Update on Ammonia Engine Combustion Using Direct Fuel Injection

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Thermodynamics/Chemistry

- Stoichiometric chemical reaction

$$NH_3 + 0.75 \cdot (O_2 + 3.76 \cdot N_2) \rightarrow 1.5 \cdot H_2O + 3.32 \cdot N_2$$

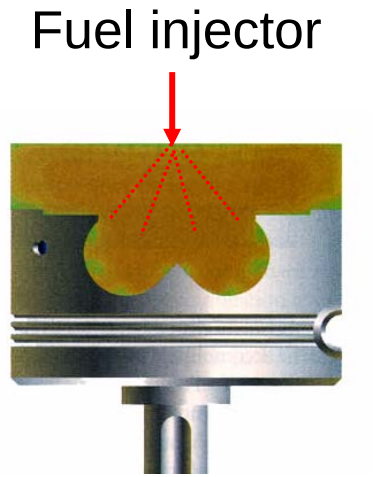
Fuel	Molecule	Boiling Point (°C)	$(Air/Fuel)_s$	Latent Heat (kJ/kg)	Energy Content (MJ/kg-fuel)	Energy Content (MJ/kg-stoichiometric mixture)
Methanol	CH_3OH	64.7	6.435	1203	20	2.6900
Ethanol	C_2H_5OH	78.4	8.953	850	26.9	2.7027
Gasoline	C_7H_{17}	---	15.291	310	44	2.5781
Diesel	$C_{14.4}H_{24.9}$	---	14.3217	230	42.38	2.7660
Ammonia	**NH_3**	**–33.5**	**6.0456**	**1371**	**18.6103**	**2.6414**

Approaches

- CI engine operation
  - Port induction of gaseous ammonia, ignited by directly injected diesel/biodiesel fuel
    - Achieved a wide range of load and speed conditions
  - Direct injection of liquid ammonia/DME mixtures
    - To be presented
- SI engine operation
  - Direct injection of gaseous ammonia, enhanced by gasoline combustion
    - On-going (to be presented)

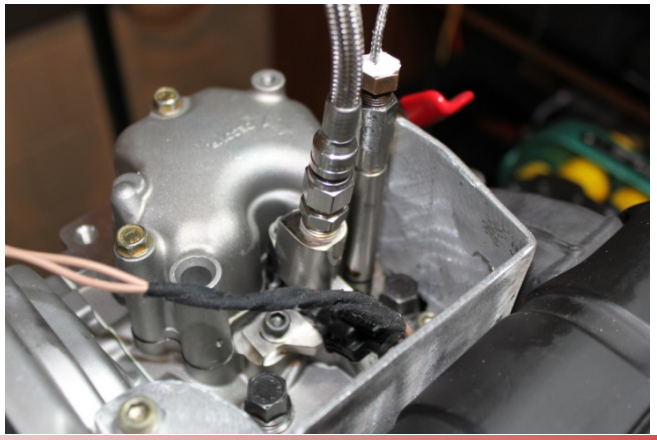
NH_3/DME

- Use direct liquid fuel injection
  - Confine combustion mixture near the center
  - To reduce exhaust ammonia emissions
- Dimethyl ether (CH_3-O-CH_3) as ignition source
  - Fuel mixing and storage at high pressure
  - New fuel injection system – without fuel return
    - Injection pump, injector, electronic control
- Various NH_3/DME ratios



Engine Setup

- Yanmar diesel engine (L70V, 320 c.c.)
  - Rated power at 6.26 hp at 3,480 rpm
- Developed new fuel injection and engine control systems
  - Bosch GDI type injector (up to 200 bar injection pressure)



Setup

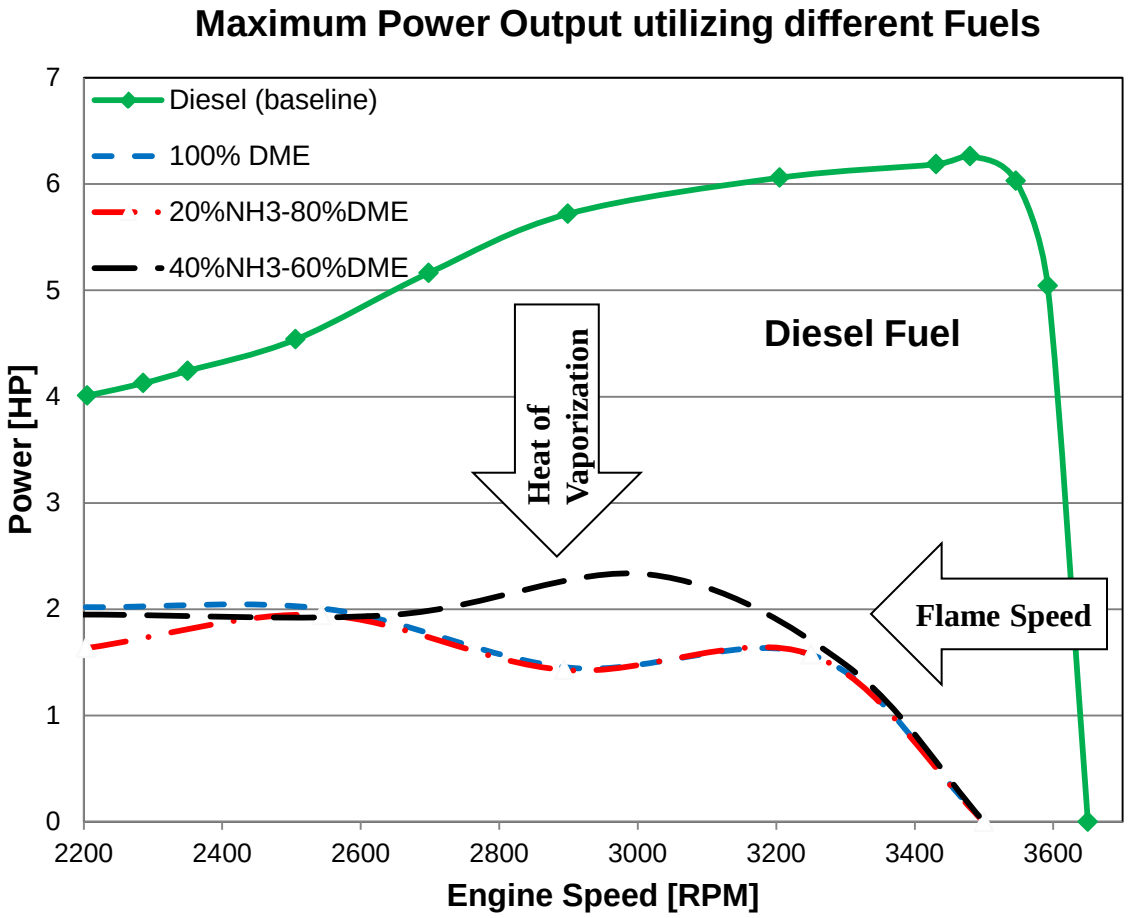
- Mixing and storage of ammonia/DME at high pressure
- Exhaust emissions measurements
  - Horiba MEXA-7100DEGR (CO_2, CO, O_2, HC)
  - Horiba 1170NX (NO_x, NH_3)
  - AVL Smoke Meter (PM)

Fuel mixing system

Emissions analyzers

Operating Range

- Challenges
  - Latent heat
  - Flame speed
- Low to medium loads at various speeds



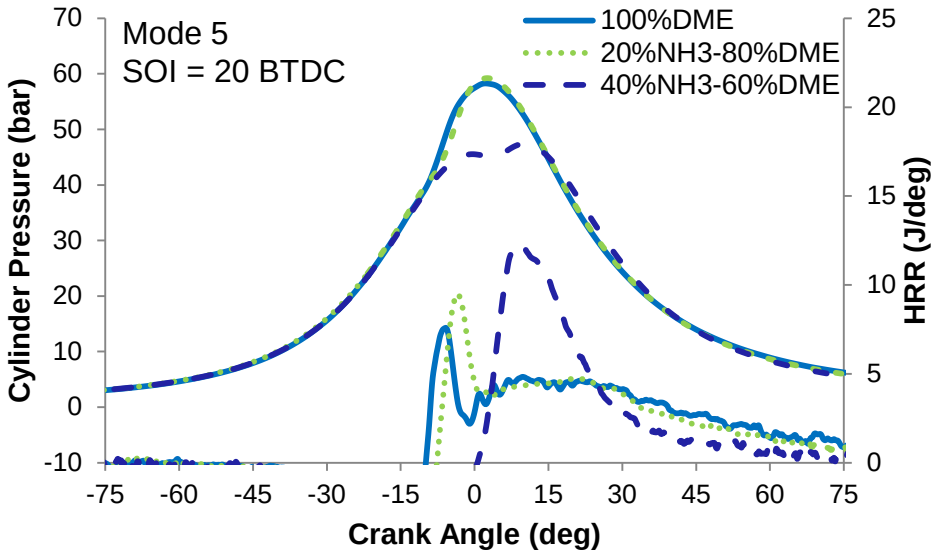
Test Conditions

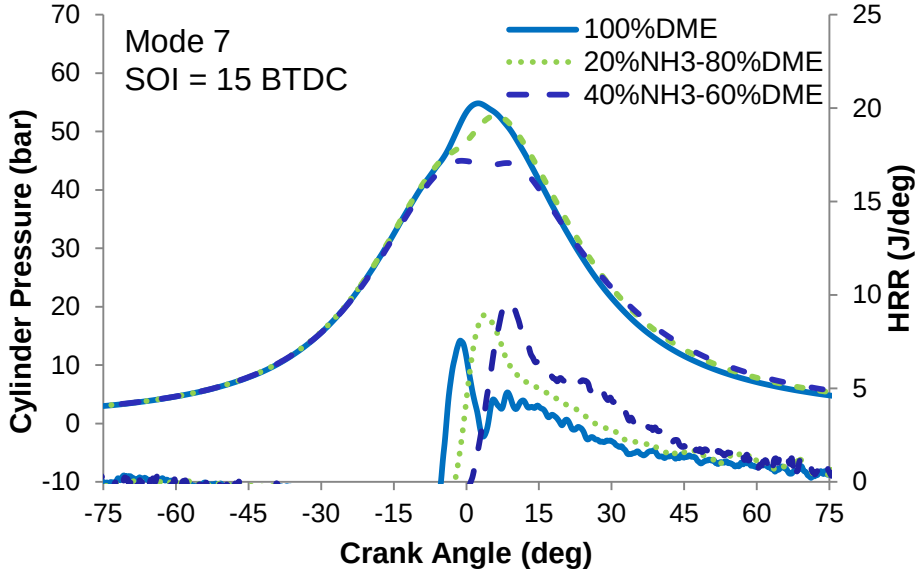
Mode	Engine Speed (rpm)	Engine Power (kW)	Engine Torque (Nm)
5	2548	1.74	6.61
7	2548	0.87	3.31
9	2895	1.05	3.52
11	3243	1.12	3.34
20	2200	1.47	6.47
21	2200	0.74	3.24

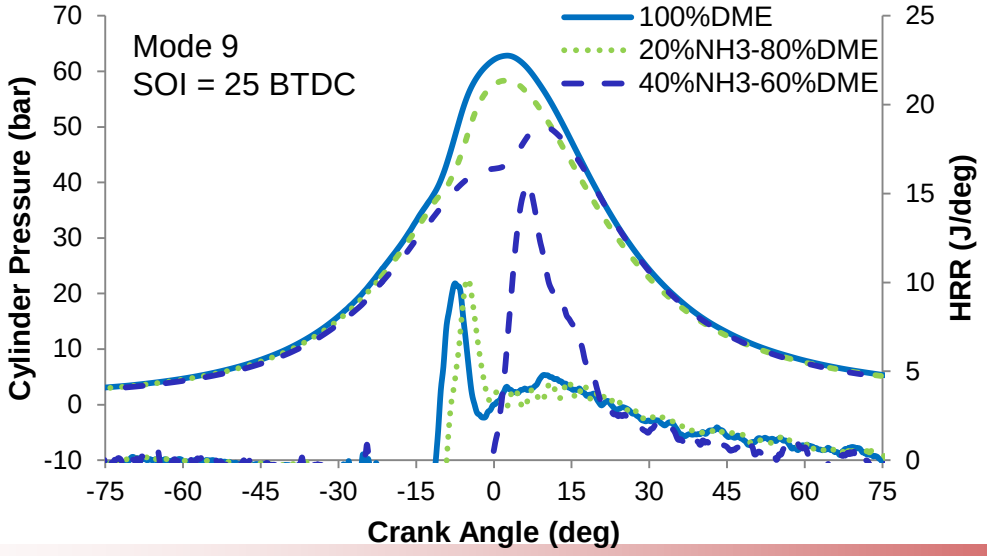
Fuel	SOI (btdc)	P_inj	T_intake air
100%DME	0 ~ 30	150 bar	30 C
20%NH_3-80%DME	5 ~ 35	150 bar	60 C
40%NH_3-60%DME	15 ~ 40	180 bar	80 C
60%NH_3-40%DME	140 ~ 180	205 bar	90 C

Results will be presented first

Sample Results (P & HRR)





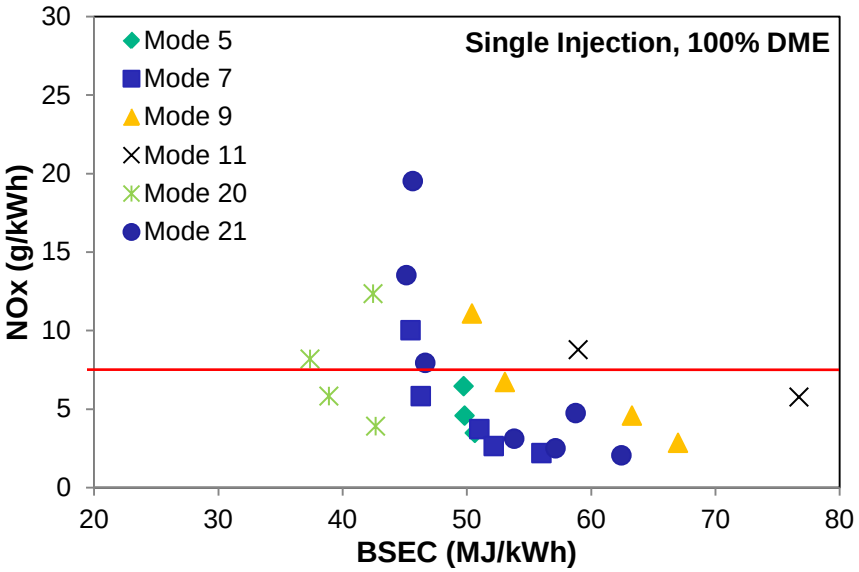


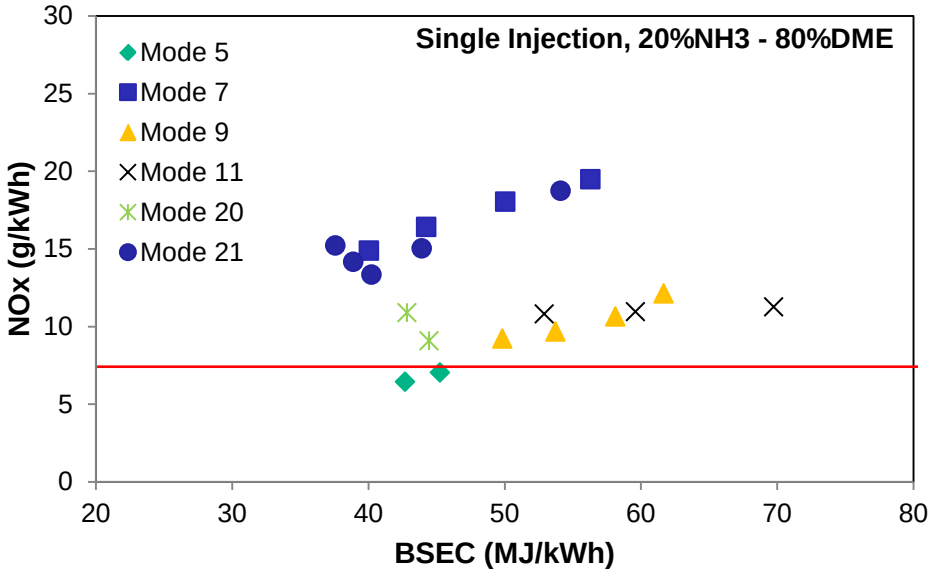
Results

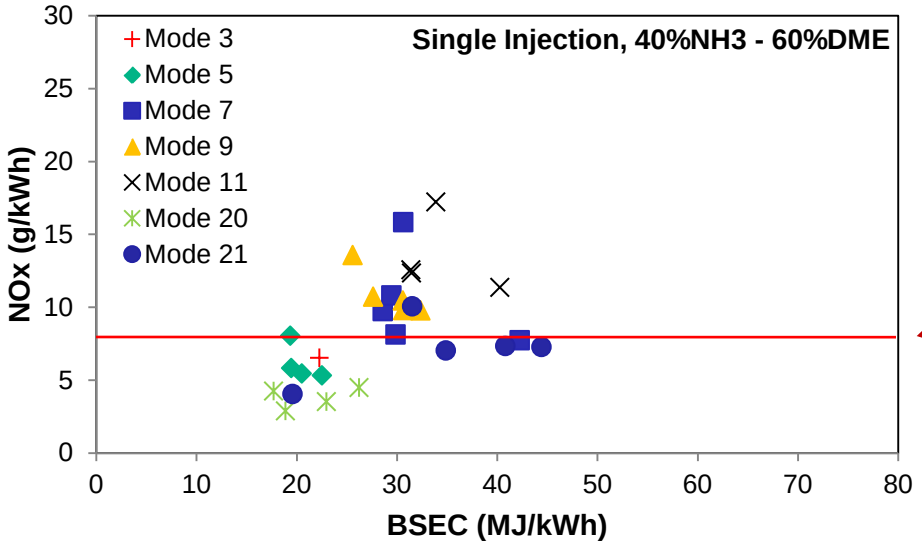
- Observation on combustion
  - No significant deterioration of combustion
  - More ammonia → longer ignition delays, more significant premixed combustion

- Reporting emissions
  - Reported in BSEC [MJ/kWh] (instead of BSFC [g/kWh])
    - Imply the fuel energy consumption rate, fuel economy
  - As reference: @ 3,250 rpm and 4.3kW running on diesel fuel
    - BSEC is 13.656 MJ/kWh, corresponding to a BSFC of 304.8 g/kWh for the current engine.

NOx Emissions

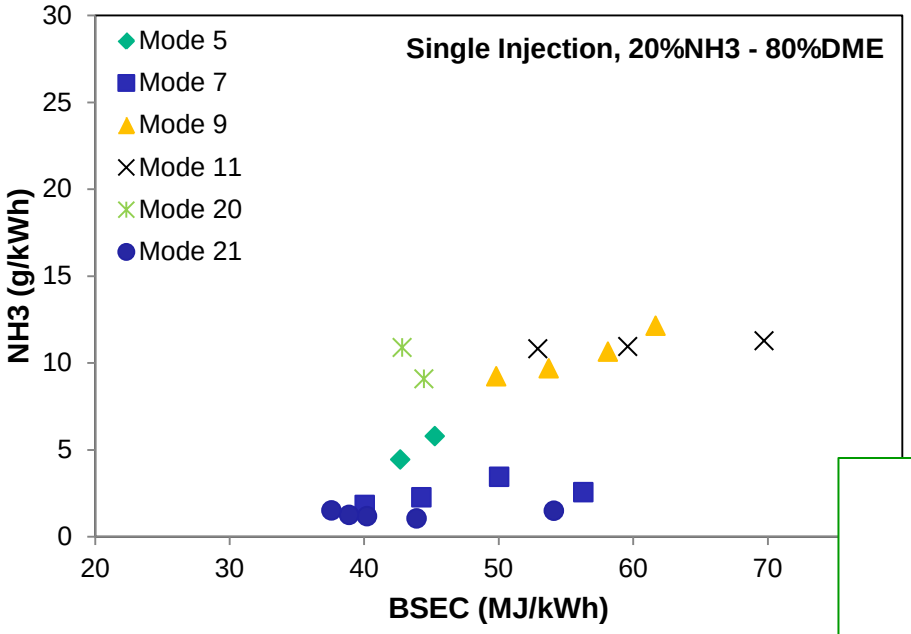


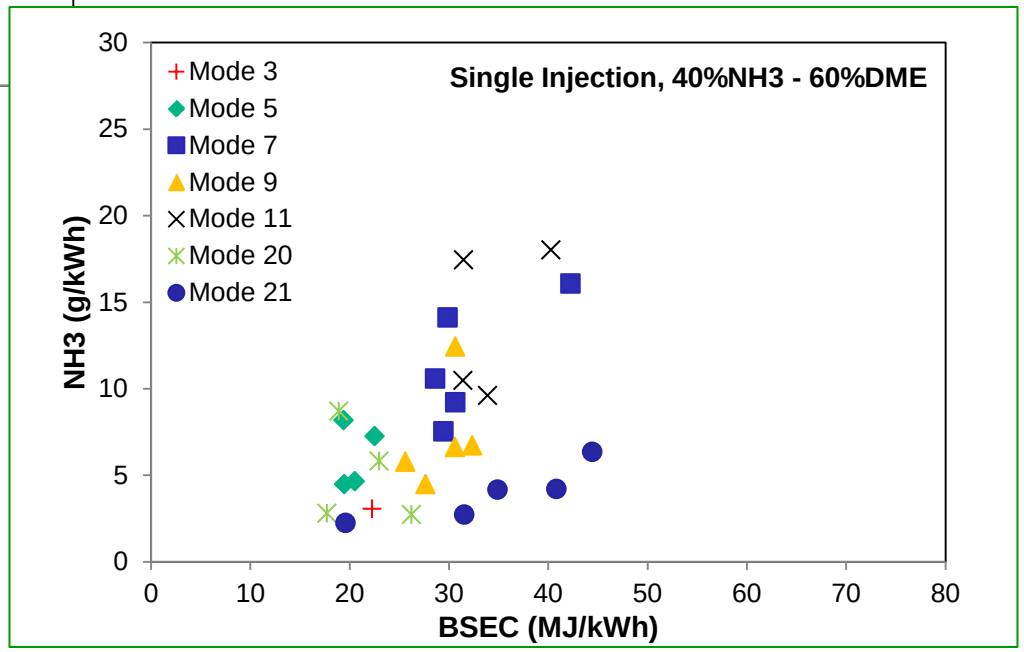




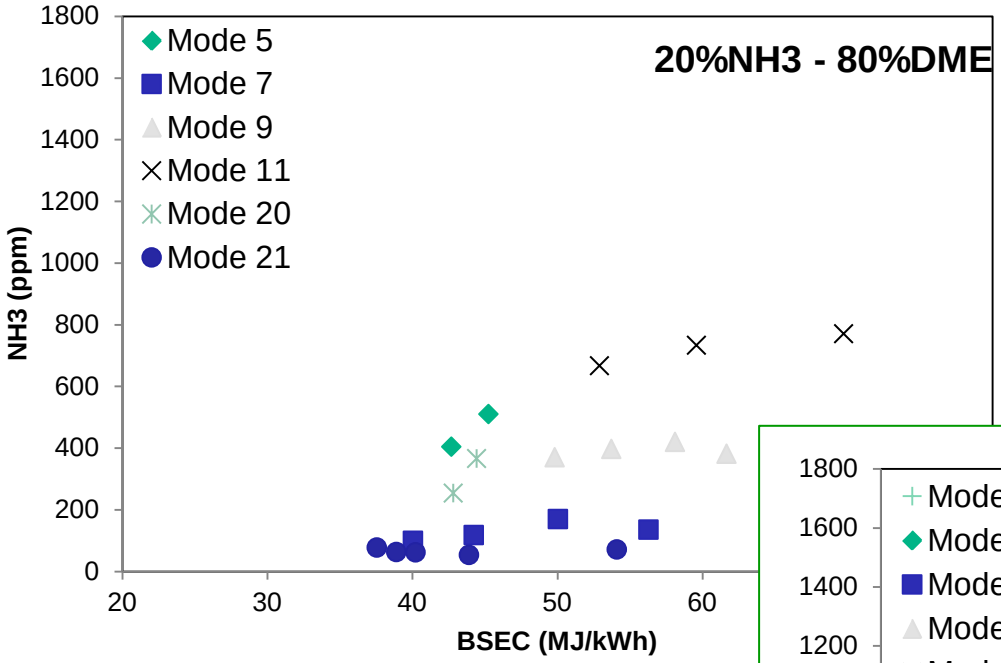
Reference data using diesel fuel

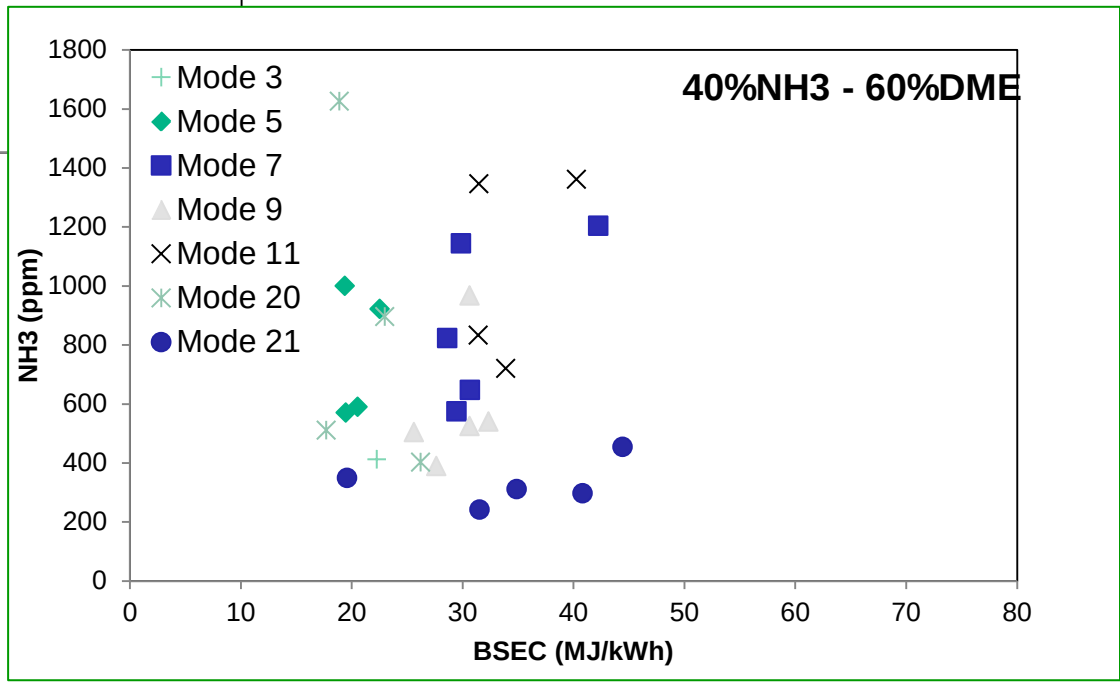
NH_3 Emissions



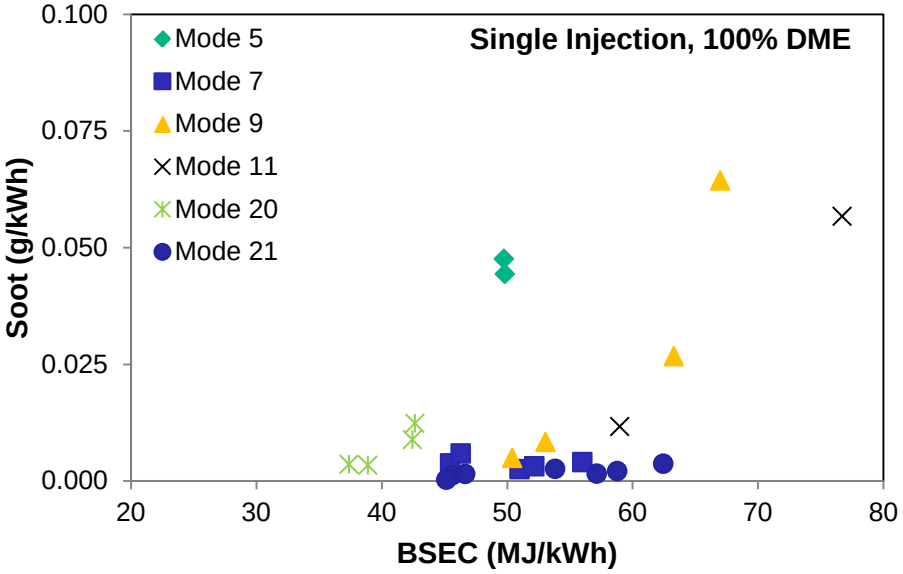


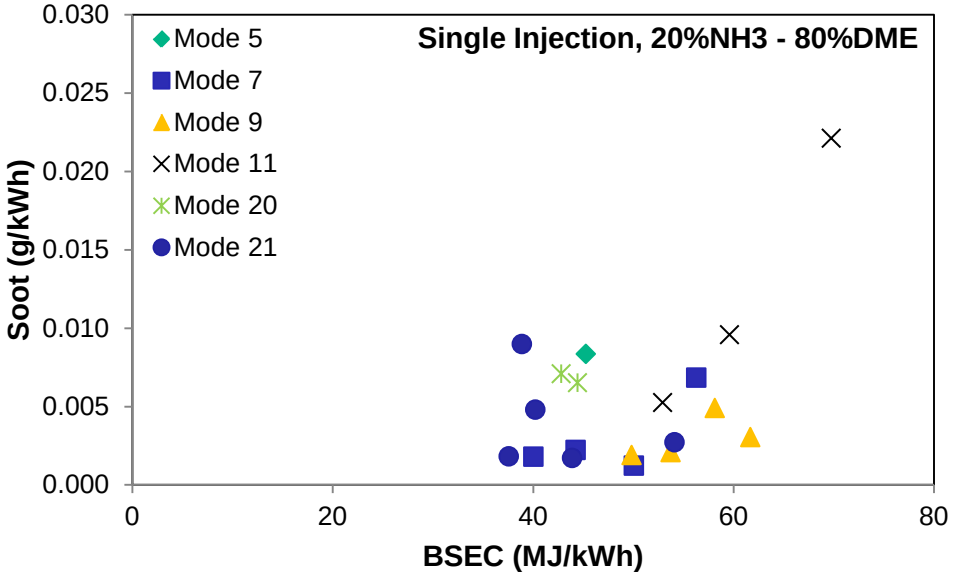
NH_3 Emissions



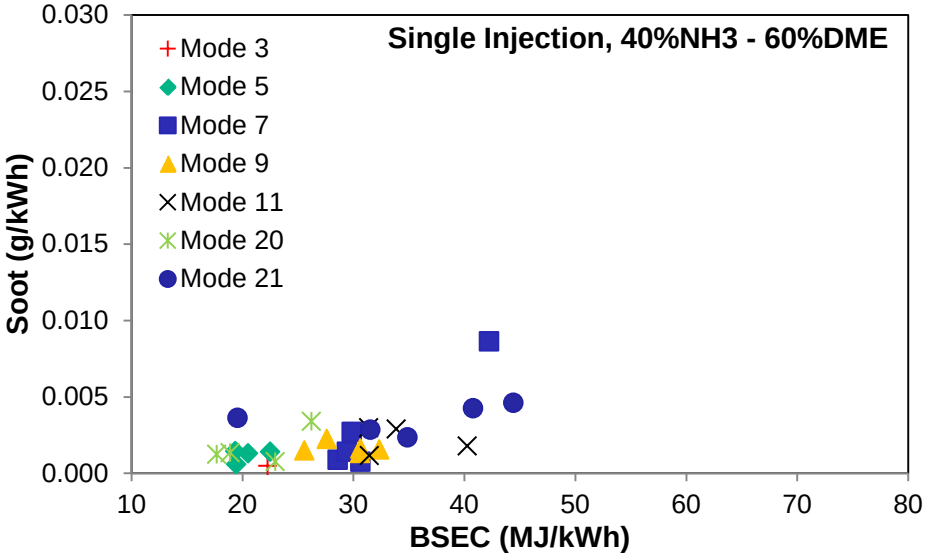


Soot Emissions



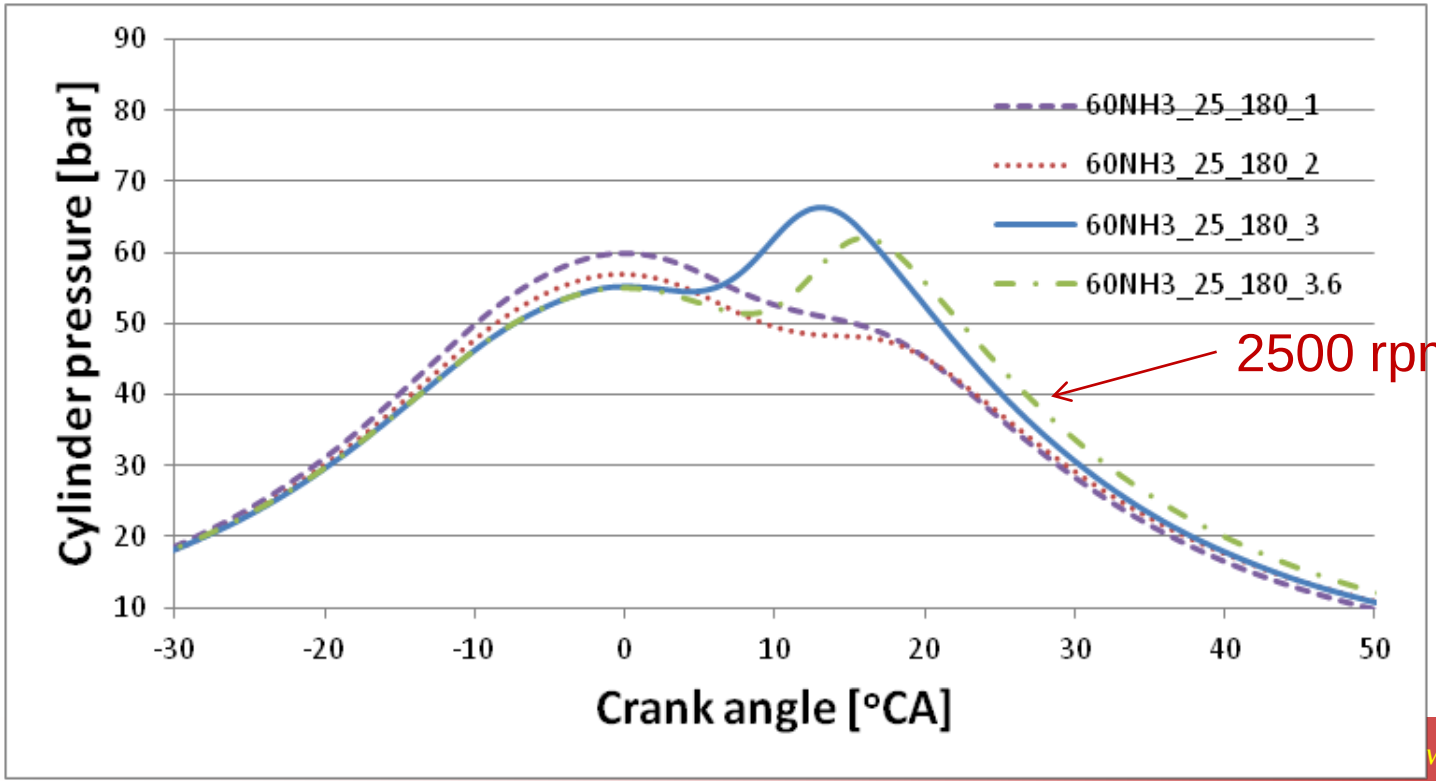


- Extremely low soot emissions
- HC and CO levels comparable among different fuel mixtures

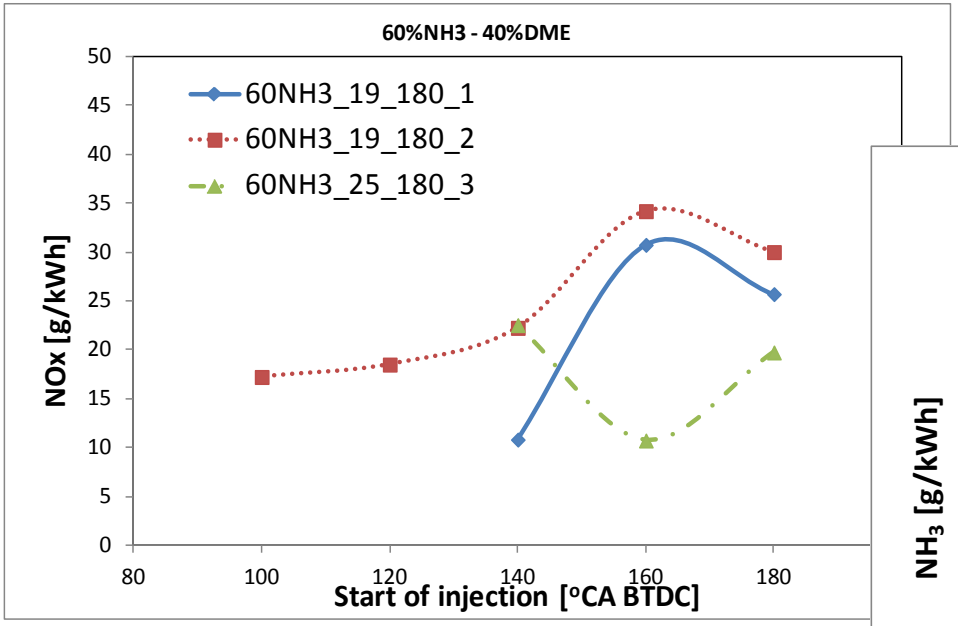


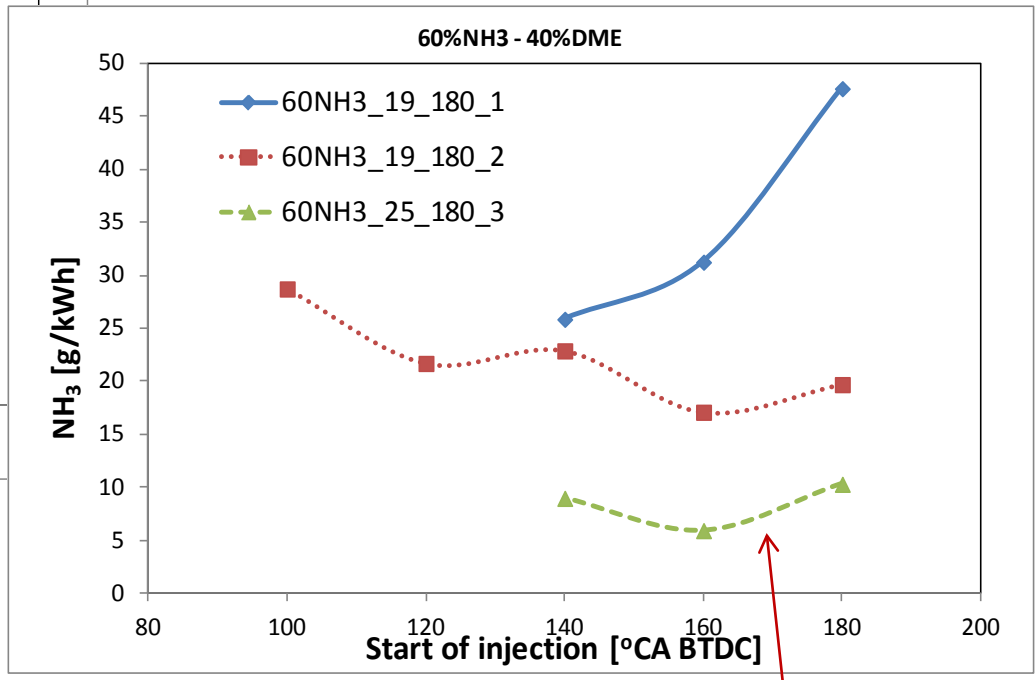
60%NH_3-40%DME

- Injection pressure – positive effects on combustion
- To enable combustion of 60%NH_3-40%DME
  - P_inj=205 bar, SOI= 180 btdc, T_intake= 90 C
  - Achieved higher load and speed operation



NOx and NH_3 Emissions





Higher load benefits NH_3 combustion;
More stable operation;
Flexibility in injection timing.

Perspectives

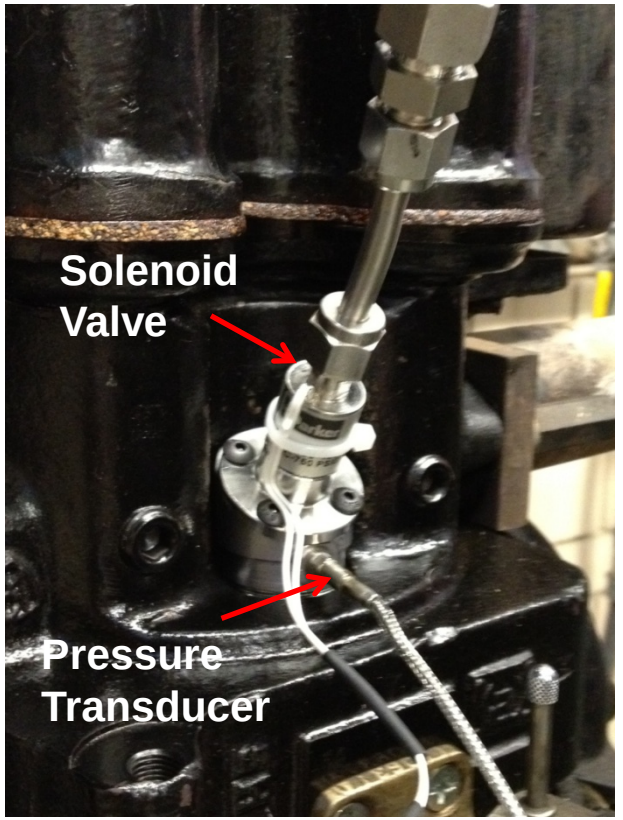
- Current test engine
  - Small size, high heat loss, operated at high speed, low injection pressure
- Application to larger diesel engine
  - Operated at lower speed, high injection pressure
  - Exhaust after-treatment (SCR system without urea injection)

Fuel cost based on $3.7/gal diesel, $550/ton ammonia, $700/ton DME

	Diesel fuel	40%ammonia/ 60% diesel	40%ammonia/ 60% DME	Ammonia
BSEC (MJ/kWh)	10.3	10.3	10.3	10.3
LHV (MJ/kg)	42	32.6	24.5	18.6
Fuel rate (kg/kWh)	0.245	0.316	0.420	0.554
Fuel price ($/kg)	$1.180	$0.950	$0.704	$0.605
Fuel energy cost ($/kWh)	$0.29	$0.30	$0.30	$0.34

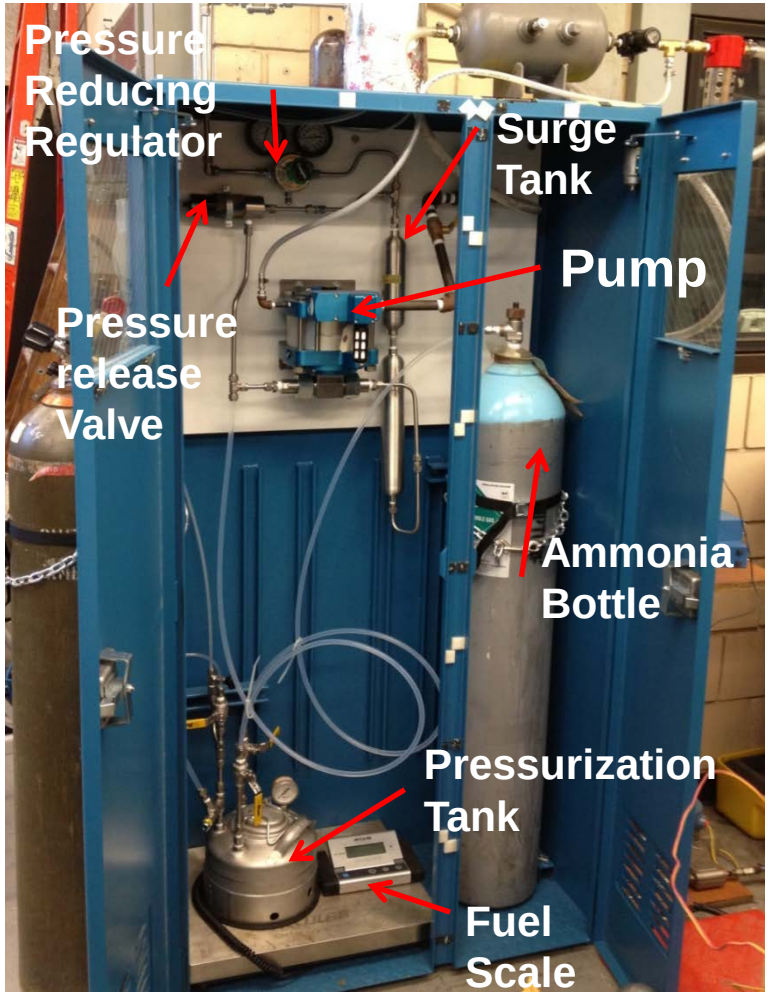
DISI NH_3 Engine

- Direct injection of gaseous ammonia
  - Maximize volumetric efficiency, thus maximizing air fuel charge
  - Prevent negative effects of high latent heat of ammonia
- Solenoid driven pulse valve
  - Withstands corrosive effects of ammonia
  - Designed for gaseous applications
  - Cheap and readily accessible



Gaseous NH_3 Injection

- Fuel pump and storage operate on liquid basis
  - Injection line pressure approx. 35 bar
- Injection line heated to achieve gaseous fuel
  - Temperature required 60°C
  - Heat provided by heat tape
  - Expansion chamber to compensate for dramatic volumetric change upon vaporization



Progress Update

- Fuel storage, heating, injection systems completed.
- Initial engine tests conducted
  - Engine operates on gasoline
  - Engine torque increases when ammonia injection is activated
- Detailed measurements in progress

Summary

- CI engines using ammonia
  - Port induction of vapor ammonia + DI diesel fuel
  - DI ammonia/DME mixtures
  - Large engine will favor operation using ammonia
  - After-treatment using SCR for NOx and ammonia reduction
- DISI ammonia engine
  - Injection system implemented
  - Detailed measurements in progress