4-cylinder stable operation of gasoline HCCI using blow-down supercharge system

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Contents

Back ground – HCCI(1)

Advantages of gasoline HCCI engine

- High thermal efficiency
- Low exhaust emission

Issues of gasoline HCCI engine

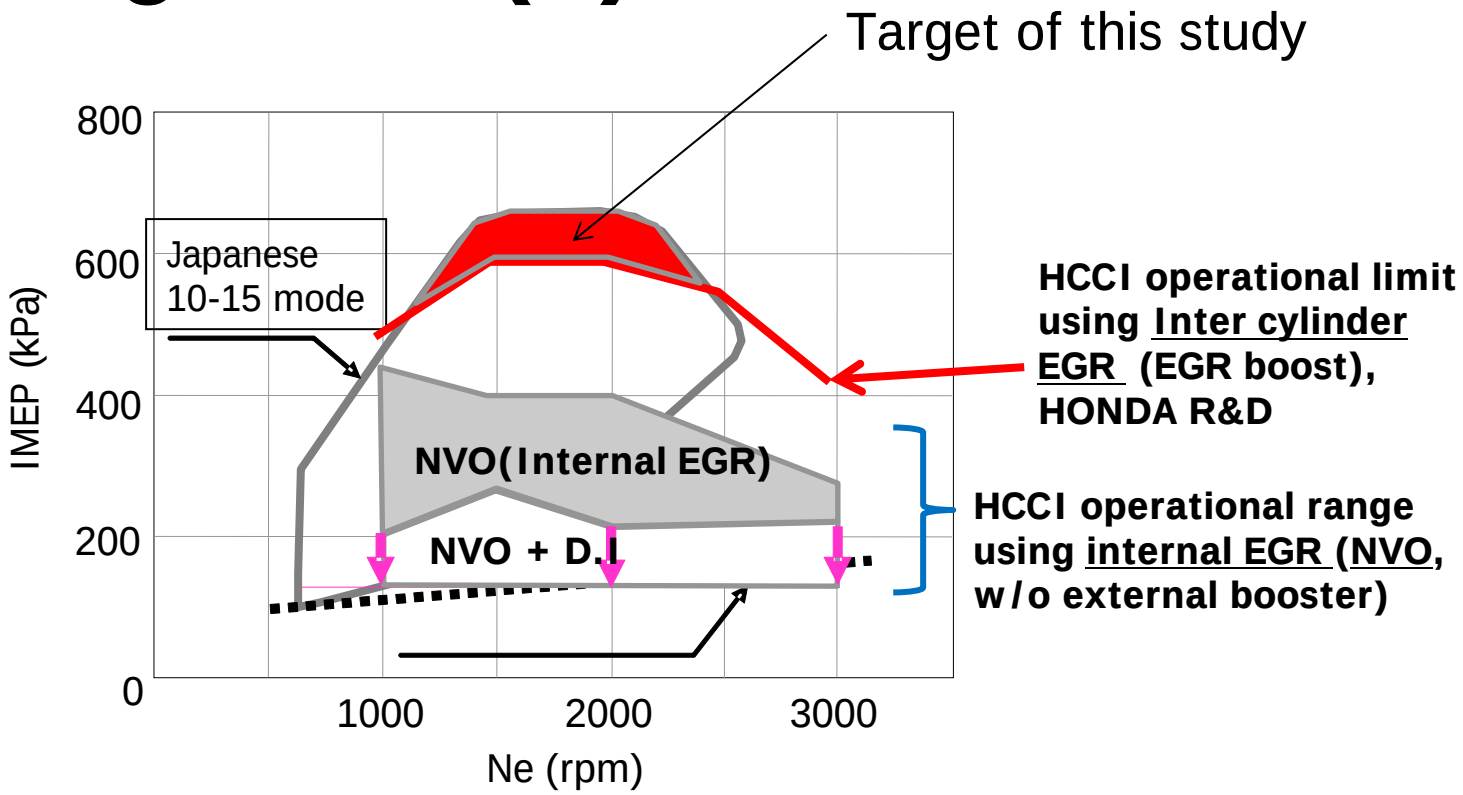
- Extension of driving load
  - High load limitation
    - Increase in $dP/d\theta$ and NOx emission
  - Low load limitation
    - Incomplete combustion; Increase in instability of combustion and CO, HC emission
- Control autoignition timing
- Switching between SI and HCCI

Previous Studies to Extend HCCI Range

- High Load Limit：Reduction in pressure-rise rate
  - ✓ Super-charge, Thermal stratification
- Low Load Limit：Control of instable combustion
  - ✓ Fuel injection during NVO

Extension of high load limit	Supercharge	J. E. Dec, et al., SAE Paper No. 2010-01-1086, etc…
	Inter cylinder EGR (EGR + Supercharge)	Takanashi, J., et al., JSAE Annual congress 2006., Spring, JSAE 20066516
	BDSC with Thermal stratification	T. Kuboyama, SAE Paper, No. 2010-01-0845, 2010.
	Fuel stratified + Spark assist	Hanho Yun, SAE Technical Paper No. 2010-01-0847 / Urushibara, T., et al. JSAE Annual congress 2004, Spring, JSAE 2004 5114, etc…
Extension of low load limit	**DI during NVO period**	Willand J., et al. SAE Paper No. 982483

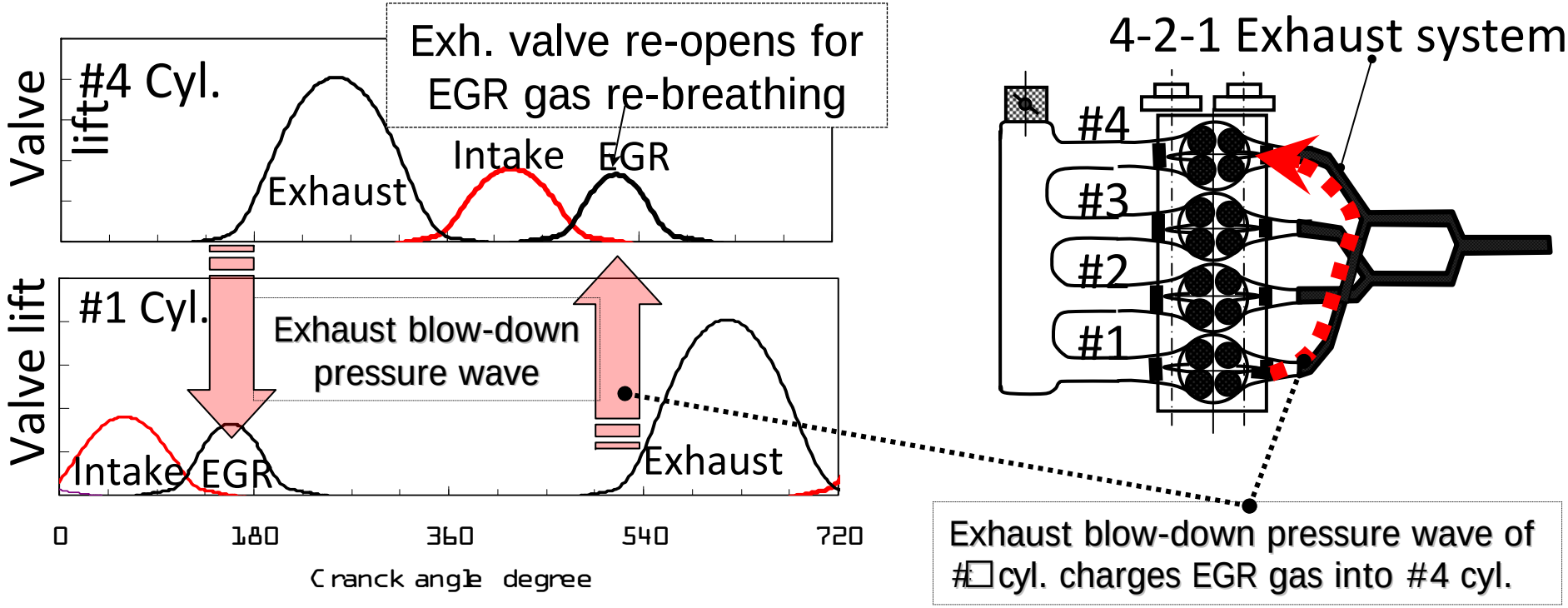
Back ground (2)



- Issue to combine BDSC with NVO
  - ✓ Quite different valve timings
  - ✓ Valve timings must be switched discontinuously.

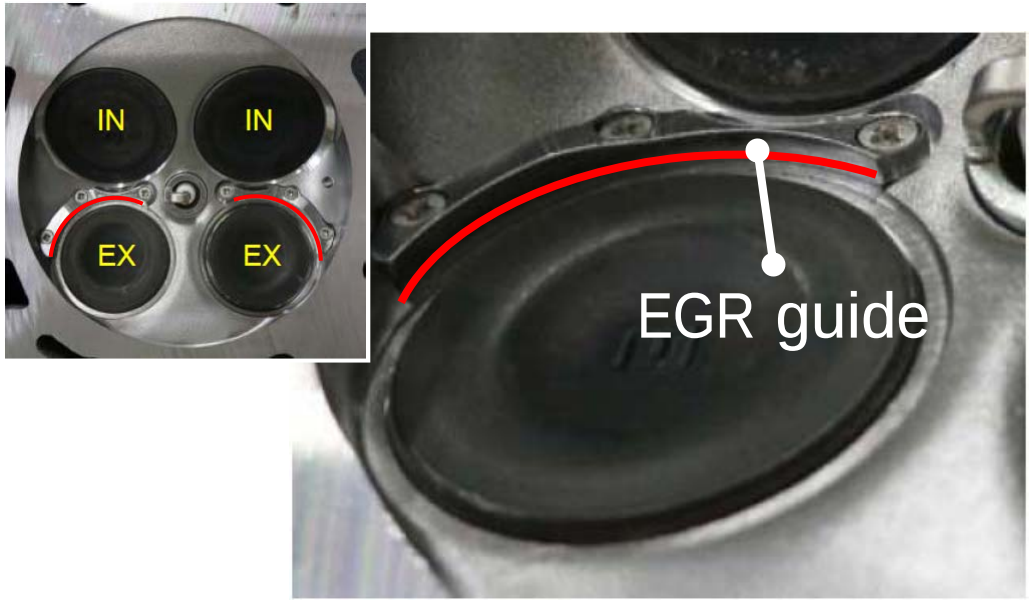
BlowDown Super-Charge (BDSC) System

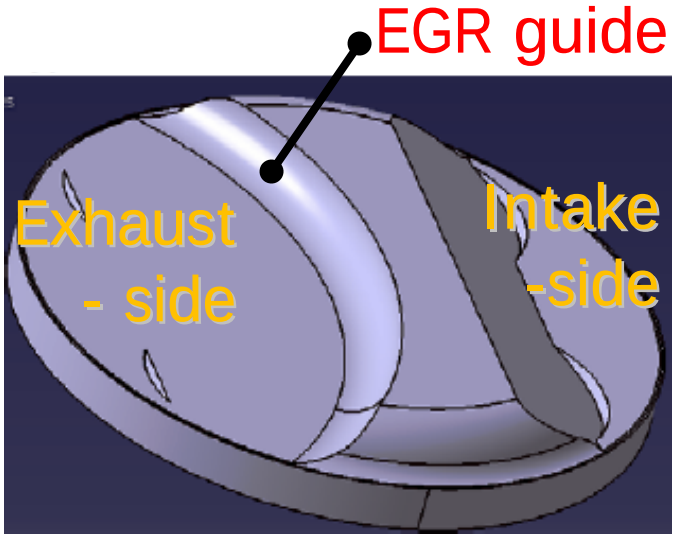
- Exhaust valves re-open during early compression stroke to boost EGR by using the blowdown pressure wave of the other (360 deg. phase-shifted) cylinder.
- EGR boost is possible with enough fresh air and without external super charger.



EGR guide for creating thermal stratification

- Thermal stratification has a high potential for inhibiting steep pressure rise.
- To create a large thermal stratification inside the cylinder, EGR guides are attached on the edge of the exhaust port and piston head.

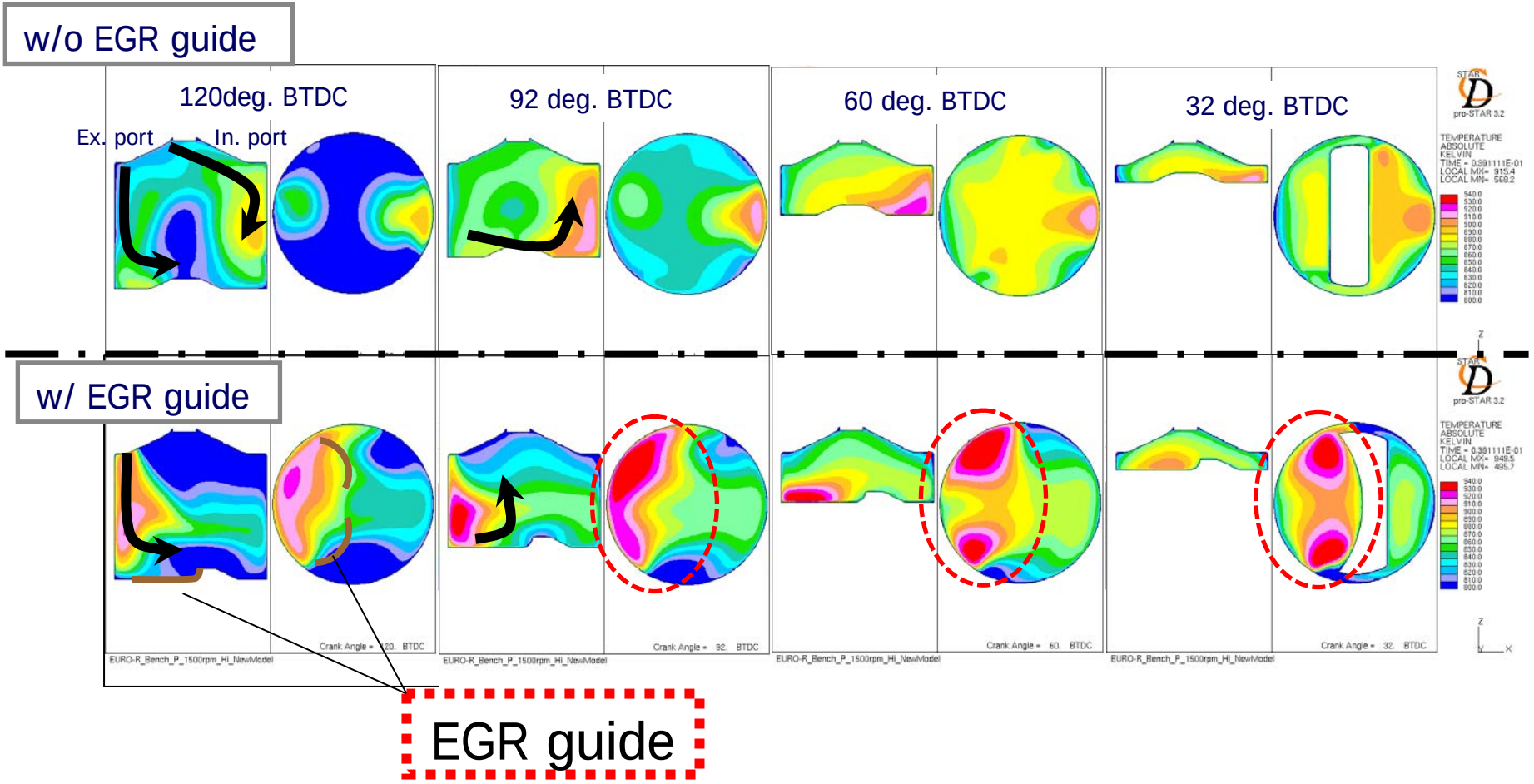




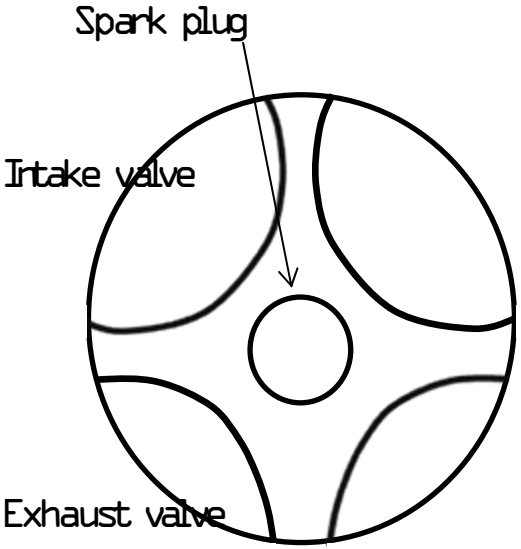
Piston head with EGR guide

Effect of EGR guide on in-cylinder temperature distribution

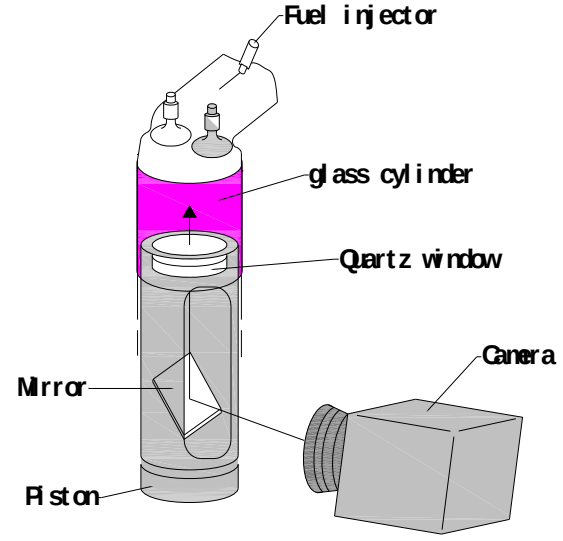
- 3-D simulation results (STAR-CD)



Evaluation of BDSC System by Visualization

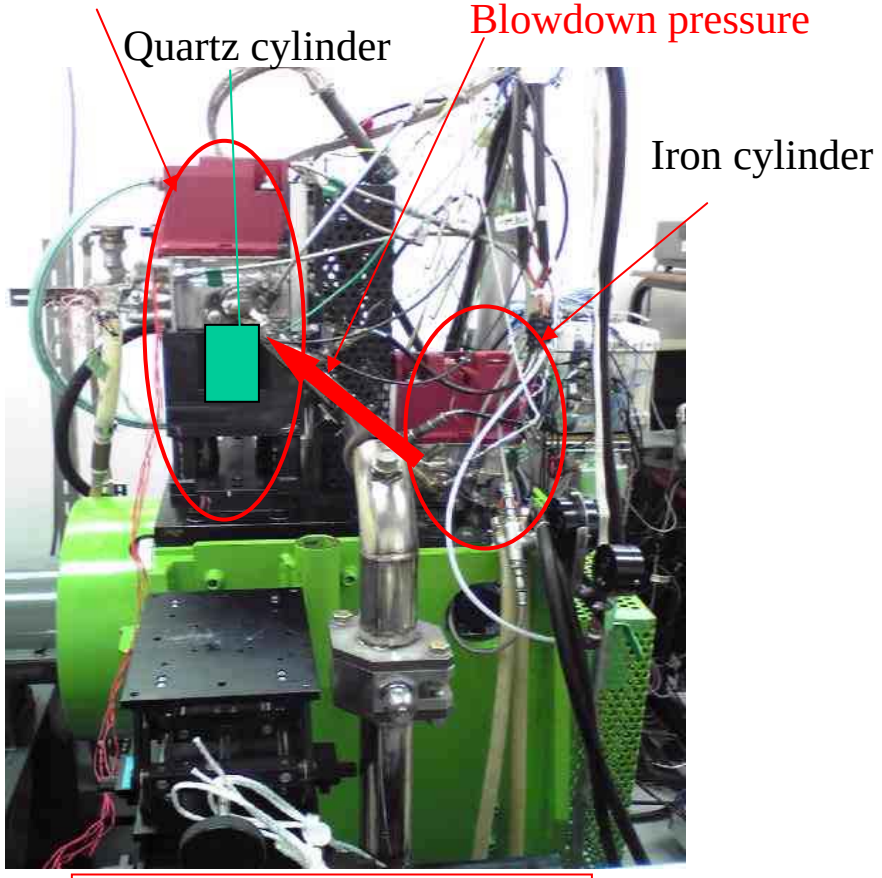


1500rpm, C500 Cam, Fuel amount 11.9mg/st
Frame speed at 30000fps, Exposure time 0.1ms
(Photron FASTCAM SA1.1)



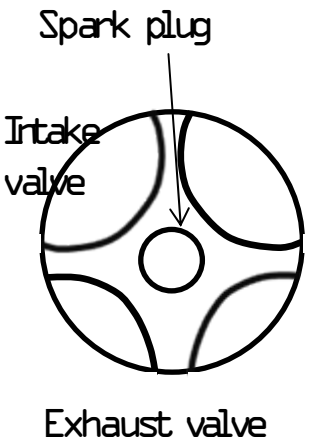
Bottom view system

Visualized cylinder

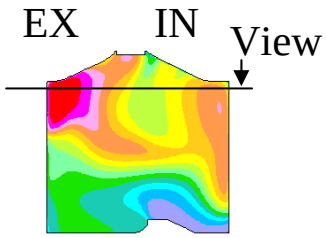


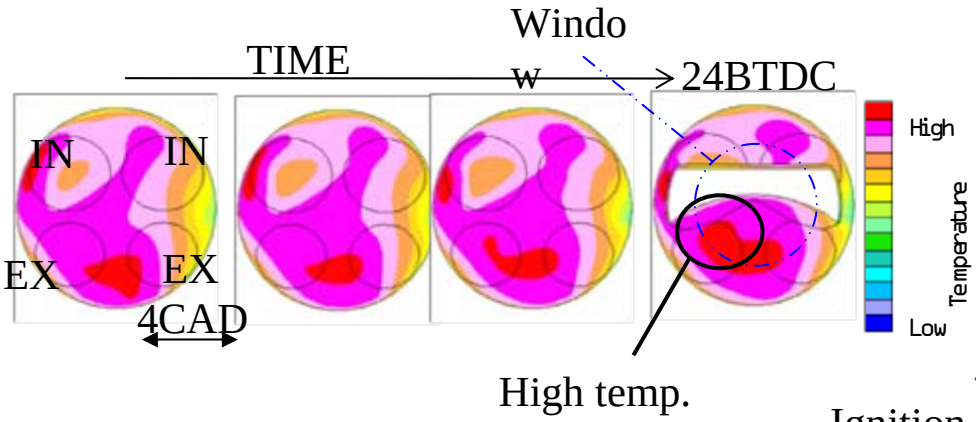
Optical access engine

Combustion Process of BDSC-HCCI

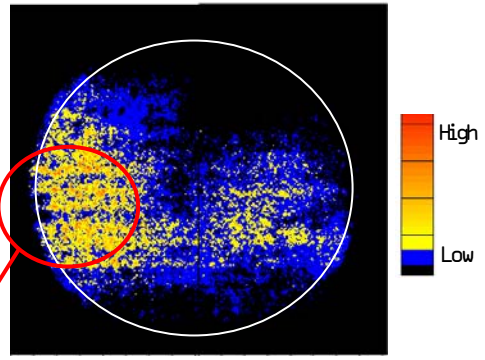


BDSC-HCCI Combustion





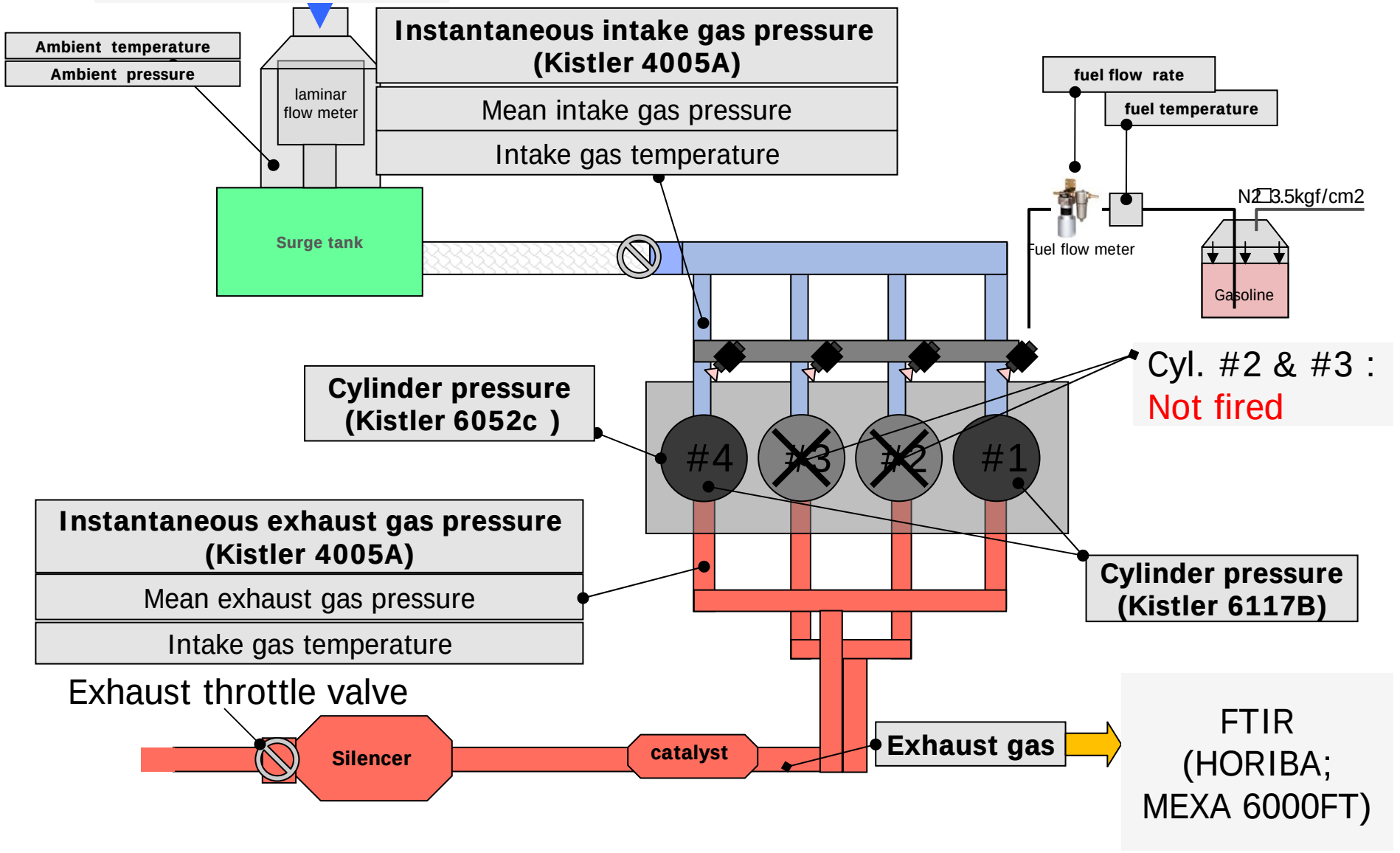
Predicted result by CFD



Accumulated ignition position（100cycles）

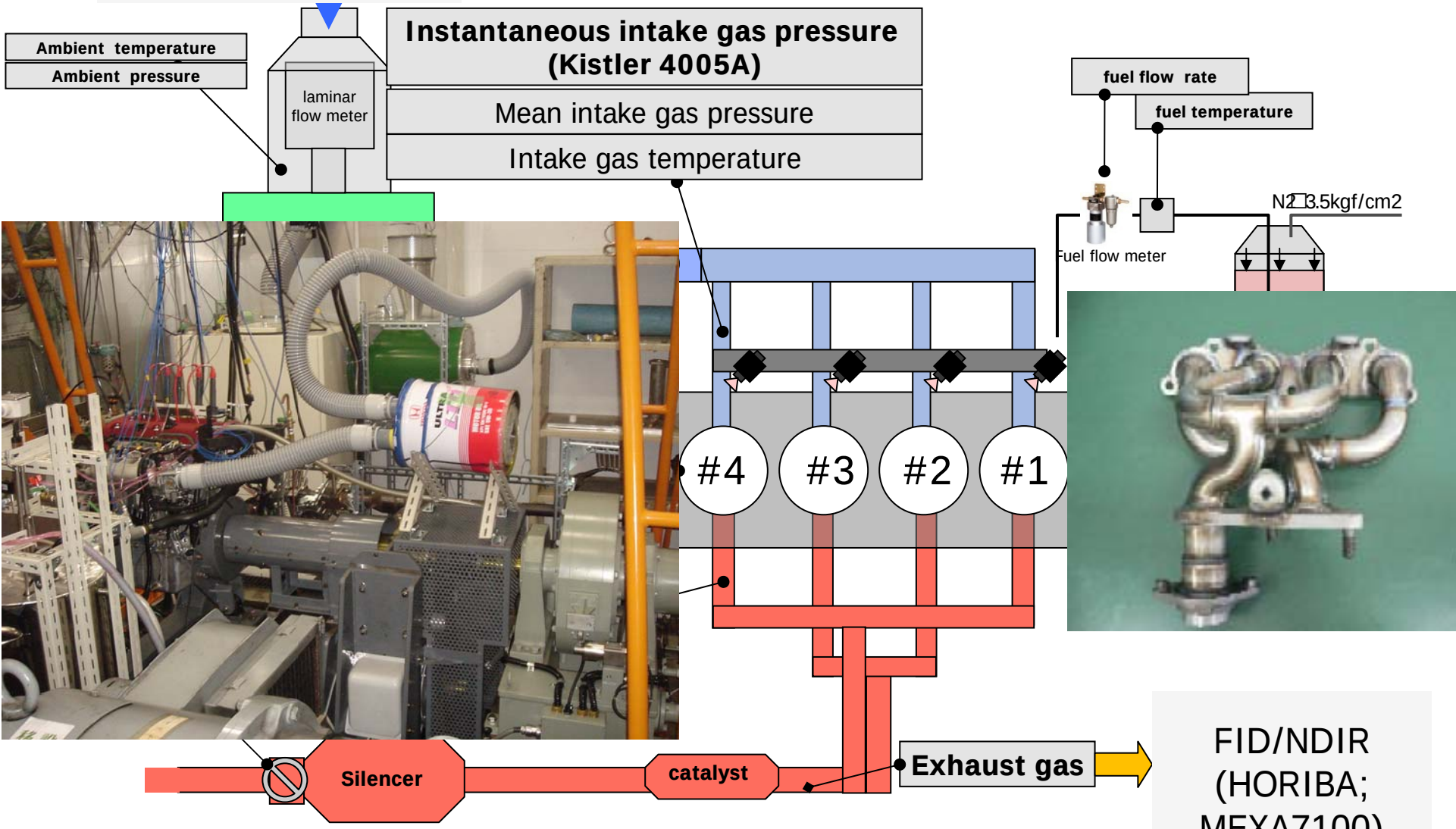
Measurement system

Air conditioner (Controlling intake gas temperature & humidity)



Performance test system

Air conditioner (Controlling intake gas temperature & humidity)



Test engine & conditions

Base engine	Honda K20A
Engine type	Inline 4 cylinder
Bore x Stroke	86 mm x 86 mm
Displacement	1998 cm^3
Compression ratio	12 (HCCI)/ 11.5 (Base)
Fuel injection	Port injection / Direct injection
Fuel	Gasoline (RON91)
Engine speed	1500 / 2500 rpm
Valve timing	Fixed cam

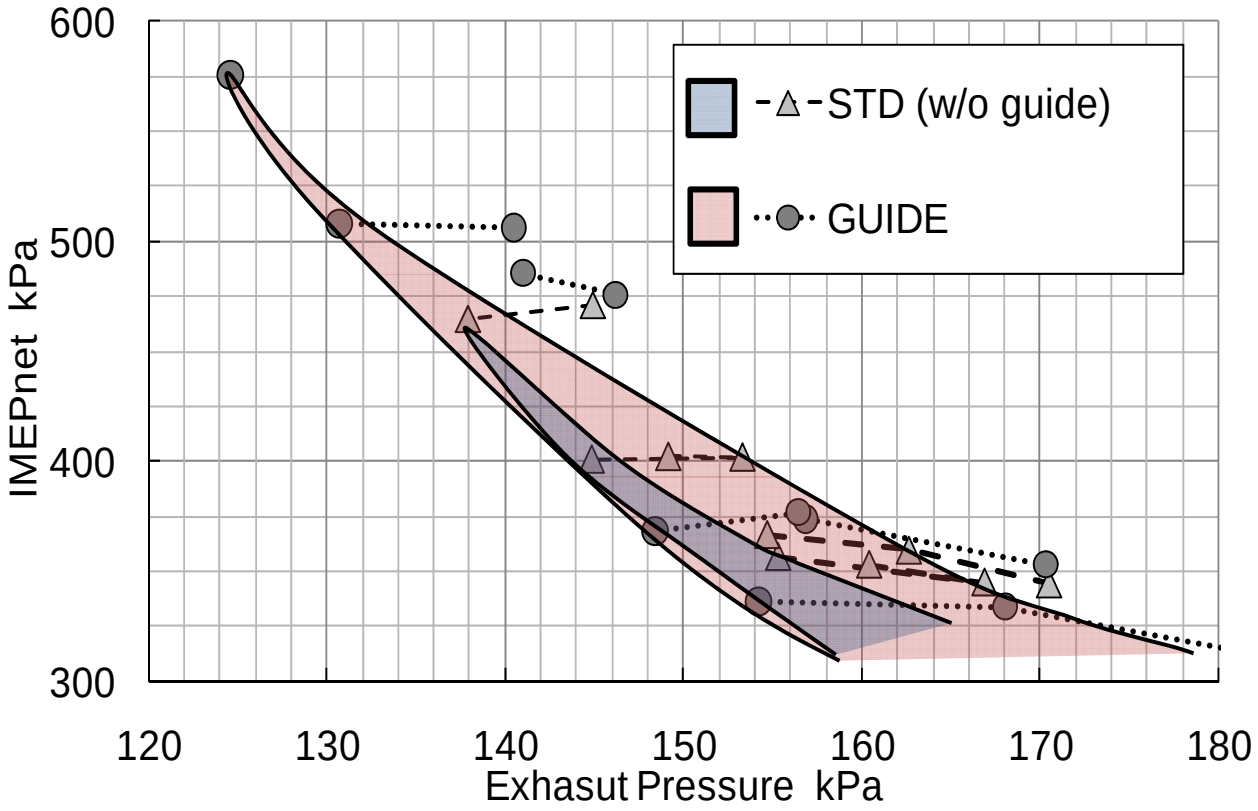
Definition of operational HCCI

- Limit of maximum pressure rise rate
  - $dP/d\theta_{max} \leq 400$ kPa/deg.
- Limit of combustion stability
  - COV. of IMEP ≤ 5 %
- Limit of NOx emission
  - ISNOx ≤ 0.1 g/kWh

Extension of High Load Operational Limit

- Blowdown Super-charge (Much fresh air)
- EGR Guide System (Thermal stratification)

Effect of EGR Guide System



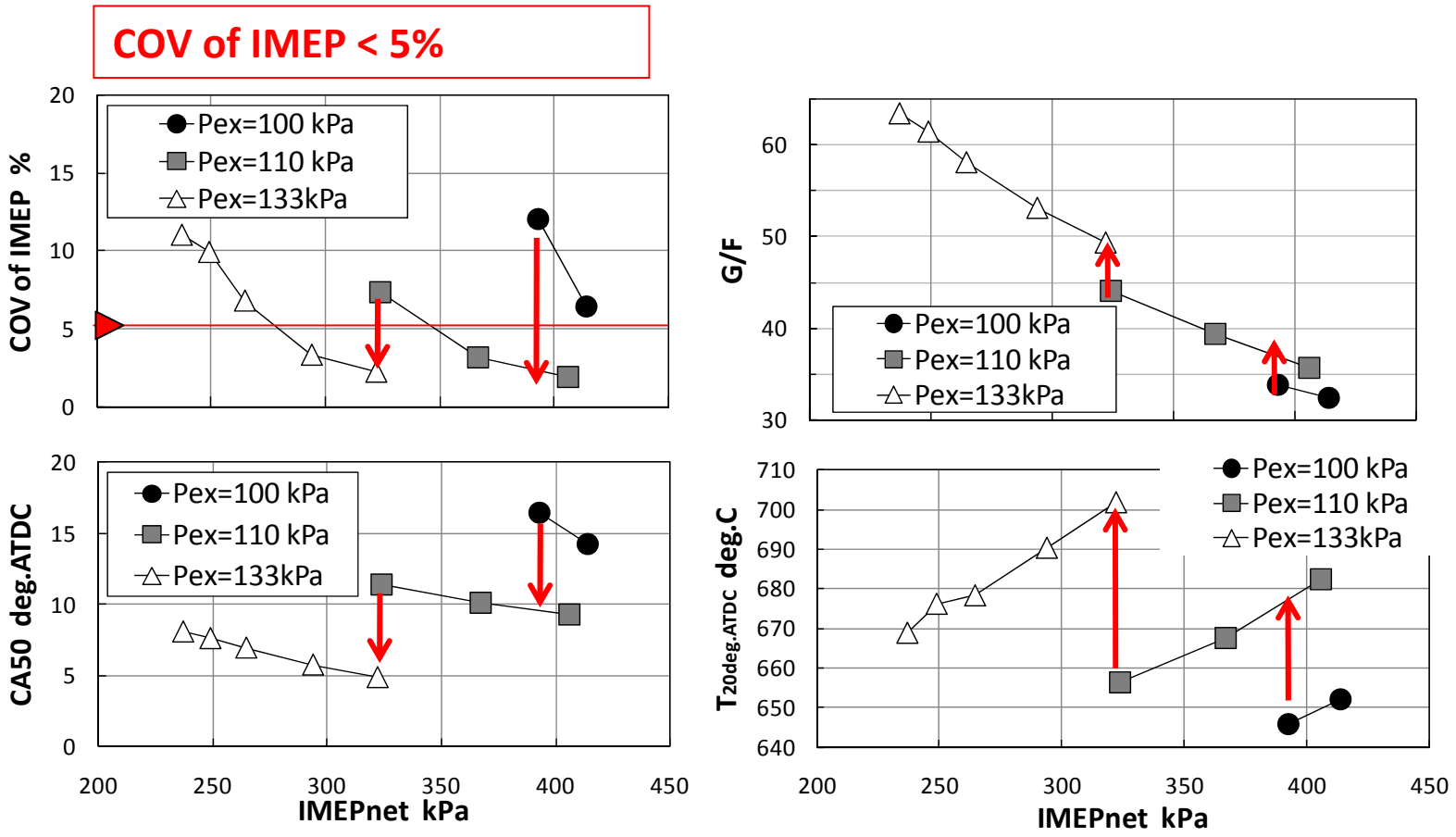
Ne: 1500 rpm
Valve timing: C500

- Required maximum IMEP in Japanese 10-15 driving cycle was attained by this system

Extension of Low Load Operational Limit

- Blowdown Super-charge (Much EGR)
- Increased Cooling Water Temperature
- Optimized Valve Timings

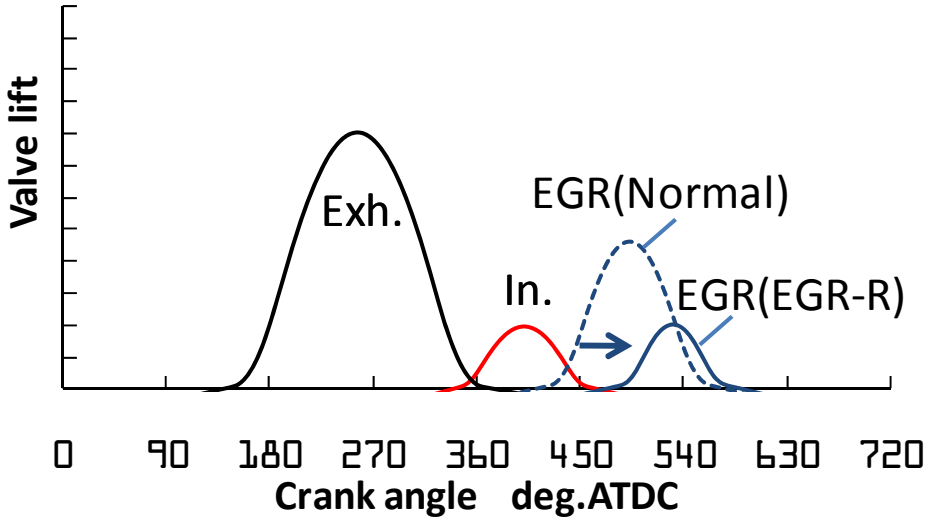
Original Low Load Limit of BDSC-HCCI



- Increased Pex causes more EGR leading to high gas temperature and also diluted mixture
- Mixture temperature should be increased w/o increasing total mass of gas at low load (dilution is not good)

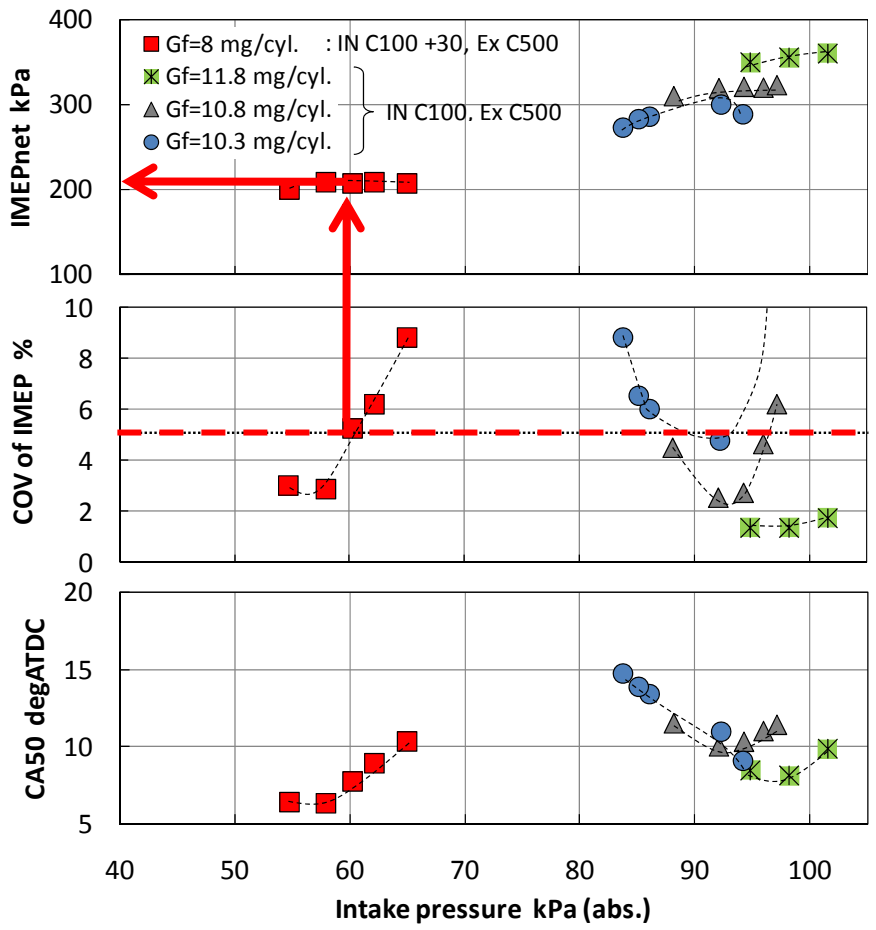
Retarding EGR Valve Timing

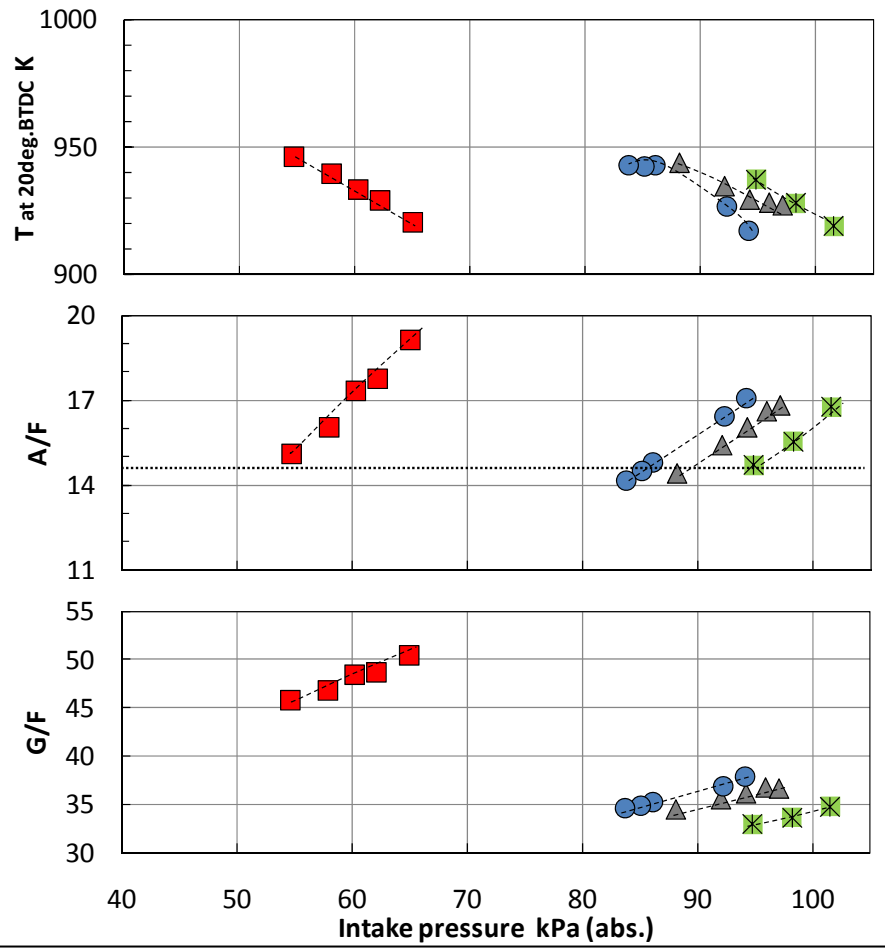
New valve strategy (**EGR-R**)



- To increase the gas temperature w/o increasing mass of gas

Effect of Intake Pressure on Performance at Low Load Condition

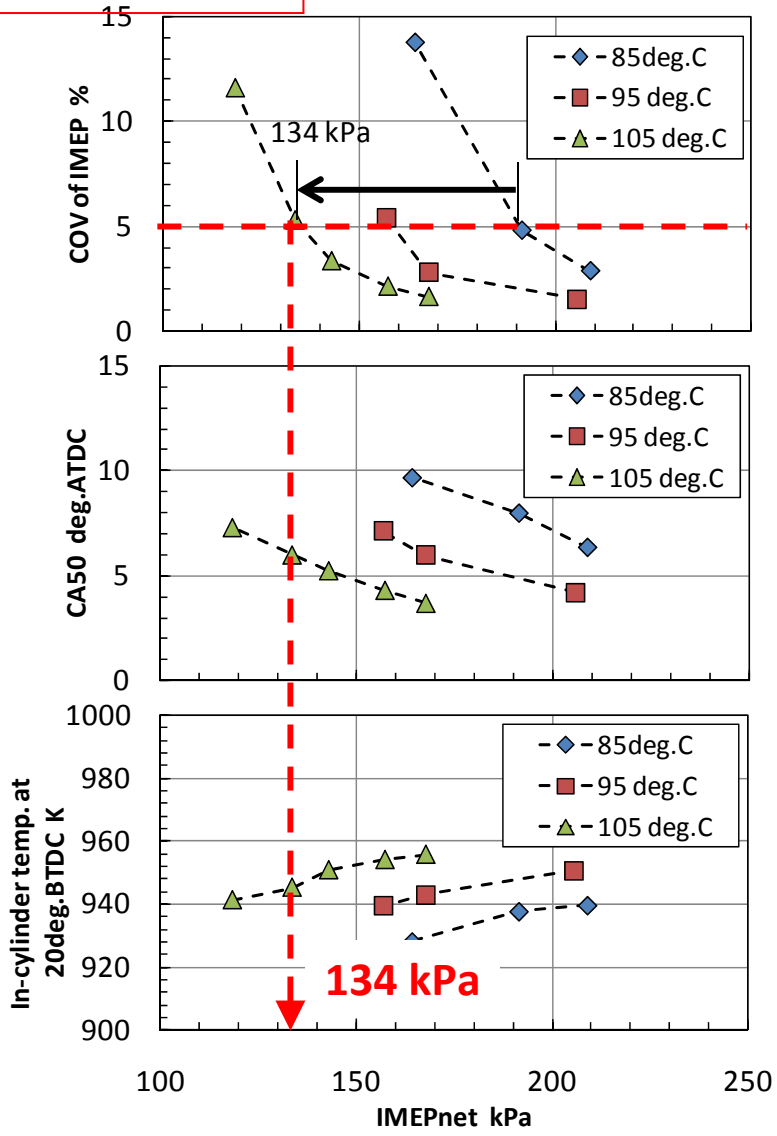


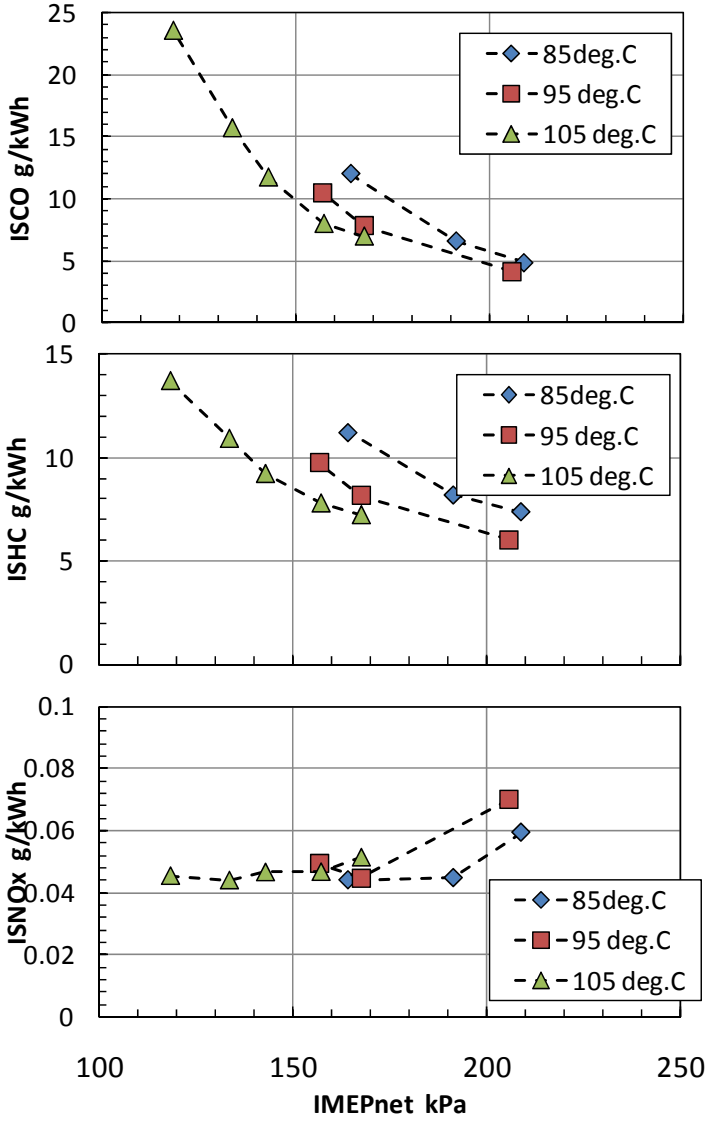


- Low intake pressure causes lower operational IMEP due to pumping loss (= heat-up of in-cylinder gas)

Effect of Cooling Water Temperature on Combustion Stability

COV of IMEP < 5%

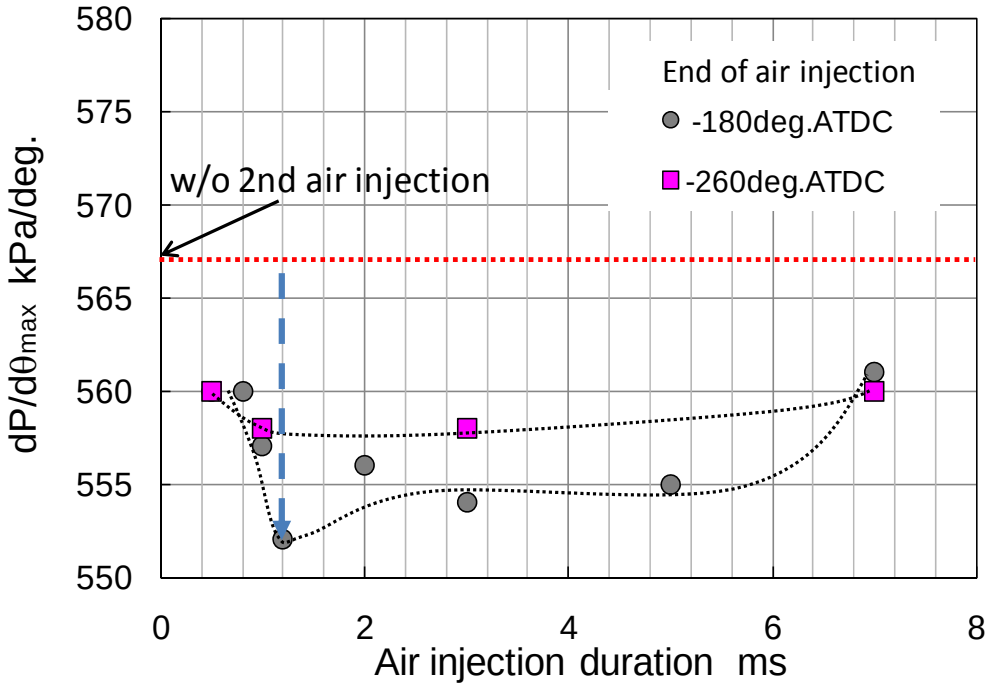


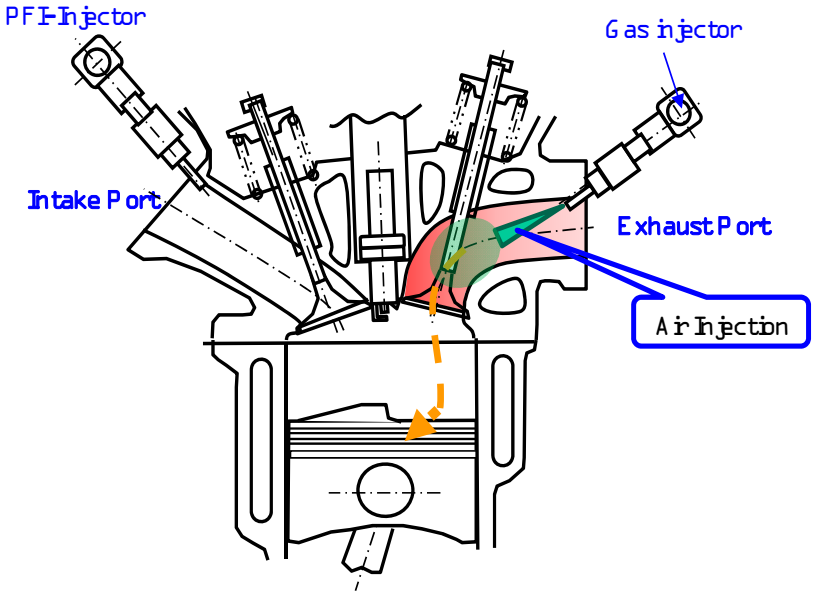


Performance Test Using 4-Cylinder Engine

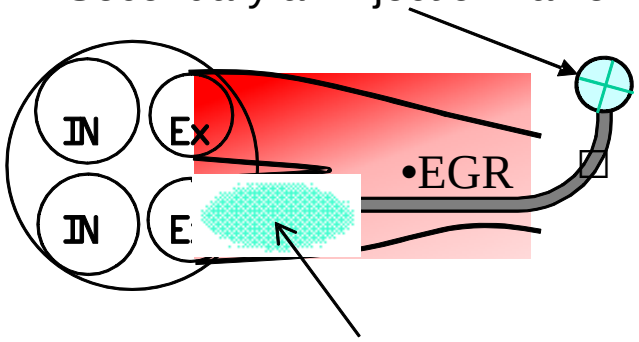
Issue: cylinder to cylinder variation

Secondary air injection was succeeded.





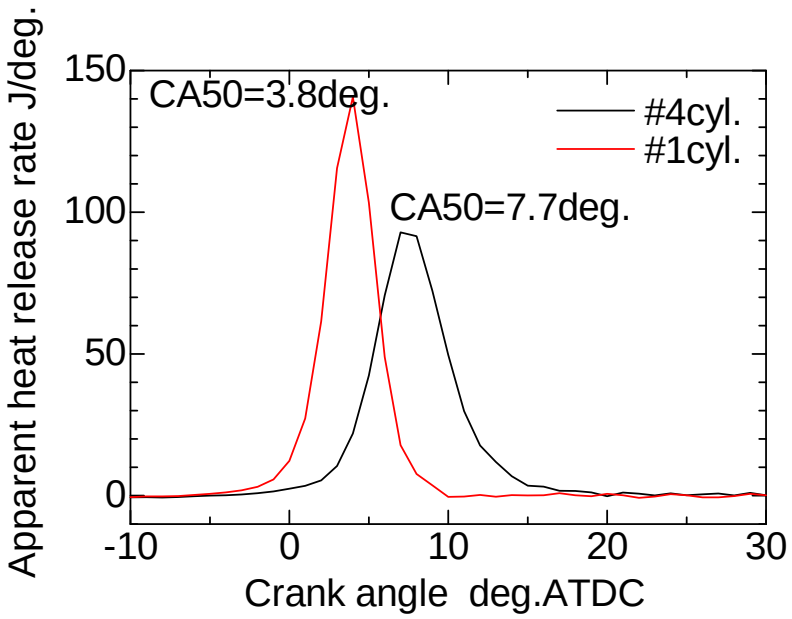
Secondary air injection valve

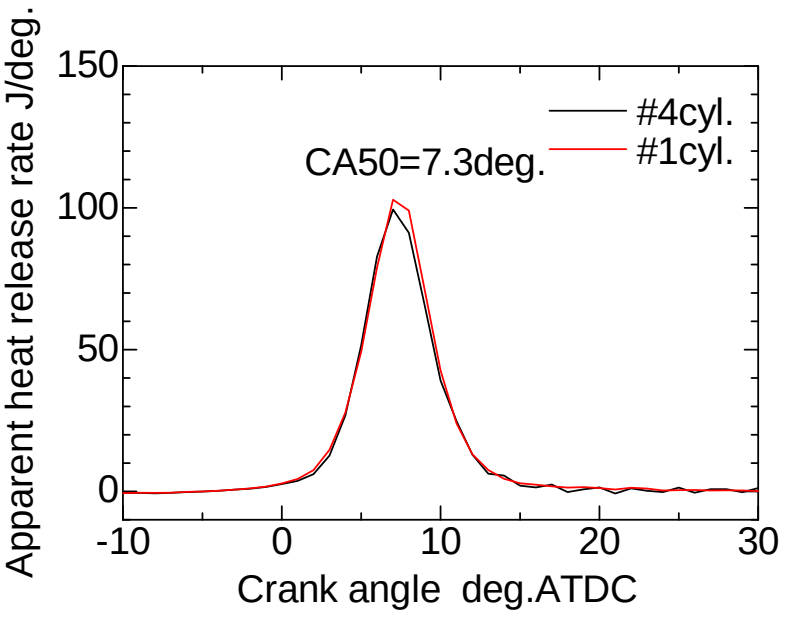


Air injection

Reduction of Cylinder to Cylinder Variation by Secondary Air Injection System

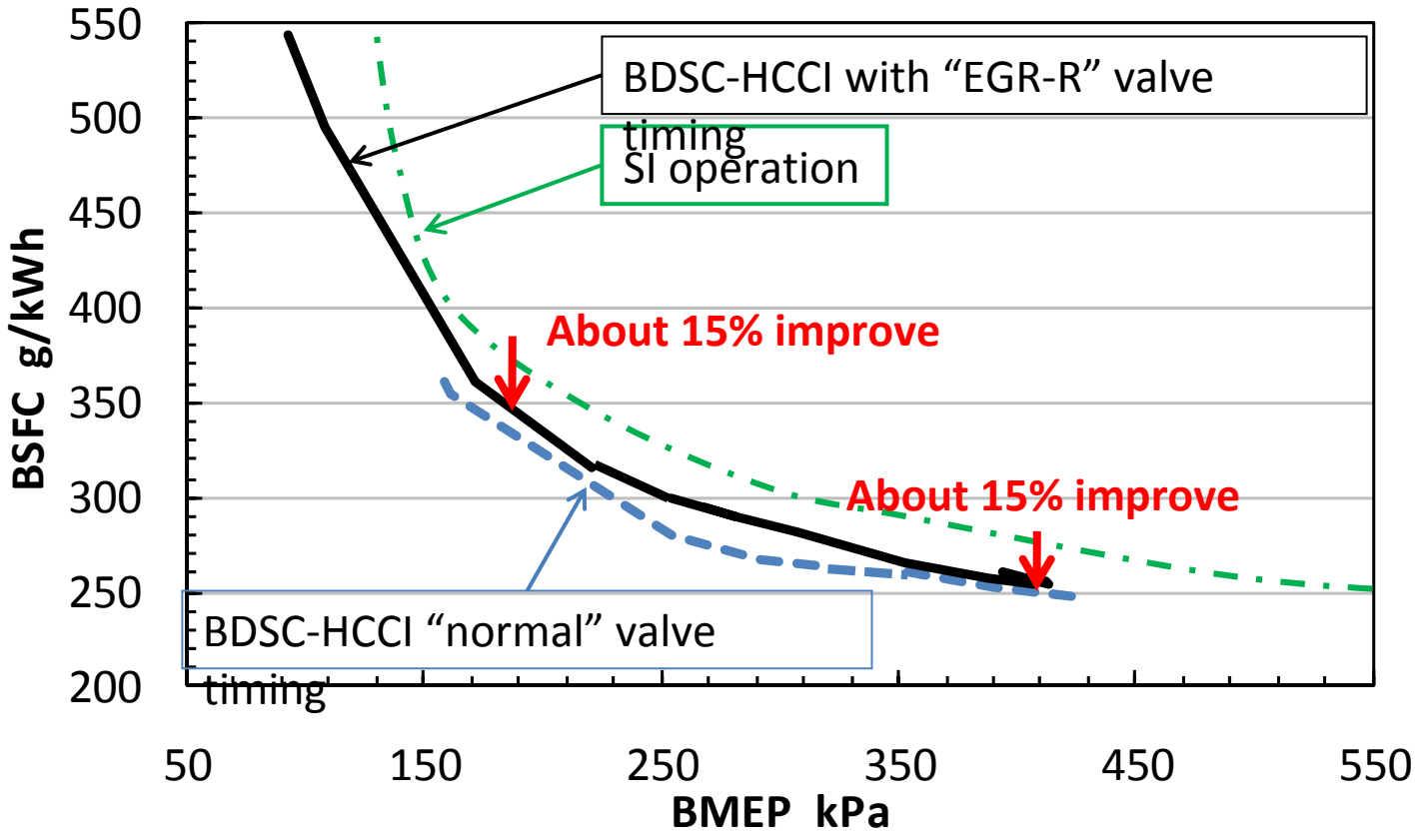
- CA50 timing and heat release profile can be controlled by changing the amount of secondary air injection in each cylinder



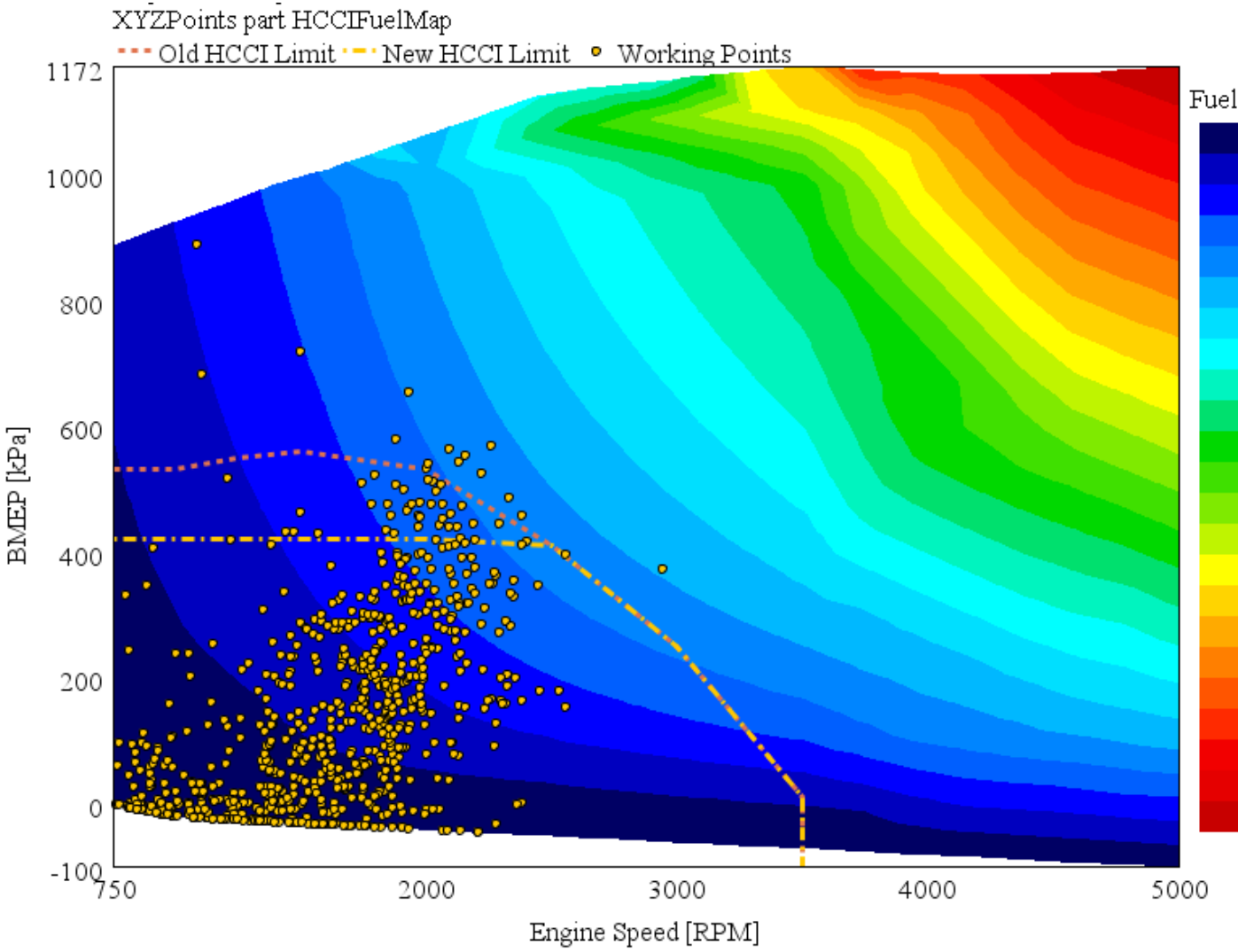


Brake Thermal Efficiency

Using 4-cylinder HCCI engine



JC08 Driving Cycle Simulation (GT-Suite Dynamic Model)



km/L

S I : 13.2

HCCI: 15.2

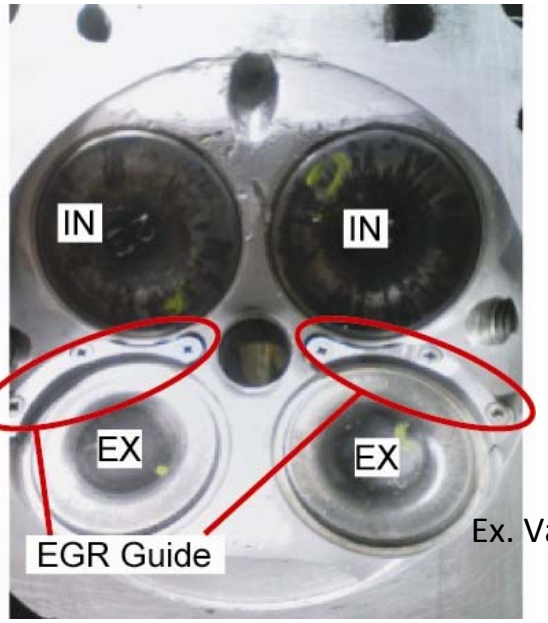
15% better

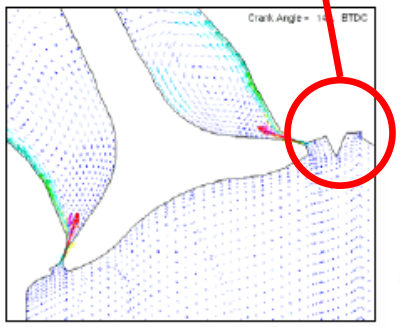
2L,1270kg,
6-speed MT

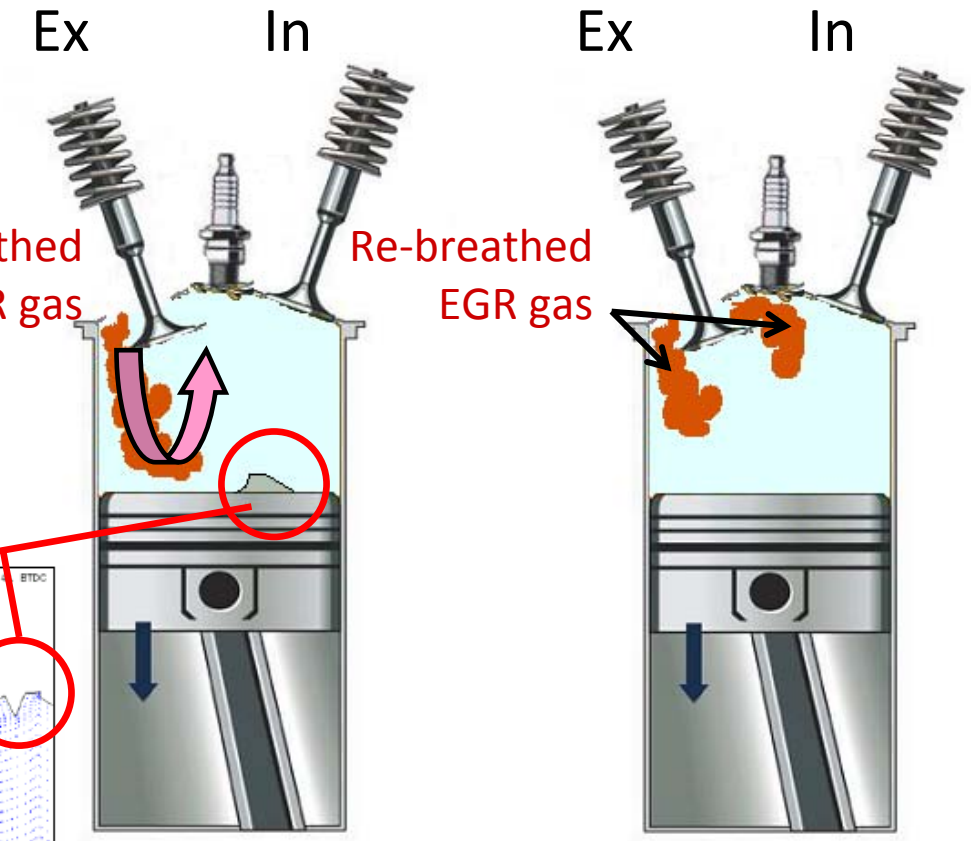
Conclusions

- A Blowdown super-charged HCCI gasoline engine was tested.
- Extension of high load limit can be attained by using thermal stratification and the max torque of Japanese 10-15 mode can be covered by BDSC.
- Extension of low load limit can be attained by retarding EGR valve timing and also increasing cooling water temperature. The low operational limit can be extended as low as IMEP 135 kPa.
- 4-cylinder BDSC-HCCI is achieved with secondary air injection system to control cylinder-to-cylinder variation. Thermal efficiency is improved by 15% compared to the original SI operation.

EGR guide for creating in-cylinder thermal stratification

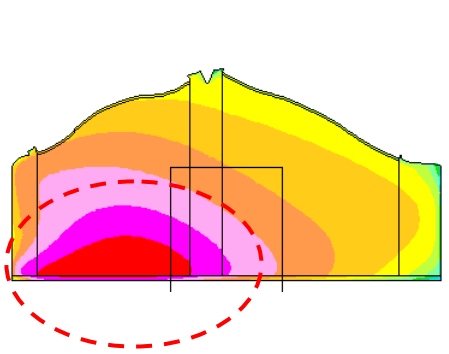


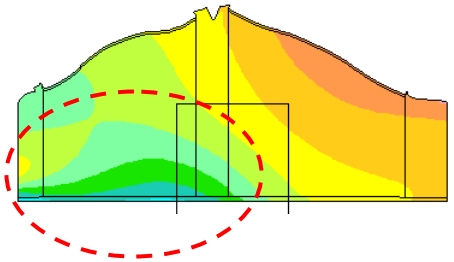




BDSC

-44 deg.ATDC IMEP 370 kPa, BDSC + EGR guide (3D-CFD)





G/F : 49

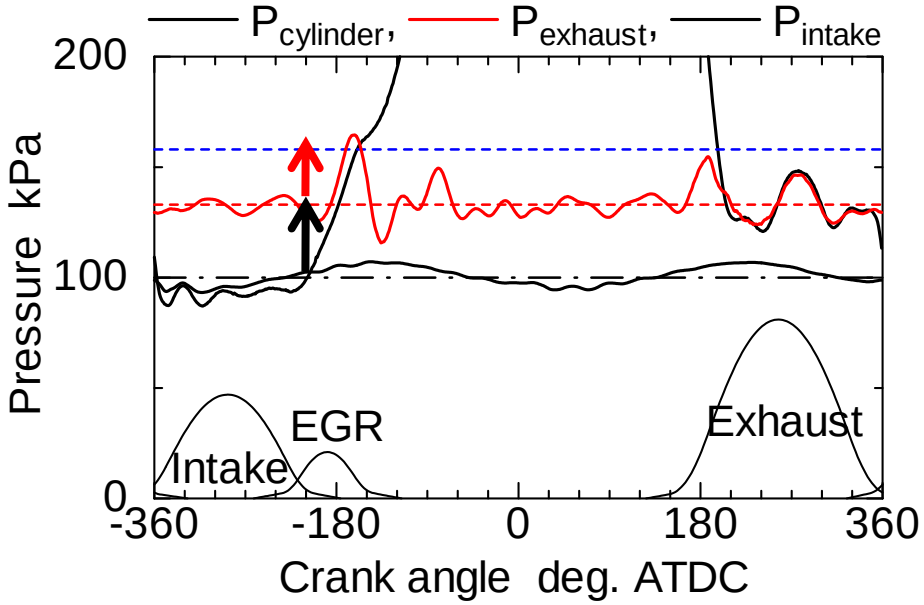
G/F

G : Gas(Air+EGR) F : Fuel

EGR

□□□□□□□□□□DSC-HCCI□□□□□□□□

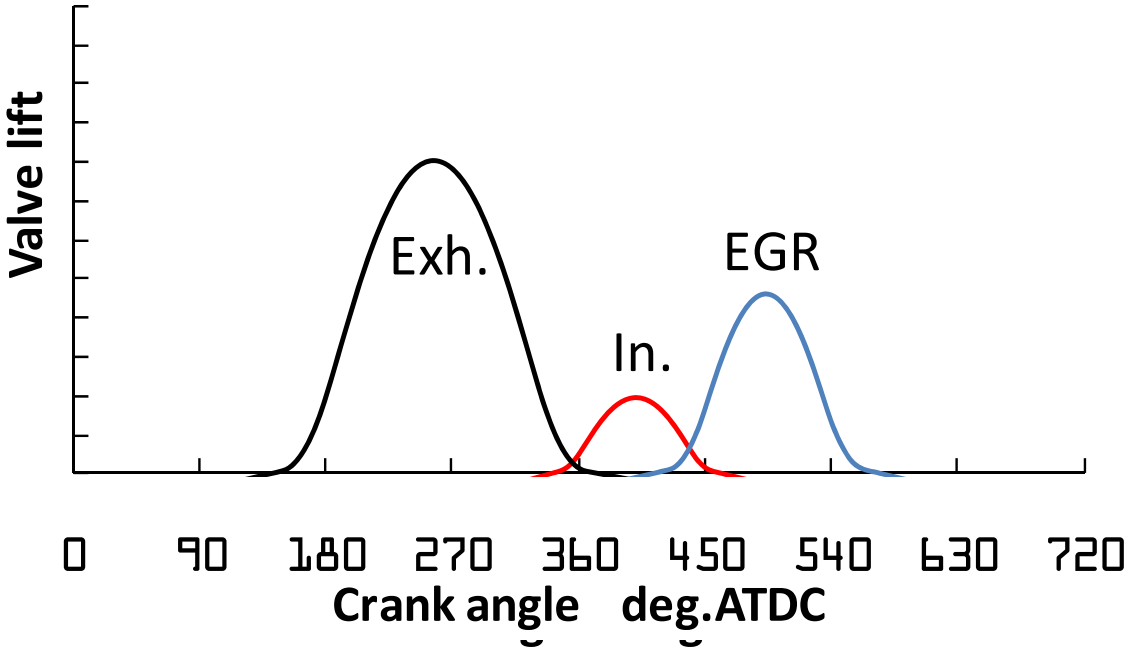
1500 rpm



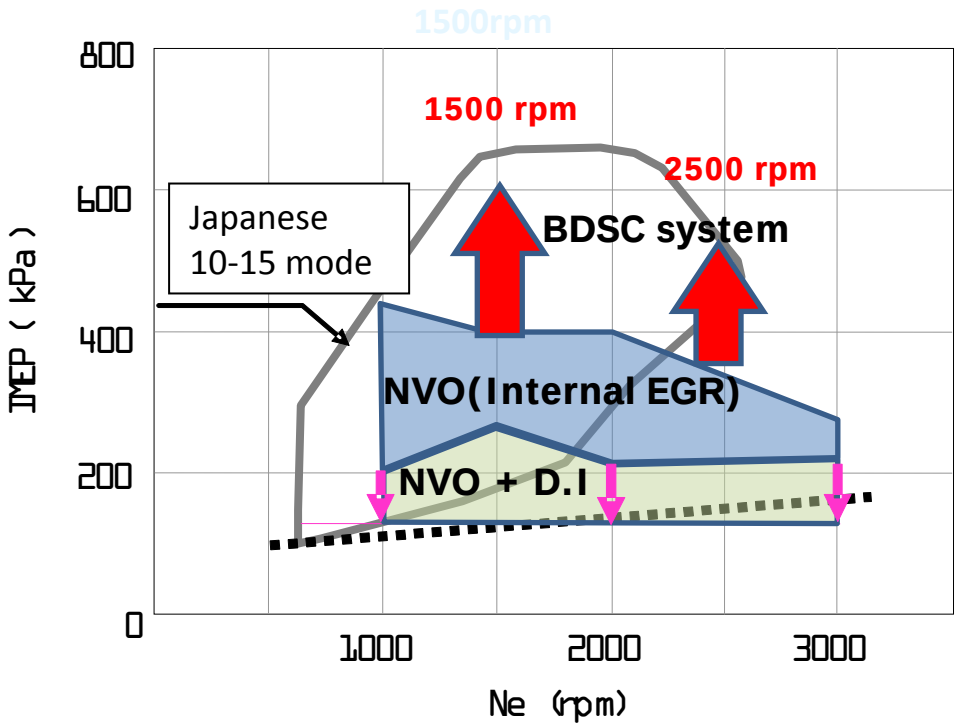
- □□□□□□□□
- □□□□EGR□□□□□□□□□□□

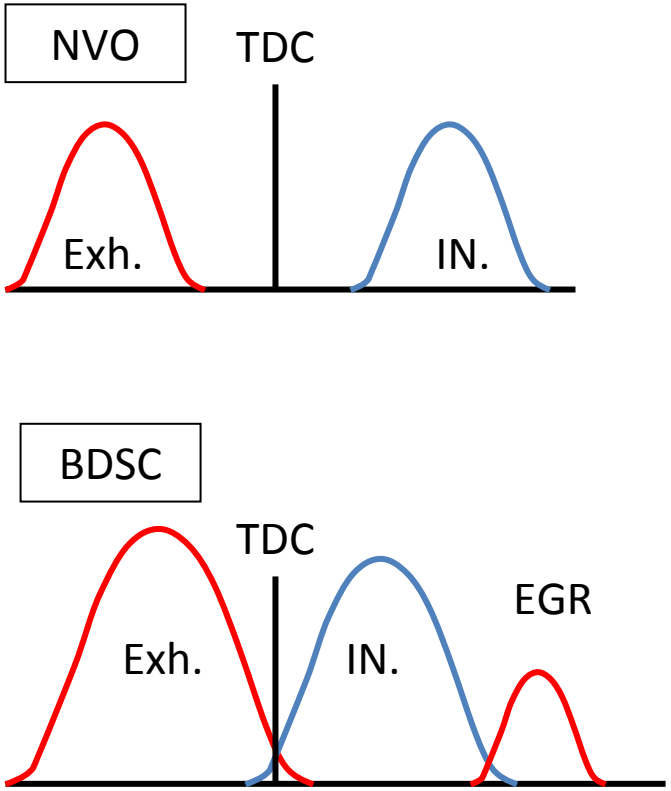
BDSC

Load	Intake	EGR
High	High	Low
Low	Low	High



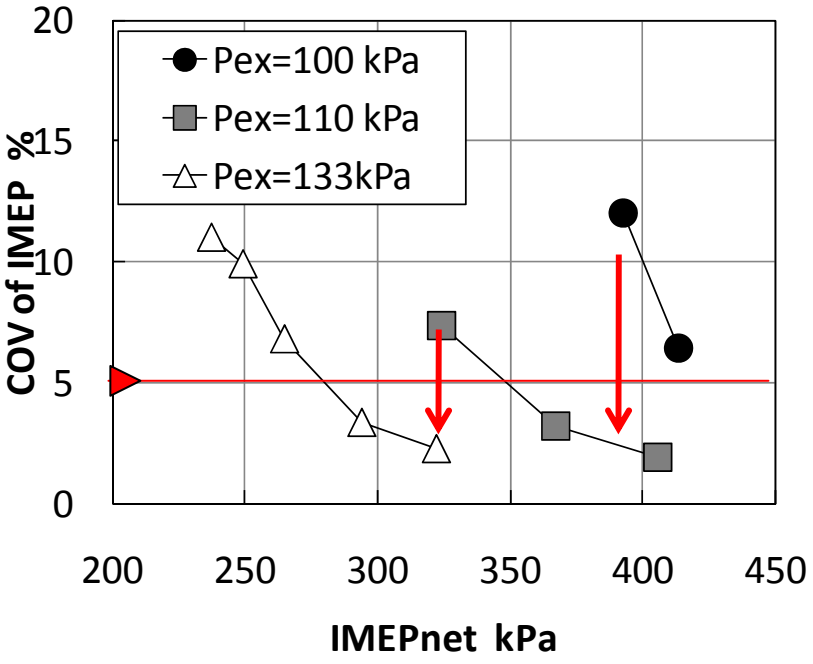
- EGR
  - EGR

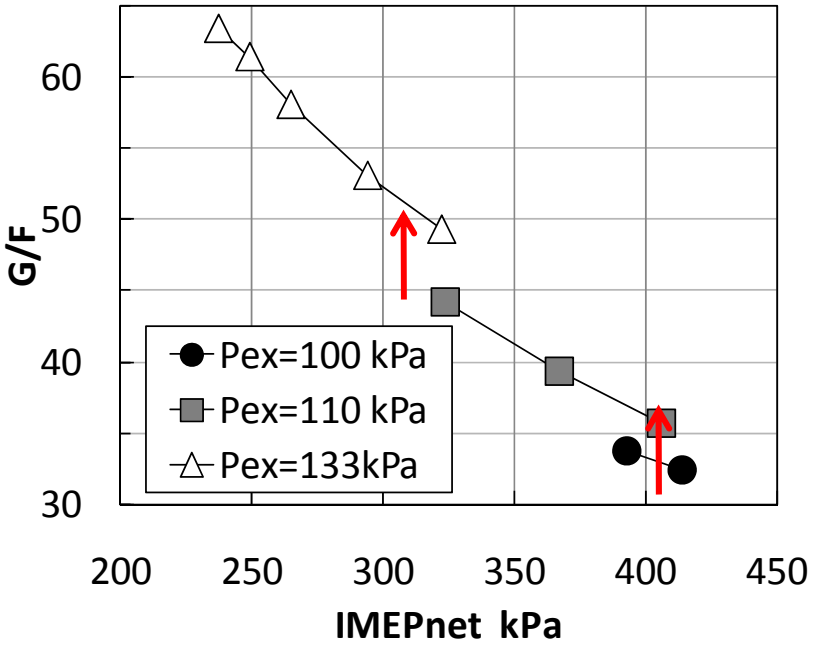

1500rpm
800
600
400
200
0
IMEP (kPa)
1500 rpm
2500 rpm
Japanese
10-15 mode
BDSC system
NVO(Internal EGR)
NVO + D.I
1000
2000
3000
Ne (rpm)


NVO
TDC
Exh.
IN.
BDSC
TDC
Exh.
IN.
EGR

NVO BDSC

BDSC-HCC□□□□□□□□


Pex=100 kPa
Pex=110 kPa
Pex=133kPa
COV of IMEP %
IMEPnet kPa
0
5
10
15
20
200
250
300
350
400
450


Pex=100 kPa
Pex=110 kPa
Pex=133kPa
G/F
IMEPnet kPa
30
40
50
60
200
250
300
350
400
450

- □□□□□□□□□□□□□□□□EGR□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□
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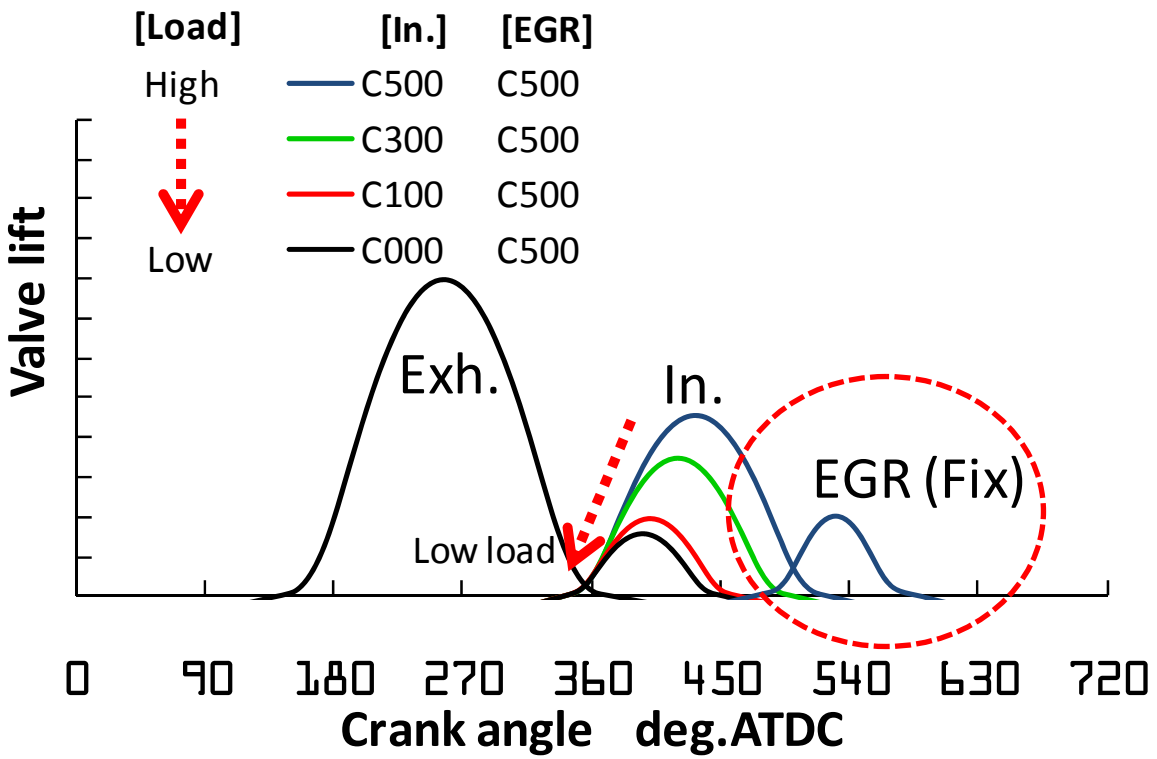
EGR

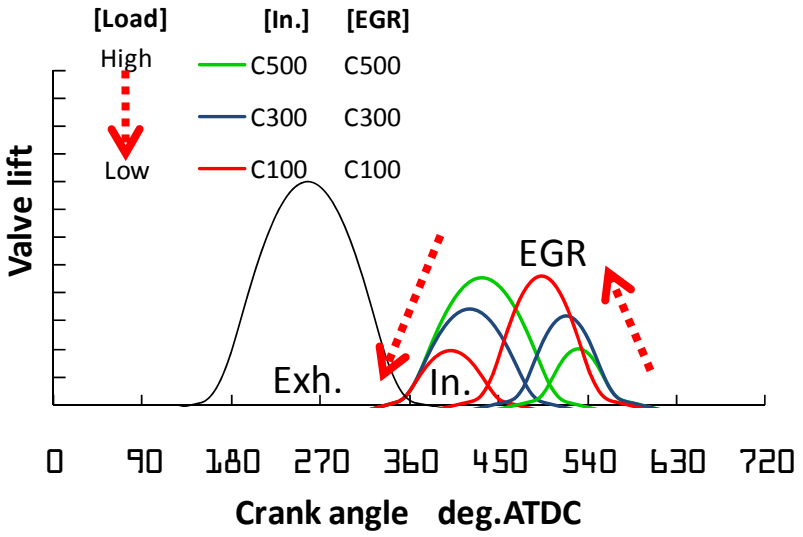


Load	Intake	EGR
High	High	Fix
Low	Low	

- [illegible]EGR[illegible]
  - ✓[illegible]
- EGR[illegible]

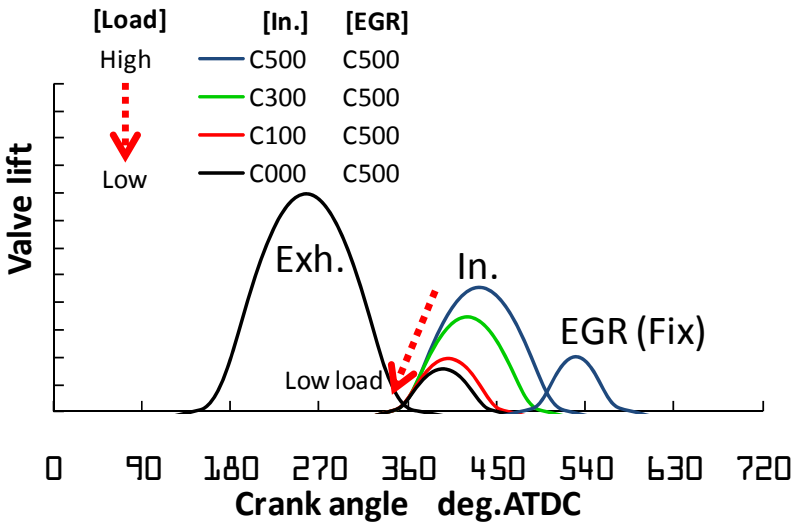
EGR

Conventional BDSC-HCCI valve strategy



- EGR
- h EGR

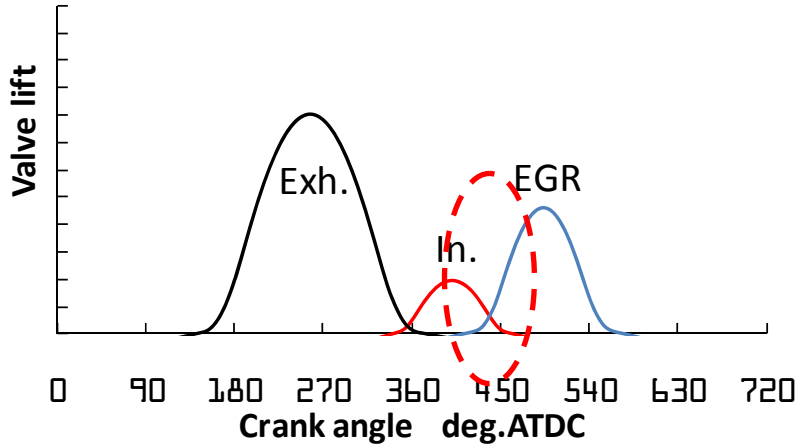
New valve strategy



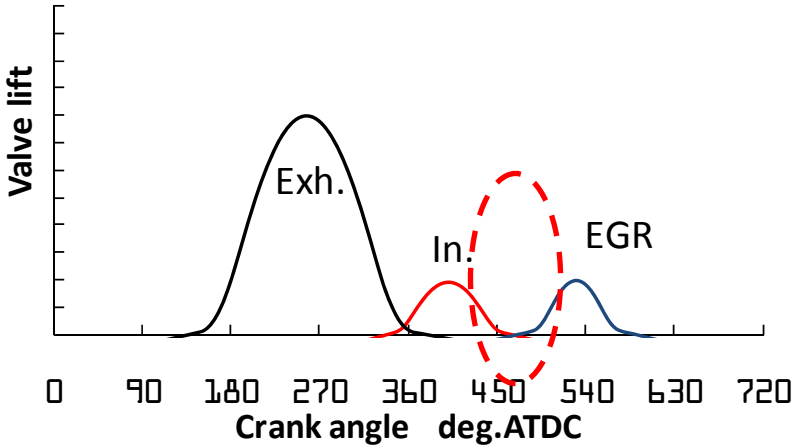
- EGR
- h

EGR

Conventional BDSC-HCCI valve strategy (Normal)



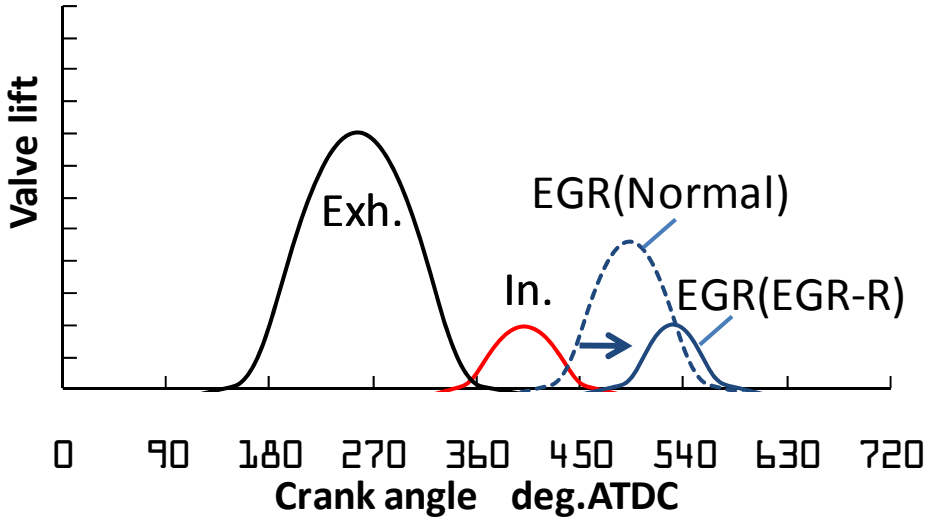
New valve strategy (**EGR-R**)



- EGR-R
  -
- In

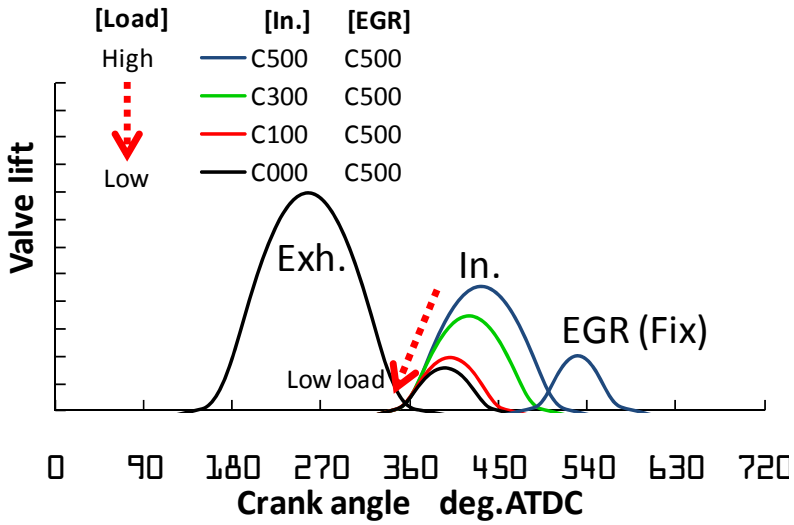
EGR

New valve strategy (**EGR-R**)

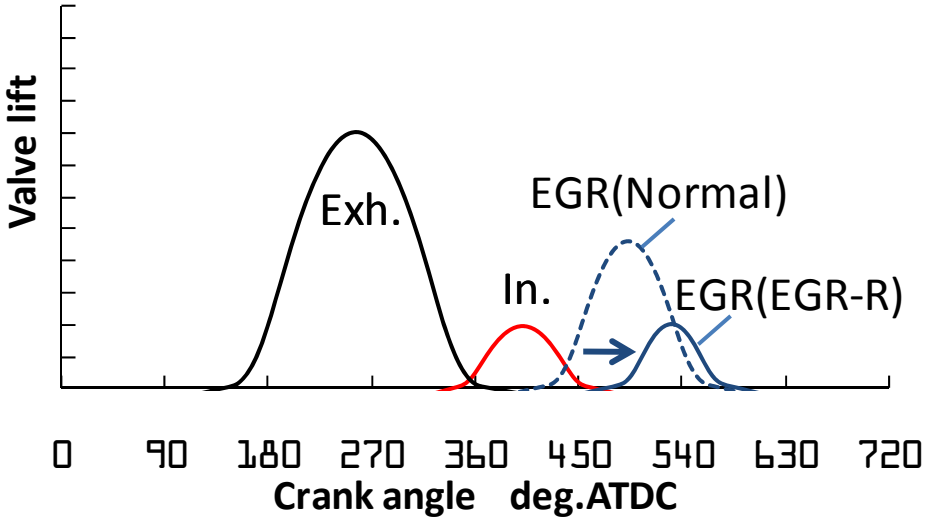


EGR

New valve strategy



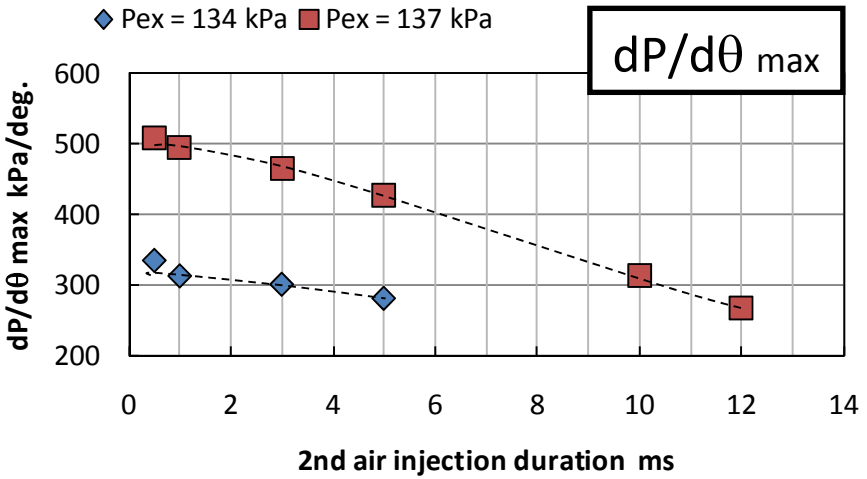
New valve strategy (**EGR-R**)

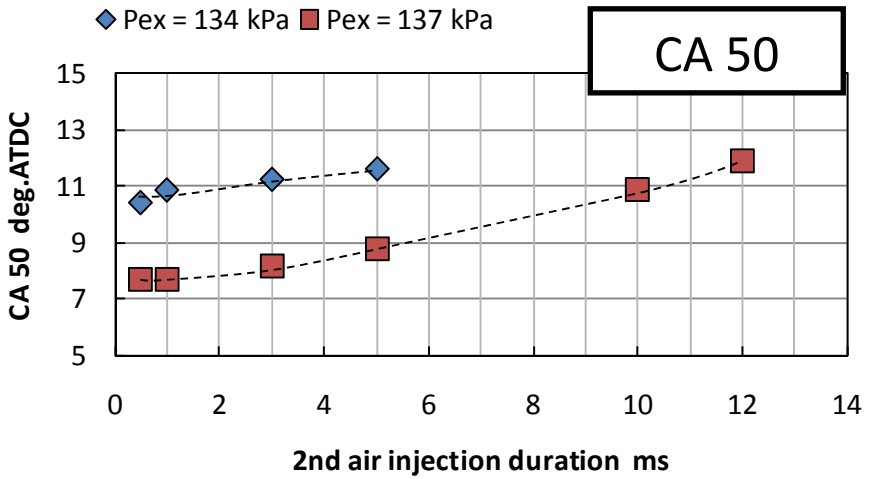


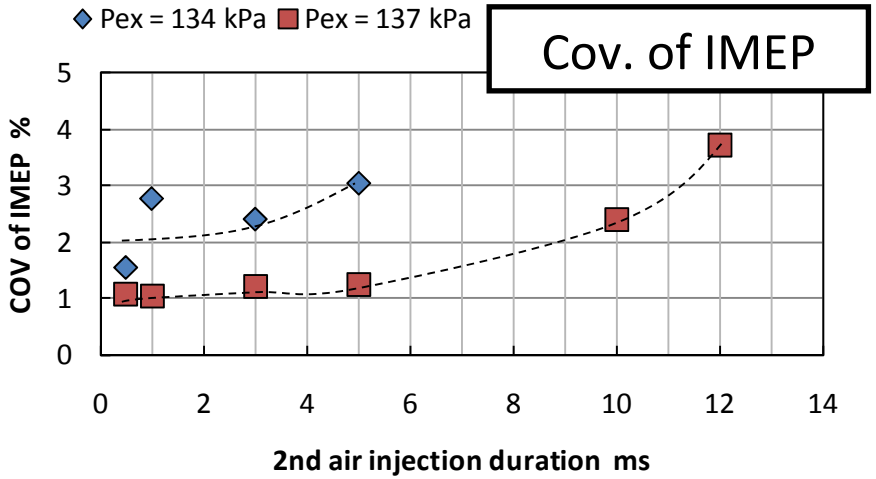
- EGR
- h

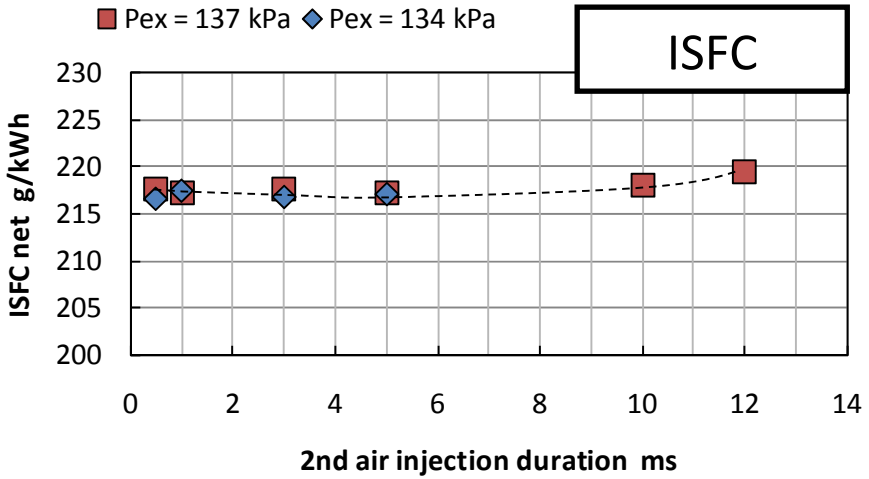
-

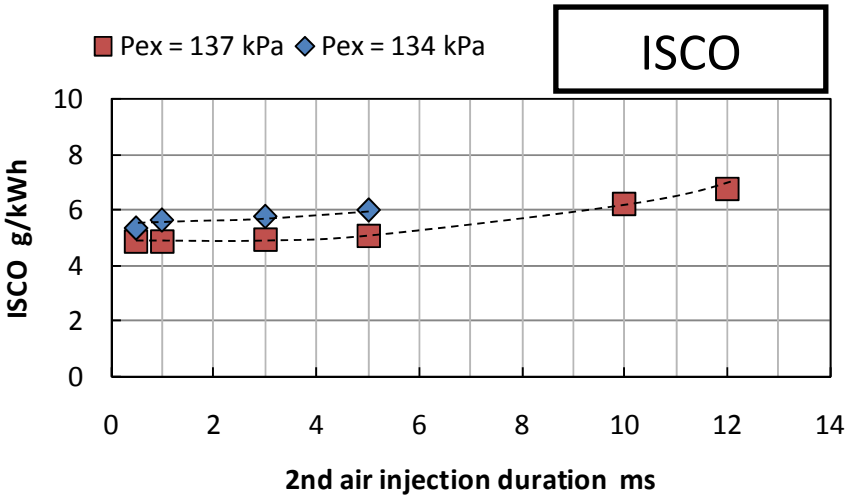
Gf : Const. (16 mg/cyl. ; IMEP 550 kPa)

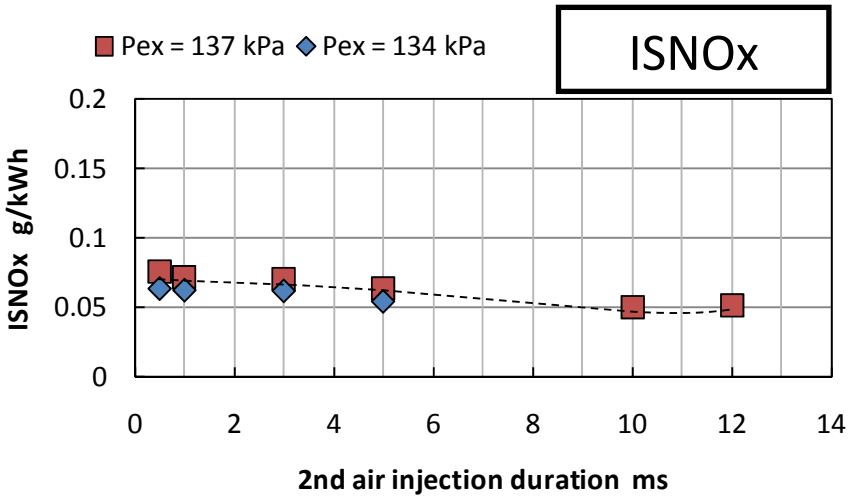


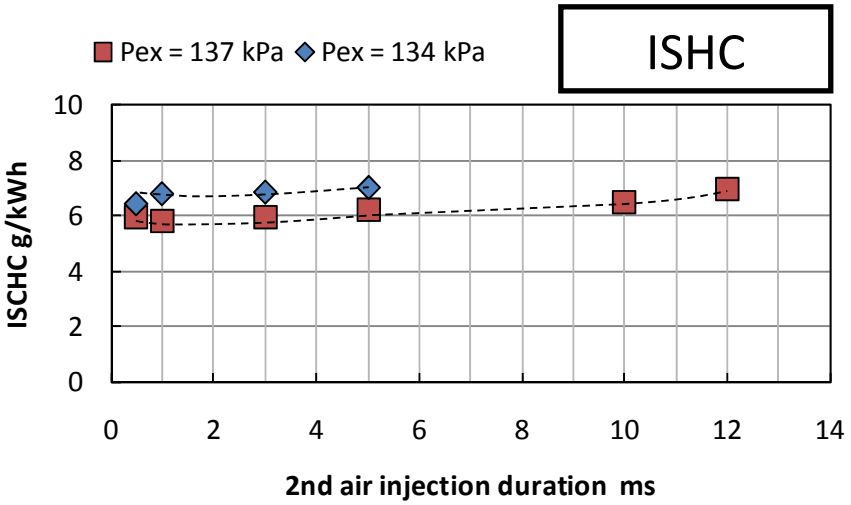


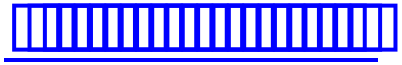





ISCO
Pex = 137 kPa
Pex = 134 kPa
ISCO g/kWh
0
2
4
6
8
10
0
2
4
6
8
10
12
14
2nd air injection duration ms

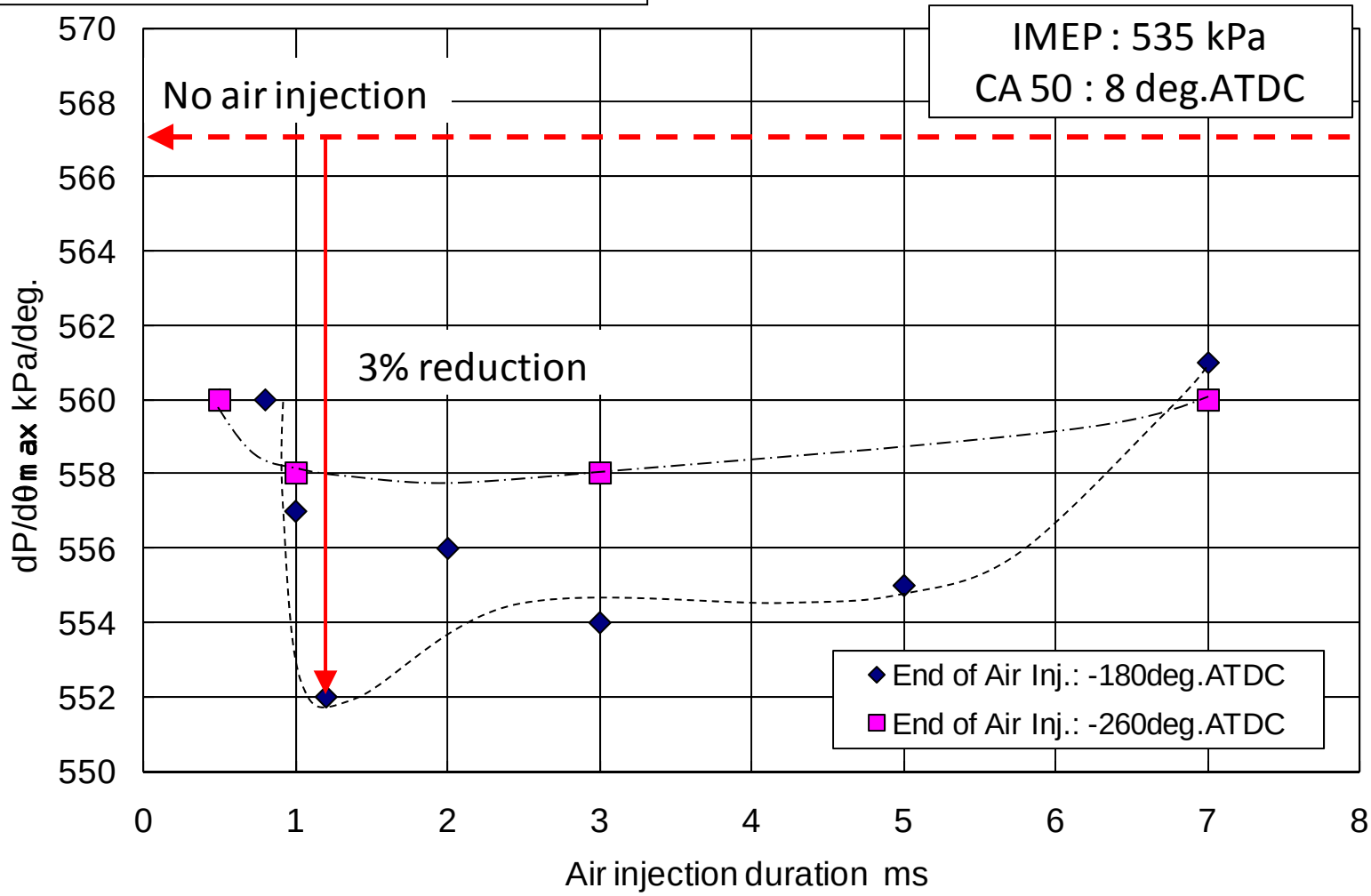

ISNOx
Pex = 137 kPa
Pex = 134 kPa
ISNOx g/kWh
0
0.05
0.1
0.15
0.2
0
2
4
6
8
10
12
14
2nd air injection duration ms


ISHC
Pex = 137 kPa
Pex = 134 kPa
ISCHC g/kWh
0
2
4
6
8
10
0
2
4
6
8
10
12
14
2nd air injection duration ms

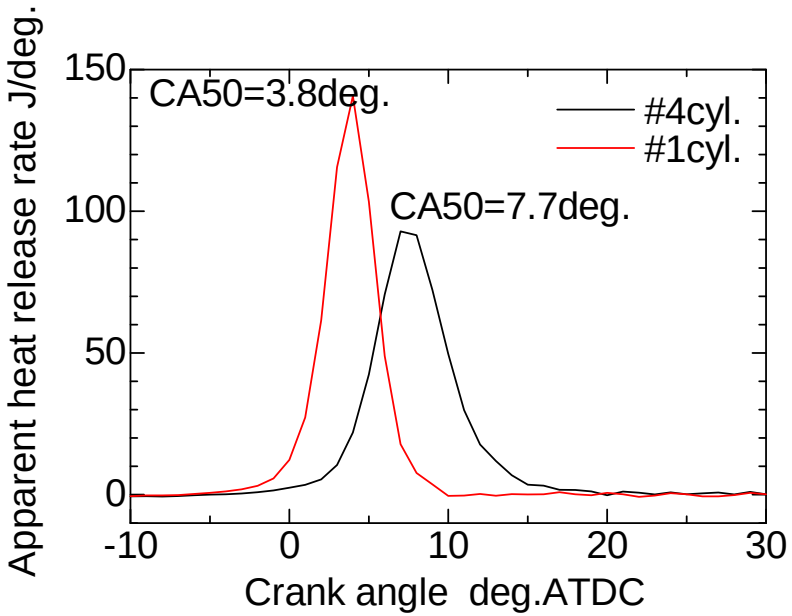


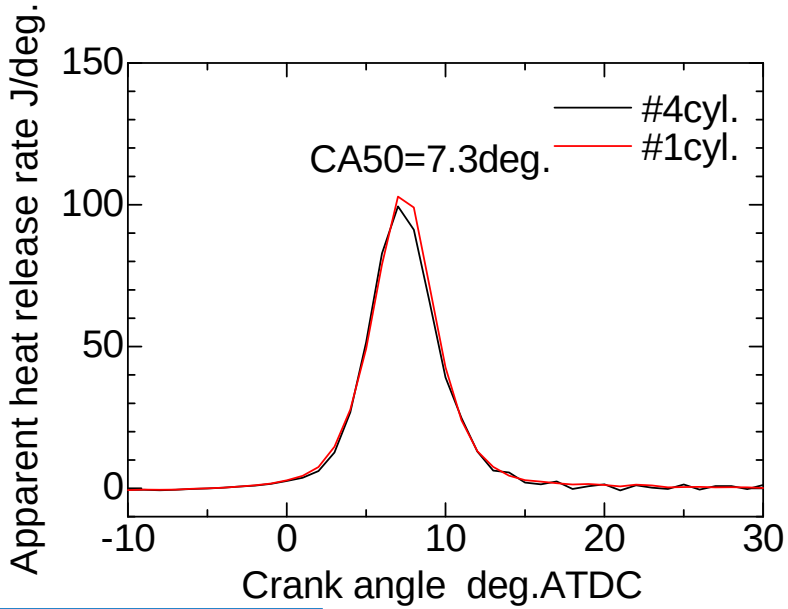
□□□□□□□□□□□□P/dθ

CA 50 = 8deg.ATDC □□

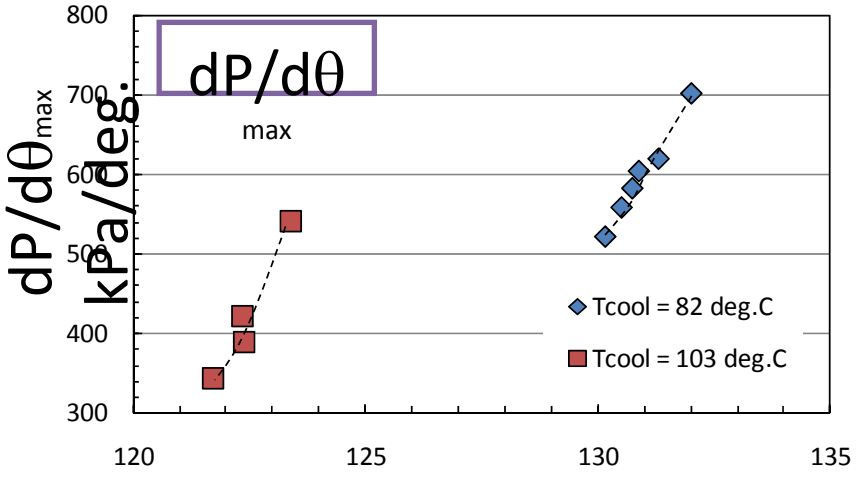


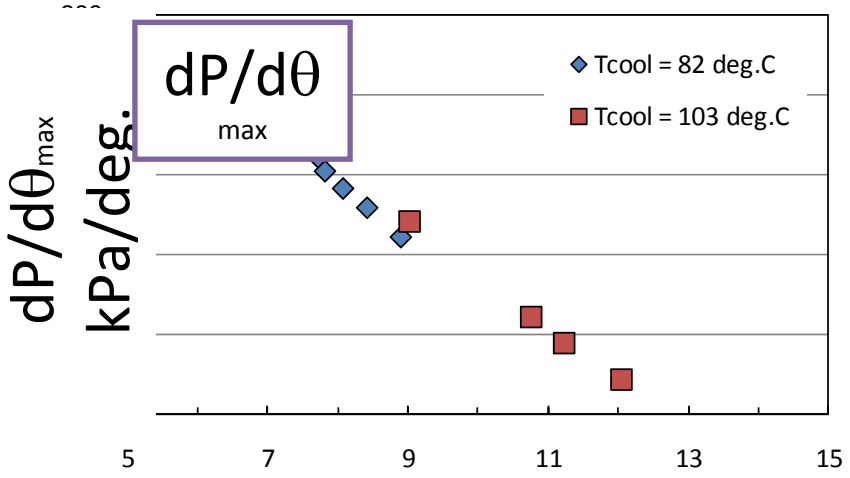
□□□□□□□□□□□□□□□dP/dθ□□□□□□□□□□□□□□□□

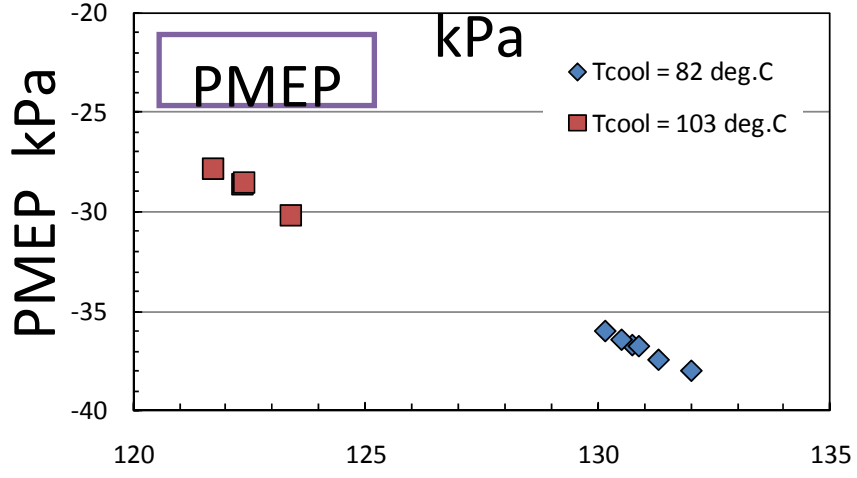

Apparent heat release rate J/deg.
150
100
50
0
-10
0
10
20
30
Crank angle deg.ATDC
CA50=3.8deg.
CA50=7.7deg.
#4cyl.
#1cyl.

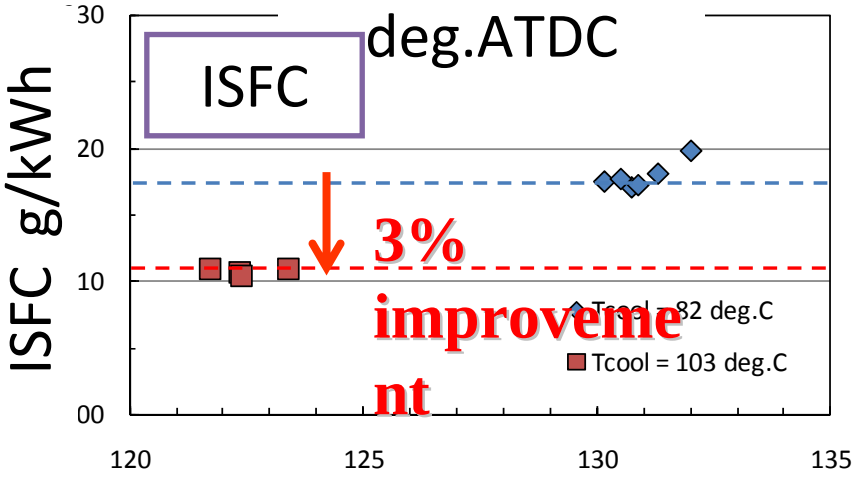

Apparent heat release rate J/deg.
150
100
50
0
-10
0
10
20
30
Crank angle deg.ATDC
CA50=7.3deg.
#4cyl.
#1cyl.

HCCI



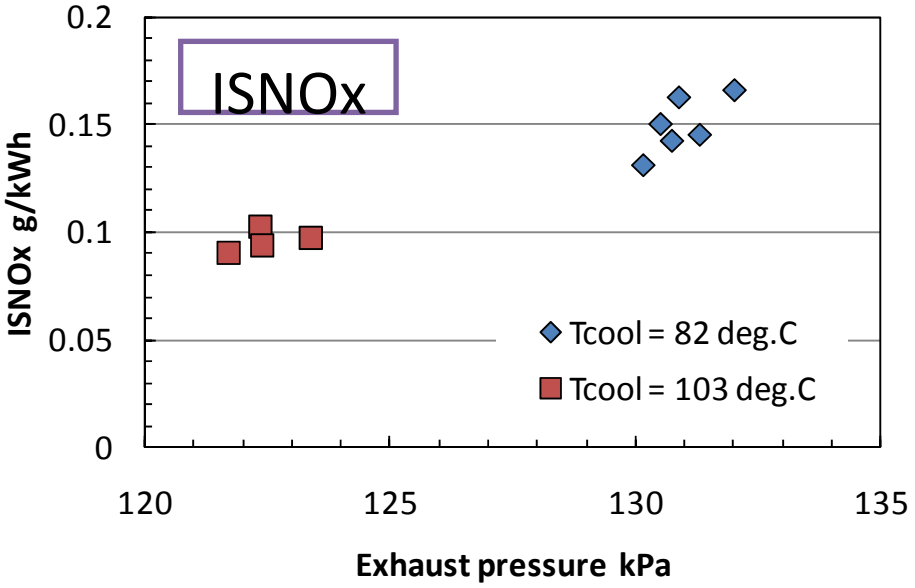


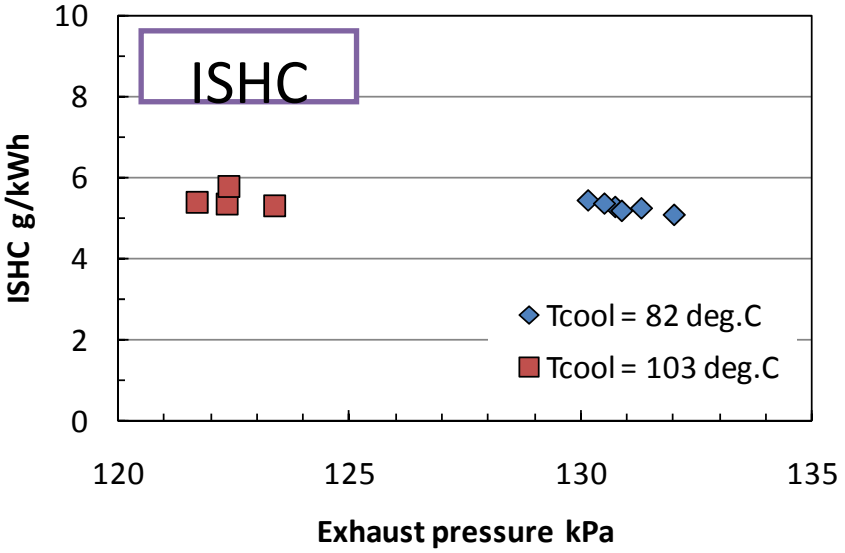




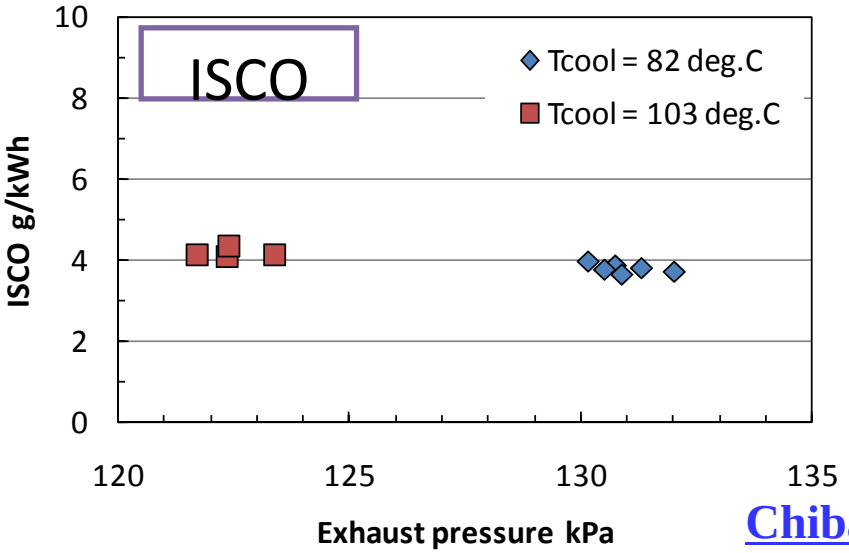
kPa dP/dθ

HCCI

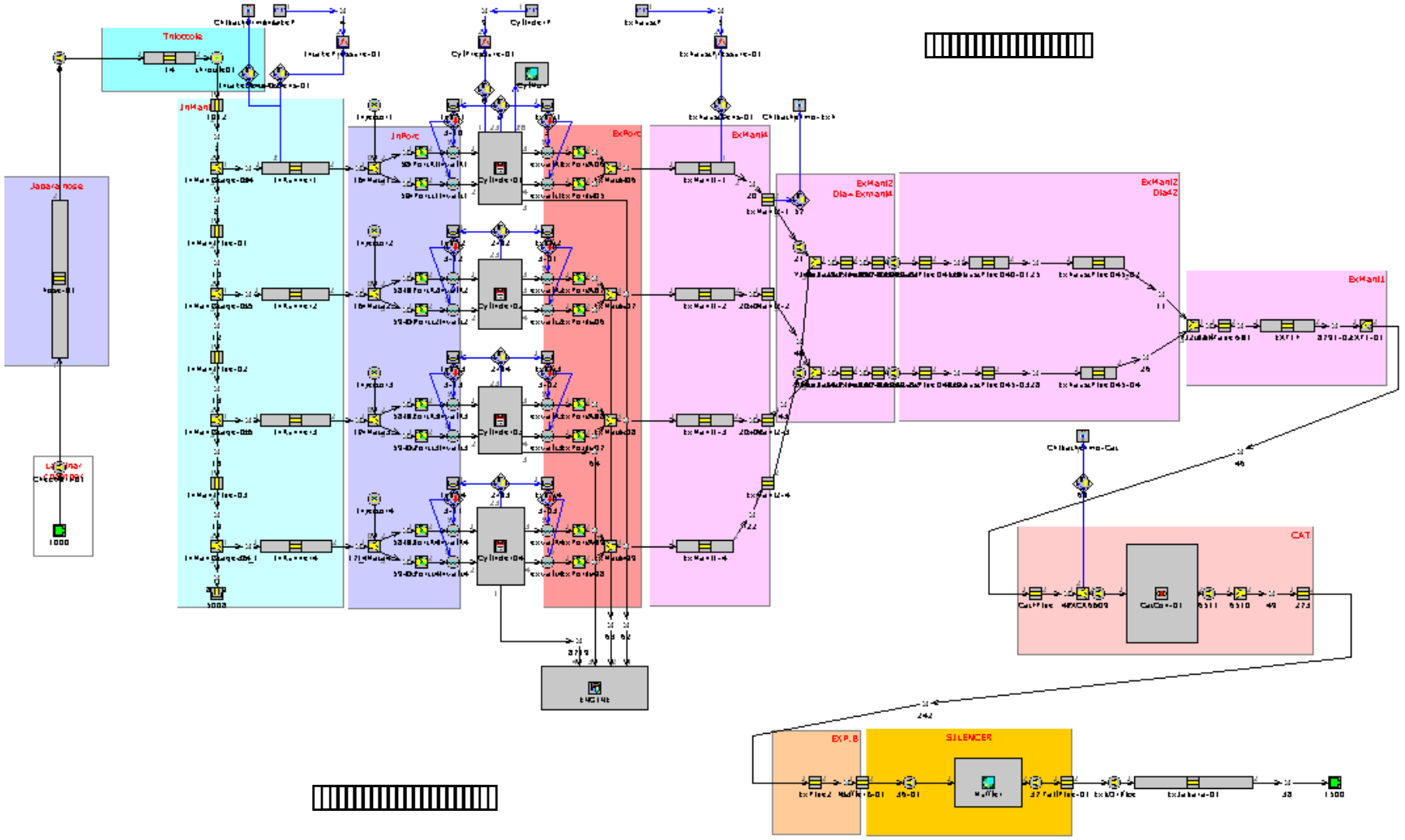

ISNOx
ISNOx g/kWh
0.2
0.15
0.1
0.05
0
120
125
130
135
Exhaust pressure kPa
Tcool = 82 deg.C
Tcool = 103 deg.C


ISHC
ISHC g/kWh
10
8
6
4
2
0
120
125
130
135
Exhaust pressure kPa
Tcool = 82 deg.C
Tcool = 103 deg.C

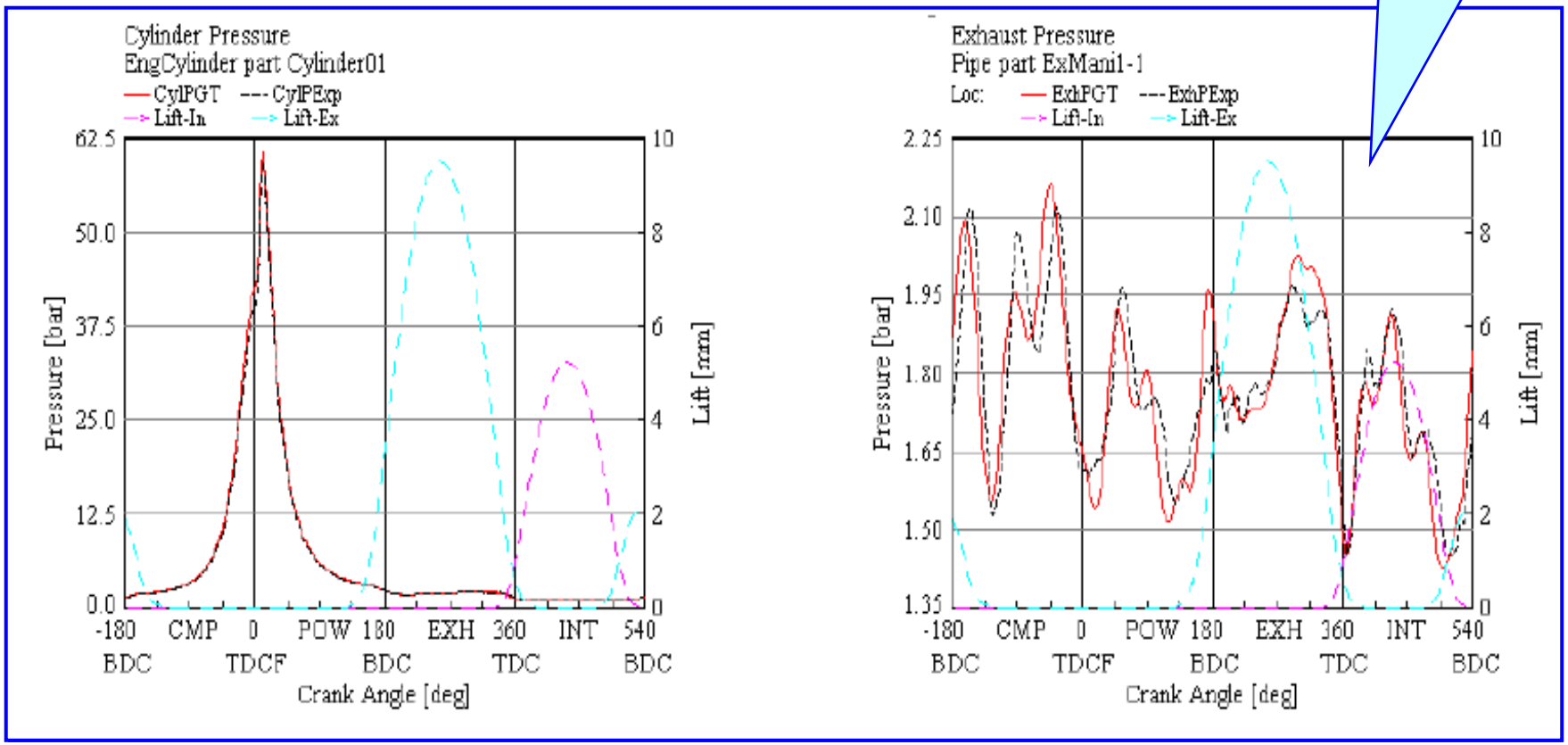
NO


ISCO
ISCO g/kWh
10
8
6
4
2
0
120
125
130
135
Exhaust pressure kPa
Tcool = 82 deg.C
Tcool = 103 deg.C

4 [illegible] 2 [illegible]

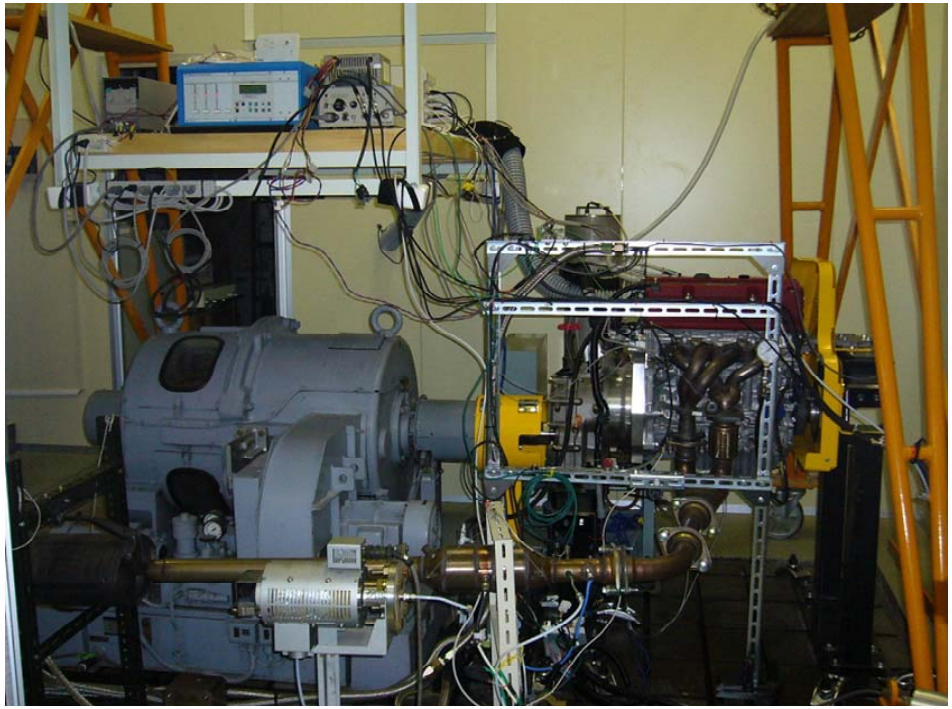

Trilocole
JnMan
JnPort
ExPort
ExMan4
ExMan2
Dia-ExMan4
ExMan2
Dia42
ExMan1
CAT
EXP.B
SILENCER

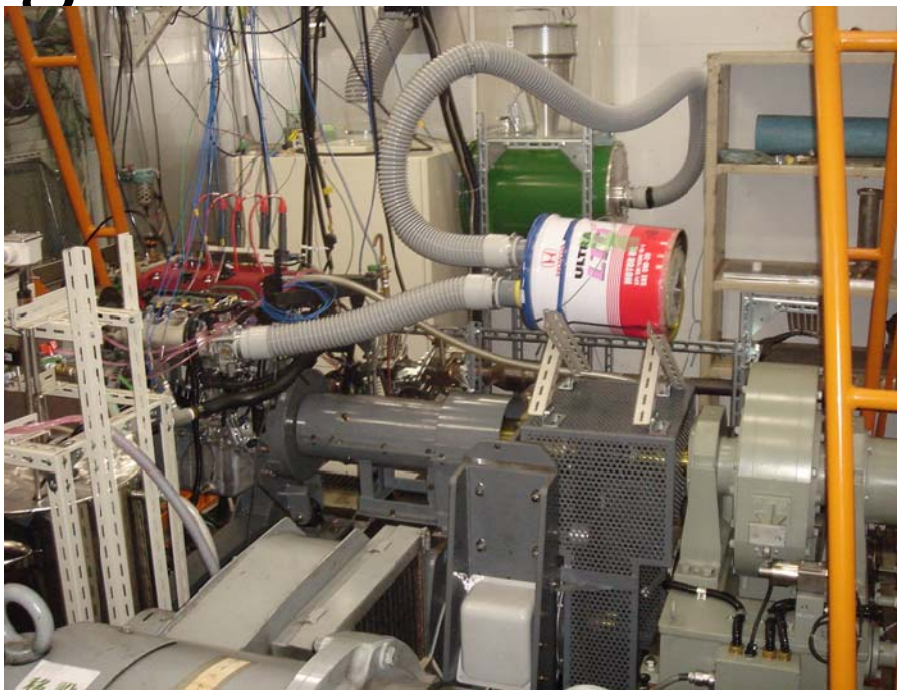
HERO


Cylinder Pressure
EngCylinder part Cylinder01
CylPGT
CylPExp
Lift-In
Lift-Ex
62.5
50.0
37.5
25.0
12.5
0.0
Pressure [bar]
10
8
6
4
2
0
Lift [mm]
-180 CMP 0 POW 180 EXH 360 INT 540
BDC TDCF BDC TDC BDC
Crank Angle [deg]
Exhaust Pressure
Pipe part ExMani1-1
Loc:
ExhPGT
ExhPExp
Lift-In
Lift-Ex
2.25
2.10
1.95
1.80
1.65
1.50
1.35
Pressure [bar]
10
8
6
4
2
0
Lift [mm]
-180 CMP 0 POW 180 EXH 360 INT 540
BDC TDCF BDC TDC BDC
Crank Angle [deg]

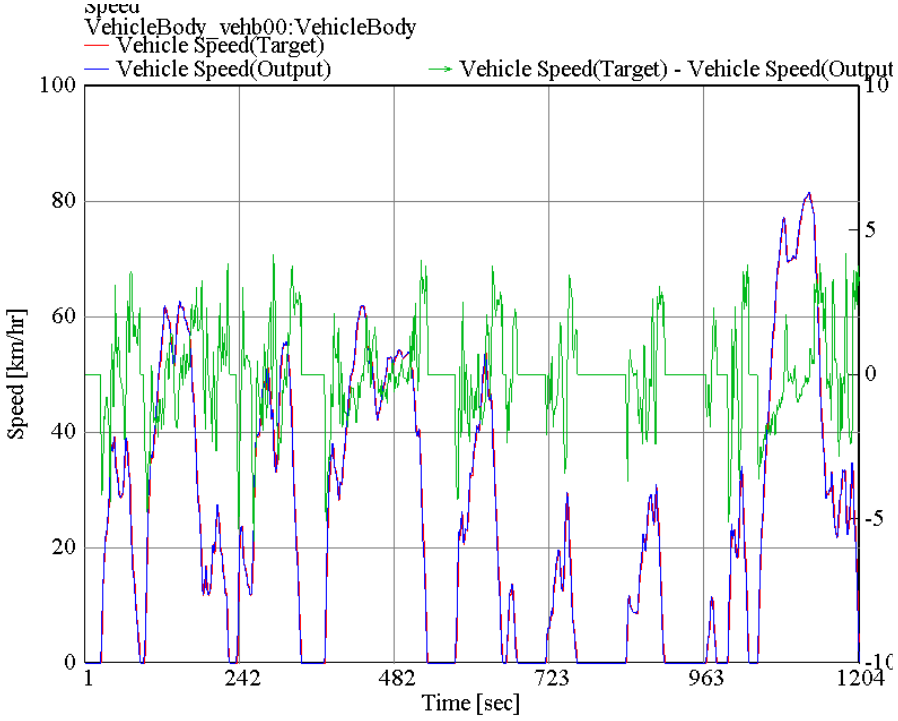
HERO

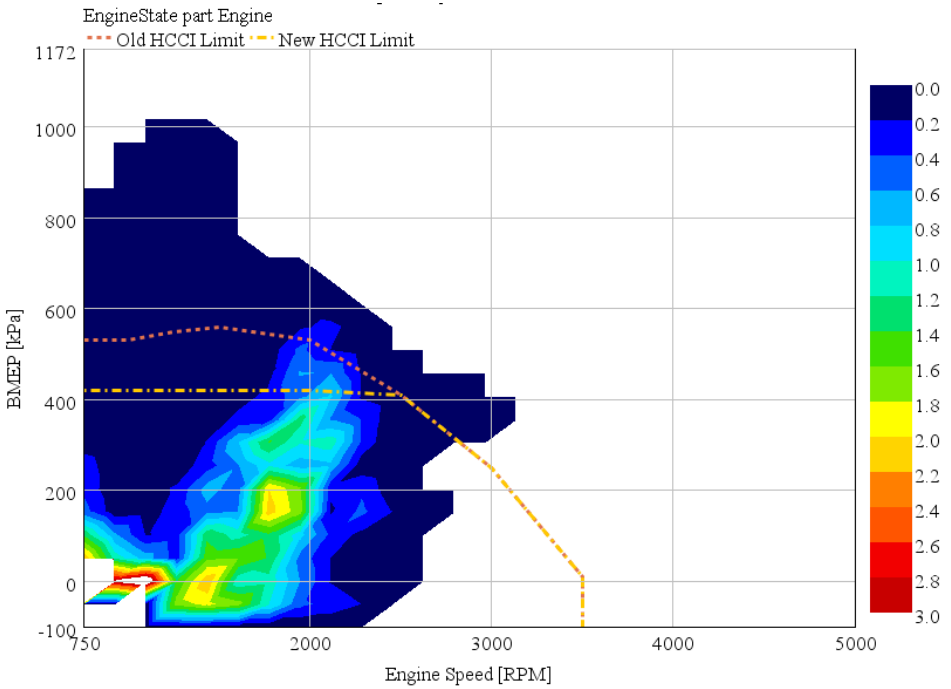
Test Engine

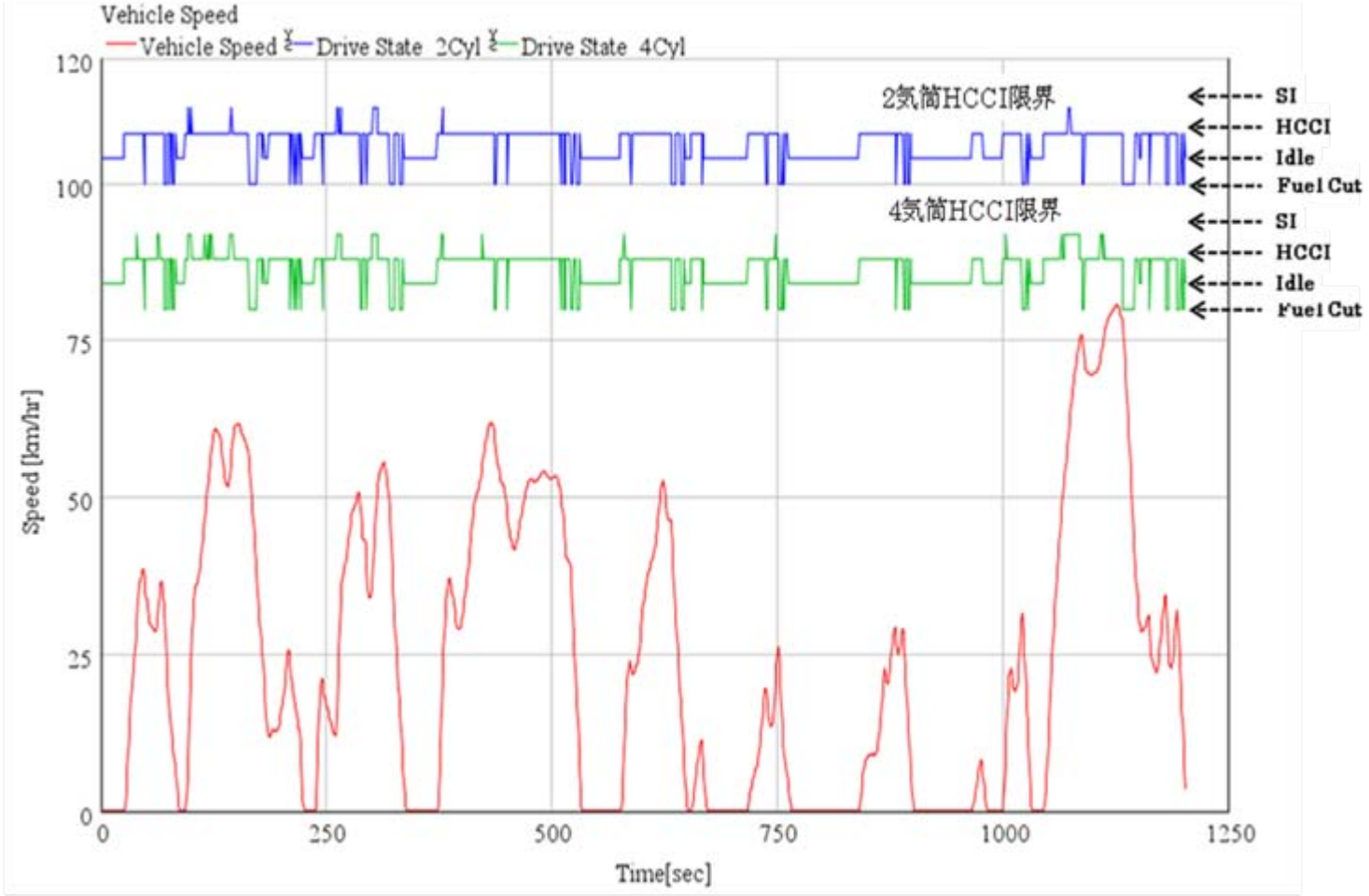




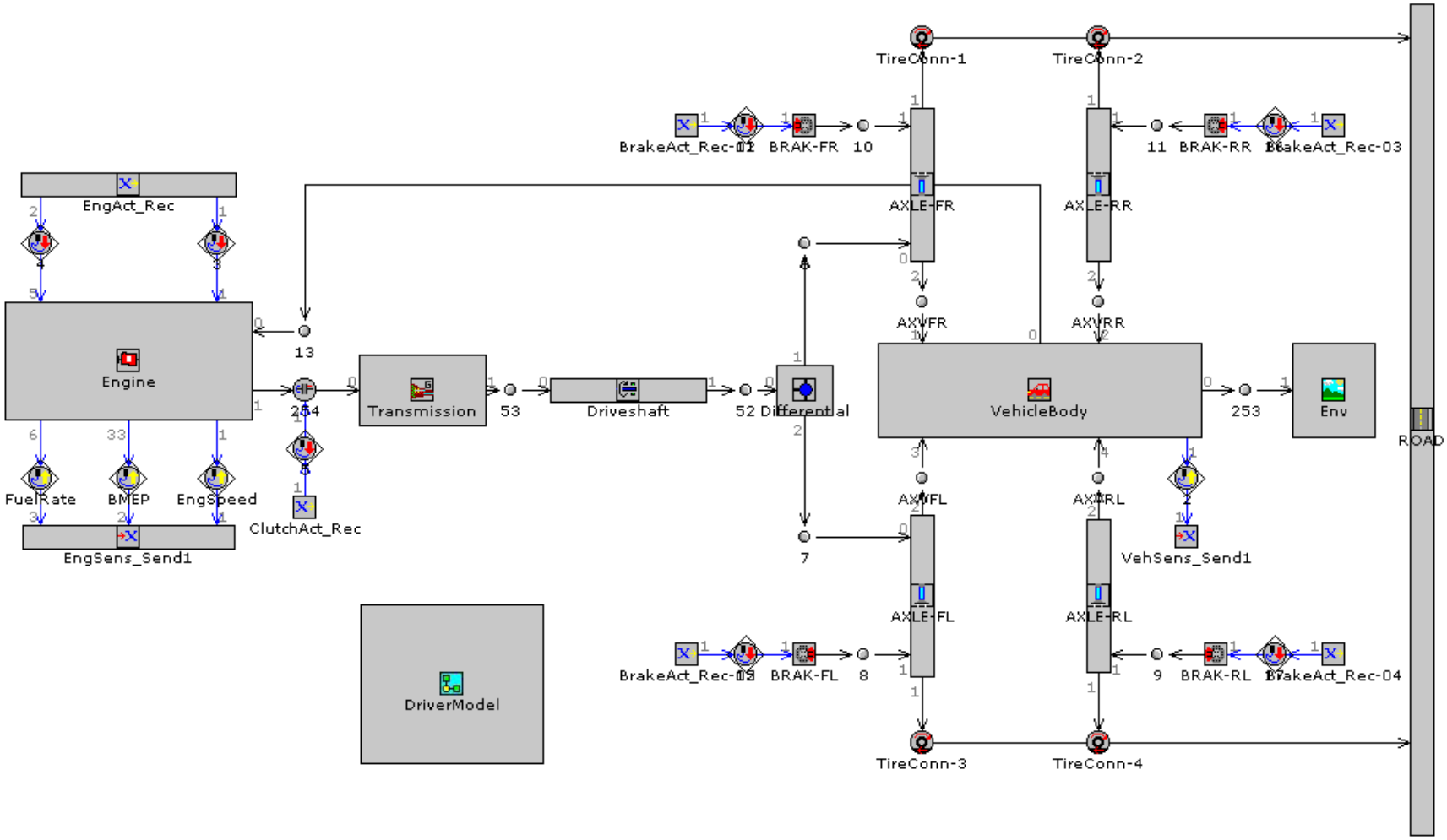
JC08 Simulation






Vehicle Speed
Vehicle Speed
Drive State 2Cyl
Drive State 4Cyl
2気筒HCCI限界
4気筒HCCI限界
SI
HCCI
Idle
Fuel Cut
SI
HCCI
Idle
Fuel Cut
120
100
75
50
25
0
0
250
500
750
1000
1250
Speed [km/hr]
Time[sec]

GT-Suite Dynamic Model



JC08 Driving Cycle