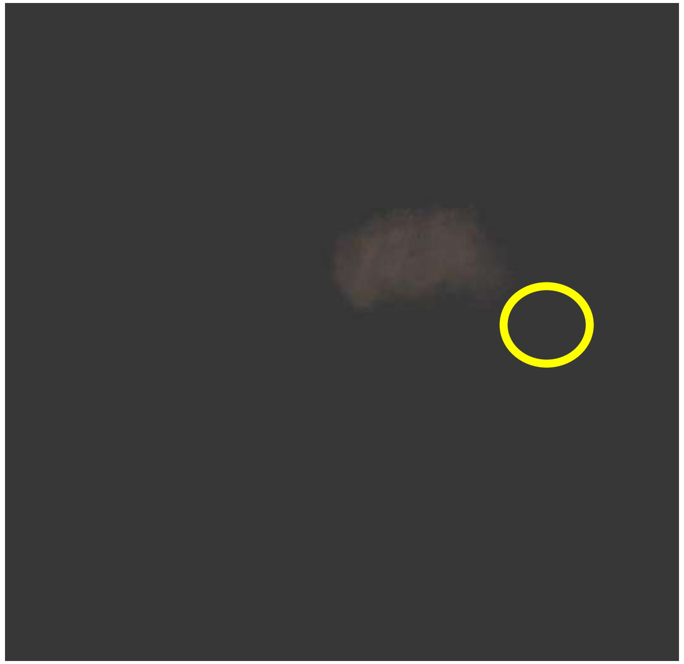




- SACI combustion mode :
  - Without H2
  - Not 2 identified phases of HRR
- Faster first phase than SI engine
  - Pressure effect

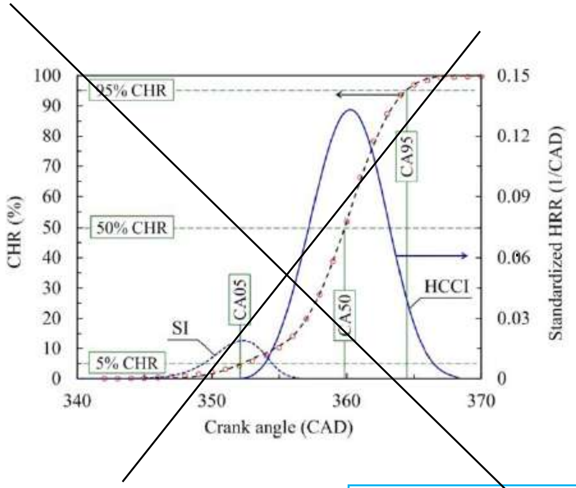
FLAME DEVELOPMENT : SACI VERSUS SI

-40 CAD to 27 CAD ATDC



Spark timing : -40 CAD

ER NH3 = 0.9 - IMEP = 6.7 b



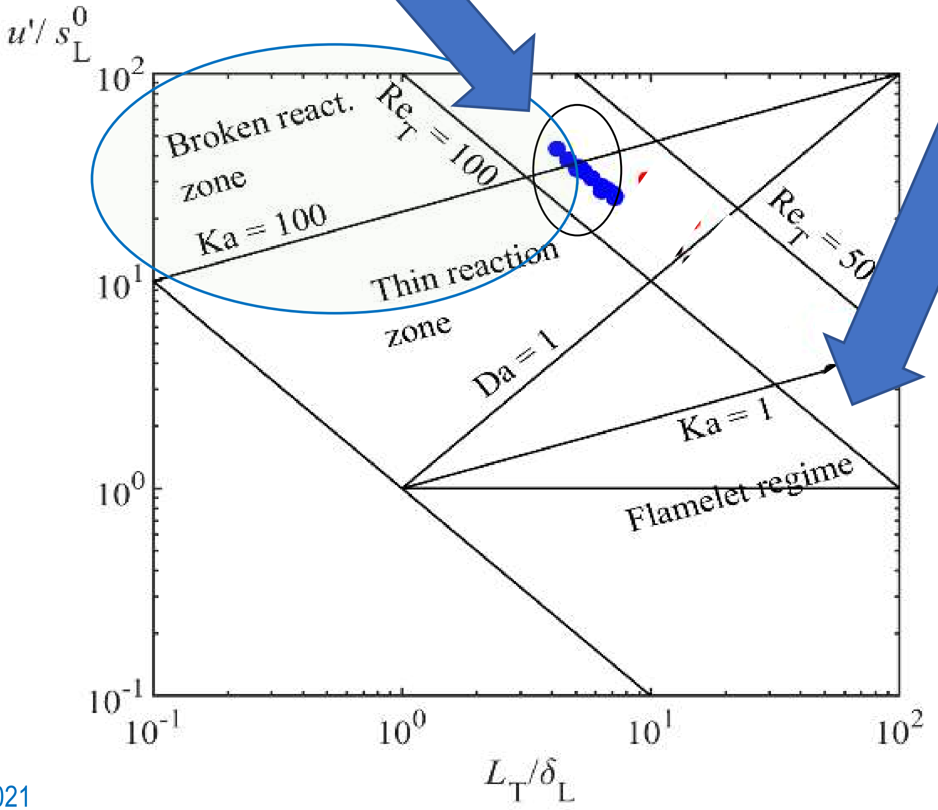
- SACI combustion mode :
  - Without H2
  - Not 2 identified phases of HRR
- Faster first phase than SI engine
  - Pressure effect
  - FULLY PREMIXED PROPAGATION

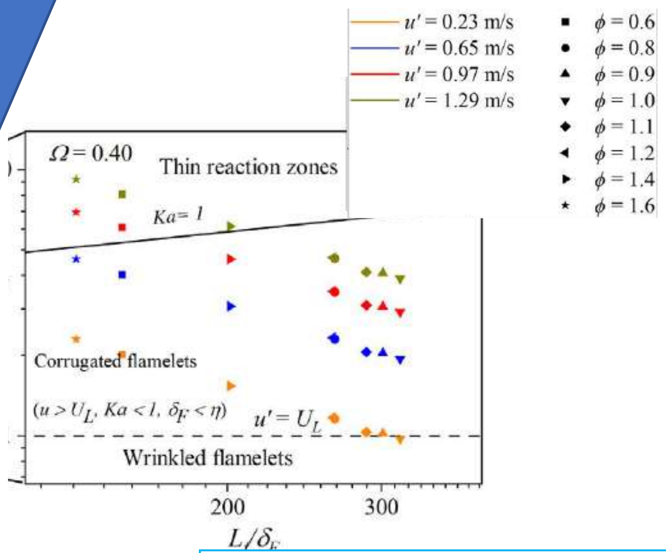
SI engine

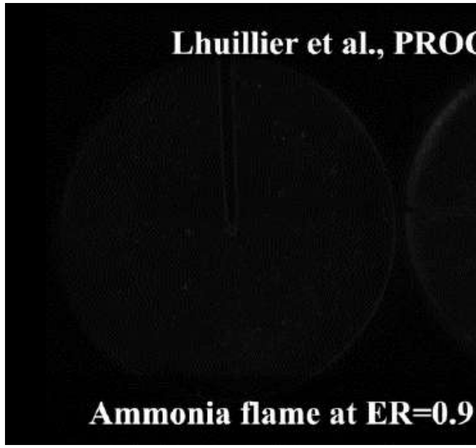
- S_L<< ⇨ U'/S_L>>
- δ_L >> ⇨ L_T/δ_L ???

SACI engine : HT/HP

- S_L ↗ U'/S_L ↘
- δ_L ↘ L_T ↗ L_T/δ_L ???







- SACI combustion mode :
  - Turbulent scale size ? Flamelet regime ?
-

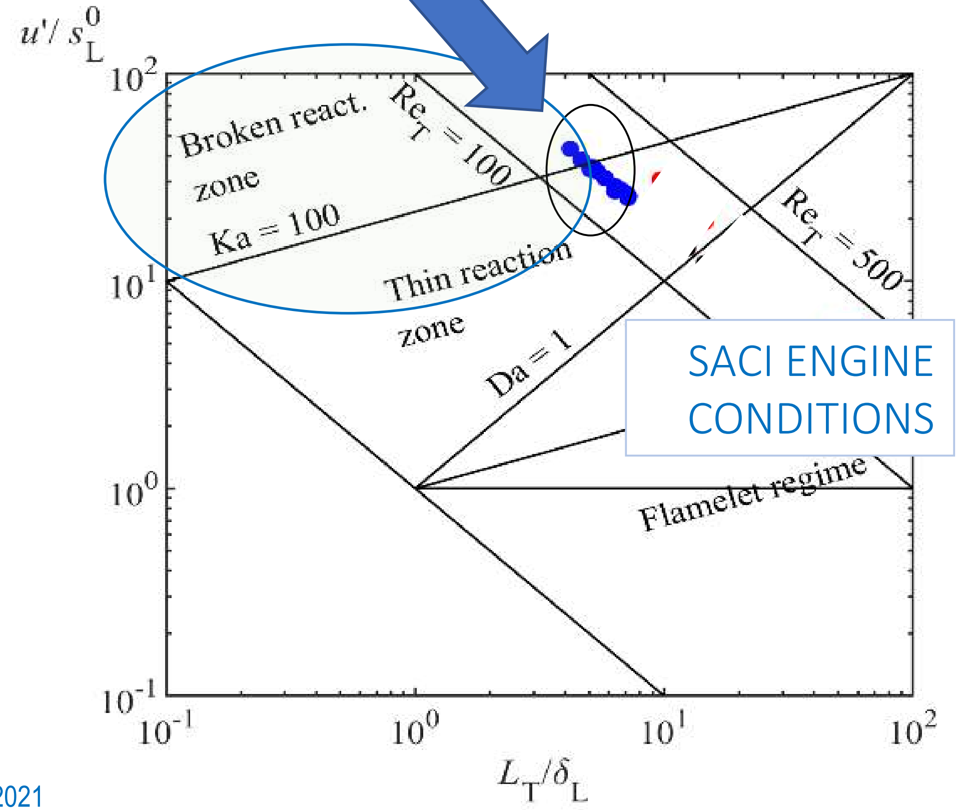
Lhuillier et al. PROCI 2021
L_T = 4 mm

SI engine

- S_L<< ⇨ U'/S_L>>
- δ_L >> ⇨ L_T/δ_L ???

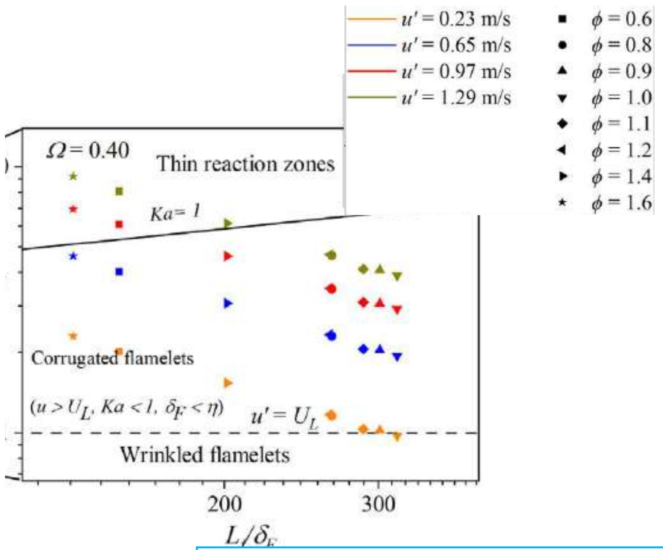
SACI engine : HT/HP

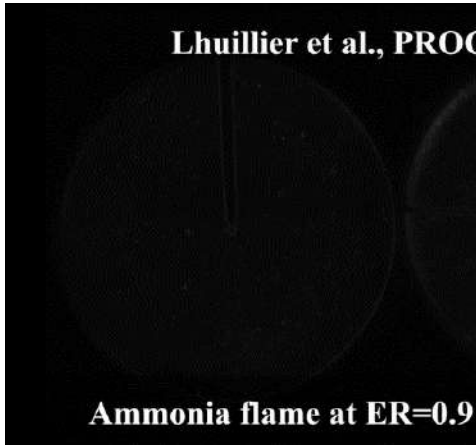
- S_L ↗ U'/S_L ↘
- δ_L ↘ L_T ↗ L_T/δ_L ???



SACI ENGINE CONDITIONS

Lhuillier et al. PROCI 2021
L_T = 4 mm

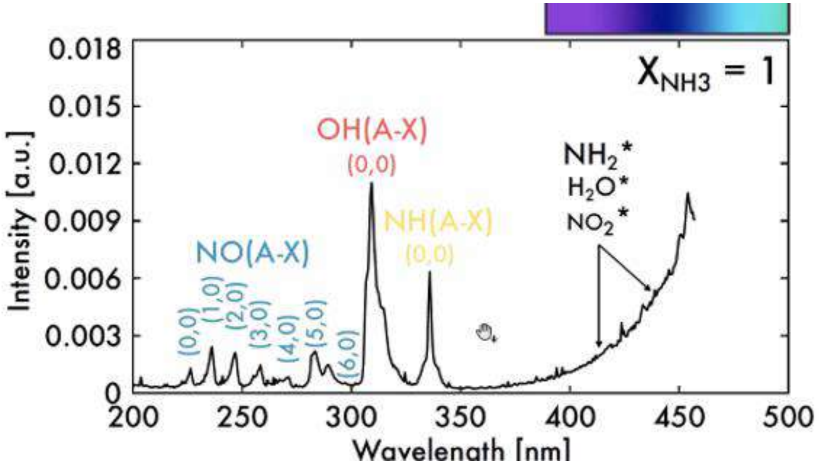




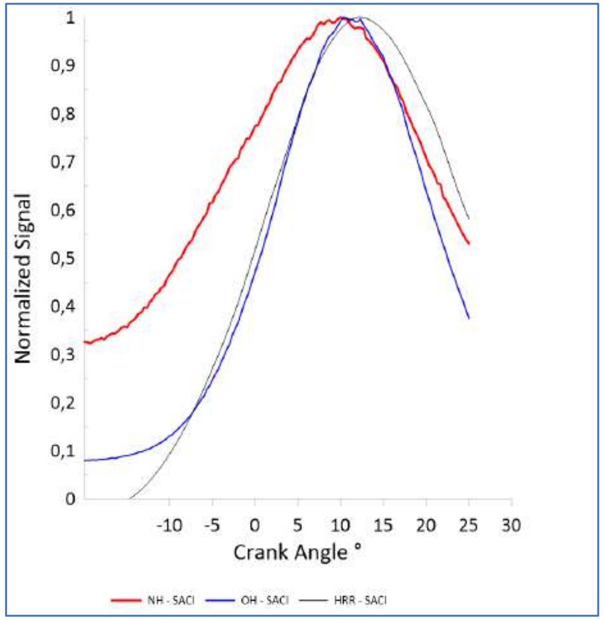
- SACI combustion mode :
  - Turbulent scale size ? Flamelet regime ?
-

FLAME DEVELOPMENT : SACI VERSUS SI

OH (blue) + NH (red) chemiluminescence

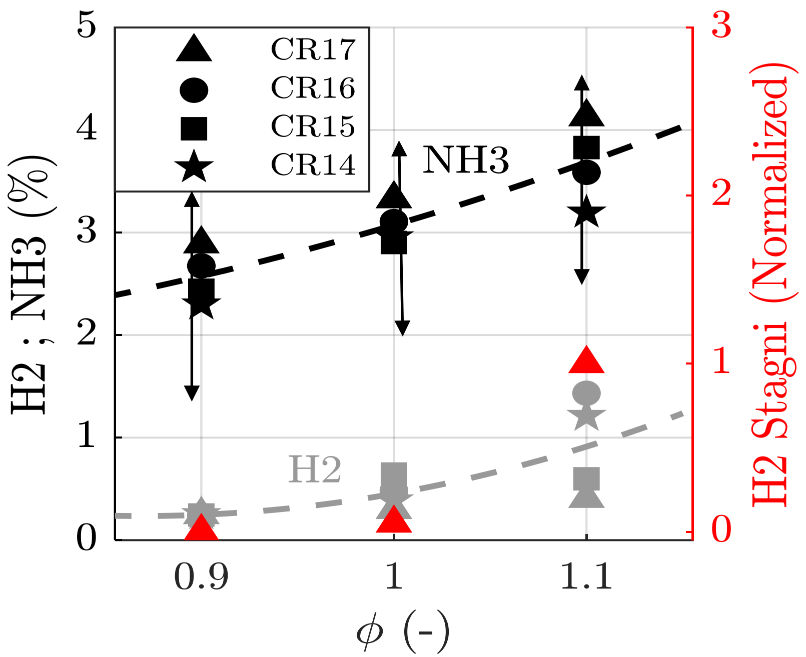


T. Guiberti, NH_3 event, 2021



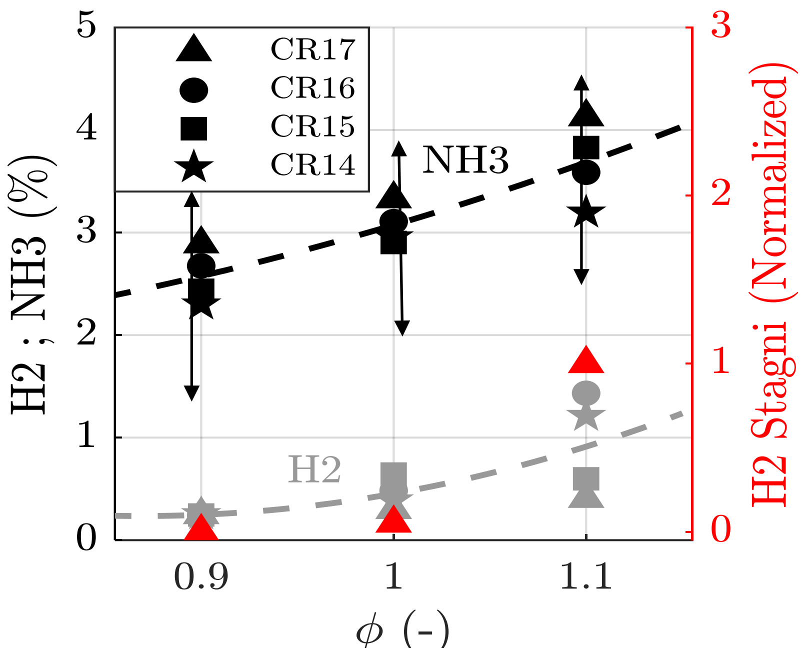
- SACI combustion mode :
  - HT/HP + Turbulent flow field = Flamelet regime ?

Flame development : SACI versus SI

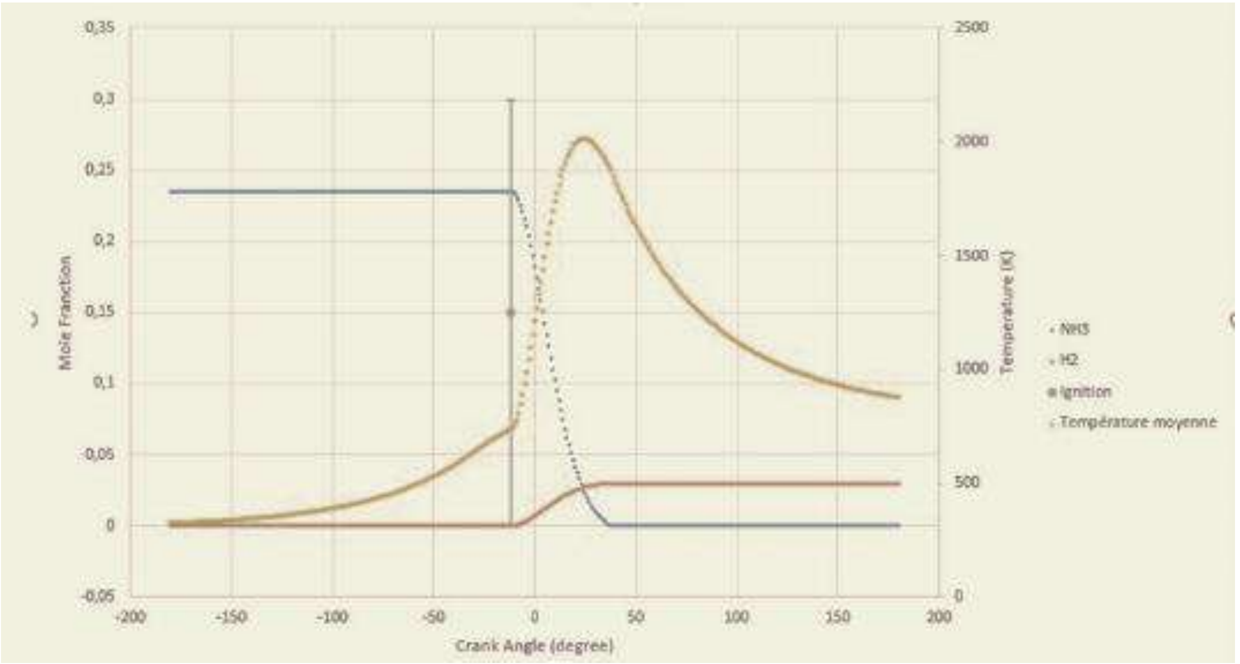


- SACI combustion mode :
  - HT/HP + Turbulent flow field = Flamelet regime ?

Flame development : SACI versus SI



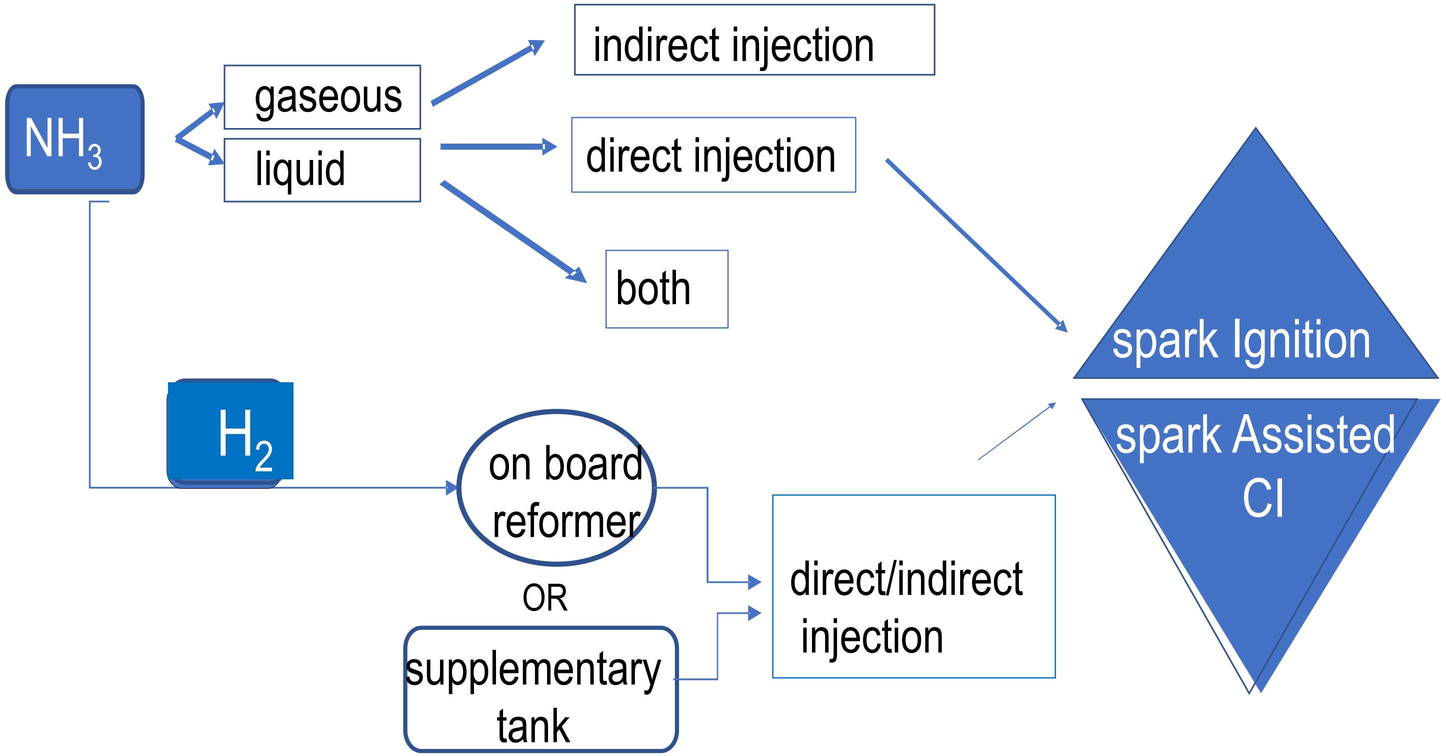
Kinetics mechanism Stagni et al. 2020



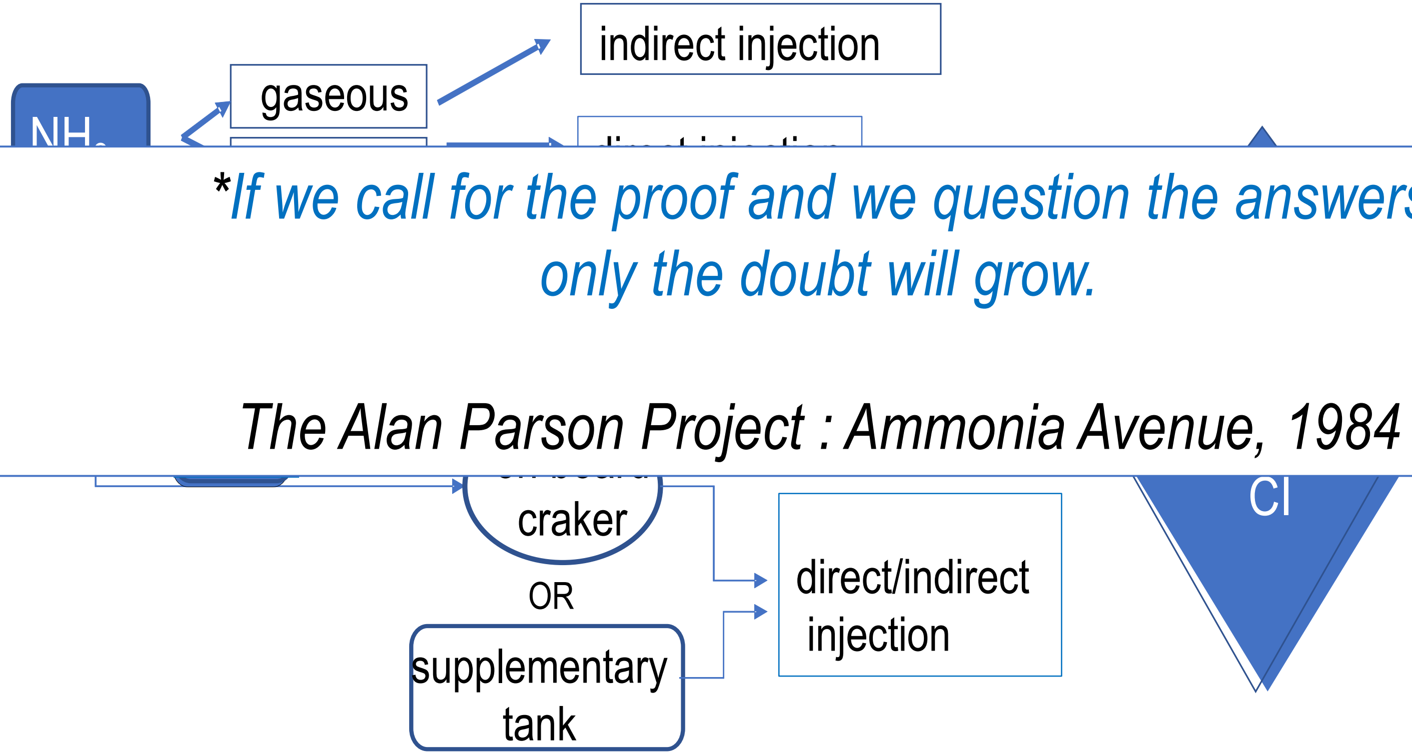
- SACI combustion mode :
  - HT/HP + Turbulent flow field = Flamelet regime ?
  - HT/HP = in situ NH_3 decomposition in H_2

For zero–carbon footprint : how ignite ammonia-air mixture,

How obtain complete combustion without any use of conventional fuels ?



Ammonia only or Ammonia+H_2



**If we call for the proof and we question the answers only the doubt will grow.*

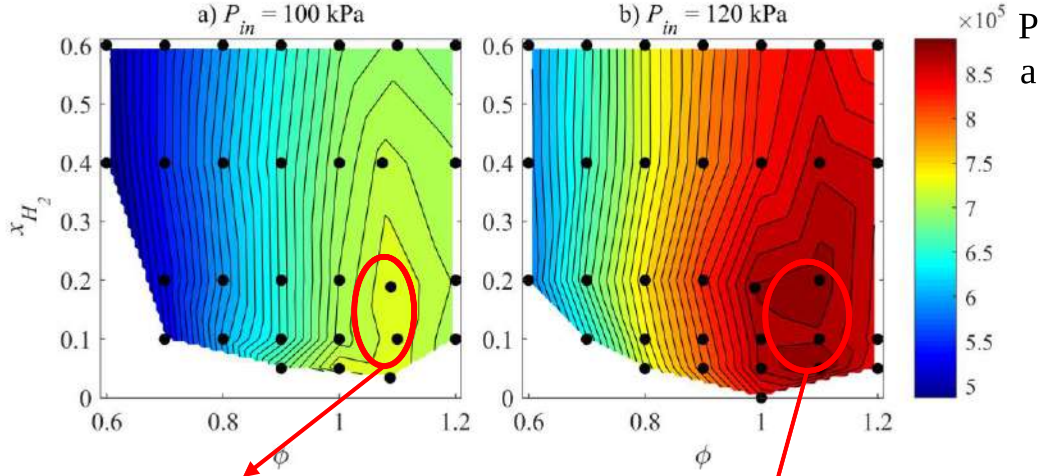
The Alan Parson Project : Ammonia Avenue, 1984

REFERENCES

- Lhuillier, C., Bréquigny, P., Contino, F., Rousselle, C., "Combustion Characteristics of Ammonia in a Modern Spark-Ignition Engine," SAE Technical Paper 2019-24-0237, 2019,
- Lhuillier, C., Bréquigny, P., Contino, F.,Rousselle, C., "Performance and Emissions of an Ammonia-Fueled SI Engine with Hydrogen Enrichment," SAE Technical Paper 2019-24-0137, 2019
- Mounaïm-Rousselle C., Brequigny P. (2020) Ammonia as Fuel for Low-Carbon Spark-Ignition Engines of Tomorrow's Passenger Cars. *Front. Mech. Eng.* 6:70.
- Lhuillier, C., Brequigny, P., Contino, F., Mounaïm-Rousselle, C., Experimental study on ammonia/hydrogen/air combustion in spark ignition engine conditions, Fuel 269,117448, 2020
- Lhuillier, C., Brequigny, P., Lamoureux, N., Contino, F., Mounaïm-Rousselle, C., Experimental investigation on laminar burning velocities of ammonia/hydrogen/air mixtures at elevated temperatures, Fuel 263, p.116653, 2020
- Shrestha K. P., Lhuillier C., Barbosa, A., Brequigny P., Contino F., Mounaïm-Rousselle C., Seidel L., Mauss F., An experimental and modeling study of ammonia with enriched oxygen content and ammonia/hydrogen laminar flame speed at elevated pressure and temperature, Symp. (Int.) Combust, 2020,
- Lhuillier C., Brequigny P., Contino F., Mounaïm-Rousselle C., An experimental and modeling study of ammonia with enriched oxygen content and ammonia/hydrogen laminar flame speed at elevated pressure and temperature, Symp. (Int.) Combust, 2020,.
- Mounaïm-Rousselle C, Brequigny P, Houillé S, et al. (2020) Potential of Ammonia as future Zero-Carbon fuel for future mobility: Working operating limits for Spark-Ignition engines. In: *SIA POWERTAIN & ENERGY 2020*, https://hal.archives-ouvertes.fr/hal-03188481
- K.H.R. Rouwenhorst, O. Elishav, B. Mosevitzky Lis, G.S. Grader, C. Mounaïm-Rousselle, A. Roldan, A. Valera-Medina, Techno-Economic Challenges of Green Ammonia as an Energy Vector , Book chapter : Chapter 13 - Future Trends, Editor(s): Agustin Valera-Medina, Rene Banares-Alcantara,, Academic Press, 2021, Pages 303-319
- A. Valera-Medina, F. Amer-Hatem, A. K. Azad, I. C. Dedoussi, M. de Joannon, R. X. Fernandes, P. Glarborg, H. Hashemi, X. He, S. Mashruk, J. McGowan, C. Mounaim-Rouselle, A. Ortiz-Prado, A. Ortiz-Valera, I. Rossetti, B. Shu, M. Yehia, H. Xiao, and M. Costa, A review on ammonia as a potential fuel: from synthesis to economics,, *Energy & Fuels,* DOI: 10.1021/acs.energyfuels.0c03685
- Pele R., Hespel C., Brequigny P., Belettre J., Mounaïm-Rousselle C. First study on ammonia spray characteristics with current injector of GDI engines, submitted Special Issue in MDPI - Fuels: “Advances in Propulsion and Energy Systems Utilising Alternative Fuels: Fuel Injection and Combustion Systems”, submitted
- Mounaïm-Rousselle C., Mercier A., Brequigny P., Dumand C., Bouriot J., Houillé S., Performance of Ammonia fuel in the case of Spark Assisted Compression Ignition engine, Special issue on the current and future use of H2 and H2 based e-fuels in combustion engines and fuel cells, International Journal of Engine Research, in process

Ammonia with H_2

- IMEP and Indicated Efficiency for mid-load



$IMEP_n \approx 7.3$ bars

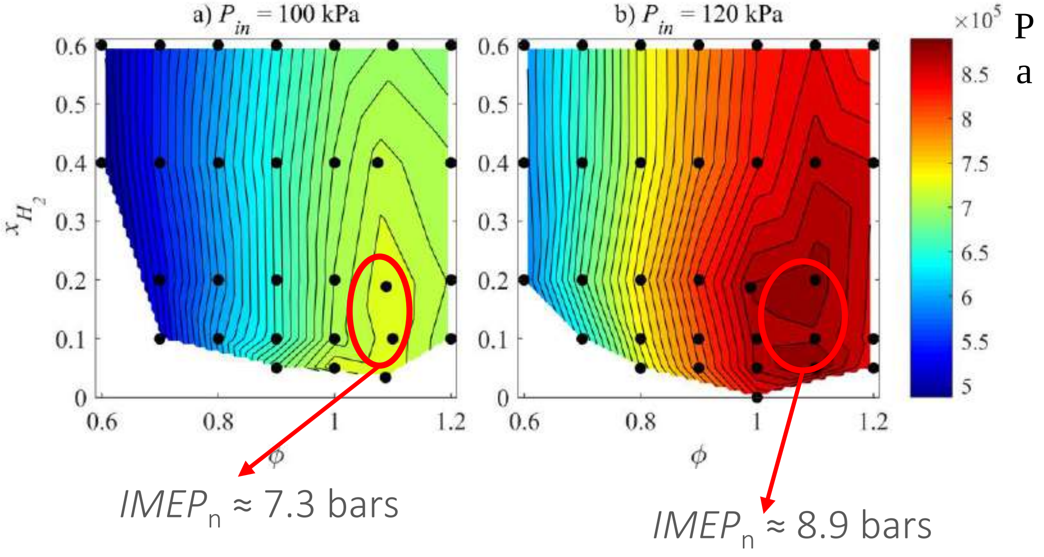
$IMEP_n \approx 8.9$ bars

- **Highest output energy**
  - with H_2 content < **20%** as Koike et al.
  - slightly rich
- Similar output energy than with **CH_4/air**, φ = 1.0
- 20% Intake Pressure increase

  = 22% IMEP increase

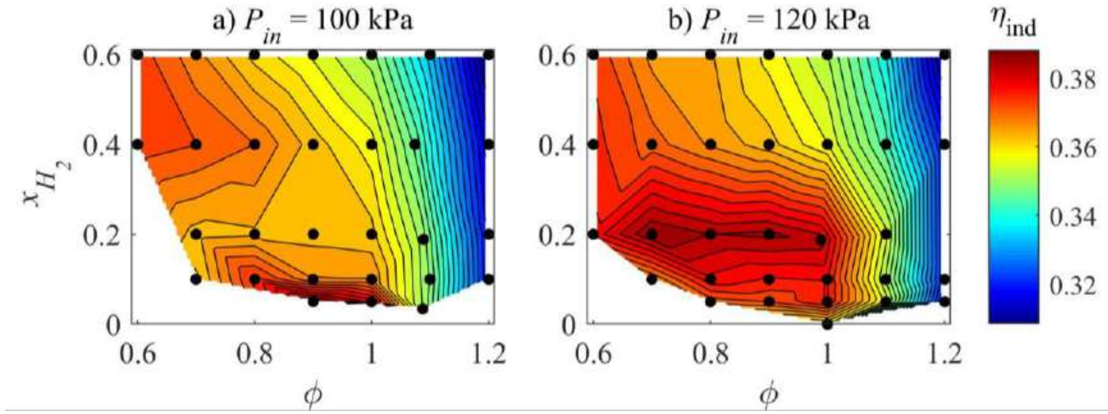
Ammonia with H_2

- IMEP and Indicated Efficiency for mid-load



- **Highest output energy**
  - with H_2 content < **20%** as Koike et al.
  - slightly rich
- Similar output energy than with **CH_4/air**, φ = 1.0
- 20% Intake Pressure increase

  = 22% IMEP increase



- **Highest efficiencies**
  - lean mixtures (no excess fuel)
  - $5\% \leq x_{H_2} \leq 20\%$
  - $\eta_{ind} \lesssim 40\ \% \rightarrow$ similar to conventional fuels