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Part 4 Combustion Approach (Conventional?, Split cycle, Dependent → Independent)

Part 5 Answering Right Questions (Learning from tests, Achieving homogeneous cool combustion)

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Split Cycle Expander Cylinder Experiments

What have we learned so far on Titan 2-stroke HD 16.5:1?

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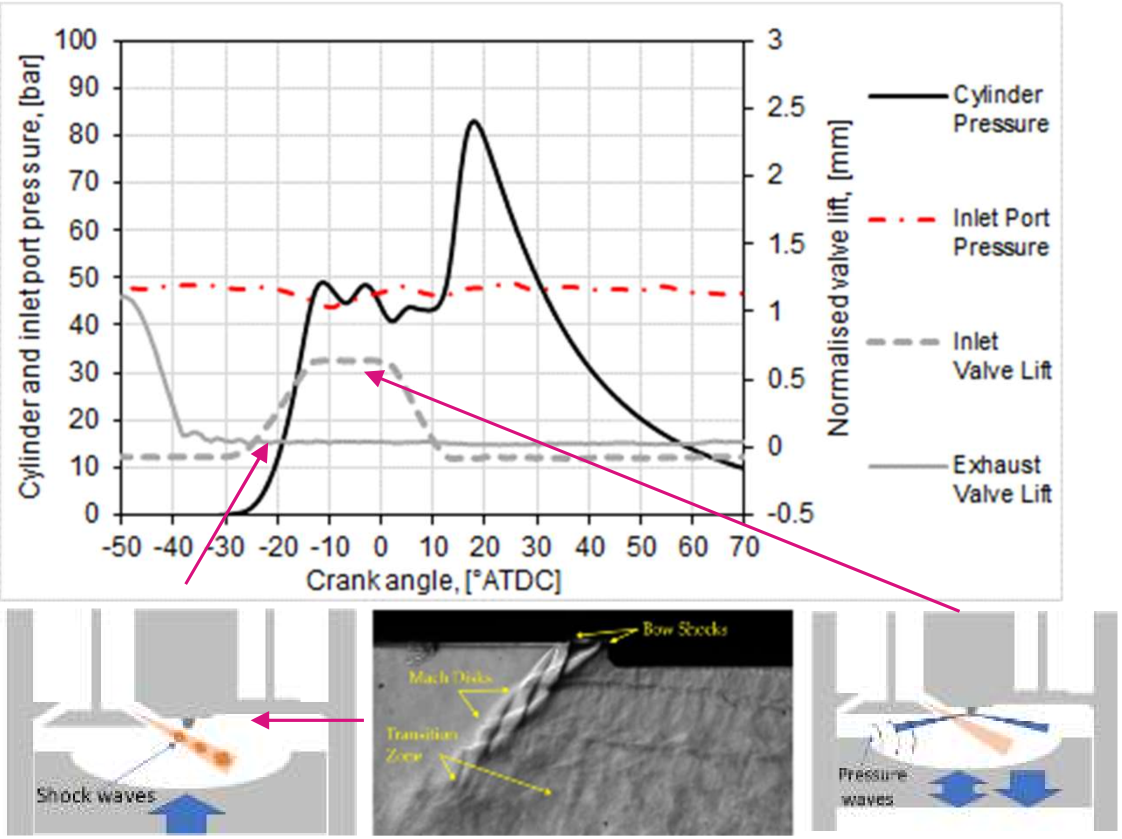
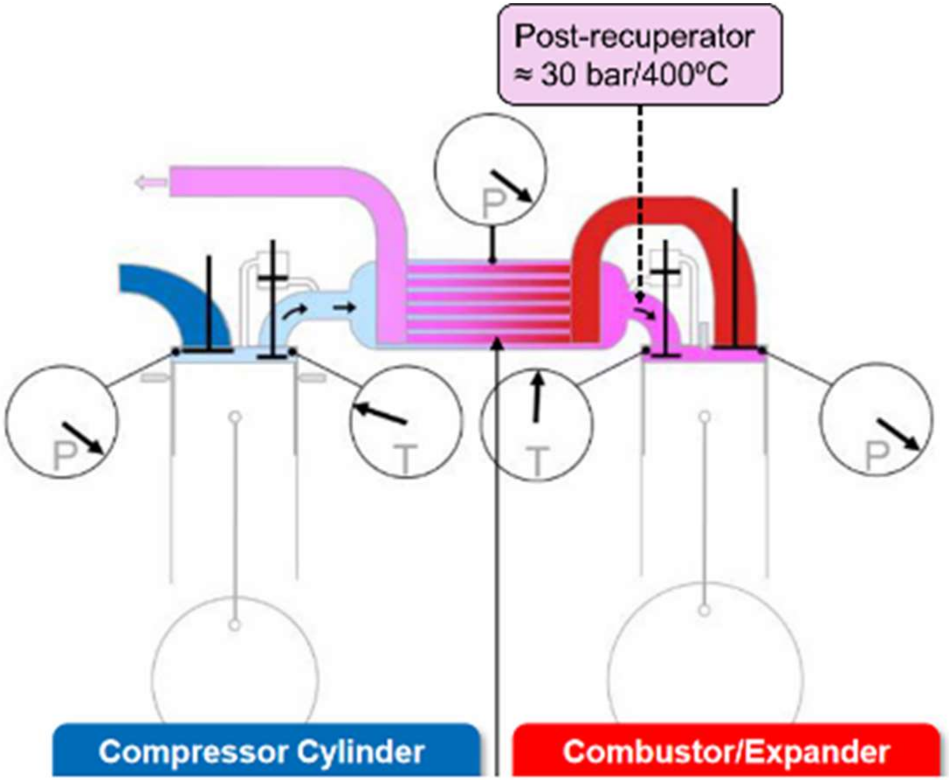


- Pressure ratio across inlet valves during start of induction is higher that critical ratio
- Cold steady state flow bench tests show shock waves in air jet
- Air jet may dissipate before the start of in cylinder fuel injection option, but conditions may remain highly turbulent
- High turbulence can improve the NH3 in-cylinder fuel-air mixing rate, combustion efficiency
- Even better if, fuel can be delivered in liquid state but consumed in gaseous state, at high pressure (Volume ↑) & temperature (Vaporisation ↑)

Answering the Right Questions

Identify & quantify the feasibility of unique benefits for gaseous NH3 homogeneous cool combustion in split cycle



- Post-recuperator temperature & pressures ≈ 30 bar/400ºC, NH3 reaches bubble point at 77ºC
- NH3 stored as liquid for maximise energy density, then port-injected post-recuperator
- Conditions enable vaporisation, near sonic flow experienced during charge induction, all this energetic mixing supports mixing conditions, development of homogeneous gaseous mixture
- Rich to lean stratified mixtures, preferential diffusion of lighter species, key to ignition, such as H2, H & OH, which can also marginally increase flame speed, compared to a homogeneous mixture

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Part 5 Answering Right Questions (Learning from tests, Achieving homogeneous cool combustion)

Part 6 Method & Chemistry (Compared CH4 & H20%, Chemkin-Pro NH3, Flammability limit)

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Method & Chemistry

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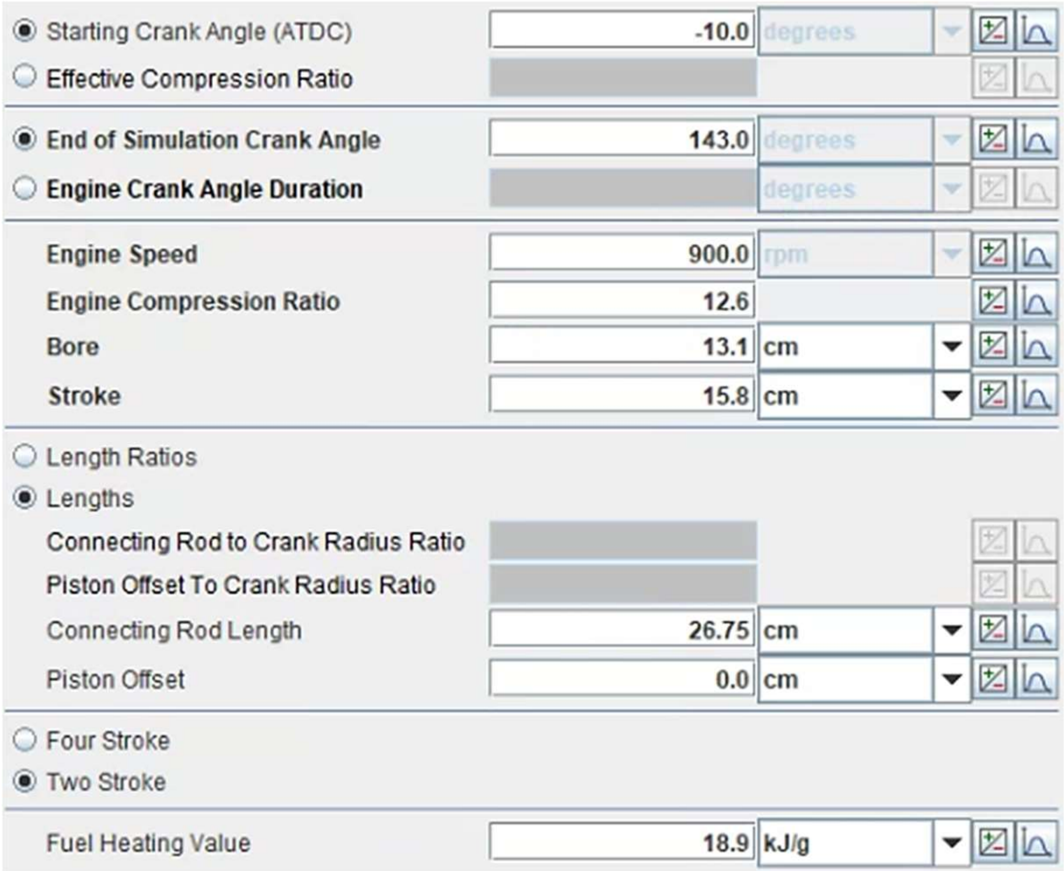

- Compared to CH4 & H20%, in single cylinder spark ignition research engine
- Chemkin-Pro NH3 in digital twin of the SCRE & expander of RSCE
- Parametric studies, manifold temperature/pressure, intake valve closing (IVC), burn efficiency (BE)
- Fuel run at leanest conditions, before combustion stability compromised, i.e. increased unburnt fuel & potential misfire (CH4 ϕ=0.74, H20% & NH3 ϕ=0.64)
- Note, decrease in NH3 concentration has been found to be more influential on flame temperature, than initial temperature or pressure

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Method & Chemistry

With P↑ & T↑ flammability limits widen, molecule internal energy & concentration increase, probability of molecular collision & reaction

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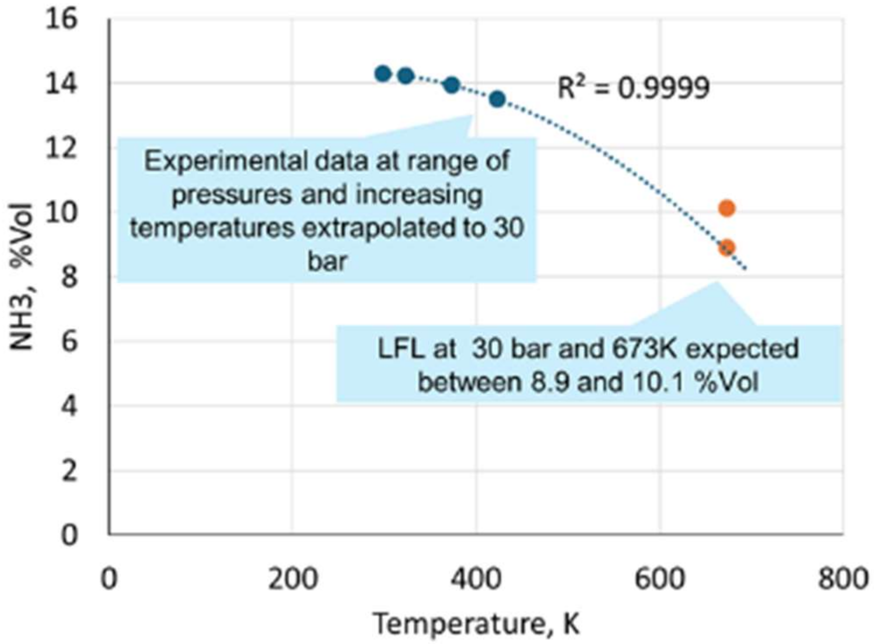
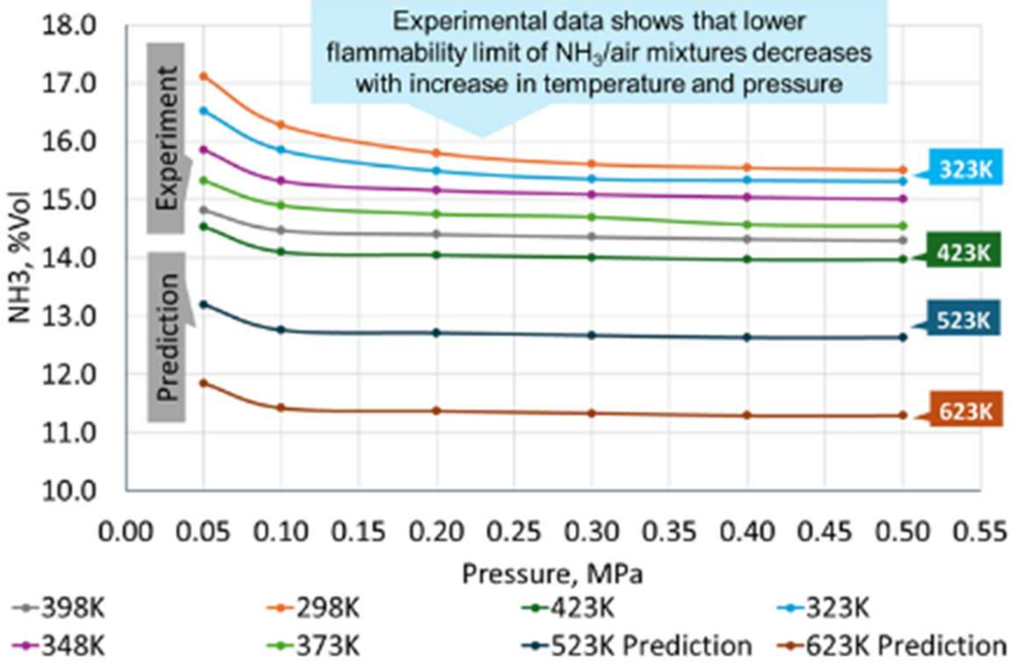
Estimated LFL of 12%Vol for NH3/air at >350 ºC, supported by experiments, 11.2%Vol at > 400 ºC, i.e. ≈ ϕ0.45. %Vol NH3 used is > 14.6%



Could run leaner RSCE manifold, due to higher autoignition temperature, to sustain flame spark ignition was utilised, RSCE & SCRE (400ºC/40 bar & 451 ºC/45 bar)



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Method & Chemistry

Cool combustion inhibiting NOx, supported by lean mixtures at high initial temperatures & pressures

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Near LFL & standard conditions, consumption of NH_3 follow

$$(1)\ H + O_2 \leftrightarrow O + OH$$

$$(2)\ NH_3 + OH \leftrightarrow NH_2 + H_2O \quad (3)\ 2OH \leftrightarrow O + H_2O \quad (4)\ NH_2 + OH \leftrightarrow NH + H_2O$$

$$(5)\ NH_2 + NO \leftrightarrow NNH + OH \quad (6)\ NH_2 + NO \leftrightarrow N_2 + H_2O$$

(1) & (5) increase flame temperatures, (6) inhibitor of temperature increase. As pressure increases, (3) is replaced with (4), whist (7) competes with (1) and (8) for H species

$$(7)\ H + O_2(+M) \leftrightarrow HO_2(+M)$$

$$(8)\ N_2O + H \leftrightarrow N_2 + OH$$

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Part 6 Method & Chemistry (Compared CH_4 & H20%, Chemkin-Pro NH_3, Flammability limit)

Part 7 Headline Findings (BSEC MJ/kWh, Parametric IVC, Initial °C, Bar)

Headline Findings & Results

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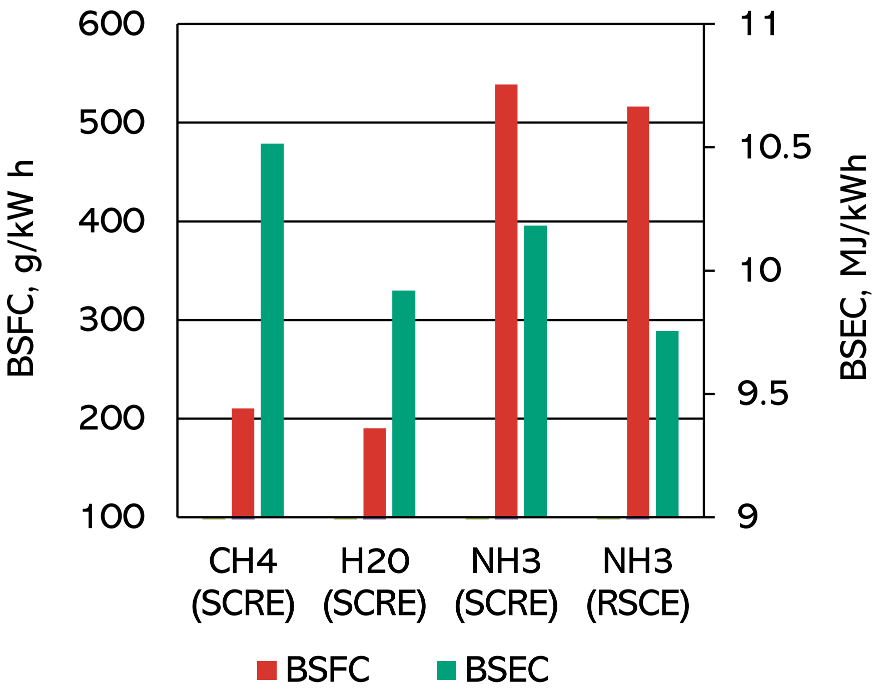

- Compared to CH4 & CH4 with H20% in SCRE, NH3 underperforms in BSFC (g/kWh) in both SCRE and RSCE
- Stoichiometric AFR for NH3, H2 & CH4 is 6, 34 & 17, low AFR & LHV of NH3 increases fuel flow
- But outperforms for BSEC (MJ/kWh) in the RSCE configuration. Whilst there is a penalty in mass to power conversion, due to the reduction in gravimetric energy density, there are gains for fuel energy to power conversion efficiency. 1.5% point increase in BTE for NH3 combustion in the RSCE architecture
- Both SCRE and RSCE utilise spark to support ignition, resulting in cool combustion, peak cylinder temperatures < 2100 K, NOx emission (g/kWh) approaching even stringent HD Euro 7 limits

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Headline Findings & Results

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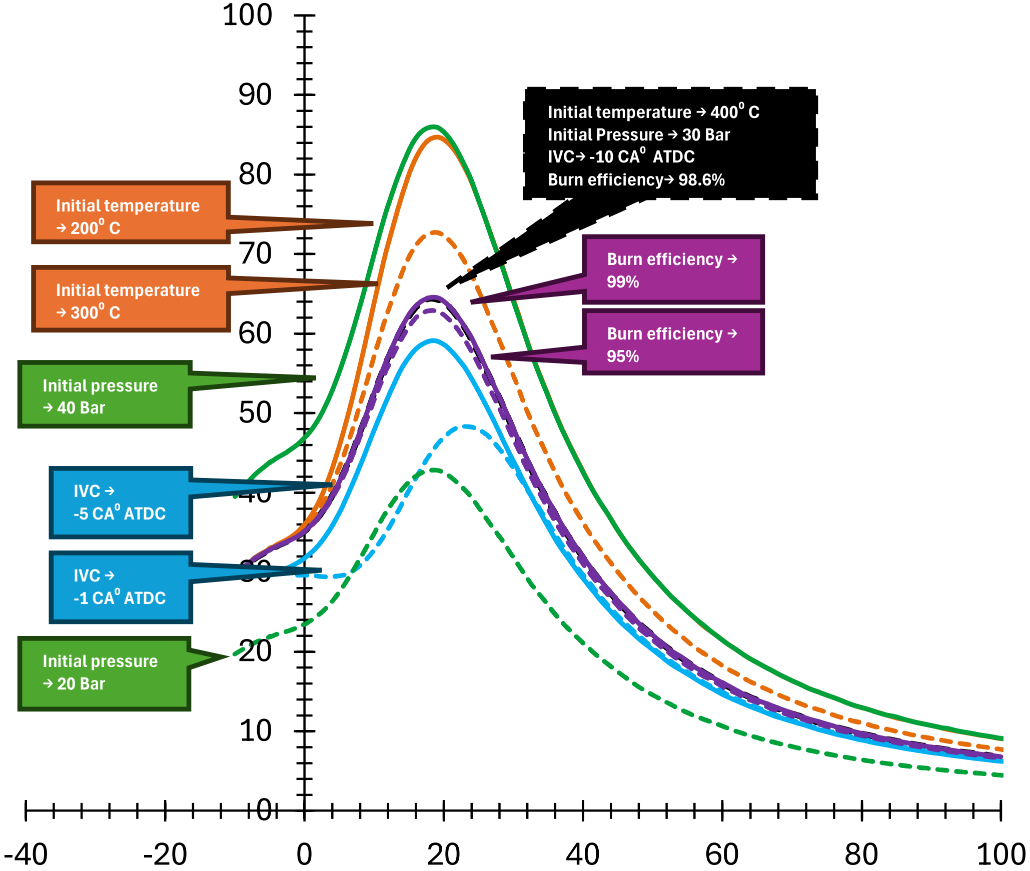

- In-cylinder pressure traces for NH3 combustion in RSCE, peak cylinder pressure + combustion duration → work extraction
- Shorter combustion duration, if optimally phased, could increase work extraction as the gas is expanding earlier in the downward piston stroke
- Greatest influence on peak pressure is the initial gas pressure (20 to 40 bar doubled the peak cylinder pressure 43 to 87 bar). Initial pressure increases fuel density, resulting in an increase in combustion event magnitude
- Next greatest increase in peak pressure was by advancing the position of intake valve close (IVC)

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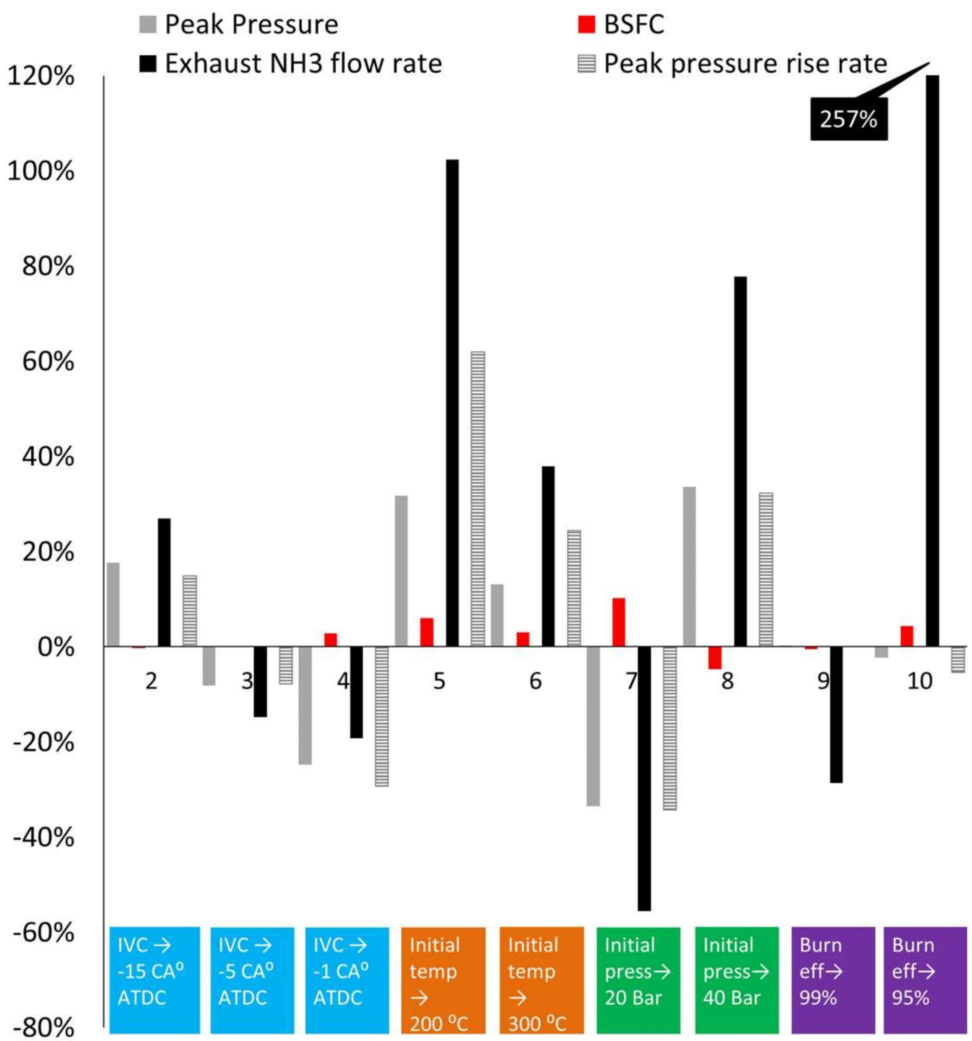

Headline Findings & Results

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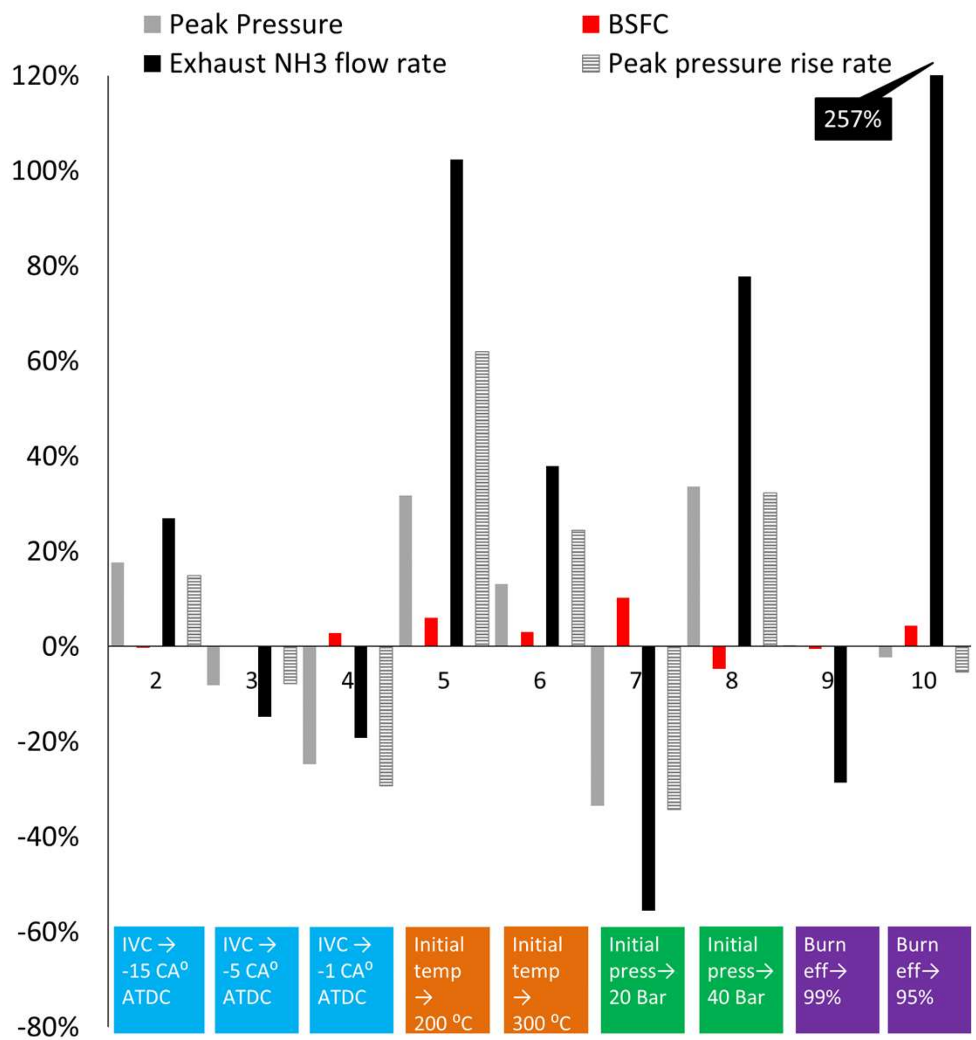
- Ref. NH3 in RSCE at IVC -10 CAº, 30 bar, 400 ºC manifold conditions
- Key metrics, peak pressure, BSFC i.e. application, exhaust NH3 flow rate (ENE) i.e. safety, peak pressure rise rate (PPRR) i.e. longevity
- Relative % change in key parameters of parameters

- Firstly, advancing IVC (-10 to -15 CAº) increases PPRE, ENE, no gain in performance (constant BSFC)
- Whilst delaying IVC (-5 to -1 CAº) reduces PPRR, ENE, detrimental to performance (increased BSFC)
- Trade-off occurs at IVC -5 CAº offering reduction in PPRR, ENE, without compromising BSFC



Headline Findings & Results

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- Secondly, reductions in initial temperature increased air & fuel density, therefore brake power (30 to 40 kW/cylinder from 400 to 200 ºC) which increased BSFC, ENE & PPRR
- Increase in PPRR was due to an increase in fuel density (at increased air density & constant ϕ) increasing the magnitude of the combustion event
- Increase in ENE & associated increase in BSFC was due to the constant BE (98.6%, as observed for this equivalence ratio in the SCRE) causing an increase in unburnt NH3 with flow rate, and a resultant reduction in fuel to power conversion efficiency.

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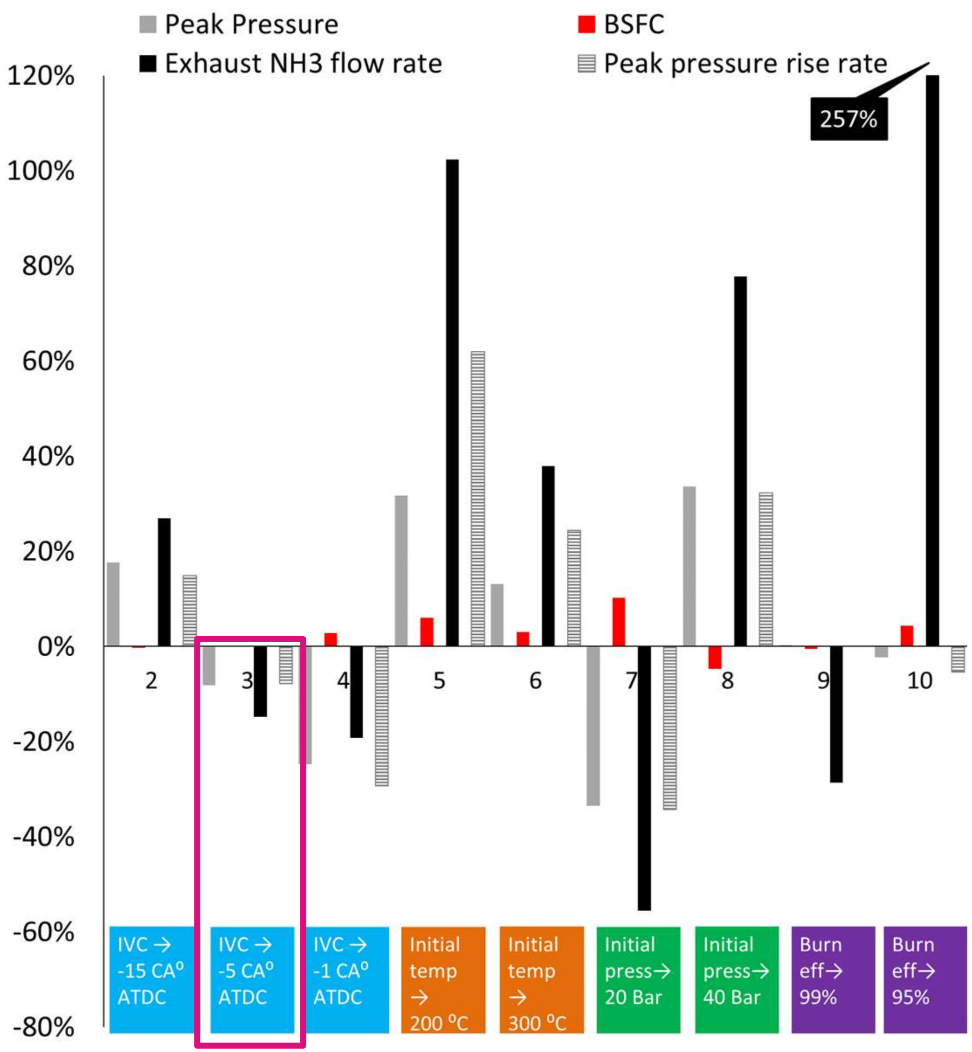

Headline Findings & Results

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- Thirdly, reduction in initial pressure was beneficial to PPRR & ENE, but detrimental to performance (increase in BSFC)
- Increase in initial pressure had the reverse effect, because <u>increasing initial pressure benefits volumetric efficiency</u>, which, at constant lambda, results in an increase in fuel density with an associated increase in ENE at constant BE
- Chemkin Pro SI engine model does not show entrainment or combustion of engine oil/lubricant
- Summary, optimum conditions for ϕ=0.64 NH3 combustion in RSCE architecture were with IVC (-5 CAº ATDC), 40 bar initial pressure, 400ºC combined, with spark ignition to support burn efficiency across engine map

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Part 7 Headline Findings (BSEC MJ/kWh, Parametric IVC, Initial °C, Bar)

Part 8 Take home message (What did we answer)

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Take Home Message

Ammonia Split Cycle Engine - Answering the Right Questions

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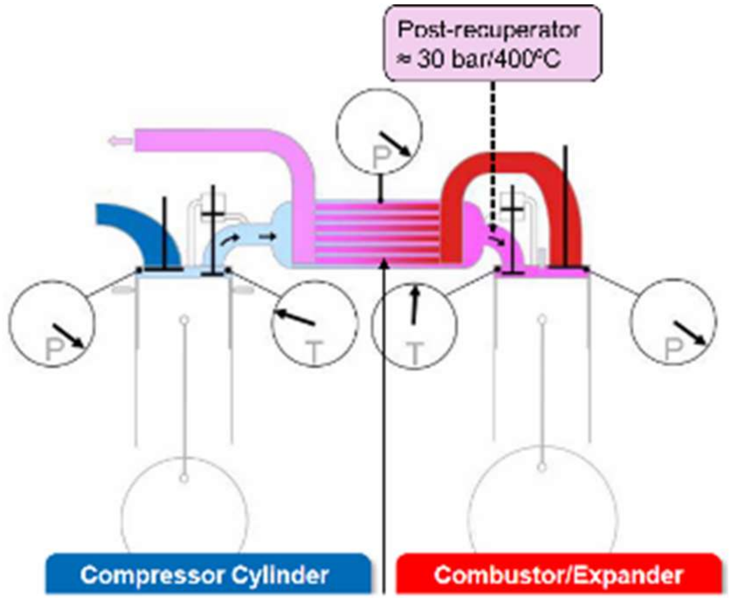
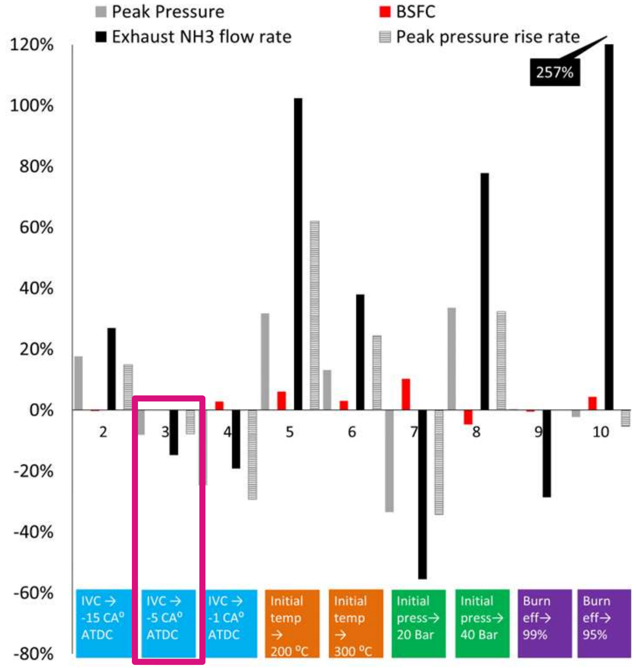
- ✓ Split cycle, with post-recuperator port-injection, enables NH3 storage & injection as liquid, & transfer into expander as homogenous lean pre-mixed, high-temperature high-pressure air-fuel gas mixture



- ✓ Cool NH3 combustion feasible using spark, gains in performance (1.5% BTE) & emissions (NOx)



The Feasibility of an Ammonia Split Cycle Engine - Answering the Right Questions

MariNH$_3$ conference - Dr. Angad Panesar

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Elisa Wylie - Always validating, rain or sunshine
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