# Ammonia Combustion in spark ignition engine conditions

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# Introduction

Search for alternatives to fossil fuels

Oxygenated fuels, biodiesel and **hydrogen** have been put forward

**BUT :** Implementing a global hydrogen-based economy is at present a non-feasible approach unless a suitable storage medium can be found

⇨ use of ammonia in a modified spark ignition engine ( = hydrogen vector )

⇩

The successful application of ammonia as an alternative transportation fuel should be grounded on a detailed understanding of its combustion characteristics

# Outline

- Combustion at low pressure
- Burning velocity
- Combustion in a spark ignition engine

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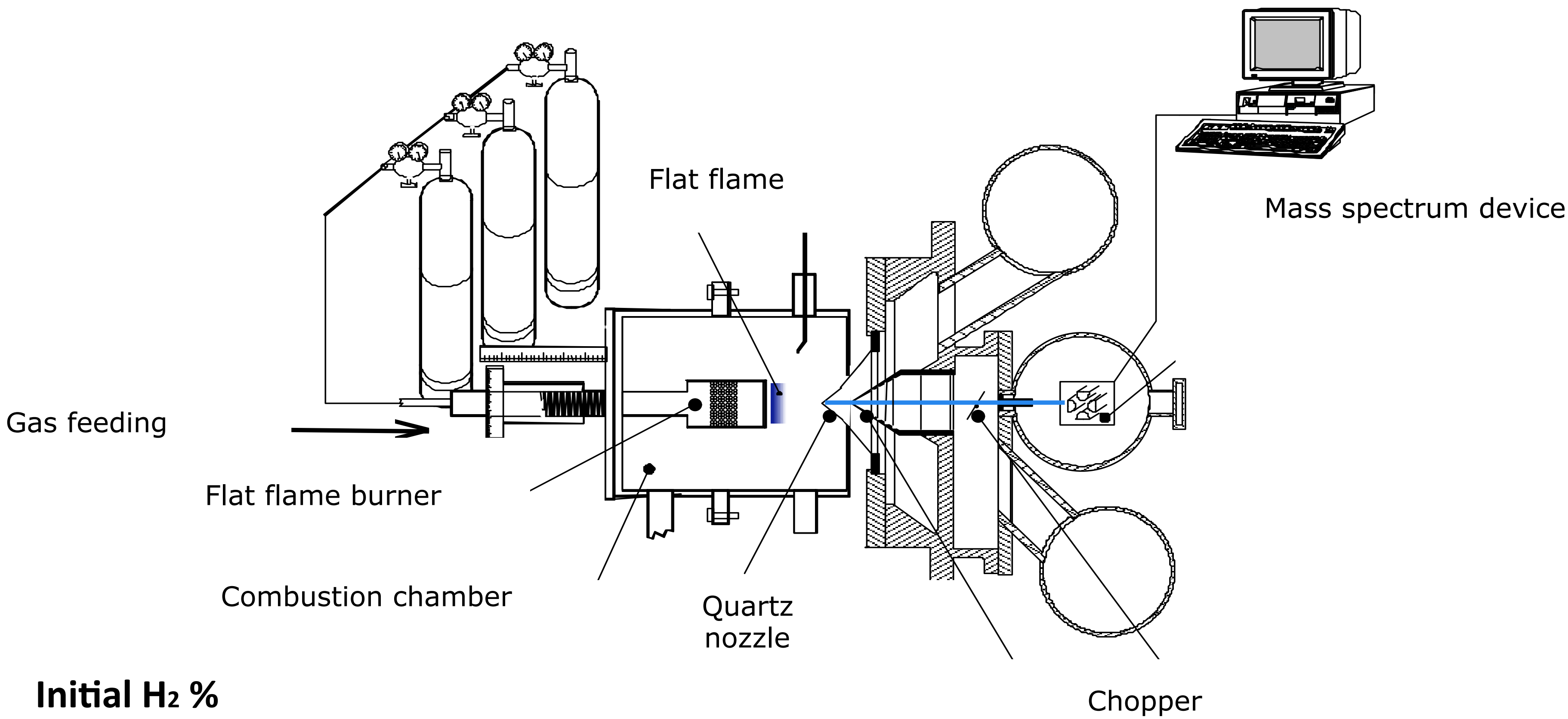
# Combustion at low pressure

Kinetic mechanisms used to simulate ammonia combustion are originated from hydrocarbon models taking into account nitrogenated species

Elaborate a new mechanism more specific for ammonia and validated at several conditions of pressure, temperature and equivalence ratio

⇨ Flame structures at low pressure

# Experimental device

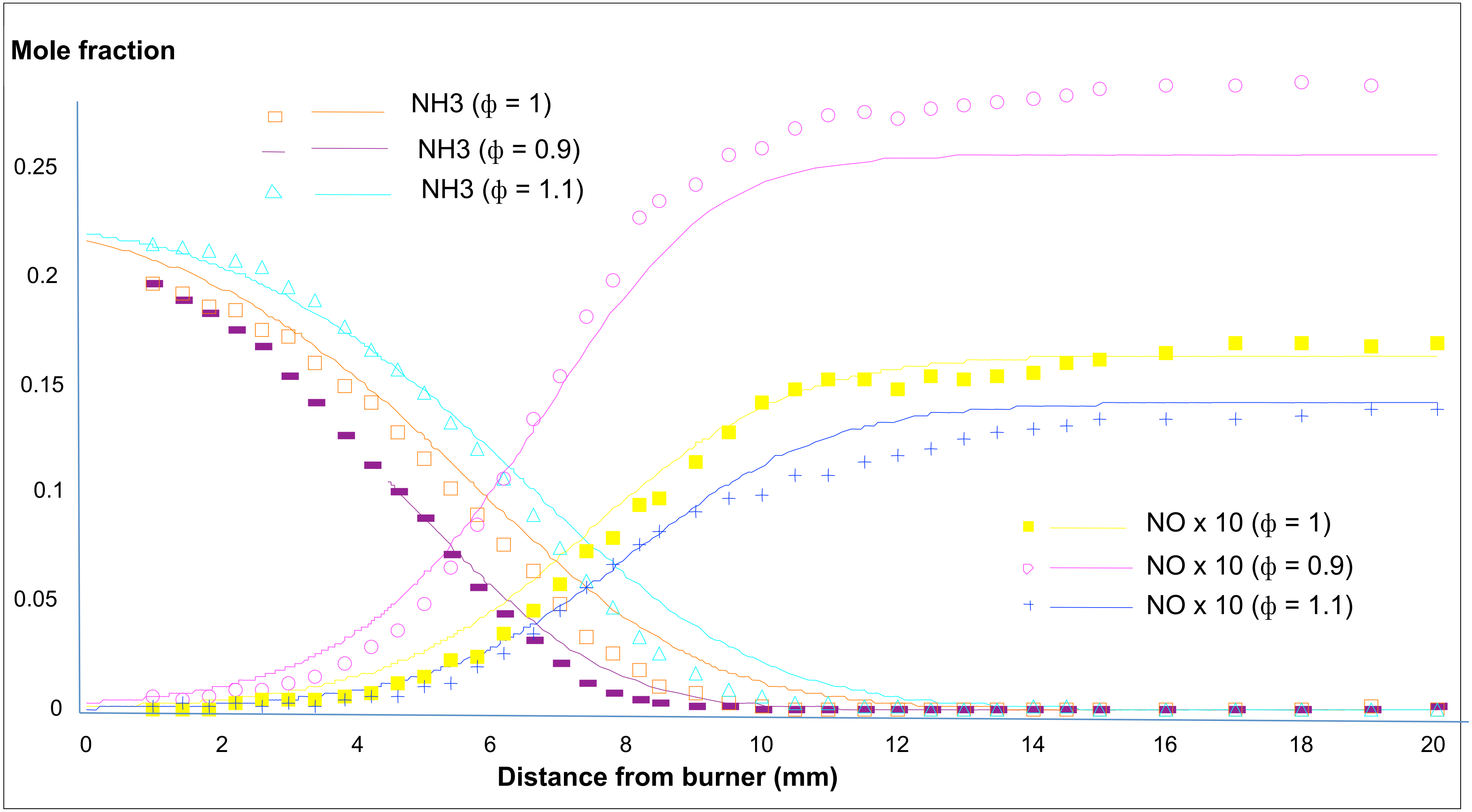



**Initial $H_2$ %**

**Equivalence Ratio**

**Pressure**

# Flame structure

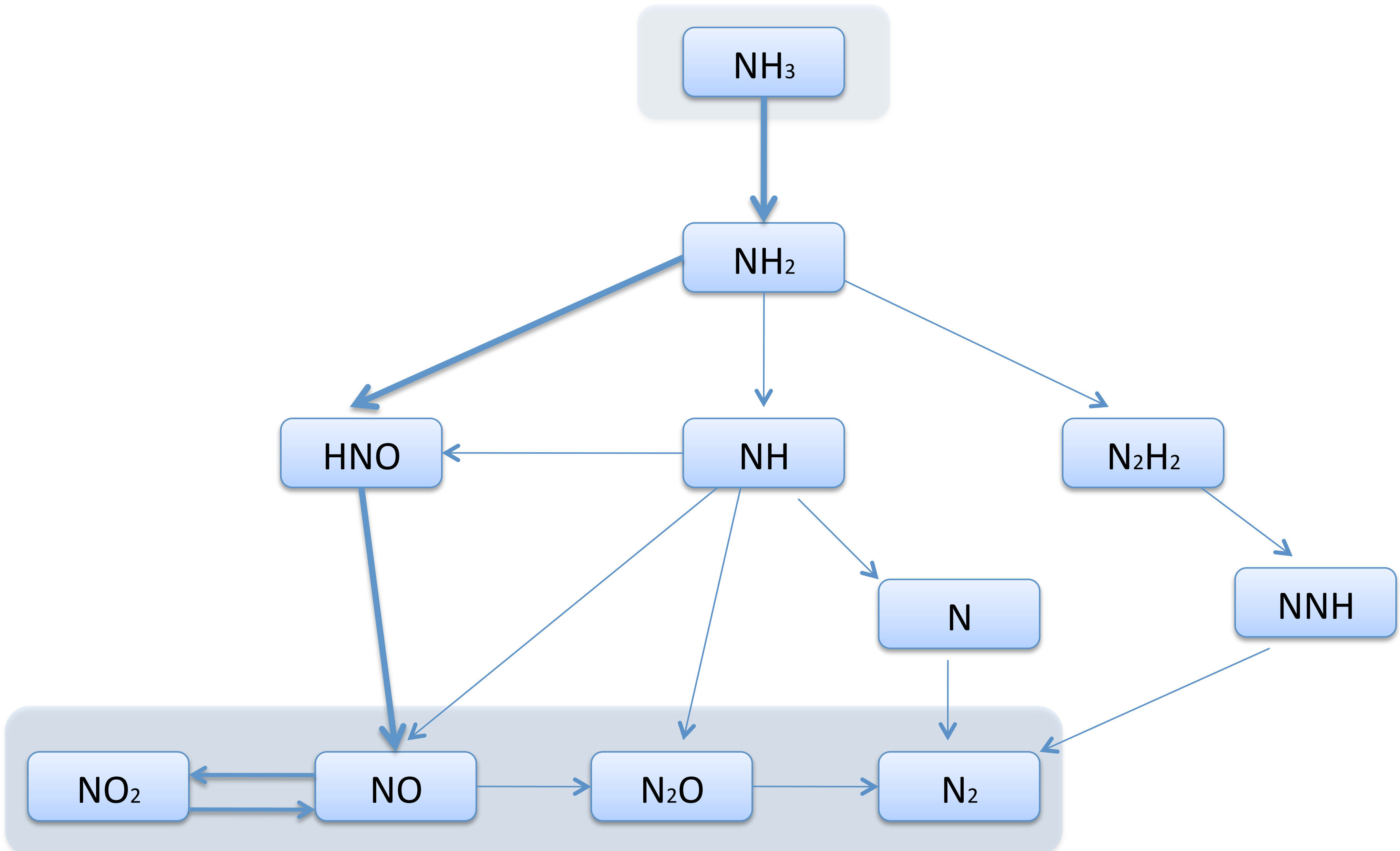



Symbols : Experience

Lines : Numerical simulation

# Reaction pathways

80 reactions
19 chemical species



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# Burning velocity

Ignition of the mixture at the open end of a tube and propagation of the flame toward the closed end.

Burning velocity obtained from the equation of mass conservation for the unburnt gas

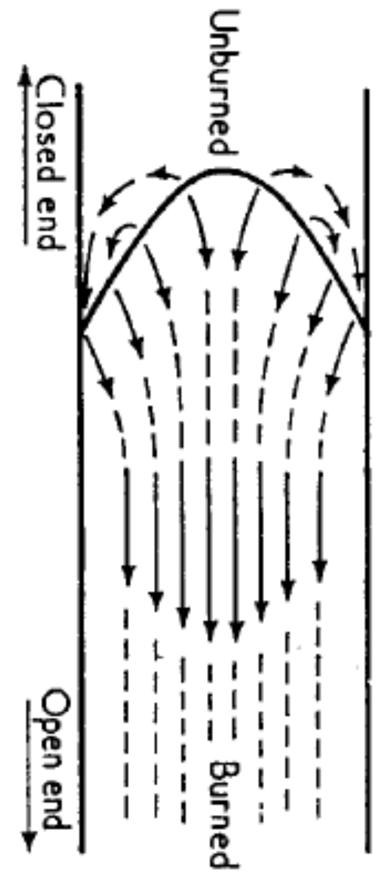
$$S_u = \frac{a}{A_f} S_s$$

a = area of tube section

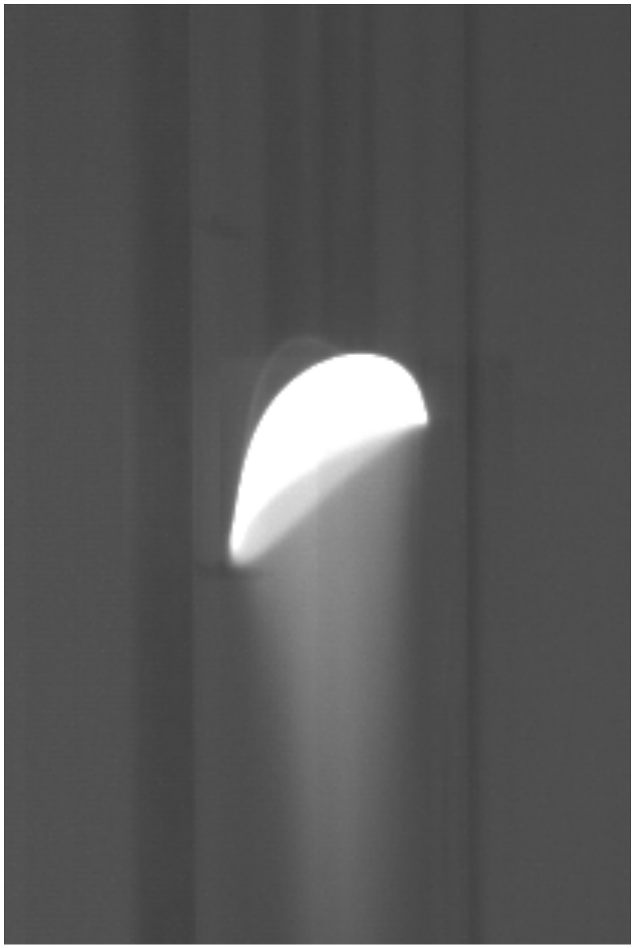
$A_f$ = area of flame surface

$S_s$ = flame speed

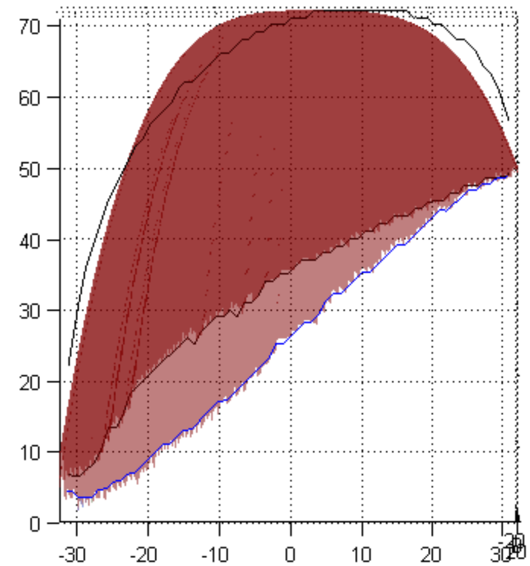
$S_u$= laminar burning velocity



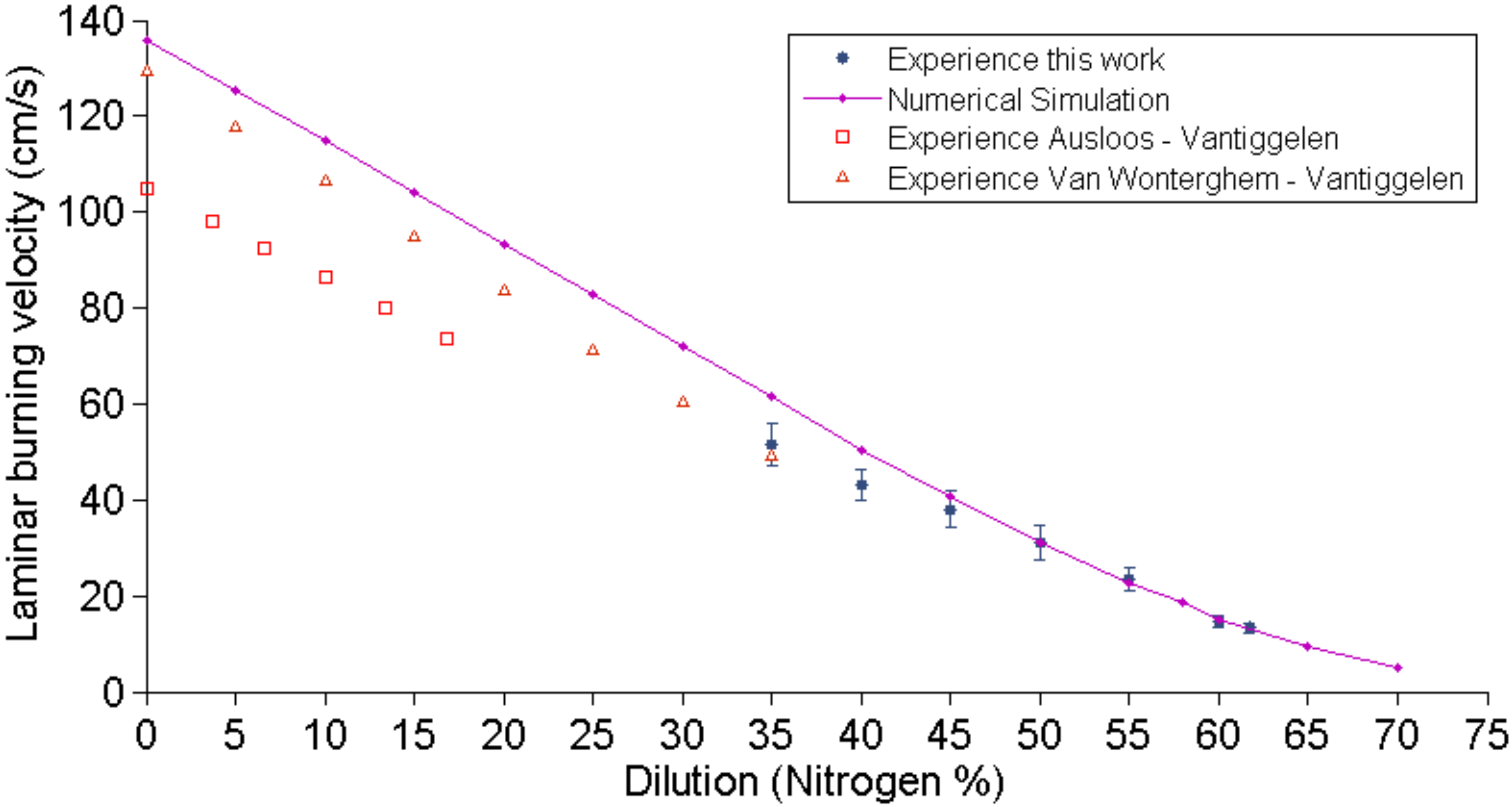
Experimental measure



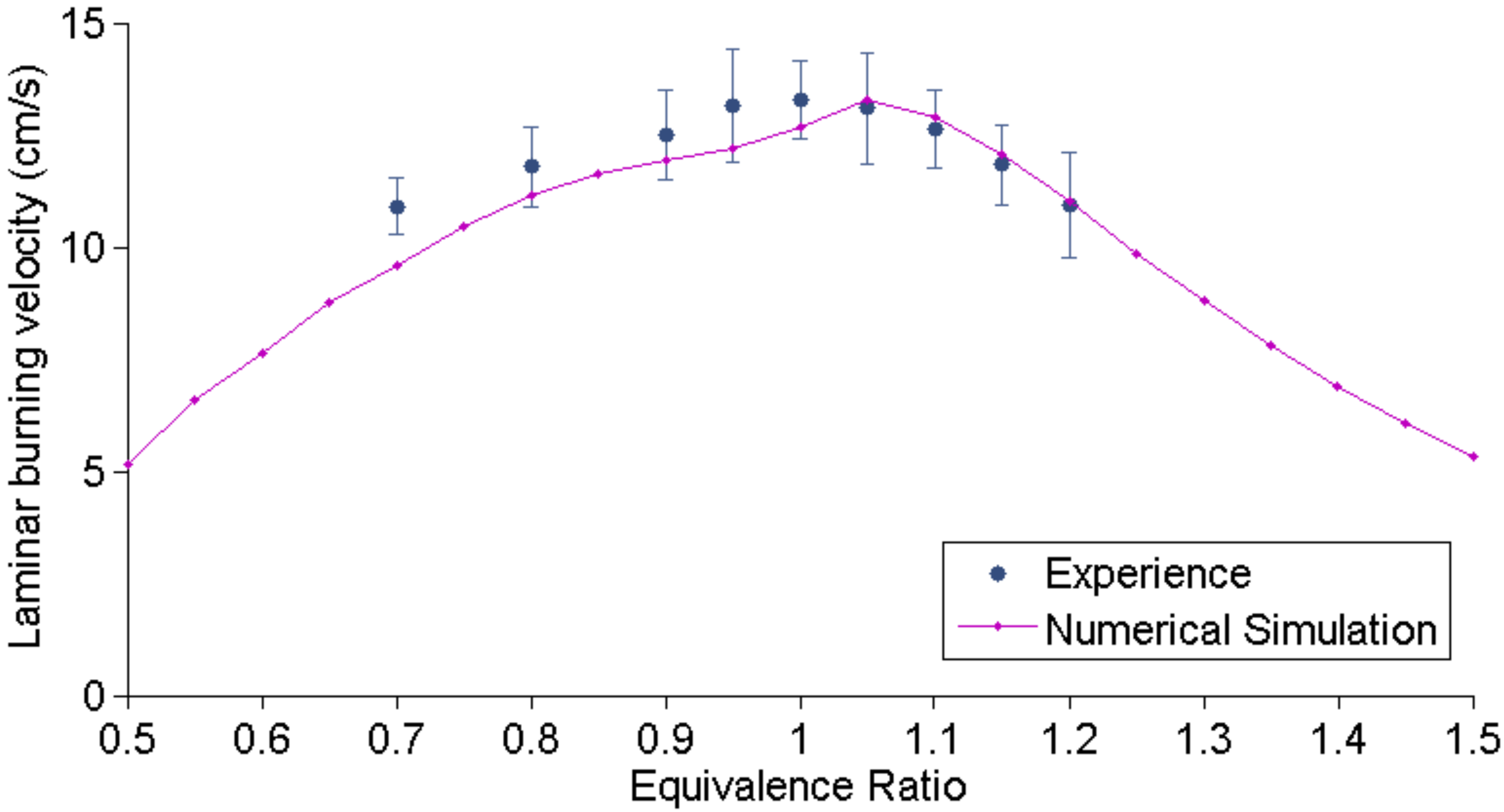
Numerical reconstitution



# Effect of dilution variation



# Effect of equivalence ratio variation



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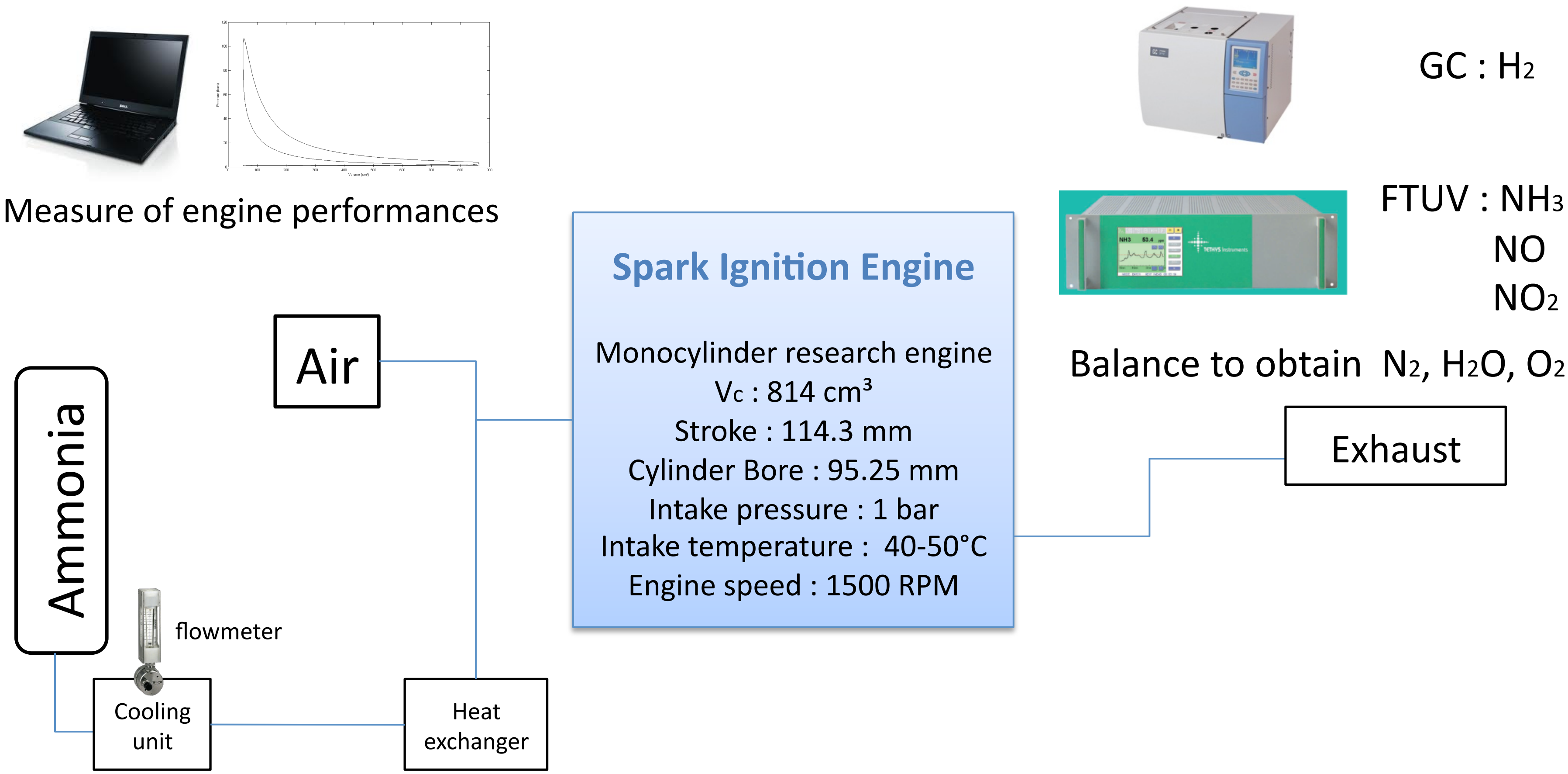
# Experimental device




Study of the impact of spark advance, compression ratio, equivalence ratio on the engine performances and on the exhaust gases

# Effect of a CR Variation

Ammonia has a high octane rating (≈ 130)

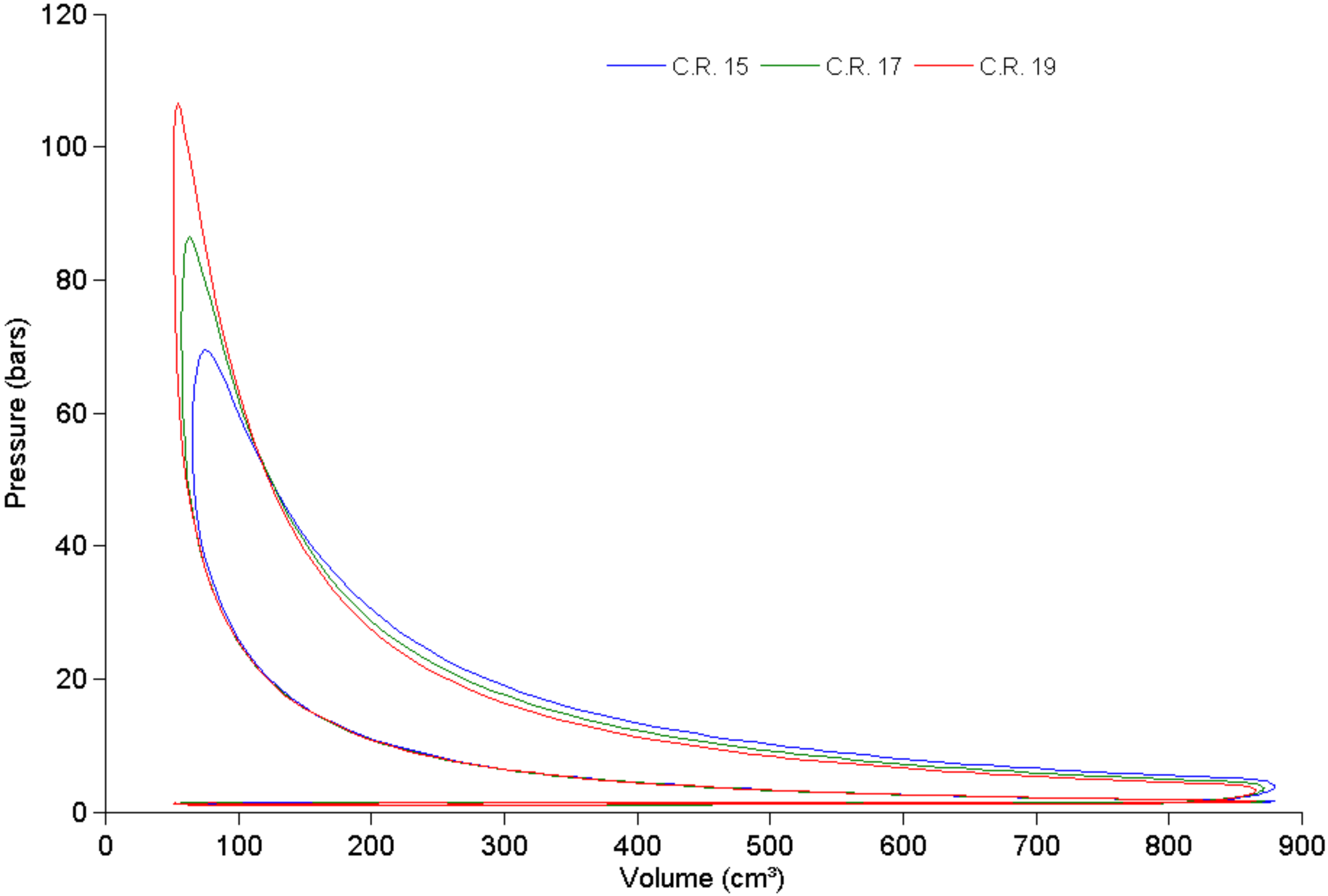
High CR can be applied to improve engine performances

Experimental conditions:

| | |
|---|---|
| Compression ratios<br>15 ; 17 and 19<br><br>(19 = max engine capacities ; 15 =minimum to allow correct $NH_3$ combustion) | Spark advance : 30° BTDC |
| | Equivalence ratio : 1 |

| C.R. | Torque [Nm] | RPM | bmep [kPa] | η eff |
| --- | --- | --- | --- | --- |
| 15 | 56 | 1490 | 858 | 0.37 |
| 17 | 57 | 1540 | 880 | 0.39 |
| 19 | 58 | 1500 | 895 | 0.40 |

| C.R. | $N_2$ (%) | $H_2O$ (%) | $O_2$ (%) | $NH_3$ (%) | NO (ppm) | $NO_2$ (ppm) | $H_2$ (ppm) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 15 | 69.1 | 28.7 | 1.55 | 1.69 | 547 | 0 | 6666 |
| 17 | 68.9 | 28.3 | 1.74 | 1.99 | 441 | 0 | 6557 |
| 19 | 68.8 | 27.9 | 1.94 | 2.31 | 375 | 0 | 6195 |



C.R. 15
C.R. 17
C.R. 19
Pressure (bars)
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
Volume (cm³)

# Effect of a spark advance variation

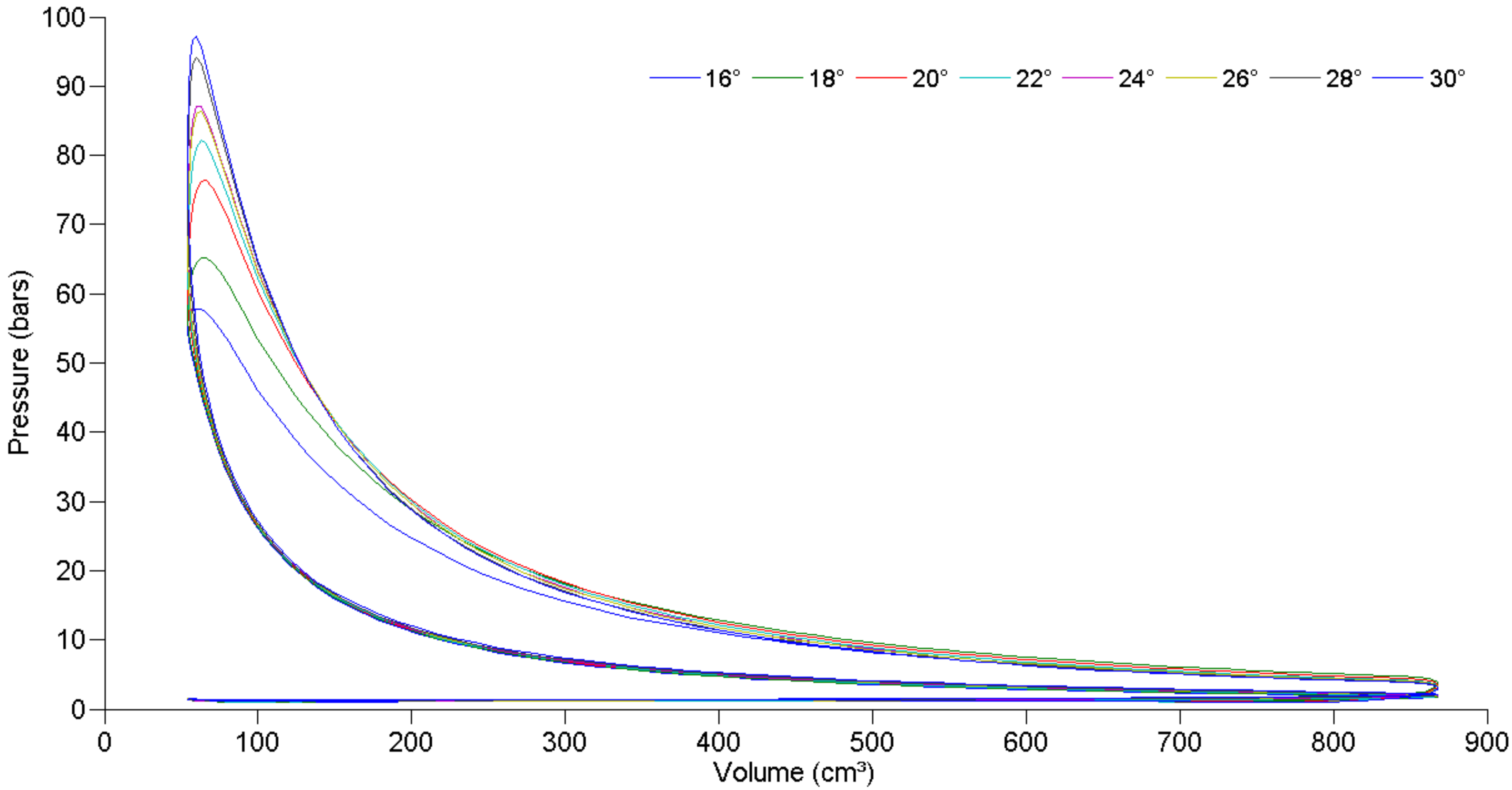
Ammonia flame has a low speed
High spark advances must be applied to keep engine performances

Experimental conditions:

| | |
|---|---|
| Spark advance from 16° to 30° (30° = max to avoid knocking ; 16° =minimum to allow correct $NH_3$ combustion) | Compression ratio : 18 |
| | Equivalence ratio : 1 |

| Spark advance [°] | Torque [Nm] | RPM | bmep [kPa] | η eff |
|---|---|---|---|---|
| 16 | 40.00 | 1456 | 618 | 0.26 |
| 18 | 51.83 | 1510 | 800 | 0.34 |
| 20 | 53.5 | 1508 | 826 | 0.36 |
| 22 | 53.5 | 1513 | 826 | 0.36 |
| 24 | 53.5 | 1517 | 826 | 0.36 |
| 26 | 53.69 | 1512 | 829 | 0.36 |
| 28 | 54.00 | 1508 | 834 | 0.36 |
| 30 | 54.00 | 1500 | 834 | 0.36 |

| Spark advance [°] | $N_2$ (%) | $H_2O$ (%) | $O_2$ (%) | $NH_3$ (%) | NO (ppm) | $NO_2$ (ppm) | $H_2$ (ppm) |
|---|---|---|---|---|---|---|---|
| 16 | 67.9 | 25.7 | 2.97 | 3.84 | 406 | 0 | 10498 |
| 18 | 69.0 | 28.5 | 1.60 | 1.80 | 438 | 0 | 10523 |
| 20 | 69.0 | 28.4 | 1.69 | 1.79 | 536 | 0 | 7676 |
| 22 | 69.0 | 28.4 | 1.70 | 1.91 | 599 | 0 | 4802 |
| 24 | 69.0 | 28.2 | 1.81 | 1.98 | 597 | 0 | 6427 |
| 26 | 68.9 | 27.8 | 1.98 | 2.11 | 538 | 0 | 8976 |
| 28 | 68.8 | 28.1 | 1.84 | 2.24 | 430 | 0 | 4925 |
| 30 | 68.8 | 27.7 | 2.06 | 2.35 | 430 | 0 | 6286 |



100
90
80
70
60
50
40
30
20
10
0
Pressure (bars)
16°
18°
20°
22°
24°
26°
28°
30°
0
100
200
300
400
500
600
700
800
900
Volume (cm³)

# Effect of an equivalence ratio variation

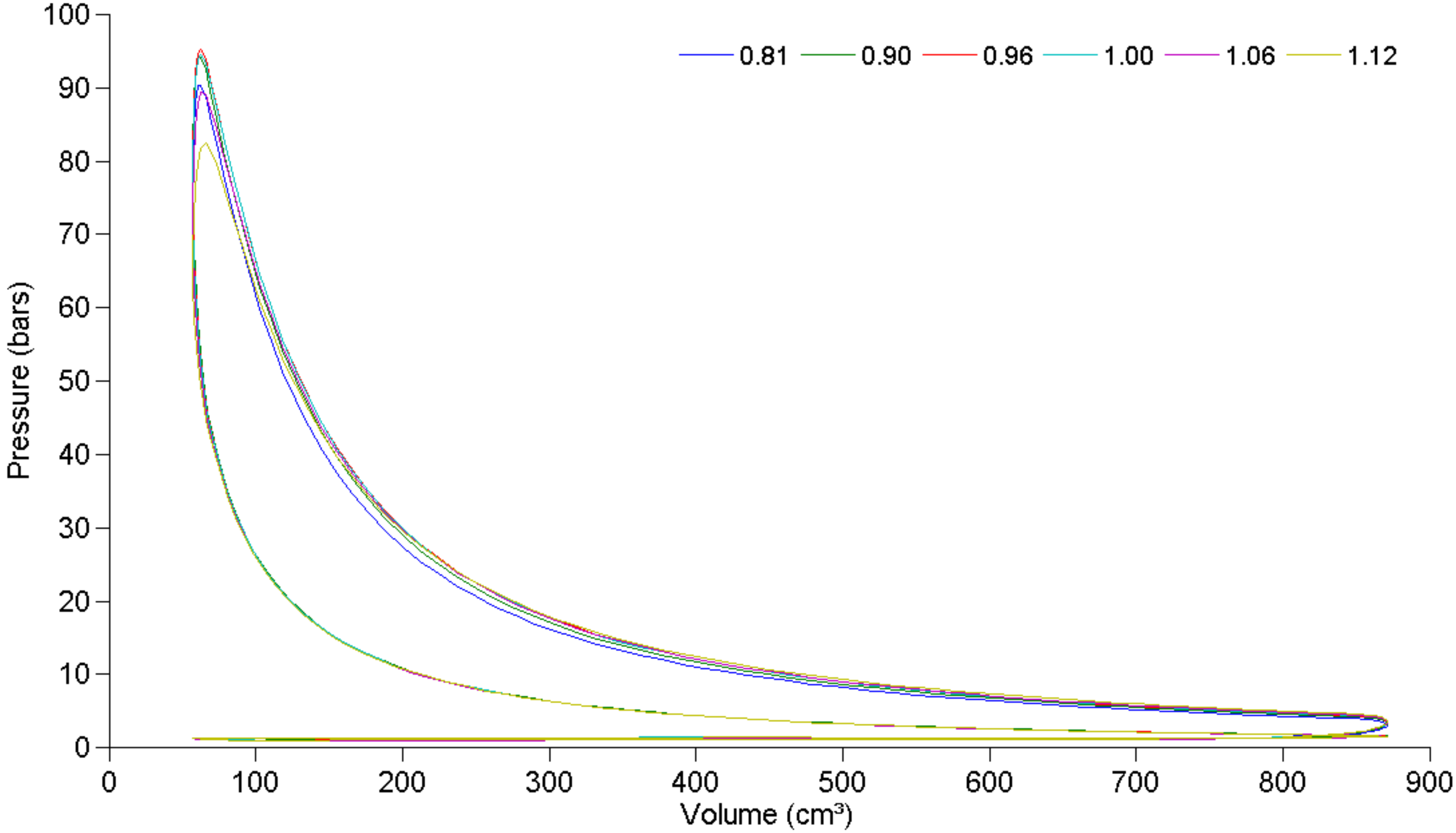
Important impact of $\phi$ on the $NO_x$ formation
especially around stoichiometric conditions

Experimental conditions:

| | |
|---|---|
| Equivalence ratios from 0.8 to 1.1<br>(Flammability limits at STP from 0.6 to 1.3) | Spark advance : 30° BTDC |
| | Compression ratio : 17 |

| $\phi$ | Torque [Nm] | RPM | bmep [kPa] | $\eta$ eff |
|---|---|---|---|---|
| 0.81 | 52 | 1445 | 803 | 0.42 |
| 0.90 | 56 | 1529 | 865 | 0.42 |
| 0.96 | 59 | 1552 | 911 | 0.42 |
| 1.00 | 59 | 1554 | 911 | 0.41 |
| 1.06 | 59 | 1519 | 904 | 0.38 |
| 1.12 | 58 | 1506 | 895 | 0.36 |

| $\Phi$ | $N_2$ (%) | $H_2O$ (%) | $O_2$ (%) | $NH_3$ (%) | NO (ppm) | $NO_2$ (ppm) | $H_2$ (ppm) |
|---|---|---|---|---|---|---|---|
| 0.81 | 69.9 | 24.3 | 4.33 | 1.71 | 2736 | 2 | 40 |
| 0.90 | 69.5 | 26.8 | 2.78 | 1.69 | 1732 | 2 | 299 |
| 0.96 | 69.3 | 28.0 | 2.02 | 1.64 | 805 | 97 | 2265 |
| 1.00 | 69.0 | 28.5 | 1.64 | 1.75 | 363 | 80 | 8407 |
| 1.06 | 68.7 | 29.8 | 0.77 | 1.86 | 217 | 0 | 7728 |
| 1.12 | 68.3 | 30.0 | 0.49 | 2.10 | 81 | 0 | 16389 |


0.81
0.90
0.96
1.00
1.06
1.12
Pressure (bars)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
Volume (cm³)

# Conclusion

Ammonia combustion characteristics

Important impact of the equivalence ratio on the nitrogen oxides formation

Ammonia flame has a low speed

Optimal SI engine combustion conditions

Compression ratio : 17
Spark advance : 20° BTDC
Equivalence ratio : slightly above 1

# Thank You