学術フロンティア「次世代ゼロエミッション・エネルギー変換システム」
技術セミナー
燃料・燃焼制御によるディーゼル燃焼の低エミッション化の研究動向

燃料の物理・化学的特性を駆使した予混合圧縮自着火燃焼の制御

同志社大学大学院
噴霧・燃焼工学研究室
和田 好充

Motivation

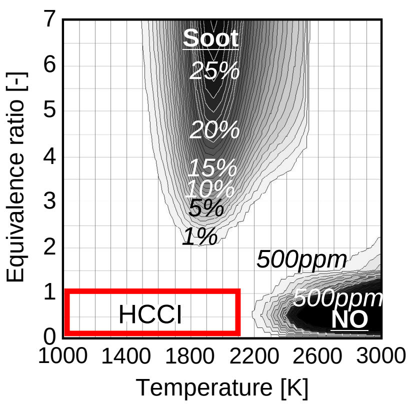
Homogeneous Charge Compression Ignition

Benefits (potential)

- fuel-flexibility
- high thermal efficiency
- reduction of NO_X emission
- reduction of PM emission

Challenges

- controlling ignition timing over a range of speeds and loads
- extending the operating range
  - stretching out the heat-release event
  - promoting the ignition
- mitigating hydrocarbon and carbon monoxide emissions



(fuel: n-heptane, p=6MPa, reaction time: t=2ms)

Ref) 北村ほか (同志社大学) 第17回内燃機関シンポジウム

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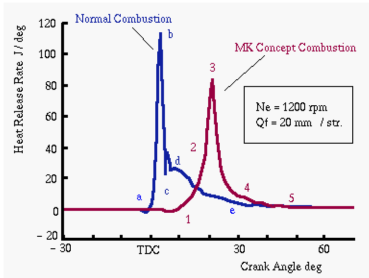
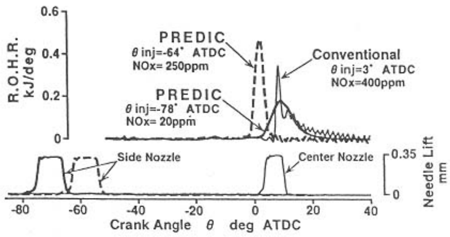
Development in DI HCCI

- **MK (NISSAN)**
  — with high swirl, high EGR and retarded injection timing
- **UNIBUS (TOYOTA)**
  — with dividing fuel injection into two stages in order to enable rapid combustion at low temperatures
- **HiMICS (HINO)**
  — with multiple injection system (early stage inj., pilot inj., main inj., late stage inj.)
- **PREDIC (New ACE)**
  — with two side injectors in order to avoid collision of the spray with cylinder wall



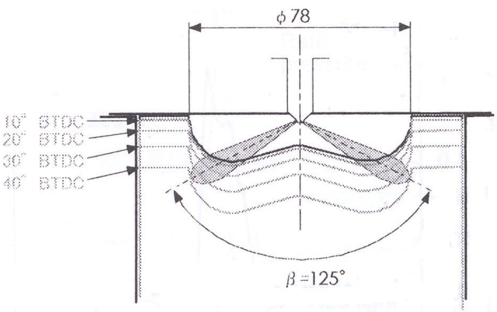
Ref: SAE Paper 1999-01-3681



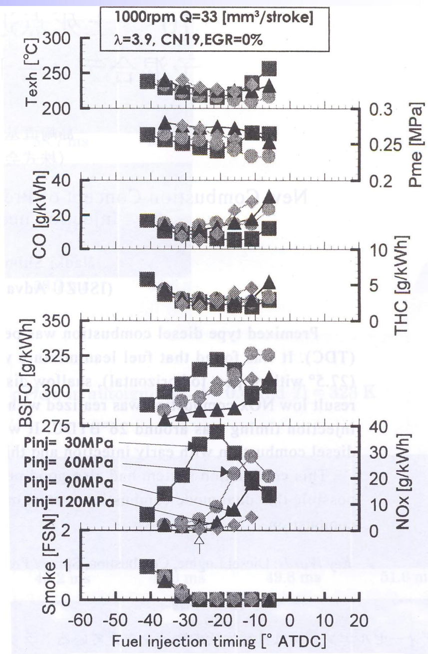
Ref: SAE Paper 961163

Introduction of Recent HCCI Approach -1-

Ref.) **島崎, 西村 (いすゞ中央研究所)**
第17回内燃機関シンポジウム



- Injection near top dead center
  — High pressure fuel injection
  — Small orifice diameter
  — Low cetane number fuel or exhaust gas recirculation

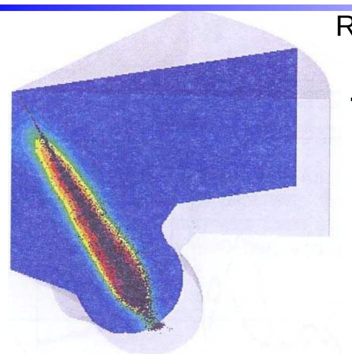


Introduction of Recent HCCI Approach -2-

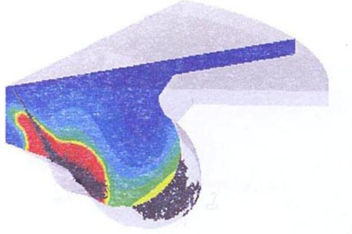
Ref.) G, A. Lechner et al. (Univ. of Michigan)
SAE Paper 2005-01-0167

<Using Narrow Spray Cone Angle Nozzle>
for example – cone angles of 80 or 60deg. about the vertical centerline

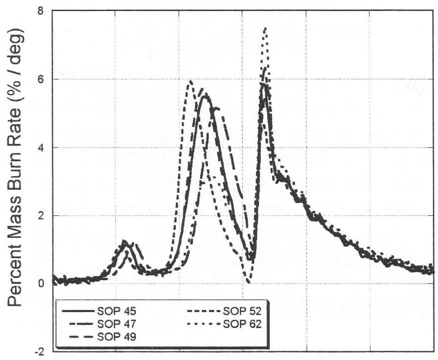
- Injection timing
  (Early injection + Injection near TDC)



First Injection

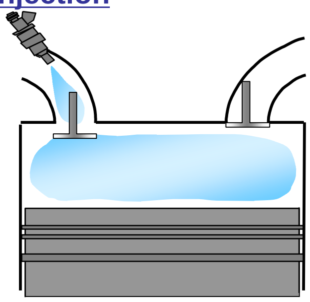


Second Injection



Purpose

Port Injection



- 均一な予混合気の形成が可能

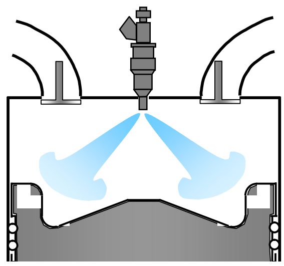
⇩

- 着火・燃焼過程が燃料の化学反応に律則

⇩

- 混合気形成過程など物理的制御が困難

Direct Injection



- 予混合気が不均一

⇩

- 着火・燃焼過程が燃料の分布形態により制御可能

⇩

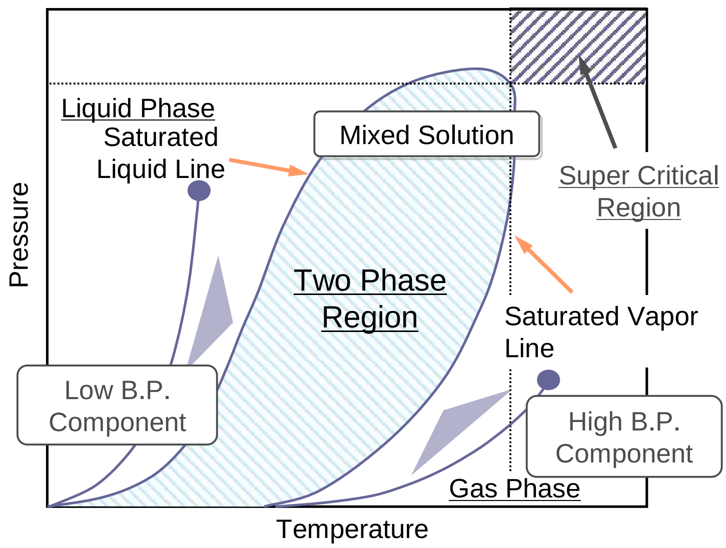
- 混合気の質により人為的な燃焼制御が可能

人為的な介入は予め決定される化学反応特性と燃焼までの物理過程のみ！

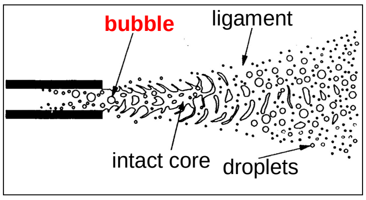
Proposal on Fuel Design Approach

- **Chemical Control** = Capability of Control on Combustion Process
  - Emission control – Soot & NOx
    simultaneous reduction of both soot and NOx (CO_2-gas oil mixing fuel)
  - Ignition control (Gasoline-gas oil mixing fuel)
  - Unburned HC control (Gasoline-gas oil mixing fuel)
- **Physical Control** = Capability of Time and Spatial Control on Fuel Vapor Distribution
  - Formation of Two-Phase Region in Mixing Fuel
    improvement of evaporation on Low Volatility Fuel
  - Use of Flash Boiling Spray
    improvement of spray atomization and evaporation
- **Modification of Fuel** = Control of Fuel Transport Properties
  = Effective Liquefaction of Gaseous and Solid Fuels
  - Fuel Conversion by Sono-Chemistry
  - Conversion of Heavy Fuels or Solid Fuels into high quality Liquid Fuels through Chemical-Thermodynamic

Evaporation Characteristics of Mixed Fuel based on Pressure-Temperature Diagram



Atomization & Evaporation in Flashing Spray



Bubble Nucleation rate

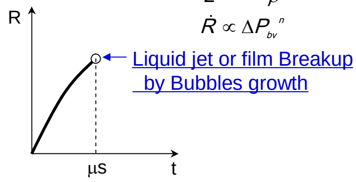
$$N \propto C \cdot \exp\left(-\frac{\Delta A}{k\Delta\theta}\right)$$

$$\Delta A = \frac{4}{3}\pi R^2 \cdot \sigma$$

Evaporation rate = Bubble growth Rate

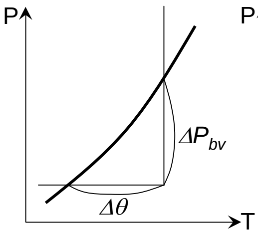
Rayleigh-Plesset **Eq.** $R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}(P_w - P_r)$

$$\dot{R} \propto \Delta P_{bv}^{\ n}$$

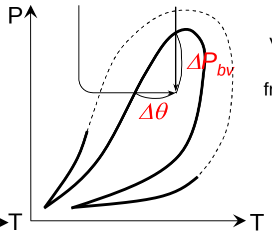


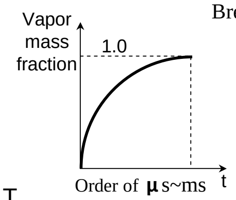
※ Evaporation due to Enthalpy balance of fuels without aerodynamic force

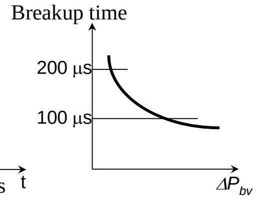
Single Component



Multi-Component







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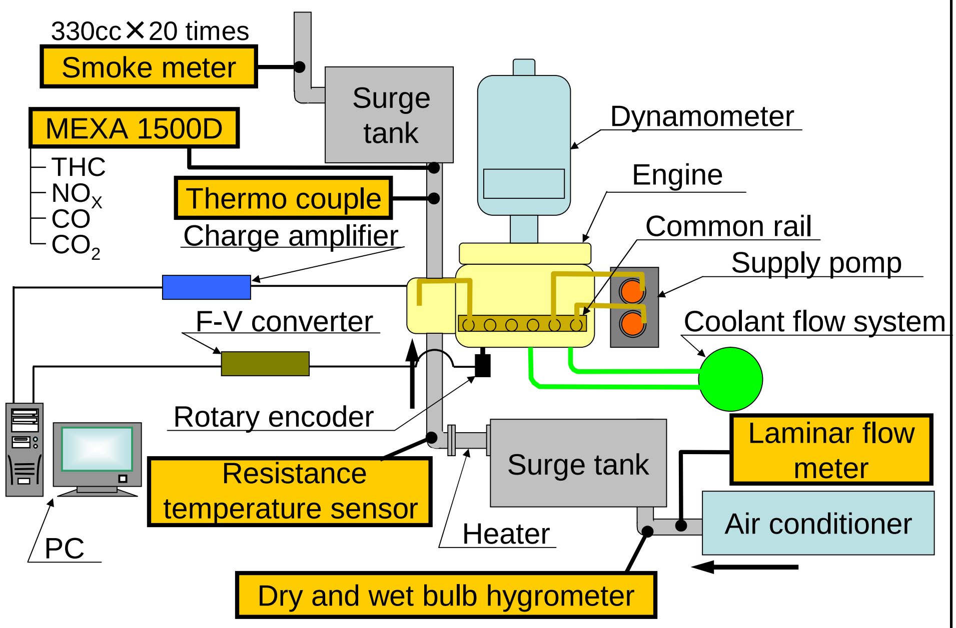
Engine Specifications and Experimental Conditions

Engine type	DI Diesel,single cylinder, water cooled 4 stroke cycle,2 valves
Bore×Stroke [mm]	ϕ110×106
Compression ratio ε [-]	16.3 , 14.0
Combustion chamber	Dish
Engine speed [rpm]	1200
Intake temperature [K]	303
Intake relative humidity [%]	35
Fuel injection system	Common-rail
Nozzle configuration	ϕ0.14×8 (Angle 60deg.)
Injection pressure [MPa]	72
Injection timing [deg. BTDC]	-100, -90, -80, -70, -60, -50, -40
Fuel (n-C_7H_{16}/i-C_8H_{18} mixture)	PRF0, 20, 40, 60, 80
Equivalence ratio ϕ [-]	varied

Schematic Diagram of Experimental Setup for Engine Test



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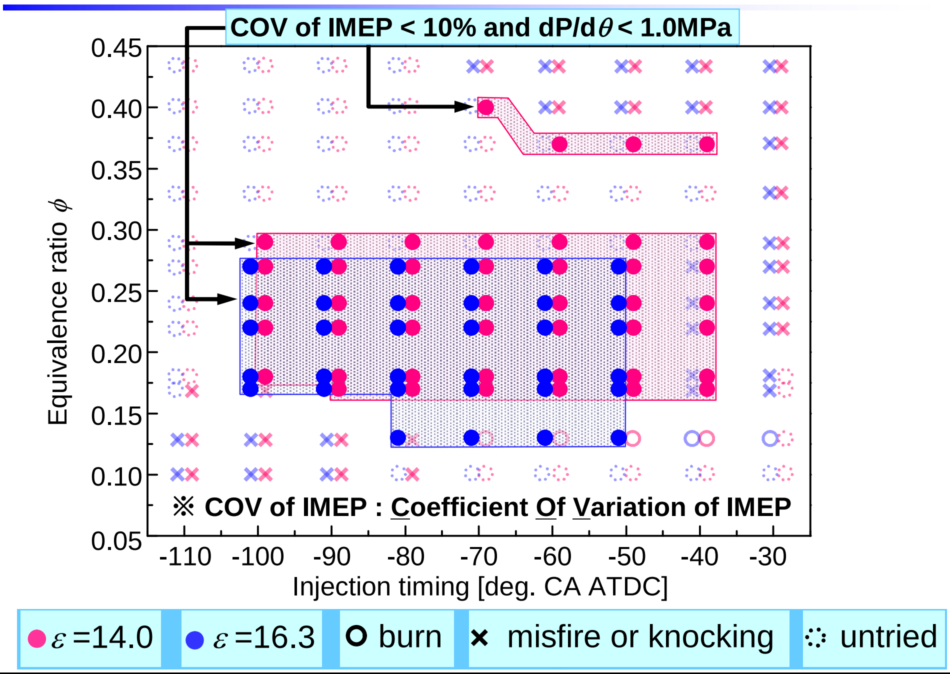
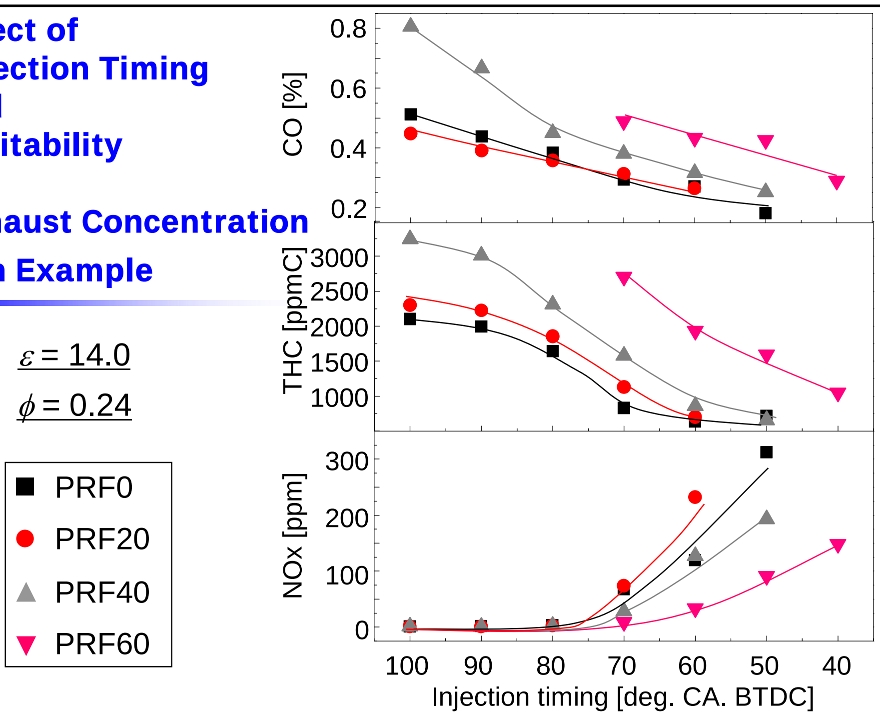
Operating Range Tested



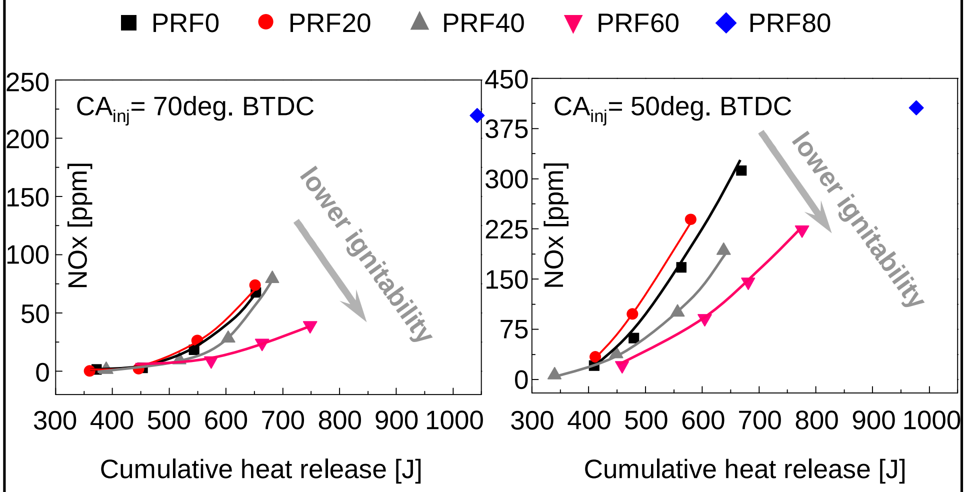
Effect of Injection Timing and Ignitability on Exhaust Concentration : An Example

$\varepsilon = 14.0$

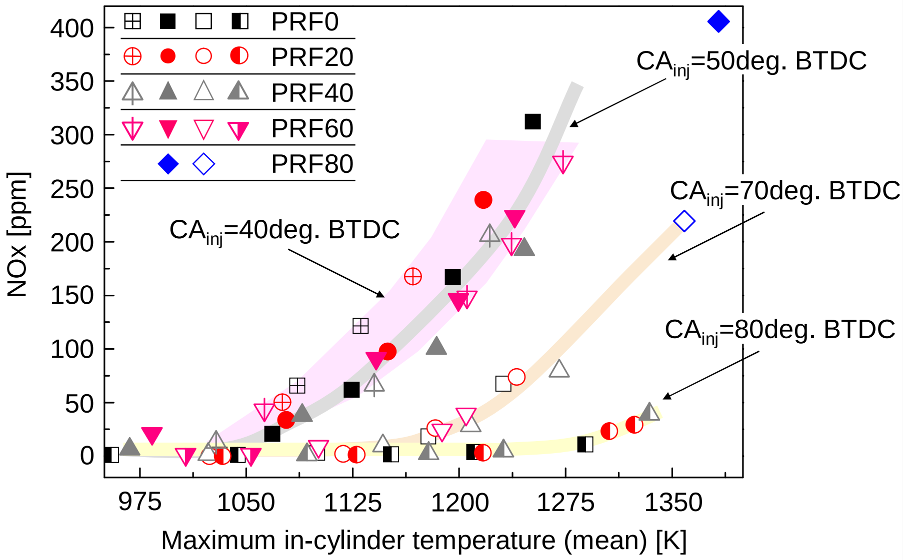
$\phi = 0.24$



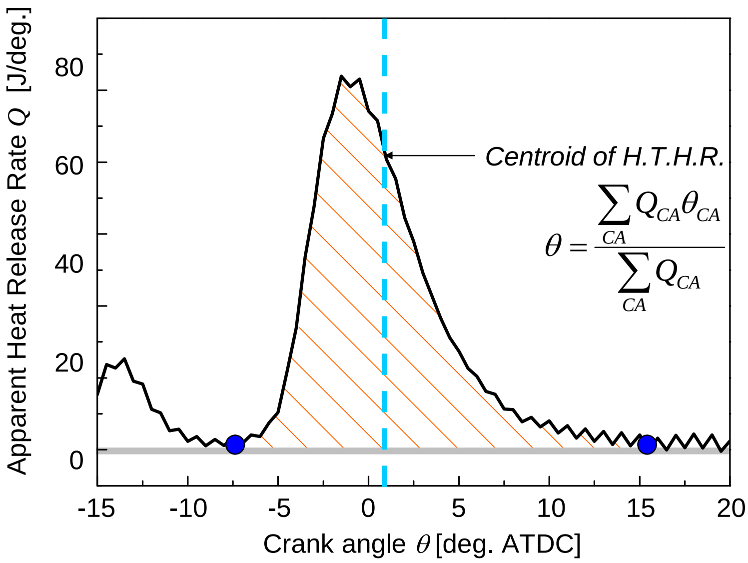
NOx Concentration as a Function of Cumulative Heat Release (ε =14.0)



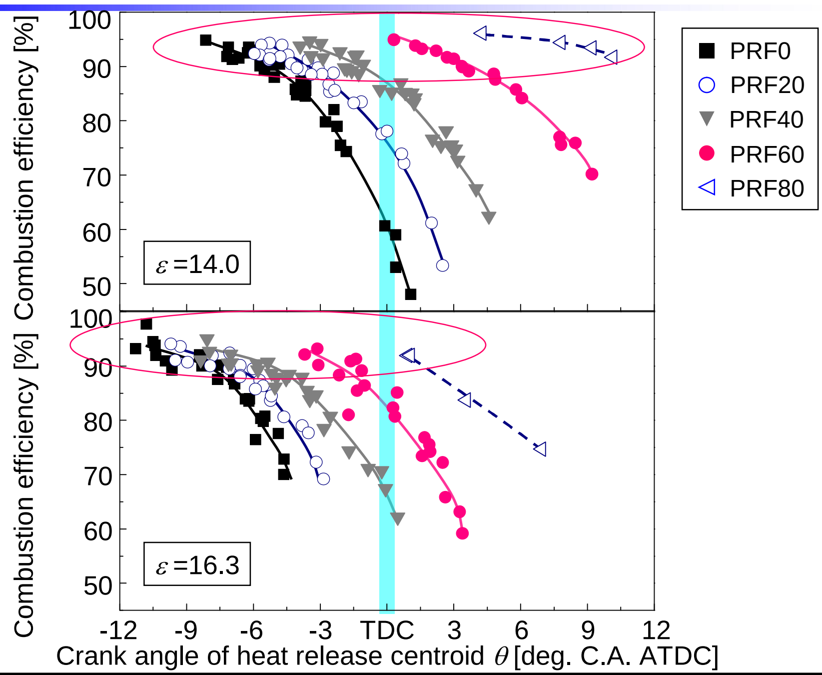
NOx Concentration as a Function of Maximum In-Cylinder Temperature (ε =14.0)



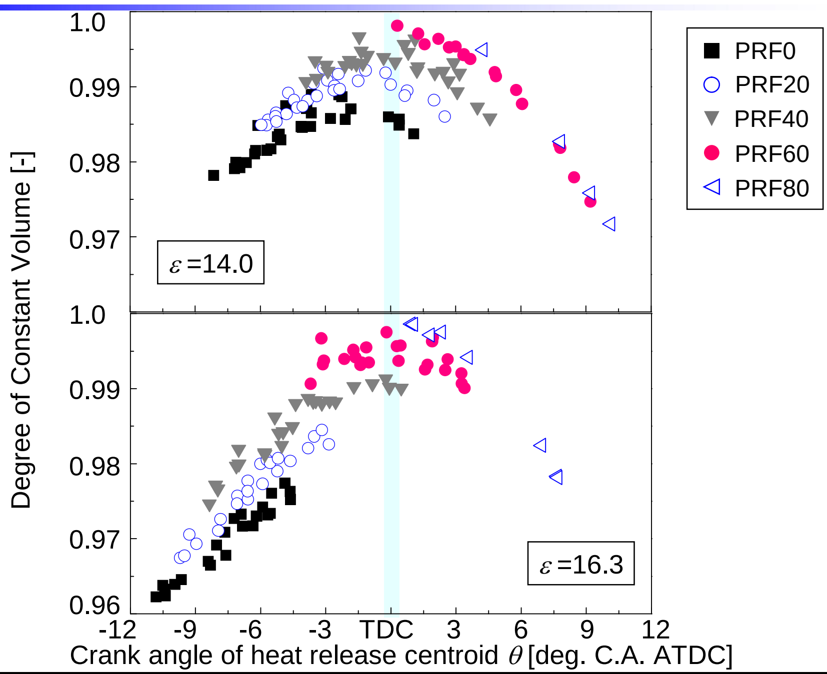
Definition of Heat Release Centroid during H.T.H.R.



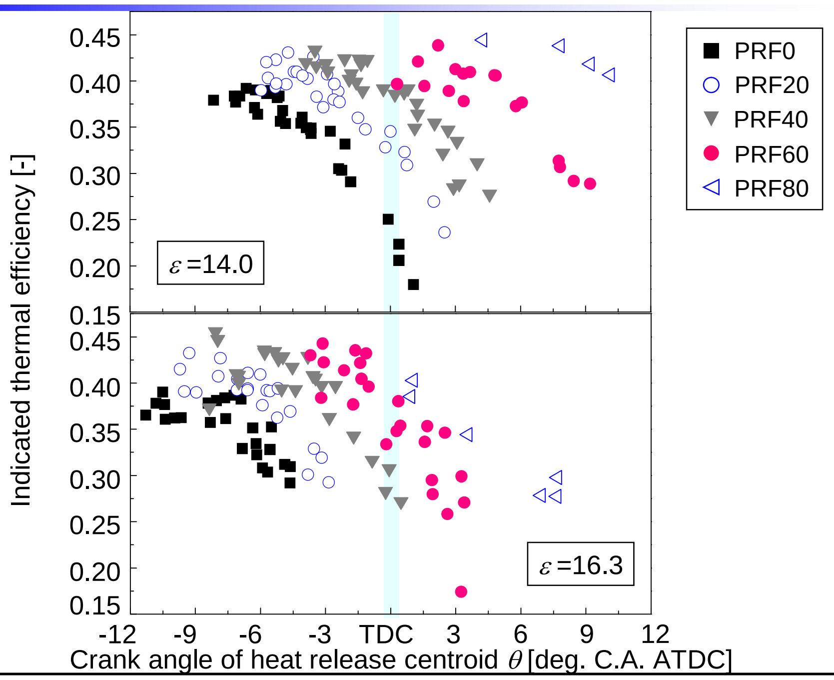
Combustion Efficiency vs. Heat Release Centroid



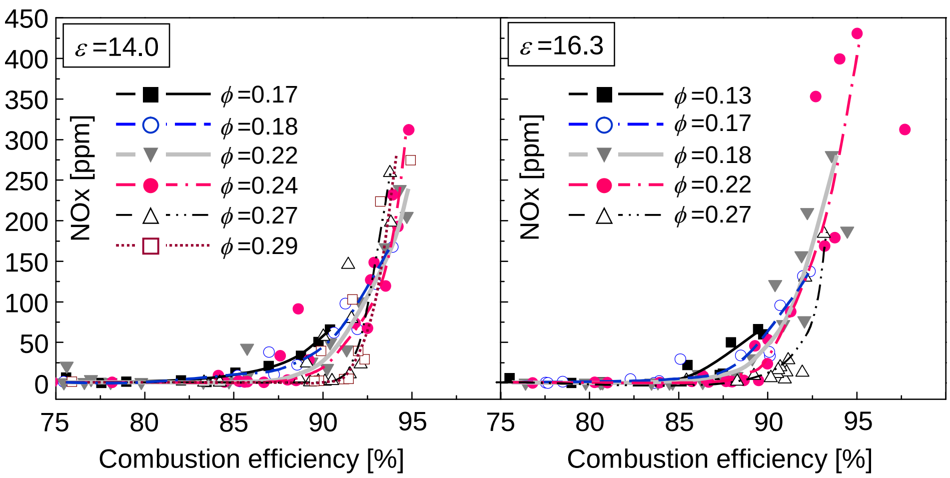
Degree of Constant Volume vs. Heat Release Centroid



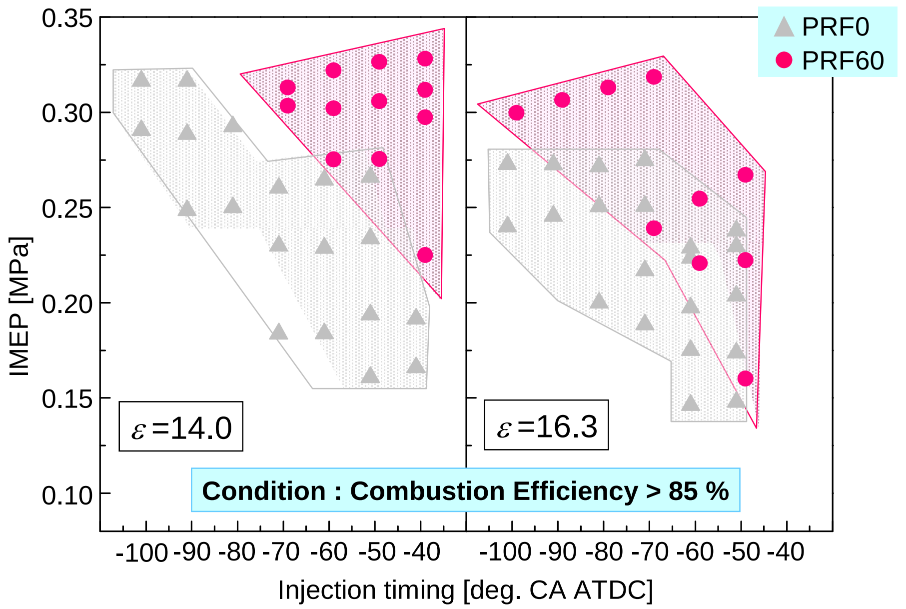
Indicated Thermal Efficiency vs. Heat Release Centroid



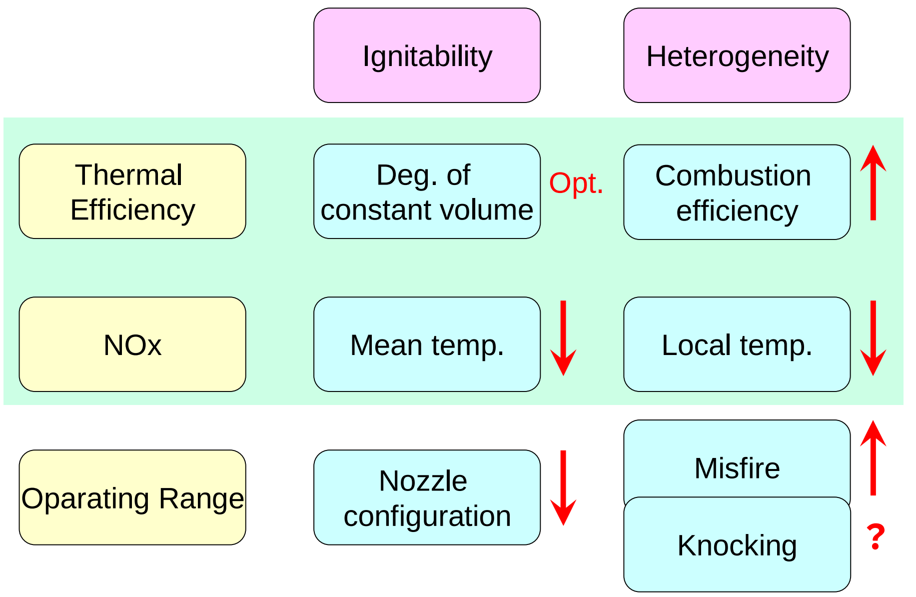
Relation between NOx Concentration and Combustion Efficiency



Successful Operating Conditions in Our Range Tested

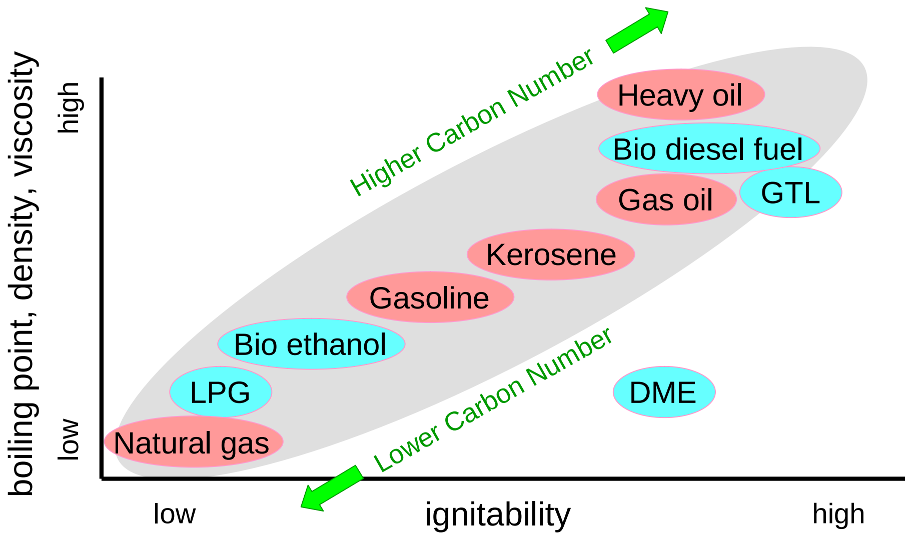


Tentative Summary



※Comparison with Gas Oil

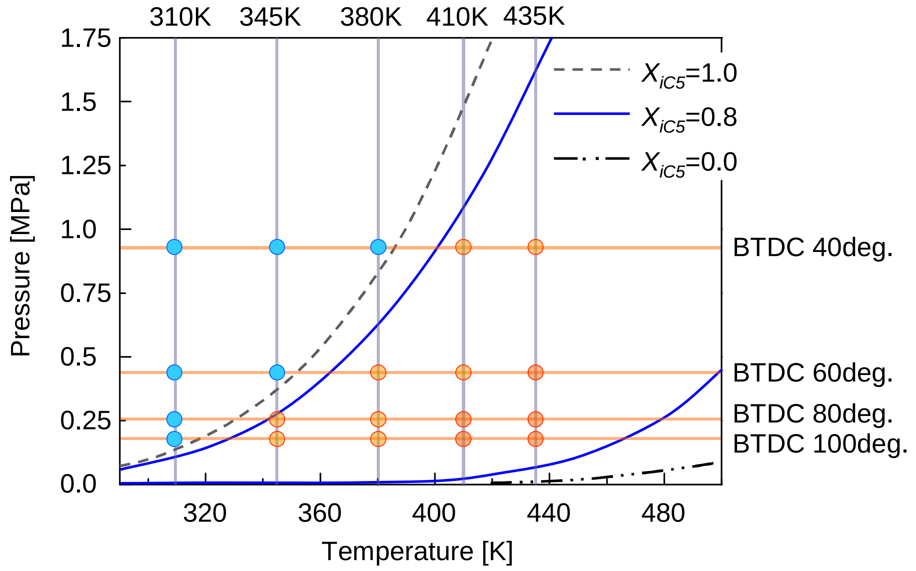
Summary of Conventional and Alternative Fuel relating to Physical and Chemical Characteristics



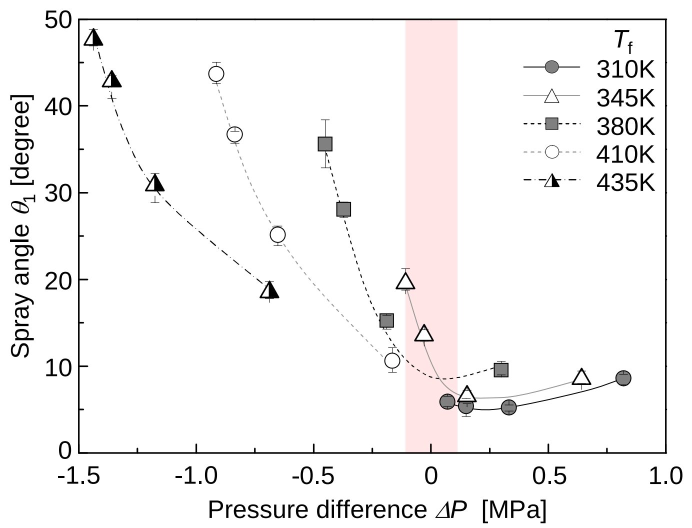
Experimental Conditions in case of Chamber Test

Injection equipment	Common-rail type			
Nozzle hole diameter [mm]	0.20 (L_n/d_n = 4)			
Orifice pressure drop [MPa]	50.0			
Injection quantity [mg]	22.2			
Fuel temperature T_f [K]	310, 345, 380, 410, 435			
Ambient gas	N_2			
Simulated crank angle [deg.BTDC]	100	80	60	40
Ambient temperature [K]	405	445	515	625
Ambient density [kg/m^3]	1.5	2.0	3.0	5.2
Ambient pressure [MPa]	0.17	0.26	0.44	0.93

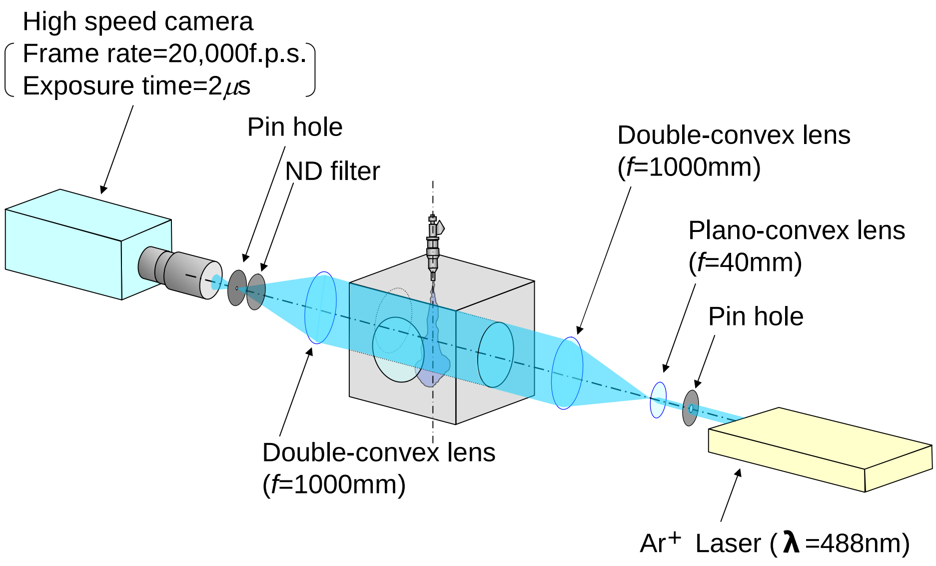
Experimental Conditions Plotted on Pressure-Temperature Diagram



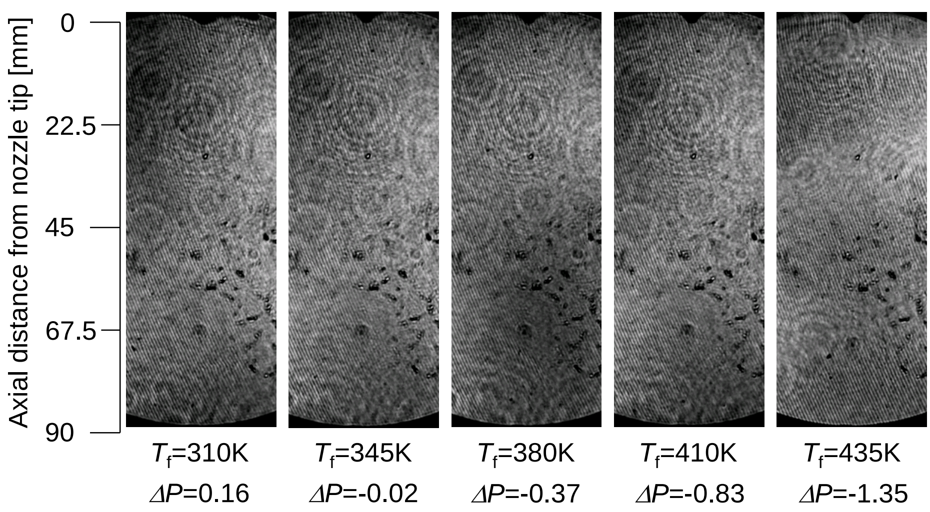
Spray Cone Angle Measured near Nozzle Exit (0 to 2mm from Nozzle Exit)



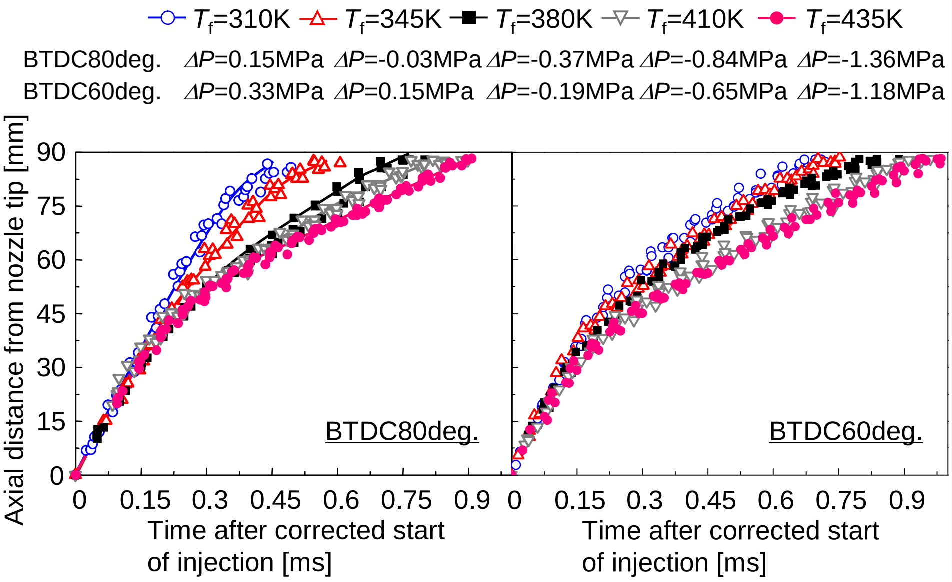
Optical Setup for Schlieren Photography



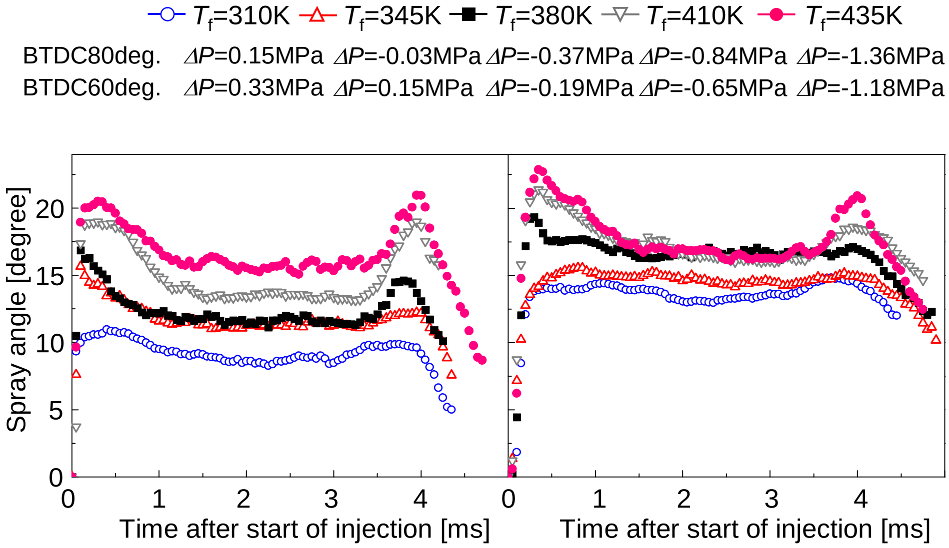
Schlieren Images for each Initial Fuel Temperature
Simulated Crank Angle = 80deg.BTDC



Temporal Change in Spray Tip Penetration for each Initial Fuel Temperature



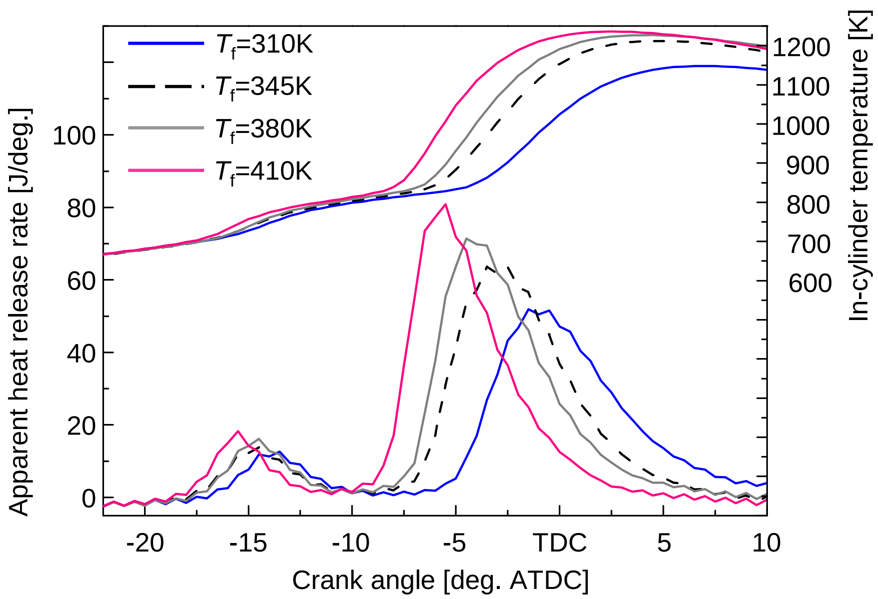
Temporal Change in Spray Dispersion Angle for each Initial Fuel Temperature



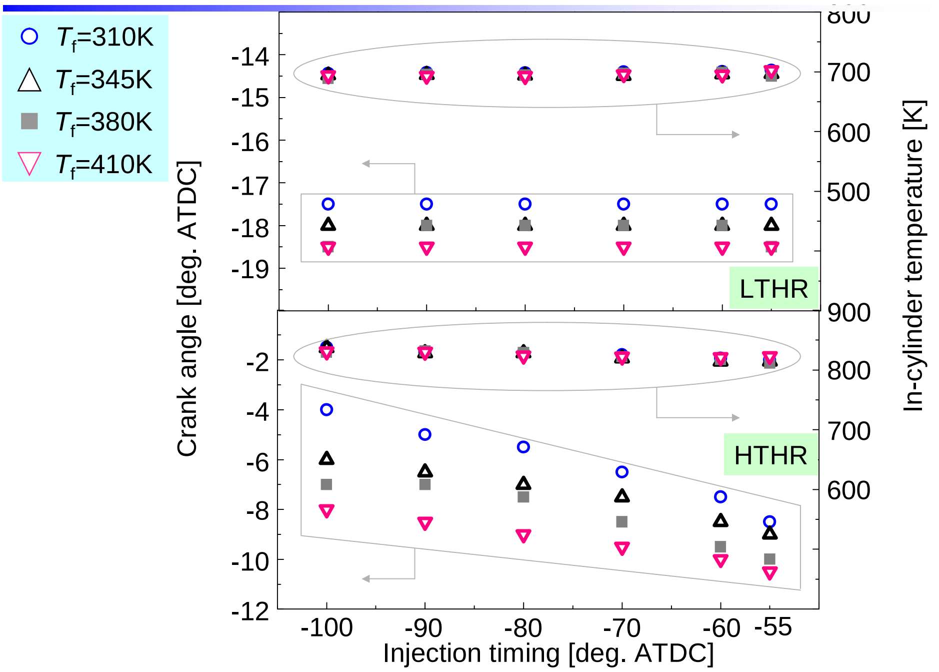
Engine Specifications and Experimental Conditions

Engine type	DI Diesel,single cylinder, water cooled 4 stroke cycle,2 valves
Bore × Stroke [mm]	ϕ110 × 106
Compression ratio ε [-]	14.0
Combustion chamber	Dish
Engine speed [rpm]	1200
Intake temperature [K]	303
Intake relative humidity [%]	35
Fuel injection system	Common-rail
Nozzle configuration	ϕ0.198 × 4 (Angle 60deg.)
Injection pressure [MPa]	50
Injection timing [deg. BTDC]	-100, -90, -80, -70, -60, -55
Fuel	n-$C_{13}H_{28}$ / i-C_5H_{12} (X_{iC5}=0.8)
Initial fuel temperature [K]	310, 345, 380, 410
Equivalence ratio ϕ [-]	0.30

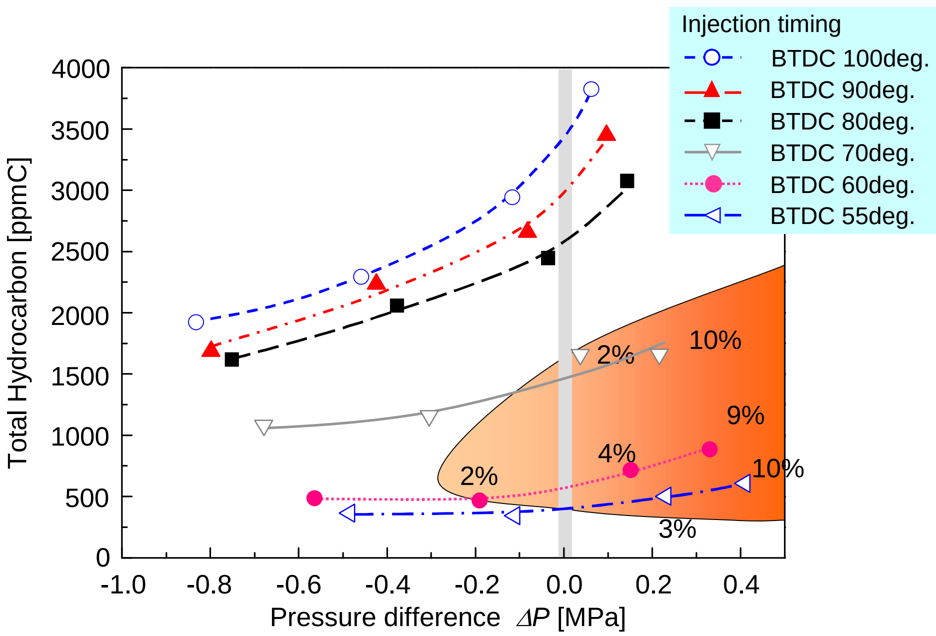
An Example of Apparent Heat Release Rate (BTDC 80deg.)



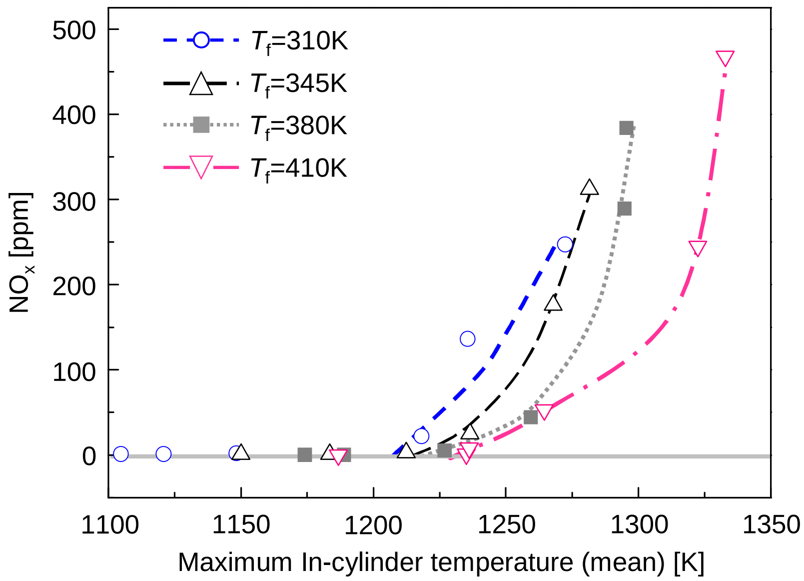
Crank Angle and Temp. when LTHR and HTHR Start



Total Hydrocarbon Emission as a Function of ΔP



NO_X Concentration vs. Maximum In-Cylinder Temperature



Conclusion (1)

- 燃料の着火性は各機関条件に対し燃焼時期を決定する役割がある.
- 比較的遅い噴射時期では燃料の着火性が混合気の不均一性に影響を及ぼす.
- 低負荷時における混合気の過度な希薄化は燃焼効率の悪化を招く.
- ただし, 混合気の不均一性はNOxの排出と深い関わりがあり, その排出量により燃焼効率ひいては熱効率が制限される.
- 噴射量の増加に伴い, 低NOxを維持したまま燃焼効率を向上できる範囲が広がる.
- 燃料の着火性と混合気の不均一性により運転可能な負荷範囲が規定される.

Conclusion (2)

- 早期燃料噴射時の低圧雰囲気条件下では低沸点成分を混合した2成分混合燃料を用いることで，容易に減圧沸騰噴霧が得られる．
- 雰囲気条件と過熱度（減圧度）の適切な組み合わせにより，早期筒内噴射式予混合圧縮着火機関の未燃排出成分は抑制可能である．
- 減圧沸騰の適用により，高い燃焼効率でも低NOx化の可能性がある．
- 減圧沸騰による噴霧性状の改善は高沸点成分のピストン表面への燃料付着に起因する黒煙の排出を改善する．

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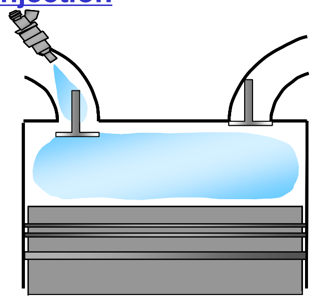
Fuel-Supply Systems in HCCI Operation

Port Injection



- 均一な予混合気の形成が可能

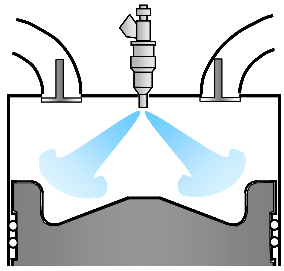
⇩

- 着火・燃焼過程が燃料の化学反応に律則

⇩

- 混合気形成過程など物理的制御が困難

Direct Injection



- 予混合気が不均一

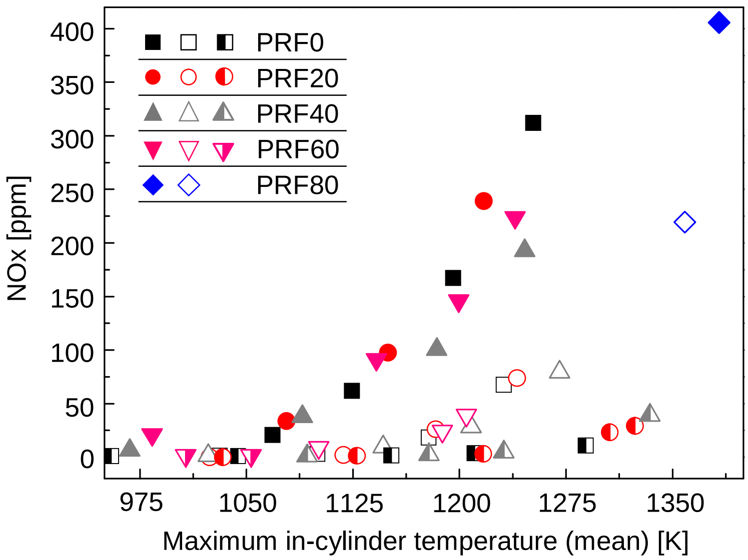
⇩

- 着火・燃焼過程が燃料の分布形態により制御可能

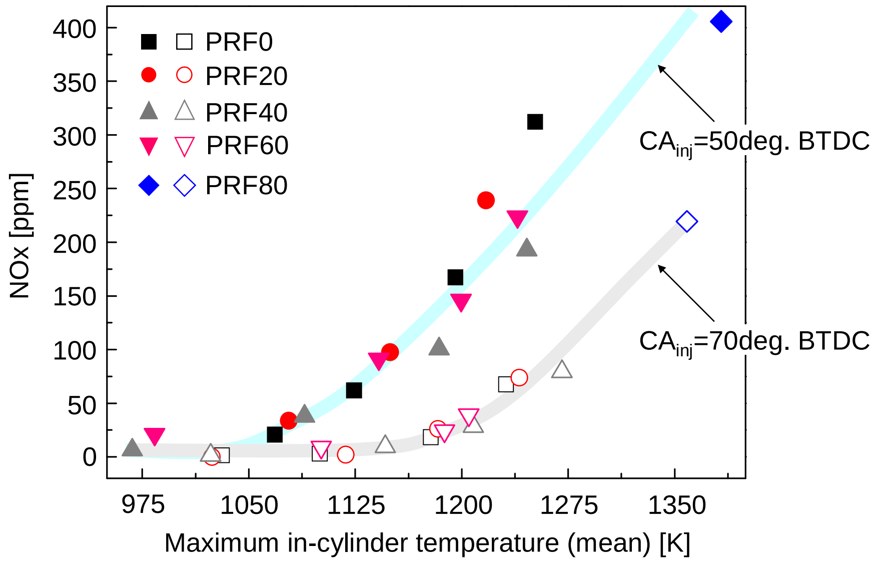
⇩

- 燃料噴霧の質により人為的な燃焼制御が可能

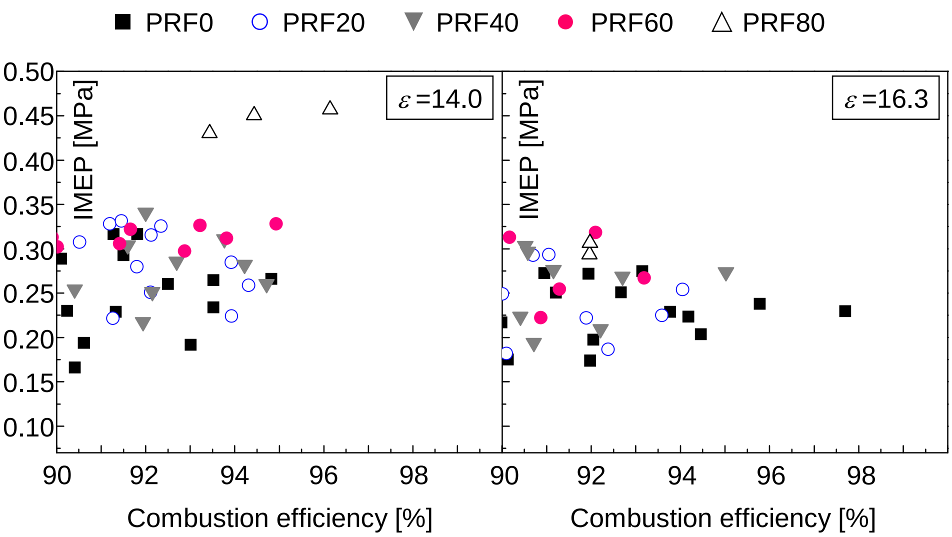
NOx Concentration as a Function of Maximum In-Cylinder Temperature (ε =14.0)



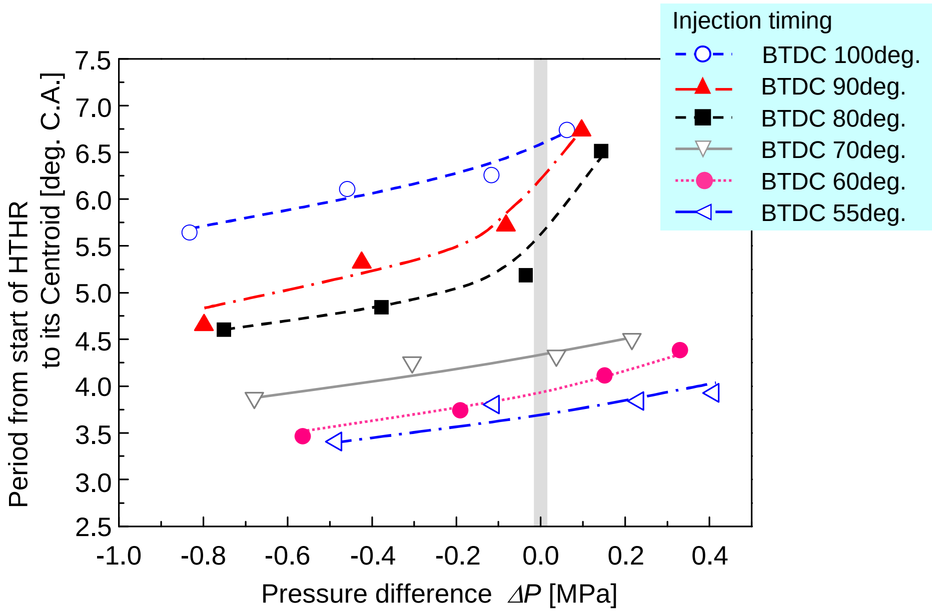
NOx Concentration as a Function of Maximum In-Cylinder Temperature (ε =14.0)



IMEP vs. Combustion Efficiency for each Octane Number



Period from Start of HTHR to its Centroid for each ΔP



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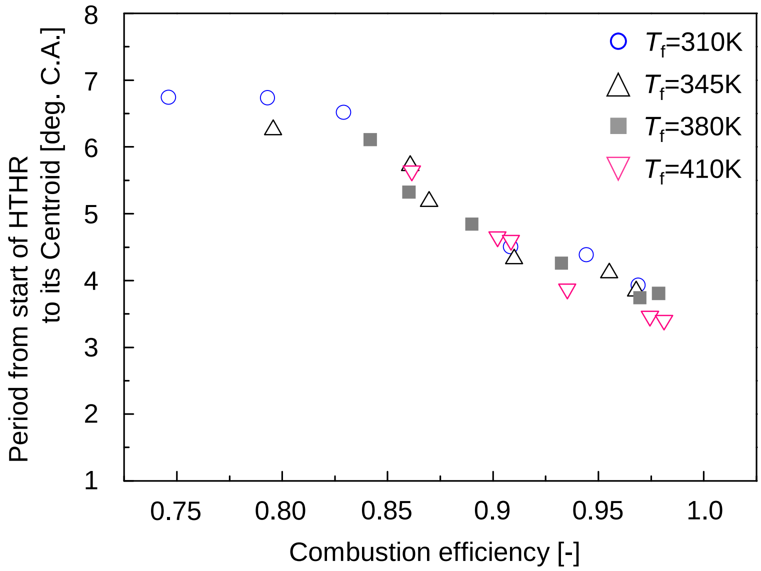
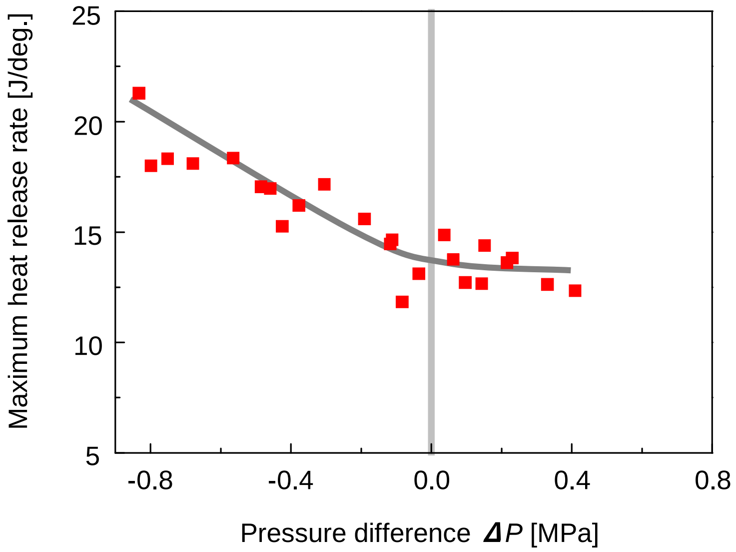
Period from Start of HTHR to its Centroid as a Function of Combustion Efficiency



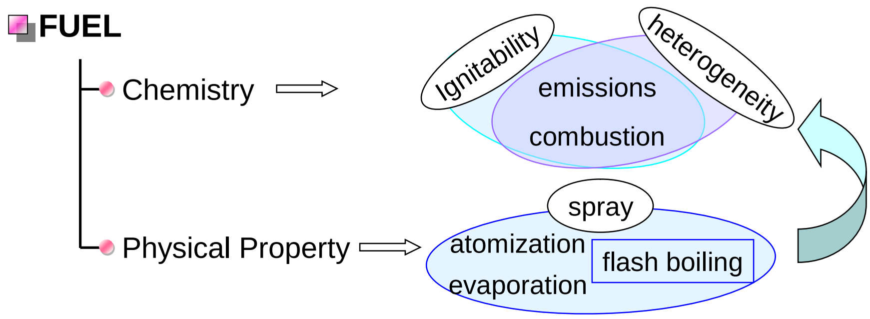
Doshisha University – Energy Conversion Research Center & Spray and Combustion Science Laboratory –

Maximum Heat Release Rate during LTHR as a Function of Pressure Difference ΔP



Purpose

1st step : for early injection



⇨ **燃料の物理･化学的特性がHCCI燃焼へ及ぼす影響を調べ，その最適化法および限界を知る**

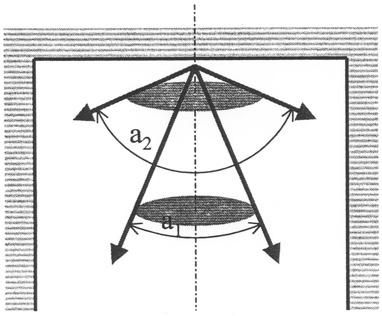
2nd step : for multiple injection

Introduction of Recent HCCI Approach -3-

Variable Geometry Spray

Ref.) Y. Ra and R. D. Reitz (ERC)
SAE Paper 2005-01-0148

is capable of changing the spray angle with time in various ways.



a_1 : starting spray angle
a_2 : ending spray angle