Int. Seminar on Engine System Combustion Process (2004.5.28)

Fuel Design Approach for Low Emission Spray Combustion

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- Background of Our Research Aspect
- Borderless in Gasoline Eng. and Diesel Eng.
- Proposal of Fuel Design Approach for Both Engines
- Author's Fuel Design Approach Researches

Background of Our Research Aspect

•Introduction of Several HCCI Approach

•Possibility of HCCI Application into Diesel Engines for High Load Operation

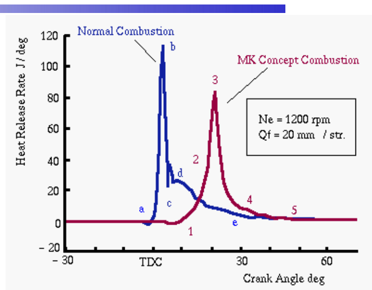
New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction

Injection + (Suction Flow)

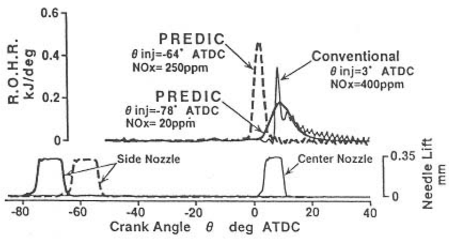
Improve atomization and turbulent mixing to reduce soot	Optimize temporal and spatial mixture distributions in-cylinder to reduce both soot (PM) and NO by DISC combustion
High-Pressure Fuel Injection ↓ High-Pressure Fuel Injection + Small Orifice Nozzle	Injection Rate Control (Boot Injection, Pilot Injection) 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

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

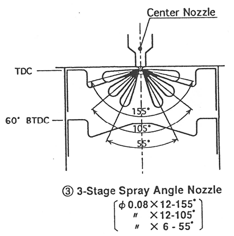


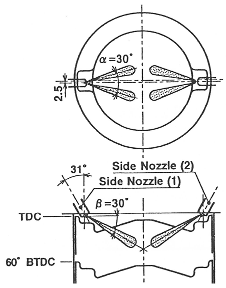
Ref: SAE Paper 961163

PREDIC (Ref : SAE Paper 961163)

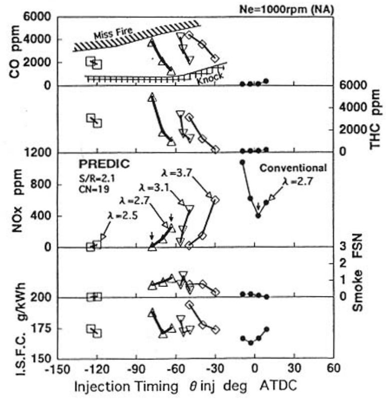
PREmixed lean DIesel Combustion :

- has an impingement spray system with two injectors
  1. to grow the air/fuel mixture in the center of combustion chamber
  2. to decrease the cylinder wall wetting of fuel
- has a set of advanced injection timing
  1. to promote the fuel and air mixing
  2. to achieve the lean diesel combustion
- provides low NO_X and smoke emissions





Injection system of PREDIC



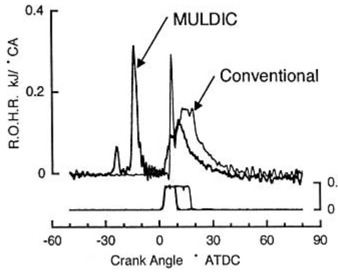
Emission characteristics of PREDIC

MULDIC (Ref : SAE Paper 980505)

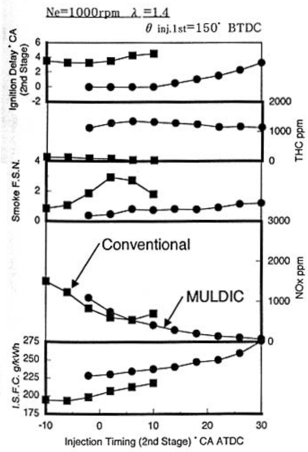
PREDIC achieved the simultaneous reduction of NO_X and smoke emissions. However, this technique can apply only to low and medium load condition. Therefore, MULDIC was developed for NO_X reduction at higher load condition.

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



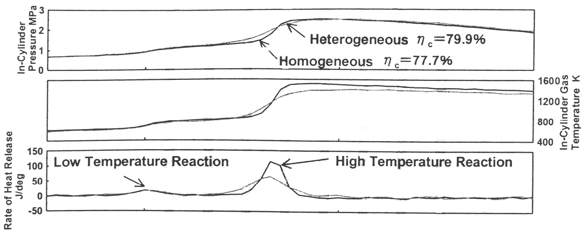
R.O.H.R. of MULDIC



Emission characteristics of MULDIC

Heterogeneous Charge Compression Ignition (1)

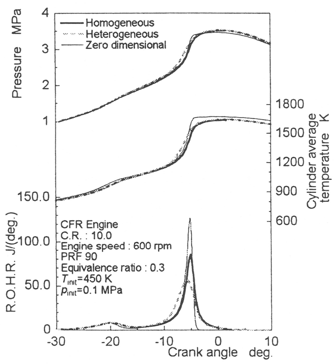
Experiment



(Keio Univ.)

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

Calculation



(Ritsumeikan Univ.)

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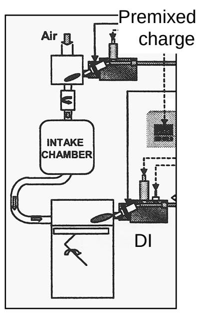
Heterogeneous Charge Compression Ignition (2)

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

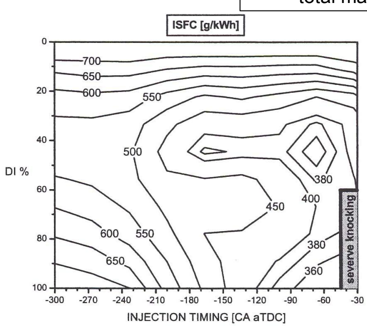
Stratification of the charge was varied 1) by retarding injection timing of DI.
2) by altering the ratio of DI fuel to the total fuel.

- 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.

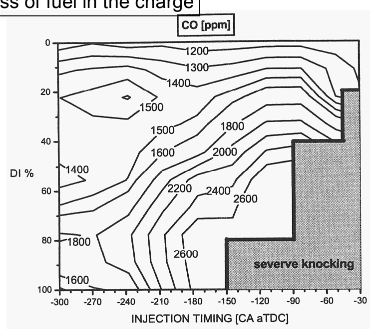
$$\text{DI \%} = \frac{\text{mass of direct injected fuel}}{\text{total mass of fuel in the charge}}$$



Fuel supply system



600rpm, ϕ=0.15 (lean limit)



600rpm, ϕ=0.27 (rich limit)

New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction

Injection + (Suction Flow)

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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 → MULDIC

UNIBUS → HiMICS

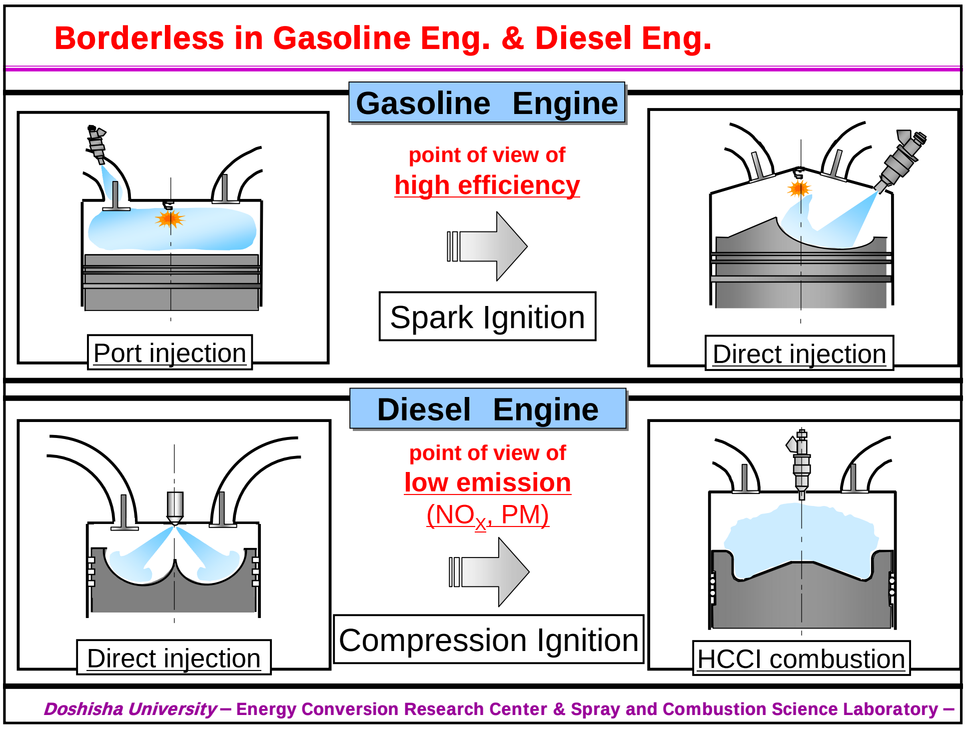
Single Stage → Two Stage

Fuel Conversion / Additive Injection

- Water Injection
- Emulsion Injection

→ Our Fuel Design Approach

Borderless in Gasoline Eng. and Diesel Eng.


Borderless in Gasoline Eng. & Diesel Eng.
Gasoline Engine
point of view of
high efficiency
Spark Ignition
Port injection
Direct injection
Diesel Engine
point of view of
low emission
(NO_X, PM)
Compression Ignition
Direct injection
HCCI combustion
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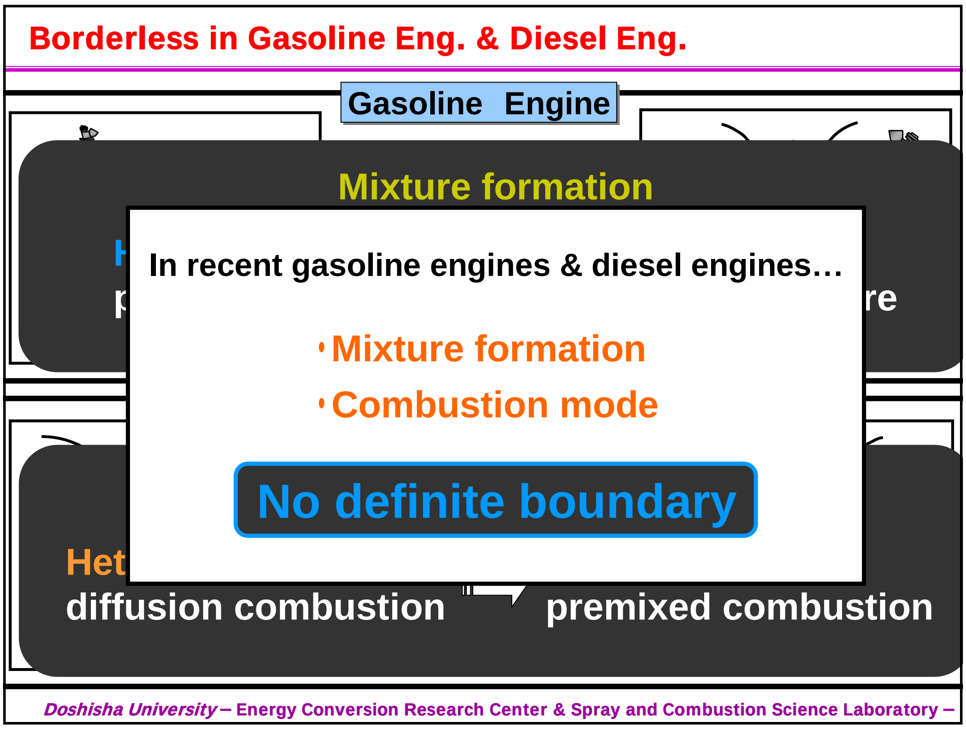
Borderless in Gasoline Eng. & Diesel Eng.
Gasoline Engine
Mixture formation
In recent gasoline engines & diesel engines…
・Mixture formation
・Combustion mode
No definite boundary
diffusion combustion
premixed combustion
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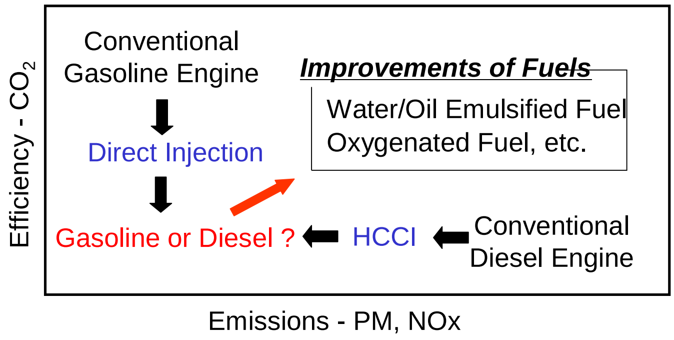
Borderless in Gasoline Eng. & Diesel Eng.

Trends in Engine Research



Our Proposal on Fuel Design Approach

1. Mixing Fuel with Liquefied CO_2
2. Mixing Fuel with High and Low Volatility Fuel
3. Soot Free Combustion with Oxygenated fuels from kinetic analysis

Proposal of Fuel Design Approach for Both Engines

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 CO_2 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**

  ① Fuel Conversion by Sono-Chemistry

  ②Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemicasl-Thermodynamic

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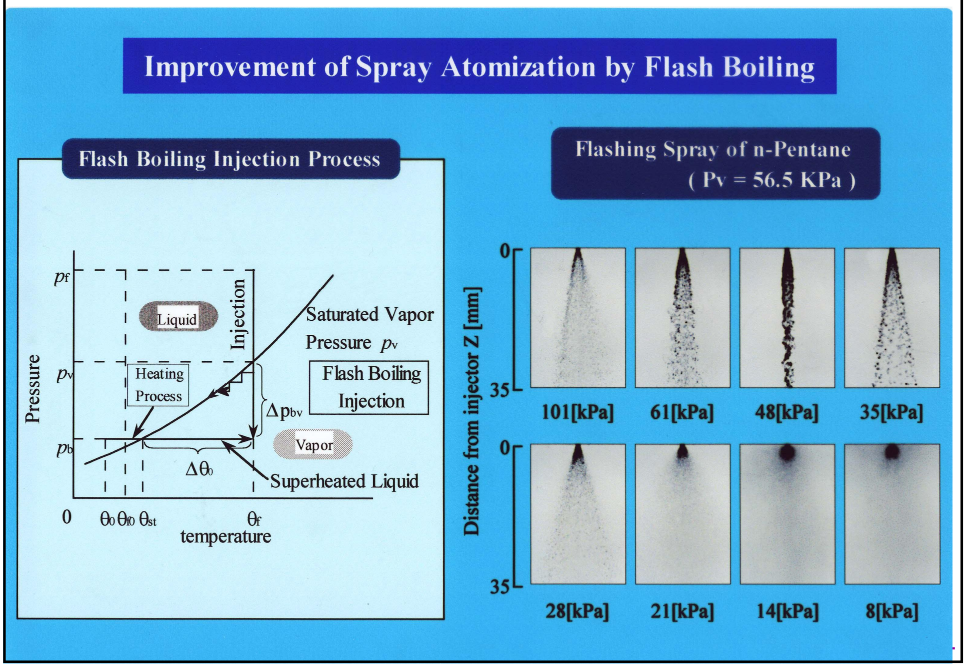
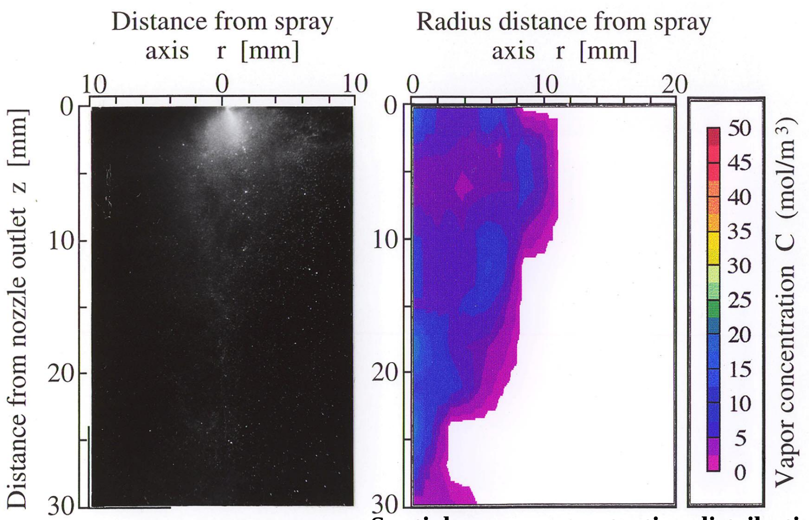
What is Flash Boiling Spray ?



Spray Measurement of Flash Boiling Spray

n-Pentane Spray(Pv=56.5KPa) injected into 21KPa ambient pressure



Mie scattering image from droplets

Spatial vapor concentration distribution by two-wave length IR absorption method

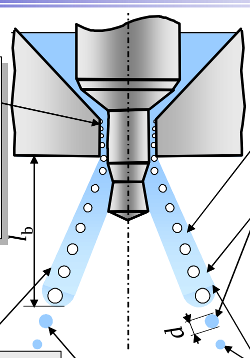
Modeling of Flash Boiling Spray

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



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

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

Bubble growth process

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

and

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

Droplet formation process

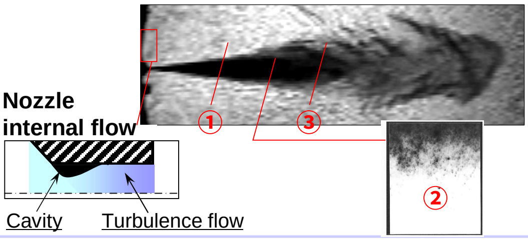
$$\varepsilon=\frac{V_{bubble}}{V_{bubble}+V_{liquid}}\geq\varepsilon_{max}$$

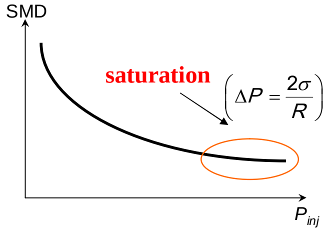
Droplet number = 2 ✕ Bubble number

Atomization & Evaporation in Pressure atomizer

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

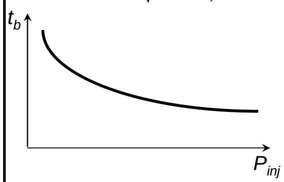
Aerodynamical Process : disturbance ⇒ ligament ⇒ droplets





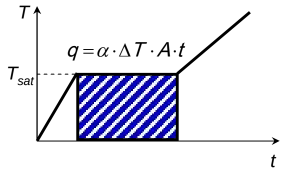
① Breakup delay of spray

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



②Evaporation of droplets

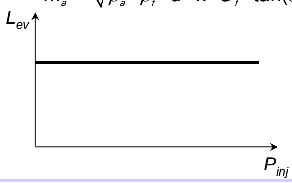
$$Nu = c \cdot \mathrm{Re}^{\alpha} \cdot \mathrm{Pr}^{\beta} \longrightarrow Nu = 2$$



③Evaporation length of spray

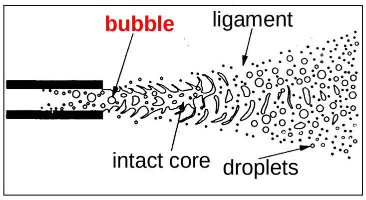
$$\dot{m}_f \propto \rho_f \cdot d_2 \cdot U_f$$

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



Atomization & Evaporation in Flash Boiling Spray

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



Bubble Nucleation rate

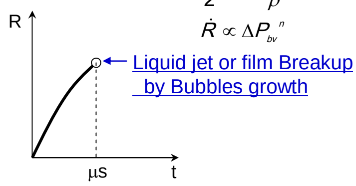
$$N \propto C \cdot \exp\left(-\frac{\Delta A}{k\Delta\theta}\right)$$

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

Evaporation rate = Bubble growth Rate

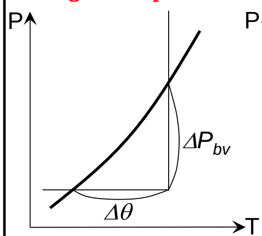
Rayleigh-Plesset Eq. $R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}(P_w - P_r)$

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

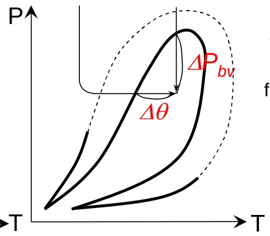


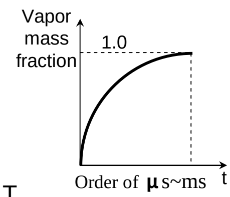
※ Evaporation due to Enthalpy balance
of fuels without aerodynamic force

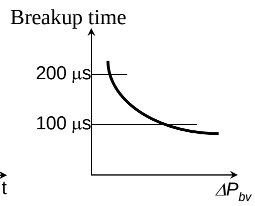
Single Component



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 (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

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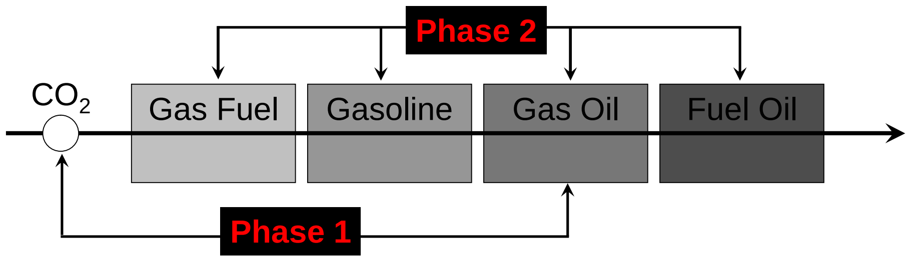
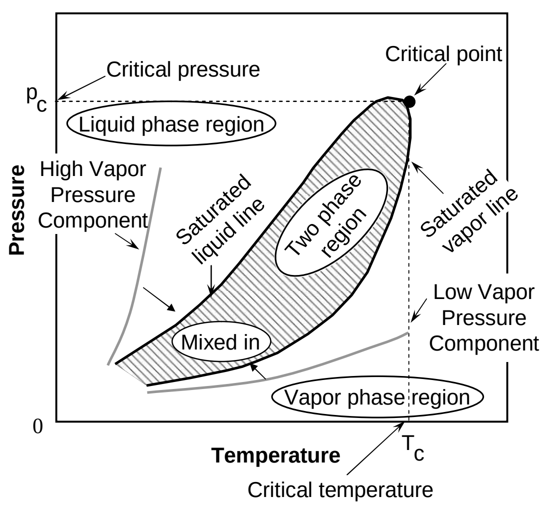
Fuel Combination for Fuel Design



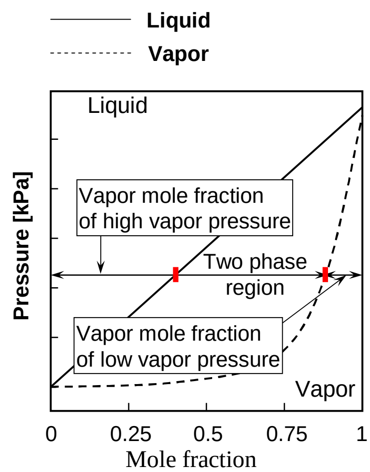
	High Volatility Fuel	Low Volatility Fuel
Phase 1	CO_2	Gas Oil
Phase 2	Gasoline Gaseous Fuel	Gas Oil Fuel Oil

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

Pressure-temperature diagram

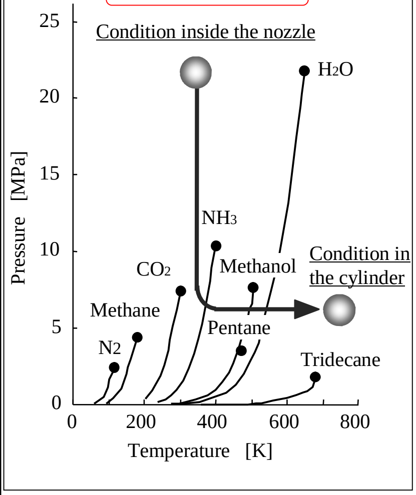


Pressure-Mole fraction diagram

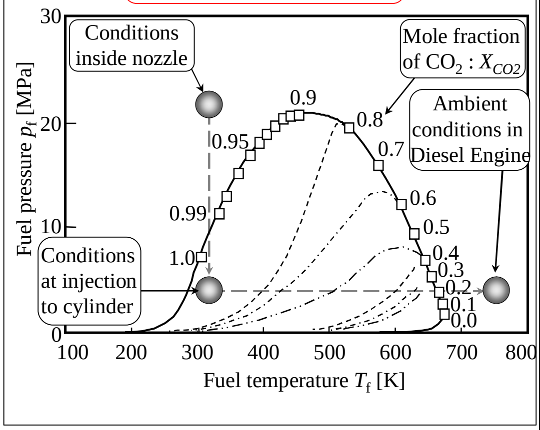


Phase Change Process in P-T Diagram

Pure Substance



Two-Component Solution [CO_2 – n-Tridecane]



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

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

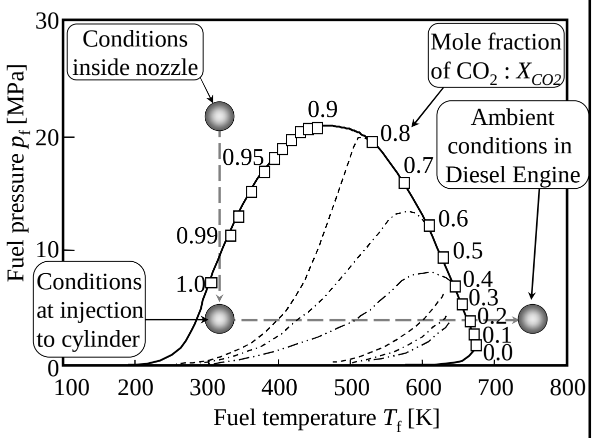
⇩

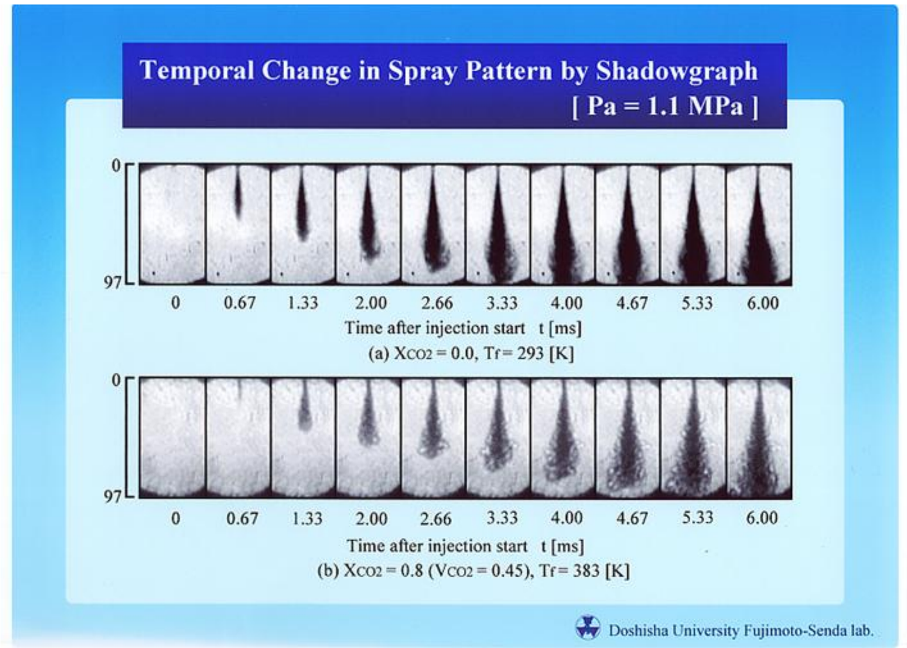
$$f_i^G = f_i^L$$

⇩

The prediction of Two-Phase Region

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



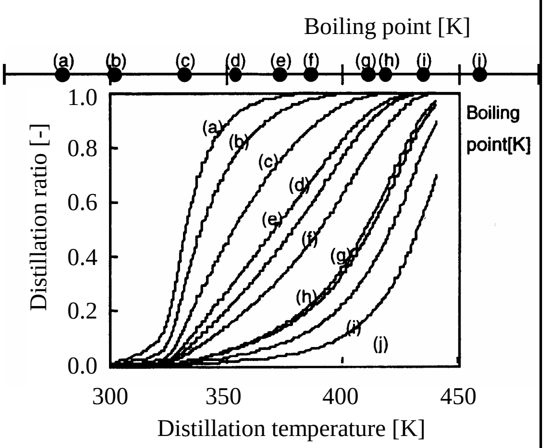


Distillation Analysis for Multi-component Fuel

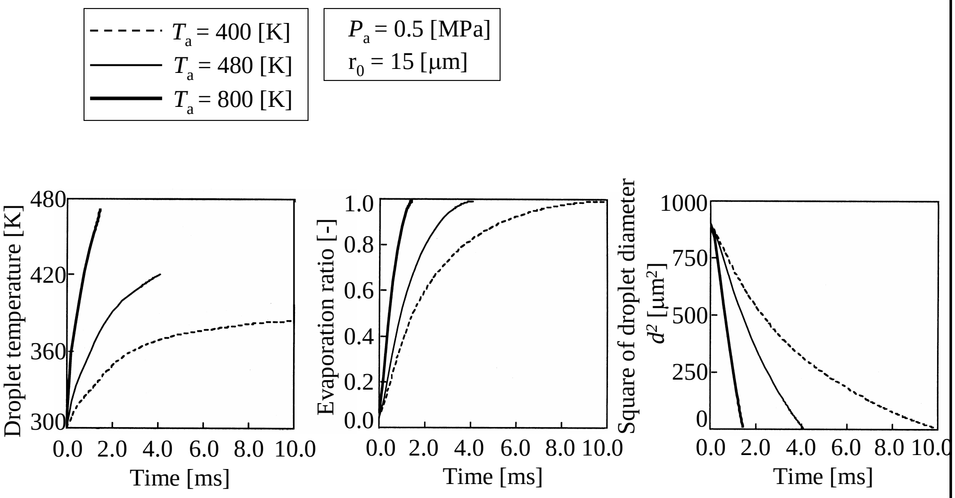
10-components Fuel

Component	Boiling Point [K]	Molar fraction
(a)n-butane	272.6	0.04
(b)isopentane	301.0	0.35
(c)2-methylpentane	333.4	0.12
(d)cyclohexane	353.9	0.06
(e)2,2,4-trimethylpentane	372.4	0.12
(f)toluene	383.8	0.06
(g)meta-xylene	412.3	0.06
(h)ortho-xylene	417.6	0.06
(i)propylbenzene	432.4	0.06
(j)butylbenzene	456.5	0.06

Distillation Curve



Time Dependence of Evaporation Analysis for 10-Components Fuel Single Drop



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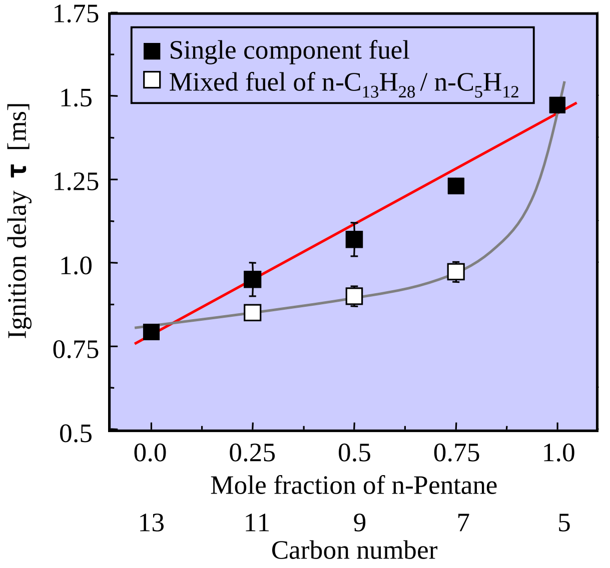
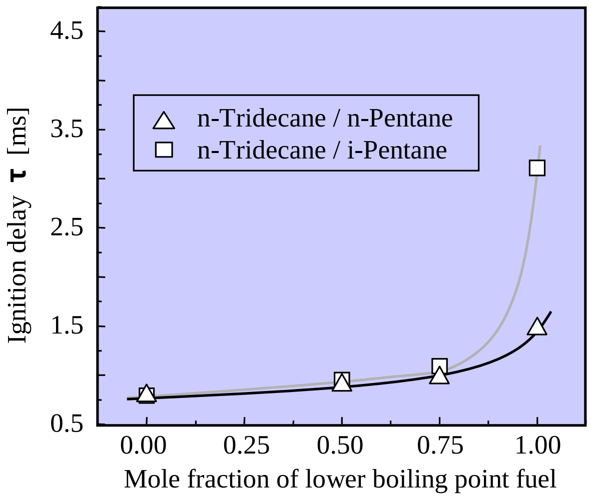
(5) Effective liquefaction of gaseous and solid fuels
→ **Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics**

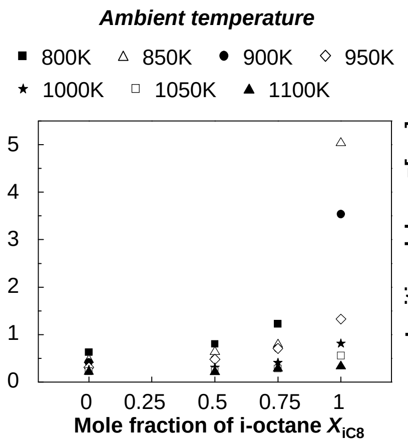
Ignition delay of mixing fuel of C_5H_{12} with $C_{13}H_{28}$ and single component fuel (Experiments)

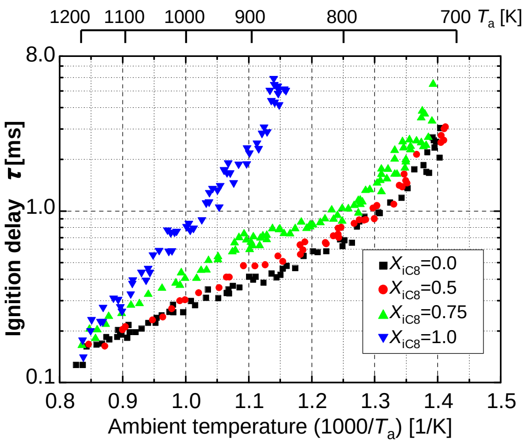


Effect of octane number of low boiling point fuel on ignition delay for mixing fuel (Experiments)

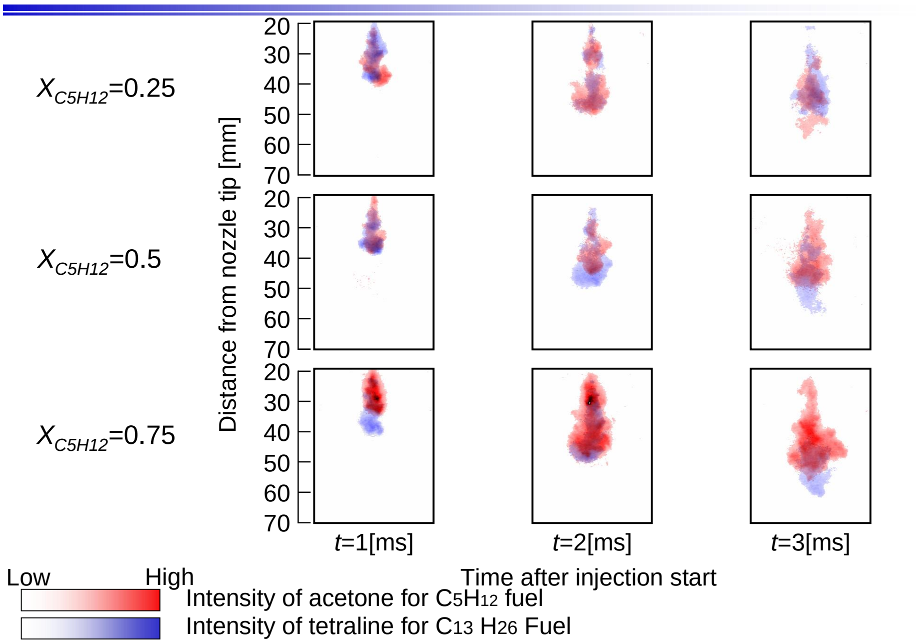


Ignition Delay of Mixing Fuel of i-Octane & n-Tridecane (Experiments)

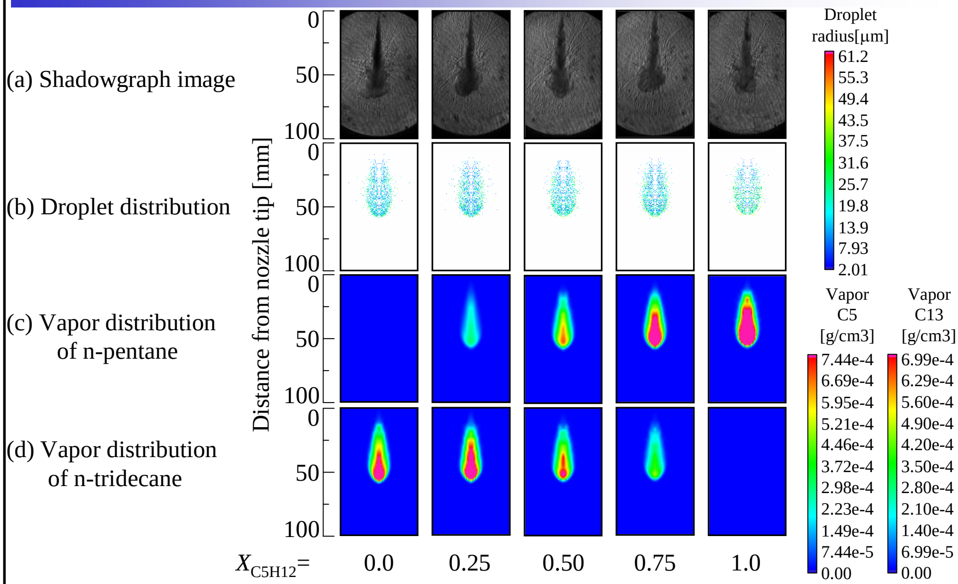




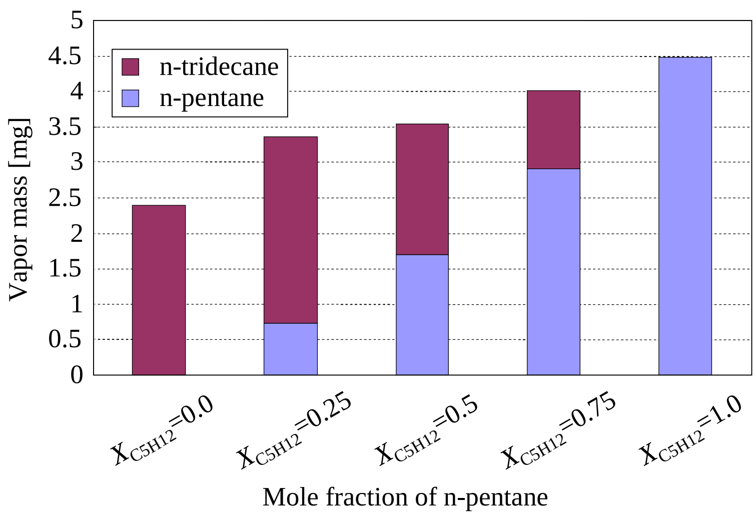
LIF Images of C_5 / C_{13} Mixing Fuels with each Tracer



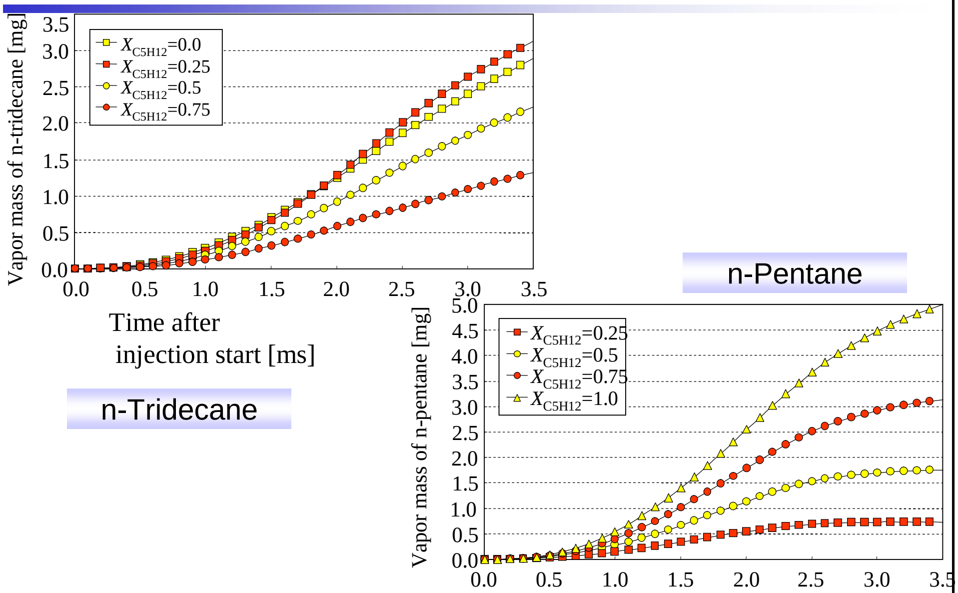
Numerical Spray Dynamics at t=3.0ms for each Mixing Fuel Spray by KIVA-3 Calculation



Vapor Mass of C_5 & C_{13} Mixing Fuel for each Mixing Fraction by KIVA Analysis (t=3.0ms)



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



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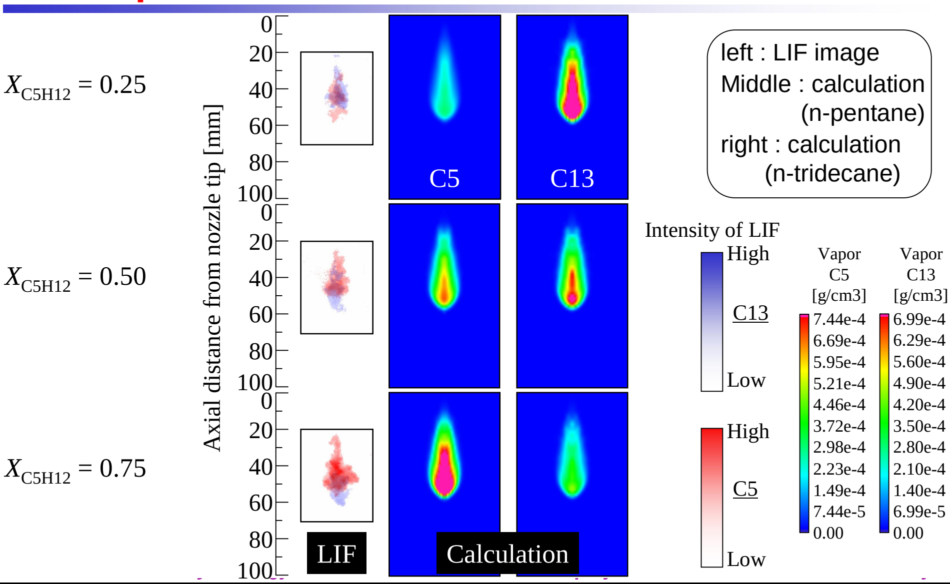
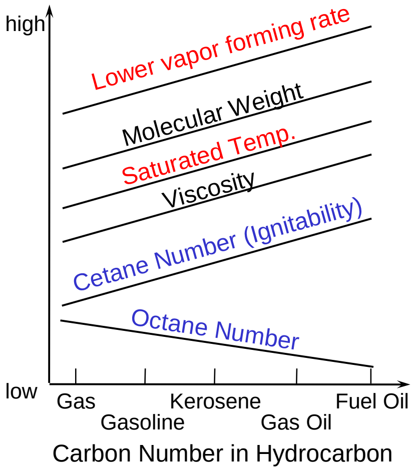
Comparison of Spray Structure –Vapor Spatial Distribution– with Experiments and Numerical Results at t=3.0ms



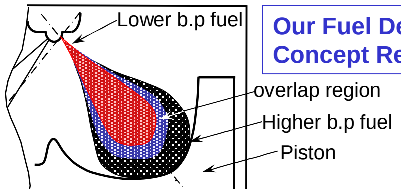
Multi-component Fuel Spray Behavior in Diesel Combustion Chamber

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

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

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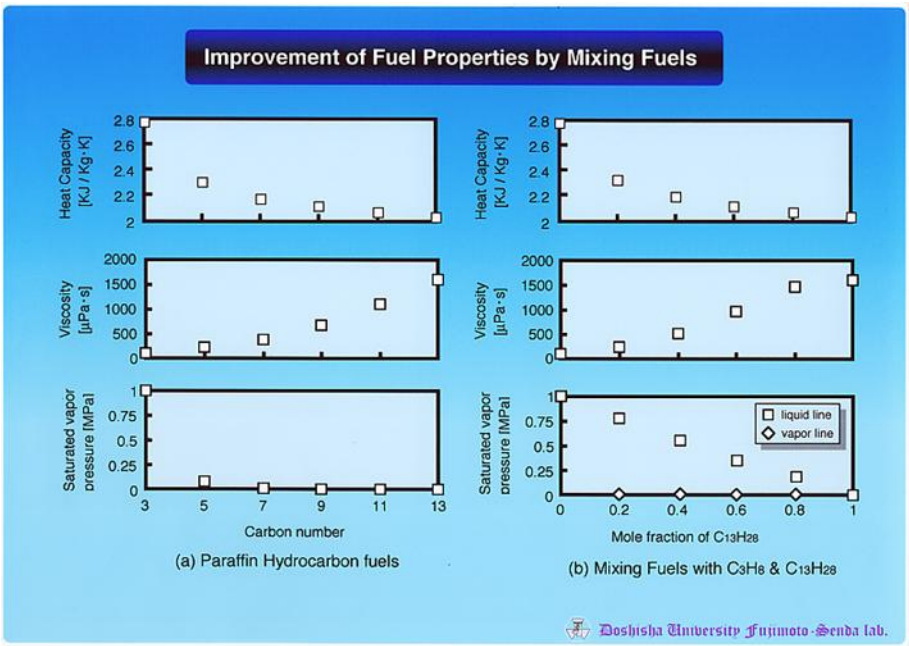
(4) Control the Fuel Transportation Properties in Mixing Fuels
→ Optimization of specific heat, viscosity ,etc

(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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As a Future Study

(5) Effective liquefaction of gaseous and solid fuels

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

Author's Fuel Design Approach Researches

① Mixing Fuel of Liquefied CO_2 and n-Tridecane(gas oil)
→simultaneous reduction both Soot and NOx

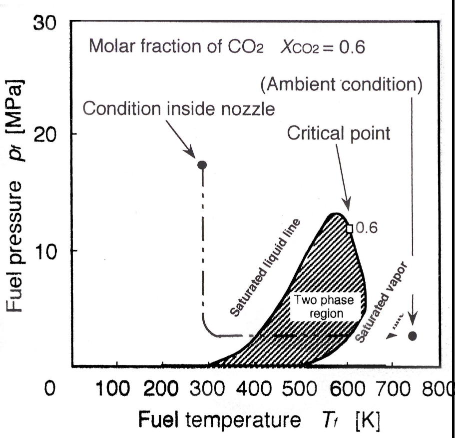
② Mixing Fuel of Gas or Gasoline Component and Gas oil Component →to control both evaporation and ignition

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

Low injection pressure
→ to improve efficiency

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

Control of combustion processes
→ to reduce both NO and soot

Low Emission Scenario

NO reduction

(1) Thermal dissociation of CO_2
($2CO_2 \Rightarrow 2CO+O_2$)

(2) Improvement of spray atomization and vaporization due to CO_2 separation and flashing

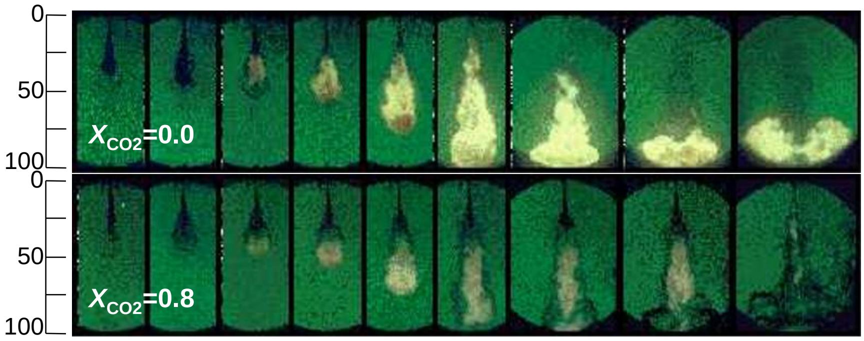
Soot reduction

(1) Soot formation
・avoid the fuel rich mixture

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

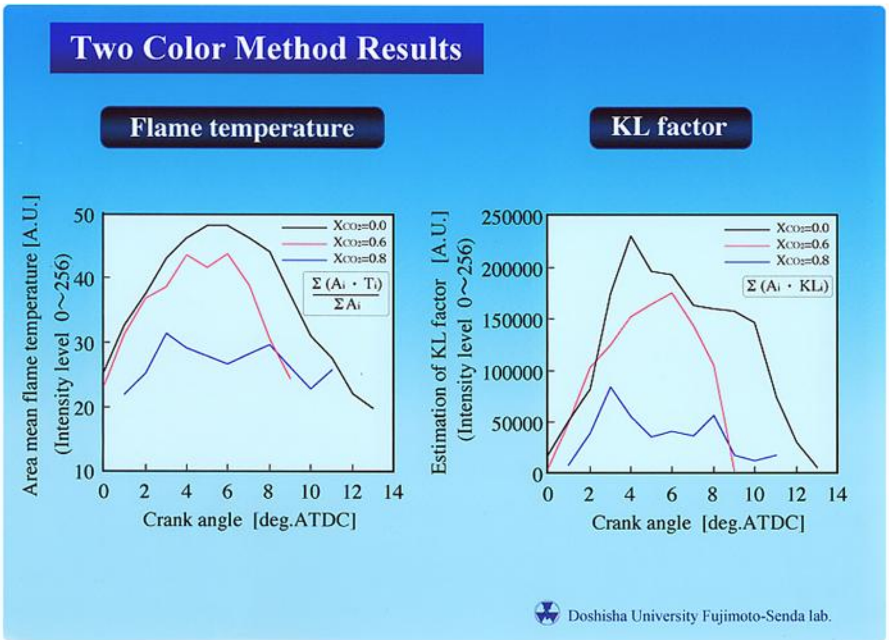
Combustion Characteristics of CO_2 / C_{13} Mixing Fuel

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

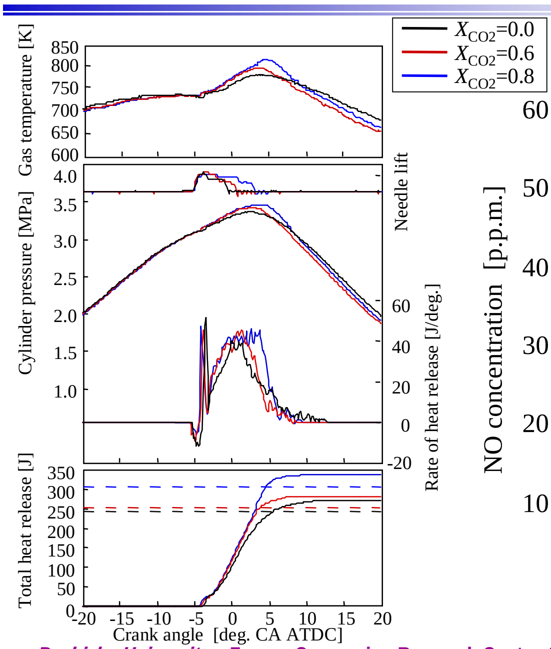


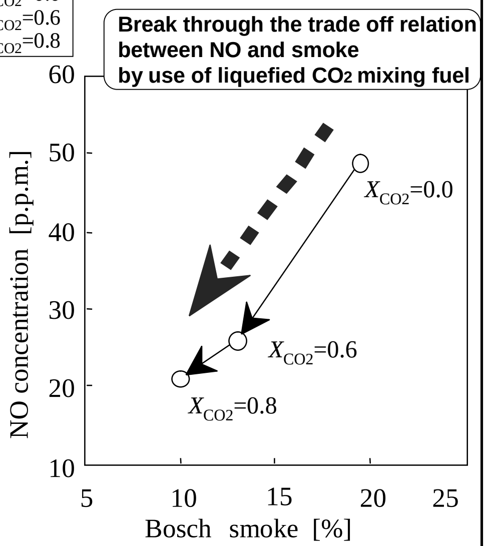
1.00 1.33 1.67 2.00 3.00 5.00 6.33 7.67 10.30

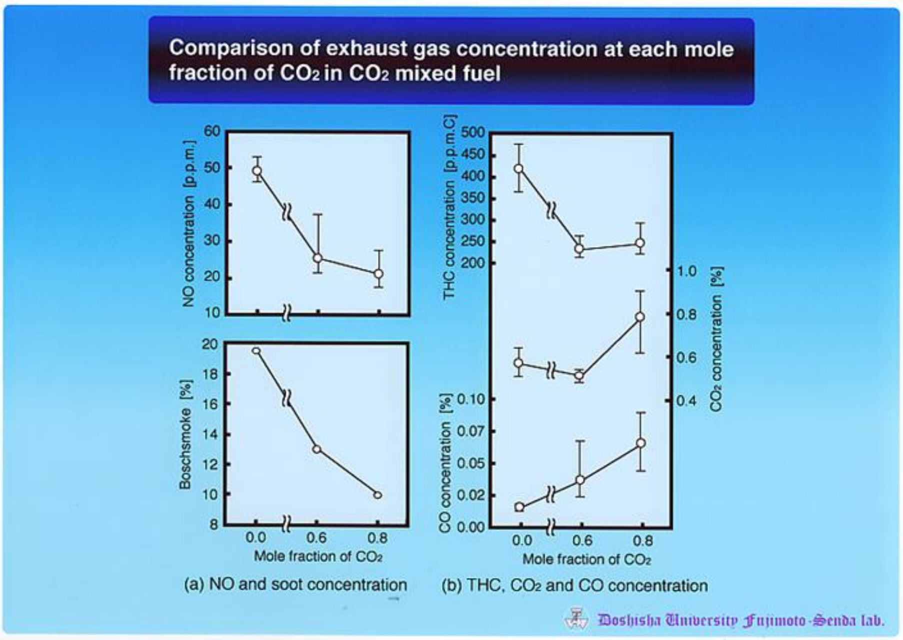
Time after injection [ms]



Combustion Characteristics of CO_2 / C_{13} Mixing Fuel







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

RCEM Condition

Equivalent crank speed	200 r.p.m
Compression ratio	15
Water jacket temperature	353 K

Injection Condition

Orifice diameter	0.20 mm
Injection pressure	15 MPa
Injection velocity	151 m/s
Injection timing	5.0 deg.BTDC
Injection duration	2.0 ms
Injection quantity	10 mg
Excess-air ratio	25
Fuel temperature	353K

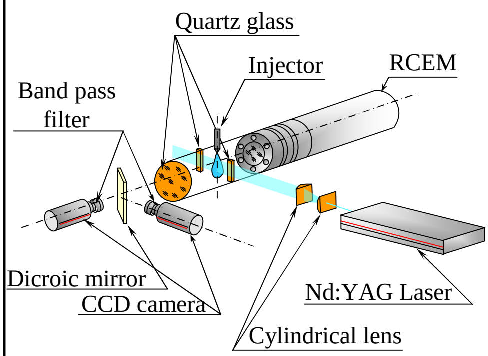
Ambient Condition

Ambient gas	N_2 : 100 %
Initial cylinder pressure	0.1 MPa
Ambient pressure*	3.4 MPa
Ambient temperature*	750 K
Ambient density*	15 kg/m^3
Ambient viscosity*	32.9 μPa·s
Ambient specific heat*	1117 J/kg·K

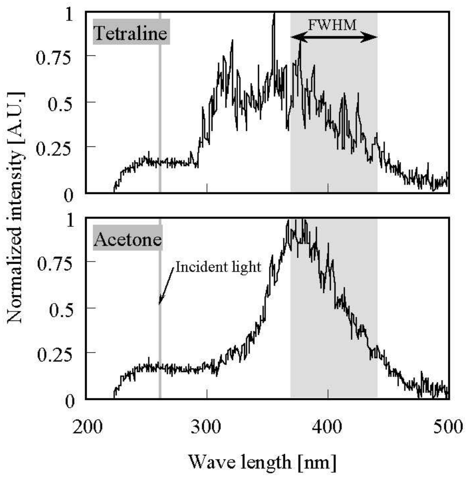
* : at TDC

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

Mie-scattering and LIF Setup



LIF Signal Excited at 266 nm



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}

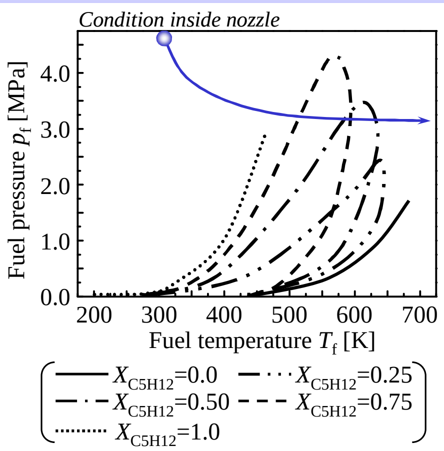
Mixing Fuel and LIF Tracer

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

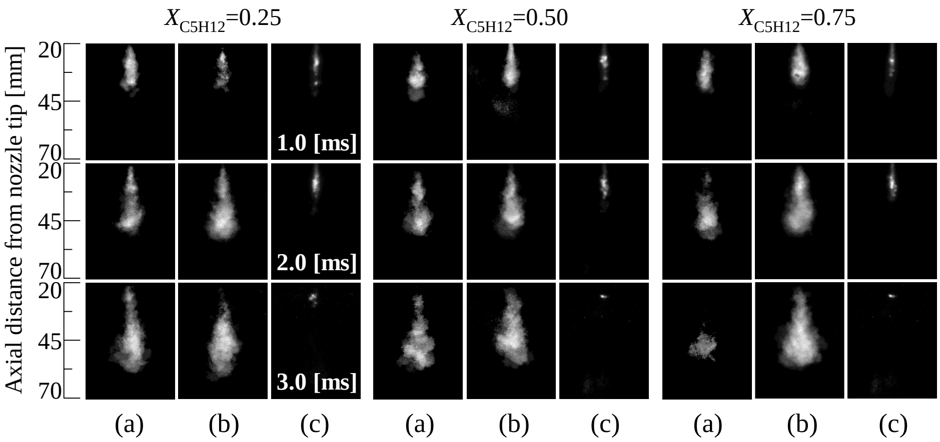
X_{C5H12}	0.0	0.25	0.5	0.75	1.0
V_{C5H12}	0.0	0.14	0.32	0.59	1.0
Acetone [vol.%]	-	0.6	1.5	2.8	5
Tetraline [vol.%]	7	5.9	4.6	2.7	-

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

Two-Phase Region in P-T diagram



LIF & Mie scattering Images in Mixing Fuel of C_5H_{12} & $C_{13}H_{28}$



(a) : Tetraline (b) : Acetone (c) : Mie-scattering

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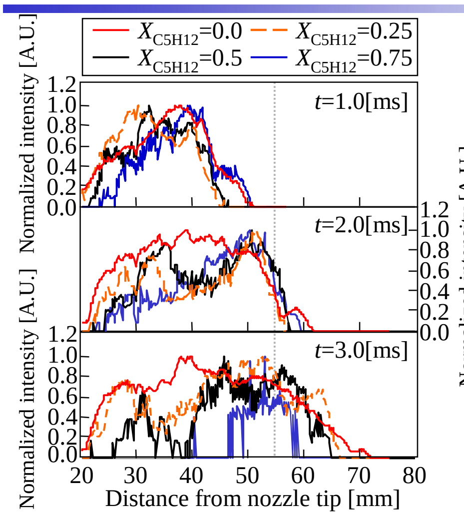
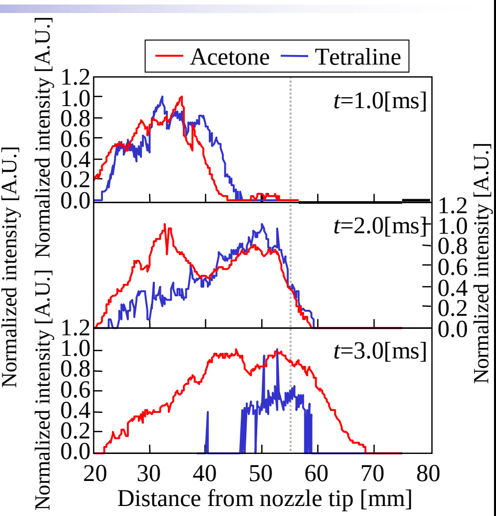
Spatial Distribution of C_5H_{12} & $C_{13}H_{28}$ Vapors in Transient Mixing Spray by LIF



(a) Intensity distribution of Tetraline



(b) Comparison of intensity distribution of each component in X_{C5H12}=0.75 spray

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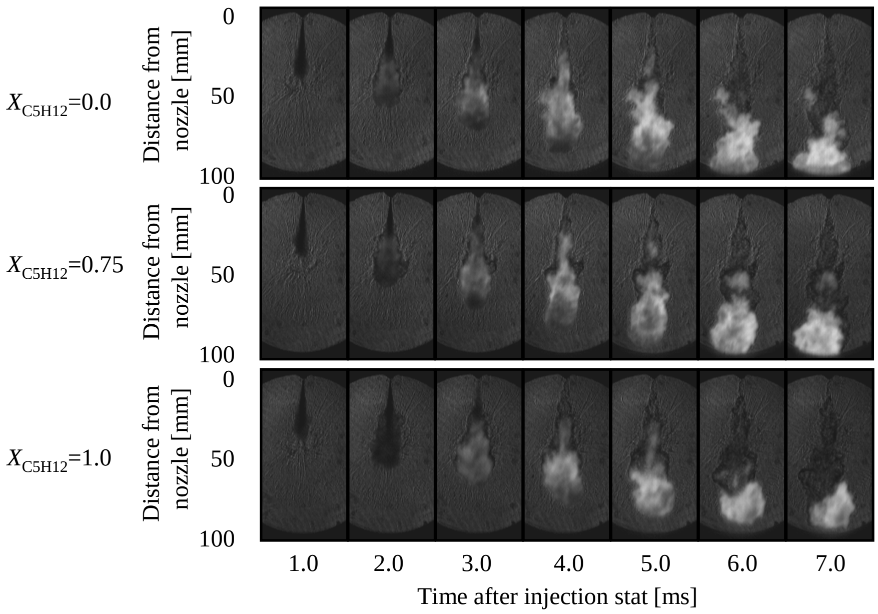
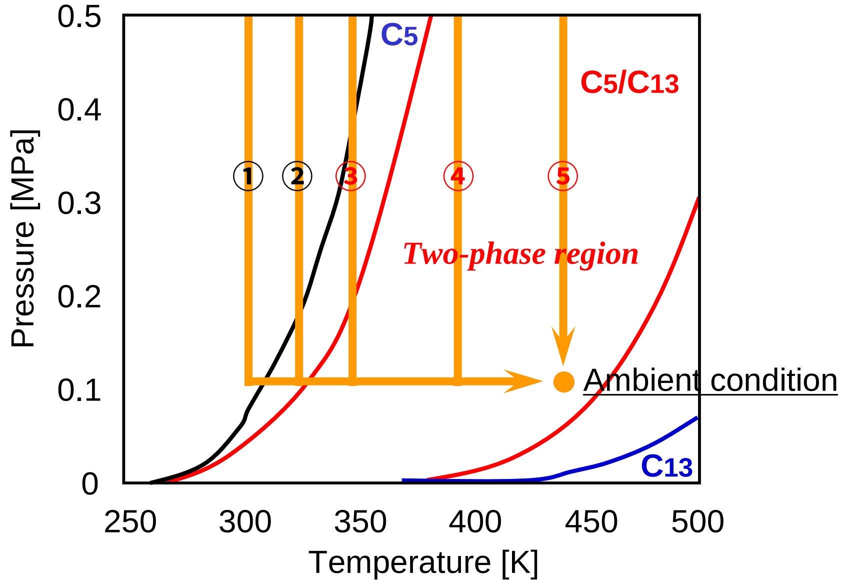
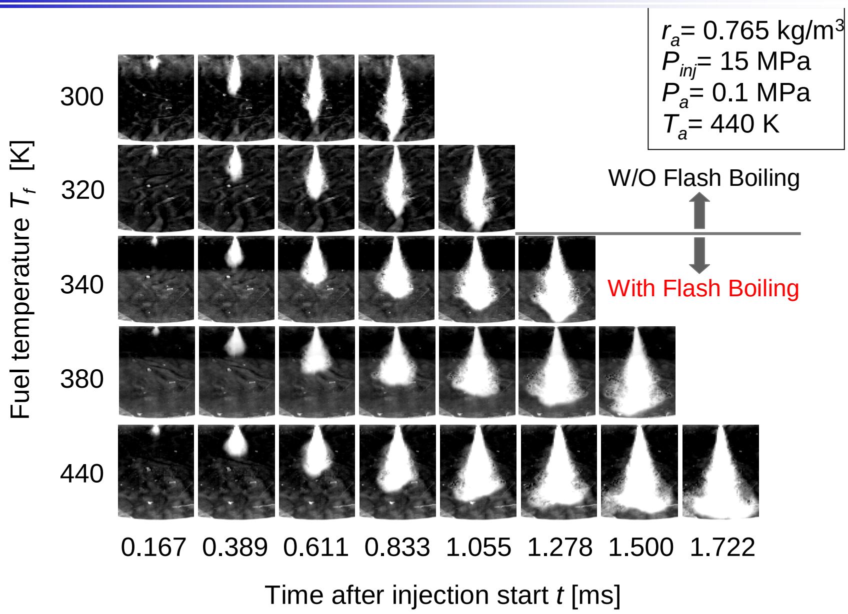
Shadowgraph Images of Flame for each Mixing Fraction



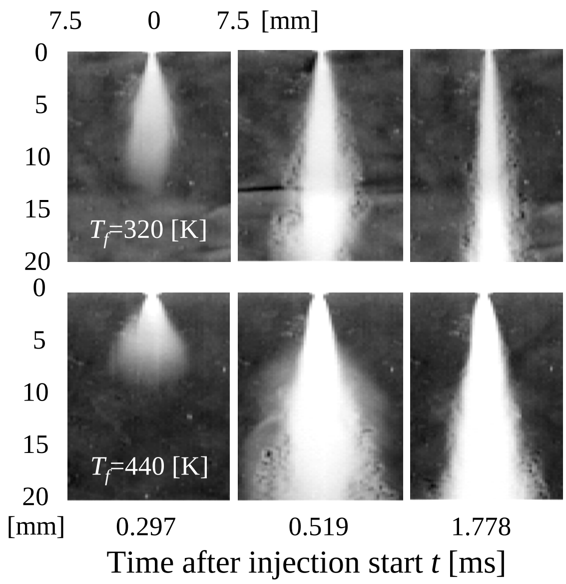
Experimental Conditions for Heated up Mixing Spray



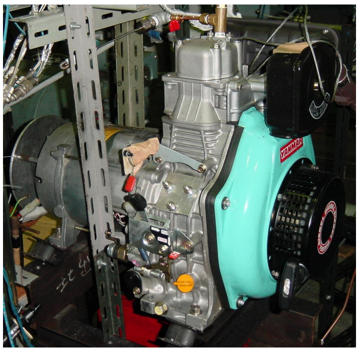
Shadowgraph Images of Flashing Spray of C5/C13 Fuels



Enlargement of Shadowgraph Images near Nozzle Tip



Specification of Test Engine for Mixing Fuel of C5 & C13



Engine type	Air-cooled 4 stroke diesel engine
Bore - Stroke [mm]	ϕ 78 -62
Displacement [cc]	
Combustion chamber shape	Troidal type
Top clearance [mm]	0.6
Compression ratio	19.0
Rated power	6.7kW/3600rpm

Experimental Conditions for Engine Test

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

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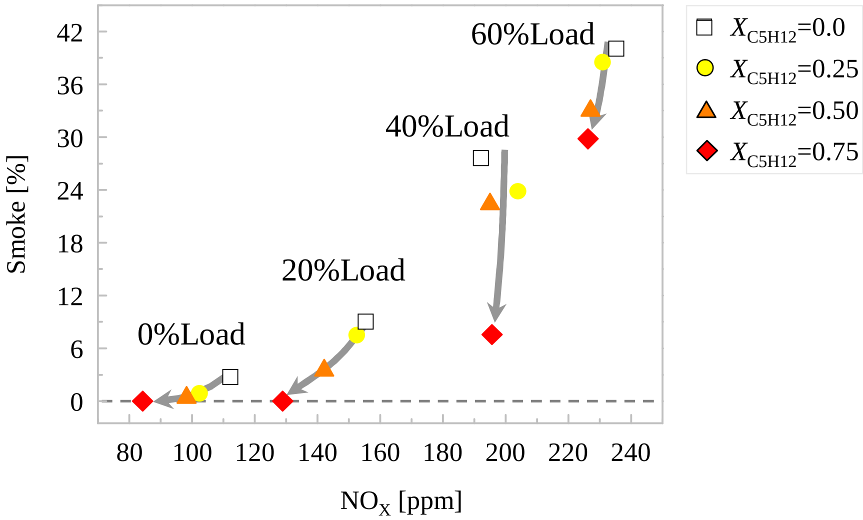
Effect of Mixing Fraction on relationship between Smoke and NO_X



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Experimental Conditions for Engine Test for Mixing Fuel of LPG

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

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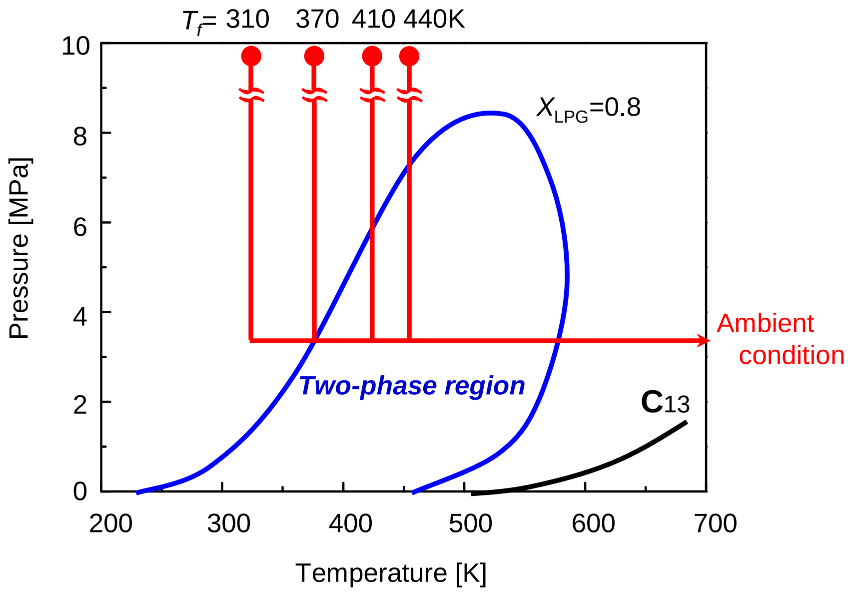
Experimental Conditions for Engine Test with LPG / C13 Fuel



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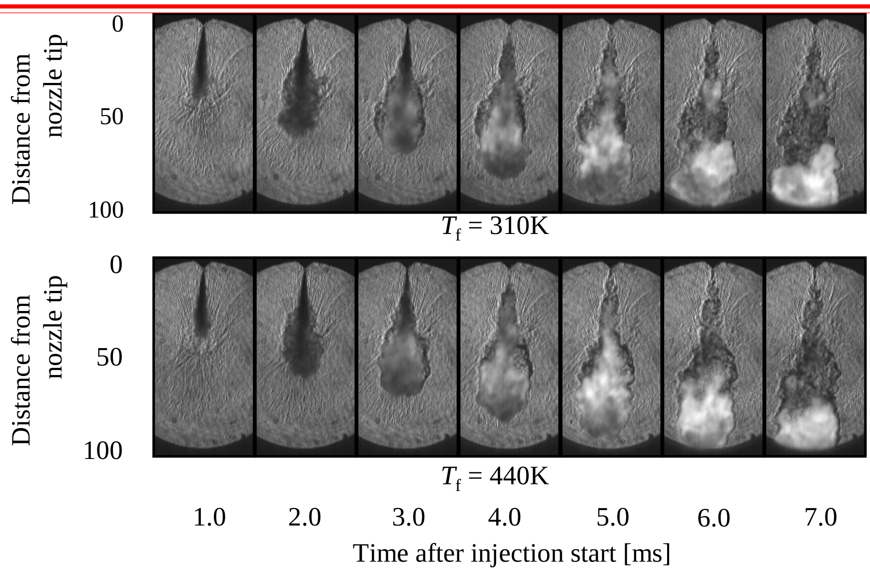
Shadowgraph Images for each Initial Fuel Temperature for Mixing Fuel of LPG and $C_{13}H_{28}$



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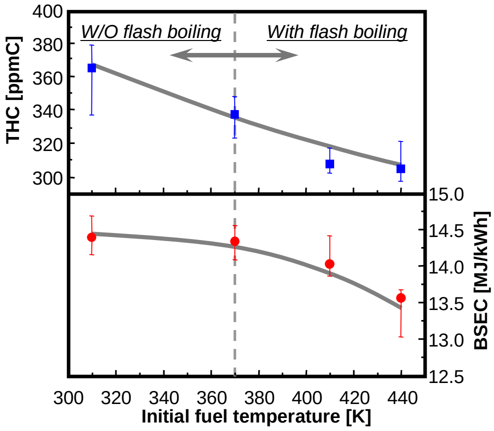
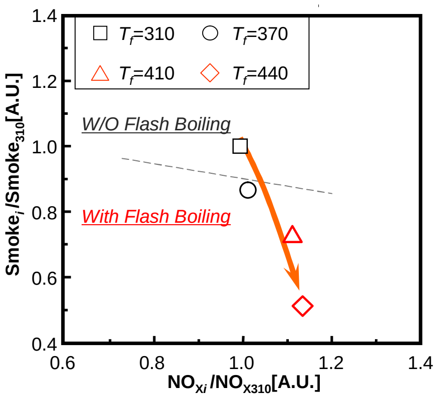
Emissions and Engine Performance (LPG/C13)



(a) THC Emission and Engine Performance



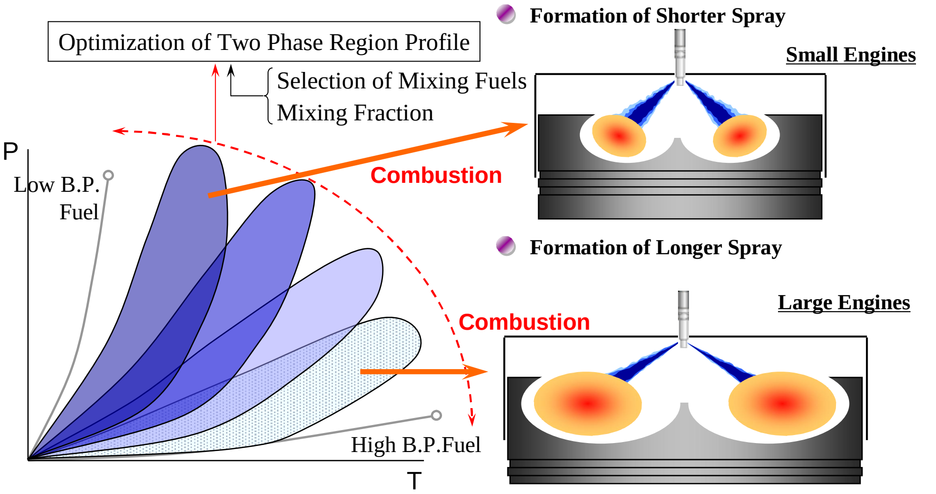
(b) Relation between Smoke and NO_X

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



Int. Seminar on Engine System Combustion Process (2004.5.28)

Fuel Design Approach for Low Emission Spray Combustion

Thank you for your kind attention

Jiro SENDA
Spray & Combustion Science Lab.
Doshisha University, Kyoto JAPAN