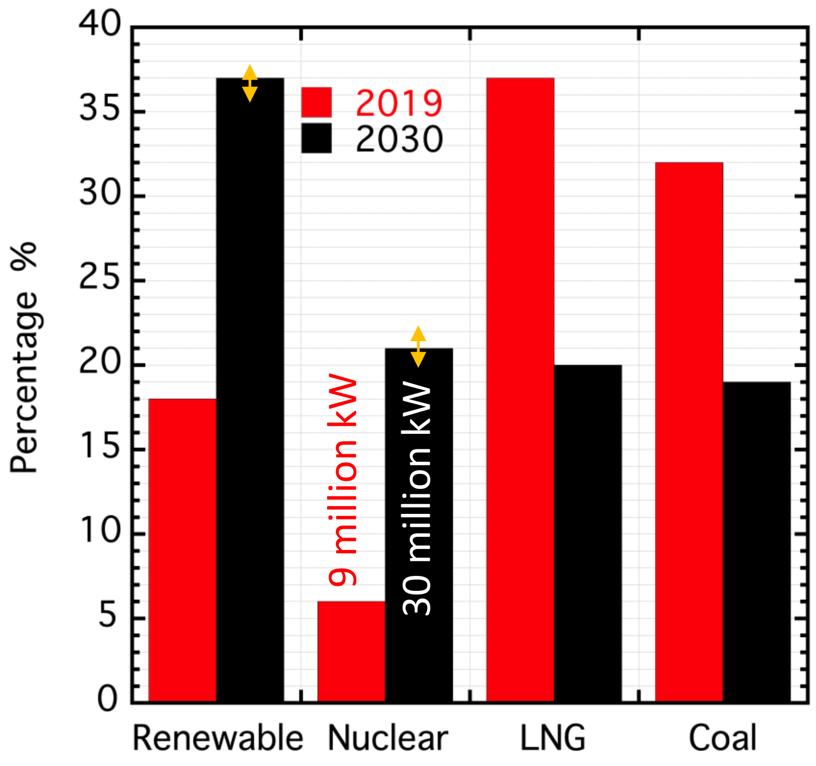
Combustion Characteristics for Carbon Neutral Fuel in Heavy Duty Diesel Engines

Jin KUSAKA, Ph.D, Professor
Dept of Modern Mech. Eng.
WASEDA University

Current status and targets of power generation mix



https://www.fepc.or.jp/theme/re-operation/

Decommissioning
Unapplied
Application
Permission
Operation

There are six plants that have not received the agreement of the local governments and are still waiting to be restarted in spite of getting permission.

7 years left until 2030.

Need for a variety of options
Customer ultimately decides

Ex. Heavy Duty Vehicles

Economy
CO_2 footprint

Energy availability
Distance traveled
Location(Region)
Loading capacity
Zero emission

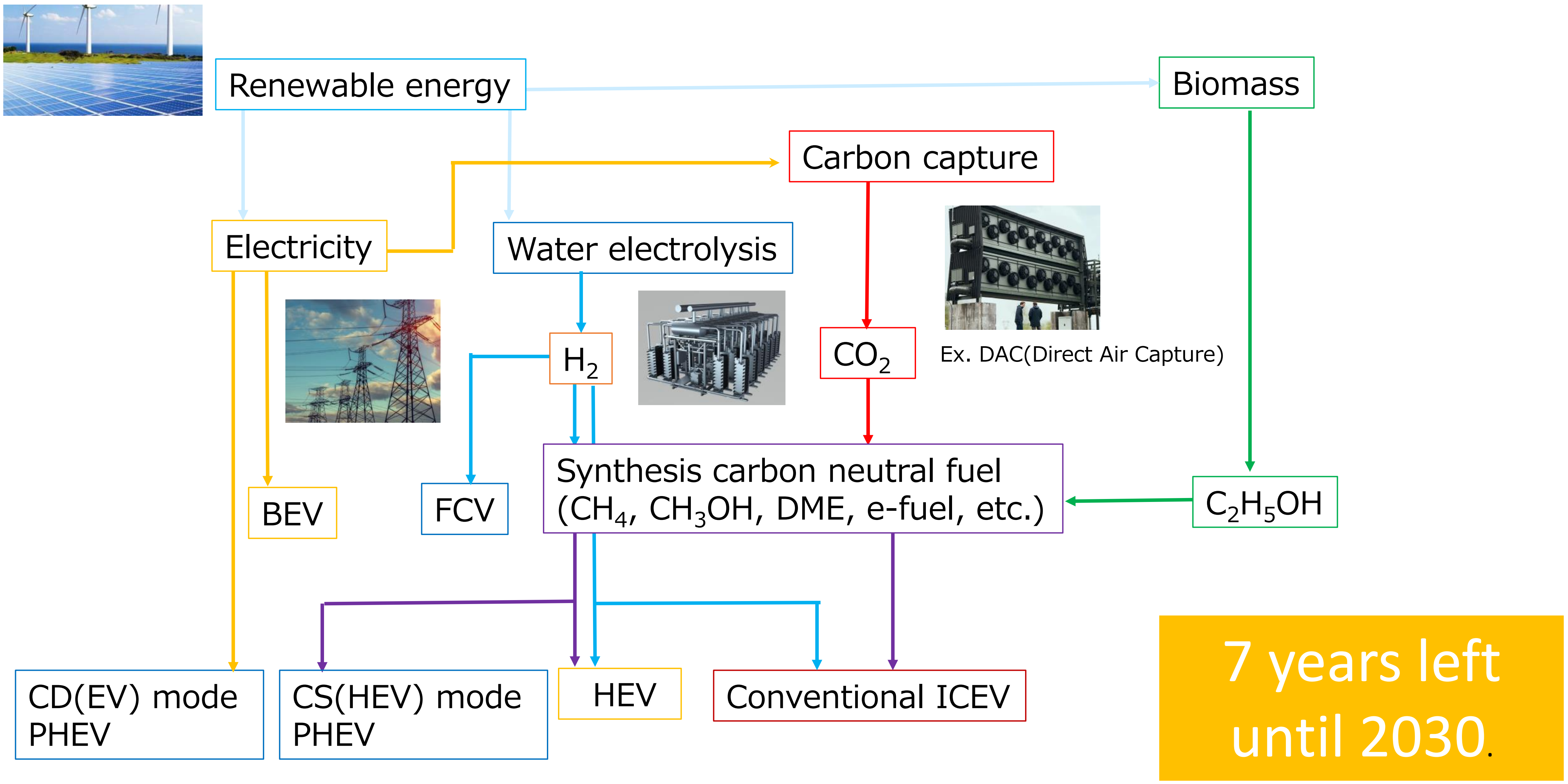
Full BEV

HEV

I.C.E

Decarbonized Fuel

Towards carbon neutral fuel for automotive



Traditional Diesel combustion

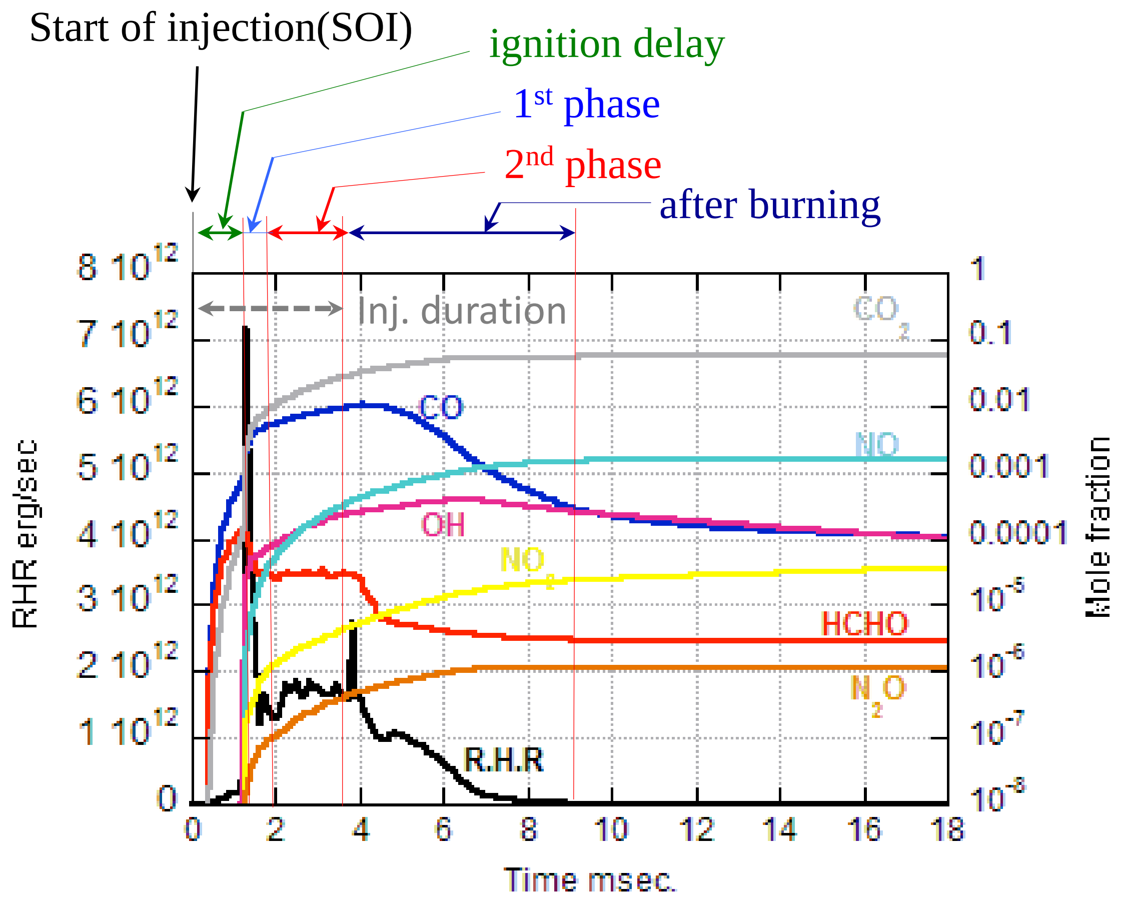
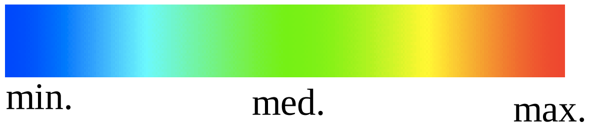
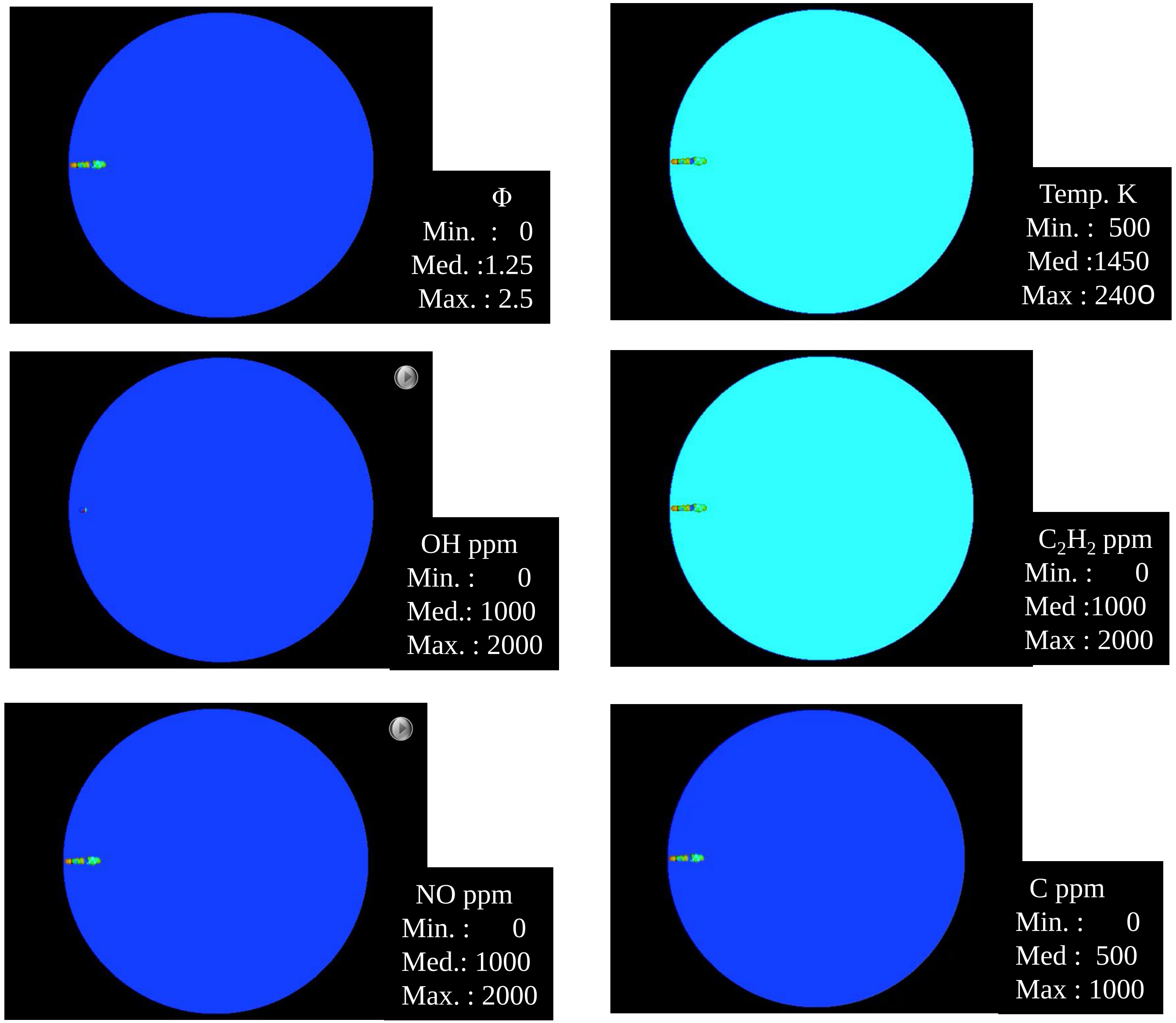
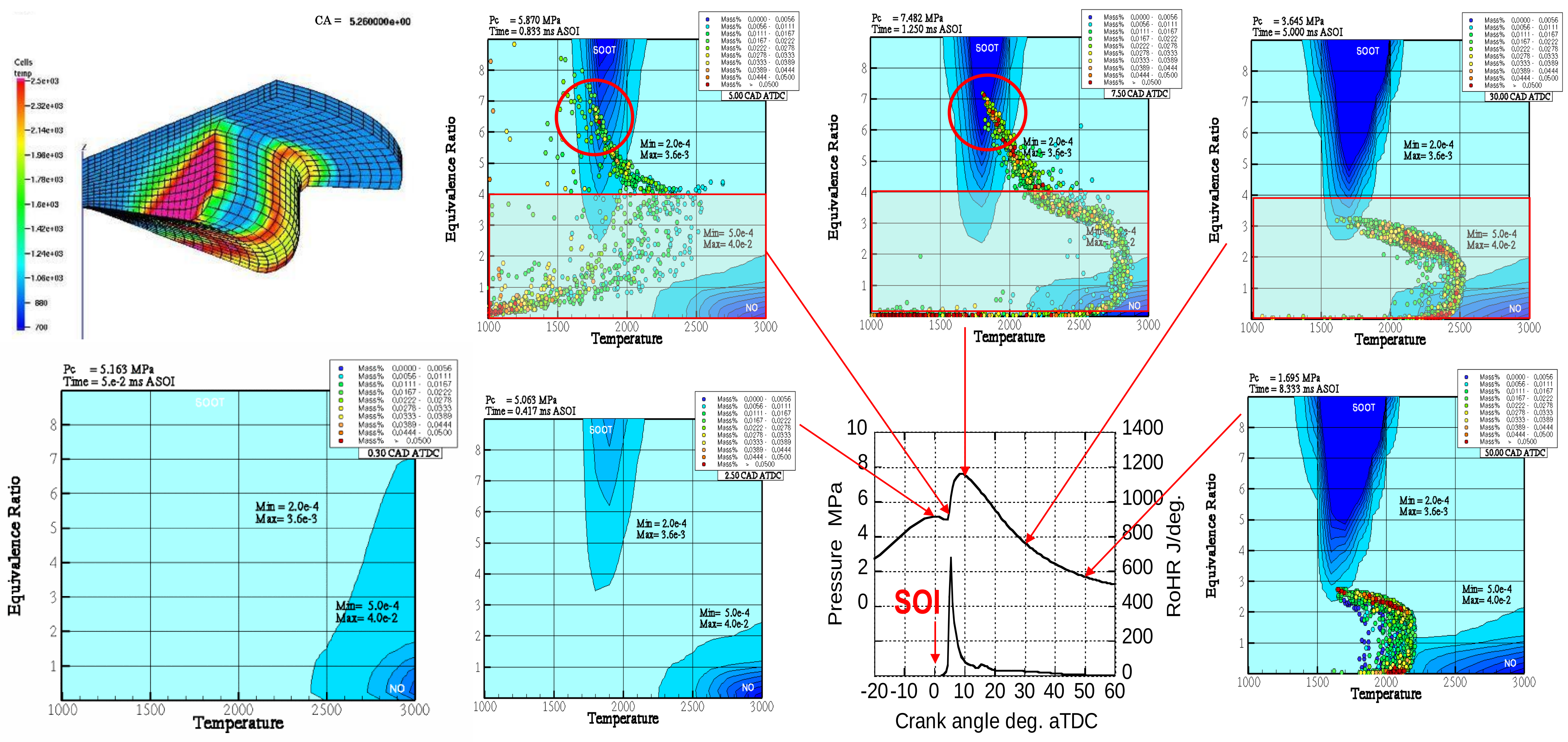


Fig. 1 Heat release and chemical species profiles (Inj. duration : 3.7 ms)



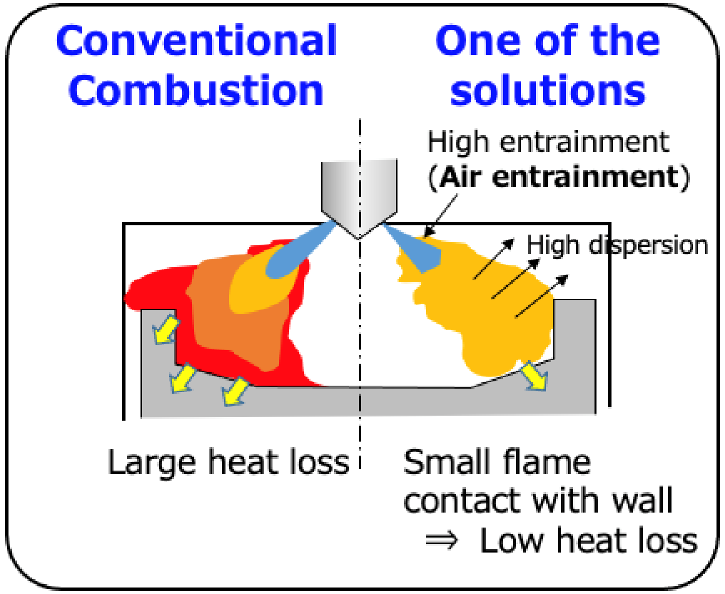


NOx-Soot trade off on φ-T map



Expectation for future Diesel engine fuel

		JIS 2nd class light gas oil	Future fuel
Physical ignition delay (Fuel spray)	break-up evaporation penetration λ distribution	moderate moderate moderate heterogeneous	quick quick moderate homogeneous
Chemical ignition delay	oxidation reaction	fast	moderate
1st stage combustion	pre-mixture	small	none
2nd stage combustion	Diffusion(momentum of the spray)	large	all
After burning	Diffusion (air motion mixing control)	medium	none



Substrate types (14 types)		Substrate composition			
		nP	iP	N	A
Fractional distillation	~200℃				
	200~250℃				
	250~300℃				
	300~350℃				

Chem. ↓ Phsic. ↑

nP: normal Paraffin, iP: iso paraffin
n: Naphthene, A: Aromatics

Test fuel set up

Composition of test fuels

DS-1	DS-2	DS-3	DS-4	DS-5	DS-6	DS-7	DS-8	DS-8A	DS-8B	DS-8C	DS-0
Base	Evaporability			Cetane Number		Density	Paraffinic (Evaporative・Structural)				JIS-2 Light oil
	LL	L	M	H	L	H	P	L・P	M・P	L・nP	

DS-1	nP	iP	N	A
~200℃				
200~250℃	10	10	10	10
250~300℃	10	10	10	10
300~350℃			10	10

DS-2	nP	iP	N	A
~200℃	40		30	30
200~250℃				
250~300℃				
300~350℃				

DS-3	nP	iP	N	A
~200℃				
200~250℃	40		30	30
250~300℃				
300~350℃				

DS-4	nP	iP	N	A
~200℃				
200~250℃				
250~300℃	20	20	30	30
300~350℃				

DS-5	nP	iP	N	A
~200℃				
200~250℃	20		10	10
250~300℃	20		10	10
300~350℃			10	10

DS-6	nP	iP	N	A
~200℃				
200~250℃		20	10	10
250~300℃		20	10	10
300~350℃			10	10

DS-7	nP	iP	N	A
~200℃				
200~250℃			16.7	16.7
250~300℃			16.7	16.7
300~350℃			16.7	16.7

nP: normal Paraffin
iP: iso paraffin
N: Naphthene
A: Aromatics

< Add Paraffin Series >

DS-8	nP	iP	N	A
~200℃				
200~250℃	25	25		
250~300℃	25	25		
300~350℃				

DS-8A	nP	iP	N	A
~200℃				
200~250℃	50	50		
250~300℃				
300~350℃				

DS-8B	nP	iP	N	A
~200℃				
200~250℃				
250~300℃	50	50		
300~350℃				

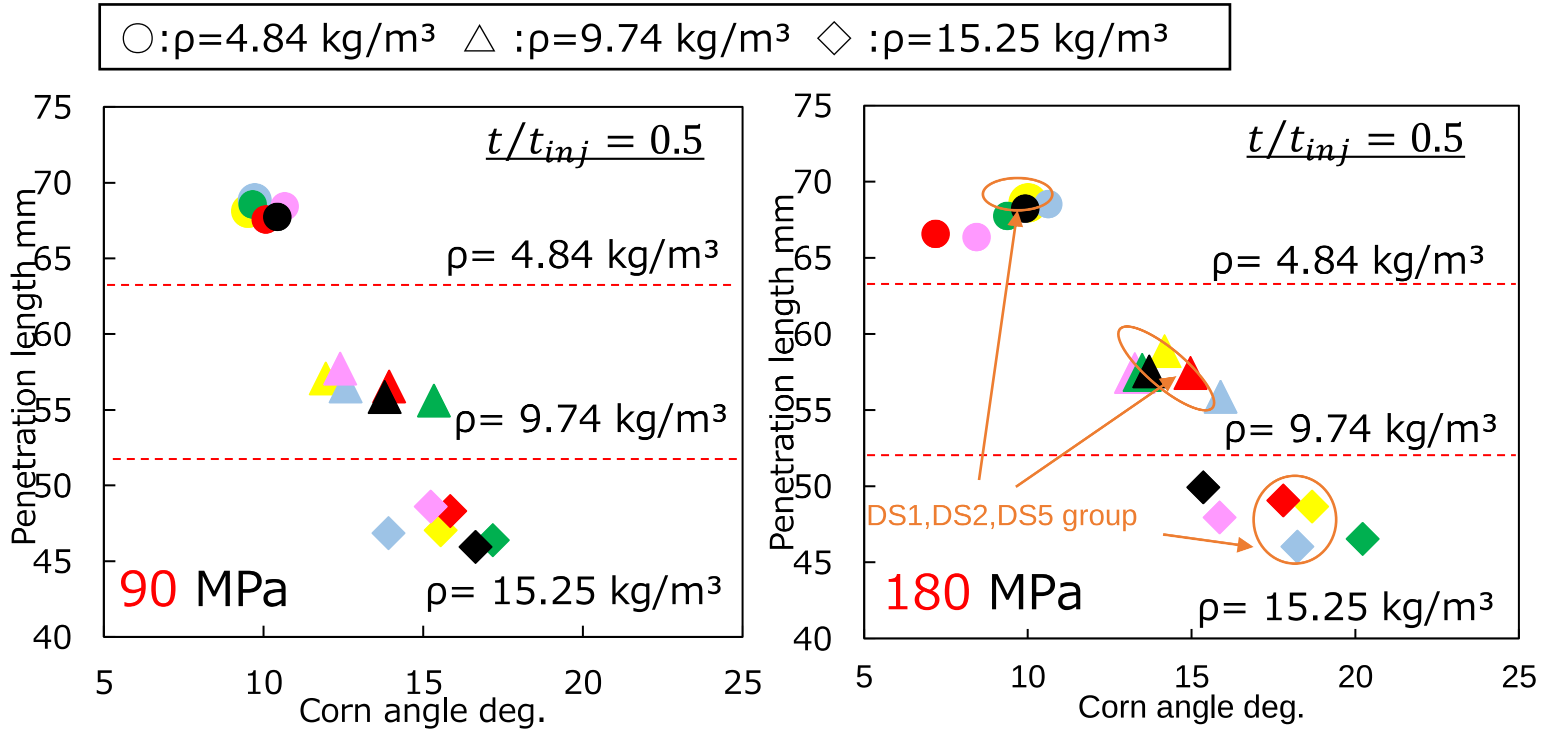
DS-8C	nP	iP	N	A
~200℃				
200~250℃	100			
250~300℃				
300~350℃				

*打ち合わせ資料より

Experimental results (comparison by vapor phase)

Fuel specifications

Fuel	DS-0	DS-1	DS-2	DS-5	DS-6	DS-7
Density g/cm^3	0.8257	0.8250	0.7972	0.8174	0.8329	0.8527
Kinematic viscosity mm^2/s	2.933	3.921	1.174	3.261	4.923	4.422
Cetane number	51.7	50.9	44.4	64.6	40.4	47.2



Higher injection pressure increases spray dispersion

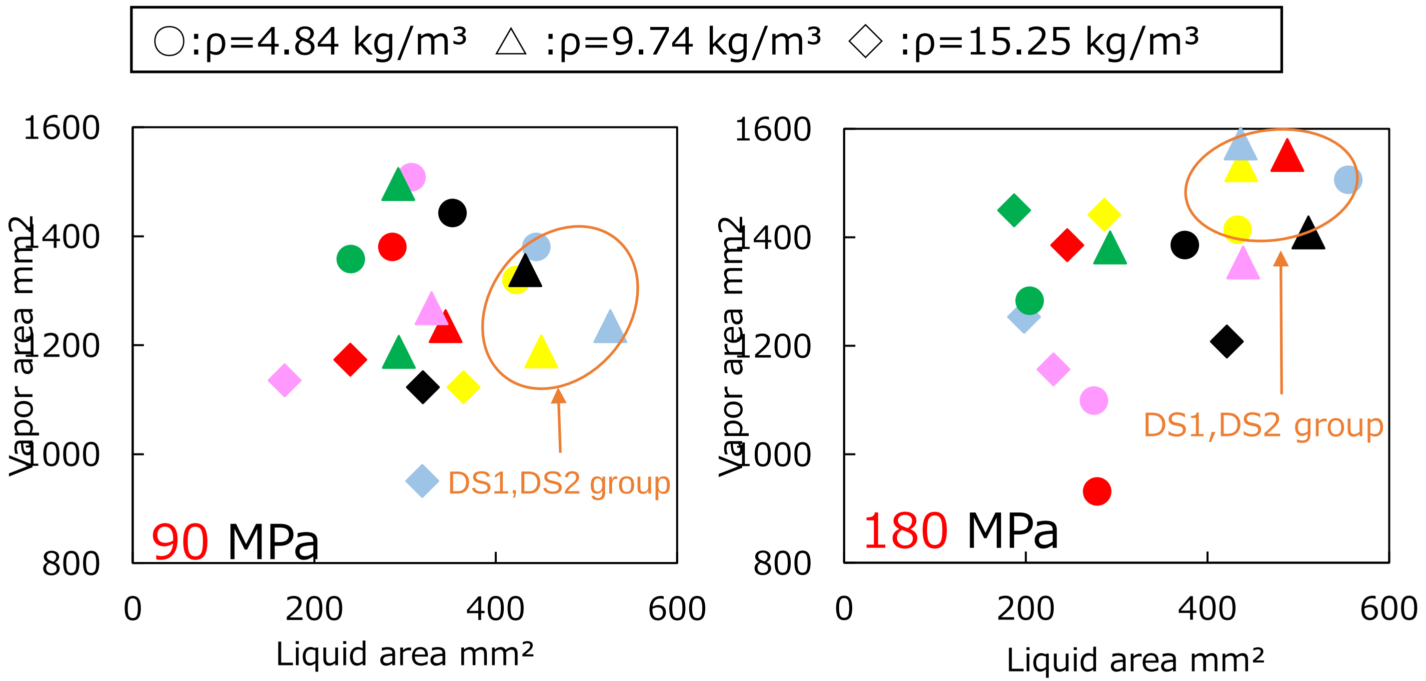
Early dispersion was observed with lighter fuels

⇒ Compositions with high normal paraffinic content were significantly affected

Experimental results (comparison by spray surface area)

Fuel specifications

Fuel	DS-0	DS-1	DS-2	DS-5	DS-6	DS-7
Density g/cm³	0.8257	0.8250	0.7972	0.8174	0.8329	0.8527
Kinematic viscosity mm²/s	2.933	3.921	1.174	3.261	4.923	4.422
Cetane number	51.7	50.9	44.4	64.6	40.4	47.2



$t/t_{inj} = 0.5$

- Under low-press. inj. conditions, light fuels have strong liquid-phase dispersion.
- Under high-press. inj. conditions, light fuels have strong dispersion in both vapor and liquid phases.

⇒ Tends to be highly dispersed, especially under early injection conditions

Suggests high dispersion and high air entrainment under early injection conditions for light fuels

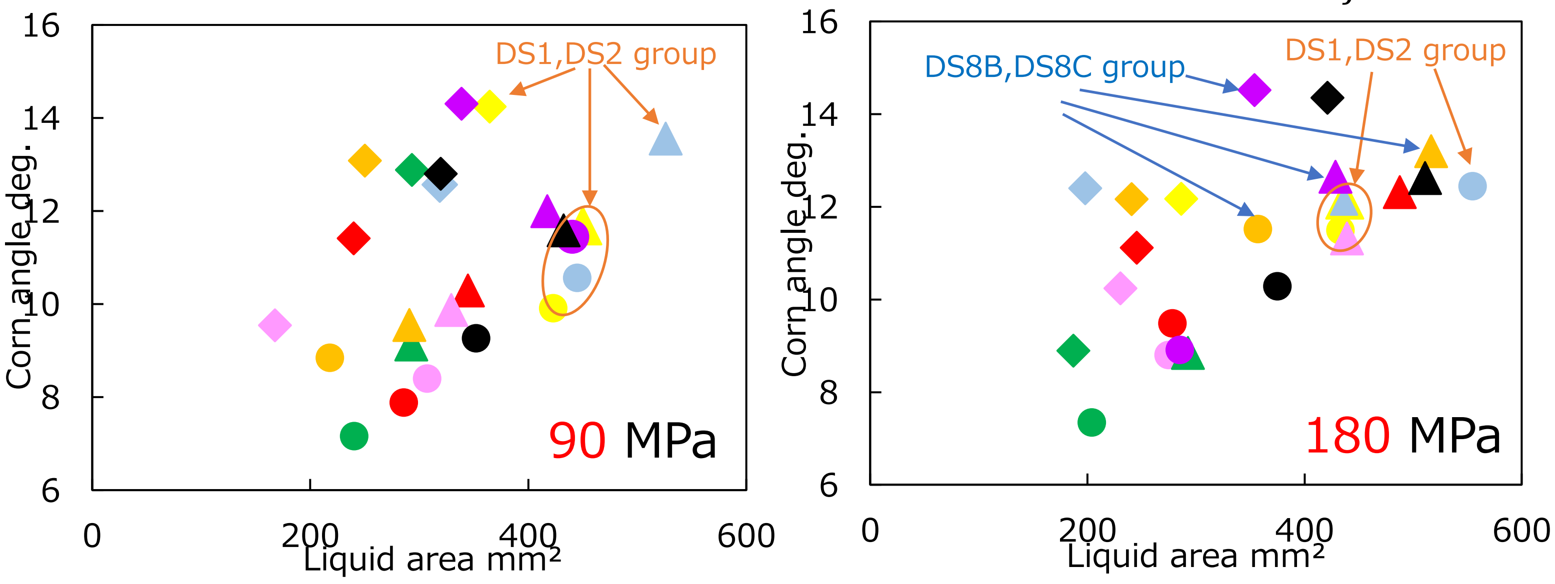
Experimental results (comparison by liquid phase)

Fuel specifications

Fuel	DS-0	DS-1	DS-2	DS-5	DS-6	DS-7	DS-8B	DS-8C
Density g/cm³	0.8257	0.8250	0.7972	0.8174	0.8329	0.8527	0.7938	0.7604
Kinematic viscosity mm²/s	2.933	3.921	1.174	3.261	4.923	4.422	4.716	2.076
Cetane number	51.7	50.9	44.4	64.6	40.4	47.2	61.6	90.4

○:ρ=4.84 kg/m³ △ :ρ=9.74 kg/m³ ◇ :ρ=15.25 kg/m³

$t/t_{inj} = 0.5$

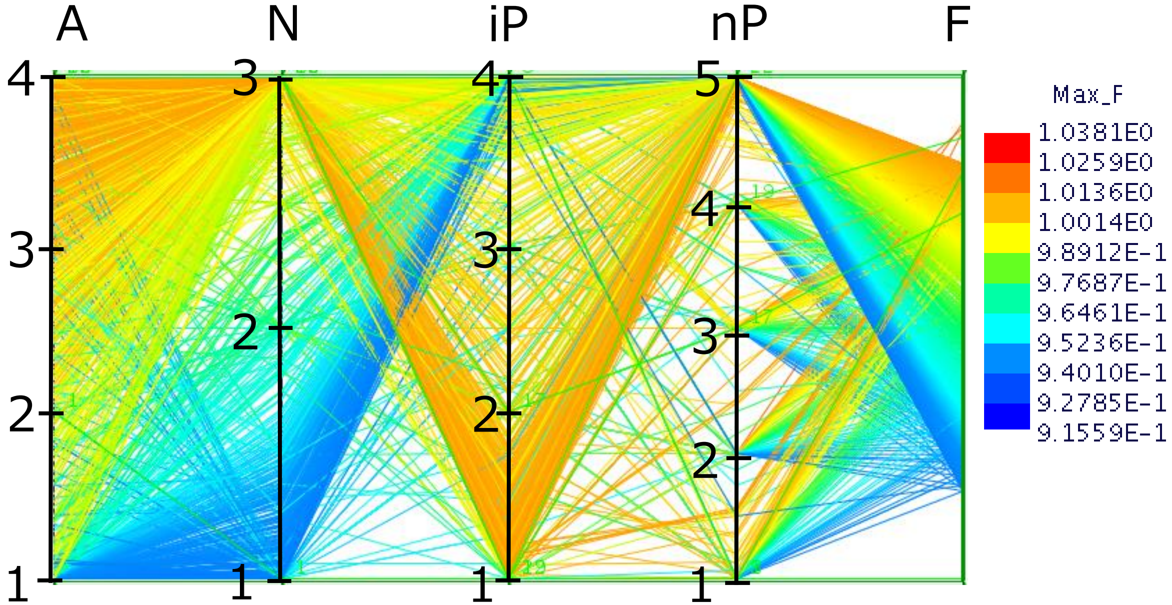


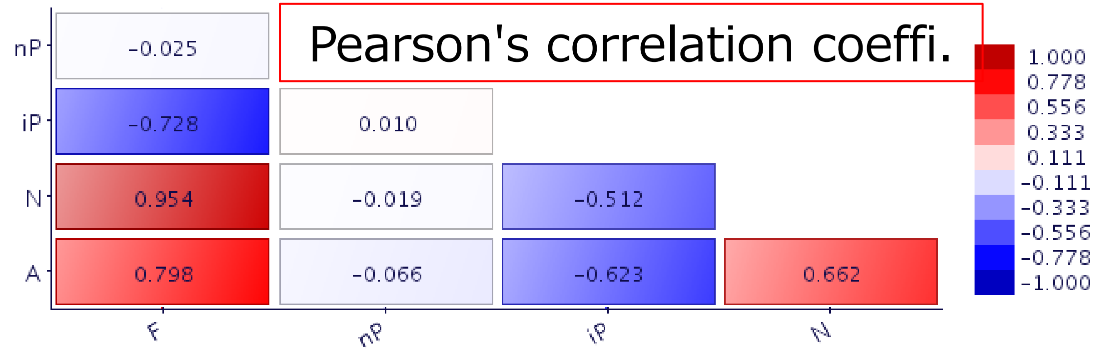
- Dispersion was observed from low inj. press. for a group of fuels with high dispersion in the vapor phase
- At high inj. press., high dispersion was observed even for fuels with only paraffinic components.

In the liquid phase, the dispersion of light fuels containing a large amount of normal paraffinic components is strong.

Surrogates for blending optimization

Multidimensional analysis





Evaluation

$$F = C_{w1}\frac{IMEP}{(IMEP)_{base}} + C_{w2}\frac{dP/d\theta_{max}}{(dP/d\theta_{max})_{base}}$$

Example of optimization table

ワークテーブル_0

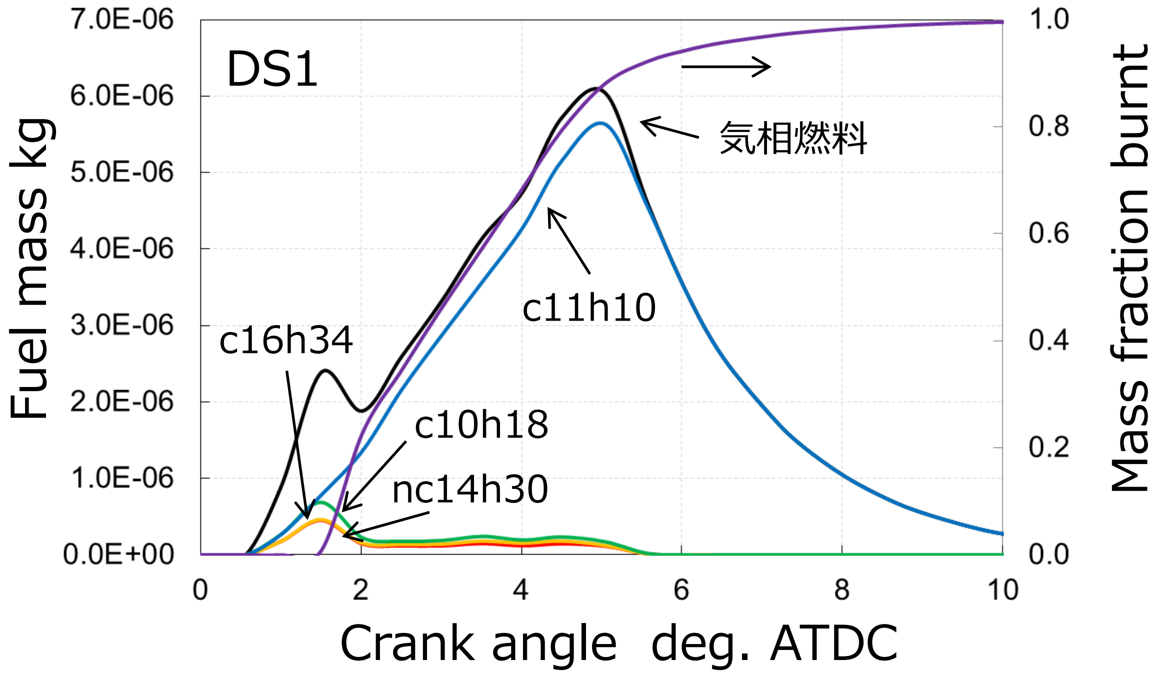
ID	M	CATEGORY	A	iP	N	nP	dPdtheta	F ▼1	ICE	IMEP	Max
196		多元配置	3.0000E0	1.0000E0	3.0000E0	5.0000E0	1.9480E0	1.0129E0	4.1390E-1	1.2151E0	4.139
195		多元配置	3.0000E0	1.0000E0	3.0000E0	4.0000E0	1.9502E0	1.0128E0	4.1356E-1	1.2136E0	4.135
194		多元配置	3.0000E0	1.0000E0	3.0000E0	3.0000E0	1.9524E0	1.0128E0	4.1321E-1	1.2120E0	4.132
193		多元配置	3.0000E0	1.0000E0	3.0000E0	2.0000E0	1.9546E0	1.0127E0	4.1287E-1	1.2104E0	4.128
192		多元配置	3.0000E0	1.0000E0	3.0000E0	1.0000E0	1.9567E0	1.0126E0	4.1252E-1	1.2089E0	4.125
137		多元配置	2.0000E0	1.0000E0	3.0000E0	5.0000E0	1.9424E0	1.0093E0	4.1430E-1	1.2099E0	4.143
136		多元配置	2.0000E0	1.0000E0	3.0000E0	4.0000E0	1.9446E0	1.0092E0	4.1395E-1	1.2083E0	4.139
135		多元配置	2.0000E0	1.0000E0	3.0000E0	3.0000E0	1.9468E0	1.0091E0	4.1361E-1	1.2068E0	4.136
134		多元配置	2.0000E0	1.0000E0	3.0000E0	2.0000E0	1.9489E0	1.0091E0	4.1326E-1	1.2052E0	4.132
133		多元配置	2.0000E0	1.0000E0	3.0000E0	1.0000E0	1.9511E0	1.0090E0	4.1292E-1	1.2037E0	4.129
201		多元配置	3.0000E0	2.0000E0	3.0000E0	5.0000E0	1.9274E0	1.0079E0	4.1451E-1	1.2162E0	4.145
200		多元配置	3.0000E0	2.0000E0	3.0000E0	4.0000E0	1.9296E0	1.0078E0	4.1417E-1	1.2147E0	4.141
199		多元配置	3.0000E0	2.0000E0	3.0000E0	3.0000E0	1.9318E0	1.0078E0	4.1382E-1	1.2131E0	4.138
198		多元配置	3.0000E0	2.0000E0	3.0000E0	2.0000E0	1.9339E0	1.0077E0	4.1348E-1	1.2116E0	4.134
197		多元配置	3.0000E0	2.0000E0	3.0000E0	1.0000E0	1.9361E0	1.0076E0	4.1313E-1	1.2100E0	4.131
78		多元配置	1.0000E0	1.0000E0	3.0000E0	5.0000E0	1.9368E0	1.0056E0	4.1469E-1	1.2046E0	4.146
77		多元配置	1.0000E0	1.0000E0	3.0000E0	4.0000E0	1.9390E0	1.0056E0	4.1435E-1	1.2031E0	4.143
76		多元配置	1.0000E0	1.0000E0	3.0000E0	3.0000E0	1.9411E0	1.0055E0	4.1400E-1	1.2015E0	4.140
75		多元配置	1.0000E0	1.0000E0	3.0000E0	2.0000E0	1.9433E0	1.0054E0	4.1366E-1	1.2000E0	4.136
74		多元配置	1.0000E0	1.0000E0	3.0000E0	1.0000E0	1.9455E0	1.0054E0	4.1331E-1	1.1984E0	4.133
142		多元配置	2.0000E0	2.0000E0	3.0000E0	5.0000E0	1.9218E0	1.0042E0	4.1491E-1	1.2110E0	4.149
141		多元配置	2.0000E0	2.0000E0	3.0000E0	4.0000E0	1.9240E0	1.0042E0	4.1456E-1	1.2094E0	4.145
140		多元配置	2.0000E0	2.0000E0	3.0000E0	3.0000E0	1.9262E0	1.0041E0	4.1422E-1	1.2079E0	4.142
139		多元配置	2.0000E0	2.0000E0	3.0000E0	2.0000E0	1.9283E0	1.0041E0	4.1387E-1	1.2063E0	4.138
138		多元配置	2.0000E0	2.0000E0	3.0000E0	1.0000E0	1.9305E0	1.0040E0	4.1353E-1	1.2048E0	4.135
206		多元配置	3.0000E0	3.0000E0	3.0000E0	5.0000E0	1.9068E0	1.0029E0	4.1512E-1	1.2173E0	4.151
205		多元配置	3.0000E0	3.0000E0	3.0000E0	4.0000E0	1.9090E0	1.0028E0	4.1478E-1	1.2158E0	4.147
204		多元配置	3.0000E0	3.0000E0	3.0000E0	3.0000E0	1.9112E0	1.0027E0	4.1443E-1	1.2142E0	4.144
203		多元配置	3.0000E0	3.0000E0	3.0000E0	2.0000E0	1.9133E0	1.0027E0	4.1409E-1	1.2127E0	4.140
202		多元配置	3.0000E0	3.0000E0	3.0000E0	1.0000E0	1.9155E0	1.0026E0	4.1374E-1	1.2111E0	4.137
83		多元配置	1.0000E0	2.0000E0	3.0000E0	5.0000E0	1.9162E0	1.0006E0	4.1530E-1	1.2058E0	4.153
82		多元配置	1.0000E0	2.0000E0	3.0000E0	4.0000E0	1.9184E0	1.0006E0	4.1496E-1	1.2042E0	4.149
81		多元配置	1.0000E0	2.0000E0	3.0000E0	3.0000E0	1.9205E0	1.0005E0	4.1461E-1	1.2027E0	4.146
80		多元配置	1.0000E0	2.0000E0	3.0000E0	2.0000E0	1.9227E0	1.0004E0	4.1427E-1	1.2011E0	4.142
79		多元配置	1.0000E0	2.0000E0	3.0000E0	1.0000E0	1.9249E0	1.0004E0	4.1392E-1	1.1995E0	4.139

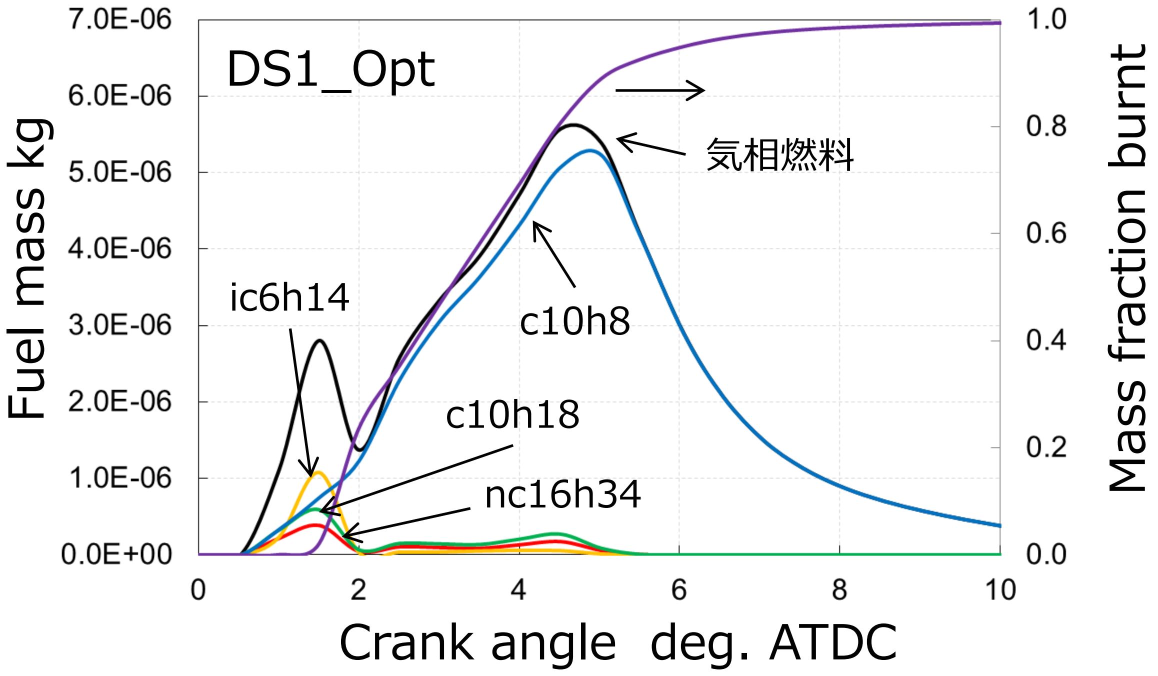
These component selections are based on validated spray penetration in CONVERGE

DS1_Optimization ⇩

nP 20%	iP 20%	N 30%	A 30%
nc16h34	ic6h14	c10h18	c10h8

Fuel evaporation characteristics in engine cylinder-DS1





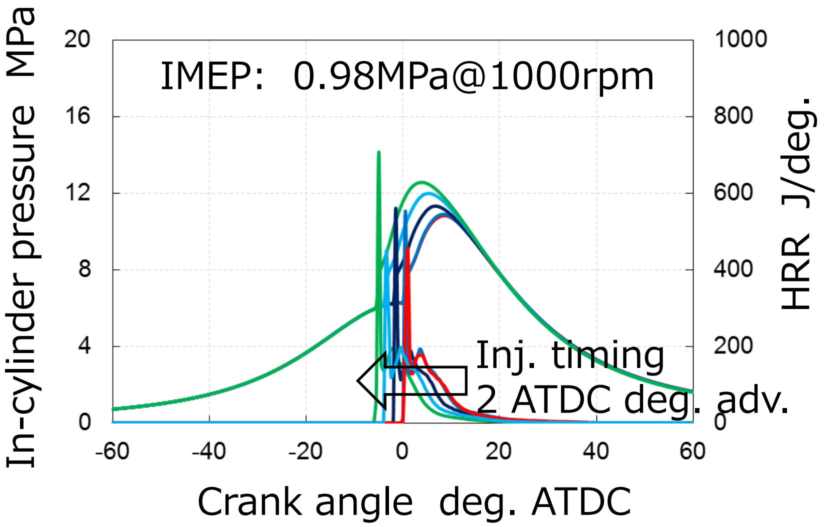
nP 20%	iP 20%	N 30%	A 30%
nc12h26	ic16h34	c10h18	c11h10

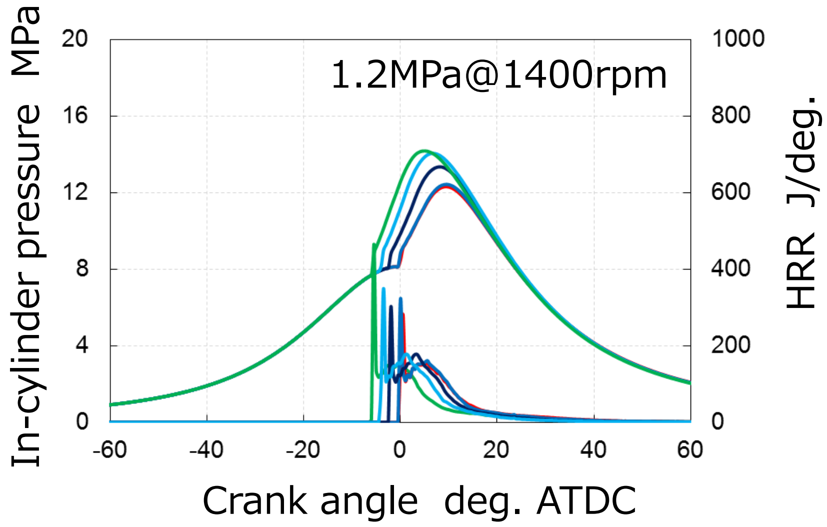
⇨

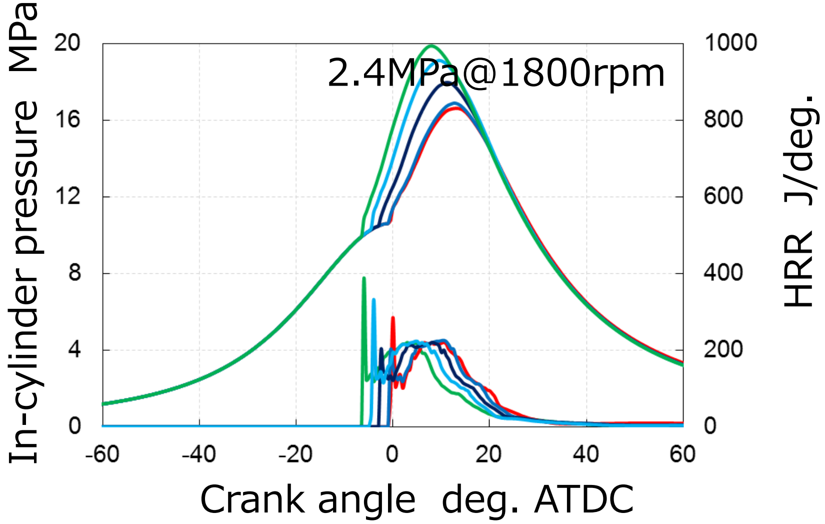
nP 20%	iP 20%	N 30%	A 30%
nc16h34	ic6h14	c10h18	c10h8

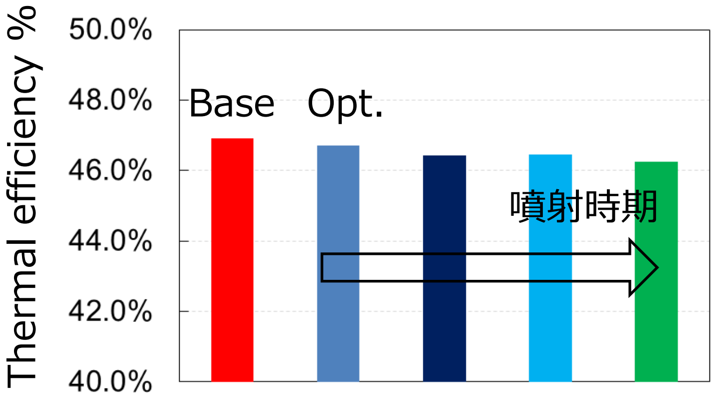
Example of in-cylinder simulation

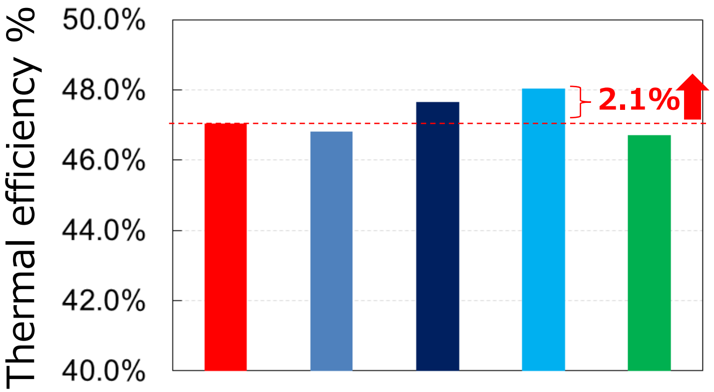
Load: for HD engine（Bore×Stroke: 102×105 mm)
Fuel : DS1(Base), DS1_Opt(Opt.)

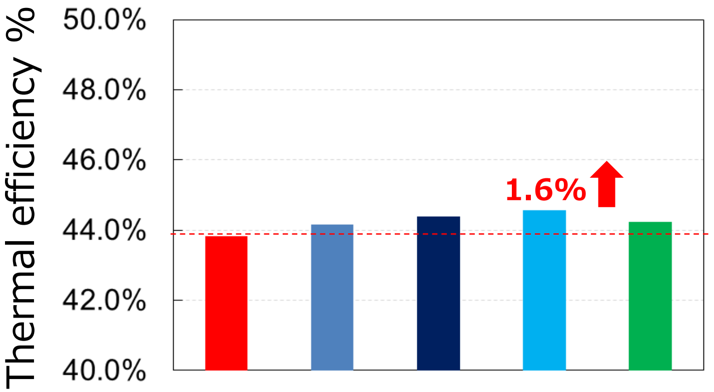




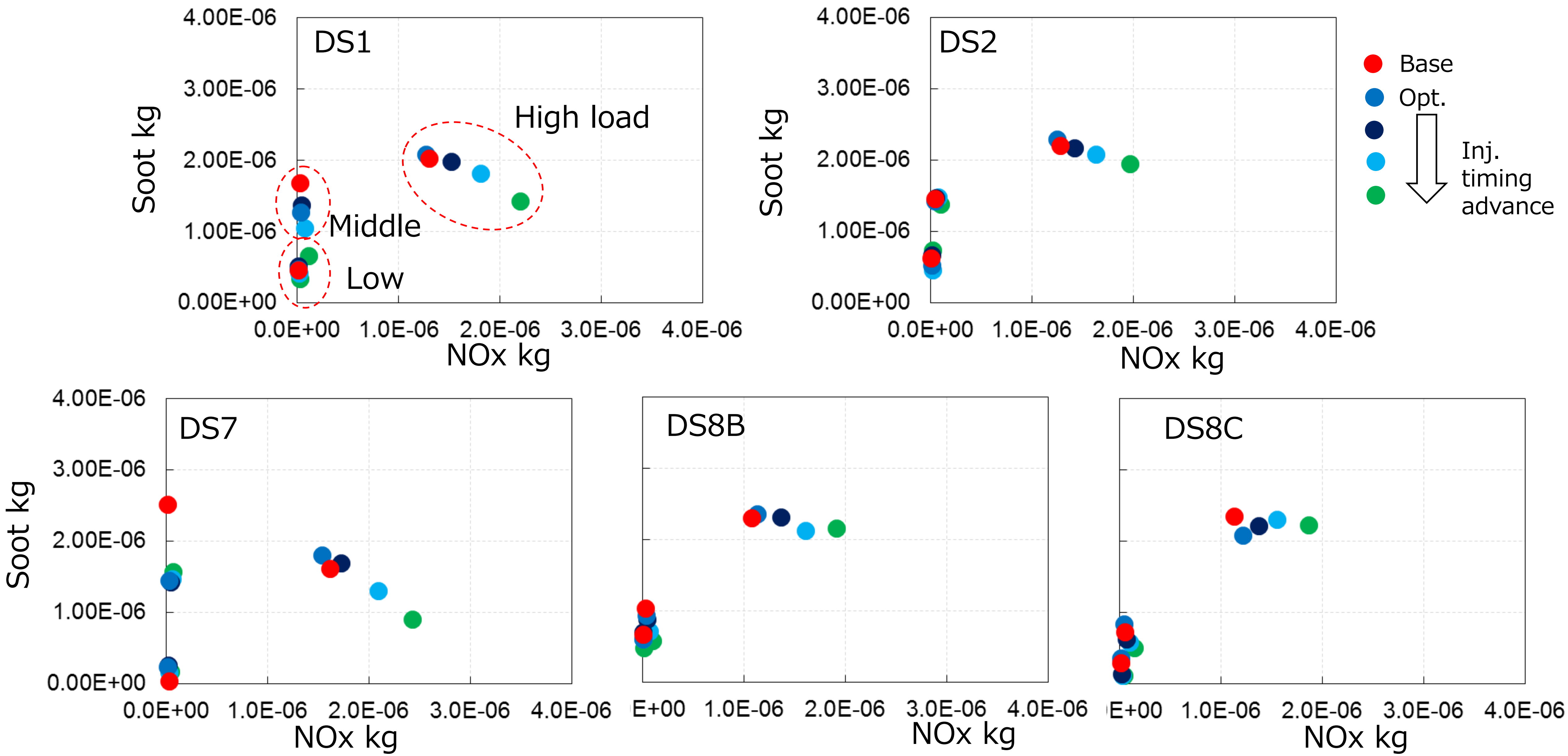








Engine emission analysis



Summary

In future diesel engines for heavy-duty vehicles, I consider that it is necessary to introduce decarbonized fuel with increased thermal efficiency, suppressing PM and PN emissions as much as possible during the combustion process, and purify nitrogen oxides with a urea SCR catalyst. Therefore, as a design concept for future decarbonized fuels for heavy-duty vehicles, it is necessary to aim for higher combustion rate and shorter post-burn period through homogenization and higher dispersion of the mixture concentration inside the fuel spray.

The following items were suggested as a result of varying the components of the surrogate fuel and manipulating its physical properties mainly.

1. Under low-density atmosphere conditions, especially for fuels with low boiling points, there is a tendency for excellent evaporation and spray dispersion.
2. Lighter fuels are effective in advancing the injection timing under high-pressure injection conditions, especially at medium and high loads, and may form a more homogeneous mixture due to the increased ignition delay period. In addition, the thermal efficiency shown in the figure increases, but NOx increases and must be purified with a urea SCR catalyst.

Continued(summary)

3. Evaporation is accelerated by mixing lower carbon number components, resulting in enhanced evaporation including other fuel components.
4. It is assumed that in actual fuel spray, highly volatile components begin to evaporate quickly from their upstream, while low-volatile components remain in the droplet for a relatively long time and form highly concentrated vapor downstream. It is necessary to reduce the core of the spray as much as possible by increasing the injection pressure.

Acknowledgments

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