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「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動向」

燃料設計手法による噴霧燃焼過程の人為的制御の可能性

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これまでの関連の講演

(1) 同志社大学エネルギー変換研究センター 第2回技術セミナー
国際セミナー「エンジンシステムの燃焼過程」 (2004.5.28)
"Fuel Design Approach for Low Emission Spray Combustion"

(2) SAE Fuel & Lubricants Meeting, Toulouse, France (2004.6.8)
Panel Discussion on Compatibility Between the Strategy for Emissions Reduction and the Strategy to Reduce CO2 Emissions (SFL42)
"Fuel Design Approach for Low Emission Spray Combustion Field"

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Ⅰ Recent Research Trend for Lower Diesel Emission

Ⅰ-Ⅰ HCCI Combustion System

Ⅰ-Ⅱ Borderless in Gasoline Eng. and Diesel Eng.

Ⅱ Fuel Design Conceptual Study

Ⅱ-1 Proposal of Fuel Design Approach for Both Engines

Ⅱ-2 Author's Fuel Design Approach Researches

Ⅱ-3 Future Extending Research Aspect

Ⅰ - Recent Research Trend for Lower Diesel Emission

Ⅰ - Ⅰ HCCI Combustion System

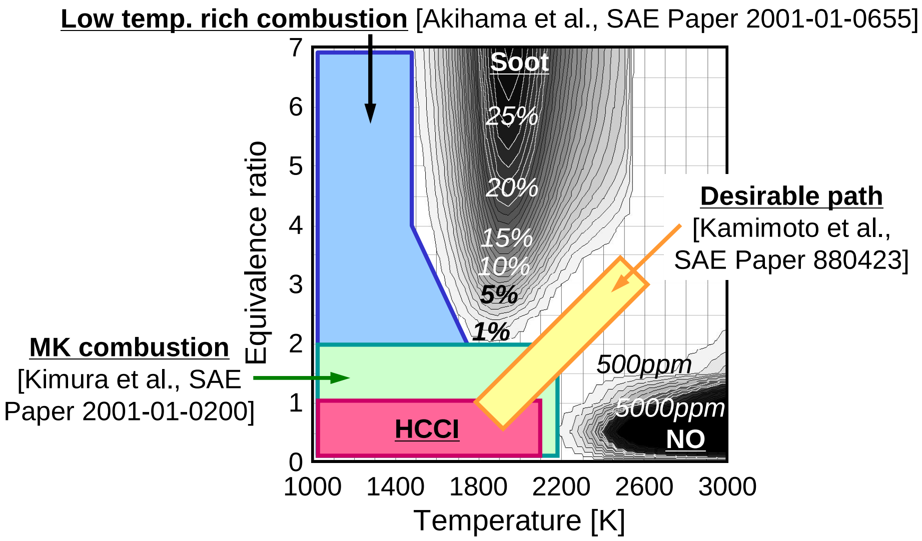
- Introduction of Several HCCI Approaches
- Possibility of HCCI Application into Diesel Engines in High Load Operation

New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction

Injection + (Suction Flow)

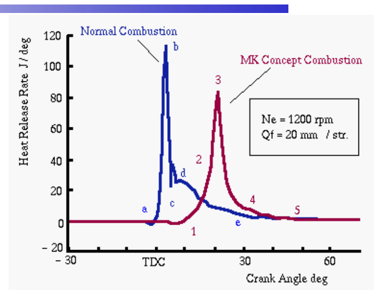
Improve atomization and turbulent mixing to reduce soot	Optimize temporal and spatial mixture distributions in-cylinder to reduce both soot (PM) and NO by DISC combustion
High-Pressure Fuel Injection ↓ High-Pressure Fuel Injection + Small Orifice Nozzle	Injection Rate Control (Boot Injection, Pilot Injection) 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) Fuel Conversion / Additive Injection: ・Water Injection ・Emulsion Injection → Our Fuel Design Approach

Diesel Combustion Scheme
In Equivalence Ratio – Temperature Map

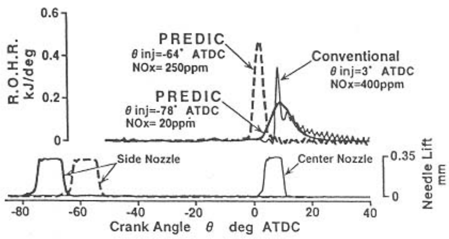


Development in DI HCCI (1995~)

- **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



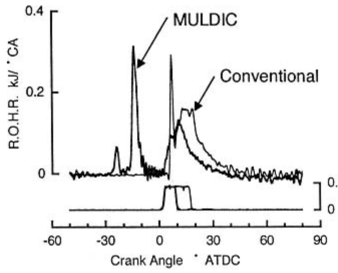
Ref: SAE Paper 961163

MULDIC (Ref : SAE Paper 980505)

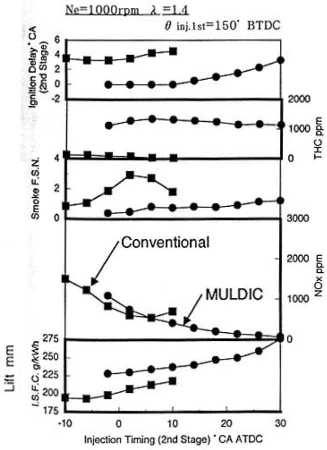
PREDIC achieved the simultaneous reduction of NO_X and smoke emissions. However, this technique can apply only to low and medium load condition. Therefore, **MULDIC was developed for NO_X reduction at higher load condition.**

MULtiple stage DIesel Combustion :

- **adopted a multiple stage injection method**
- can decrease NO_X and smoke emissions even at high load condition
- resulted in further improvement in exhaust emissions with EGR
- has trade-off correlation between NO_X emission and fuel consumption



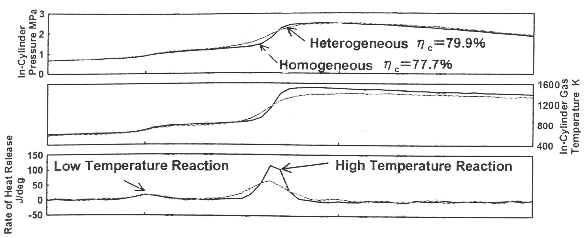
R.O.H.R. of MULDIC



Emission characteristics of MULDIC

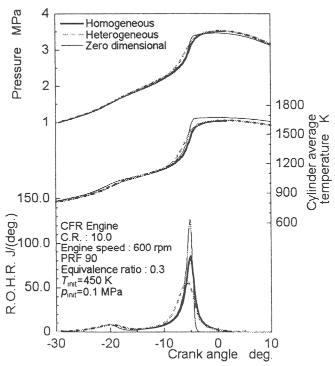
Heterogeneous Charge Compression Ignition (1)

Experiment



(Keio Univ.)

Calculation



(Ritsumeikan Univ.)

- **Heterogeneity of fuel distribution can achieve more moderate heat release rate.**
- Heterogeneous charge has a possibility to control the occurrence of main ignition.

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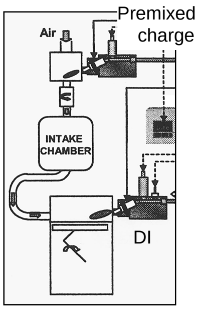
Heterogeneous Charge Compression Ignition (2)

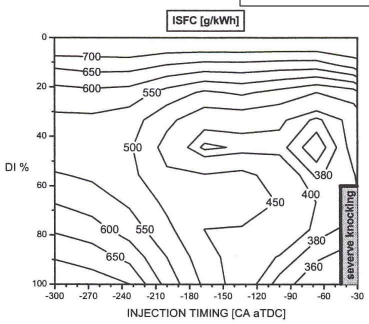
(Ref : SAE Paper 2004-01-1756, Engine Research Center in U of W)

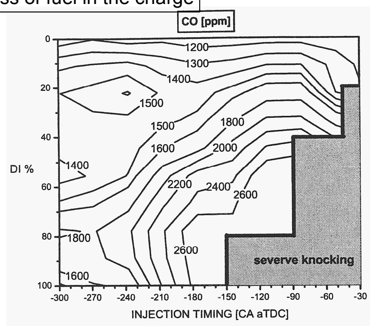
Stratification of the charge was varied 1) by retarding injection timing of DI.
2) by altering the ratio of DI fuel to the total fuel.

- **Stratified charge shows potential as a viable enhancement for HCCI combustion at the lean limit.**
- At the rich limit, the stratification was limited by the high pressure-rise rate and high CO and NO_X emissions.

$$\text{DI \%} = \frac{\text{mass of direct injected fuel}}{\text{total mass of fuel in the charge}}$$







Fuel supply system 600rpm, ϕ=0.15 (lean limit) 600rpm, ϕ=0.27 (rich limit)

Ⅰ-Ⅱ Borderless in Gasoline Eng. and Diesel Eng.

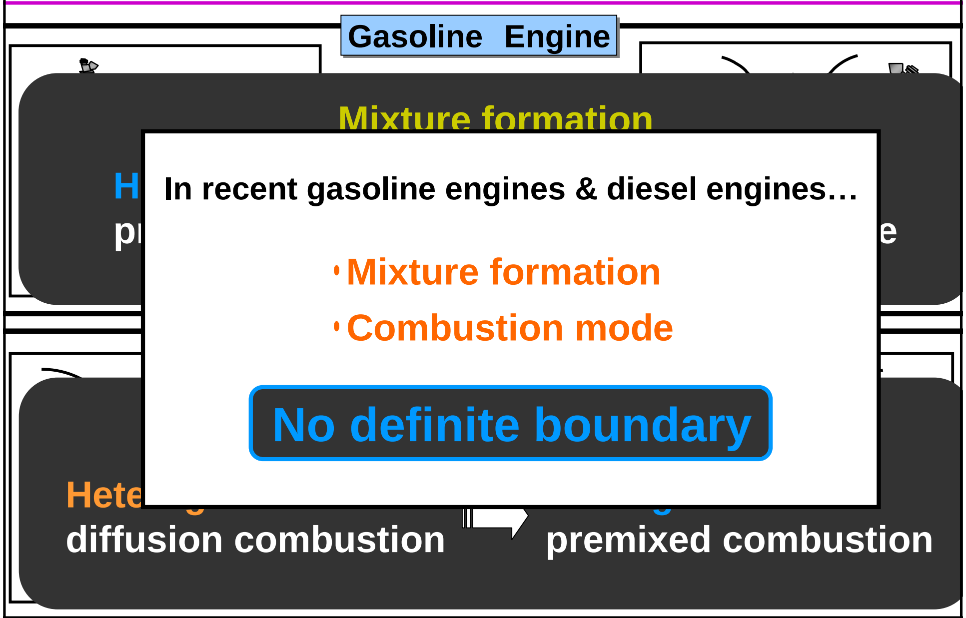
Harmonization of Combustion Scheme in Gasoline Engine and Diesel Engine
→ **Higher thermal efficiency and Lower emissions**

1. **Gasoline Engine → Direct Injection for higher efficiency**
   Diesel Engine → HCCI for lower emission
   → **just Fuel is changed**
   → **Application of Mixing Fuels or on-board reformulation**
   → **FFV; Fuel sensing ?**

2. **Application of HCCI, HCSI, Rich-SI into one Engine (AVL)**
   → **Control of spark ignition**

3. **Several Variable Control in engine system**
   → **VVT (compression ratio), wide range EGR, higher pressure Fuel Injection, higher Boosting(T/C,S/C),･･･**

Borderless in Gasoline Eng. & Diesel Eng.



Ⅱ Fuel Design Conceptual Study

Ⅱ-1 Proposal of Fuel Design Approach for Both Engines

1. Mixing Fuel with Liquefied CO2
2. Mixing Fuel with High and Low Volatility Fuel
3. (1) Soot Free Combustion with Oxygenated fuels from kinetic analysis
   (2) Bio-Diesel Fuel research
   (3) Direct-injected Hydrogen Diesel research

Fuel Design Approach Researches with Focusing Artificial Control of Spray Atomization and Evaporation

- **Use of Flash Boiling Spray** ⟶ **Artificial control of Spray Evaporation Process**
- **Control of Spray Evaporation Process through Two Phase Region in Liquid – Vapor Equilibrium in Mixing Fuels**
  - **① Mixing Fuel of Liquefied CO2 and n-Tridecane(gas oil) →simultaneous reduction both Soot and NOx**
  - **② Mixing Fuel of Gas or Gasoline Component and Gas oil Component →control both evaporation and ignition**
- **Future Study in Fuel Control**
  - **① Fuel Conversion by Sono-Chemistry**
  - **②Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamic**

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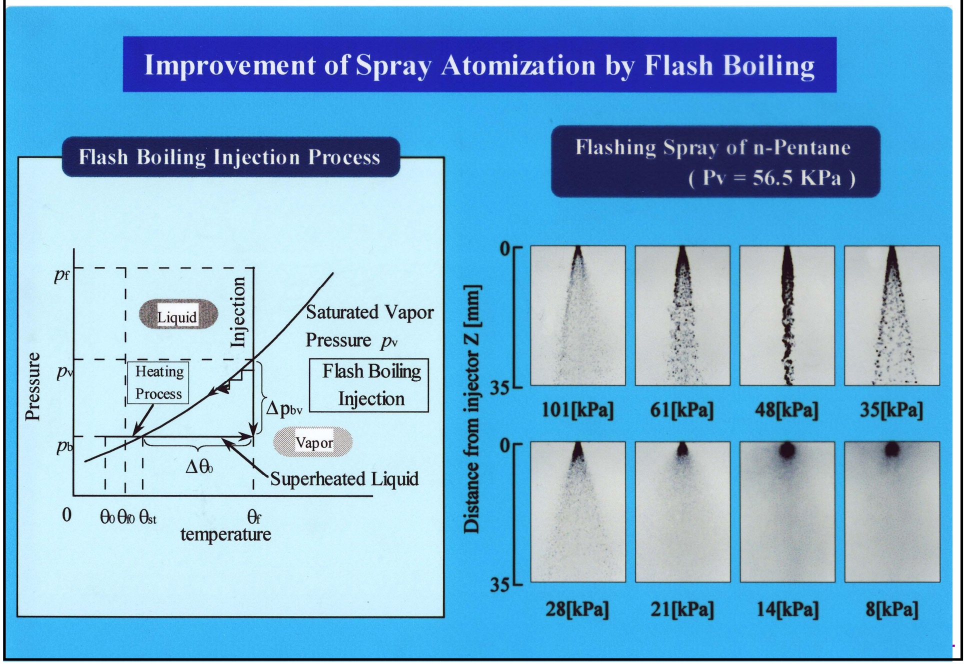
What is Flash Boiling Spray ?

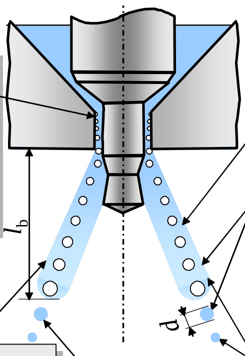


Modeling of Flash Boiling Spray

Nucleation process

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

Initial bubble diameter $2R_0$
$2R_0$=20mm



Bubble growth process

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

and

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

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

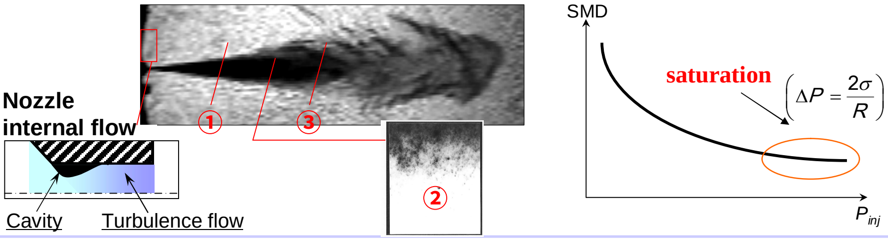
$$\varepsilon=\frac{V_{bubble}}{V_{bubble}+V_{liquid}}\ge\varepsilon_{max}$$

Droplet number = 2×Bubble number

Atomization & Evaporation in Pressure atomizer

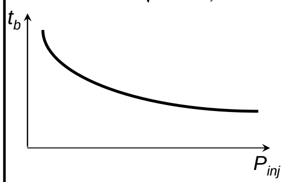
→ Time & Spatial delay depending on P_{inj} , ρ_a , T_a

Aerodynamical Process : disturbance ⇒ ligament ⇒ droplets



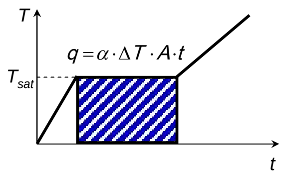
① Breakup delay of spray

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



②Evaporation of droplets

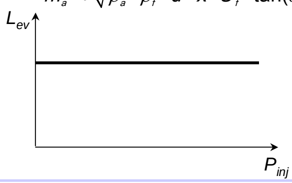
$$Nu = c \cdot \mathrm{Re}^{\alpha} \cdot \mathrm{Pr}^{\beta} \longrightarrow Nu = 2$$



③Evaporation length of spray

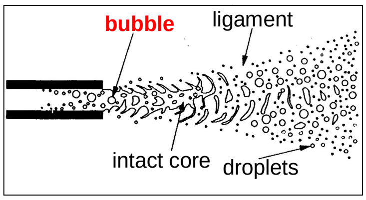
$$\dot{m}_f \propto \rho_f \cdot d_2 \cdot U_f$$

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



Atomization & Evaporation in Flash Boiling Spray

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



Bubble Nucleation rate

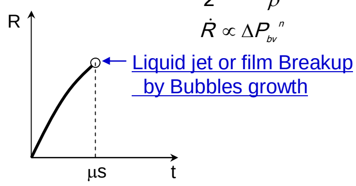
$$N \propto C \cdot \exp\left(-\frac{\Delta A}{k\Delta\theta}\right)$$

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

Evaporation rate = Bubble growth Rate

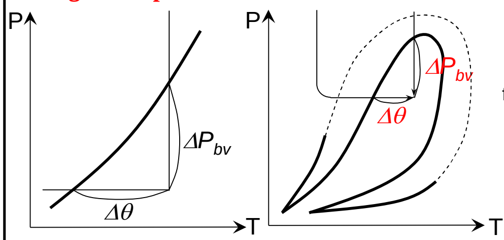
Rayleigh-Plesset **Eq.** $R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}(P_w - P_r)$

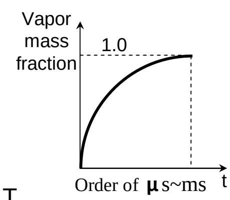
$$\dot{R} \propto \Delta P_{bv}^{\ n}$$

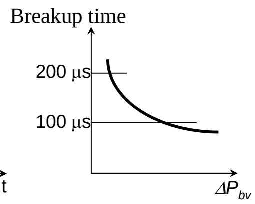


※ Evaporation due to Enthalpy balance
of fuels without aerodynamic force

Single Component **Multi-Component**







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 (CO_2-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

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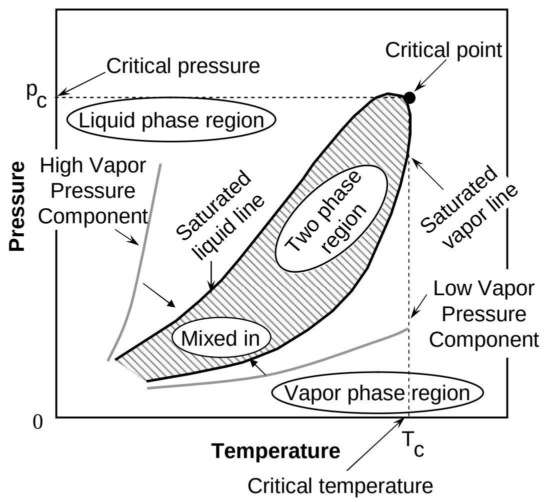
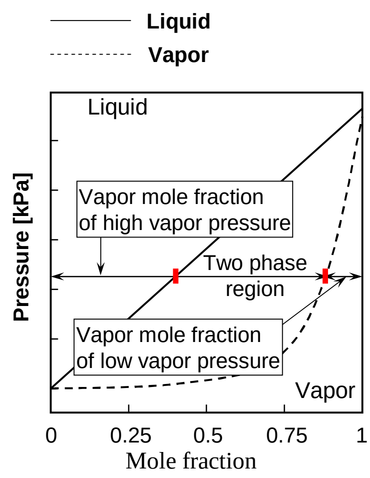
Two Phase Region Formation in Multi-component Fuel in Phase Change Process

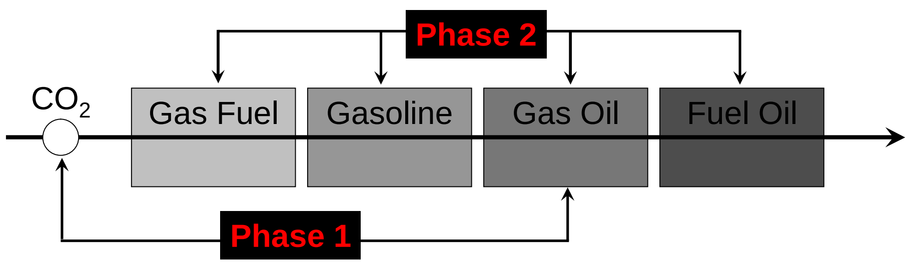
Pressure-temperature diagram



Pressure-Mole fraction diagram



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

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

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

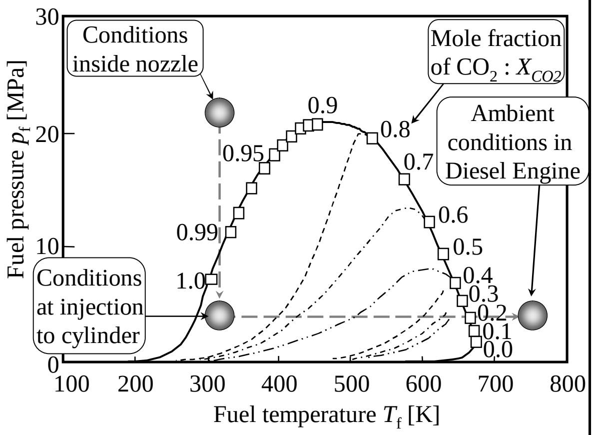
⇩

$f_i^G = f_i^L$

⇩

The prediction of Two-Phase Region

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



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→ **Formation of Flash Boiling Spray →Improvement of Spray Evaporation**

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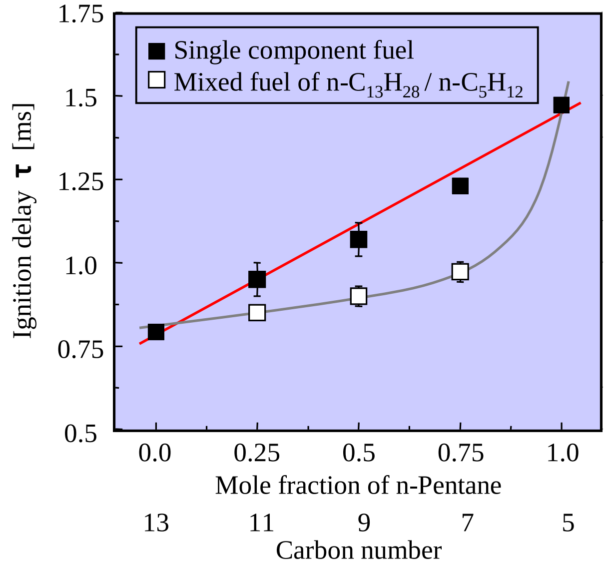
→ **Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics**

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



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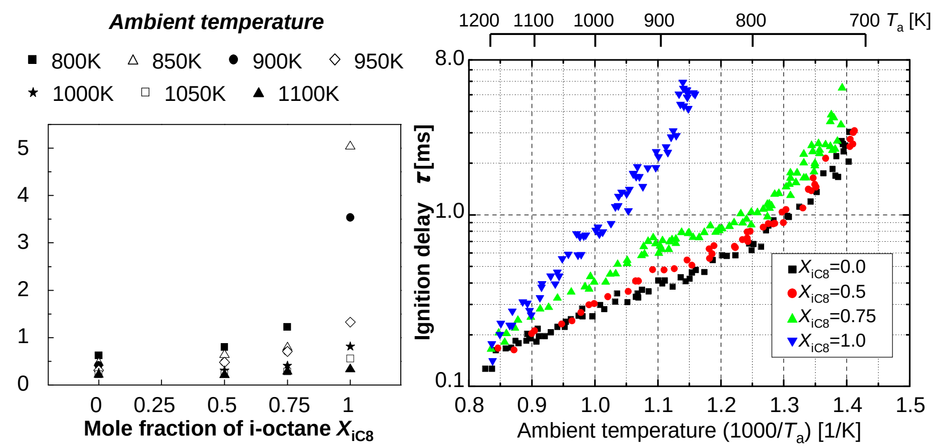
Ignition Delay of Mixing Fuel of i-Octane & n-Tridecane (Experiments)



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Spray Evaporation Experiments in Mixing Fuel of n-Pentane & n-Tridecane

n-C_5H_{12} : boiling point 309.3 K
n-$C_{13}H_{28}$: boiling point 508.7 K

X_{C5H12} : Mixing fraction of C_5H_{12}

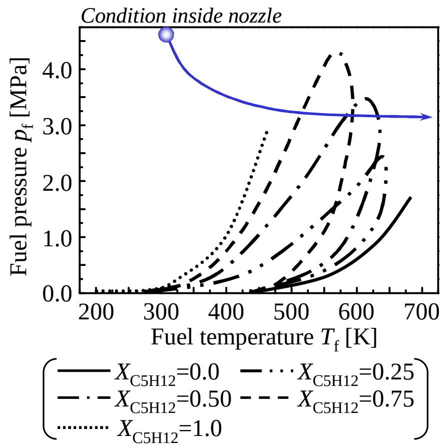
Mixing Fuel and LIF Tracer

X_{C5H12} : Mole fraction of n-pentane
V_{C5H12} : Volume fraction of n-pentane

X_{C5H12}	0.0	0.25	0.5	0.75	1.0
V_{C5H12}	0.0	0.14	0.32	0.59	1.0
Acetone [vol.%]	-	0.6	1.5	2.8	5
Tetraline [vol.%]	7	5.9	4.6	2.7	-

Acetone : C_5H_{12} Tracer
Tetraline : $C_{13}H_{28}$ Tracer

Two-Phase Region in P-T diagram

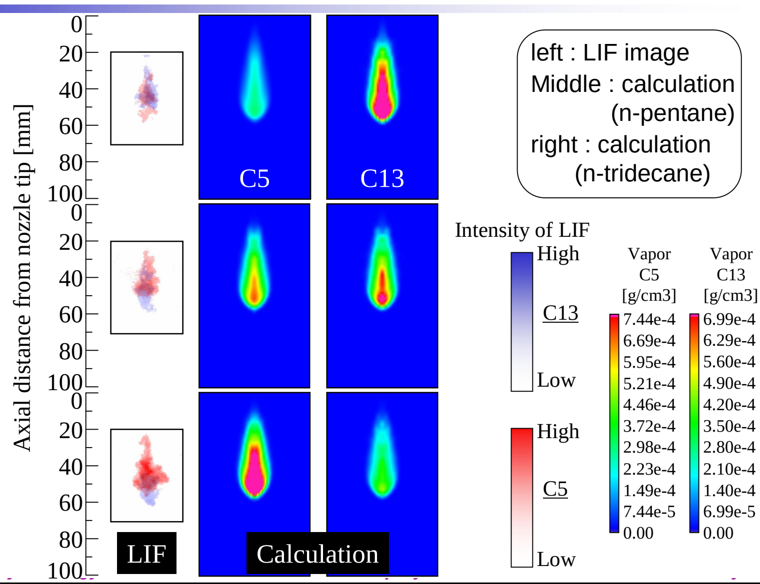


Comparison of Spray Structure –Vapor Spatial Distribution– with Experiments and Numerical Results at t=3.0ms

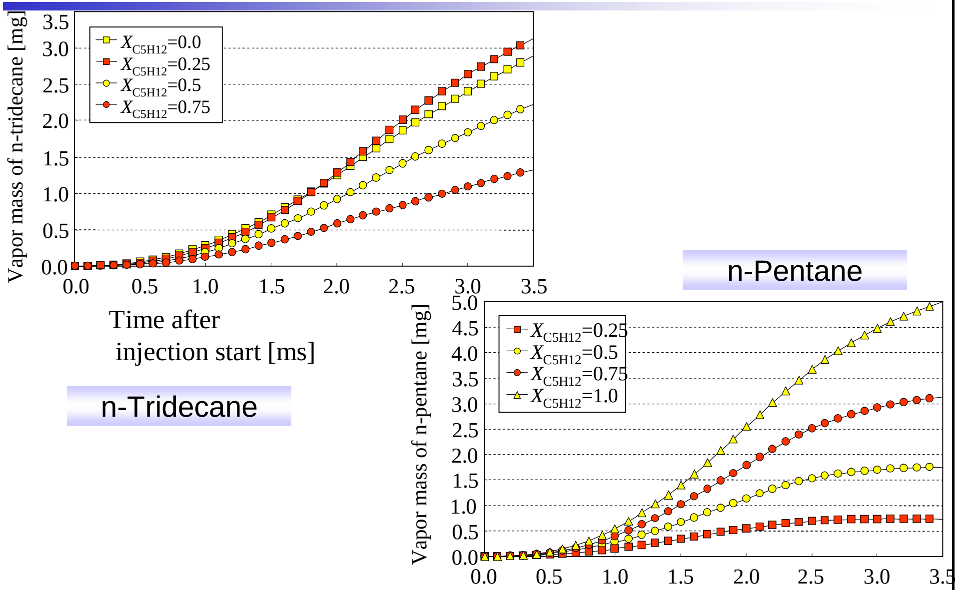
X_{C5H12} = 0.25

X_{C5H12} = 0.50

X_{C5H12} = 0.75

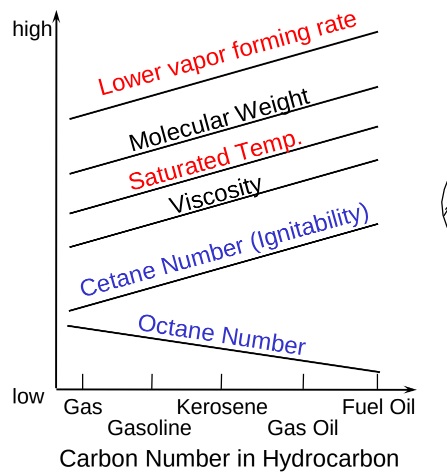


Temporal Changes in Vapor Mass for C5 & C13 Mixing Fuel KIVA Analysis



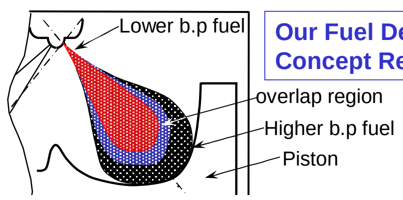
Multi-component Fuel Spray Behavior in Diesel Combustion Chamber

The chemical & physical properties of n-paraffin Hydrocarbon



Lower boiling point fuel (gasoline)
→ higher evaporation
higher octane number = poor ignitability

Higher boiling point fuel (gas oil)
→ lower evaporation
higher cetane number = high ignitability



Our Fuel Design Concept Research

- stratified fuel vapor distribution
- ignition at the middle part of the spray
  ↑ balance of physical and chemical
- Disc shaped chamber is selected reasonably through fuel physical and chemical properties

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

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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
→ Optimization of specific heat, viscosity ,etc

(5) Effective liquefaction of gaseous and solid fuels
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(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

Ⅱ Fuel Design Conceptual Study

Ⅱ-2 Author's Fuel Design Approach Researches

① Mixing Fuel of Liquefied CO2 and n-Tridecane(gas oil)
→simultaneous reduction both Soot and NOx

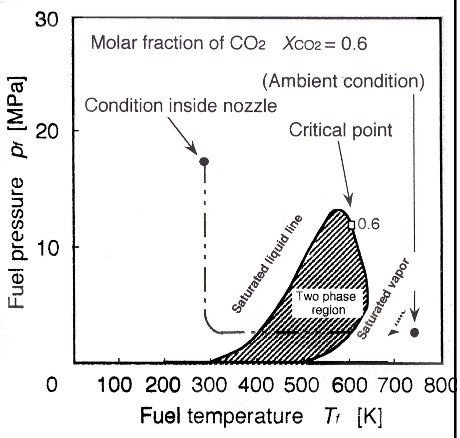
② Mixing Fuel of Gas or Gasoline Component and Gas oil Component →to control both evaporation and ignition

Combustion Experiments in CO_2 & 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 + CO_2)	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 CO_2 & 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 CO_2 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

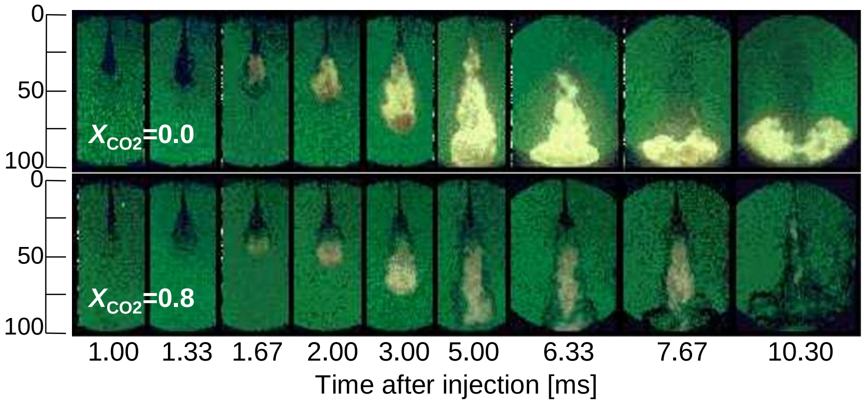
Soot reduction

(1) Soot formation
・avoid the fuel rich mixture

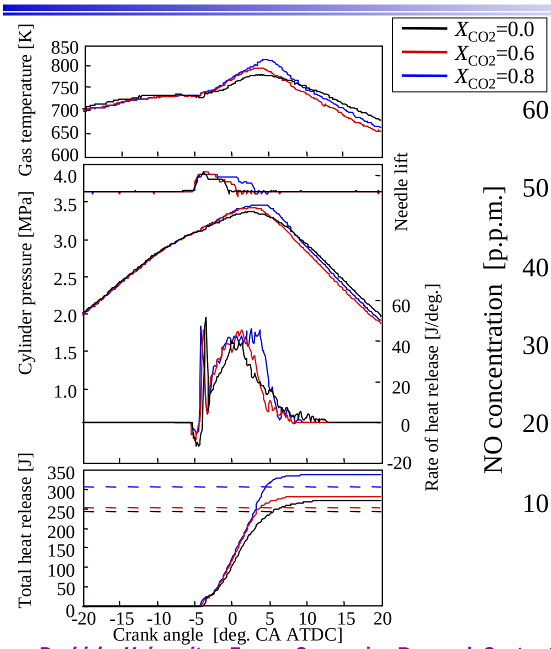
(2) Soot oxidation & re-burning
・Dissociation of CO_2 into CO and O
・Boudouard reaction $C+CO_2 \Rightarrow 2CO$

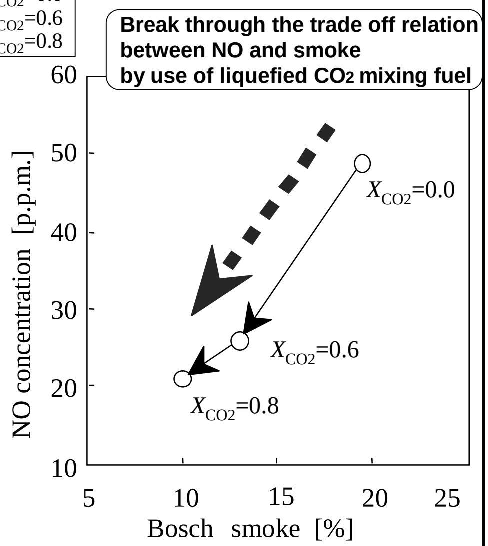
Combustion Characteristics of CO_2 / C_{13} Mixing Fuel

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

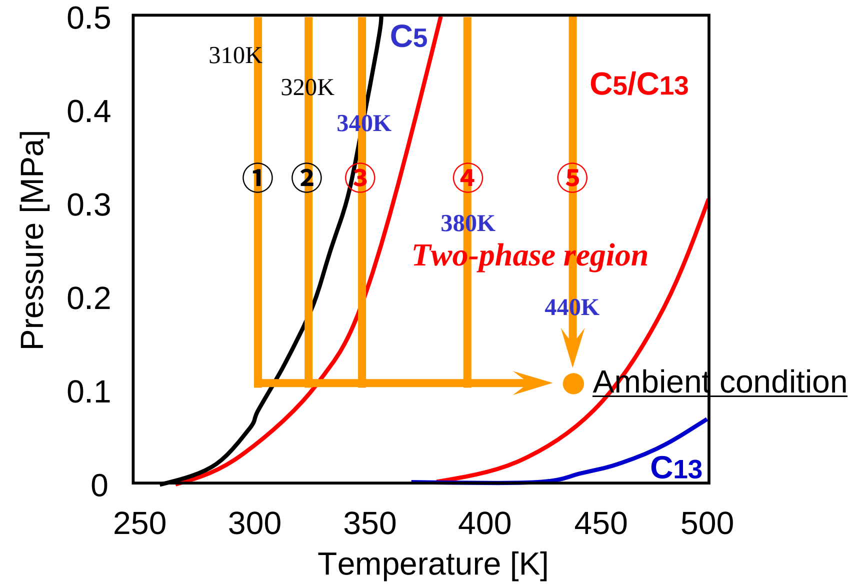


Combustion Characteristics of CO_2 / C_{13} Mixing Fuel

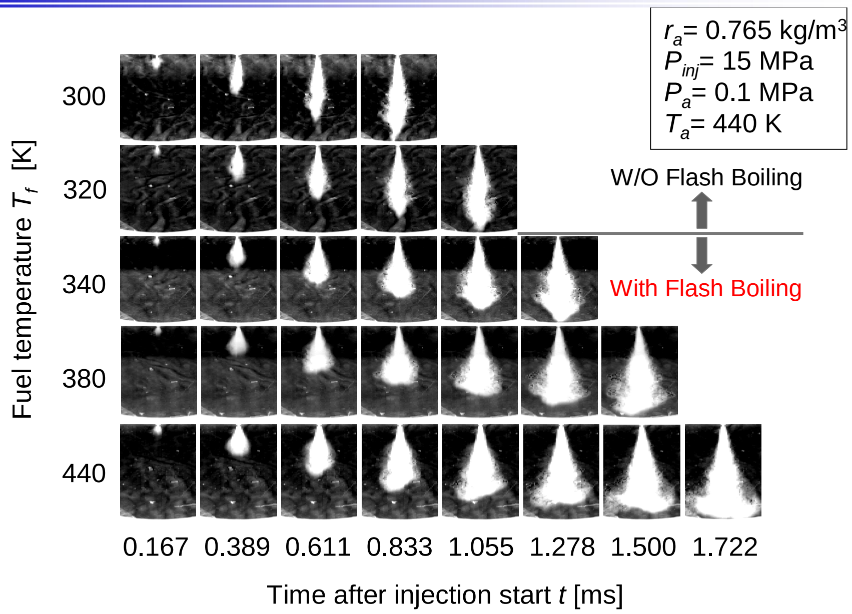




Experimental Conditions for Heated up Mixing Spray



Shadowgraph Images of Flashing Spray of C5/C13 Fuels



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

Test fuel

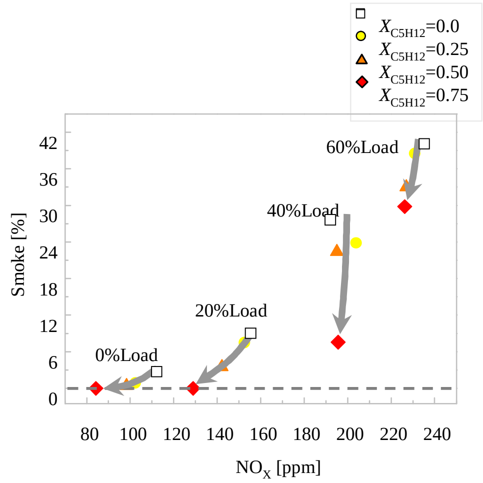
n-C_5H_{12} + n-$C_{13}H_{28}$ (C5/C13)	X_{C5H12}=0.0 , 0.25 0.50 , 0.75

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



Combustion Experiments – Conditions and P-T diagram for LPG & C13 Mixing Fuel with Fuel Temperature

Test fuel

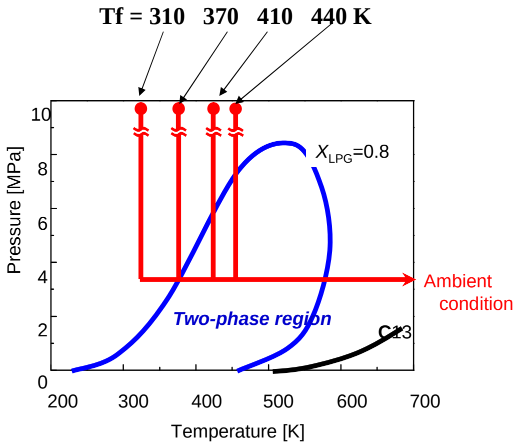
LPG + n-$C_{13}H_{28}$ (LPG/C13)	X_{LPG}=0.8

Operating condition

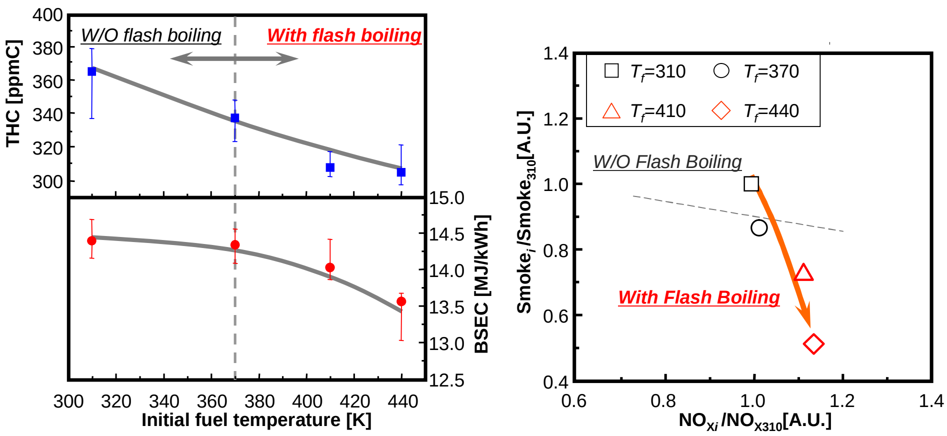
Engine speed [rpm]	3600
Engine load [%]	60

Injection condition

Injection nozzle (n–ϕ d)	4-ϕ 0.21
Injection pressure [MPa]	15MPa
Injection timing [deg.C.A.BTDC]	12.5



Emissions and Engine Performance (Mixing of LPG / C13)



(a) THC Emission and Engine Performance

(b) Relation between Smoke and NO_X

II Fuel Design Conceptual Study

II -3 Future Extending Research Aspect

1. Application of Fuel Design Approach into HCCI engines for Lower Emissions and Ignition Control

2. Coupling of Fuel Design Approach with Combustion Chamber Geometry Design

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

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

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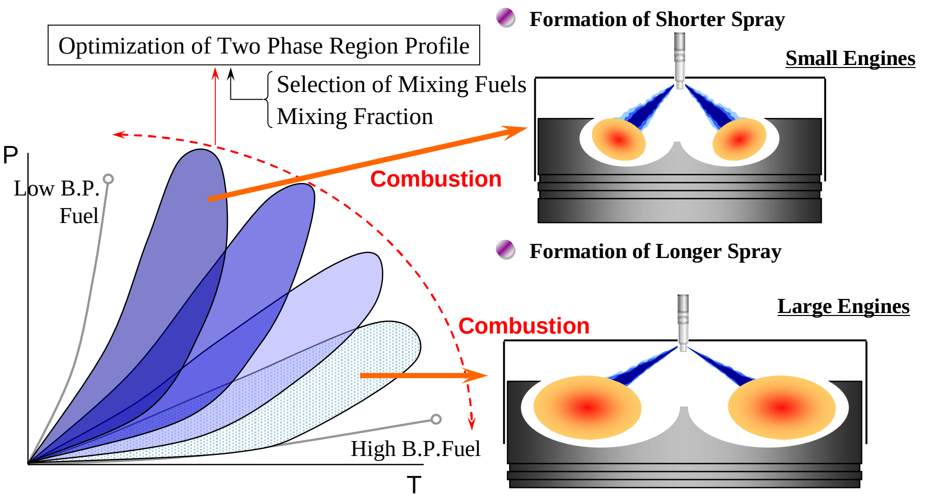
Optimization of Spray Evaporation Process and Chamber Geometry by adjusting Two Phase Profile of the Fuel

- 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



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The END - 完 -

My standpoint is that ;

1. **In-Cylinder ultimate NOx & PM reduction can reduce the catalyst load**
2. **For both engines, simultaneous reduction of NOx and PM should be required with reducing CO_2 (with improving the efficiency)**
3. **It might be better that PM is reduced up to the limitation level inside the cylinder through spray –combustion improvement with fuel research. And NOx is reduced with NOx catalyst (Urea-SCR, LNT,DPNR**

Thank you for your kind attention

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