Engine Fuel Overview and Fuel Design Approaches for Diesel Spray Combustion

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

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Japan's New National Energy Strategy

Target :

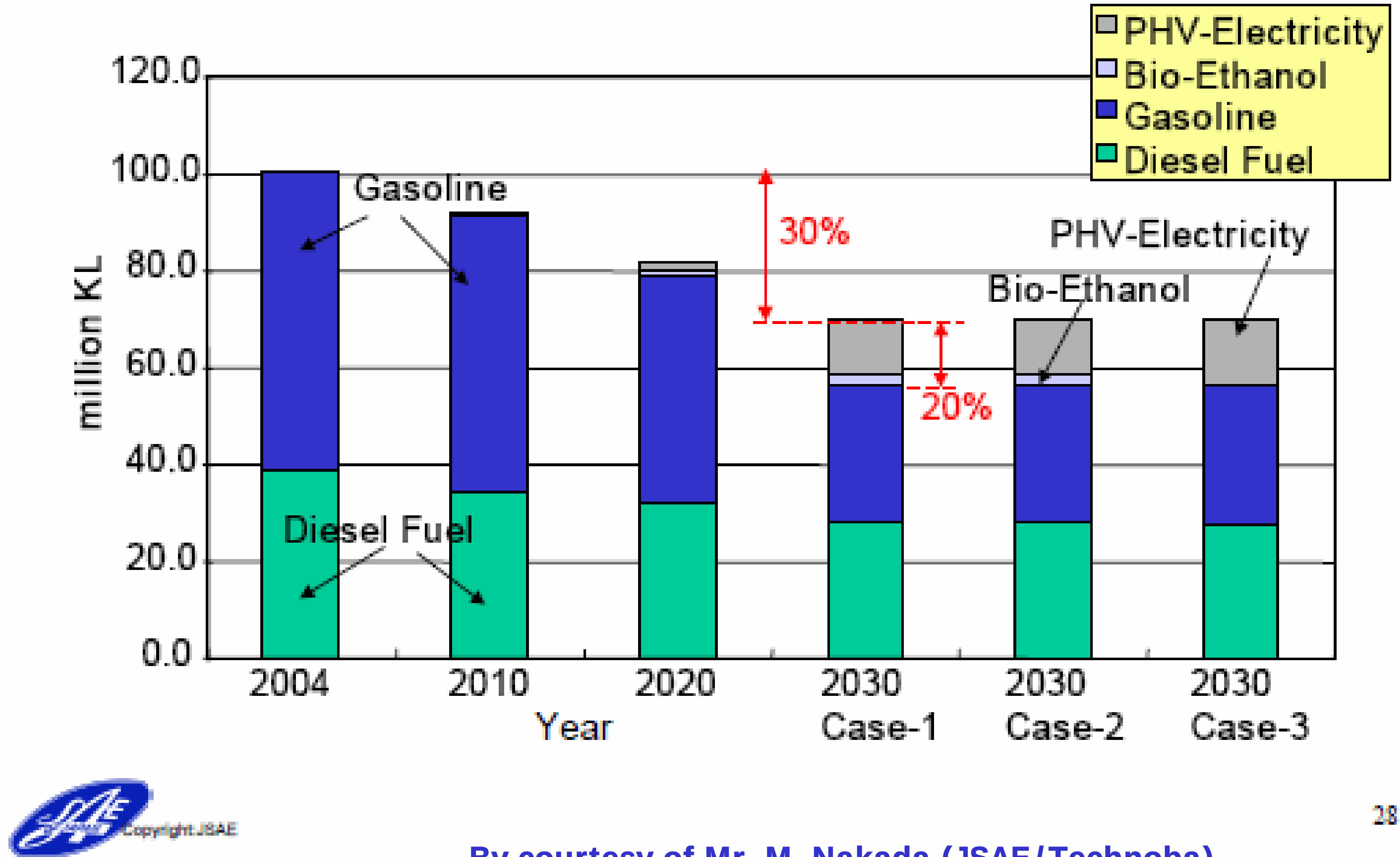
- Energy Efficiency:Minimum 30% Improvement
- Total Oil Dependency:Less Than 40%
- Oil Dependency of Transportation Sector:Less Than 80%
- Nuclear Power Generation:More Than 30-40% in the Total Power Generation
- Oversea Resource Development:about 40% in the Total Resource Development

-- Should Be Achieved by 2030 --*

* Guideline with No Penalty

By courtesy of Mr. M. Nakada (JSAE/Technoba)
" Future Fuel Scenario in Japan "
(10th Int. Conf. on Present and Future Engines for Automobiles)

Future Fuel Scenario in Japan



By courtesy of Mr. M. Nakada (JSAE/Technoba)
" Future Fuel Scenario in Japan "
(10th Int. Conf. on Present and Future Engines for Automobiles)

Ⅰ Overview of Engine Fuels

- Current Crude Petroleum Oil →Gasoline, Diesel Oils (Light oil & Heavy Oil)
  # shift to high quality oil → surplus of A class Heavy Oil and Life Cycle Oil
  # demand to reduce the dependency of fossil fuel up to 80% by 2030
  in transportation in Japan

current petroleum fuels → Alternative Fuels

Liquid Fuels < XTL = Synthetic Oil >

Another Fossil Resources → Liquefied resources --- < GTL & CTL >
→Gas to Liquid (FTD oil, DME etc) , Coal to Liquid

Biomass -- < BTL >
→ Ethanol / ETBE & Bio Diesel Fuel (BDF) (Hydrogenated Bio Diesel)

Gaseous Fuels

Natural Gas (CH_4)

Hydrogen, Hydrogen/CH_4 (Hythane)
→ Application for both Fuel Cell (FC) and Engines – Which is major ?
→ Optimum Hydrogen Energy Application is depending on H_2 production procedure or path , thermal efficiency in the power unit

Considerable points

■ **Well to Tank analysis for current fossil resources**

Natural Gas → GTL: Gas to Liquid (FTD / DME)

Coal → CTL: Coal to Liquid

Fuel production way with CO_2 minimum

Resources amount ?

■ **Renewable Fuels ;** BTL: Biomass to Liquid (Ethanol & BDF)

Ethanol blend Gasoline / ETBE blend Gasoline (3 % in Japan)

Neat BDF / BDF blend Diesel Gas Oil (B20 et. al) (5 % in Japan)

nearly carbon neutral but global warming gas free ?

How is energy density / resources amounts / small production capacity ?

generation process: from 1^{st} =based on food crop to 2^{nd} = based on biomass

■ **Fuel Diversity for Engines → Flexible Fuel Engine**

→ Engine modification or Engine adaptation

■ **On-Board Reformulation of Fuels**

→ need to On-Board Fuel Sensing

(Chemical and Physical Fuel Properties)

GTL Researches in Japan

■ Researches on FTD and DME in Japan

AIST- National Institute of Advanced Industrial Science and Technology
JARI – Japan Automobile Research Institute
LEVO – Low Emission Vehicle Organization &
NTSEL – National Traffic Safety and Environment Laboratory (2001-)
Several Automotive Makers

■ FTD Performance (ref.SAE-2007-01-2004 by Toyota)

Lower Density, Higher Heating Value, Lower Sulfur, Lower Aromatic Species (High Cetane Index)
Lower PM, HC,CO & Equal NOx
Non problem in Fuel Supply and Injection Equipment

■ DME Performance (general view & LEVO Project)

Lower Sulfur, Lower Aromatic, Oxygenated Fuel, Volatile Property, Lower Viscosity
Lower NOx, HC,CO & PM Free
Problem of Cavitation and Erosion/Abrasion in Fuel Supply and Injection Equipment

■ Engine Modification for FTD & DME

Load reduction of DPF by Lower PM
NOx Reduction by EGR and NOx Catalyst

BDF research

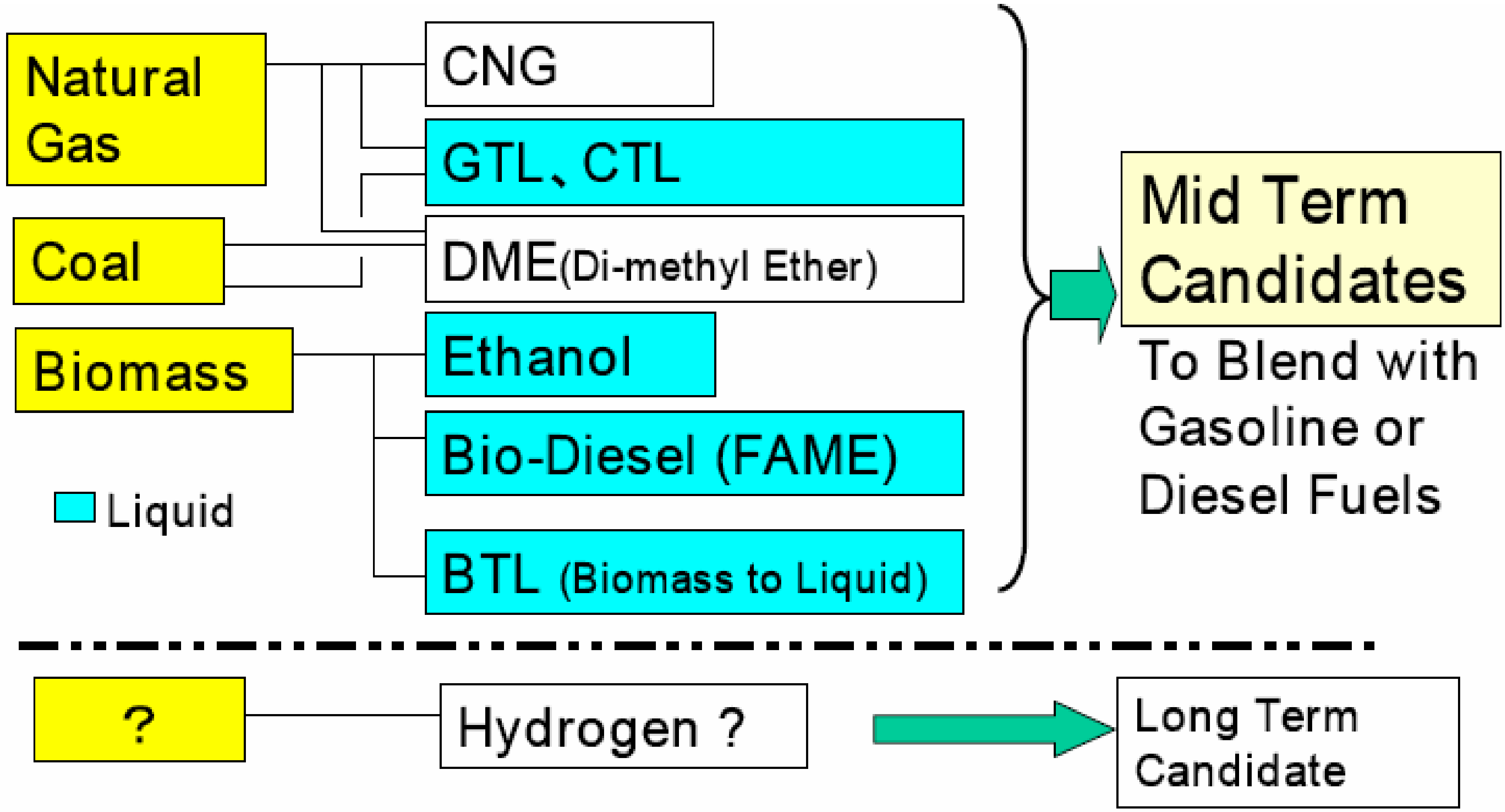
■ Fuel Property – Ex. RME (Rapeseed Methyl Ester)

Oxygenated Fuel, Similar Cetane Number, Sulfur free, Aromatic free
High Boiling Point, Unstable in Oxidation for Liquid State
Lower Potential in Low Temperature Properties such as CFCP(Cold Filter Clogging Point), CFPP(Cold Start Filter Plugging Point)

■ General engine performance

① Soot or PM is reduced remarkably, but SOF slightly increases in light load conditions
② Few emissions in SOx
③ NOx is almost same or slightly increasing.
④ CO and HC are depending on the fuel properties or engine operating conditions.

Candidates for Alternative Fuels



Ⅱ Recent Diesel Engine Combustion Scheme

Recent Research Trend

New Attempts in Diesel Fuel Injection System for Exhaust Emission Reduction

Introduction of Several HCCI Approaches

→Possibility of HCCI Application into Diesel Engines in High Load Operation

Borderless in Gasoline Engine and Diesel Engine

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 → MULDIC

UNIBUS → HiMICS

Single Stage → Two Stage

<u>Fuel Conversion / Additive Injection</u>

- Water Injection
- Emulsion Injection

→ **Our Fuel Design Approach**

Progress in Engine Combustion

HCCI combustion

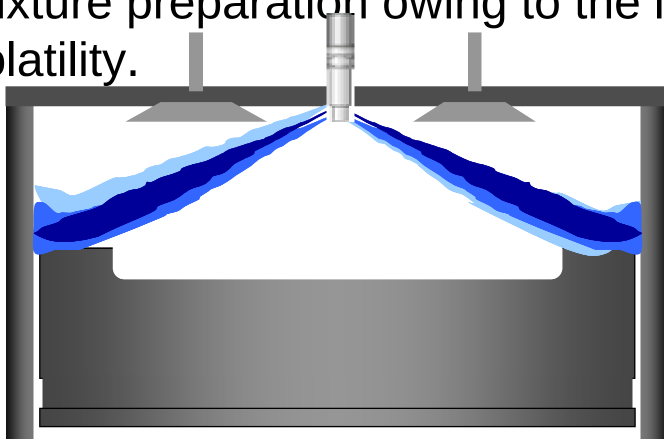
has the potential to be highly efficient and to produce low PM and NO_x emissions.

In direct injection system…

to realize HCCI combustion, injection timing has to be advanced.

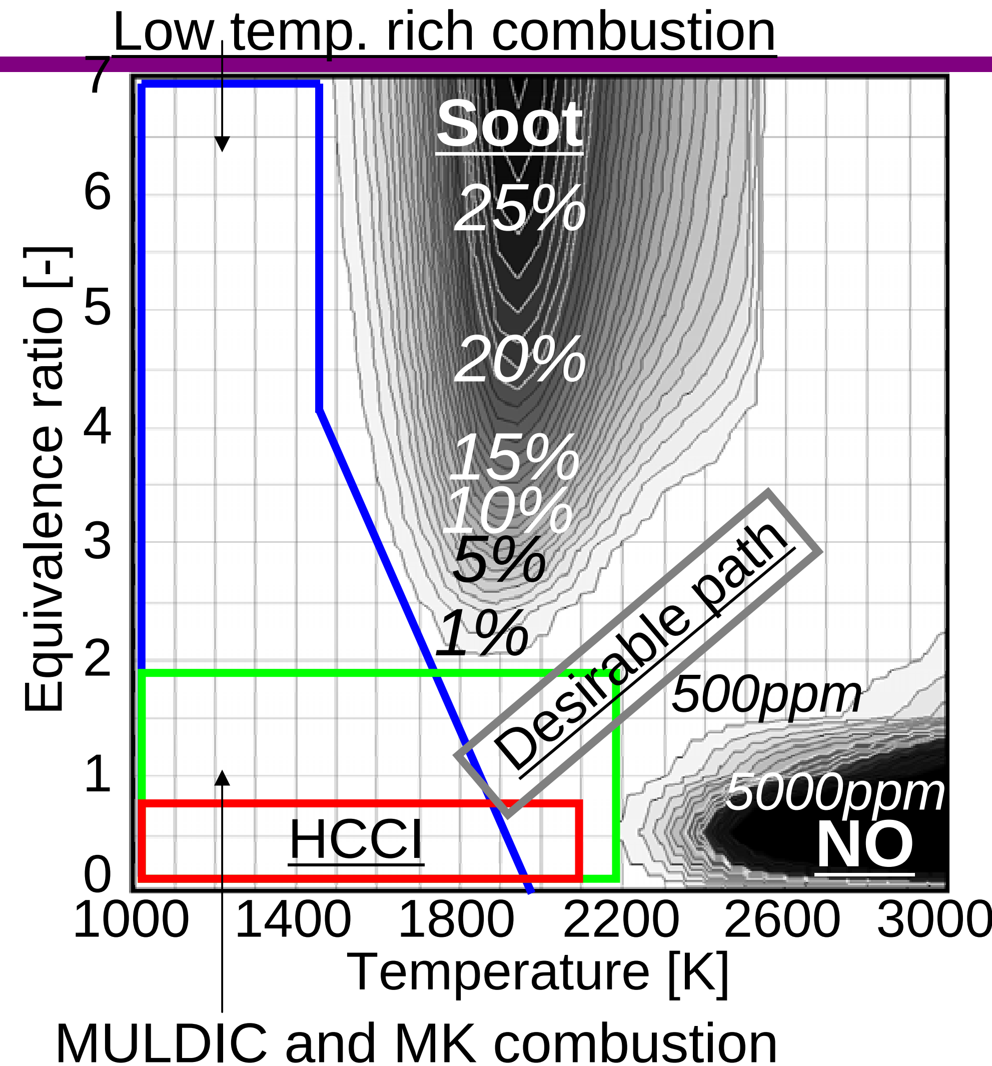
However, in diesel engine…

gas oil causes wall-wetting and poor mixture preparation owing to the low volatility.



Therefore…

The other lean combustion concepts where Injection timings are set close to TDC have been proposed in diesel engine.



*n-heptane, reaction time=1ms

Ref) Kitamura, T. et al., *Int. J. Engine Res.*, 2002

Importance of Fuel in Engine Systems

■ Borderless situation in Gasoline Engine and Diesel Engines

- **Harmonization of Combustion Scheme in Gasoline Engine and Diesel Engine**

  for Higher thermal efficiency and Lower emissions

Direct injection has been applied to Gasoline engines to improve the thermal efficiency. And, homogeneous charge is introduced into Diesel engines as HCCI system to reduce NOx emission.

From the point of both mixture formation and basic combustion mode, we have no definite boundary for these engines, in another words, we are in the stage of borderless situation in both engines.

■ Engine design from the Fuel properties

To improve thermal efficiency and exhaust emissions

Engine Control and Fuels in Current Engines - Fuel Sensing for the Future FFV System?

■ **Several Variable Control in engine system**

→ **VVT(Valve-toronich, Valvematic,VVEL)→**

Variable Compress. ratio

Wide Range EGR,

Higher Pressure Multiple Fuel Injection,

Higher Boosting(T/C(VGT),S/C)→Engine Down Sizing

■ **Application of HCCI, HCSI, Rich-SI into one Engine**

→ **Control of spark ignition**

■ → **Application of Mixing Fuels or on-board reformulation ?**

■ → **FFV; Fuel sensing ?**

HCCI Gasoline Engines

(1) **Starting ~ Very Light Load = SI Operation** (up to 1000 rpm)
(2) **Light Load = HCCI Operation** (1000 ~ 3000 rpm) without a throttle restriction

→ Higher Efficiency & Lower NOx (Low Temp. Combustion)

(3) **Higher Load = SI Operation** (3000 rpm ~ wide open throttle)

General Motors – Saturn Aura

 # 2.2-L Ecotec 4-cylinder engine
 # 4 key technology enablers – direct multiple injection, 2-step valve lift, electric phasing of the intake and exhaust camshaft

Mercedes Benz – DiesOtto

 # 1.8-L 4-cylinder engine ; 238ps / 400Nm, 6ℓ/100km
 # 7 key technological features

Ⅲ Our Fuel Design Approach Researches

① Mixing Fuel of Liquefied CO2 and n-Tridecane(gas oil)

→ for simultaneous reduction both Soot and NOx

② Mixing Fuel of Gas or Gasoline Component and Gas oil Component

→ to control both evaporation and ignition

③ Application into HCCI(PCCI) Combustion Mode

→ to control vapor heterogeneity and mixture ignition

④ Mixing Fuel of Bio-Diesel Fuel and Lower Boiling Point Hydrocarbon Fuel

→ to improve fuel distillation and the viscosity

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

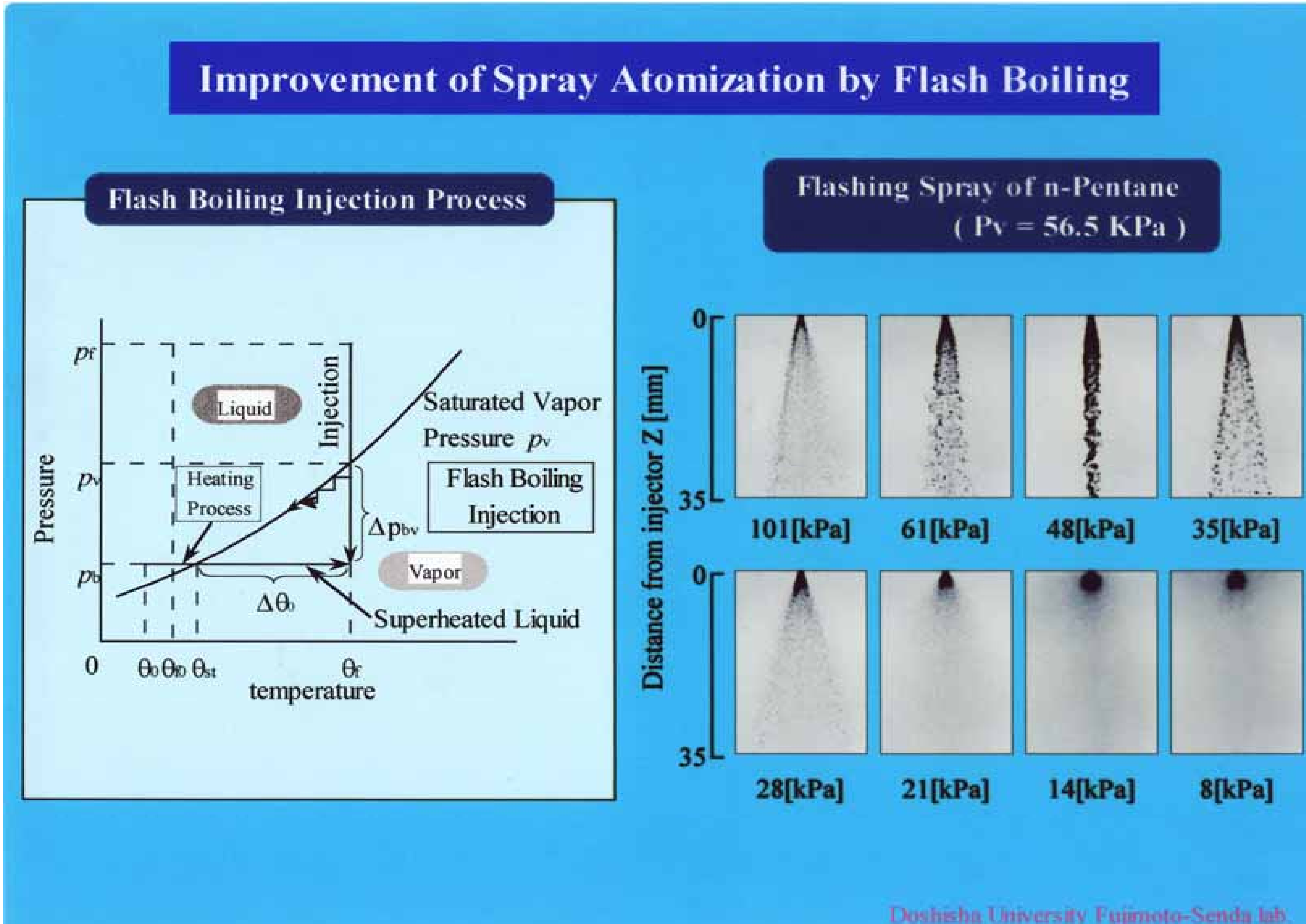
(2) Chemical Control = Capability of Control on Combustion Process
→ Emission Control – Soot & NOx
Simultaneous reduction of both Soot and NOx (CO_2-gas oil mixing fuel)
→ Ignition Control (Gasoline-gas oil mixing fuel)
→ HC Control (Gasoline-gas oil mixing fuel)

(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

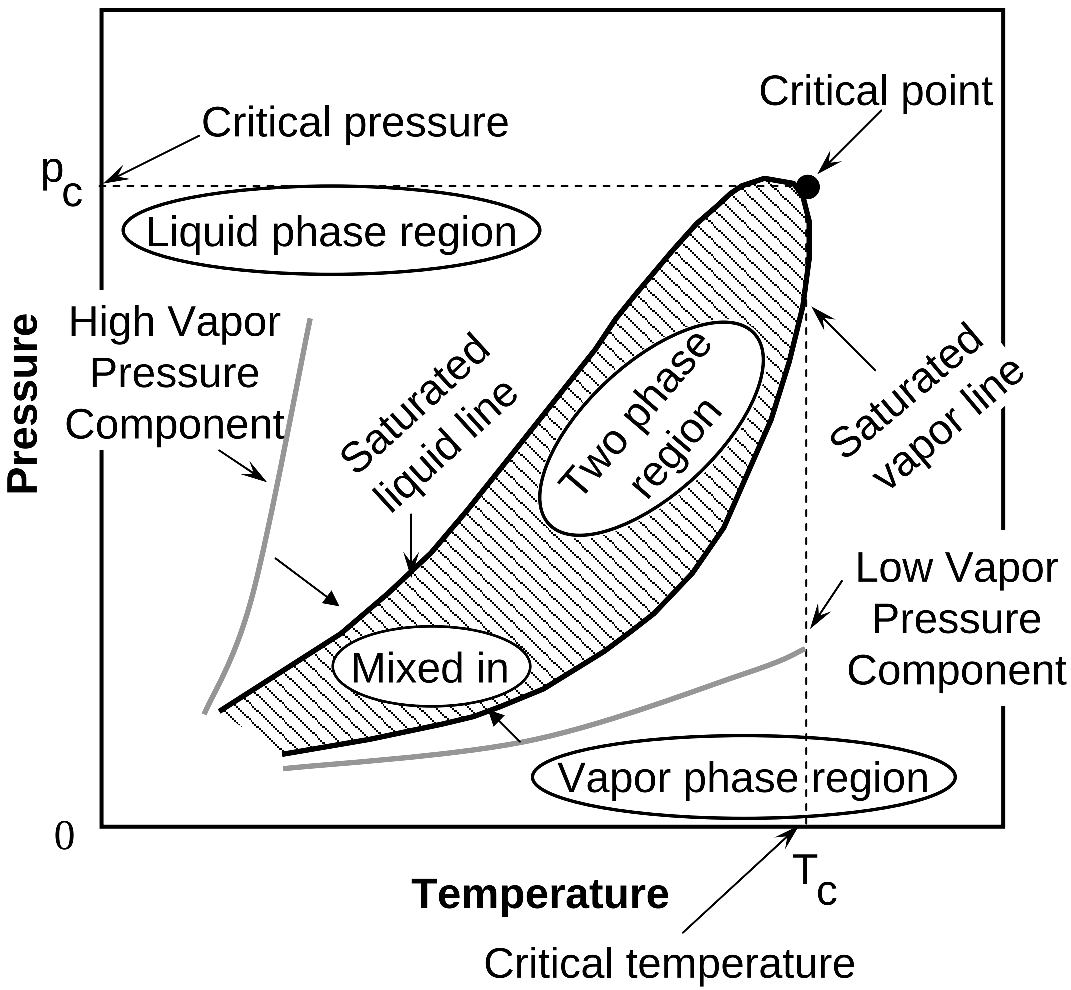
(5) Effective liquefaction of gaseous and solid fuels
→ Conversion of Heavy Fuels or Solid Fuels into high quality Lighter Liquid Fuels through Chemical-Thermodynamics

What is Flash Boiling Spray ?

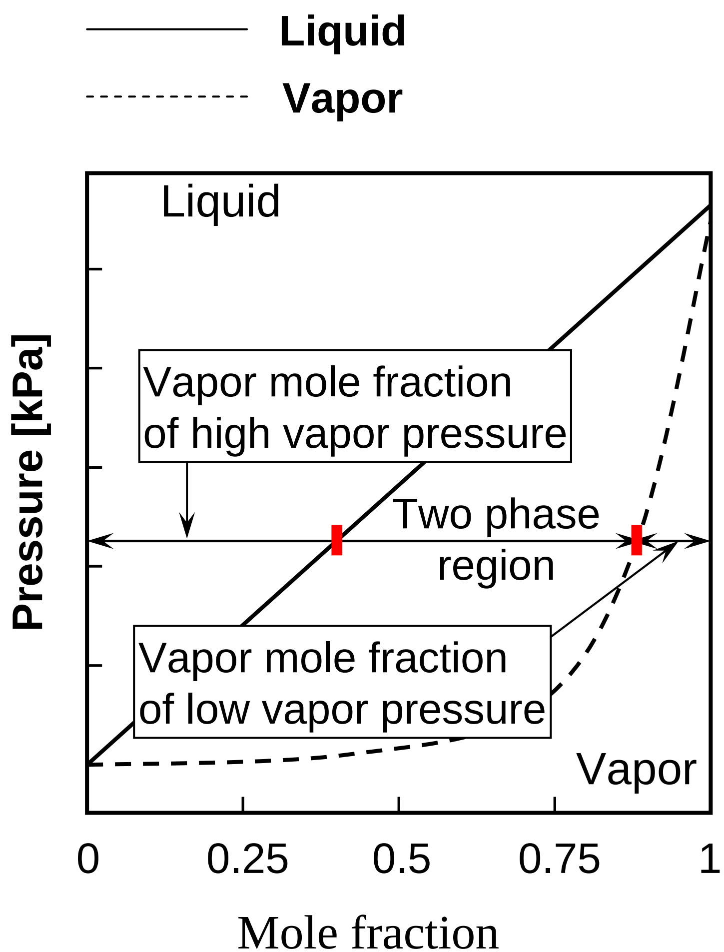


Two Phase Region Formation in Multi-component Fuel in Phase Change Process

Pressure-temperature diagram



Pressure-Mole fraction diagram



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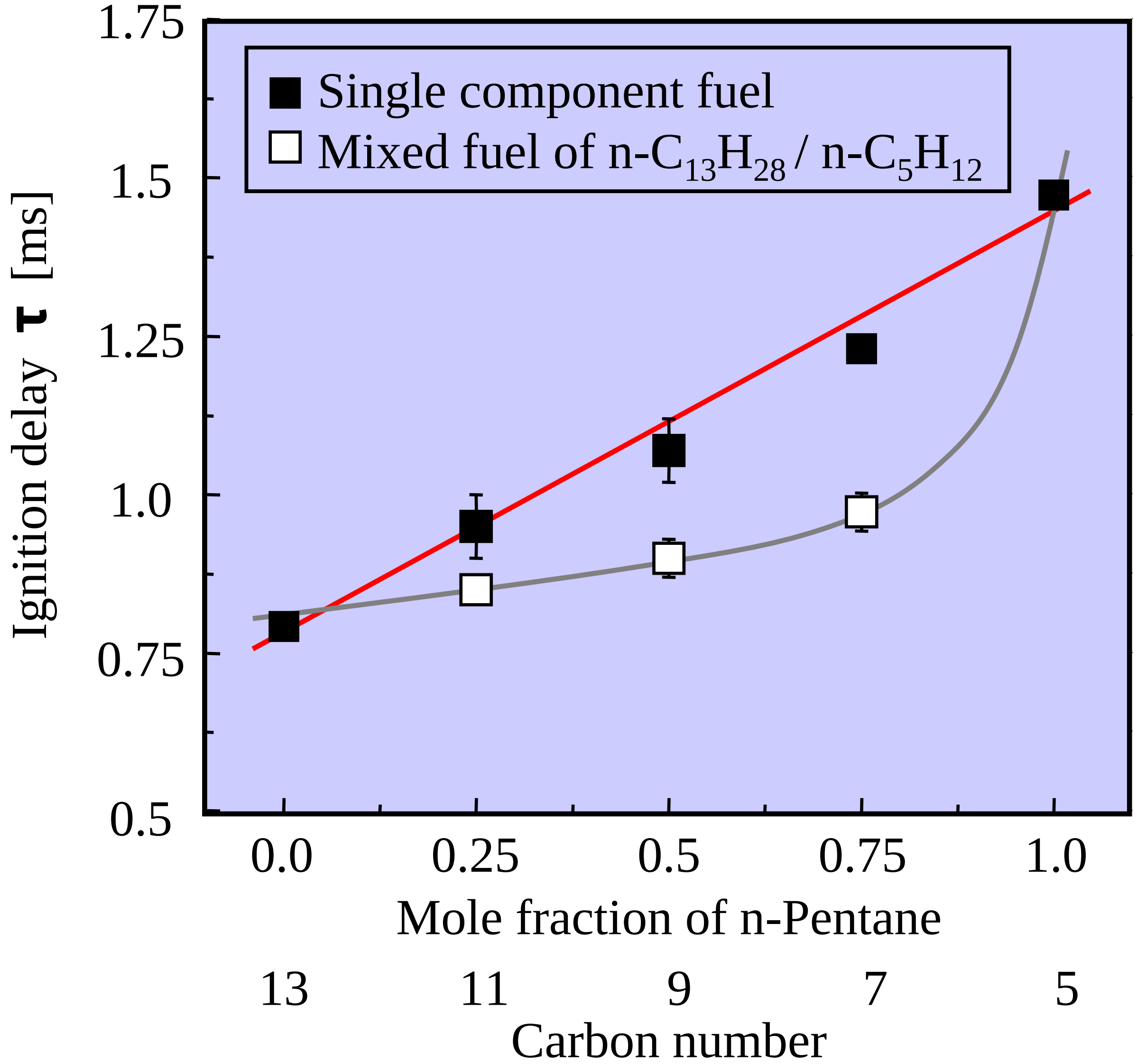
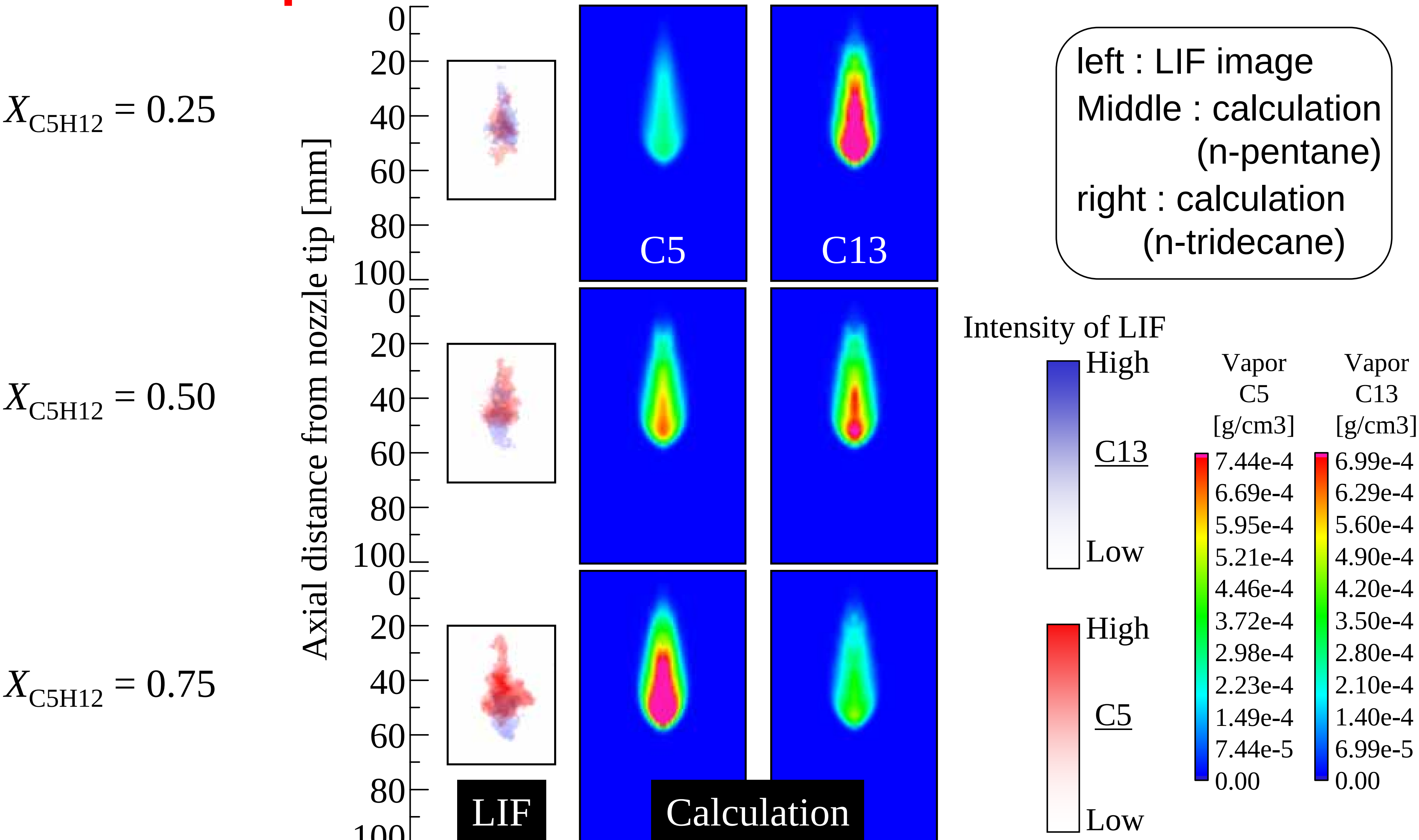
Ignition delay of mixing fuel of C_5H_{12} with $C_{13}H_{28}$ and single component fuel (Experiments)



Comparison of Spray Structure –Vapor Spatial Distribution–

with Experiments and Numerical Results at t=3.0ms



① 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

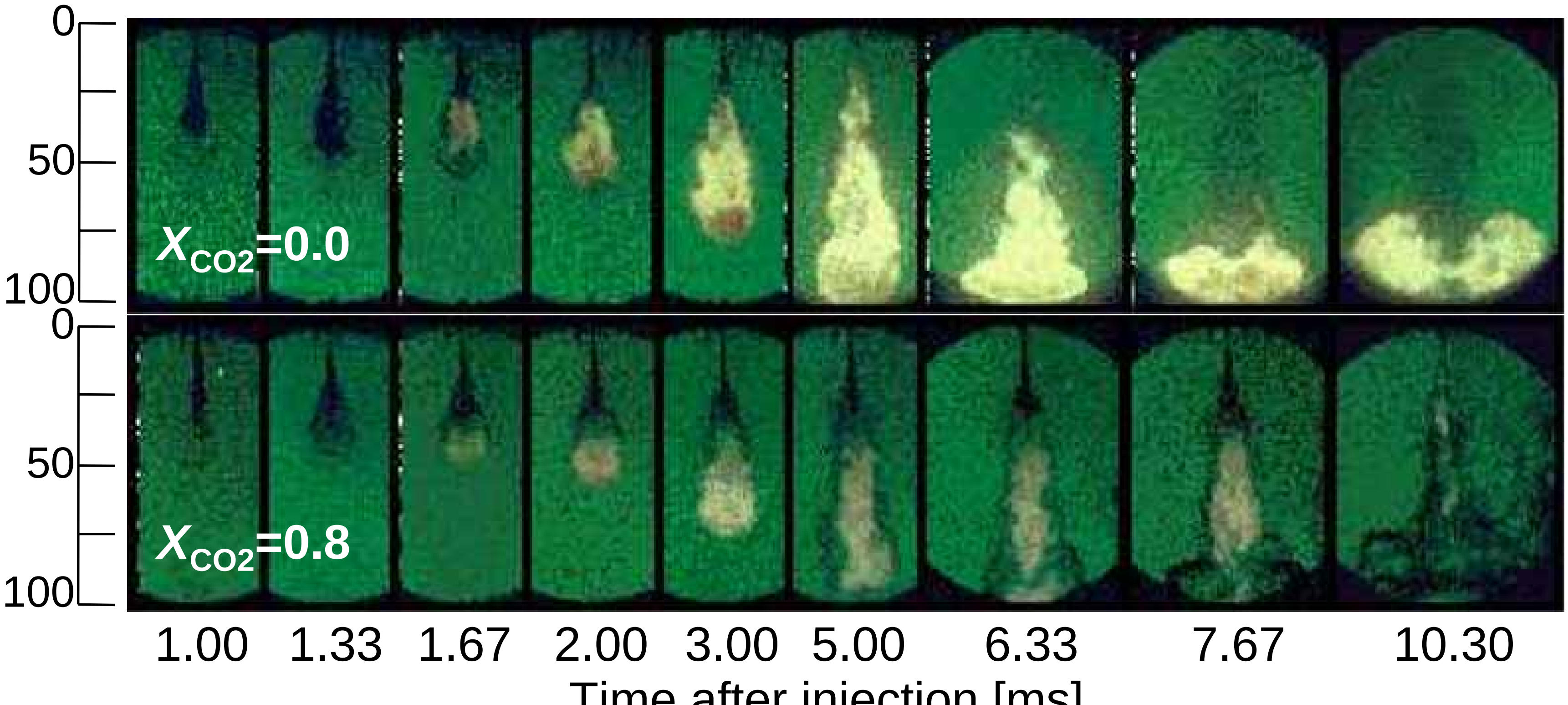
Soot reduction

(1) Soot formation
- avoid the fuel rich mixture

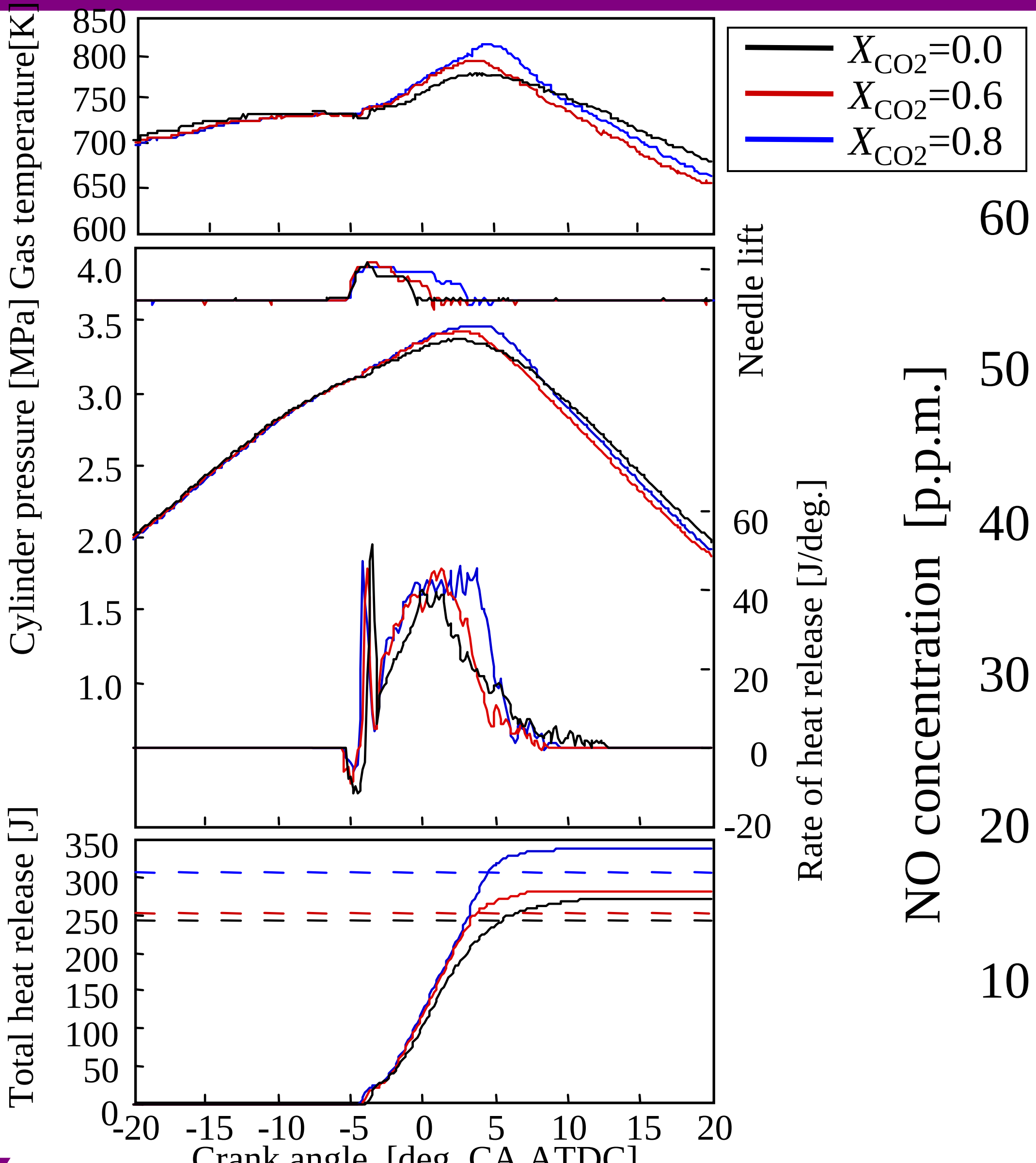
(2) Soot oxidation & re-burning
- Dissociation of CO_2 into CO and O
- Boudouard reaction $C+CO_2 \Rightarrow 2CO$

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

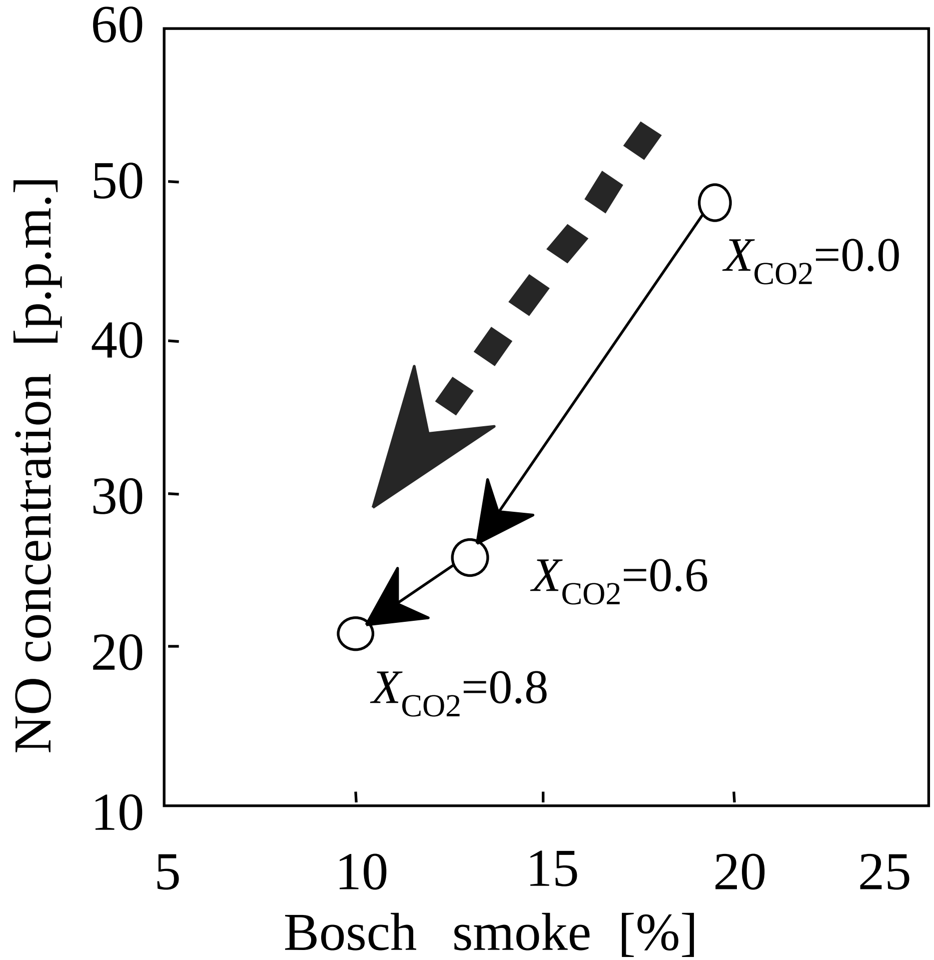
- **Low pressure injection** → **Improve the Thermal Efficiency**
- **Flash boiling spray by CO_2 component** → **Promotion of Spray Evaporation**
- **Spray internal EGR** → **Reduction of NOx**



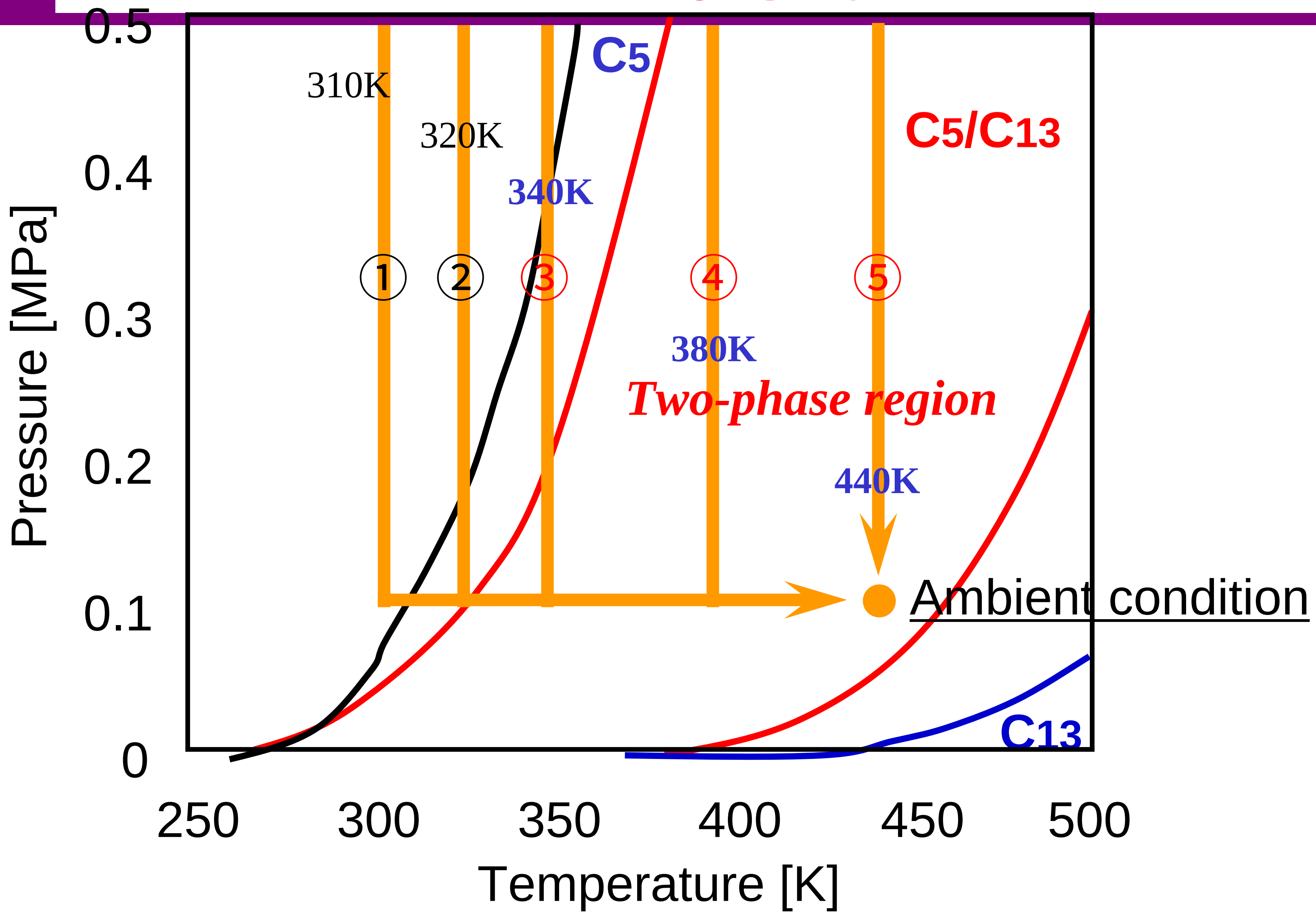
Combustion Characteristics of CO_2 / C13 Mixing Fuel in RCEM



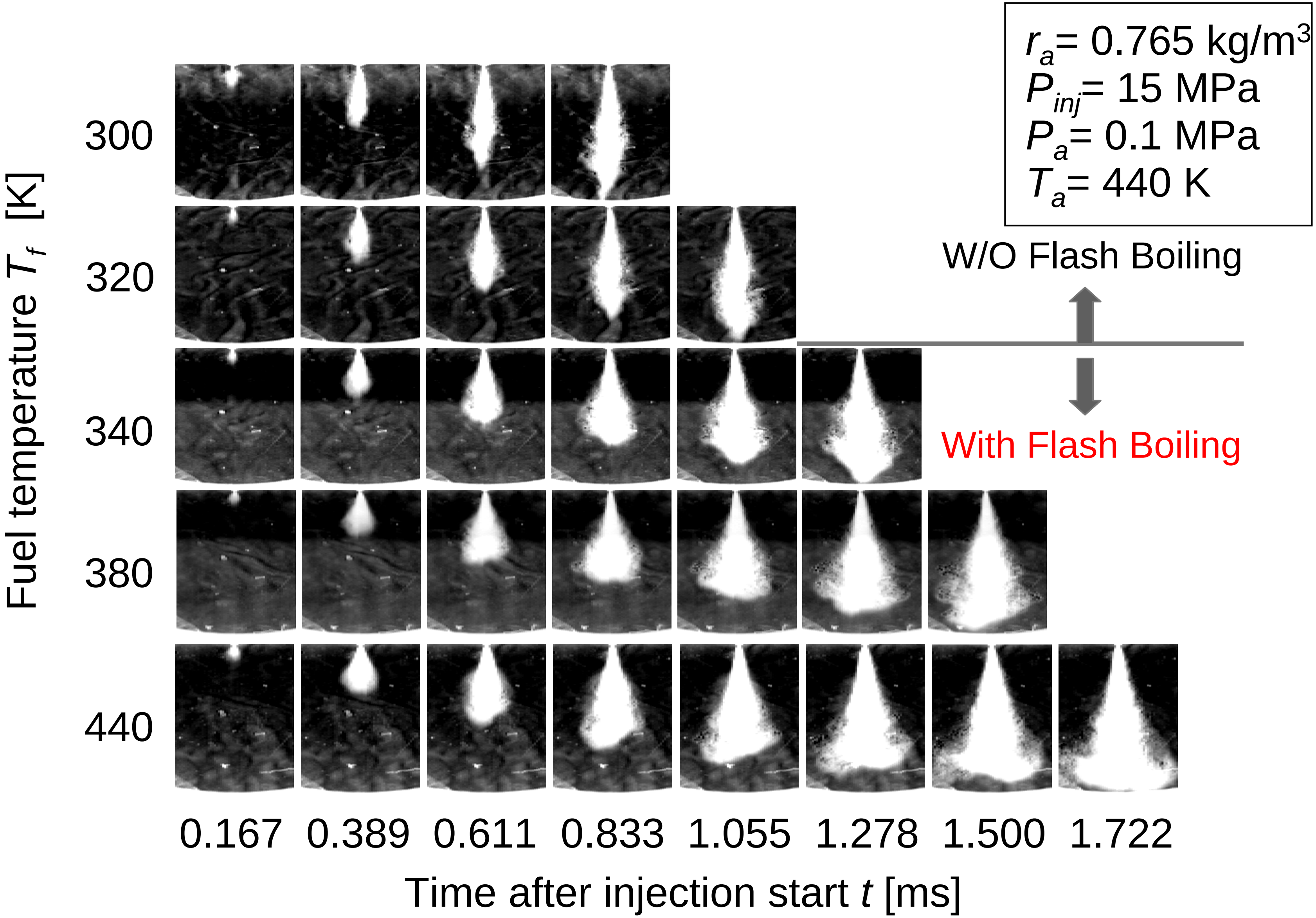
Break through the trade off relation between NO and smoke by use of liquefied CO_2 mixing fuel



② Experimental Conditions for Heated up C5 / C13 Mixing Spray

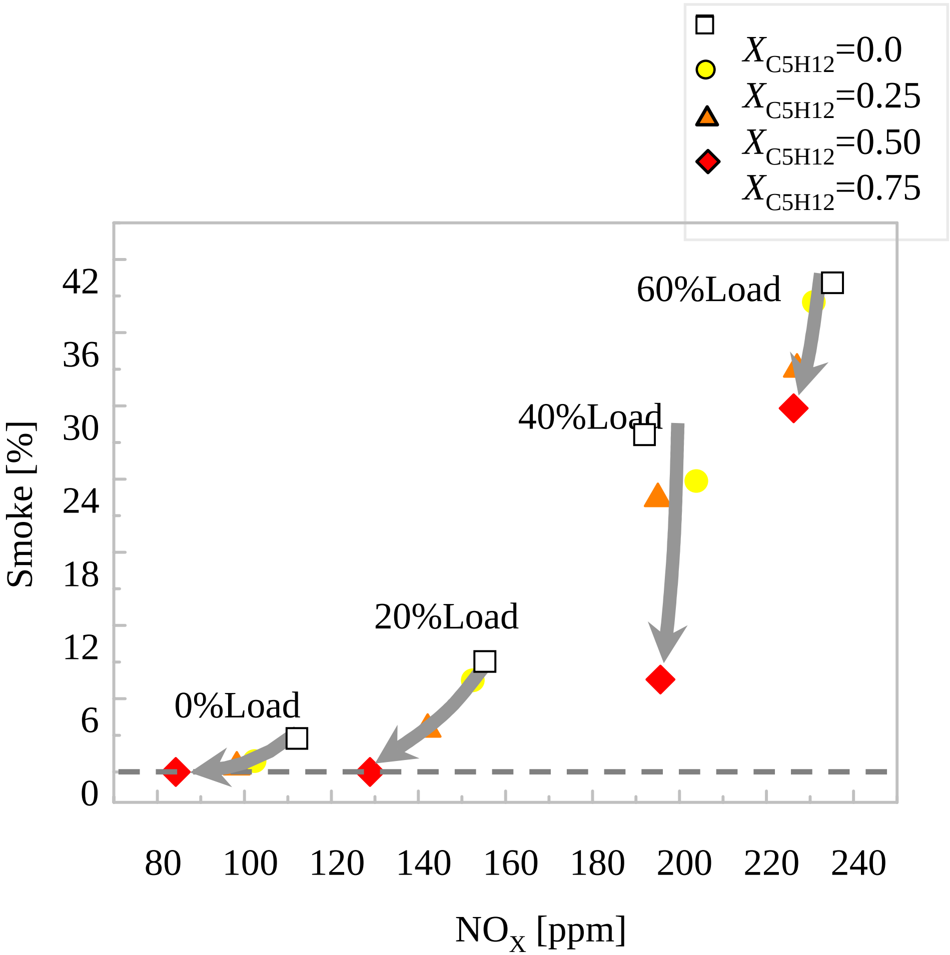


Shadowgraph Images of Flashing Spray of C5/C13 Mixing Fuels in RCEM



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

Test fuel	
n-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



④ Mixing Fuel of Bio-Diesel Fuel and Lower Boiling Point Hydrocarbon Fuel

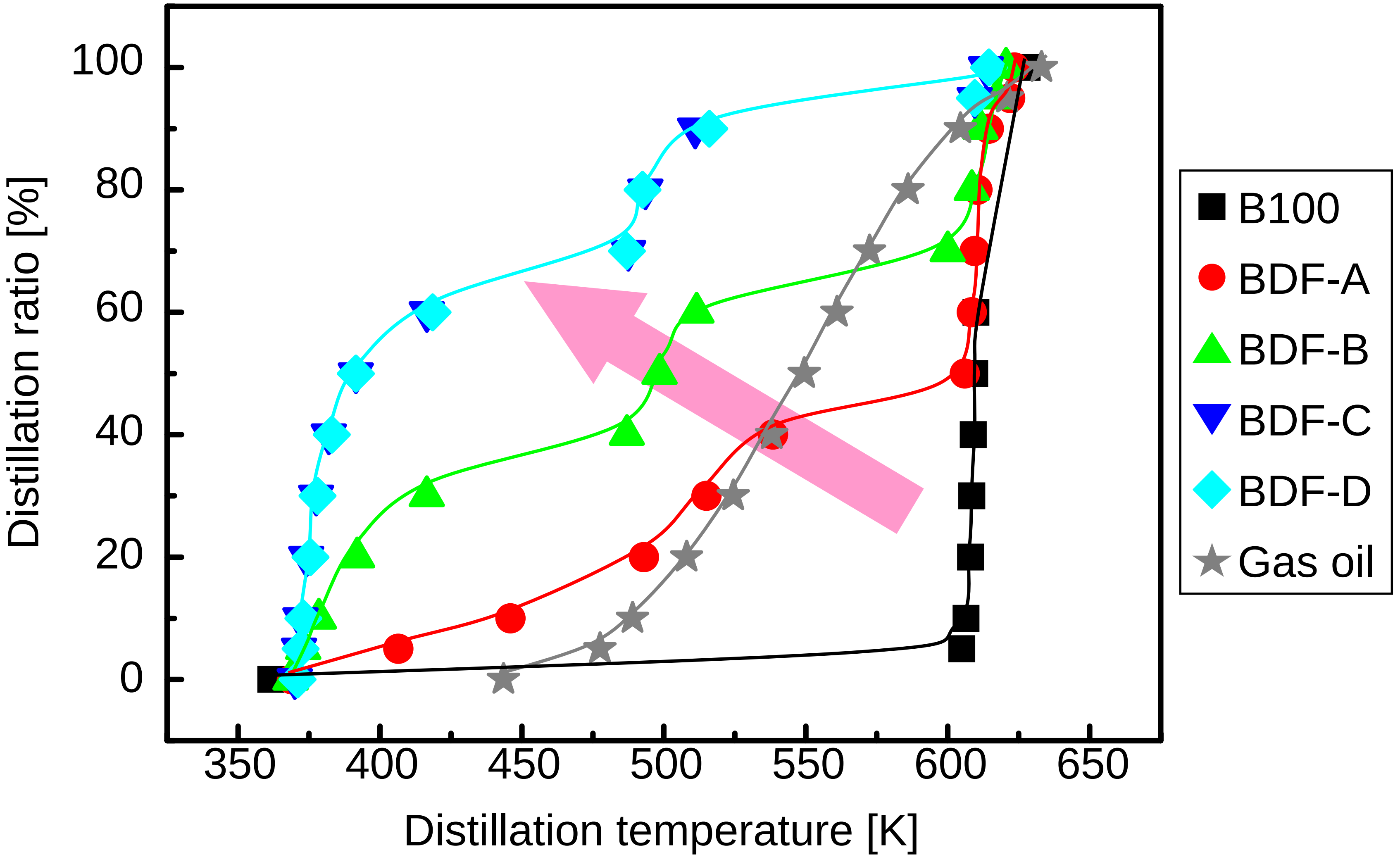
	C_7H_{16} or i-C_8H_{18}*	$C_{12}H_{26}$	B100
B100	0	0	1
BDF-A	1	3	6
BDF-B	1	1	1
BDF-C	6	3	1
BDF-D	6*	3	1

Composition of Test Fuels and Their Properties

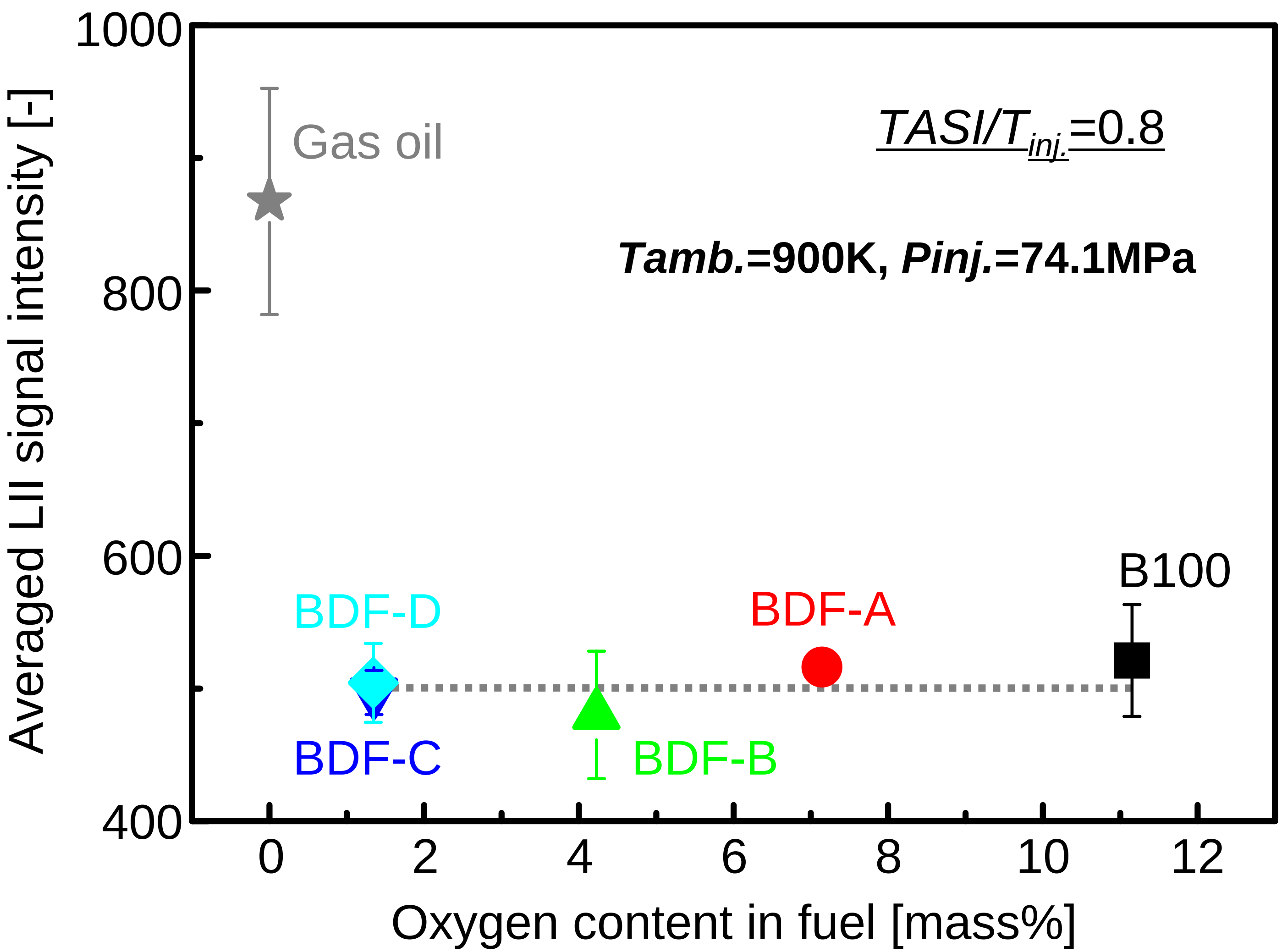
Volume ratio

	B100	BDF-A	BDF-B	BDF-C	BDF-D	Gas oil JIS No.2
Density(288K) [g/cm^3]	**0.8861**	**0.8291**	**0.7810**	**0.7287**	**0.7345**	0.835
Kinetic viscosity(313K) [mm^2/s]	**4.614**	**2.622**	**1.495**	**0.853**	**0.959**	2.70
T10 [K]	606-616	446	378.5	372	373	488-498
T50 [K]	**609-619**	**606**	**498.5**	**391.5**	**391.5**	548-558
T90 [K]	628-641	614.5	611.5	511	516	605-618
CFPP [K]	268	258	253	239	243	264-271
Cloud point [K]	269	266	266	252	243	-
Pour point [K]	235	250	245	240	240	260

Distillation Curve of each Fuel Tested

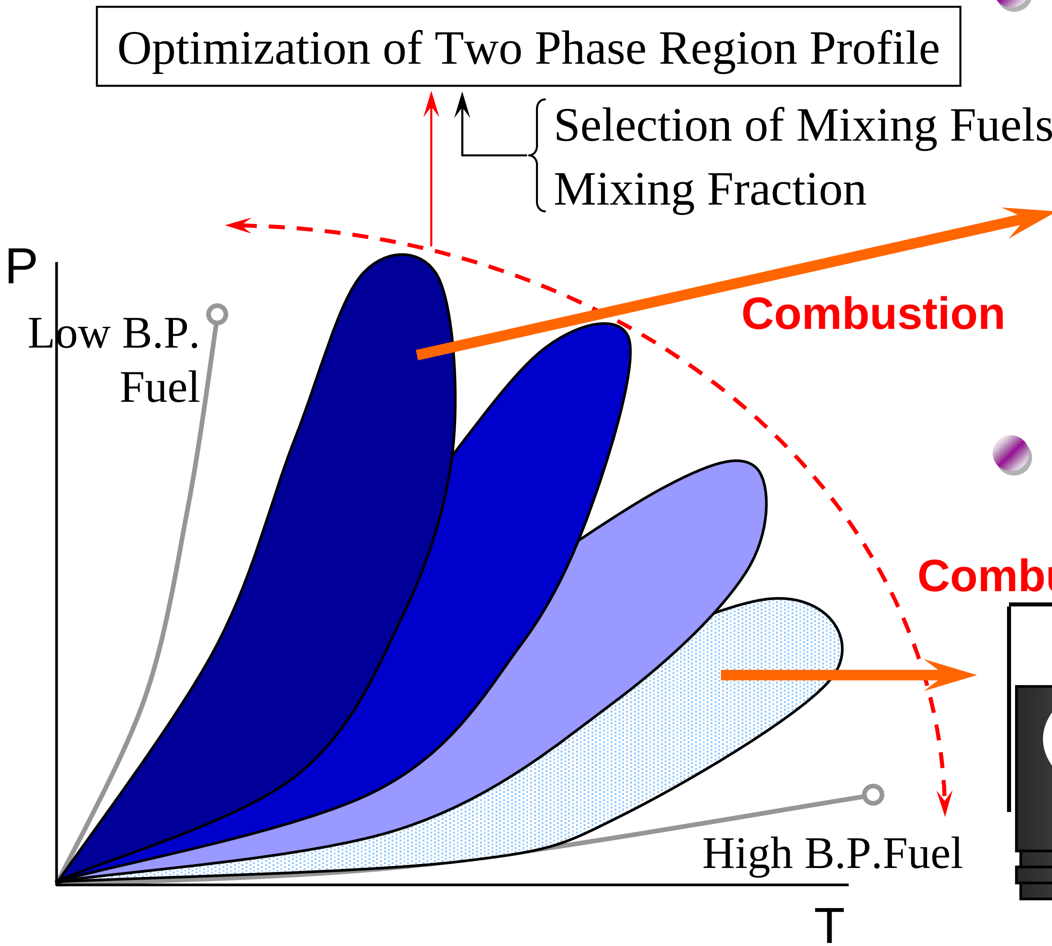


Effect of Oxygen Content in Fuel on Soot Formation

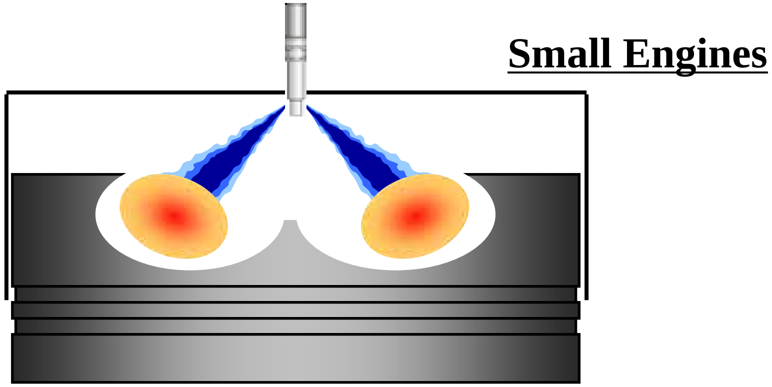


Optimization of Spray Evaporation Process and Chamber Geometry by adjusting Two Phase Profile of the Fuel

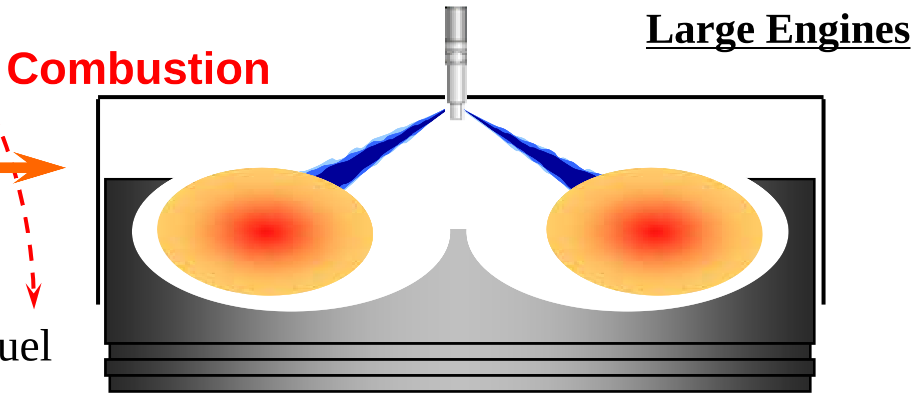
- Spray should be penetrated to near the chamber wall where air mass is enough
- HC and PM should be reduced by avoiding the spray and wall interaction



Formation of Shorter Spray



Formation of Longer Spray



Ⅳ Summary - 1

<u>External Factors</u>

1. Emission Regulation – Tier Ⅱ Bin 5(EPA), Euro 4 → Euro 5(EU)
   2005 Standards → Proposed 2009 standards (JP)
2. Lower Fuel Consumption (Higher Thermal Efficiency)
   (Ex. CO_2 emission 140g/km in vehicle (EU), CAFE (UA))
3. Fuel Diversity for Engines → Flexible Fuel Engine
   (← exhaustion of crude petroleum oil & reduction of fossil fuel dependency)

<u>For the Small Engines (for mainly Diesel Engines)</u>

<u>1. Fuel Application</u>

Synthetic Oil Application from another fossil resources (GTL(FTD･DME)) will be getting major

2nd generation based on biomass - Cellulose (Ethanol / ETBE / BDF) will be one candidate as the blended fuels

<u>Several Mixing Fuels with Current Crude Petroleum Oil & GTL/BTL should be focused to improve spray and combustion phases in engines < This is our Fuel Design Concept ></u>

Ⅳ Summary - 2

2. Combustion Mode

HCCI (PCCI), Multi-Stage HCCI, MK(Modulated Kinetics) should be applied as the optimized operation mode (lower load) to reduce emissions

These several combustion modes are very sensitive to fuel properties (Direct injected spray evaporation & Ignition)

These modes might be extended to higher load operation assisted by several variable control systems (VVT, EGR, Injection Control, Higher Boosting) and application of several mixing fuels

In higher load operation, Low Temp. Rich Combustion or Conventional Rich Spray Diffusion Burning should be applied, with after-treatment device of oxidation catalyst, DPF and NOx catalyst (LNT/SCR) (it cause fuel penalty)

3. Engine System Control

→ optimum matching to Fuel Application & Combustion Mode

4. After-treatment System

→ optimum matching to Combustion Mode

Thank you for your kind attention