Characteristics of an SI Engine Using Direct Ammonia 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**

Ammonia Fuel Characteristics

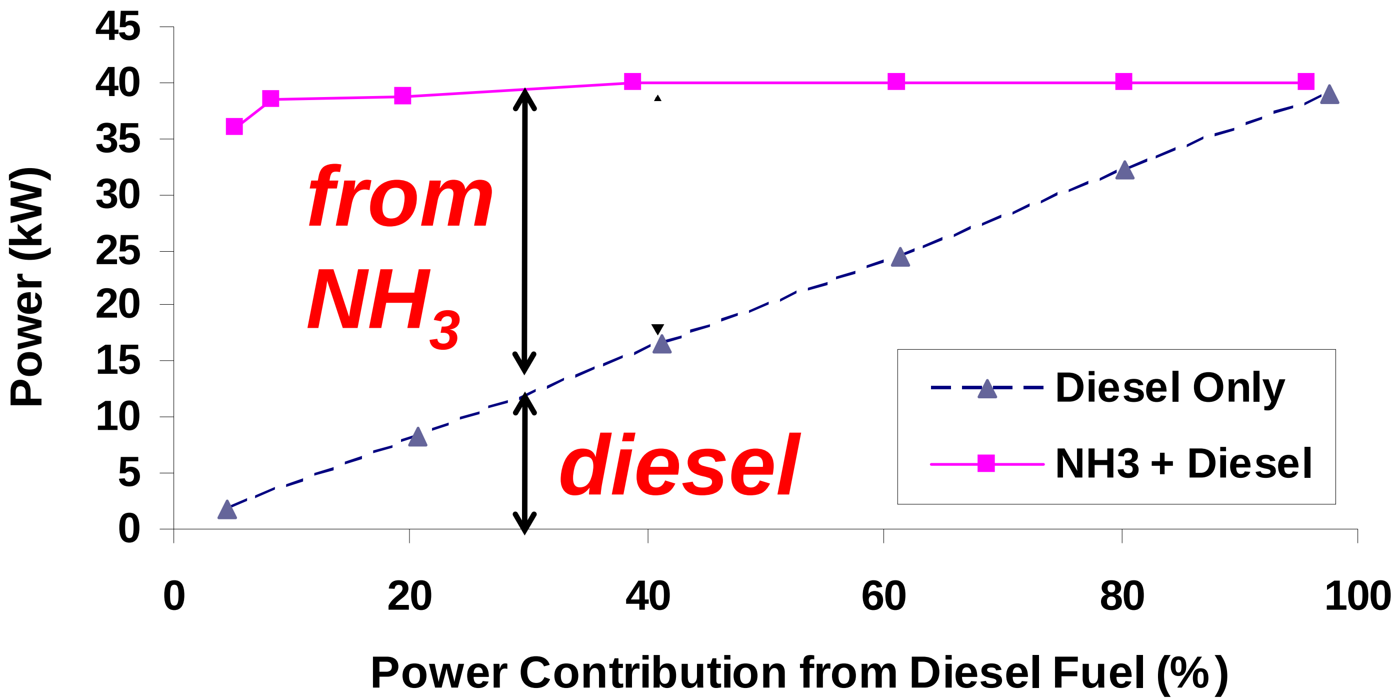
- Challenges
  - Ammonia is very difficult to ignite
    - Octane number ~ 130
    - Autoignition T ~ 651 ºC (gasoline: 440 ºC; diesel: 225 ºC)
  - Ammonia flame temperature is lower than diesel flame T
  - Erosive to some materials
  - Ammonia emissions can be harmful
  - Potential high NOx emissions due to fuel-bound nitrogen

Approaches

- CI engine operation
  - #1 Port induction of gaseous ammonia, ignited by directly injected diesel/biodiesel fuel (2008 – 2009)
    - Achieved a wide range of load and speed conditions
  - #2 Direct injection of liquid ammonia/DME mixtures (2010 – 2011)
    - Achieved successful operations using various ratios
- SI engine operation
  - Port induction of ammonia has been done by others.
  - #3 Direct injection of gaseous ammonia, enhanced by gasoline combustion (2012 – 2013)
  - #4 Direct injection of gaseous ammonia with decomposition catalyst, enhanced by gasoline combustion (2013)

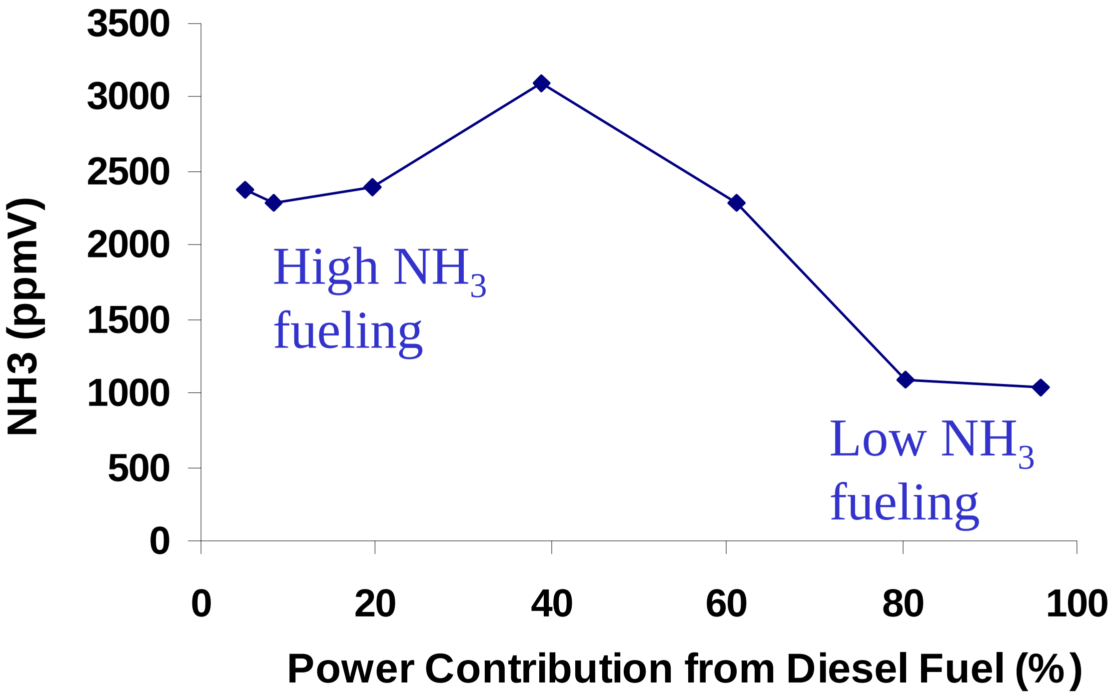
#1: Results – Constant Torque

- John Deere, 4-cylinder 4.5-liter diesel
- Gaseous ammonia introduced thru intake manifold
- Fixed at different diesel fueling, adjusted NH3 flow rate to maintain constant torque
  - Can achieve 5% diesel / 95% NH_3 energy ratio

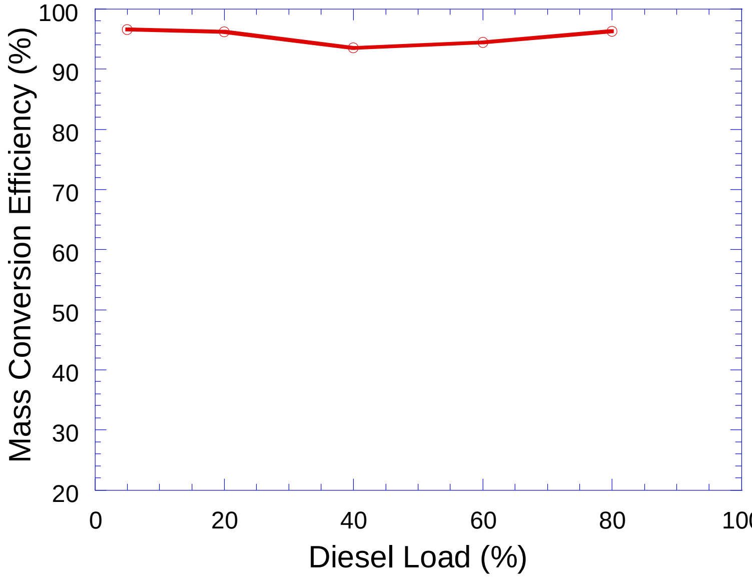


NH_3 Exhaust Concentrations

- Concentrations vary depending on NH_3 fueling rate
- Further study is required to reduce NH_3 emissions.

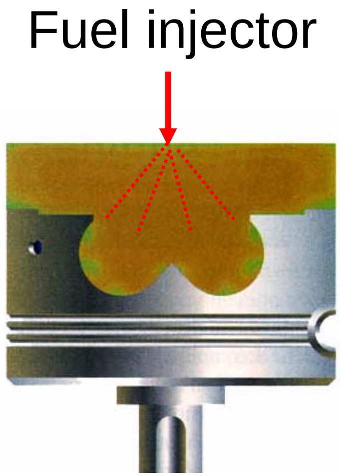


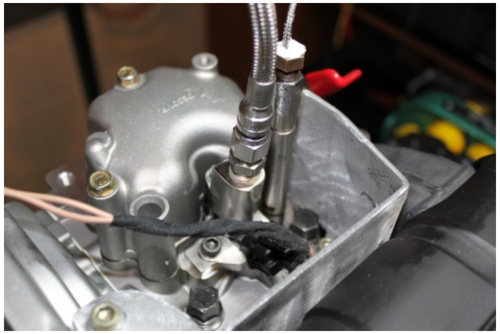
Ammonia combustion efficiency



#2 Results – 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
  - Various NH_3/DME ratios
  - Fuel mixing and storage at high pressure
- Yanmar diesel engine (L70V, 320 c.c.)
  - Rated power at 6.26 hp at 3,480 rpm
  - Developed new fuel injection system



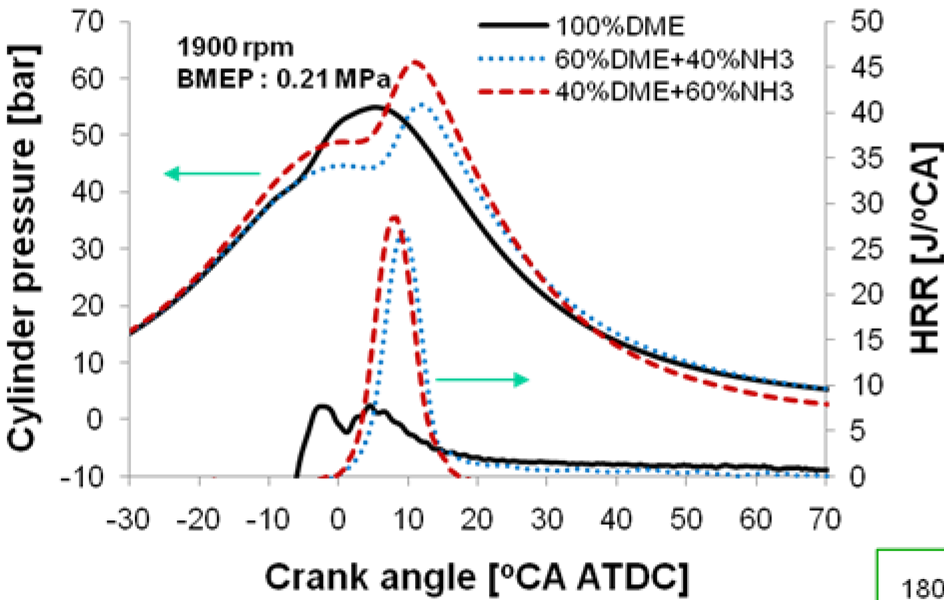


Test Conditions

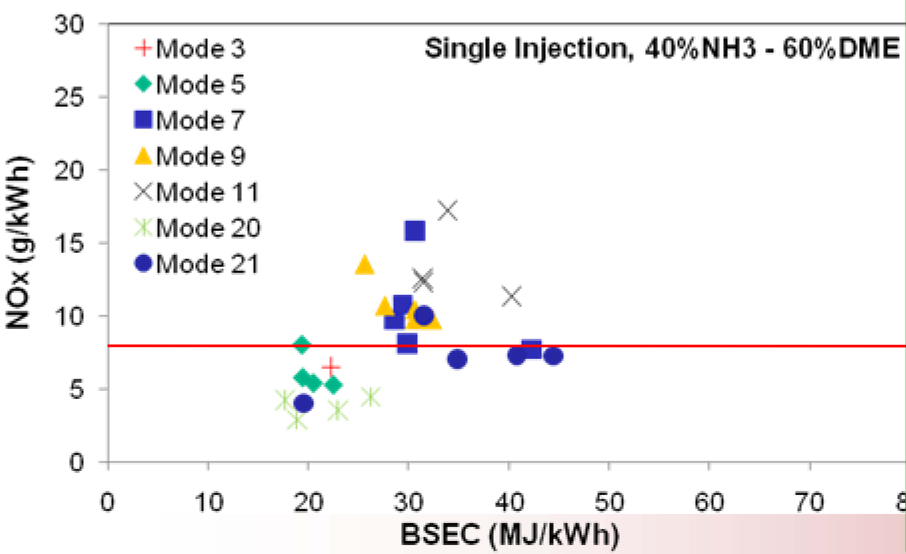
Mode	Engine Speed (rpm)	Engine Power (kW)	Engine Torque (Nm)
5	2548	1.74	6.61
7	2548	0.87	3.31
9	2895	1.05	3.52
11	3243	1.12	3.34
20	2200	1.47	6.47
21	2200	0.74	3.24

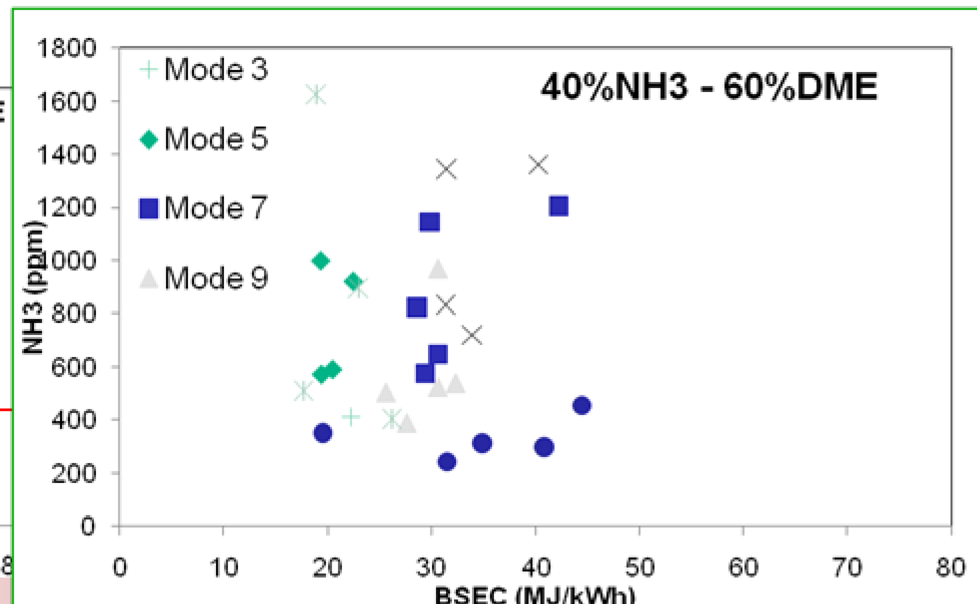
Fuel	SOI (BTDC)	P_inj	T_intake air
100%DME	0 ~ 30	150 bar	30 C
20%NH_3-80%DME	5 ~ 35	150 bar	60 C
40%NH_3-60%DME	15 ~ 40	180 bar	80 C
60%NH_3-40%DME	140 ~ 180	205 bar	90 C

Sample Results



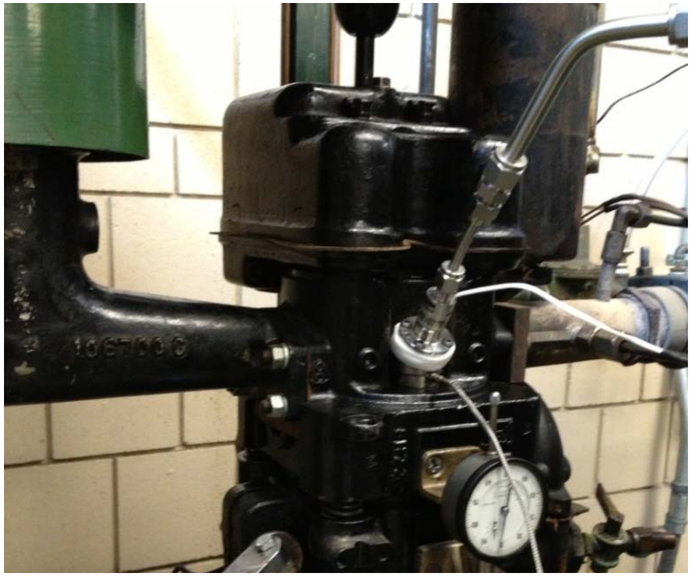
- High latent heat of liquid ammonia
- Cooling down in-cylinder gas
- Causing incomplete combustion
- Combustion instability

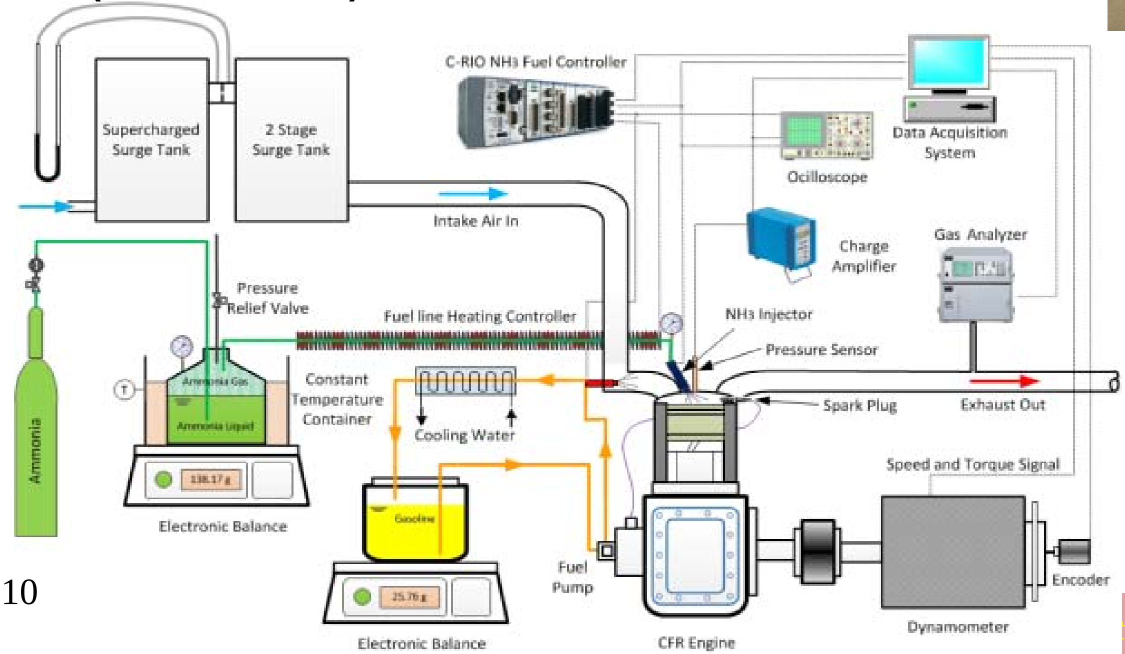


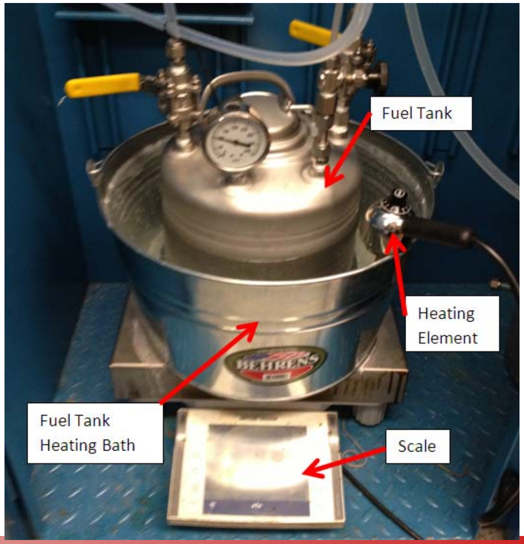


#3 Results – DISI NH_3

- Single cylinder CFR engine
  - Spark ignition; 10:1 compression ratio
- Port gasoline injection
- Direct gaseous ammonia injection
  - Better volumetric efficiency
  - Solenoid pulse valve as the injector
- Heated water bath to achieve injection (10~12 bar)

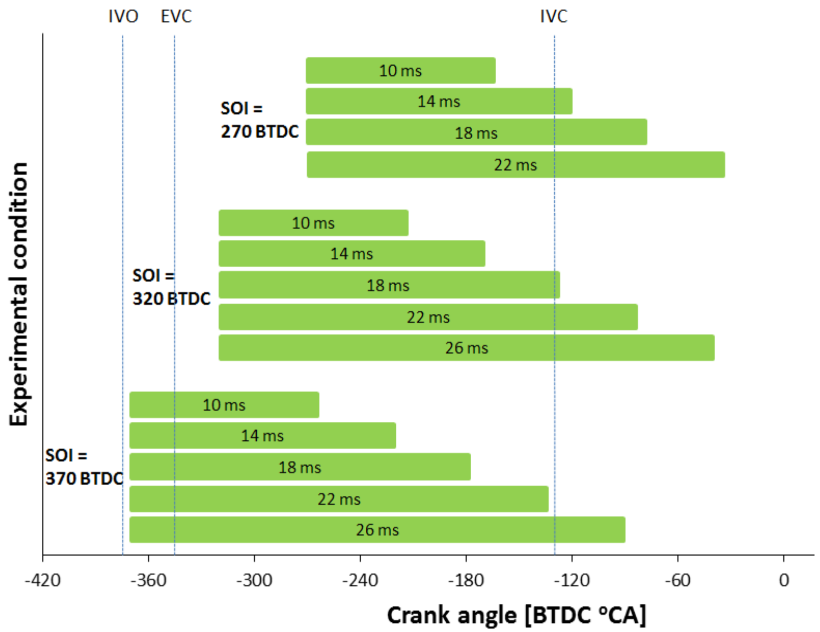




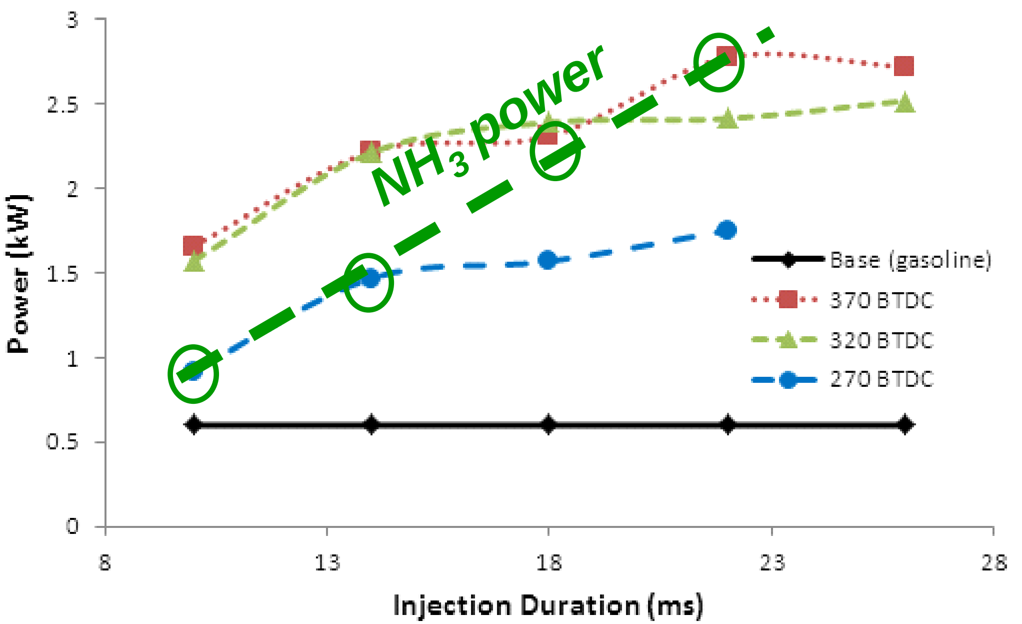


PFI Gasoline + DI NH_3

- Ammonia injection conditions

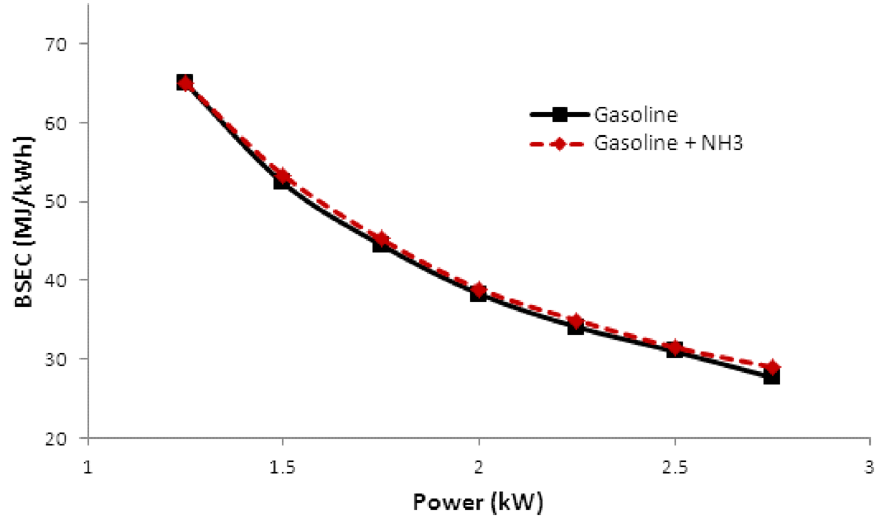


- Engine power boost by ammonia
  - Gasoline produce 0.6 kW

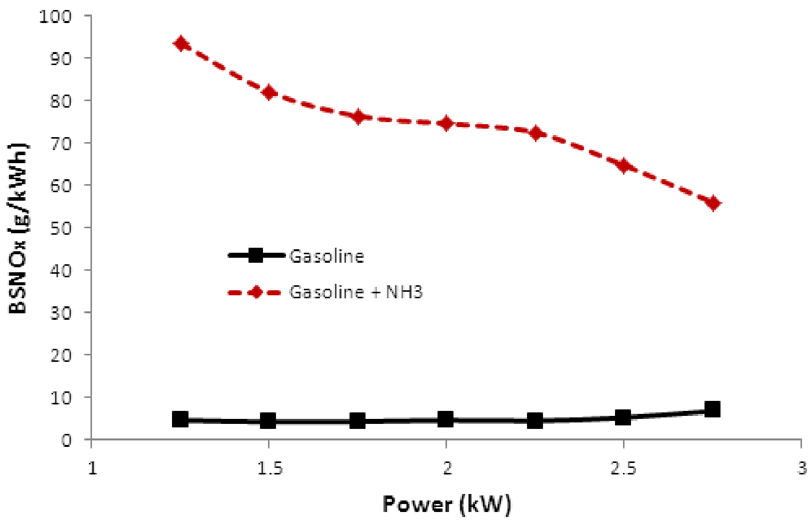


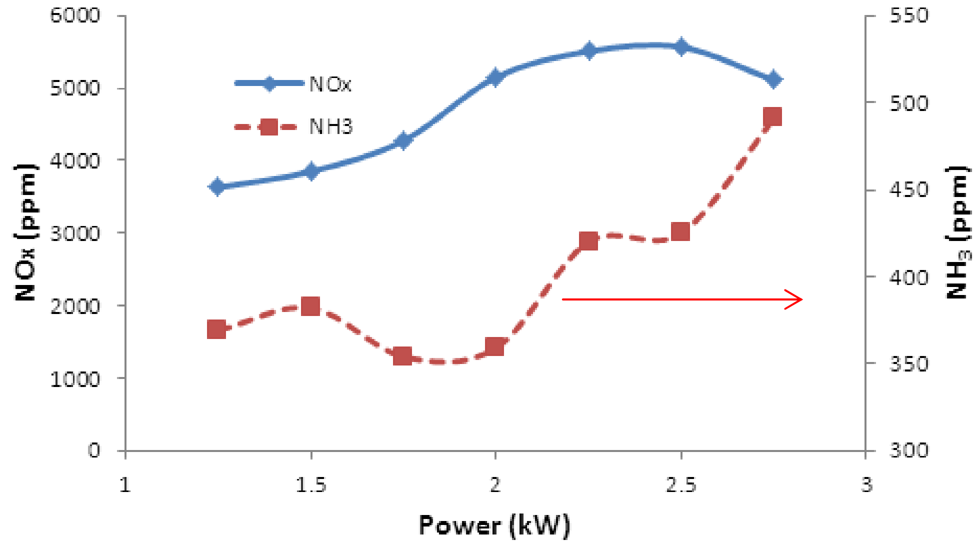
PFI Gasoline + DI NH_3

- Same power achieved by “gasoline alone” and “gasoline + NH_3”
- Comparable fuel efficiency



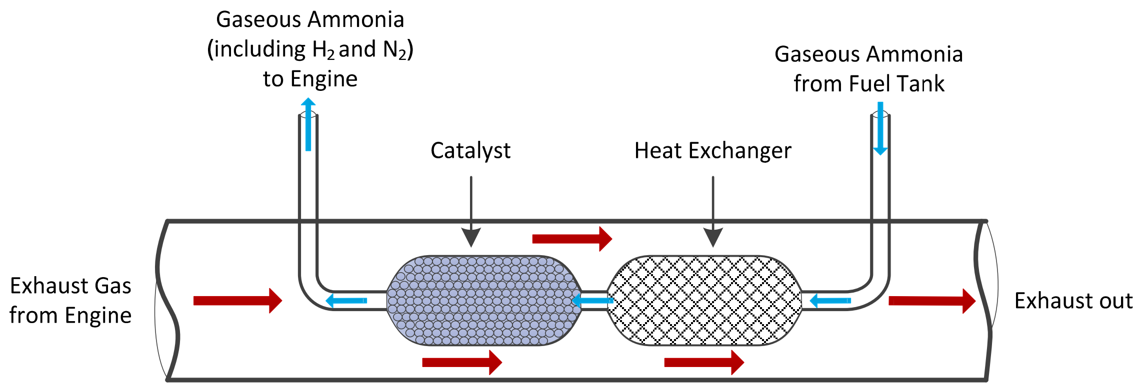
- Higher NOx emissions using “gasoline + NH_3”





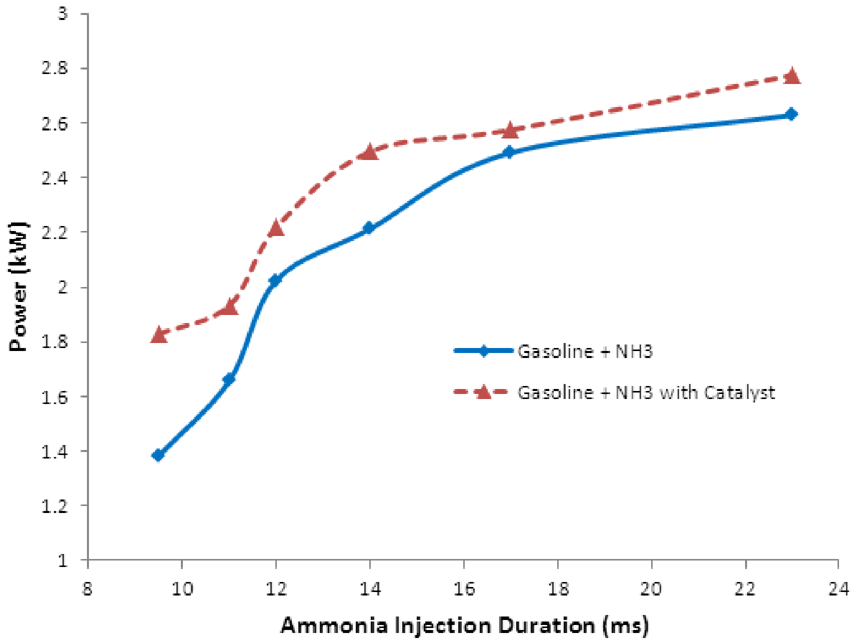
#4 Results – DISI NH_3 with Catalyst

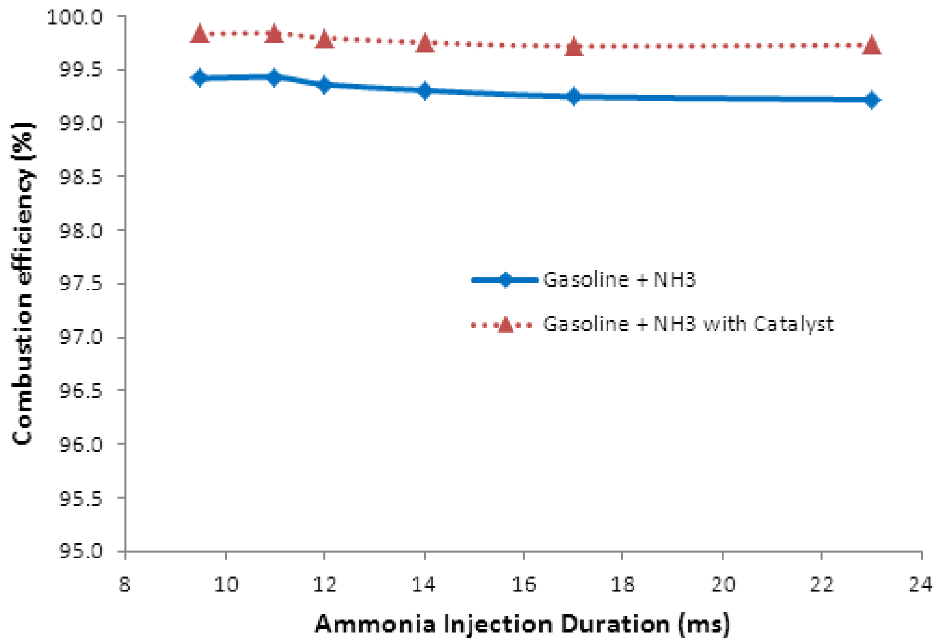
- Ammonia dissociation catalyst coated with 2% ruthenium on 3.175-mm alumina pellets
- Utilize engine exhaust heat



Ammonia Decomposition Catalyst

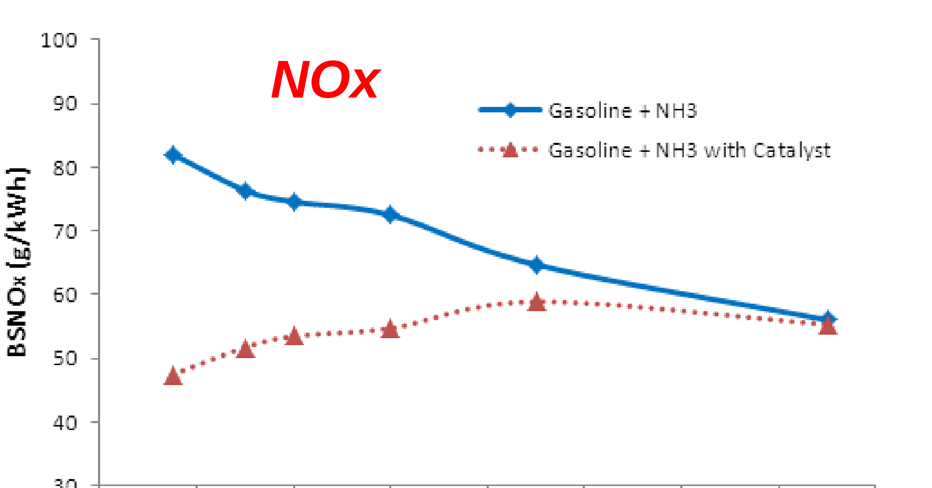
- Engine power and efficiency are increased

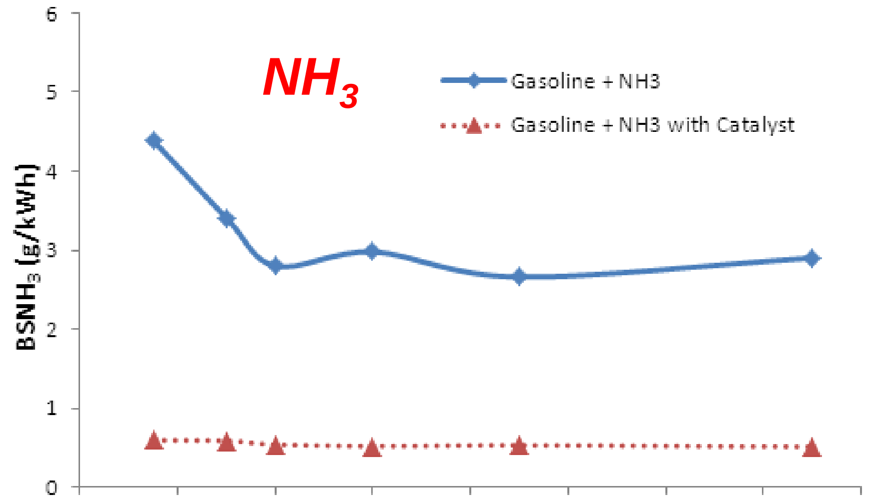


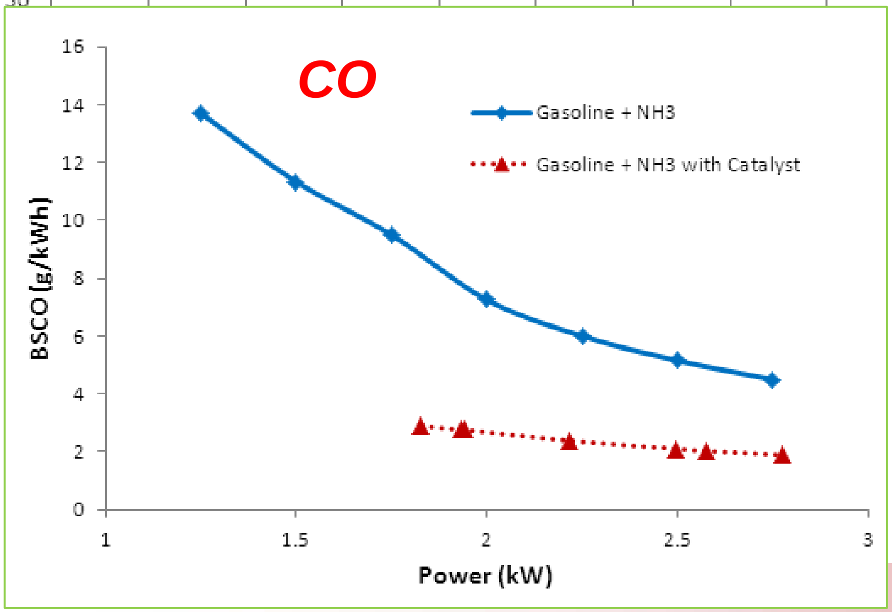


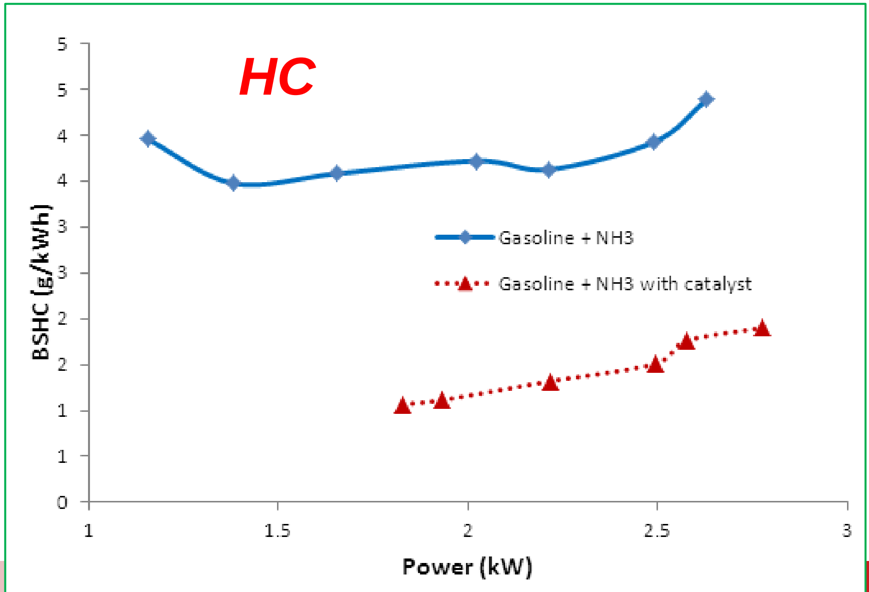
Ammonia Decomposition Catalyst

- Exhaust emissions are reduced









Perspectives

- Current test engine
  - Small size, high heat loss
  - Simple injection system, low injection pressure, low flow rate
  - Simple catalyst arrangement, small quantity
- Future improvement
  - Better injection system, higher flow rate
  - Improved catalyst design and arrangement

Future Direction – Diesel Application

- DON'T
  - Direct injection of liquid ammonia into the cylinder
  - Direct injection of gaseous ammonia into the cylinder
    - Needs to use high injection pressure to overcome the in-cylinder pressure → ammonia will liquefy in the injection line
- DO
  - Diesel pilot injection to initiate combustion
  - Port injection of gaseous ammonia
  - Use ammonia decomposition catalyst
- Key technology
  - Injector – suitable for gaseous ammonia: material compatibility, low pressure, large flow rate
  - Catalyst – geometry/arrangement, utilizing engine exhaust heat
  - Exhaust after-treatment – SCR

Potential Study – Diesel Application

- Our earlier study – older diesel engine
  - Mechanical diesel fuel injection pump
  - Continuous induction of gaseous ammonia into a single point at the intake manifold
- Possible future study
  - New engine, electronically-controlled diesel injection
  - One ammonia injector per cylinder, electronically controlled
    - Preventing unburned ammonia
- RCCI Concept
  - Reactivity-controlled compression ignition
  - Reactive fuel (diesel) to control ignition, less reactive fuel (ammonia) to control combustion duration

Future Direction – Gasoline Engine

- DON'T
  - Direct injection of liquid ammonia into the cylinder
- DO
  - Gasoline to enhance ammonia combustion
  - Port injection of gaseous ammonia
    - Risk of displacing air and reducing volumetric efficiency and engine power
  - Direct injection of gaseous ammonia
    - Narrow injection window – before cylinder pressure rises
- Key technology
  - Injector
  - Catalyst
  - Exhaust after-treatment – SCR

Potential Study – Gasoline Engine

- Our earlier study – CFR engine, DI gaseous NH_3
  - Without throttle control
  - Small injector
- Possible future study
  - Production engine
  - Electronically-controlled gaseous ammonia injection
    - Port injection or direct injection