Development of new combustion strategy for internal combustion engine fueled by pure ammonia

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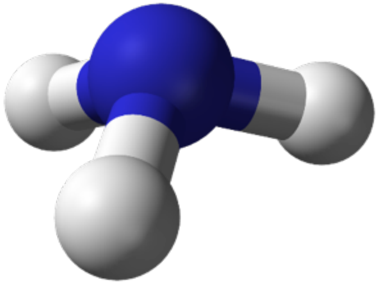
Ammonia as an energy storage medium

Ammonia (NH_3)



- 1.5 times more hydrogen per molecule than H_2
- Carbon-free – no CO, CO_2, UHC, soot and etc.
- Liquid phase @ 25 ℃, 10 bar → Good storability & transportability

As an energy storage medium

- Energy conversion device is necessary

  : internal combustion engine, turbine, fuel-cell …

  - One of the most widely used energy conversion device
  - More cost-effective than other devices

Limitation of previous study

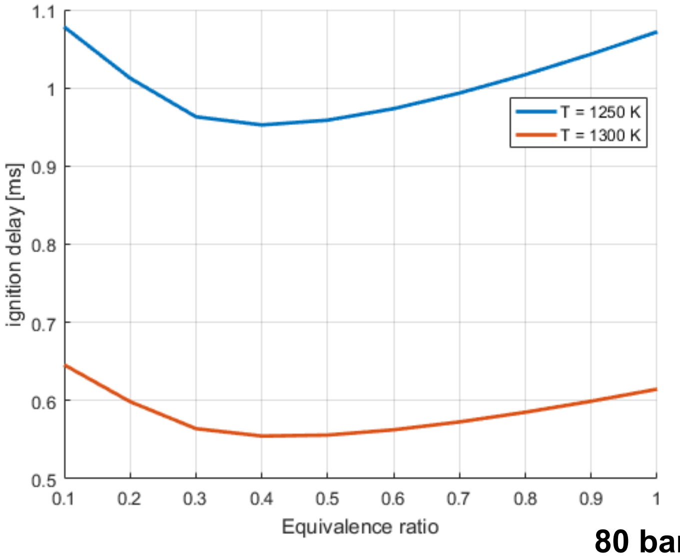
- Use of combustion promotor – diesel, DME, gasoline…
- Energy conversion device fueled ONLY by ammonia is essential to use ammonia as an energy storage medium
- Without combustion promotor…? possible… but, EXTREME Temperature & CR

Objectives

- Development of new combustion strategy operating only with ammonia

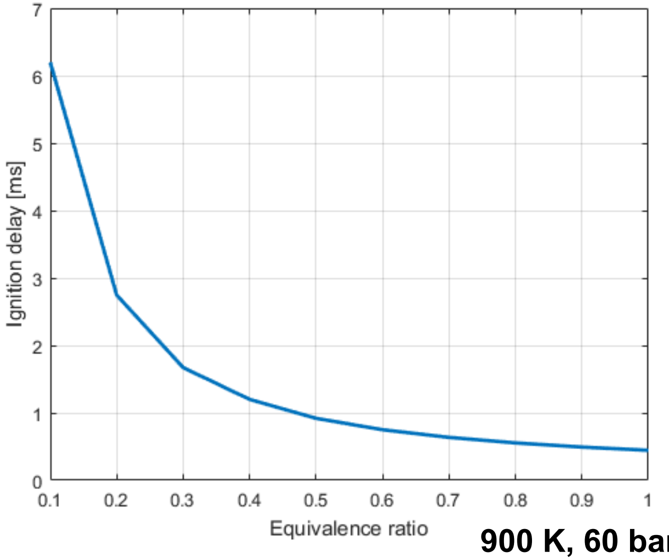
Ignition delay characteristics of ammonia

Ammonia



80 bar

n-heptane



900 K, 60 bar

NH_3 + **0.75**(O_2 + 3.76N_2)

X_{O_2} (ϕ=1.0)=16.4%

X_{O_2} (ϕ=0.1)=20.4%

×**1.24**

C_7H_{16} + 11(O_2 + 3.76N_2)

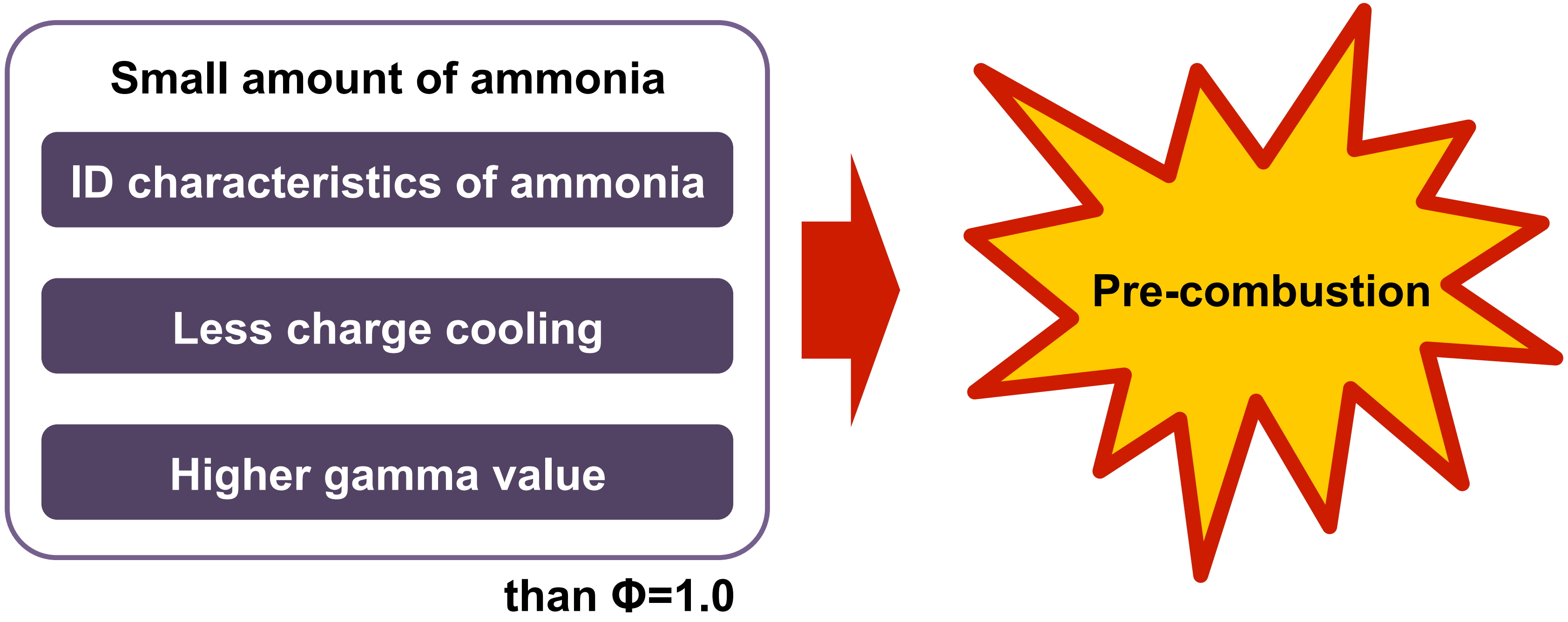
X_{O_2} (ϕ=1.0)=20.6%

X_{O_2} (ϕ=0.1)=21.0%

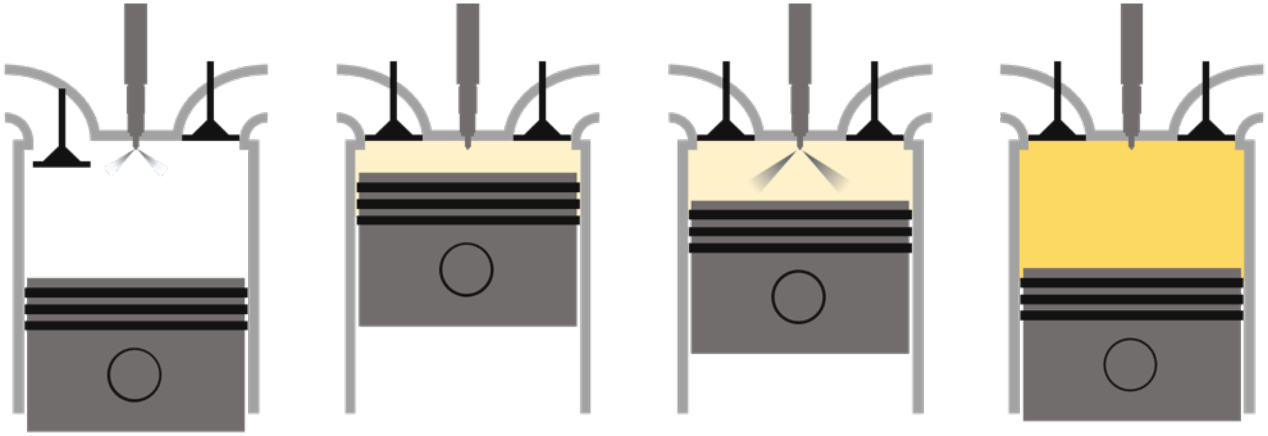
Characteristics of ammonia combustion

Ammonia as a combustion promotor

- Pre-combustion of lean ammonia-air mixture during compression stroke
- Pilot injection during intake process can make well-mixed lean ammonia-air mixture



New combustion strategy for ammonia



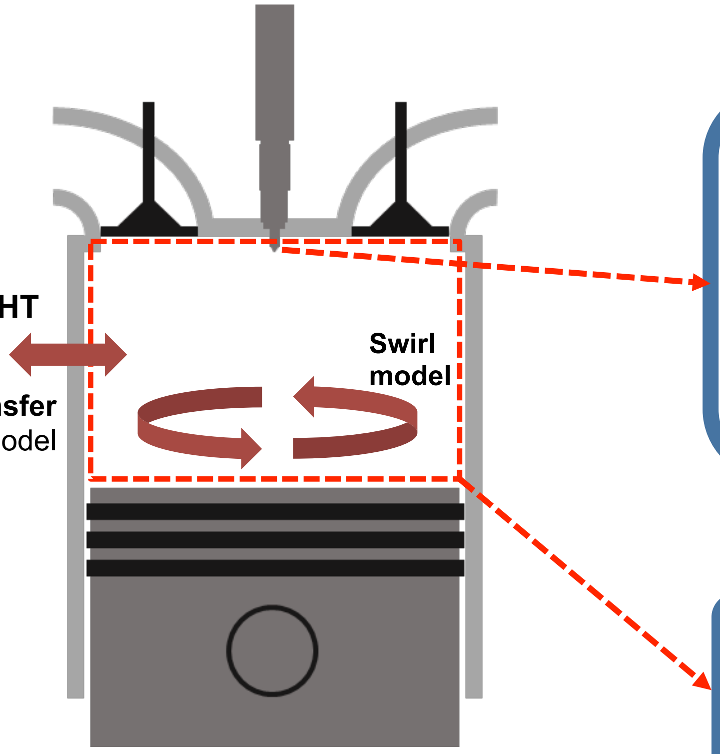
1. Pilot injection of ammonia during intake process
2. Auto-ignition of ammonia-air mixture formed during compression stroke
3. Ammonia main injection into the cylinder whose temperature and pressure are raised high enough to burn an ammonia spray
4. Work is extracted by an expansion of in-cylinder gas

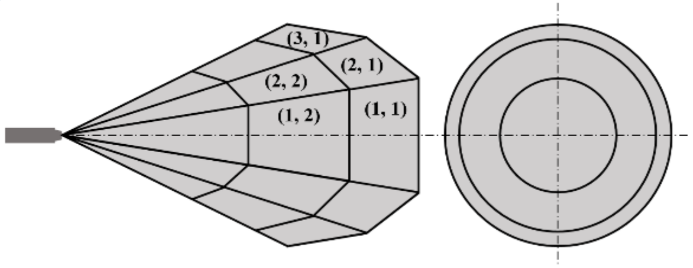
Model type selection

0-dimensional model	Quasi-dimensional model	multi-dimensional model (CFD)
Empirical heat release mo del	Empirical model + physical sub-model	Momentum conservation + turbulent flow + physical sub-model
Detailed chemical reaction mechanism	Detailed chemical reaction mechanism or chemical reaction sub-model	Chemical reaction sub-model
Low accuracy	Moderate accuracy and cost	High accuracy & high time cost

- Use of detailed chemical reaction mechanism (sensitive pre-combustion timing)
- Consideration of physical characteristics of spray
- Compensation of time cost by using Q-D model

Quasi-dimensional simulation model





Packet spray model

Energy conservation

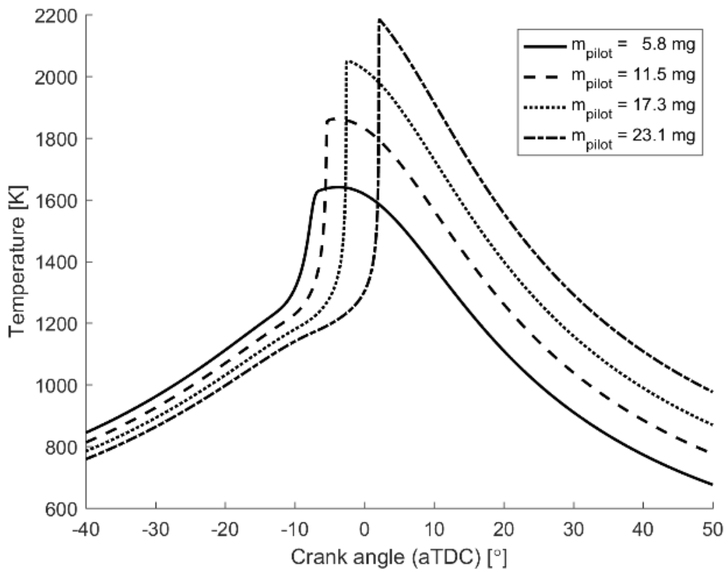
Chemical reaction model
: Ammonia detailed chemical reaction mechanism

Engine parameters for simulation

Engine type	4-stroke
Bore	83.0 mm
Stroke	92.0 mm
Con. Rod length	145.8 mm
Compression ratio	35 : 1
RPM	1000
Injection pressure	500 bar
Intake temperature	220 ℃

- Engine specification refer to D-engine from HMC
- Undersquare engine type → Easy to implement a high CR
- GDI injector → more suitable to low viscosity of ammonia

Pre-combustion

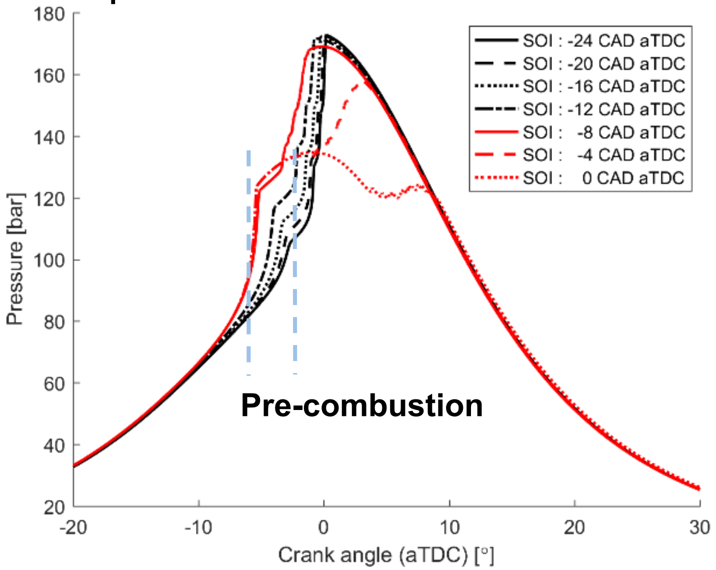


each amount of pilot injection corresponds to φ of 0.1, 0.2, 0.3, 0.4

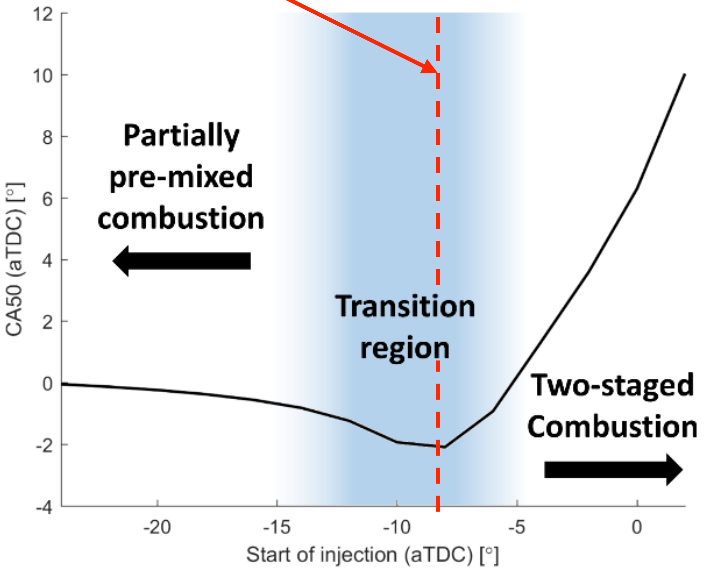
- Auto-ignition of lean ammonia-air mixture
- As the amount of pilot injection increases
  - Pre-combustion timing is retarded
  - Peak temperature increases
- There will be optimal quantity and injection timing of main spray for each pilot injection condition
- Amount of pilot injection is limited to a maximum of 17.3 mg (ϕ = 0.3) for the stability

Operation at different SOI timing

m_{pilot} = 11.5 mg, m_{main} = 11.5 mg



θ_p =crank angle where pre-combustion occurs without an influence of main injection



- SOI < θ_p

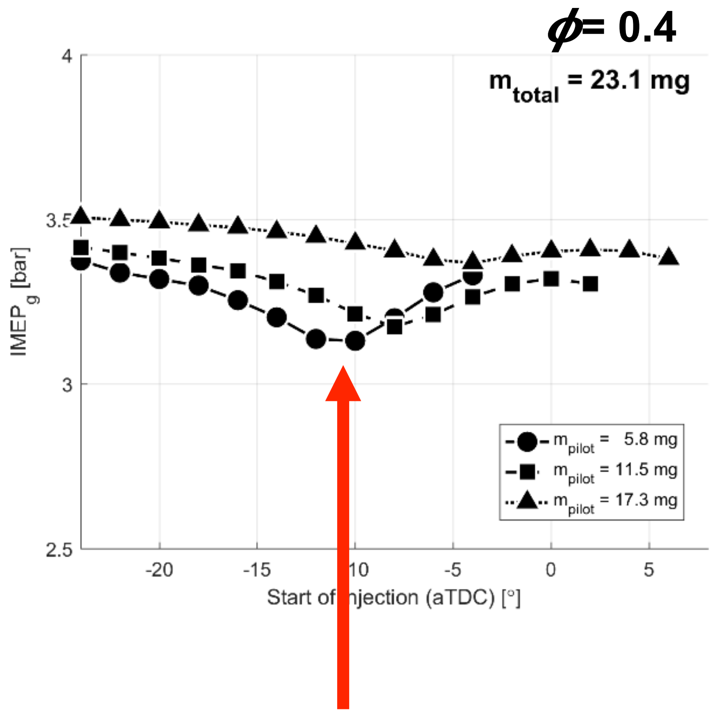
  pre-combustion is disturbed by main injection

  more advanced SOI = more disturbance → delayed spray combustion

- SOI ≥ θ_p

  two-staged combustion occurs → pre-combustion + spray combustion

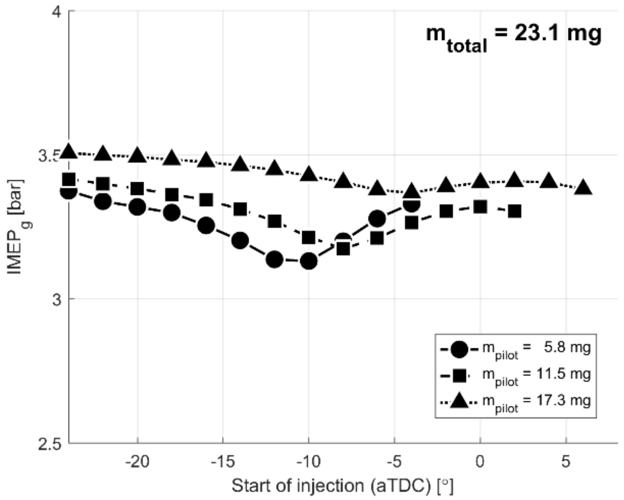
Operation at different SOI timing & m_{pilot} : m_{main}



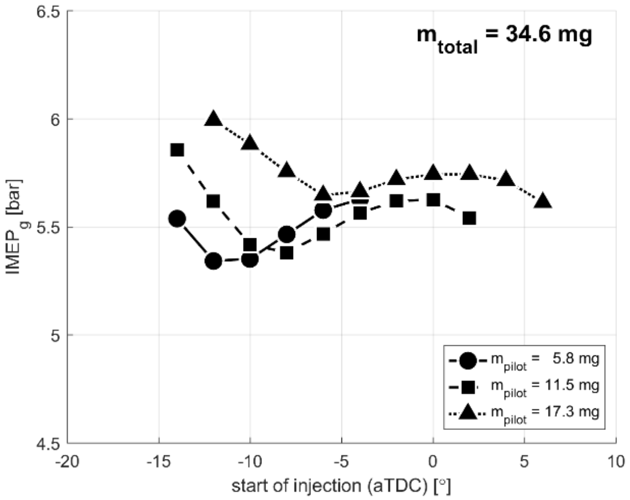
- more pilot injection = less main injection
- with increased pilot injection amount operable range decreases
- more pilot injection = delayed pre-combustion
  → decreased compression work
  → overall efficiency increases

Influence of
Increased **compression work** by pre-combustion + **heat transfer**

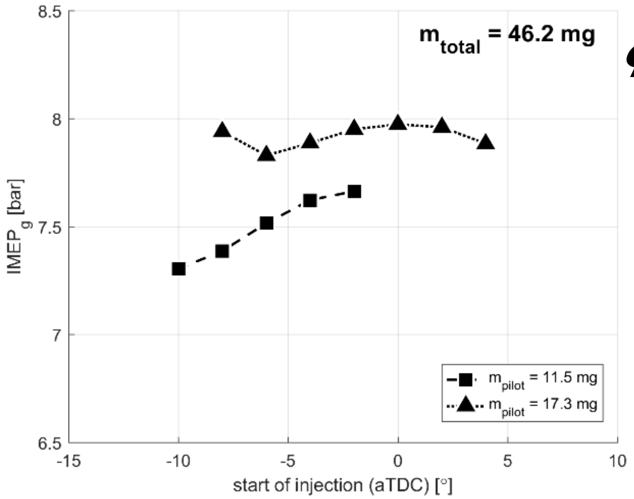
Total amount of fuel variation



ϕ= 0.4



ϕ= 0.6

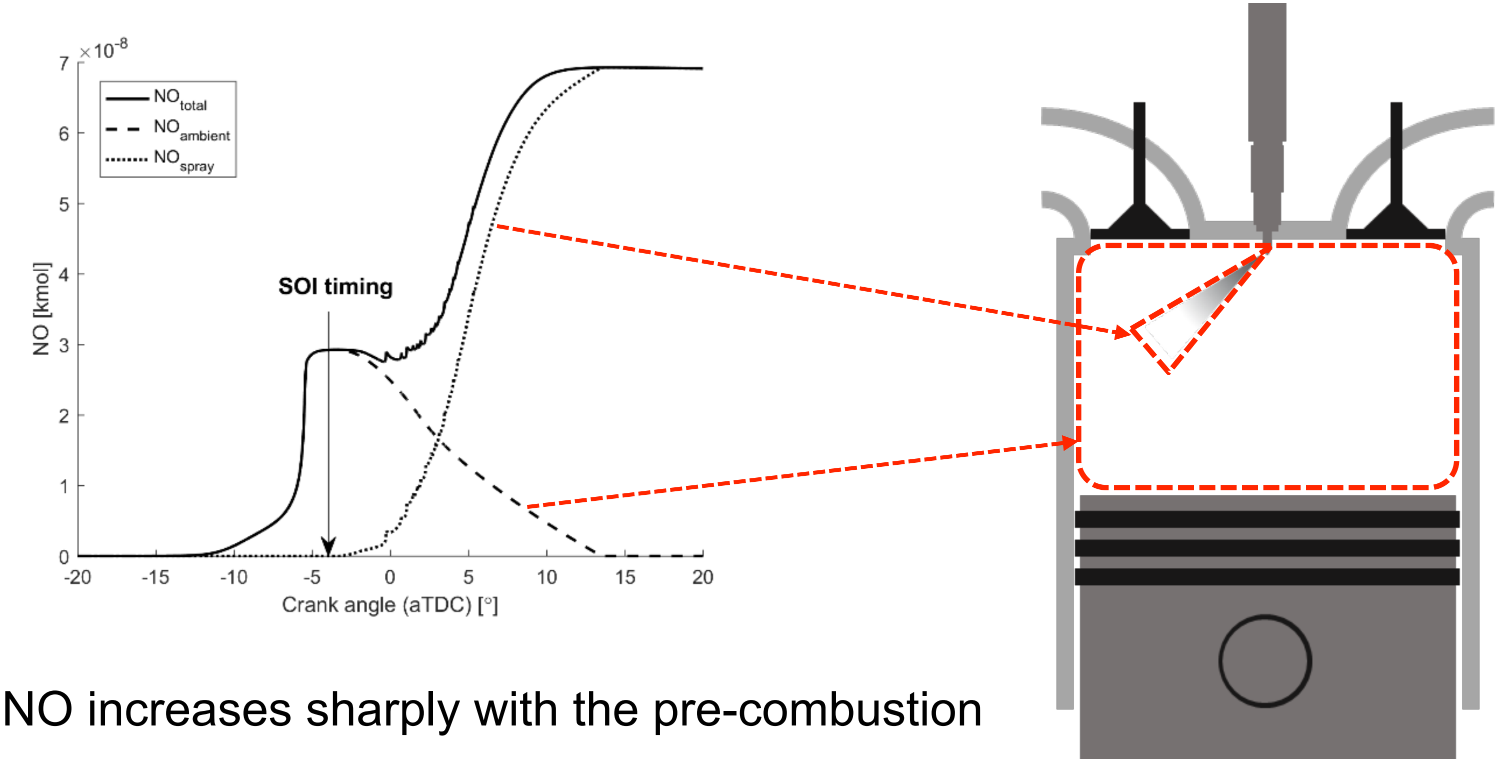


ϕ= 0.8

- total fuel amount ↑
  ➔ operable SOI range ↓
  (effect of charge cooling)

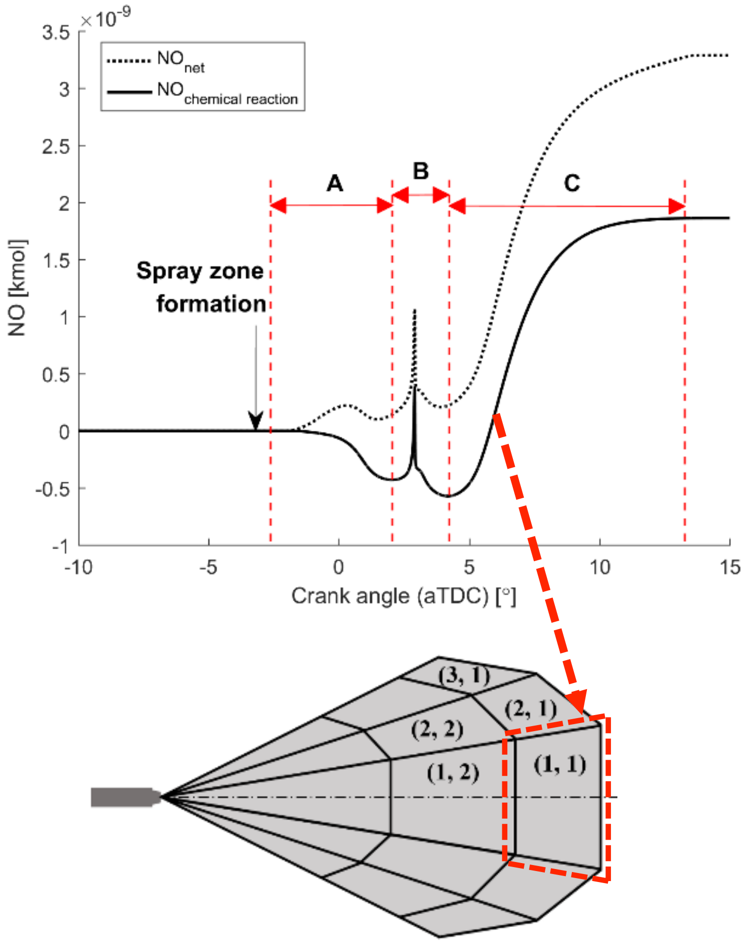
- For total fuel amount more than 46.2 mg stable operation can not be guaranteed

NO production in the ammonia engine



- NO increases sharply with the pre-combustion
- At the initial stage of main injection, NO reducti on is observed
- But, why…?

NO production in a single spray zone

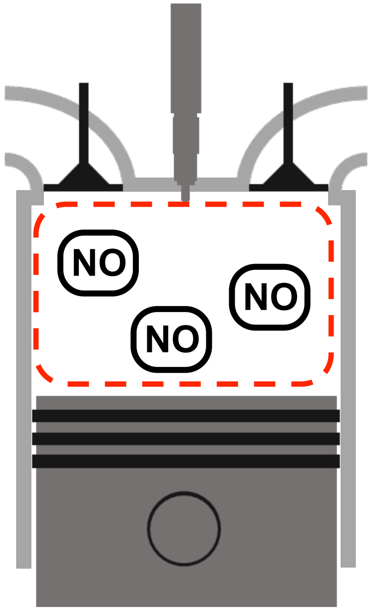


4 phases of NO production

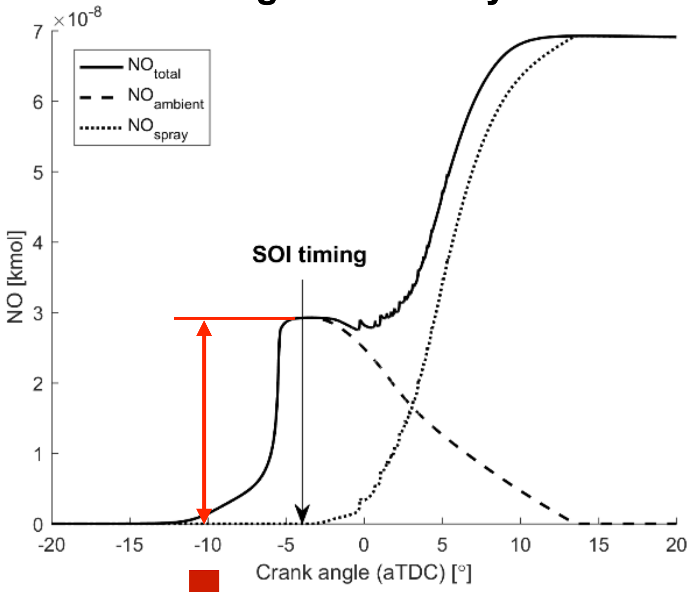
1. Pre-combustion NO phase
2. Reduction NO phase (A)
3. Combustion NO phase (B)
4. Thermal NO phase (C)

NO production in a single spray zone

Pre-combustion NO phase



NO change in entire cylinder

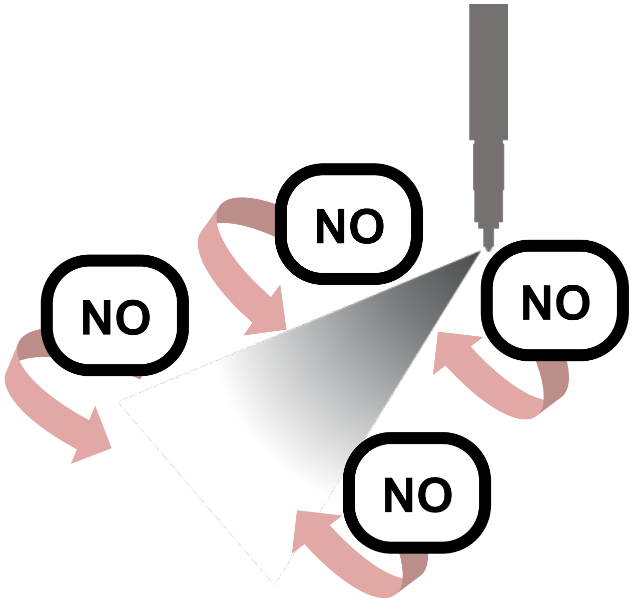


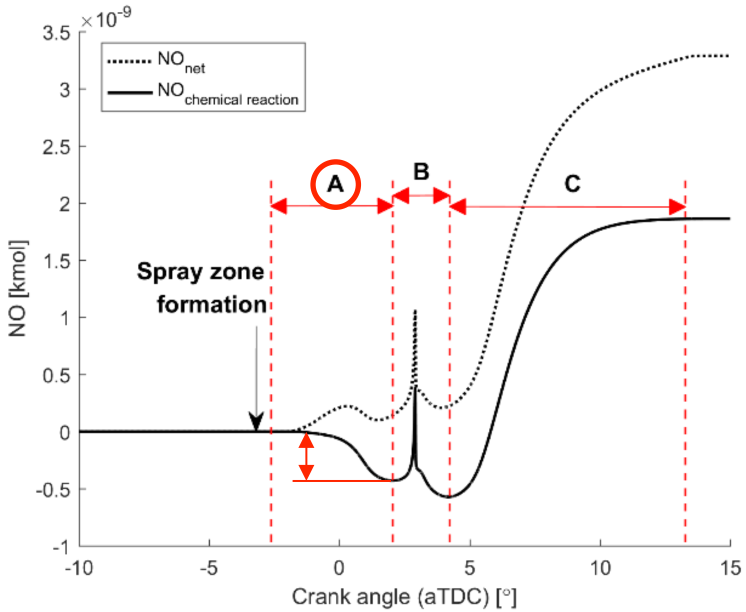
- NO production by auto-ignition of lea
n ammonia-air mixture

NO production
in Pre-combustion NO phase

NO production in a single spray zone

Reduction NO phase

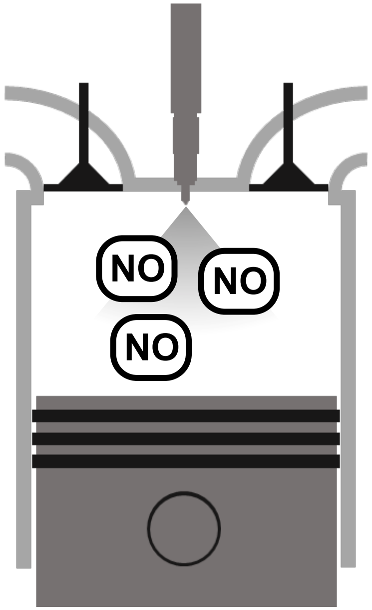


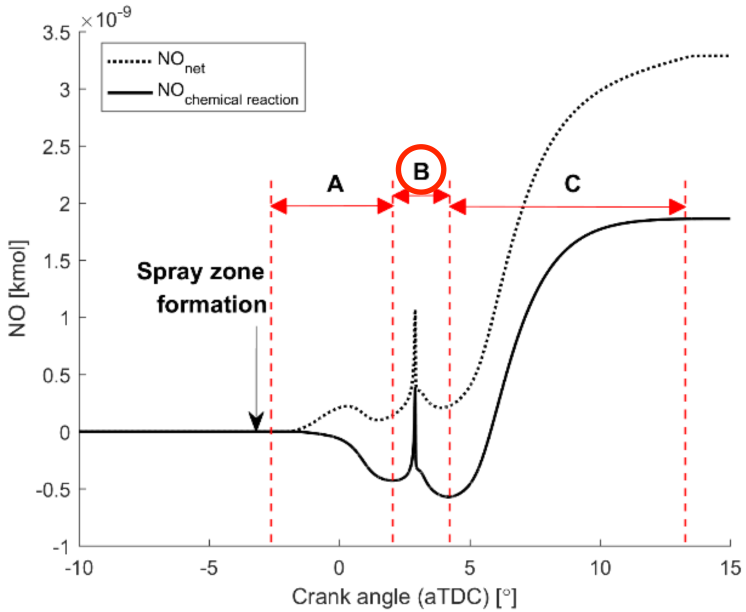


- Reduction of NO produced in Pre-co mbustion phase at early stage of spr ay formation → similar to SNCR

NO production in a single spray zone

combustion NO phase

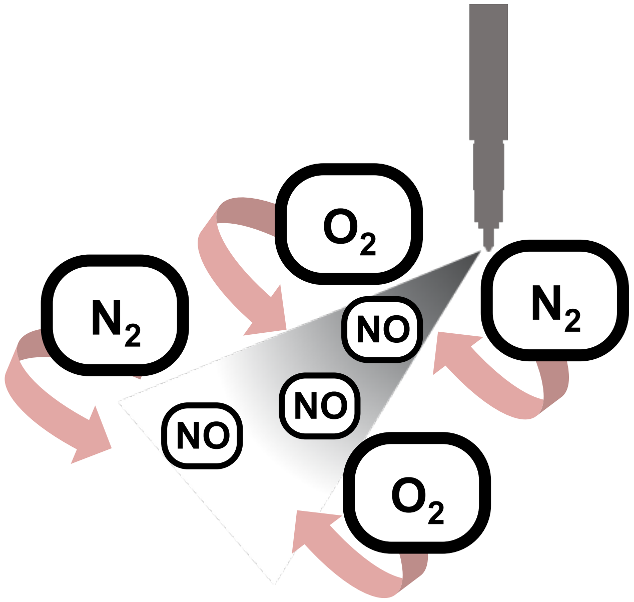


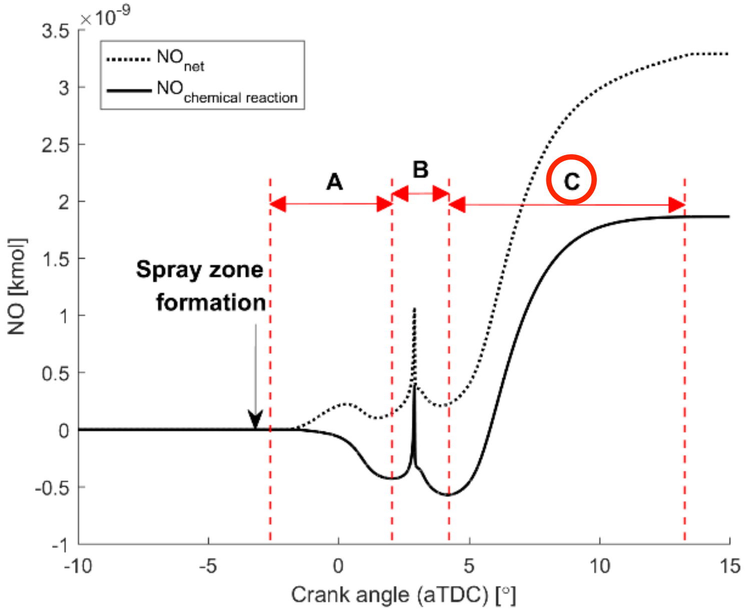


- NO production by spray combustion
- φ at the start of combustion is the mo st influential factor

NO production in a single spray zone

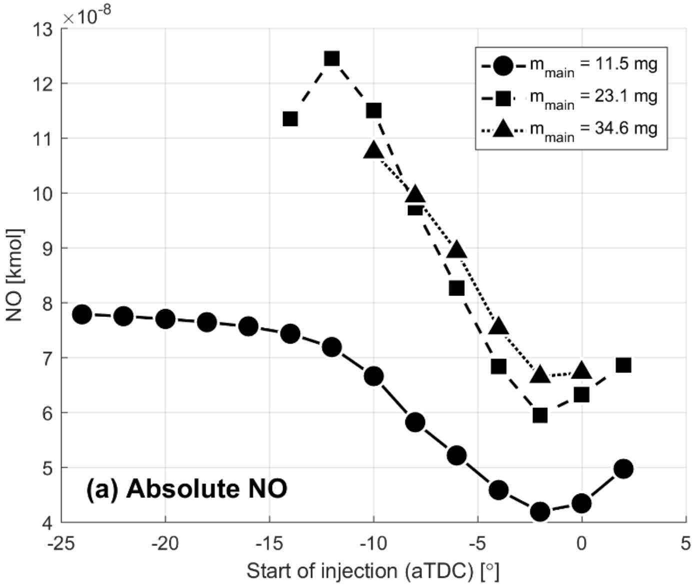
Thermal NO phase

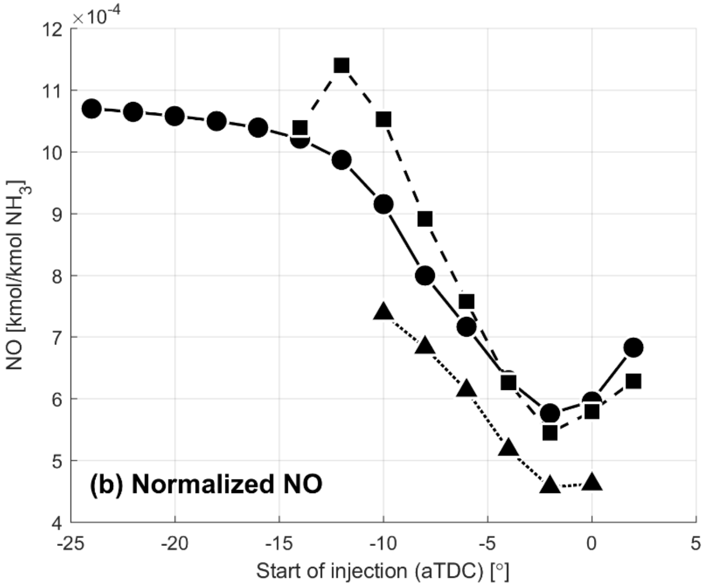




- Production of thermal NO due to high temperature after combustion
- mainly affected by peak temperature

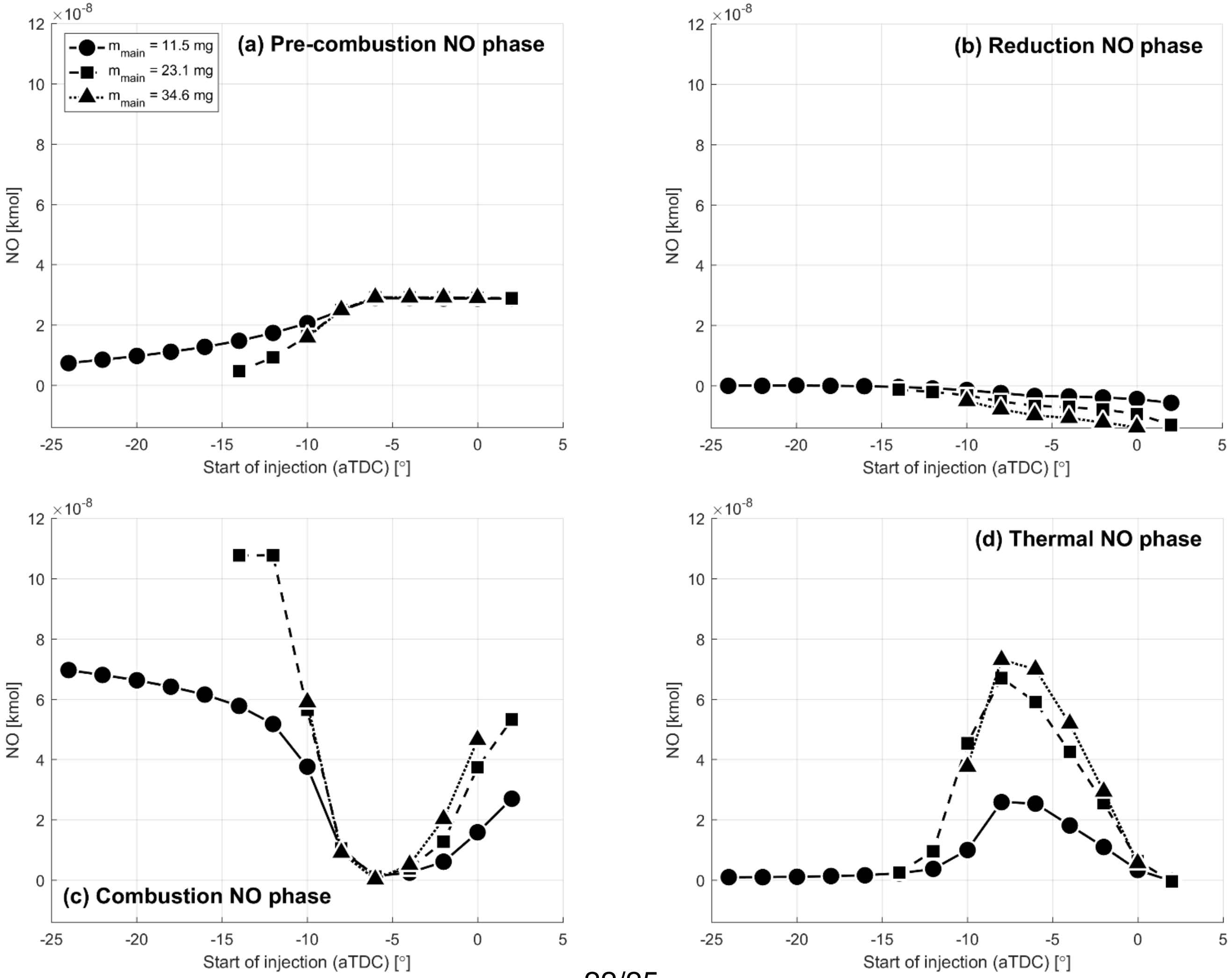
Parametric study – amount of main injection



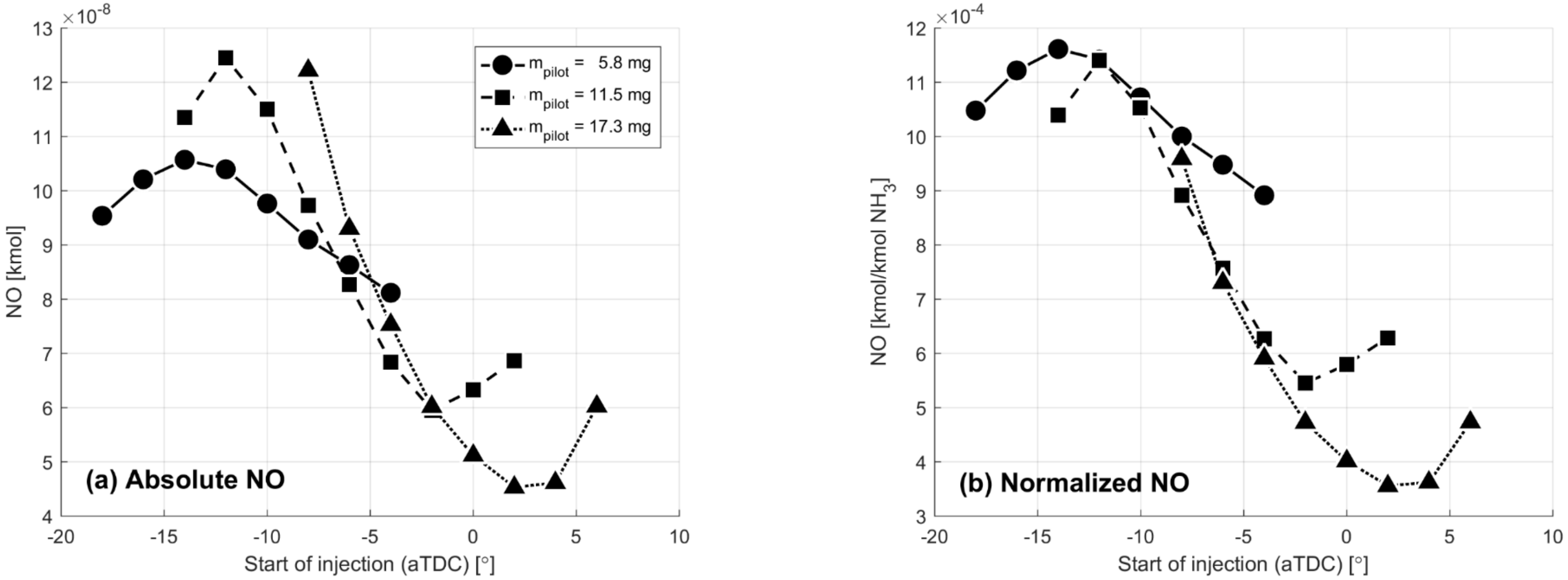


- NO decreases with delayed SOI timing
- With the largest amount of main injection, the smallest NO production can be a chieved

Parametric study – amount of main injection



Parametric study – amount of pilot injection



- Similar trend to result with main injection variation
- The smallest NO appears with the largest amount of pilot injection

Conclusion

- Combustion strategy for the engine only fueled by ammonia has bee n proposed

- Through simulation, the characteristics of engine using proposed am monia combustion strategy has been verified.

- Operable SOI timing range decreases with the increase of fuel amou nt and stable operation can not be guaranteed with the fuel amount more than the value corresponding to phi of 0.8

- NO production mechanism was analyzed by dividing the process int o 4 phases

- NO can be reduced by using more pilot injection or main injection, b ut it can causes the reduction in operable SOI timing range.

Thanks for listening!