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Anatomy of the cooled EGR effects on soot emission reduction in boosted spark-ignited direct-injection engines

增压直喷汽油机中冷却EGR消烟机理解析

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Outline

1 Research Background and Objectives

2 Experimental and Simulative Methodology

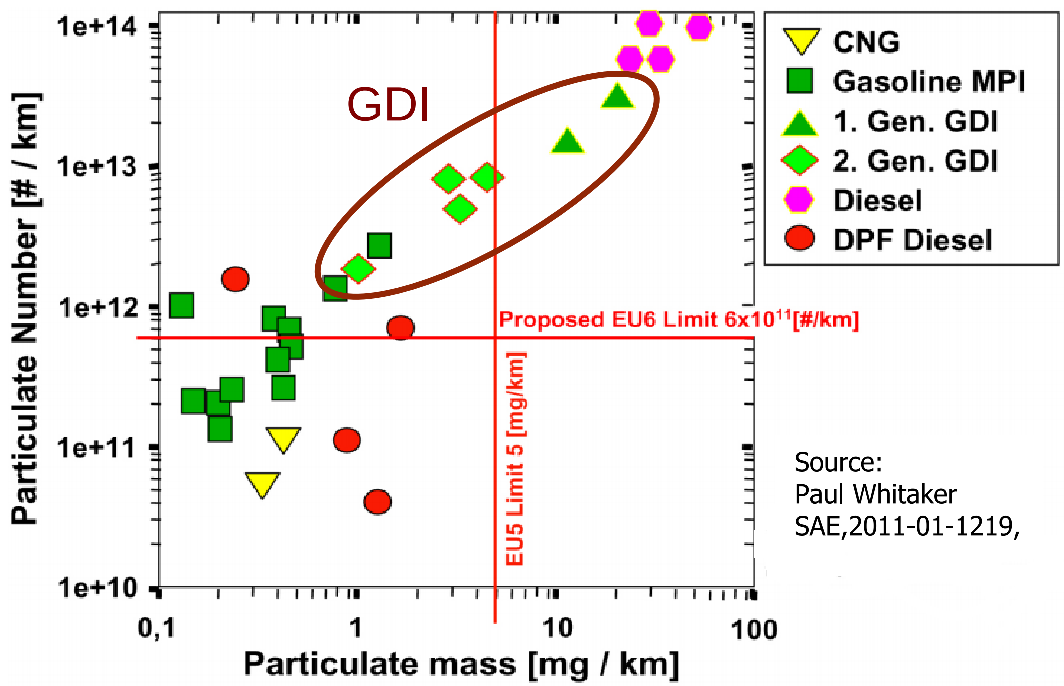
3 Results and Discussion

4 Summary and Conclusions

Outline

Background

- Downsizing, boosting and direct injection are effective in improvements of fuel economy (or reduce CO_2) of SI engines.
- High PM emissions are concerned before widespread application of downsized, boosted SIDI engines, especially for the upcoming EU6 regulations.
- EGR is effective in reduction of soot emissions (Hedge, M., et al., SAE 2011-01-0636).
- However, mechanism of soot emission reduction with EGR is not clear, and further investigation of EGR's potentials is necessary.



Source:
Paul Whitaker
SAE,2011-01-1219,

Objectives

- To explore the soot reduction potentials with EGR for a boosted SIDI engine at high load conditions.
- To clarify the mechanism of soot emission reduction with cooled EGR.

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Engine test bench

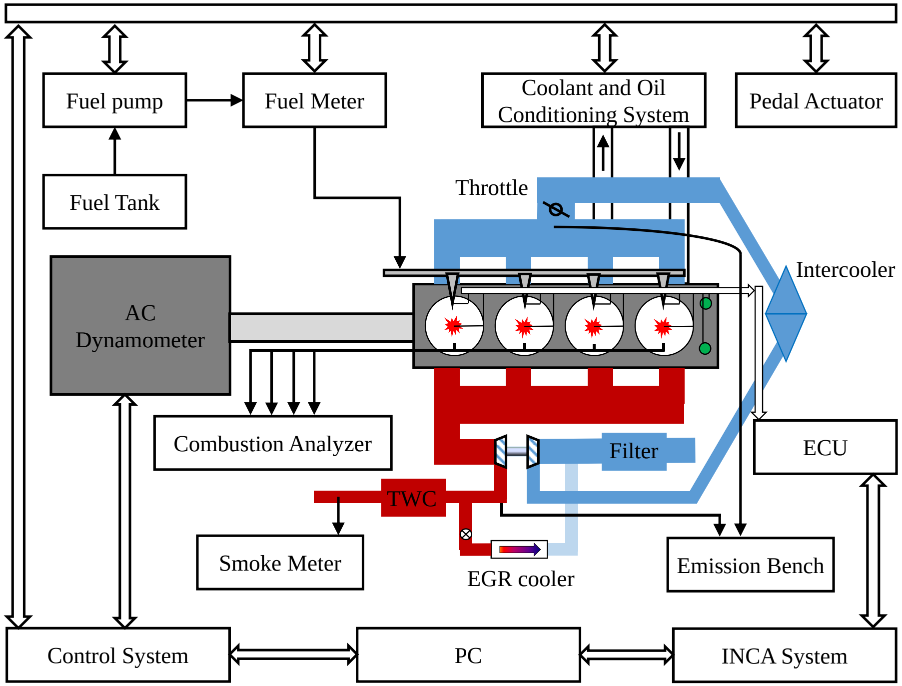


Figure 1. Schematic diagram of the engine test equipment

Table 1. SIDI engine specifications

Engine Type	4 cylinder, 4-stroke, direct injection
Bore × Stroke	86 × 86 mm
Displacement	1.988 L
Compression Ratio	10.9:1
Fuel RON	97
Injector Type	6-hole, side mounted
Injection Pressure	<150 bar
Boosting System	Twin-scroll turbocharger
Cylinder head	Pent-roof
Piston shape	Shallow-dish

Spray visualization

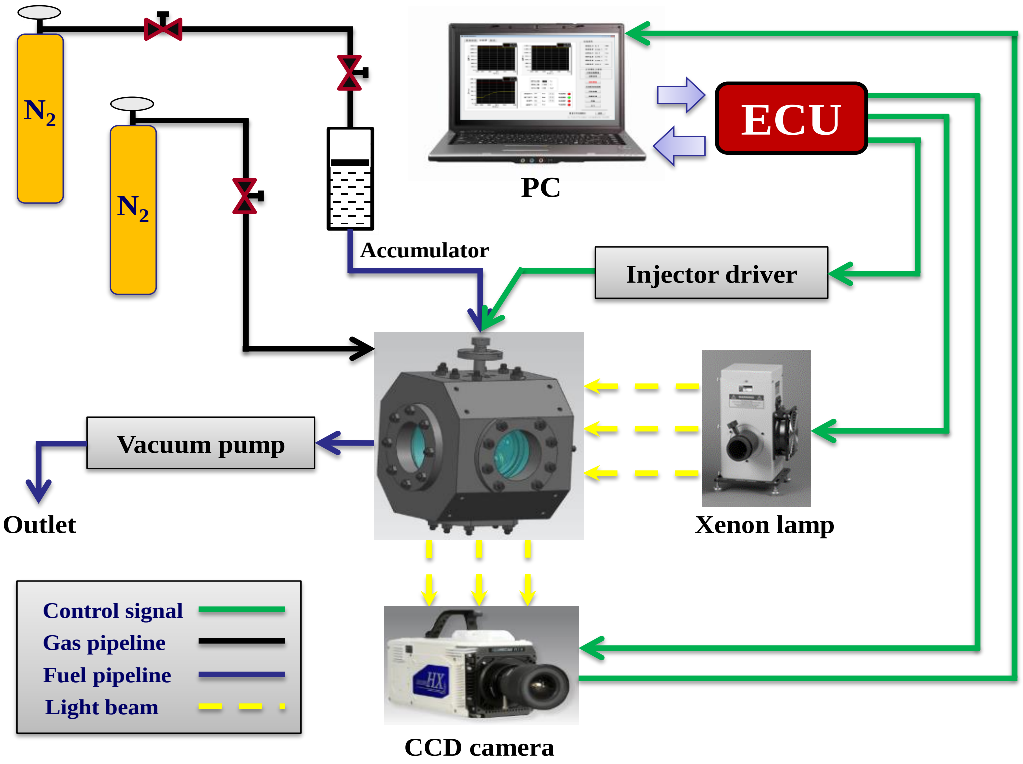
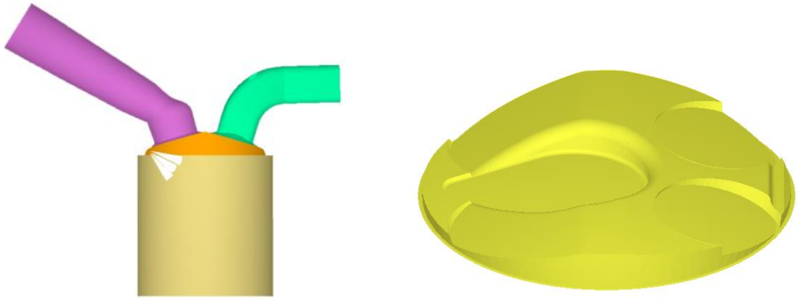


Figure 2. Schematic diagram of Mie-scatting imaging setup for the 97#gasoline spray under the non-evaporating condition.

Numerical models



(a) (b)

Figure 3. Geometric shape of the engine.

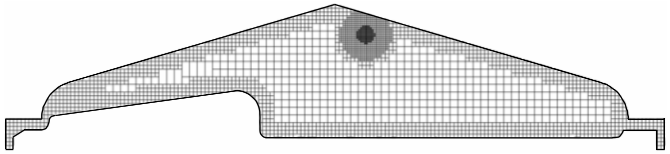


Figure 5. Computational mesh of the SIDI engine at spark timing (n = 1000 rpm, Torque = 210 Nm, spark timing = 5° CA aTDC, without EGR).

Table 2. Mesh details (base grid size: 4 mm)

Embedding position	Level	Grid size after embedding	Embedding period
Cylinder	2	1 mm	Full process
Spray	3	0.5 mm	Injection process
Spark electrode	5	0.125 mm	Sparking process
Spark	4	0.25 mm	Sparking process
Valve seat	3	0.5 mm	Full process
Chamber wall	3	0.5 mm	Full process

Numerical models

Term	Model type
Turbulence	RNG k-ε
Spray breakup	KH-RT
Injection drop distribution	Rosin-Rammler
Drop evaporation	Frossling
Drop collision	O'Rourke
Spray/wall interaction	Wall film
Combustion	G-Equation
Wall Heat flux	O'Rourke&Amsden
Soot emission	Hiroyasu&NSC

Grid independence study

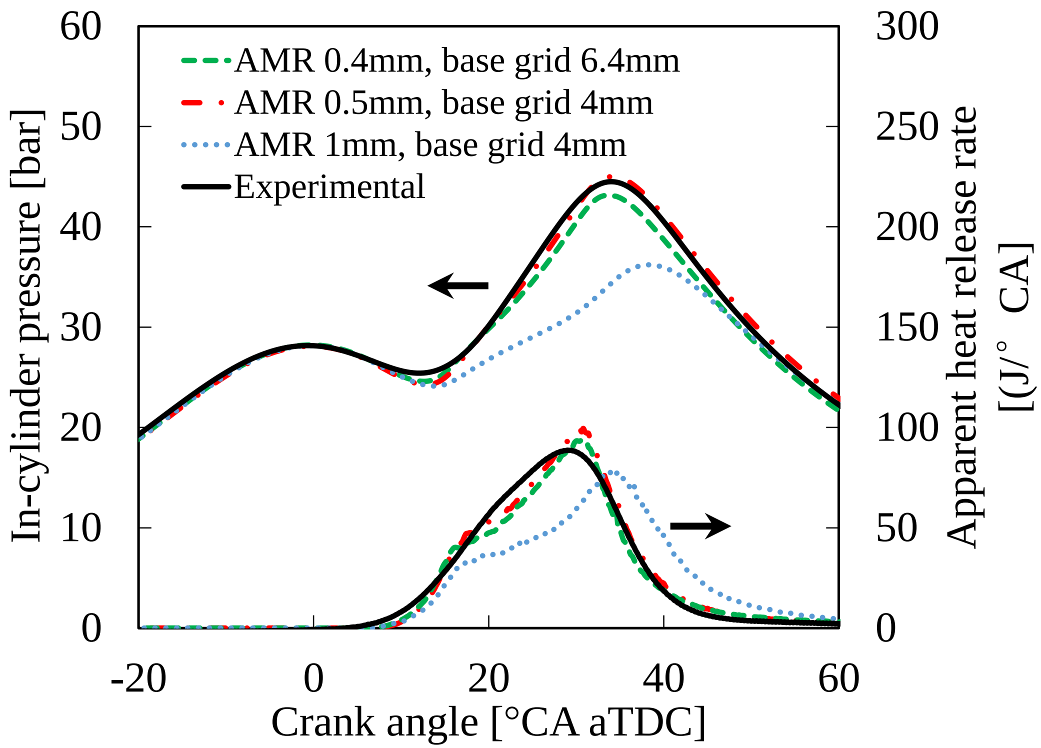


Figure 4. The grid independence study with different AMR settings (n = 1000 rpm, Torque = 210 Nm, spark timing = 5° CA aTDC, without EGR).

Model validation

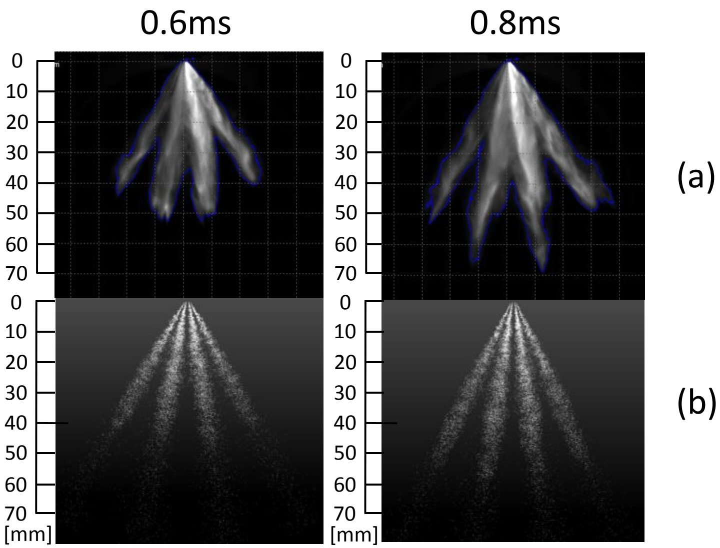


Figure 6. The temporal developments of the gasoline spray for (a) Mie-scattering images; (b) CFD simulation results (P_{inj} = 120 bar, P_{vessel} =1 bar, T_{vessel} = 298 K).

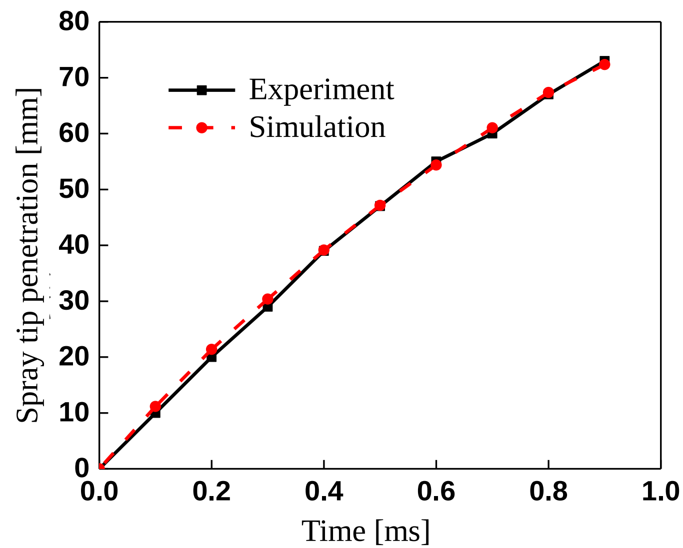
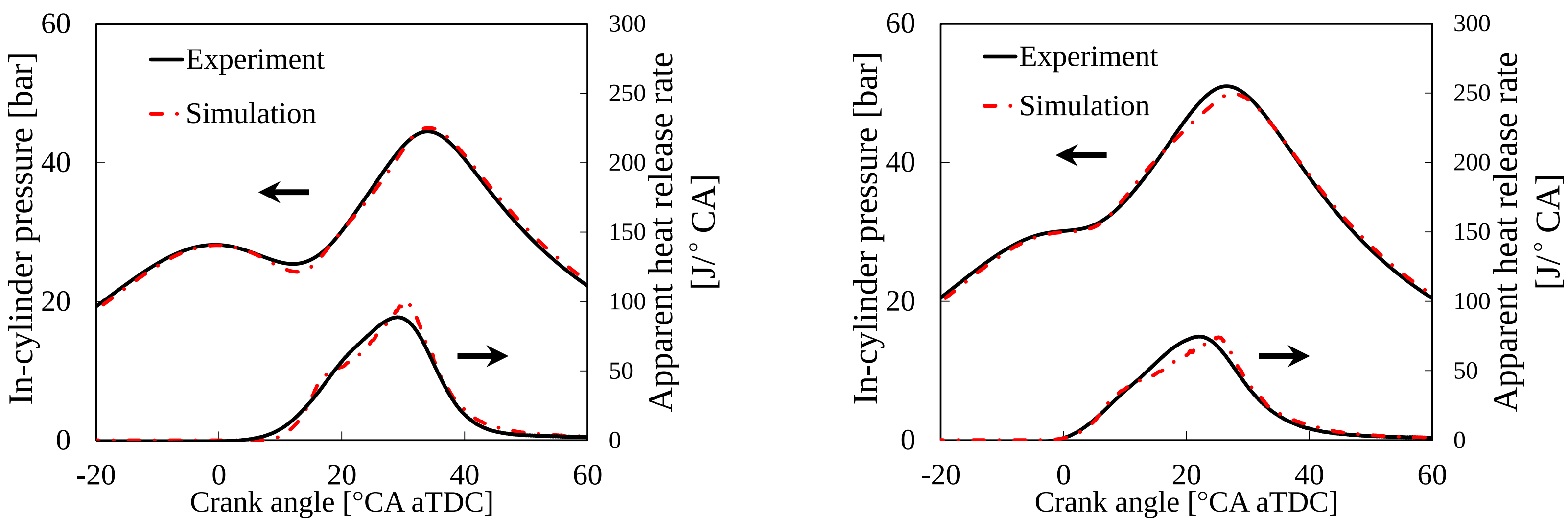


Figure 7. Comparison of the measured and predicted gasoline spray tip penetration. (P_{inj} =120 bar, P_{vessel} = 1 bar, T_{vessel} = 298 K).

Model validation



(a) 0% EGR (b) 16.7% EGR

Figure 8. Model validation for in-cylinder pressure and apparent heat release rate (Left: n = 1000 rpm, Torque = 210 Nm, spark timing = 5° CA aTDC; Right: n = 1000 rpm, Torque = 210 Nm, spark timing = -6° CA aTDC).

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1 **Performance of cooled EGR on soot emission reduction**

2 **Effects of cooled EGR on soot oxidation processes**

3 **Effects of cooled EGR on soot formation processes**

Smoke intensity

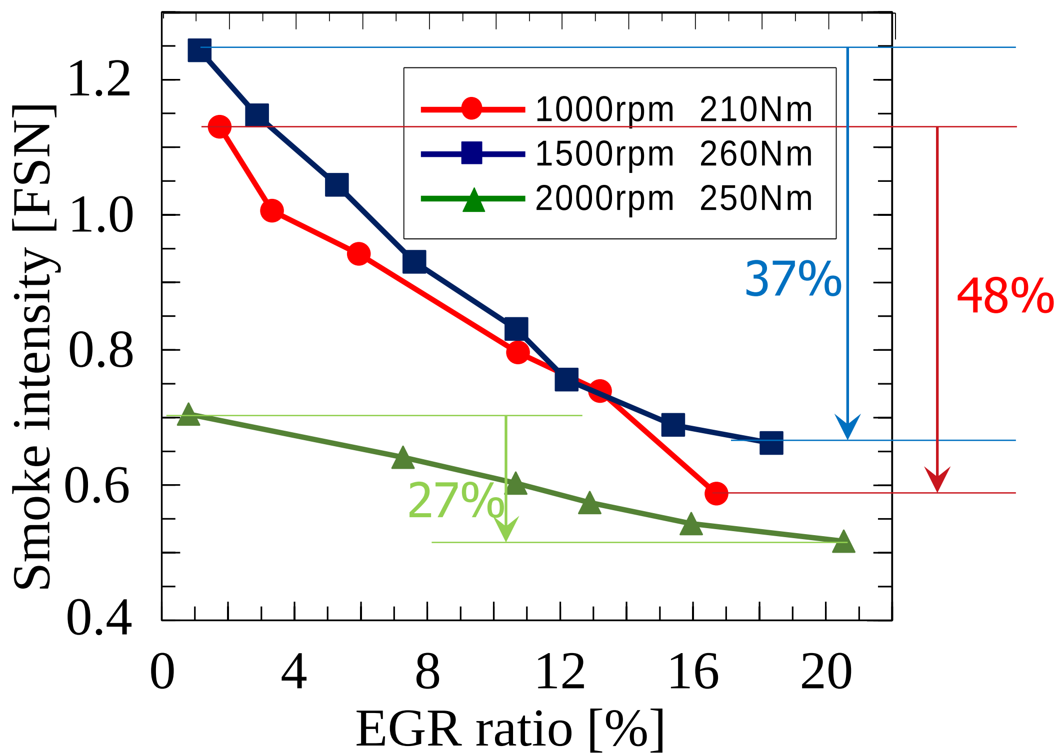


Figure 9. The effect of cooled EGR on smoke intensity.

Influencing factors of soot emission reduction

- ☐ **Dilution effect of EGR gas on soot concentration**

- ☐ **Influencing factors in soot oxidation process**
  - Oxygen concentration
  - Temperature

- ☐ **Influencing factors in soot formation process**
  - Fuel composition
  - In-cylinder pressure
  - Local mixture concentration
  - Temperature

Dilution effect of recycled exhaust gas

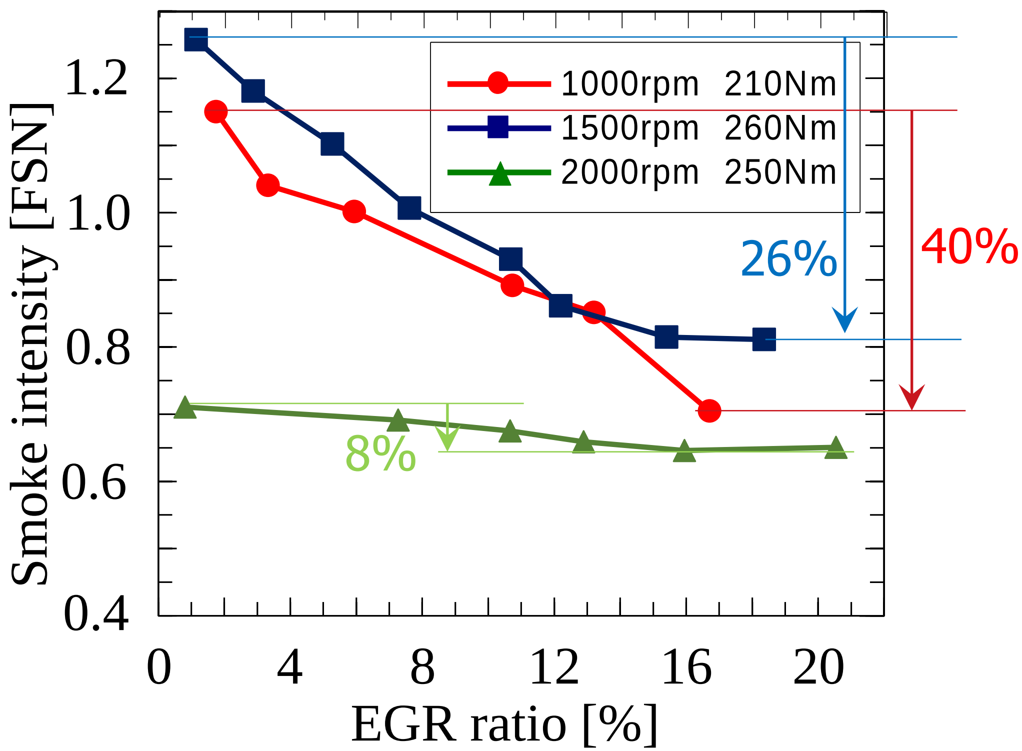


Figure 10. The dilution effect of cooled EGR on the soot emissions reduction.

Less fuel injected and Higher intake pressure

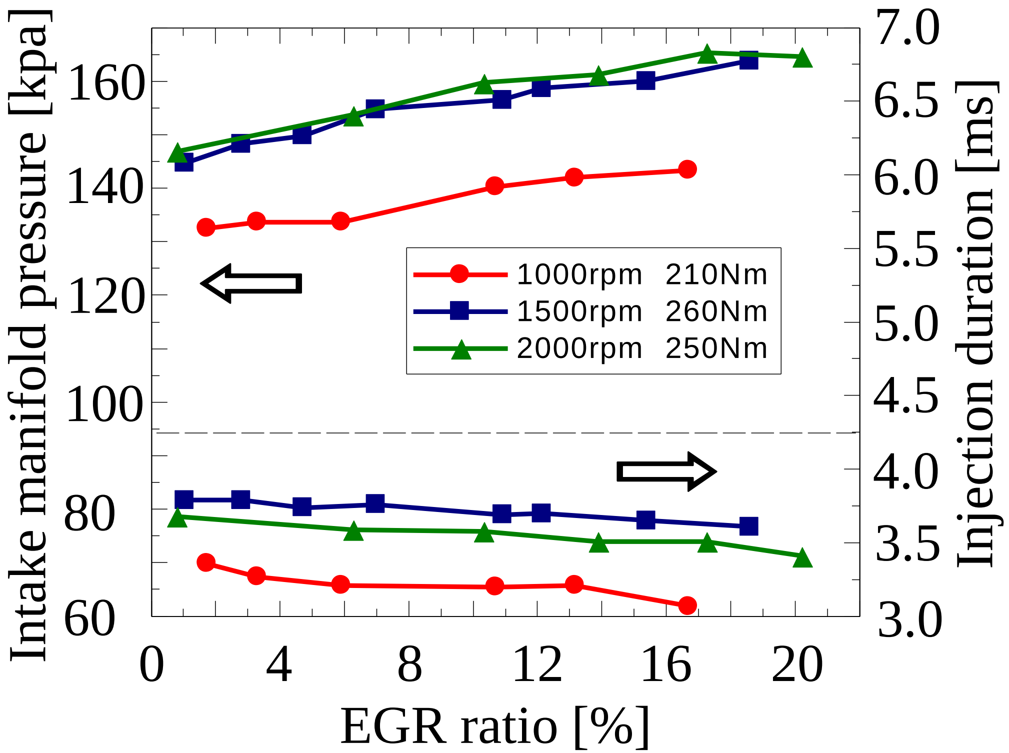
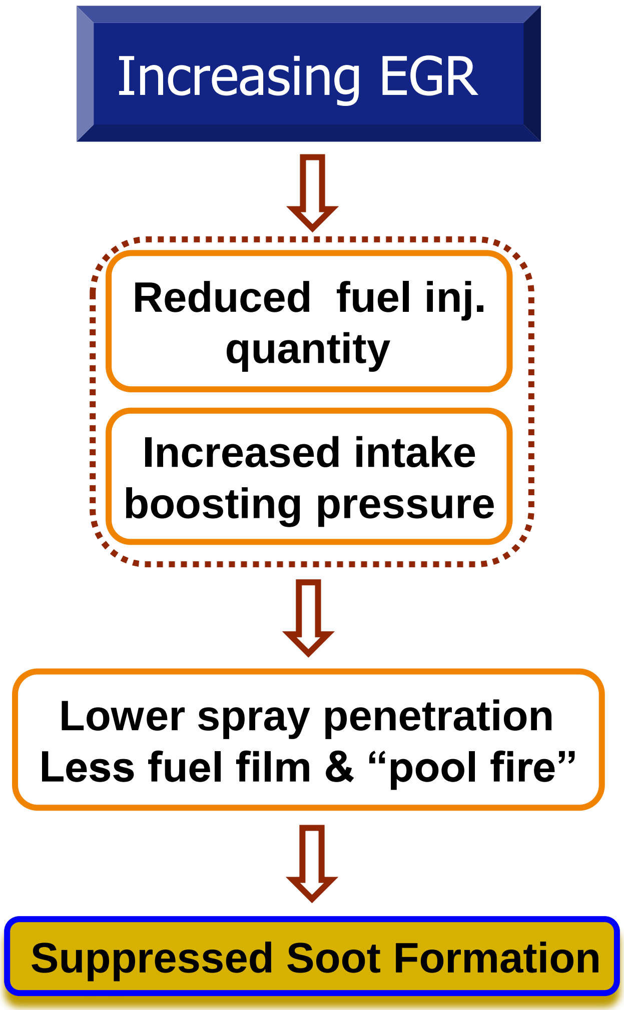


Figure 11. The effect of cooled EGR on Intake manifold pressure and duration of injection.



Results and Discussion

1 Performance of cooled EGR on soot emission reduction

2 Effects of cooled EGR on soot oxidation processes

3 Effects of cooled EGR on soot formation processes

Influencing factors of soot emission reduction

- ☐ **Dilution effect of EGR gas on soot concentration**
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  - Temperature
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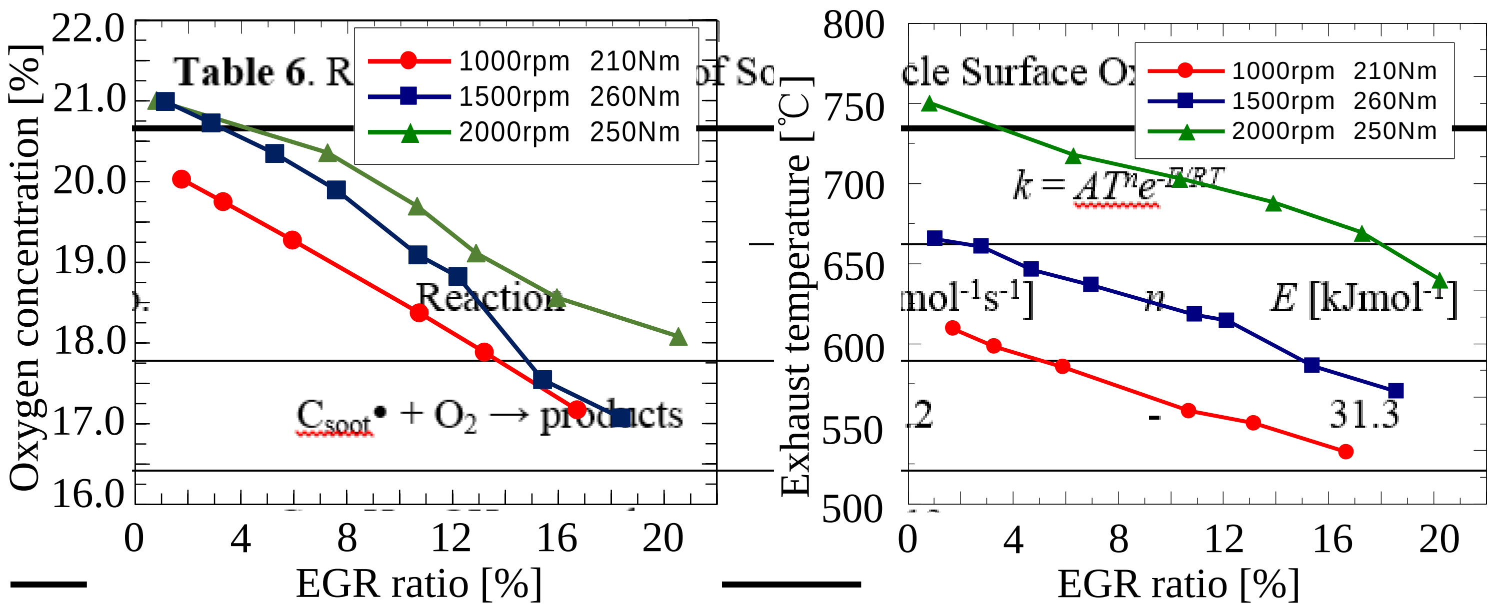
  - Temperature

Factors associated to soot oxidation processes



- EGR plays adverse effects on soot oxidation.
- Reduction in the engine-out soot emissions is attributed to suppressed soot formation by EGR.

Results and Discussion

1. Performance of cooled EGR on soot emission reduction
2. Effects of cooled EGR on soot oxidation processes
3. Effects of cooled EGR on soot formation processes

Influencing factors of soot emission reduction

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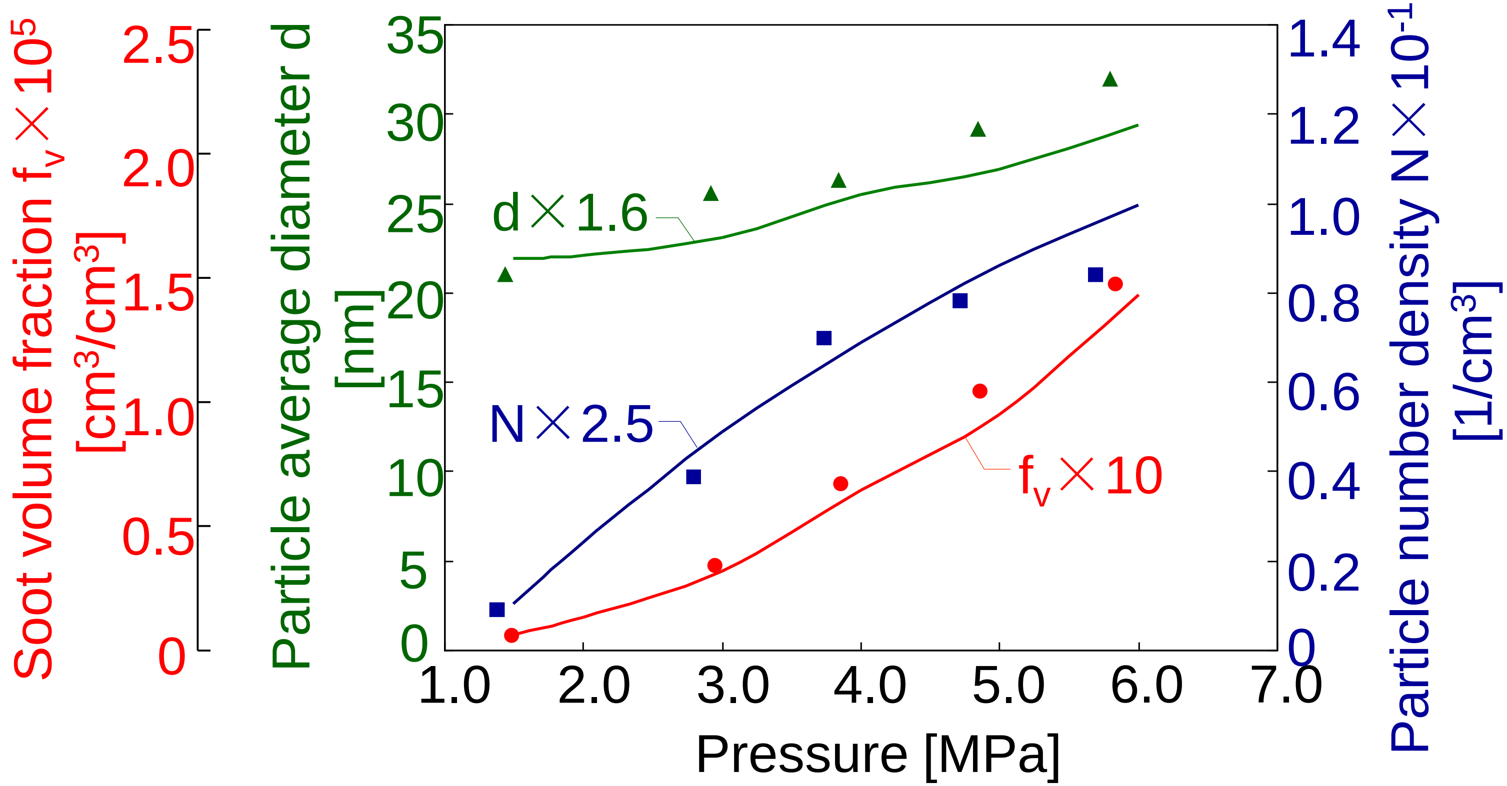
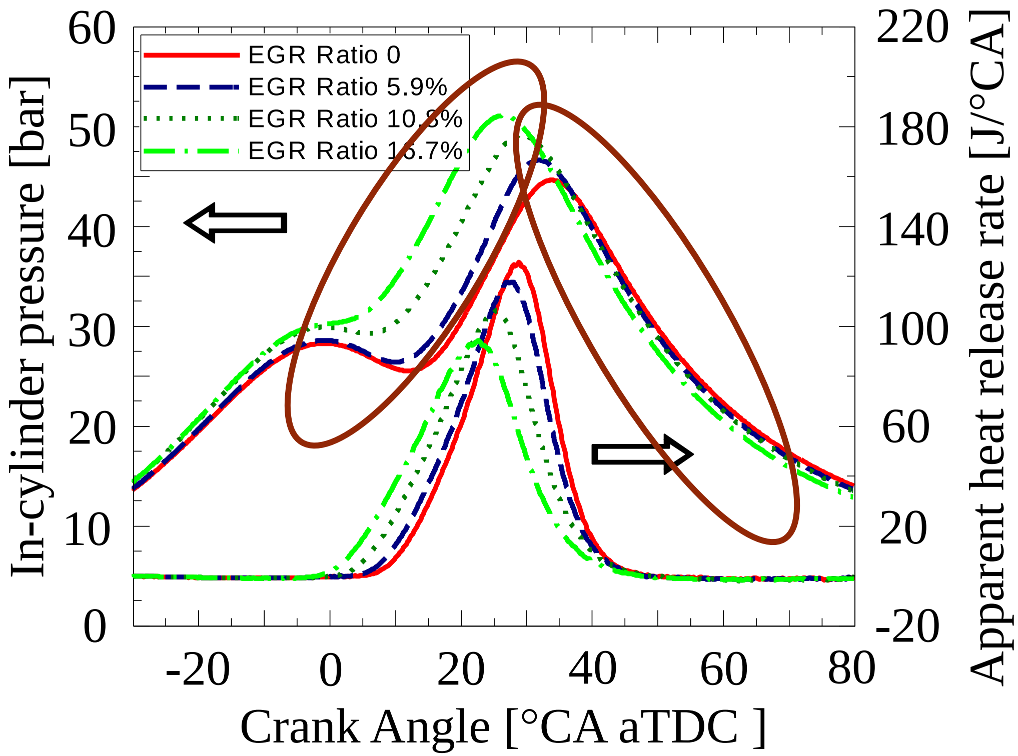
Pressure Dependence of Soot Formation



The experimental data (symbols) taken 1.5 ms after the appearance of the first particles; The calculated data (solid lines) at the time of number density peak. (ϕ=5, n-heptane/air mixture, Ar=99%, T=1820 K)

Experimental data source: H. Kellerer, et al., Combust Flame 120: 188-199 (2000). T. Li, et al., SAE 2011-01-1847.

Effect of in-cylinder pressure



- If soot generated before the pressure peak, EGR would play adverse effects in soot reduction.
- If after the pressure peak, EGR's effect would be little.

Evolution of fuel film mass

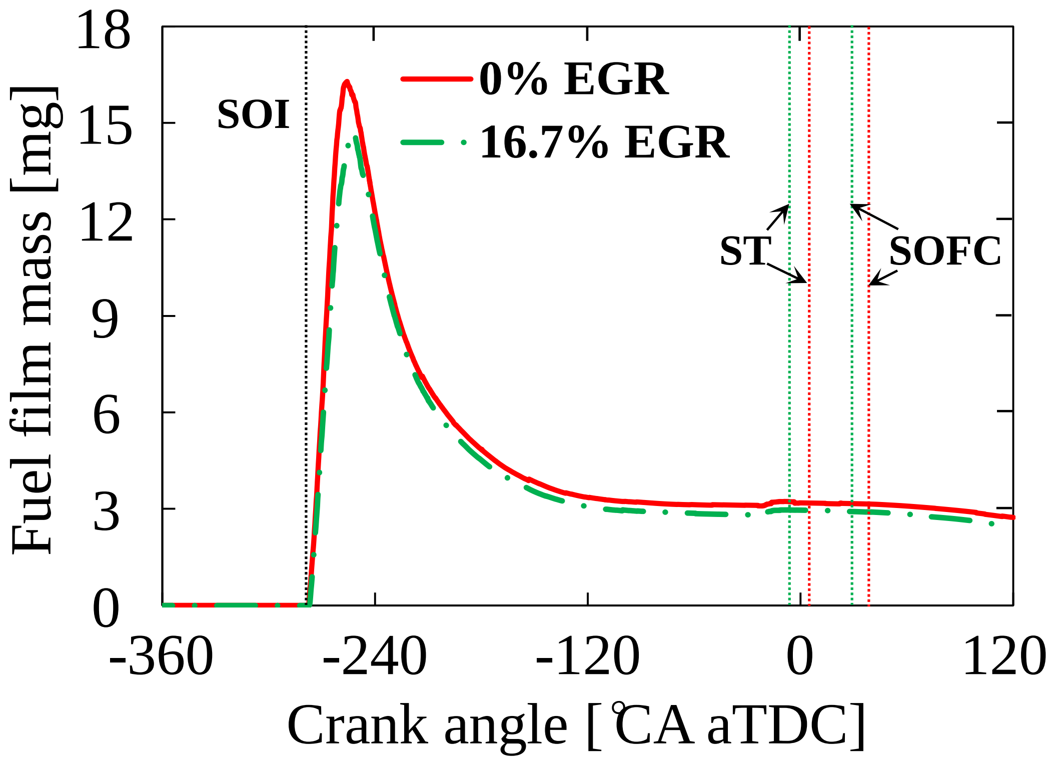
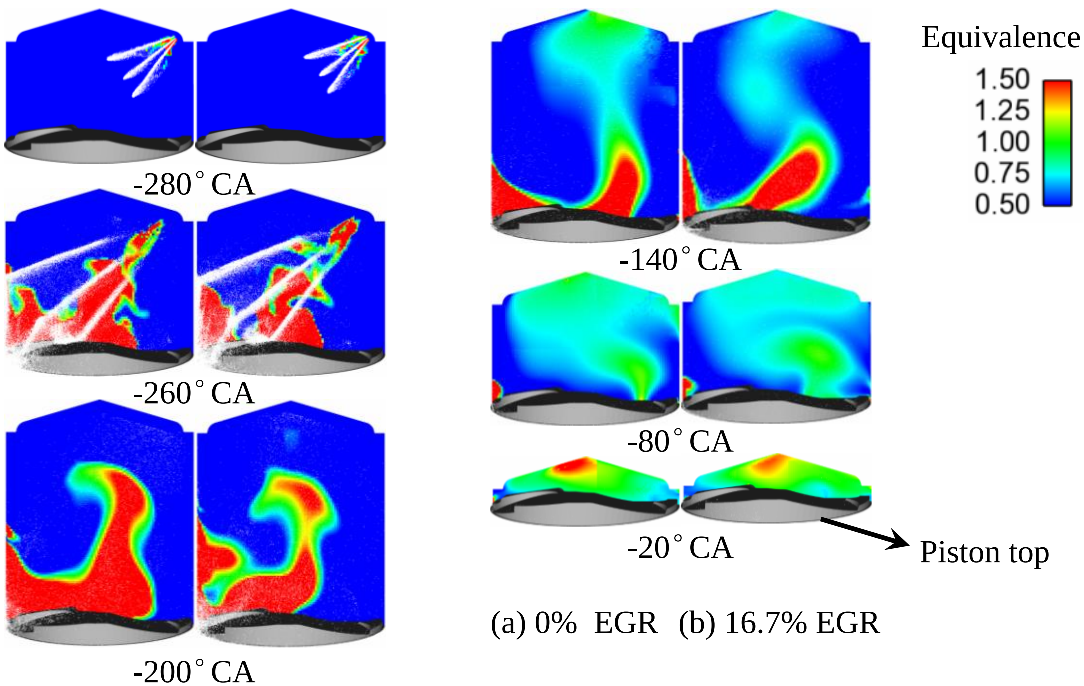


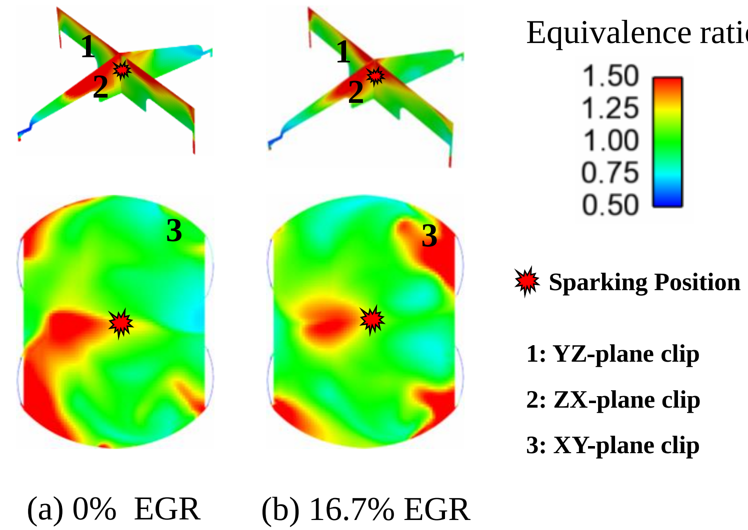
Fig. 14. The effect of cooled EGR on evolution of fuel film mass (SOI: start of injection, ST: spark timing, SOFC: start of liquid film combustion).

no EGR case: n = 1000 rpm, Torque = 210 Nm, spark timing = 5° CA aTDC
16.7% EGR case: n = 1000 rpm, Torque = 210 Nm, spark timing= -6° CA aTDC

Equivalence ratio distribution comparison



During intake and compression strokes

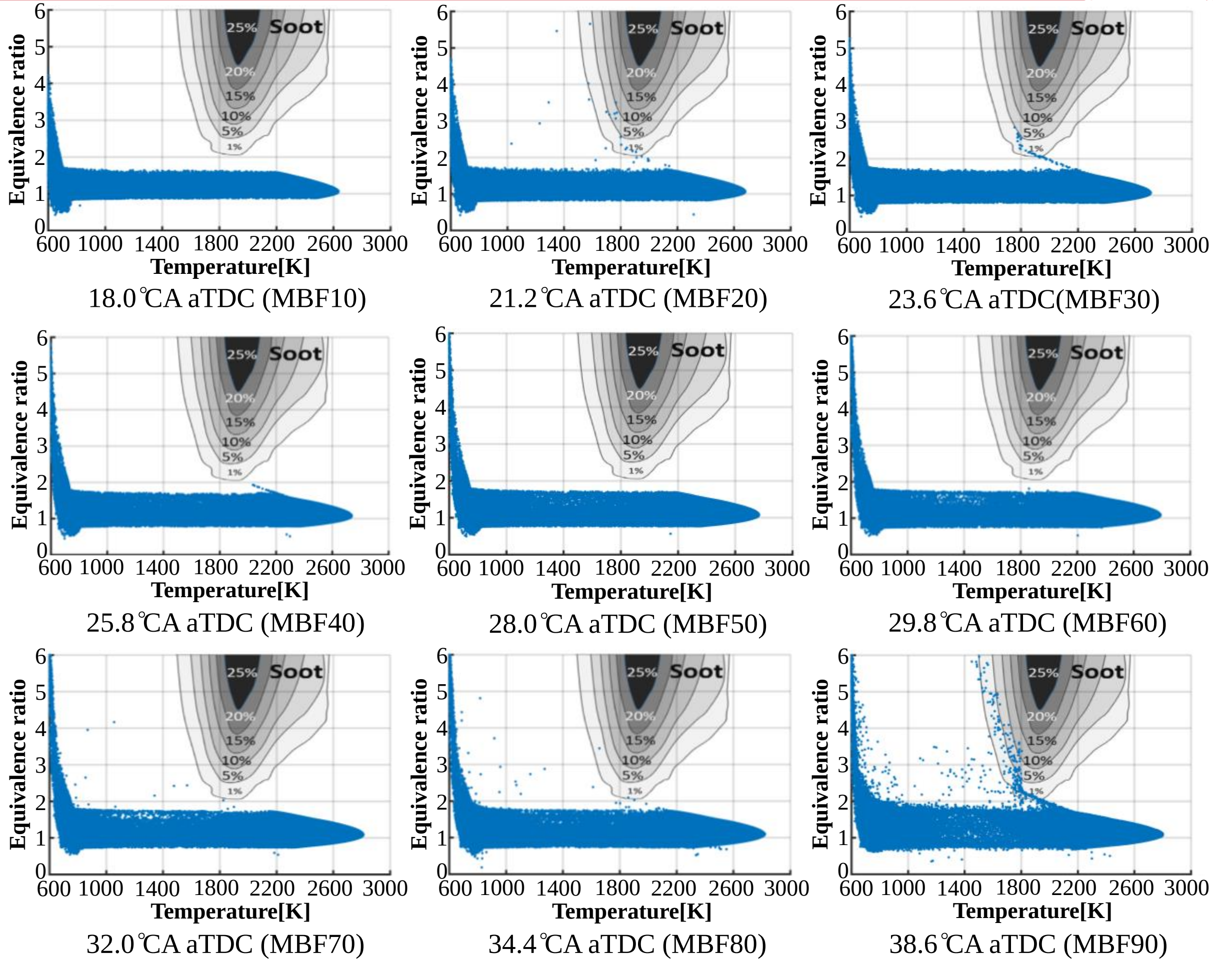


At the spark timings

no EGR case: n = 1000 rpm, Torque = 210 Nm, spark timing = 5° CA aTDC

16.7% EGR case: n = 1000 rpm, Torque = 210 Nm, spark timing= -6° CA aTDC

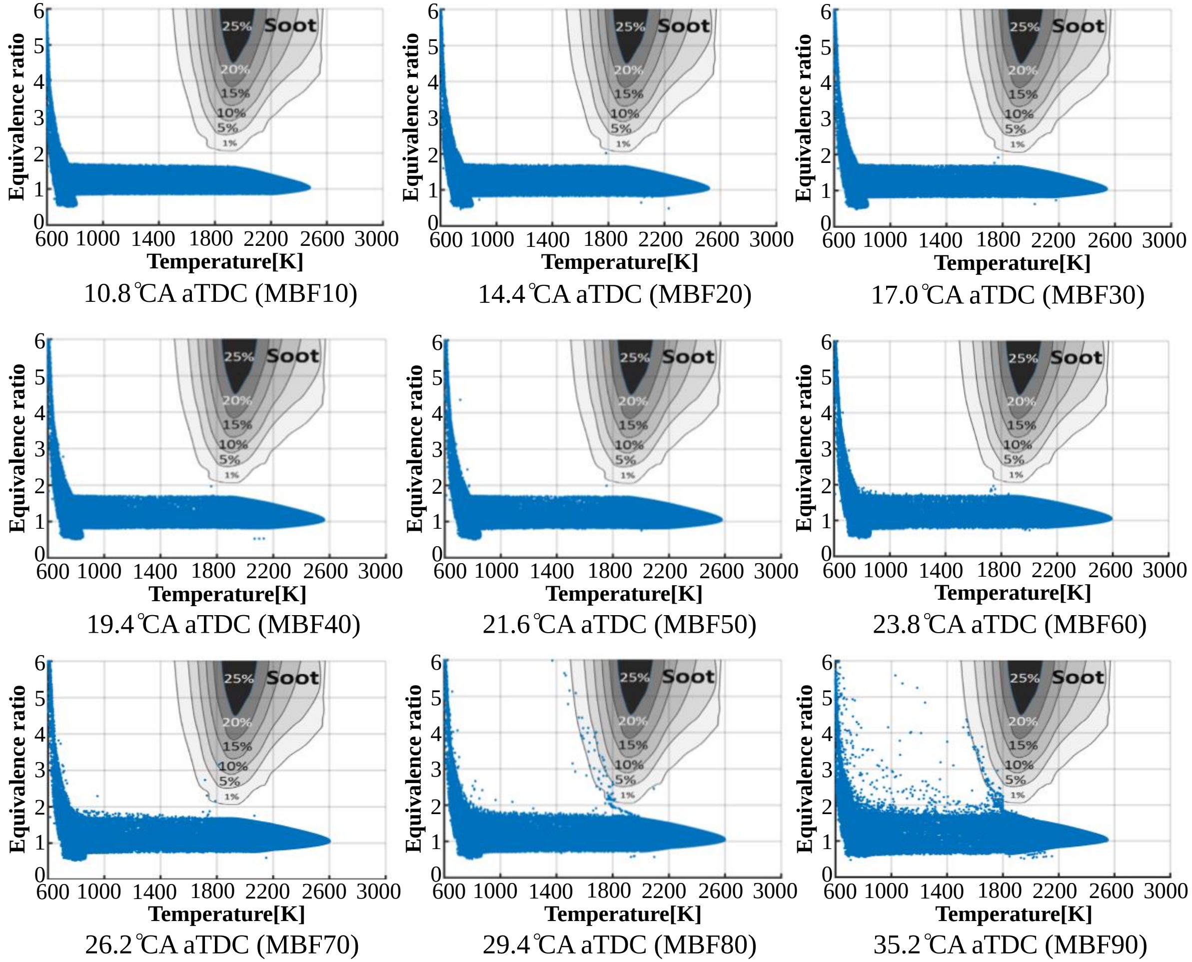
Equivalence ratio-temperature diagram（no EGR）



The soot contours are adapted from Akihama et al.

(*n*=1000 rpm, Torque=210 Nm, without EGR, spark timing= 5° CA aTDC).

Equivalence ratio-temperature diagram（16.7% EGR）



10.8℃A aTDC (MBF10)

14.4℃A aTDC (MBF20)

17.0℃A aTDC (MBF30)

19.4℃A aTDC (MBF40)

21.6℃A aTDC (MBF50)

23.8℃A aTDC (MBF60)

26.2℃A aTDC (MBF70)

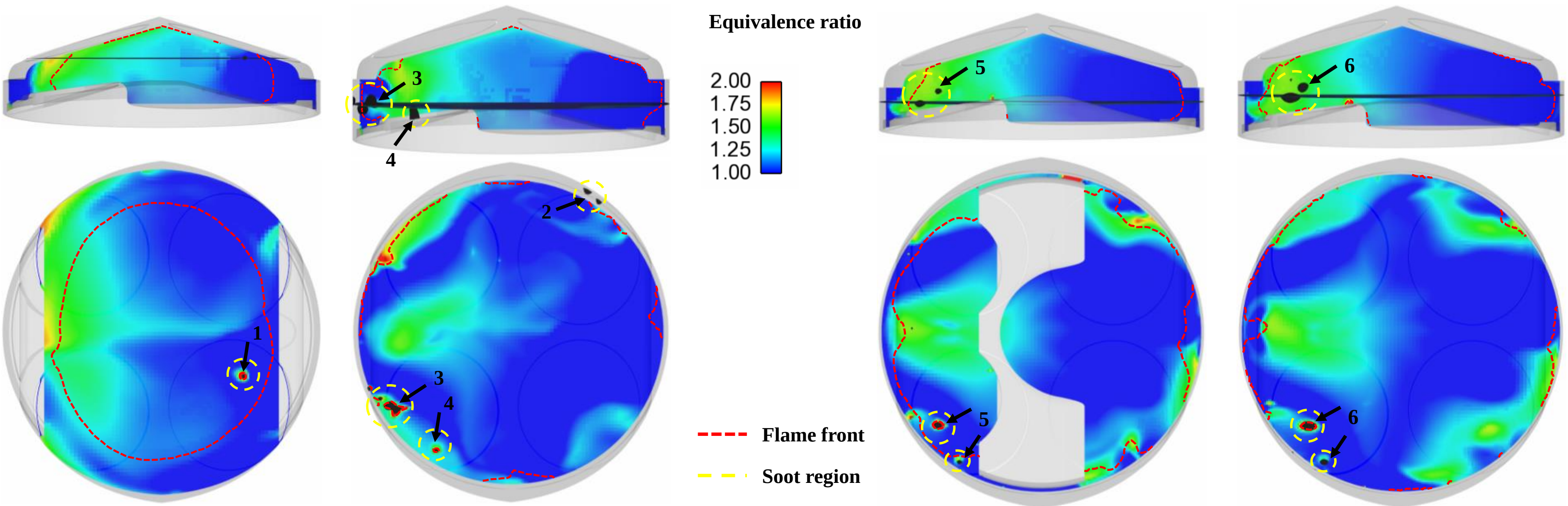
29.4℃A aTDC (MBF80)

35.2℃A aTDC (MBF90)

The soot contours are adapted from Akihama et al.

(*n*=1000 rpm, Torque=210 Nm, with 16.7% EGR, spark timing = -6° CA aTDC).

Equivalence ratio distribution and soot distribution



0%EGR, MBF30 | 0%EGR, MBF90 | 16.7%EGR, MBF80 | 16.7%EGR, MBF90

0% EGR case | 16.7% EGR case

- All these sooting regions can be attributed to the “pool” fire originated from the liquid fuel films on the walls.
- Sophisticated spray design to circumvent spray-wall impingement should be the most effective way to reduce the soot emissions.

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Summary

Mechanism of soot emission reduction by cooled EGR in SIDI engines.

☐ **Dilution effect of EGR gas on soot concentration**

☐ **Influencing factors in soot oxidation process**

- Oxygen concentration: *adverse effect*
- Temperature: *adverse effect*

☐ **Influencing factors in soot formation process**

- Fuel composition: *no effect in this study*
- In-cylinder pressure: *little effect*
- Local mixture concentration: *positive effect*
- Temperature: *primary positive effect*

Conclusions

The dilution effect of EGR gas on the soot concentration should be considered.

EGR plays adverse effects on the soot oxidation, owing to reduced oxygen availability and lowered reaction temperature.

Since the most soot particles are generated at the later phase of the combustion period, the cylinder pressure changed with EGR is too small to have a significant impact on soot formation.

Conclusions

Reduced fuel injection quantity and spray penetration with the cooled EGR does help reduce the possibility of fuel rich pockets splashed from the fuel wall impingement and reduce the soot formation during the initial combustion stage.

Lowered reaction temperature of "pool" fires near the walls with the cooled EGR is the primary contributor to the soot emission reduction.

To further reduce the soot emissions, a reduction of "pool" fire through sophisticated spray design is suggested.

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