The 32th IEA/TLM in Nara (2010.7)

Combustion Control by Use of Several Mixing Fuels Related to Flash Boiling Spray

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Ⅰ Background – Recent Research Trend (HCCI etc.)
Borderless in Gasoline Eng. and Diesel Eng.

Ⅱ Flash Boiling Spray Process

Ⅲ Proposal of Fuel Design Approach for Both Engines

Ⅳ Author's Fuel Design Approach Researches

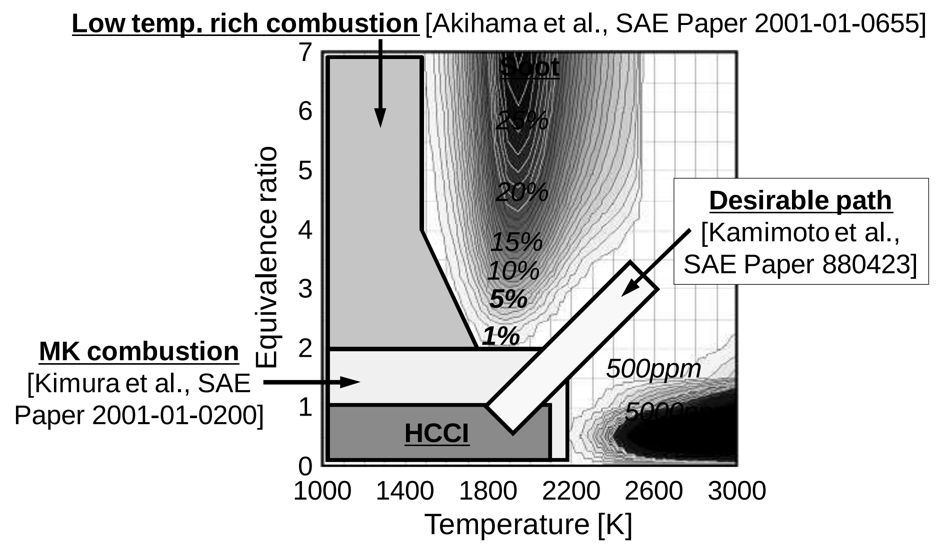
Ⅴ Future Extending Research Aspect

BACKGROUND - New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction

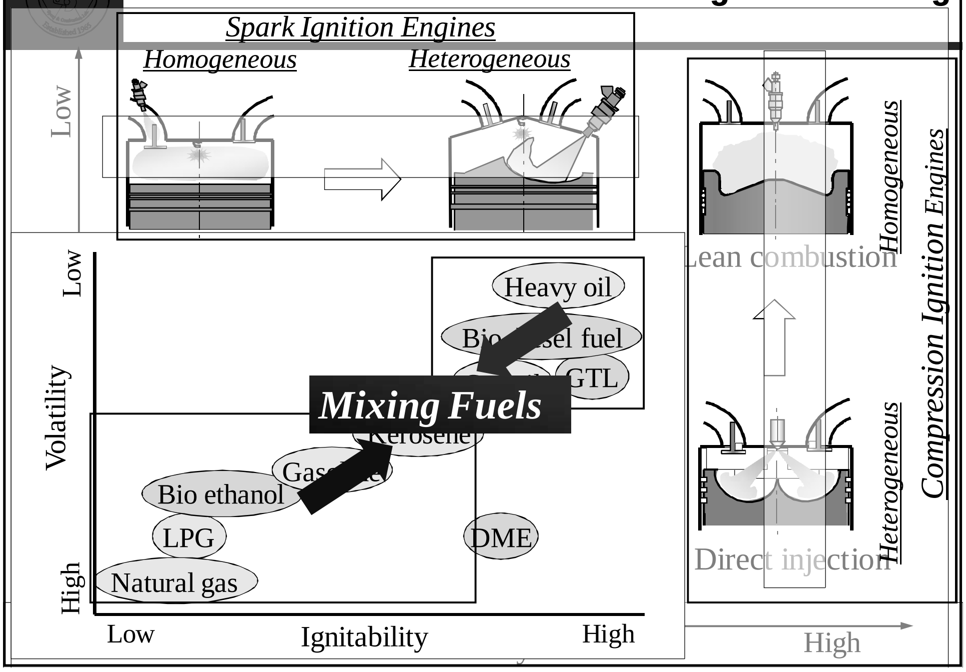
Injection + (Suction Flow)

Improve atomization and turbulent mixing to reduce soot	Optimize temporal and spatial mixture distributions in-cylinder to reduce both soot (PM) and NO by DISC combustion
High-Pressure Fuel Injection ↓ High-Pressure Fuel Injection + Small Orifice Nozzle	Injection Rate Control (Boot Injection, Pilot Injection) Pre-mixture Intake + In-cylinder Injection (Fumigation, Dual-Fuel) Split Injection Lean-Homogeneous Mixture Formation and Rapid Combustion by Early Injection or Retard Injection: PREDIC, UNIBUS (Single Stage) → MULDIC, HiMICS (Two Stage) <u>Fuel Conversion / Additive Injection</u>: ・Water Injection ・Emulsion Injection → **Our Fuel Design Approach**

Diesel Combustion Scheme in Equivalence Ratio – Temperature Map



Borderless Situation in Gasoline Eng. & Diesel Eng.



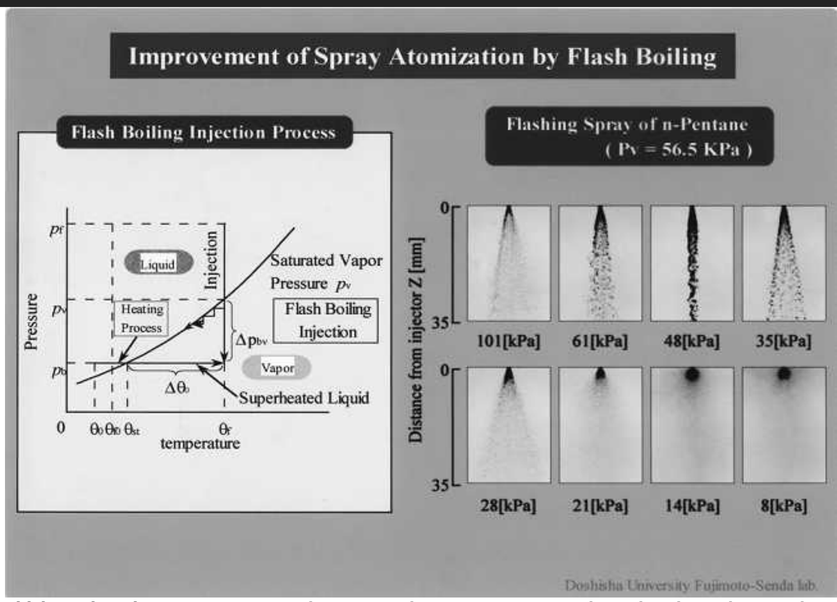
Proposal of Fuel Design Approach for Both Engines

Key technology = Flash Boiling Spray

1. Mixing Fuel with Liquefied CO2
2. Mixing Fuel with High and Low Volatility Fuels
3. We are now extending the Fuel Design Approach into HCCI
   →we will present the summary of this approach in future

*Possibility of Flashing Spray due to lower Ta & Pb
*Mixing Additives can control the Ignition Process
*Controllability of Spatial Vapor Distribution due to the Two Phase Region Profile

What is Flash Boiling Spray ?



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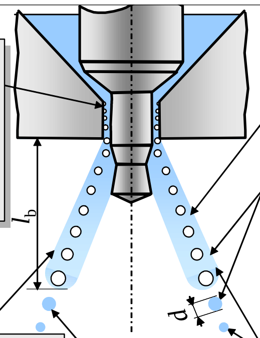
Modeling of Flash Boiling Spray

Nucleation process

$$N=1.11\times10^{12}\exp\left(-5.28/\Delta T_0\right)\times\left\{10^{-4.34\exp(-5t)}\right\}$$

Initial bubble diameter $2R_0$

$2R_0$=20mm



Bubble growth process

$$R\ddot{R}+\frac{2}{3}\dot{R}^2=\frac{1}{r}\left(P_W-P_r\right)$$

and

$$P_W=P_V+\left(P_{r0}+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3n}-\frac{2\sigma}{R}-\frac{4\mu_1\dot{R}}{R}-\frac{4\kappa\dot{R}}{R^2}$$

Vapor formation process

(1) By cavitation bubbles growth

$$dM_{cb}=\frac{4}{3}\rho_v\pi N\left(R_{n+1}{}^3-R_n{}^3\right)$$

(2) Owing to heat transfer

$$dM_{ht}=\frac{\alpha_{ht}\left(T_a-T_f{}'\right)A\cdot dt}{h_{fg}}$$

(3) By superheated degree

$$dM_{sh}=\frac{\alpha_{sh}\left(T_l{}''-T_{st}\right)A\cdot dt}{h_{fg}}$$

Droplet formation process

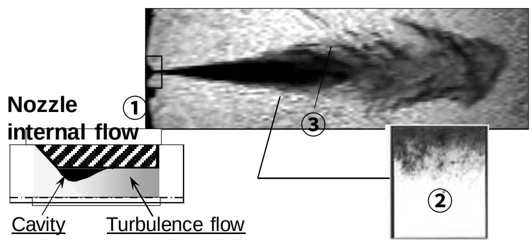
$$\varepsilon=\frac{V_{bubble}}{V_{bubble}+V_{liquid}}\geq\varepsilon_{max}$$

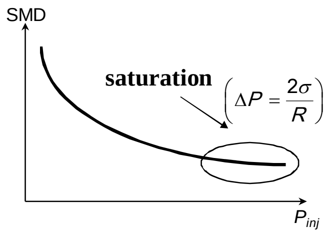
Droplet number = 2 × Bubble number

Atomization & Evaporation in Pressure atomizer

→ Time & Spatial delay depending on P_{inj}, ρ_a, T_a

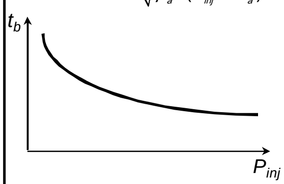
Aerodynamical Process : disturbance ⇒ ligament ⇒ droplets





① Breakup delay of spray

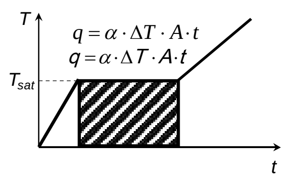
$$t_b=28.65\frac{\rho_l\cdot d_0}{\sqrt{\rho_a\cdot(P_{inj}-P_a)}}$$



②Evaporation of droplets

$$Nu=c\cdot\mathrm{Re}^{\alpha}\cdot\mathrm{Pr}^{\beta}\longrightarrow Nu=2$$

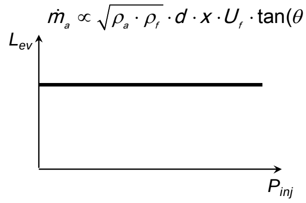
$Nu=c\cdot\mathrm{Re}^{\alpha}\cdot\mathrm{Pr}^{\beta}$



③Evaporation length of spray

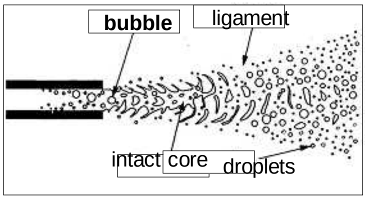
$$\dot{m}_f\propto\rho_f\cdot d_2\cdot U_f$$

$$\dot{m}_a\propto\sqrt{\rho_a\cdot\rho_f}\cdot d\cdot x\cdot U_f\cdot\tan(\theta/2)$$



Atomization & Evaporation in Flash Boiling Spray

→Non Time & Spatial delay depending on Two Phase profile($\Delta P_{bv}(\Delta\theta)$)



Bubble Nucleation rate

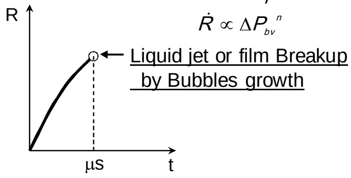
$$N \propto C \cdot \exp\left(-\frac{\Delta A}{k\Delta\theta}\right)$$

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

Evaporation rate = Bubble growth Rate

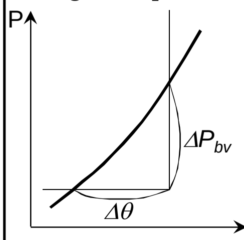
Rayleigh-Plesset **Eq.** $R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}(P_w - P_r)$

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

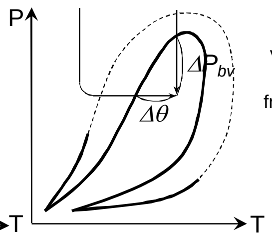


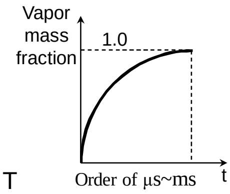
※ Evaporation due to Enthalpy balance of fuels without aerodynamic force

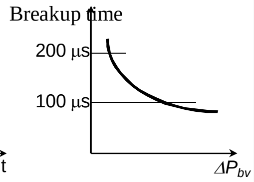
Single Component



Multi-Component







Our Fuel Design Approach Concept

1.Physical Control = Capability of Time and Spatial Control on Fuel Vapor Distribution by Formation of Two Phase region in Mixing Fuel

→ **Formation of Flash Boiling Spray →Improvement of Spray Evaporation**
Lower B.P. fuel could promote the evaporation of Higher B.P. fuel

2.Chemical Control = Capability of Control on Combustion Process

→ **Emission Control – Soot & NOx**
Simultaneous reduction of both Soot and NOx (CO2-gas oil mixing fuel)

→ **Ignition Control (Gasoline-gas oil mixing fuel)**

→ **HC Control (Gasoline-gas oil mixing fuel)**
Higher B.P.fuel could assist the ignition and combustion of Lower B.P. fuel

3.Improving Thermal Efficiency by Lower Injection Pressure

→ **High Spray Atomization and Evaporation Quality with Flashing Process**

4.Control the Fuel Transportation Properties in Mixing Fuels

5.Effective liquefaction of gaseous and solid fuels

→ **Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics & Sono-chemistry**

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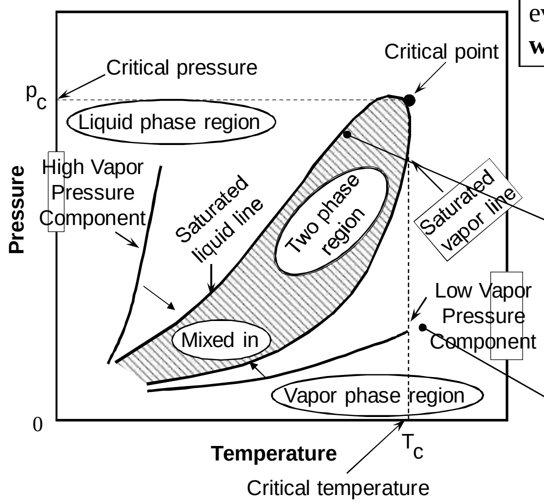
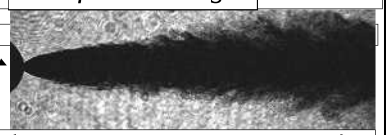
Two Phase Region Formation in Multi-component Fuel in Phase Change Process

Pressure-temperature diagram



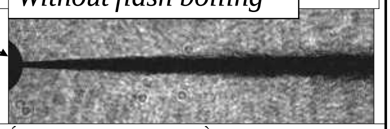
Fine atomization and prompt evaporation
without High Pressure Injection

With flash boiling



（Fuel : n-tridecane + i-pentane）

Without flash boiling



（Fuel : n-heptane）

Numerical Simulation of Two-component Fuel Spray

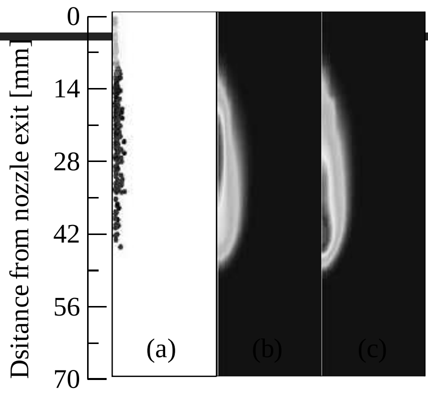
Initial fuel properties
- NIST mixture database
- ($f(T) \Rightarrow f(T, P)$)

Fuel injection
- Injection of multicomponent fuel parcel

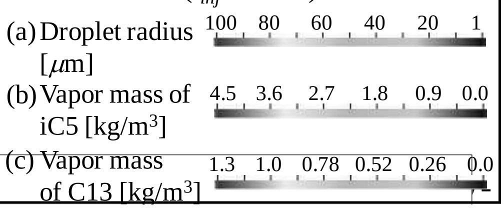
Breakup
- KH-RT model
- *Ref) Reitz et al, SAE Paper 971591*

Evaporation
- Vapor-liquid equilibrium (non-ideal mixture)
- Modified spalding model (Le=1 $\Rightarrow$ $Le \neq 1$)
- Two-zone model

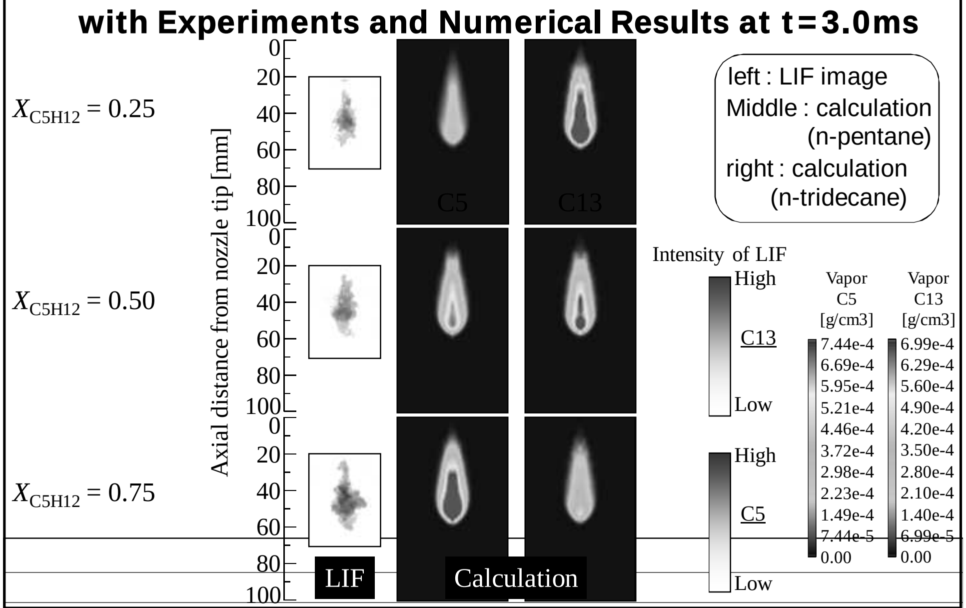
Renewal of fuel properties
- NIST mixture database
- ($f(T) \Rightarrow f(T, P)$)



$nC_{13}H_{28}$(B.P.509K) / iC_5H_{12}(B.P.301K)
(t_{inj}=0.8 ms)



Comparison of Spray Structure –Vapor Spatial Distribution–



Proposal on Fuel Design Approach Research

(1) Physical Control = Capability of Time and Spatial Control on Fuel Vapor Distribution by Formation of Two Phase region in Mixing Fuel
→ Formation of Flash Boiling Spray →Improvement of Spray Evaporation

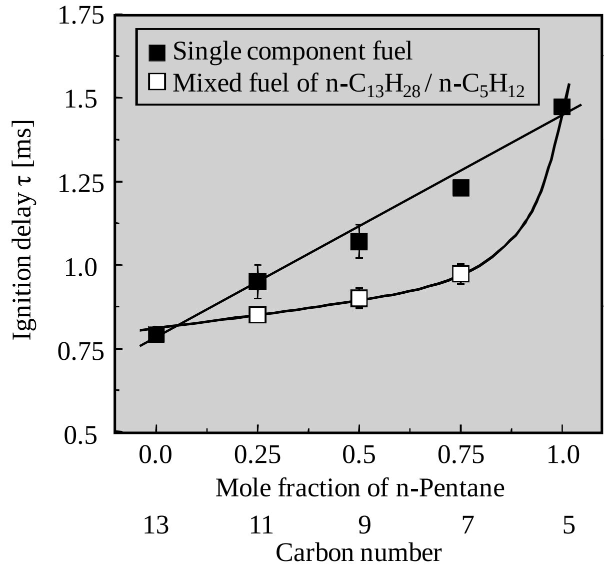
(2) Chemical Control = Capability of Control on Combustion Process
→ Emission Control – Soot & NOx
Simultaneous reduction of both Soot and NOx (CO2-gas oil mixing fuel)
→ Ignition Control (Gasoline-gas oil mixing fuel)
→ HC Control (Gasoline-gas oil mixing fuel)

(3) Improving Thermal Efficiency by Lower Injection Pressure
→ High Spray Atomization and Evaporation Quality with Flashing Process

(4) Control the Fuel Transportation Properties in Mixing Fuels

(5) Effective liquefaction of gaseous and solid fuels
→ Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics

Ignition delay of mixing fuel of C_5H_{12} with $C_{13}H_{28}$ and single component fuel (Experiments)



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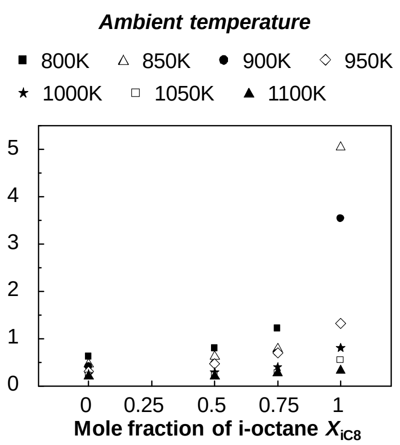
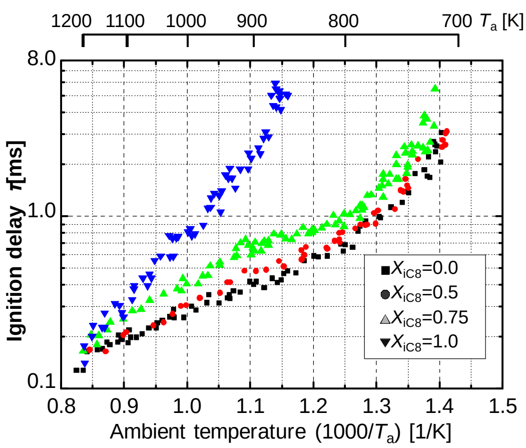
Ignition Delay of Mixing Fuelof i-Octane & n-Tridecane (Experiments)





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Possibility in coupling of Physical Control and Chemical Control for Spray Combustion

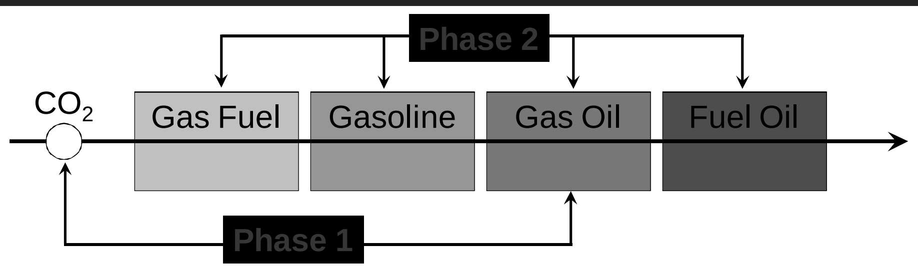
By using the Mixing Fuel of Higher Boiling Point Fuels (gas oil, etc) and Lower Boiling Point Fuels (gas fuel or Gasoline, etc)

1.Lower B.P. fuel could promote the evaporation through the formation of Two Phase Region

→Spatial overlap vapor distribution in the chamber

2.Higher B.P.fuel could assist the ignition and Higher B.P. fuel could burn out the lower ignitability fuel such as Lower B.P. fuel

Fuel Combination for Fuel Design



	High Volatility Fuel	Low Volatility Fuel
Phase 1	CO_2	Gas Oil
Phase 2	Gasoline Gaseous Fuel	Gas Oil Fuel Oil

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Chemical Thermodynamics and Two-Phase Region

Estimation of Two-Phase Region

Expanded Corresponding State Principle

$P_r = P/P_C$, $T_r = T/T_C$

Peng-Robinson Equation of States

$$P = \frac{RT}{V-b} - \frac{a(T)}{\{V(V+b)+b(V-b)\}}$$

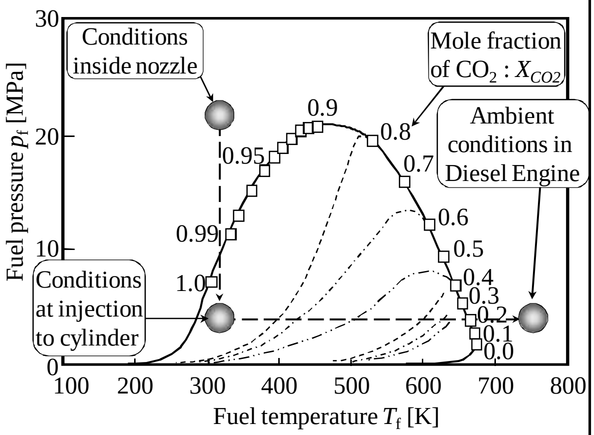
Fugacity of Liquid & Gas

$$\phi_i^G = f_i^G/(y_i \cdot P)\ ,\ \phi_i^L = f_i^L/(X_i \cdot P)$$

$$f_i^G = f_i^L$$

The prediction of Two-Phase Region

P-T Diagram for Mixing Fuel with Liquefied CO_2 & n-tridecane

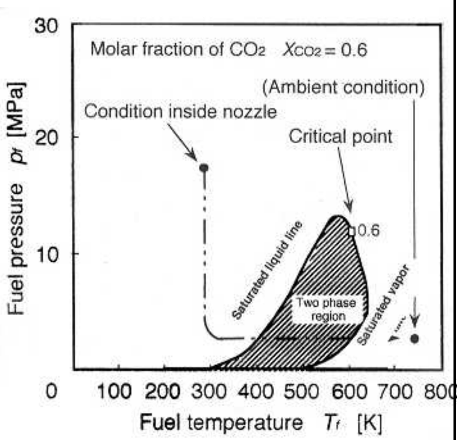


Combustion Experiments in CO2 & n-Tridecane Mixing Fuel

Experimental conditions

Equivalent crank speed		200 [rpm]
Water jacket temperature		353 [K]
Compression ratio		15
Injection nozzle dimension		*dn*=0.18 [mm] *ln*/*dn*=4.17
Injection pressure		16 [MPa]
Injection quantity (n-tridecane + CO2)	X_{CO2}=0.0	10.0 + 0.0 [mg]
	X_{CO2}=0.4	10.0 + 1.6 [mg]
	X_{CO2}=0.6	10.0 + 3.6 [mg]
	X_{CO2}=0.8	10.0 + 9.5 [mg]
Injection timing		5.0 ± 0.5 [deg.CA.BTDC]
Excess-air ratio		25
Ambient temperature at injection		750 [K]
Ambient pressure at injection		3.2 [MPa]
Initial cylinder pressure		0.1 [MPa]

P-T Diagram for Mixed Fuel in RCEM



Scenario of Low Emission Diesel Combustion by Mixing Fuel Injection of Liquid CO2 & n-Tridecane (gas oil)

Concept

1.Low injection pressure
→ to improve efficiency

2.Improvement of spray atomization & Formation of vaporizing spray
→ to form lean & homogeneous mixture

3. Control of combustion processes
→ to reduce both NO and soot

Low Emission Scenario

NO reduction

Lower Flame Temperature by
(1) Latent heat of CO2 flashing
(2) Thermal dissociation of CO_2 ($2CO_2 \Rightarrow 2CO+O_2$)
(3) Improvement of spray atomization and vaporization due to CO_2 separation and flashing

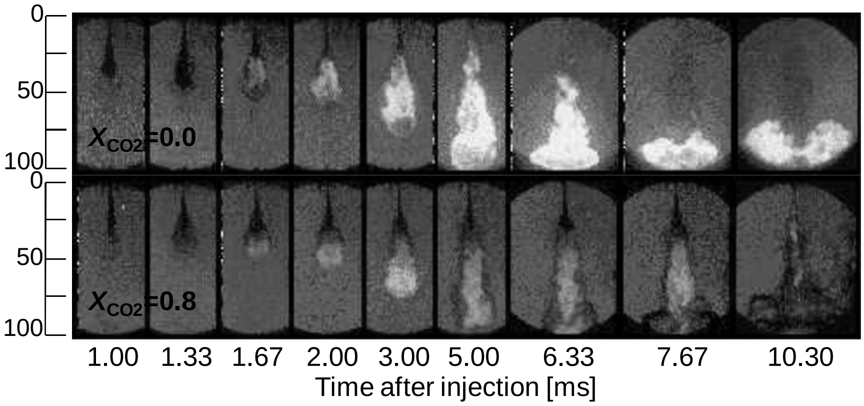
Soot reduction

(1) Soot formation
- avoid the fuel rich mixture

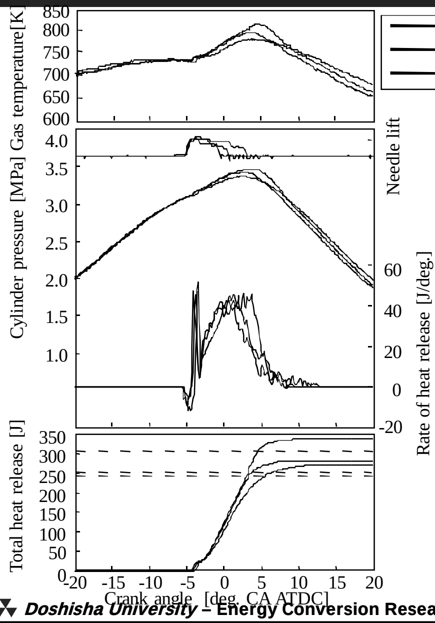
(2) Soot oxidation & re-burning
- Dissociation of CO_2 into CO and O
- Boudouard reaction $C+CO_2 \Rightarrow 2CO$

Spray and Flame Structure of CO_2 / C_{13} Mixing Fuel in RCEM

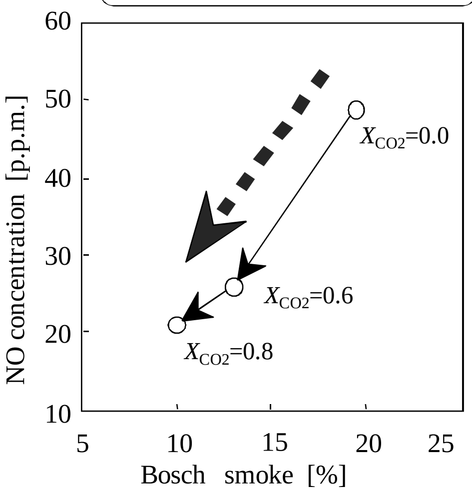
- Low pressure injection → Improve the Thermal Efficiency
- Flash boiling spray by CO_2 component → Promotion of Spray Evaporation
- Spray internal EGR → Reduction of NOx



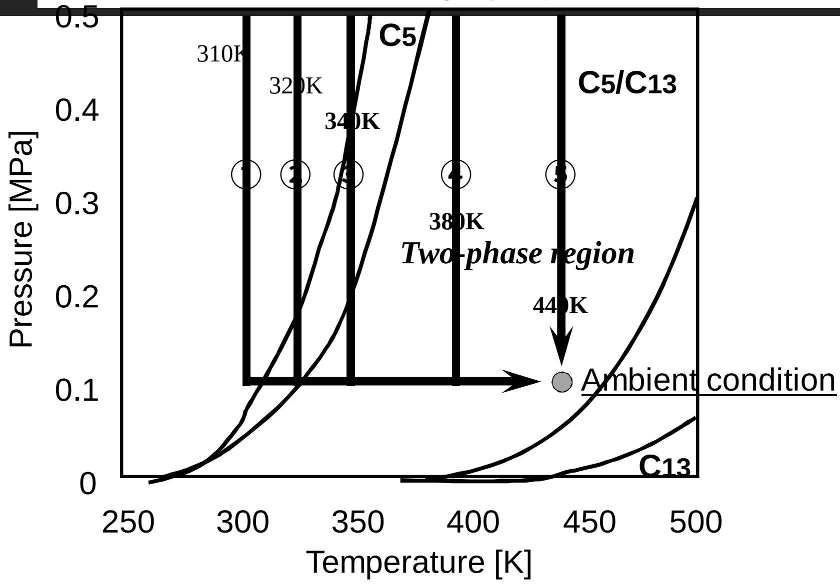
Combustion Characteristics of CO_2 / C_{13} Mixing Fuel in RCEM



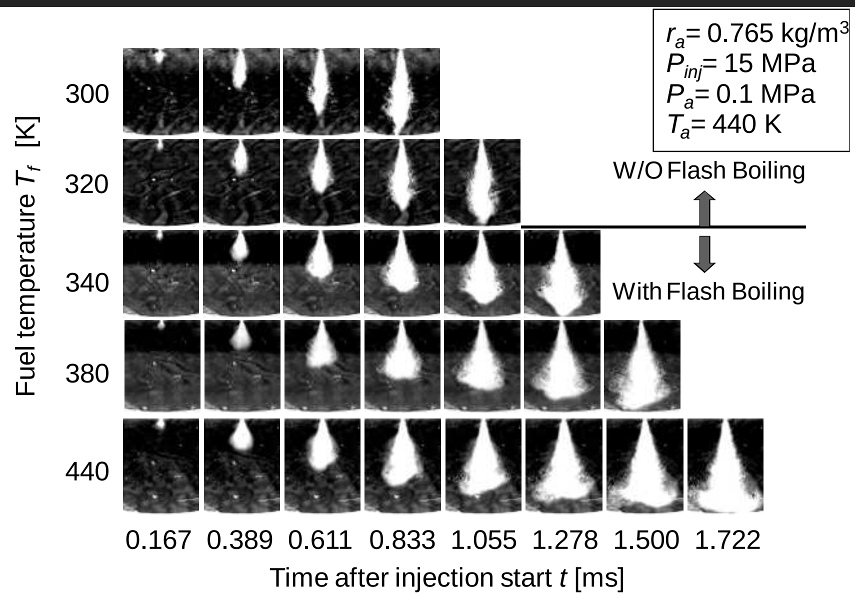
Break through the trade off relation between NO and smoke by use of liquefied CO_2 mixing fuel



Experimental Conditions for Heated up C5 / C13 Mixing Spray

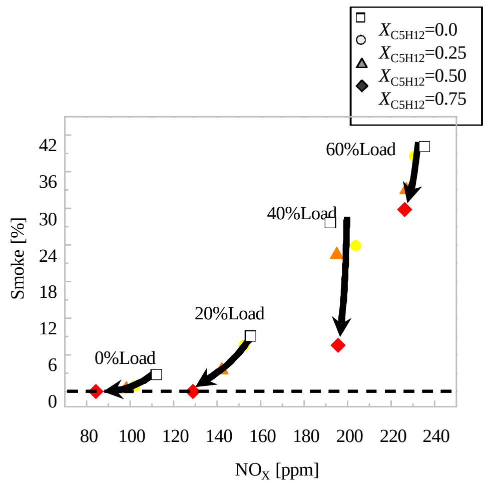


Shadowgraph Images of Flashing Spray of C5 / C13 Mixing Fuels in RCEM

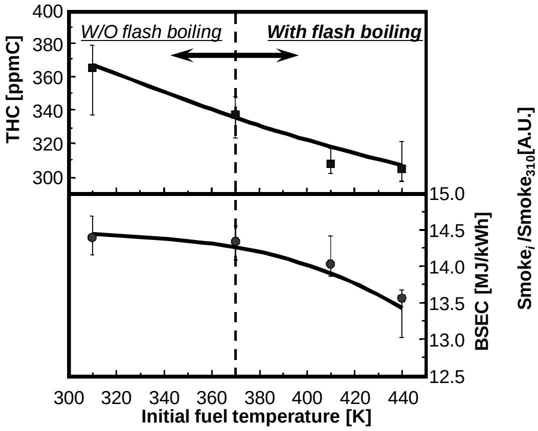


Combustion Experimental Conditions and Emission Results in C5 & C13 Mixing Fuel in Engine

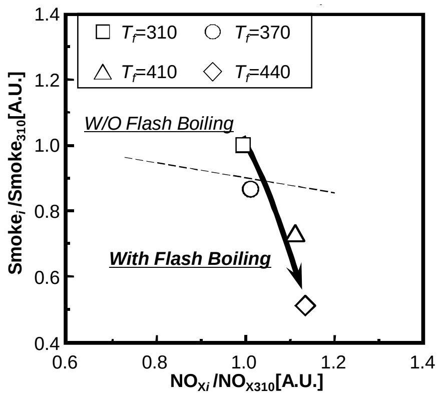
Test fuel	
$n\text{-}C_5H_{12}$ + $n\text{-}C_{13}H_{28}$ (C5/C13)	X_{C5H12}=0.0 , 0.25 0.50 , 0.75
Operating condition	
Engine speed [rpm]	3600
Engine load [%]	0, 20, 40, 60
Injection condition	
Injection nozzle (n–ϕ d)	4-ϕ 0.21
Injection pressure [MPa]	15MPa
Injection timing [deg.C.A.BTDC]	12



Emissions Result in LPG / C13 Mixing Fuel in Engine



(a) THC Emission and Engine Performance



(b) Relation between Smoke and NO_X

(5) Effective liquefaction of gaseous and solid fuels

1.Possible application for Gas Fueled Engines and Transportation

Liquefied Pressure of Gas Fuels can be reduced by mixing the higher boiling point fuel through the Two Phase Region
(It means saturated vapor pressure is reduced)
→ Safety of compressed gas bomb or liquefied gas bomb
→ Longer driving distance in CNG or LNG engine transportation

2.As a Future study

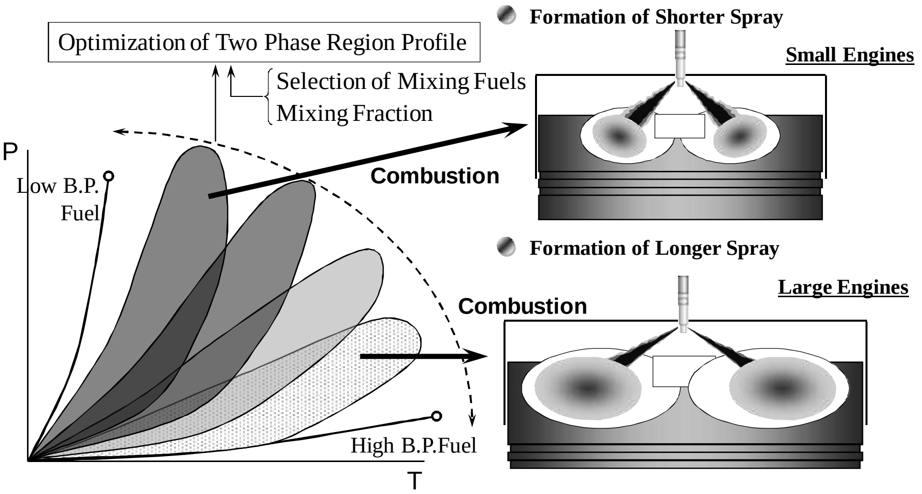
Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics with assisting by Sono-Chemistry Process
→ Effective usage of fossil energy resources

Finally,
We are intending to couple Fuel Design Process
- Two Phase Region Profile -
with Combustion Chamber Geometry Design
considering Fuel Spray Evaporation Process

→Artificial Control to optimize the Fuel Spray Evaporation Process for each Engine Chambers

Optimization of Spray Evaporation Process and Chamber Geometry by adjusting Two Phase Profile of the Fuel

- Spray should be penetrated to near the chamber wall where air mass is enough
- HC and PM should be reduced by avoiding the spray and wall interaction



HCCI Application of Fuel Design Approach

< HCCI Engines >

•Advanced fuel Injection → Lower Ta & Pb

•Ignition control is required → Ignition improver
Some additives

•Importance in Spatial Vapor Distribution
→ Homogeneity or Heterogeneity ?

< Fitting of Mixing Fuels to HCCI >

*Possibility of Flashing Spray due to lower Ta & Pb

*Mixing Additives can control the Ignition Process

*Controllability of Spatial Vapor Distribution
due to the Two Phase Region Profile

Considerable Issues in HCCI Combustion Scheme

1. Formation of Lean Mixture inside cylinder/combustion chamber

∗Early Injection → Fuel –Wall interaction → HC emission

∗Rapid Evaporation ← Application of partially Flash Boling Spray

2. Mixture Ignition Control

∗Diesel fuels → early ignition ; Gasoline fuels → emission of HC & CO

∗Promising Mixing Fuels are required to control the ignition timing

3. Range extension to Higher Load operation

∗suffering from Knocking & NOx Emission due to higher pressure rise rate

Here, Heterogeneous Mixture allows substantially Higher Load Operation due to equivalence ratio dependence of Low Temperature Reaction of the Fuel (UW-Madison, Sandia Labo., Keio Univ., Ritsumeikan Univ. etc)

Our HCCI Research with focusing Mixture Distribution Control

① 2 Stage DI Injection (1st Early Injection = Partially flashing Spray)

② Combination of Port Injection & Direct Injection

③ Spatial Separated Distribution of Fuel Species inside Single Injected Spray

The END - 完 -

1. Mixing fuel of liquefied CO_2 and n-Tridecane is applied to Diesel like combustion field with a variation of CO_2 mole fraction. As a result, the simultaneous reduction both soot and NOx can be obtained with improving the combustion efficiency.
2. Mixing fuel of n-Pentane as a component of Gasoline and n-Tridecane is applied into actual small DI Diesel engine with a variation of the fuel temperature. And the reduction of soot emission can be obtained for all engine load conditions.
3. Finally, mixing fuel of LPG and n-Tridecane is applied into actual small DI Diesel engine with a variation of the fuel temperature. And the simultaneous reduction of BSFC and HC and soot emissions can be obtained for flashing spray cases.

Thank you for your kind attention