COMBUSTION RESEARCH FACILITY

SAND2020-1856PE

Effect of In-Cylinder Flow and Skip-Firing Strategy on Cold-Start Soot Emission of a DISI Engine

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Abstract

Predictive simulation tools are important for future engine development. CFD should allow the engineer to identify sources of excessive exhaust emissions and mediocre combustion behavior. For such high-fidelity modeling work, it is crucial for CFD to be able to capture basic trends of the combustion behavior. For example, it should be able to correctly capture the order of magnitude change of exhaust soot emissions that can occur as in-cylinder conditions change from cold-start to fully warmed-up conditions. The objective of this study is to illustrate the role of the in-cylinder flow on combustion and soot emissions in a DISI engine. In addition, this study aims to provide guidance for future research on soot studies based on all-metal and optical engine experiments. A dramatic change to the in-cylinder flow was realized by altering the intake configuration from "one intake valve" to "two intake valves + intake blockage plate" for promoting a strong tumble flow. For these stoichiometric conditions, the new intake configuration sped up inflammation and combustion. However, the new intake configuration seems to cause a substantial increase in PM and PN levels when the same double injection schedule is use as for the 1-valve operation. At the same time, the data reveals that changes to the fouling level of the combustion chamber can affect the PM/PN level strongly, so more testing is required to isolate the effect of the flow field on the soot emissions. Even so, it is evident that the effect of cross-flow on the spray development is very strong and points to the necessity of CFD to correctly capture these phenomena. Flame images from 20/80 skip-fired operation revealed very strong effects of changes to the coolant temperature. For a high $T_{coolant}$ = 90°C, blue deflagration dominated the combustion, while scattered sooting flames and a diffusion flame on the injector tip seem to be the primary contribution pathways to the engine-out soot. In contrast, for a low $T_{coolant}$ = 20°C, the combustion process was dominated by sooting flames, both in the bulk gases and as strong pool-fires on the rim of the piston bowl. In addition, variability of the combustion was high within each batch of 20 fired cycles, with a general increase of soot formation for each subsequent cycle. This was attributed to the build-up of persistent wall-films affecting the stoichiometry and conditions of following cycles. Hence, the study of soot formation becomes more complex for operation with a low coolant temperature. Hence, for future studies the coolant temperature has to be carefully selected to enable a practical way for probing the relevant soot-formation mechanisms and provide validation data for CFD models.

Mike Weismiller, Gurpreet Singh
Kevin Stork

U.S. DEPARTMENT OF ENERGY

PACE

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Outline

1. Motivation – PACE effort
2. Effect of intake configuration / in-cylinder flow
3. Natural luminosity images from skip-firing operation
4. Effect of various skip-firing schemes
5. Conclusions
6. Future work

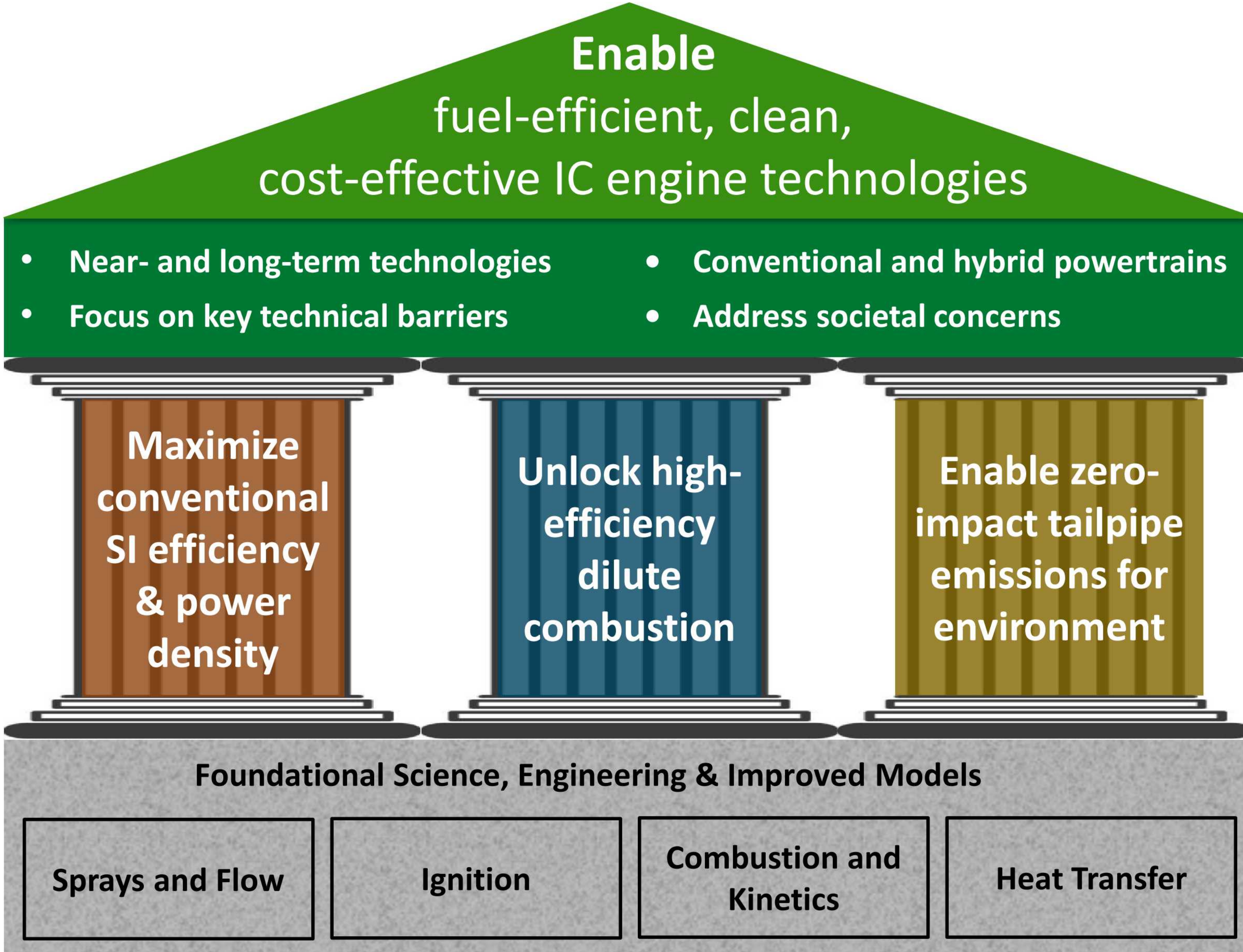
PACE – Partnership to Advance Combustion Engines

Major Outcomes for the Three Purposes

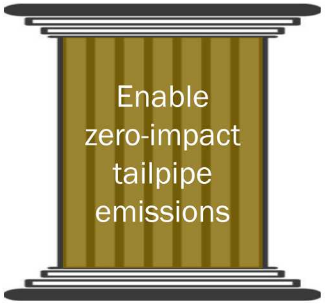





The work is organized to support three key PURPOSES



Major PACE Outcomes to Support Emissions Reduction PURPOSE



- **Deeper understanding of cold-start physics to achieve faster, numerically-aided calibration**
  - **Tier 3 Bin 20 FTP Emissions**
  - **50% reduction in reduction in tailpipe emissions**
  - **50% reduction in catalyst warm-up time**

Major Outcomes 1 – 9 have been identified.

The work reported here supports <u>Major Outcome 8:</u>

Validated cold-start modeling capability that accurately predicts injection and spark timing trends on combustion phasing and emissions at catalyst warm-up conditions.

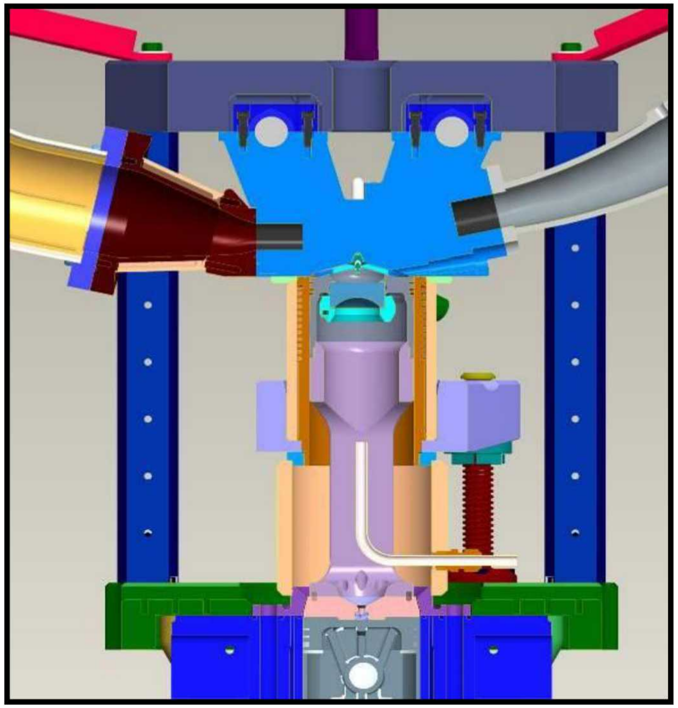
Major PACE Outcomes to Support Emissions Reduction PURPOSE

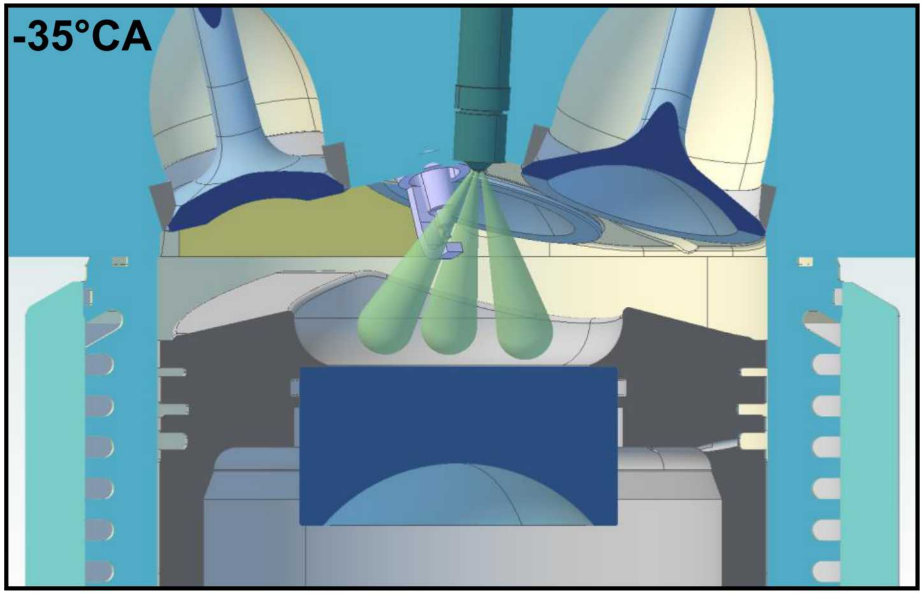
The work reported here is organized within the Spray and Fuel Films Team:

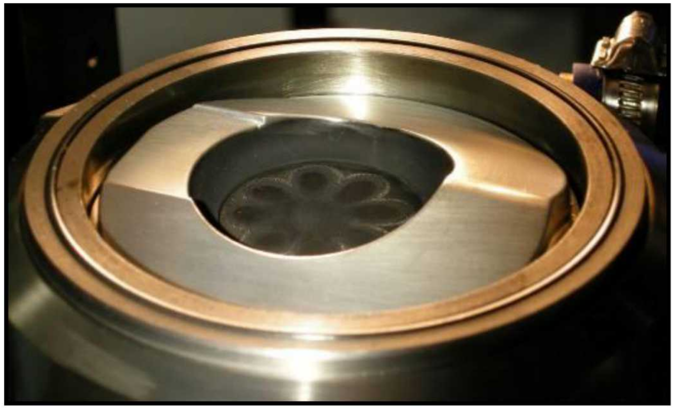
High Load Purpose	Major Outcomes	Task Areas	Specific Task	Task #	Team	PI
Enable zero-impact tailpipe emissions aided by a numerical calibration capability	Improved modeling of cold-start fundamentals	Appropriate surrogates and Kinetic mechanisms	Define surrogates with appropriate distillation	A.01.03/05	Combustion	Pitz
			Develop detailed/reduced kinetic mechanisms	A.01.03/05	Combustion	Pitz
		Sprays and Mixture Formation	Experiments and modeling of multiple cold, short, low injection pressure, transient injections	D.01.01 D.01.05	Spray	Pickett/Powell
		Spray-Wall interactions, films, vaporization, and heat transfer	Evaluate current CFD predictive capability	D.02.01 D.02.02	Spray	Torelli/Carrington
			Experiments & modeling of wall vortex formation	D.02.01 D.02.02/05	Spray	Carrington/Pickett/Torelli
			Experiments & modeling of film formation	D.01.01/02/05 D.02.01/03/04	Heat Transfer and Spray	Carrington/Pickett Torelli/Powell//Sjöberg
			Validated models for heat transfer and vaporization	B.01.01/03 D.01.05	Heat Transfer and Spray	Wissink/Carrington/Pickett
			DNS to characterize near-wall quenching, vaporization	E.02.01	Spray	JC
		Ignition and Combustion	Experiments and modeling of kernel/flame transition for low turbulence conditions	C.01.02 C.02.04	Ignition	Ekoto/Scarcelli
			Validated low turbulence flame propagation models			
		Soot Formation	Baseline performance of current soot models			
			Develop DNS database & extract statistics describing soot from wall films (pyrolyzing)	E.02.01	Combustion	Chen
			Experiments quantifying wall film soot production	D.01.04/E.01.02	Combustion/Spray	Pickett/Sjöberg
			Development of improved engineering soot models	A.01.03/D.01.04	Combustion/Spray	Pitz/Hansen
		Foundational data near spark gap for model V&V	Measure flow direction & turbulence			
			Understand & model residual with wacky cam phasing			
	Integrated assessment of cold-start modeling	Development of fully instrumented engine and exhaust system	Initial instumentation of LNF engine	E.01.01	Cold Start	Curran
			Instrumentation of common platform engine			
		Experiments and modeling characterizing retardability, sensitivities of emissions to various parameters, etc	Characterization of retardabilty/sensitivities to operating parameters for model validation	E.01.01	Cold Start	Curran
			Characterize thermal transients and specied evolution	E.01.01	Cold Start	Curran
			Characterize heat release in exhaust manifolc	E.01.01	Cold Start	Curran
			Development of psuedo-transient test protocol	E.01.01	Cold Start	Curran
			Full-engine geometry (including head and block) CFD engine models with coupled CHT	B.02.01	Heat Transfer	Edwards
			Develop efficent CHT workflows	B.02.01	Heat Transfer	Edwards
	Understanding of cold-start processes & design/operation requirements	Assess ability and optimize advanced igniters to enhance catalyst warm-up	Characterize cold-start performance of PC igniters	F.01.01	Ignition	Rockstroh
			Characterize cold-start performance of BDI igniters/O3			
		Develop understanding of cold-start ignition and emissions processes	Identify key sources of soot formation	D.01.04/E.01.02	Combustion/Spray	Pickett/Sjöberg
			Identify root causes of ignition failure under various conditions	E.01.02	Combustion/Spray	Sjöberg
		Mitigate cold-start variability and misfire	Acquire extensive data sets	E.01.01	Abnormal	Curran
			Apply statistical/AI/ML analysis	G.02.01	Abnormal	Kaul
			Devise and test mitigation strategies	G.02.01	Abnormal	Kaul

Research Engine

- Designed for spray-guided stratified-charge operation.
- 8-hole injector. 60° included angle. P_{inj} = 120 bar.
- Drop-down single-cylinder engine.
- Identical geometry for All-metal and Optical.
- One valve operation for swirl.
- Two valve + plate operation for stronger tumble.
- 0.55 L, CR = 12:1.

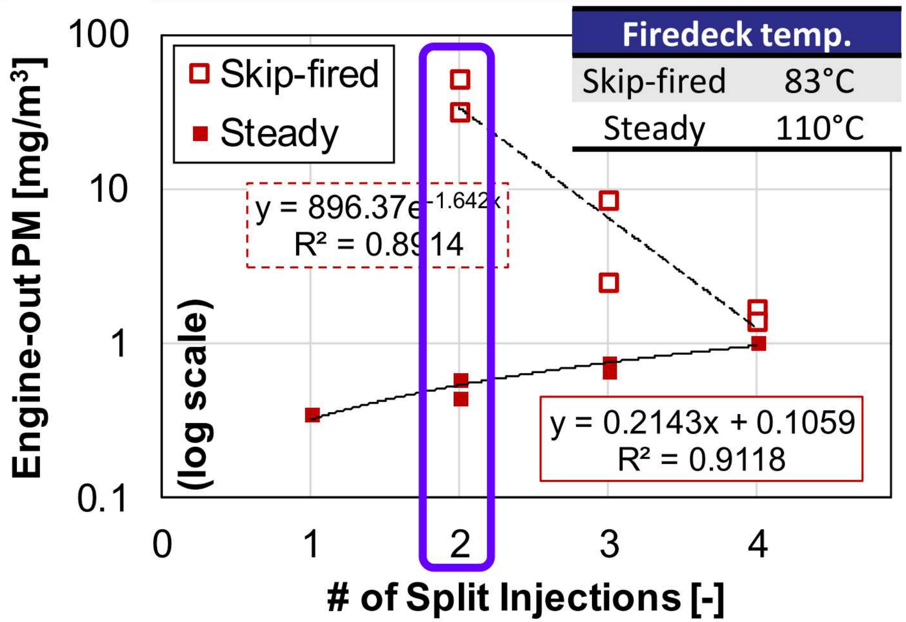




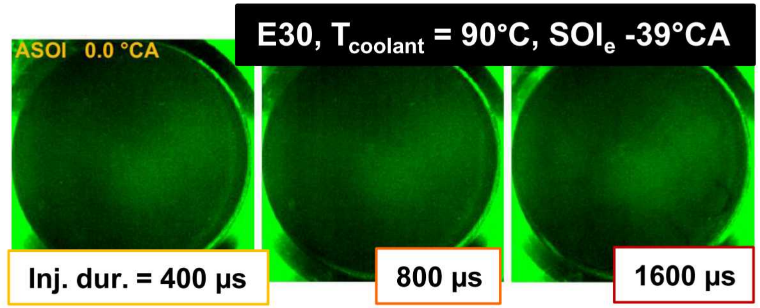


Effect of Injection Schedule on Soot PM

$T_{coolant}$ = 75°C, RD5-87, SOI_{a1} = -307° CA

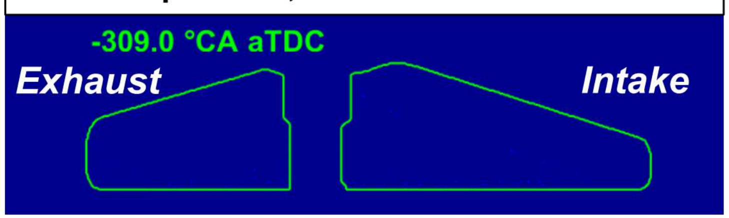


- Review 2019 Aug. AEC results for 1-valve operation.
- Response of Soot PM to # of split injections depends on operating mode.
- For cooler engine operation, wall-wetting can be a major source of soot emission.



- CFD models need to account for intake-flow effects on sprays and the resulting soot formation.
- Here, we are expanding existing data base to include the effect of increased in-cylinder tumble on combustion and emissions formation.
- Use full-range RD5-87 now, glean insights from concurrent Co-Optima fuel efforts.
- Next, assess RD5-87 surrogate(s).
- Focus on operation with double injections, which shows high sensitivity to the thermal state of the engine.

High Olefin, Well-mixed stoich.,
1-valve operation, SOIa1 -307.6°CA

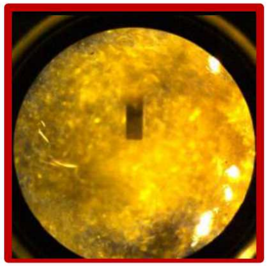


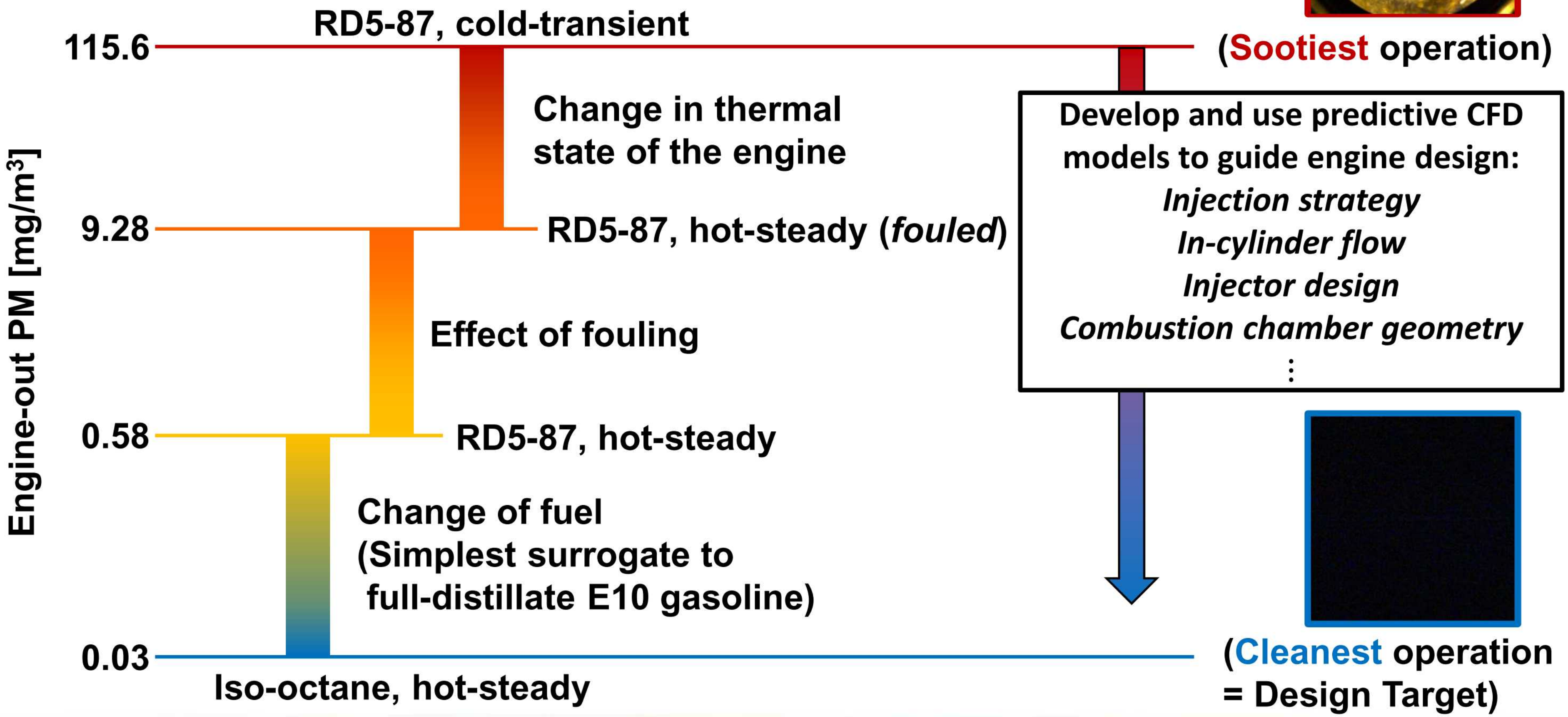
Soot PM Sensitivity to Fuel and Thermal State of Engine

- CFD models need to capture effects of key phenomena that lead to excessive PM.
- PM/PN measurements show relative importance of various factors.

  A. Imperfect bulk-gas mixture formation and free-flow soot formation.

  B. Fuel wall-films with diffusive combustion or pyrolysis.





Motivation for Increasing the Tumble Strength

- High tumble engines are becoming more popular in the market.
  - Increased tumble strength helps to increase turbulence level and speed up combustion.
  - Faster combustion reduces knocking propensity and increases EGR tolerance.

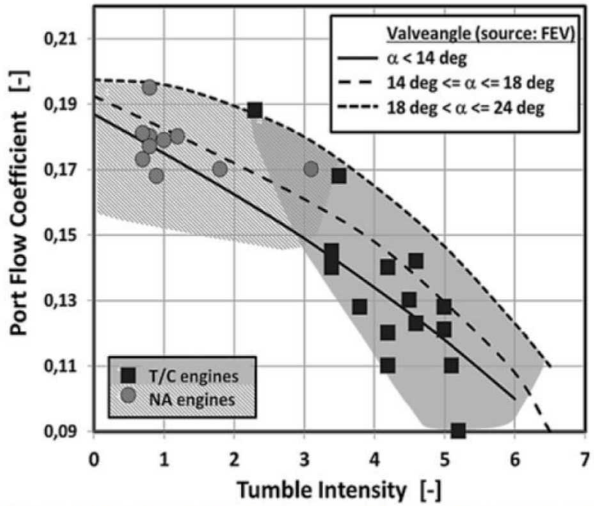


Figure 1. Benchmarking study on port flow coefficient vs. tumble intensity for T/C-engines and NA engines. Source: FEV

Ruhland *et al.* SAE 2017-24-0065

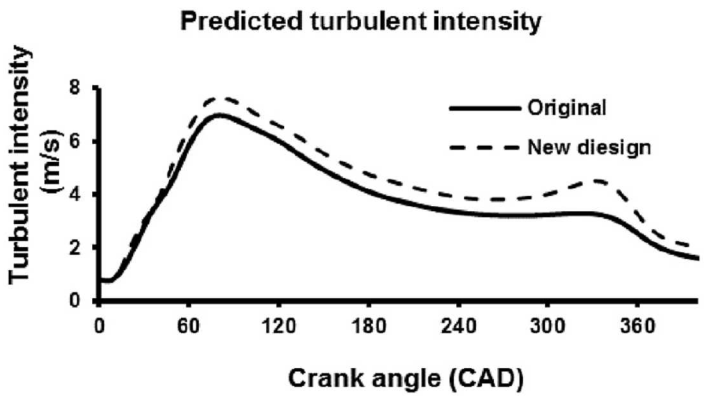
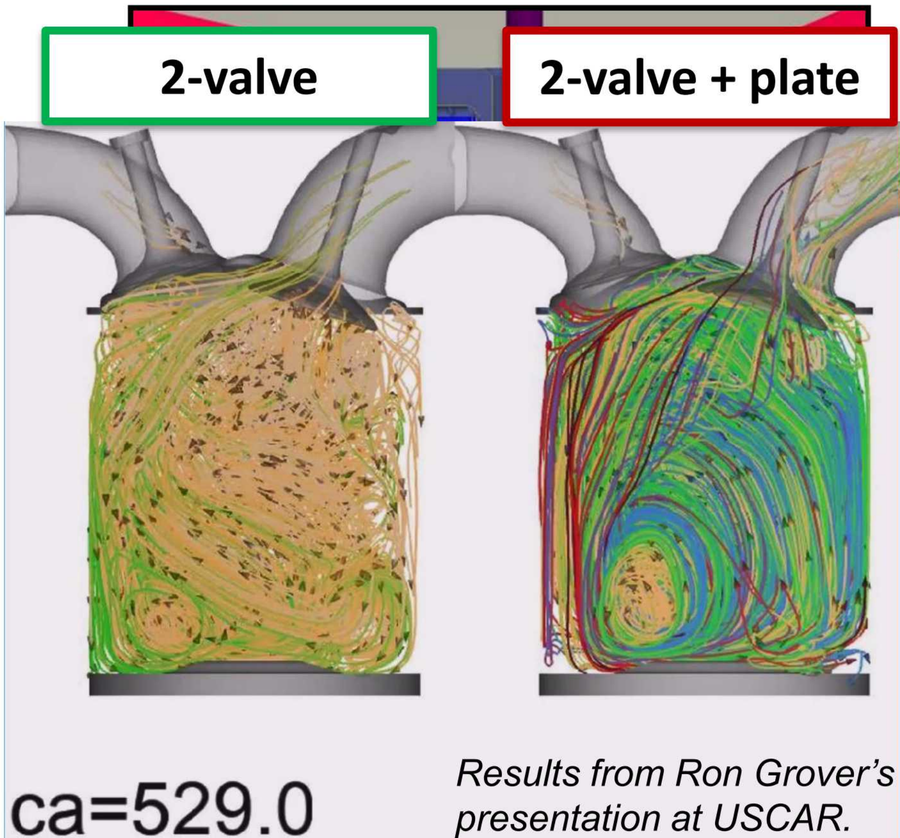


Figure 29. Turbulent intensity as a function of crank angle.

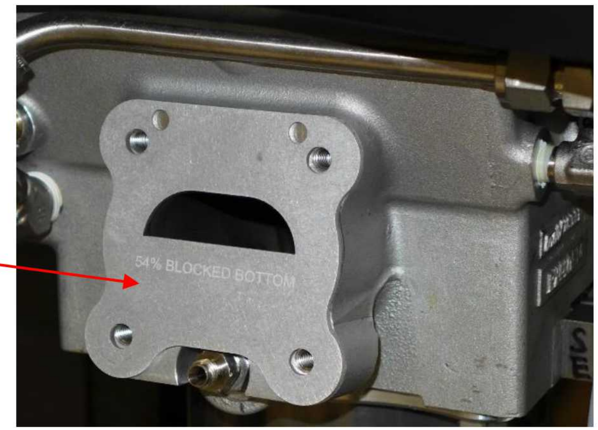
Qi *et al.*, SAE 2015-01-0379

New Intake Configuration

- The intake port of current DISI engine at Sandia generates a relatively weak tumble flow.
- Simple options to enhance tumble strength were evaluated numerically by Ron Grover.
- Following this, a plate was installed at the entrance of intake port, blocking lower 54% of the flow area. Thanks for Jim Szybist for sharing ORNL-manufactured plates.



Results from Ron Grover's presentation at USCAR.

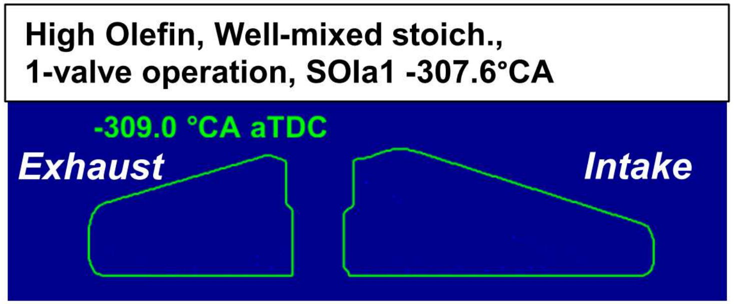


Intake configurations	Swirl Index	Tumble Index
1-valve	2.7	0.6
2-valve	0	0.27
2-valve + tumble plate	0	1.6

×2.7
×6

Tumble Effects on Fuel-Air Mixing

- Dramatic change to the in-cylinder flow field was realized by altering the intake configuration from "**one intake valve**" to "**2 intake valves + tumble plate**".
- However, the altered flow field can lead to the formation of rich pockets.
  - DI fuel sprays are subject to strong cross-flow during the intake process.
- CFD models need to capture correctly effect of tumble on fuel-air mixing and emissions formation.



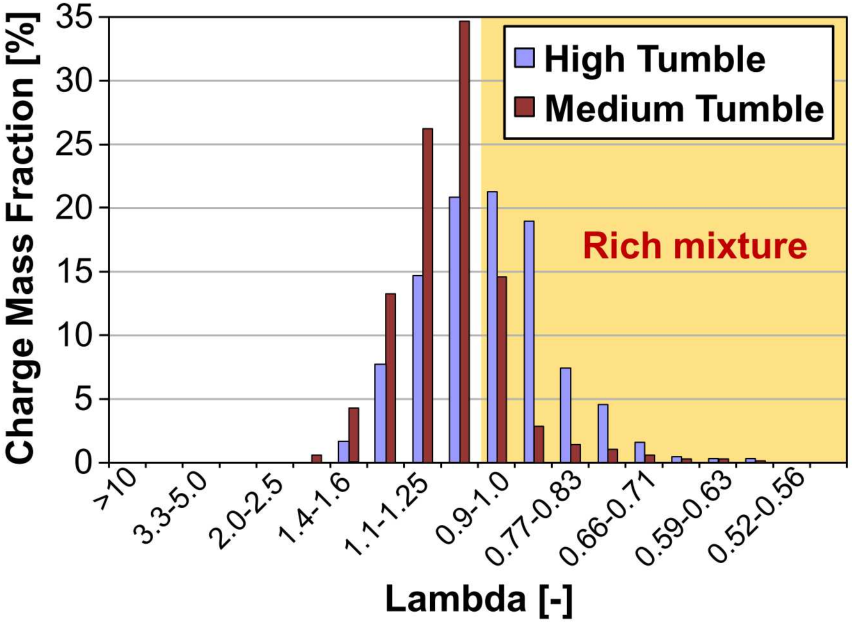
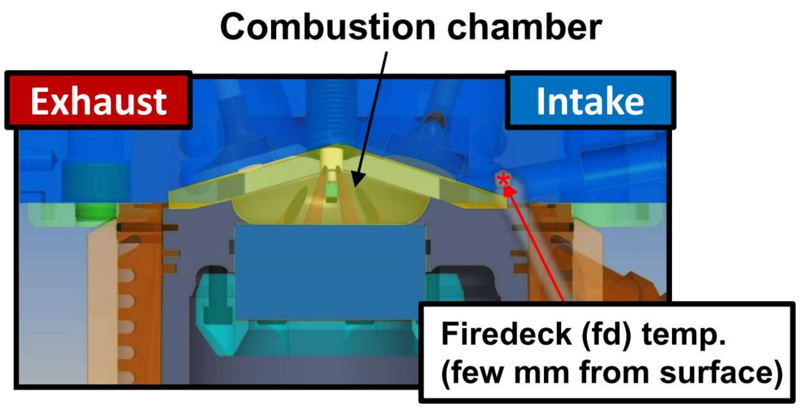


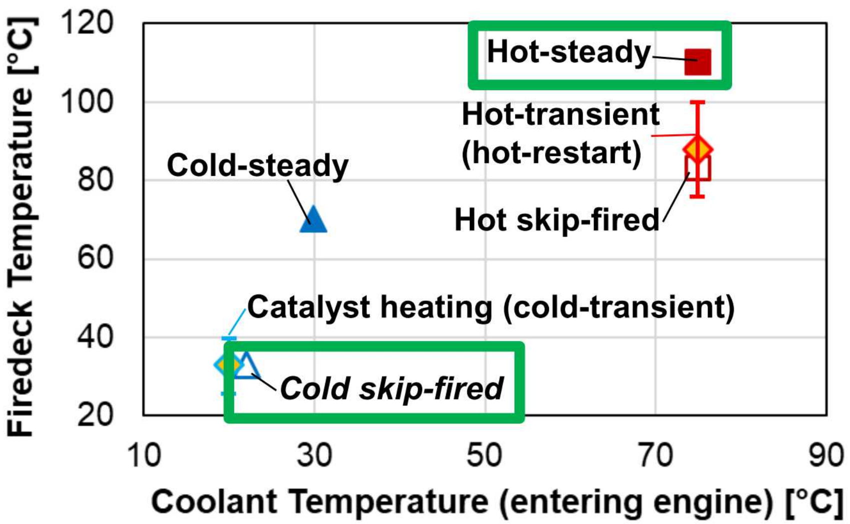
Figure 19. Mixture homogeneity at TDC for 10 bar NMEP, 0% EGR.

Wheeler *et al.*, SAE 2013-01-1123

Thermal States of the Engine

- Various thermal states of the engine have been tested.
- For new high-tumble data, focus on two extremes.





Mode	Thermal State	$T_{coolant}$ = 20-30°C	$T_{coolant}$ = 75°C
Continuously fired	Steady	T_{in} = 24°C / T_{fd} = 70°C	T_{in} = 32 / T_{fd} = 110°C
	Transient (Cold-start or hot-restart)	T_{in}=22°C / T_{fd}=25-40°C	T_{in}=30°C / T_{fd}=76-100
Skip-firing	Quasi-steady	T_{in} = 22°C / T_{fd} = 35°C	T_{in} = 32°C / T_{fd} = 83°C

Experimental Conditions

- RD5-87 : representative of market E10 gasoline of AKI 87
- Intake air-flow rate based on ACEC cold-start guidelines (see August 2019 AEC presentation).
- CA50 = 15°CA to avoid knock at hot steady-state operation.
- Tested two spark plugs with different length for an initial assessment of the new intake configuration.

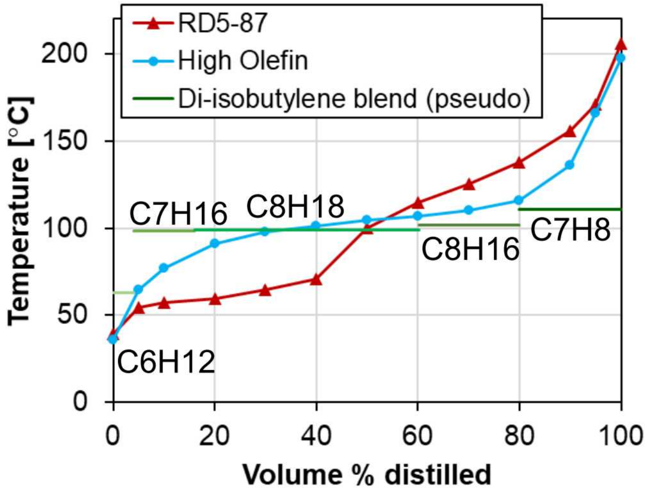
Parameter	Value	Unit
Fuel	RD5-87(2A)	
Engine speed	1300	rpm
Coolant temperature (**entering engine**)	~20 (skip-firing), 75 (steady)	°C
Intake air temperature	~22 (skip-firing), 30 (steady)	°C
Average intake air flow rate	3.06	g/s
Intake pressure	~ 55	kPa
Target Lambda	1.00	
Injection pressure	120	bar
Injection strategy	Double injection	
Split ratio (Based on electric command)	50/50	
Injection duration/pulse	**823** to 990 (longer for skip-fired operation)	μs
Injection timings (SOIa1, SOIa2)	-307.4 , -293.4	°CA
CA50	15	°CA

Key Fuel Properties

- T90 and PMI of RD5-87 are relatively high.

The fuel used for experiments | **Co-Optima Fuels**

	E10 RD5-87	Iso-octane	High Olefin	Di-isobutylene blend
RON	92.1	100.0	98.3	98.3
MON	84.8	100.0	87.9	88.5
Octane Sensitivity	7.3	0.0	10.4	9.8
Oxygenates [vol.%]	10.6	0.0	0.0	0.0
Aromatics [vol.%]	20.9	0.0	13.4	20.1
Alkanes [vol.%]	49.4	100.0	56.4	56.3
Cycloalkanes [vol.%]	11.3	0.0	2.9	0.0
Olefins [vol.%]	4.9	0.0	26.5	23.6
T10 [°C]	57	-	77	63
T50 [°C]	98	-	104	-
T90 [°C]	**156**	-	136	111
Boiling point [°C]	-	99	-	-
Net Heat of Combustion [MJ/kg]	41.9	44.3	44.1	43.2
Heat of Vaporization [kJ/kg]	412	271	333	337
AFR Stoichiometric	14.1	15.1	14.8	14.7
HoV [kJ/kg stoichiometric charge]	27.3	16.8	21.1	21.5
Particulate Matter Index	**1.68**	0.19	1.00	0.47

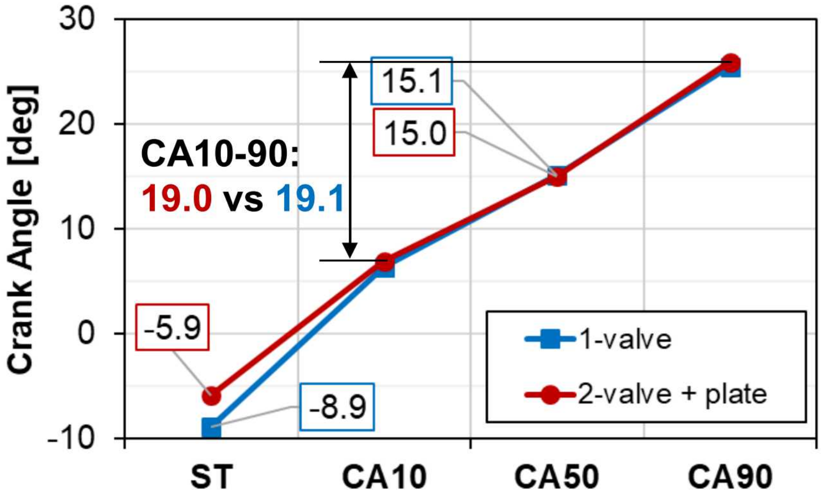


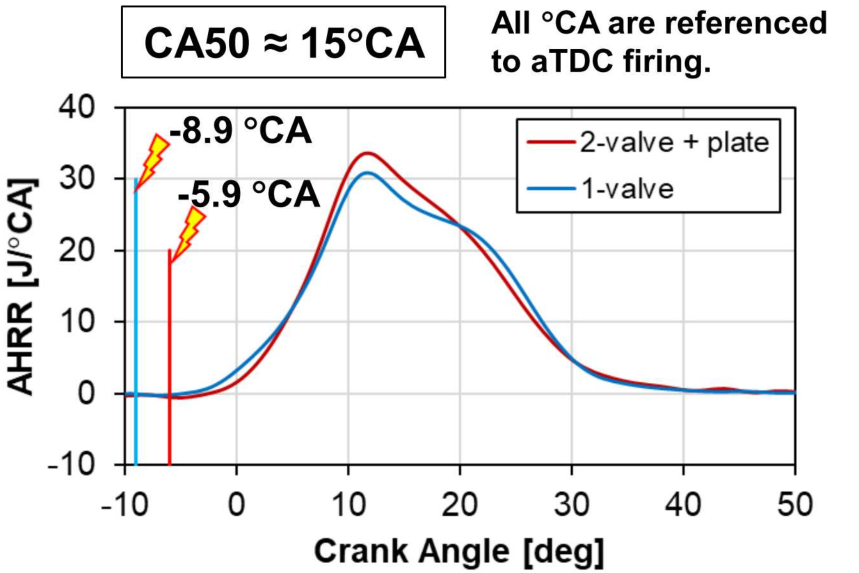
Effect of Intake Configuration on Combustion

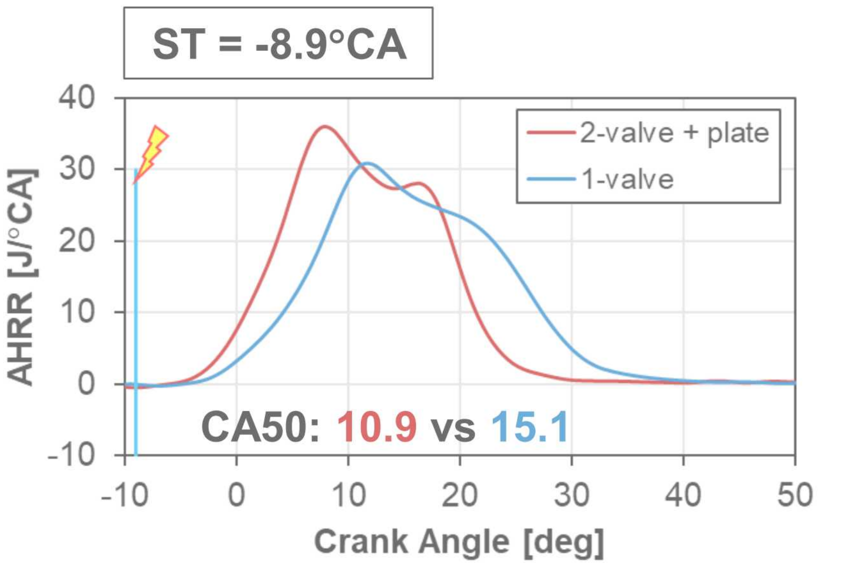
- Enhanced tumble increases peak AHRR and speeds up the inflammation, as indicated by:
  - Retarded spark timing for a given CA50.
  - Advanced CA50 at a fixed spark timing.
- Slightly more stable CA10 and CA50:

Std. dev.	CA10	CA50
1-valve	0.93	1.38
2-valve + plate	0.80	1.30

- Combustion durations (CA10-90) are nearly identical for this $\phi = 1$ operating condition.

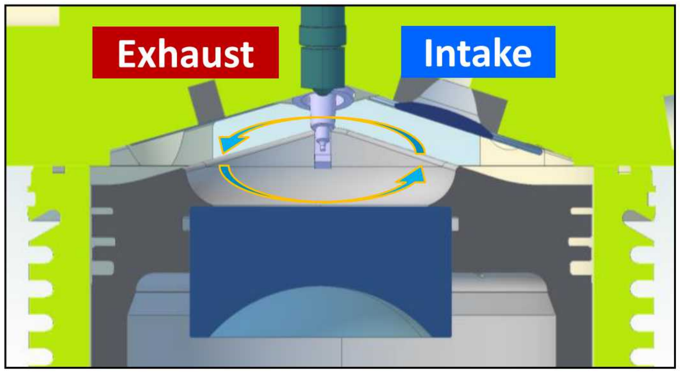


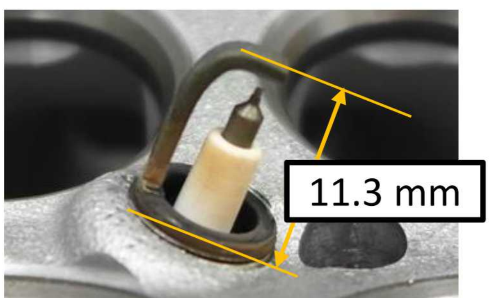




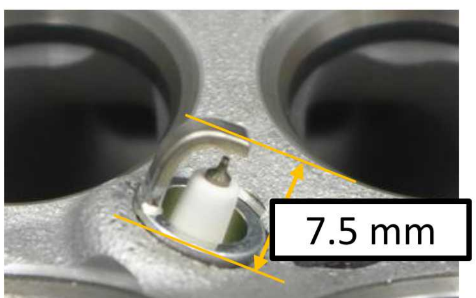
Effect of Spark Plug on Combustion

- Tested spark plugs with different protrusions into the combustion chamber to investigate any possible changes to combustion characteristics.
  - Flow near spark plug can be different which may affect initial flame development and propagation.





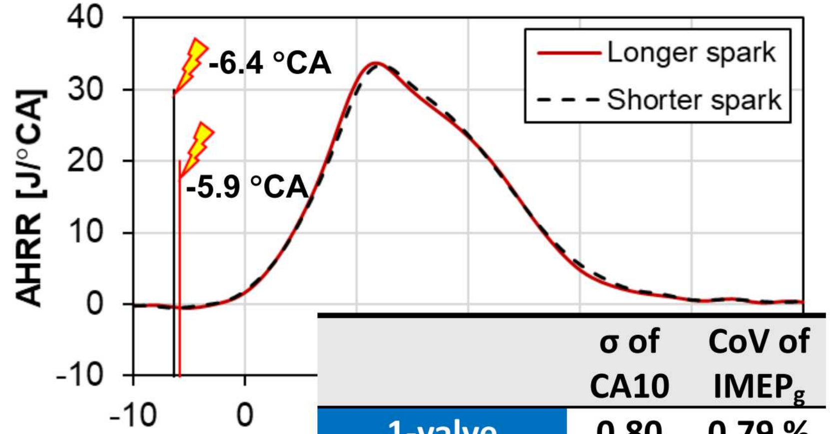
Longer spark (originally used)



Shorter spark (newly tested)

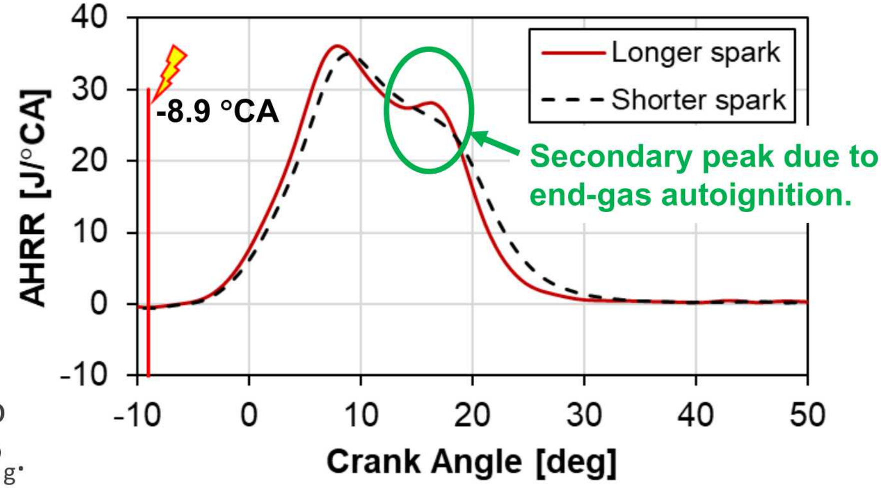
- At the given operating condition, longer spark plug leads to shorter ST-CA10 with a similar variability in CA10 and $IMEP_g$.

ϕ = 1, CA50 ≈ 15°CA



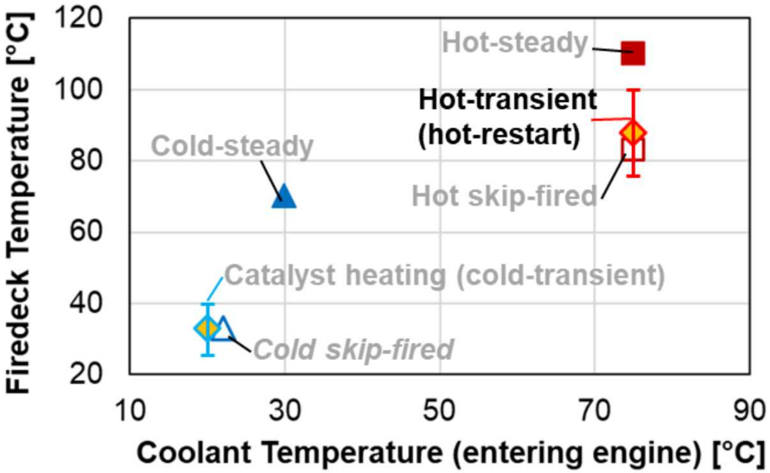
	σ of CA10	CoV of $IMEP_g$
1-valve	0.80	0.79 %
2-valve + plate	0.80	0.80 %

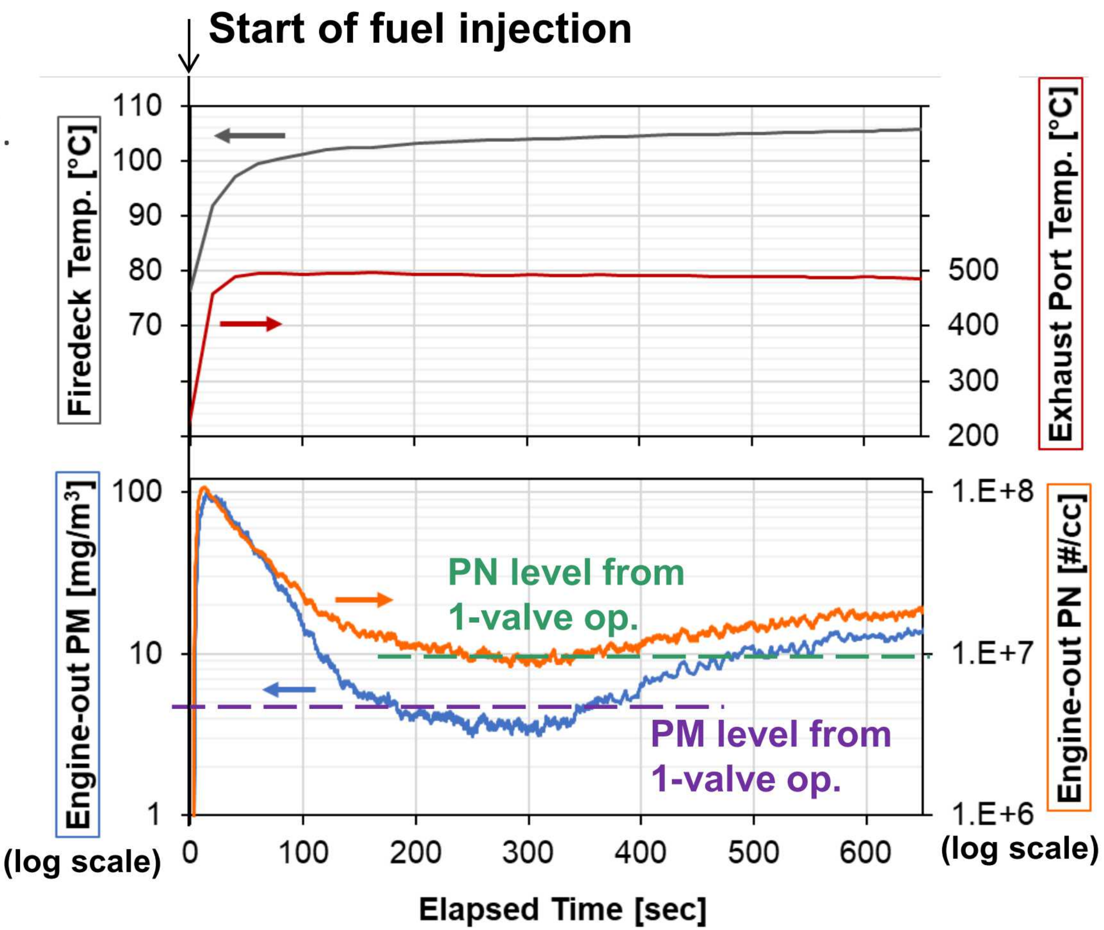
ϕ = 1, ST = -8.9°CA



PM/PN Results with New Intake Configuration

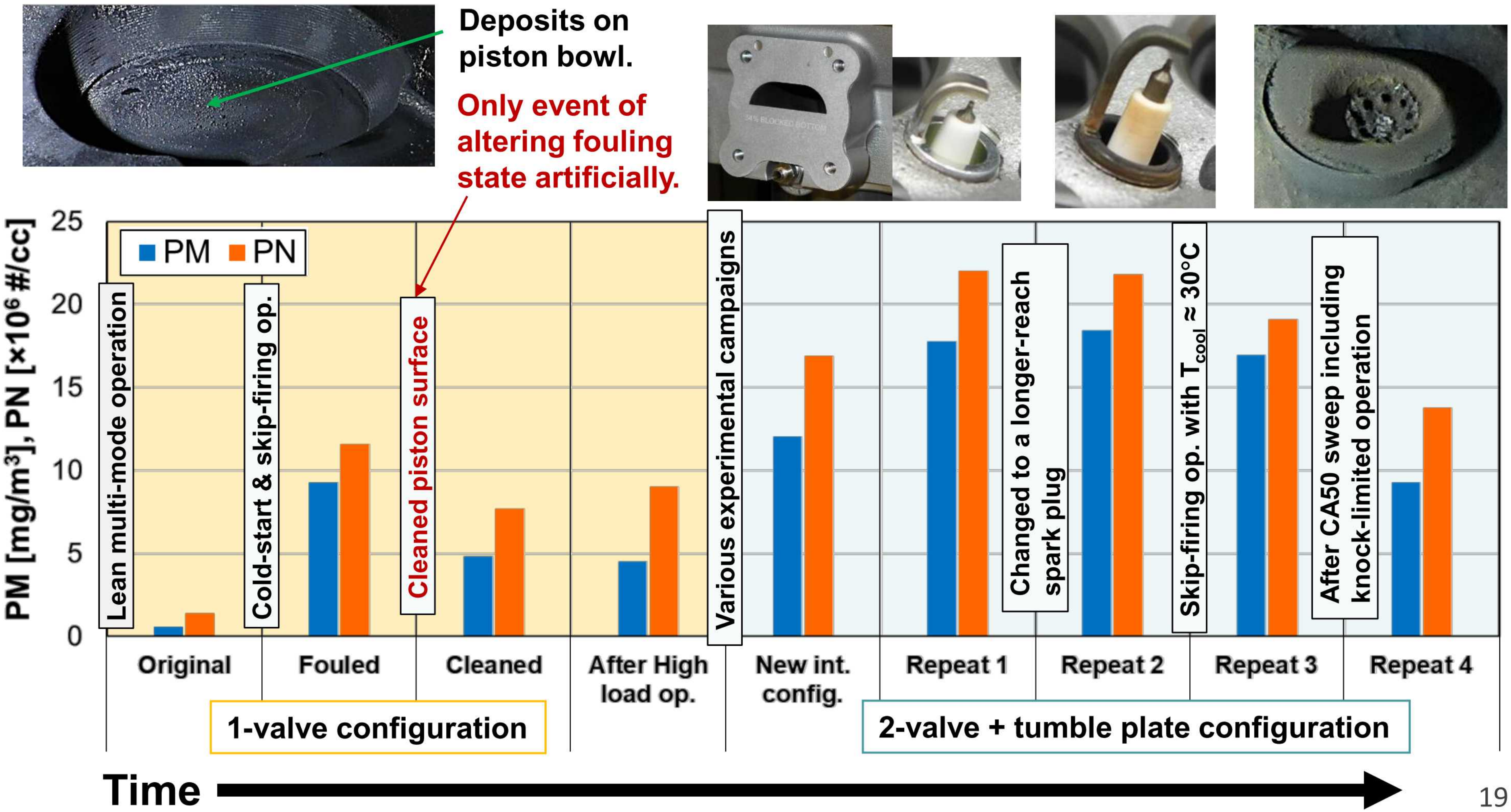
- First PM/PN data acquired with the new intake configuration and RD5-87.
- It was speculated that stronger in-cylinder flow could enhance mixing of air and fuel, thus may lead to more homogenous mixture and reduced soot.
- The result shows this is not the case.
  - PM initially dropped below that of 1-valve operation, but rose later.
  - Likely due to change in fouling level.





PM/PN Variability for Hot-Steady Operation

- Change from 'clean' to 'fouled' combustion chamber can change PM levels one order of magnitude. Other events have less influence on variability.
- Operation with tumble plate appears to increase PM/PN levels. However, injector-tip fouling may have been different between '1-valve' and '2-valve + plate' operation.
  - Next step of future work is to repeat with clean injector tip.



Factors Affecting Spray and Fuel-Air Mixing

- Following factors can contribute to changes in PM/PN level.
  - A. Interactions between in-cylinder flow and spray
  - B. Strength of cross-flow on liquid fuel spray
  - C. Distillation characteristics of fuels
  - D. Viscosity of fuel
  - E. Surface tension of fuel

Effect of intake configuration (A, B)

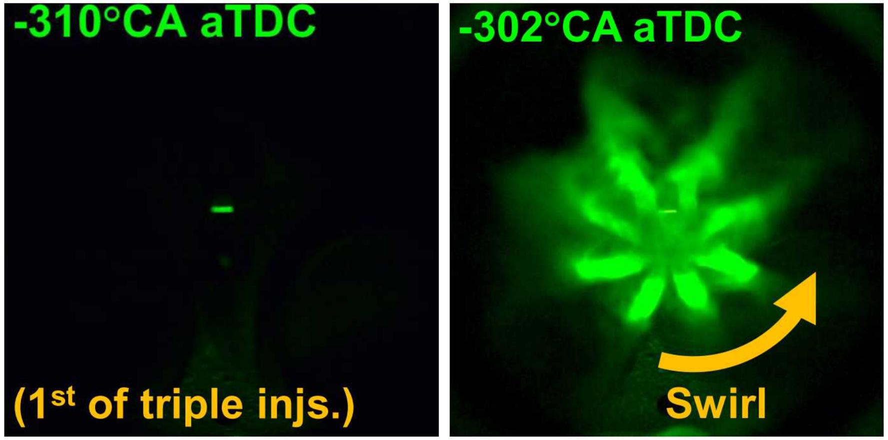
Fuel effects (C, D, E)

- Show examples of spray images acquired with "1-valve" configuration.

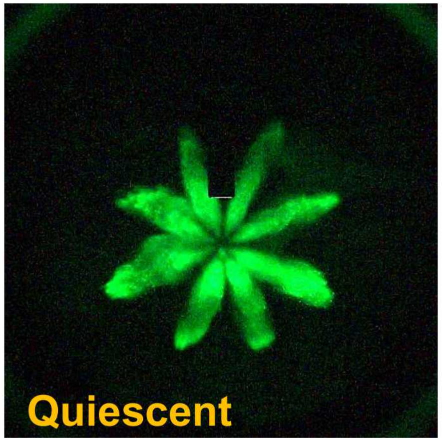
A. Interactions between In-cylinder Flow and Spray

- The example shows that the plumes are highly influenced by swirl flow.

Injection during intake stroke
(1-valve, 1400 rpm, P_{in} = 1 bar, Di-isobutylene blend)

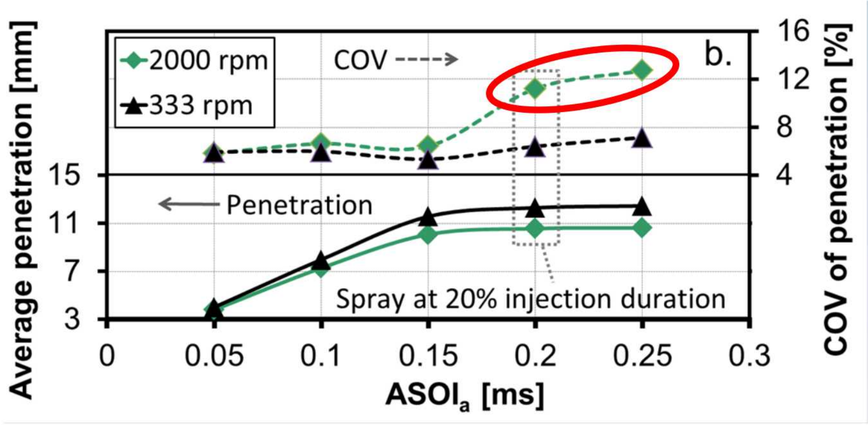


Injection into 1 bar.
(0 rpm, E30 fuel)



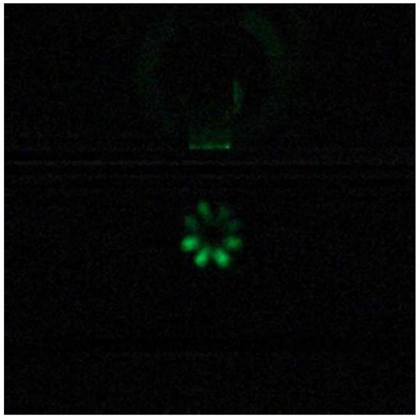
B. Strength of Cross-Flow on Liquid Fuel Spray

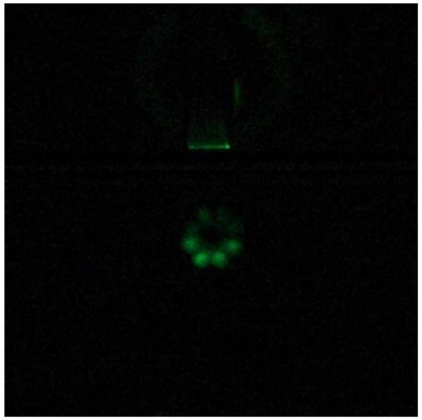
- Increased tumble may increase the local flow velocities, affecting the spray.
- With stronger cross-flow, cycle-to-cycle variability of the liquid penetration may increase.
- Examine existing data for stratified operation with late injection (SOI_a = -21°CA).
- Large change from 333 to 2000 rpm represents an increase of cross-flow velocity.
- Spray analysis indicates strongly increased variability of spray-tip penetration.

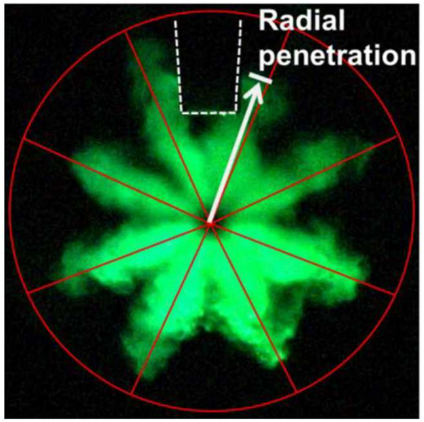


333 rpm

2000 rpm







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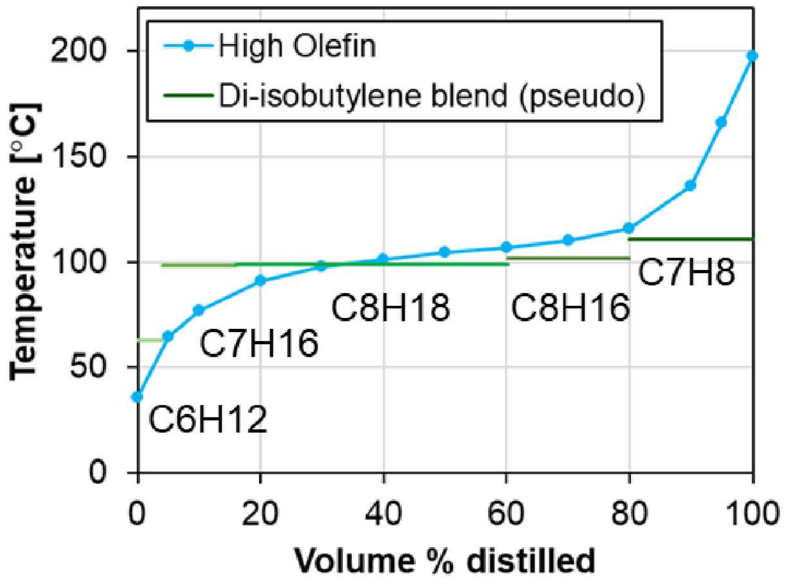
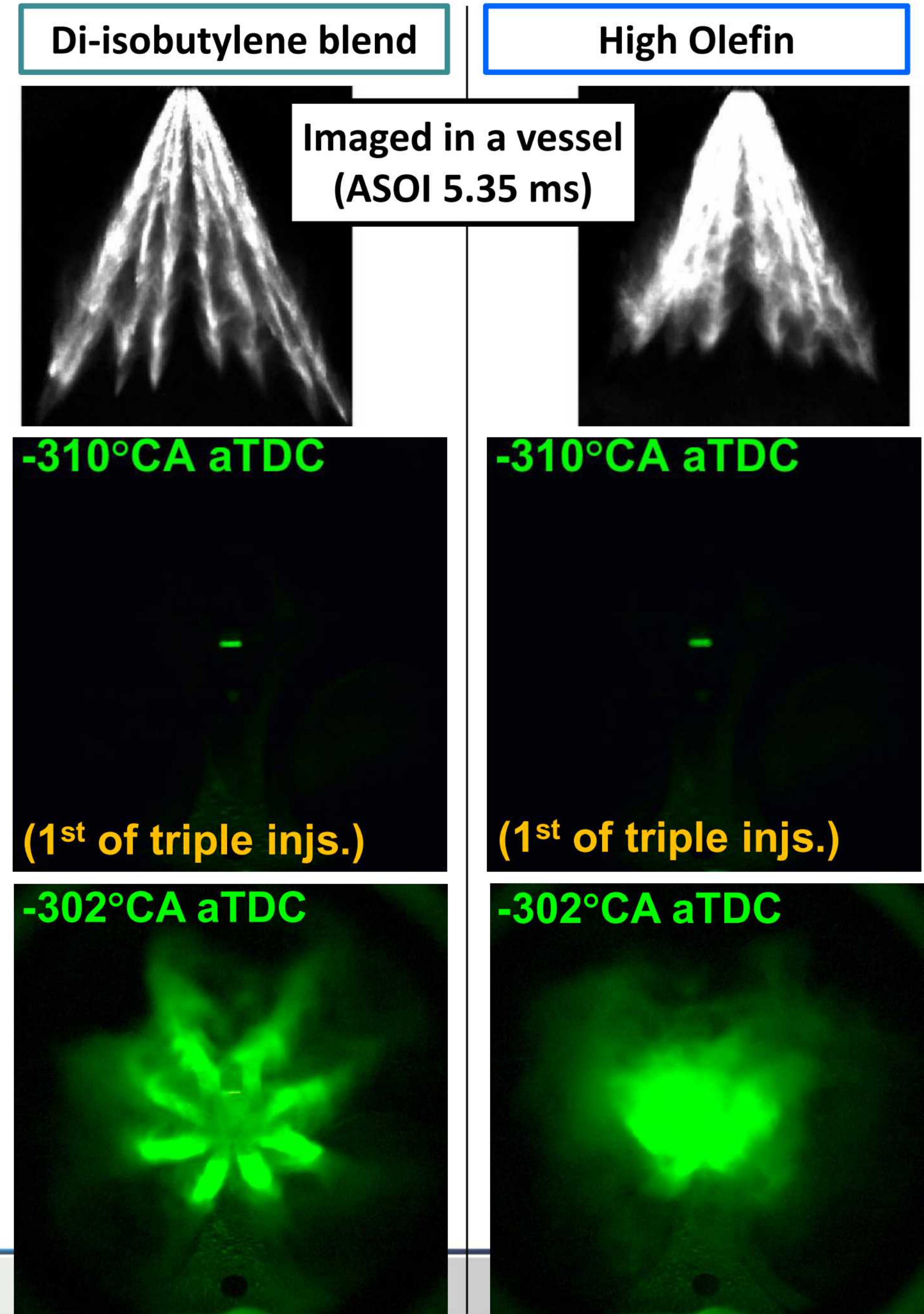
C. Distillation Characteristics of Fuels

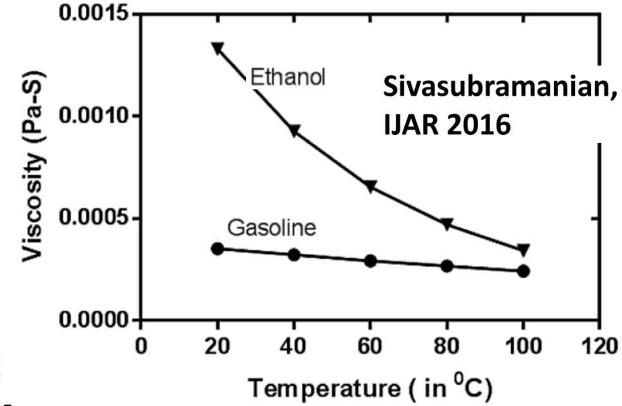
- Spray observed in a constant-volume vessel showed distinct features.
  - Distillation characteristics are important.
  - One of the fuel properties considered for designing a "golden" surrogate of RD5-87.
- Volatility deviations between RD5-87 and its surrogate can alter spray-flow interaction and air-fuel mixture formation.





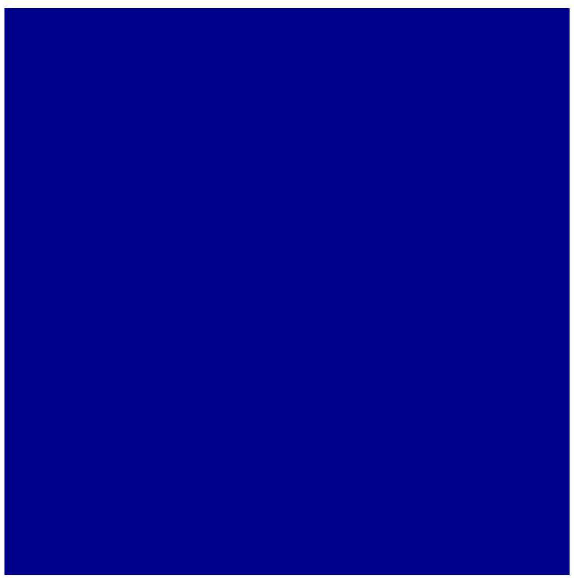
D. Viscosity of Fuel (Temperature Effect)

- Fuel viscosity changes with temperature, which may affect injector behavior and soot formation.
- Extra injections due to needle bouncing effect were seen clearly at $T_{coolant}$ = 90°C, but less evident at lower $T_{coolant}$.



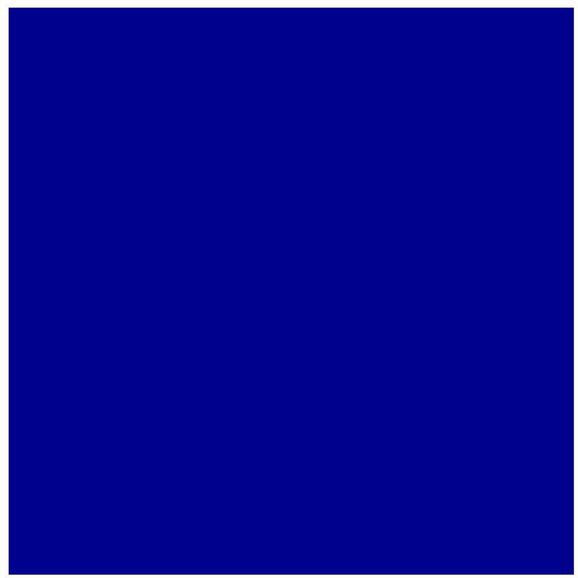
Fuel:
Splash-blended E30

$T_{coolant}$ = 90°C
SOIe = -40°CA
SOIa = -38.1°CA
(delay:1.9°CA)

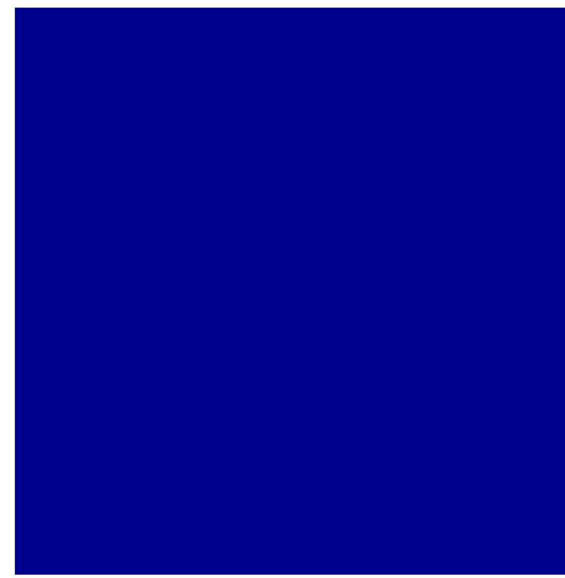


Inj. dur. = 399 µs

$T_{coolant}$ = 40°C
SOIe = -30°CA
SOIa = -28°CA
(delay:2.0°CA)



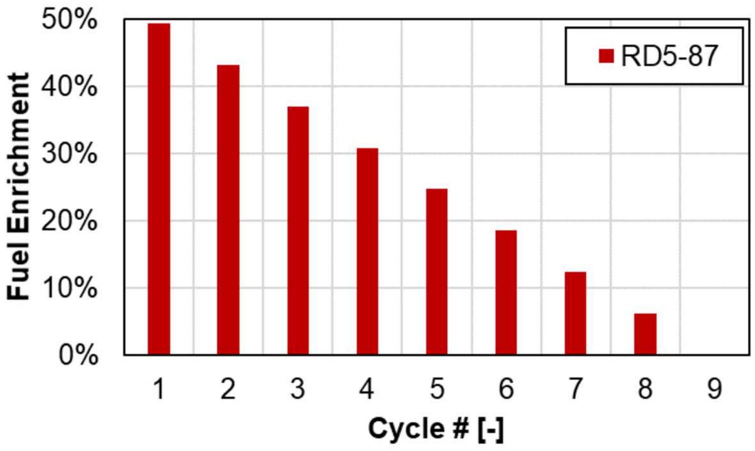
Inj. dur. = 400 µs

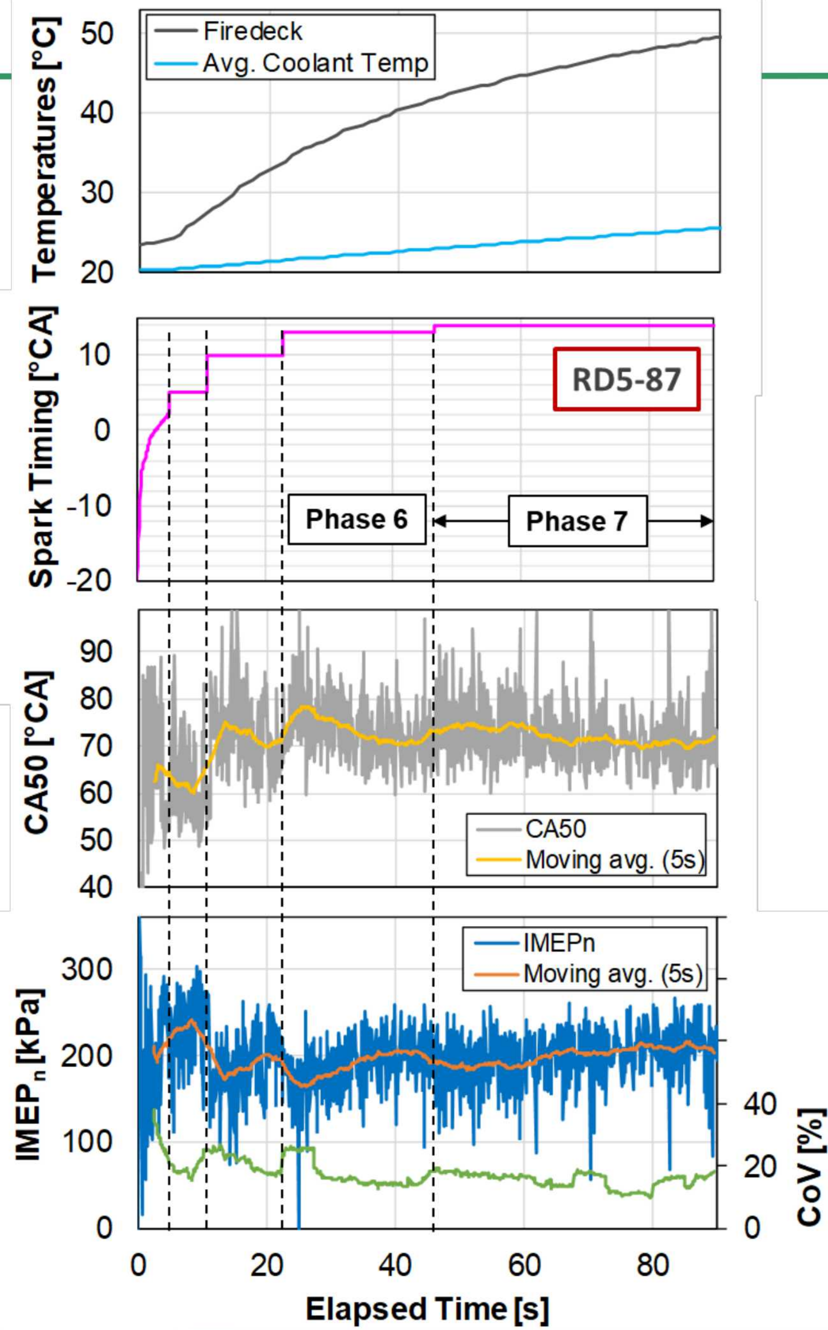


Inj. dur. = 800 µs

Transient Cold-Start Operation

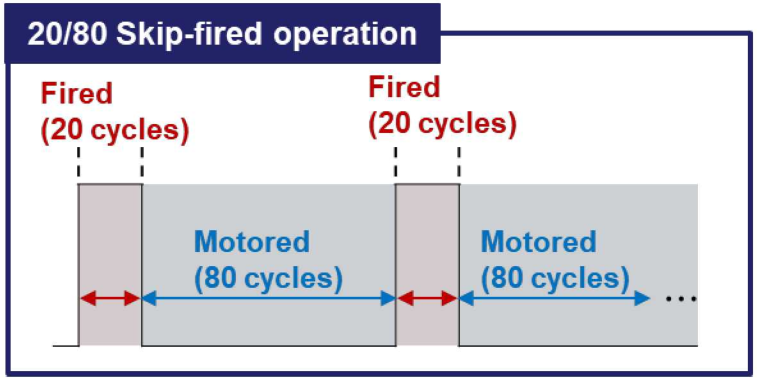
- **Pros**
  - Most realistic.
- **Cons**
  - Boundary conditions are different for each cycle.
    - Enrichment is required initially because of very slow fuel vaporization.
  - Cycle-to-cycle variability is high, but obtaining sufficient statistics is very time consuming.
    - ≈ 8 repetitions per day.

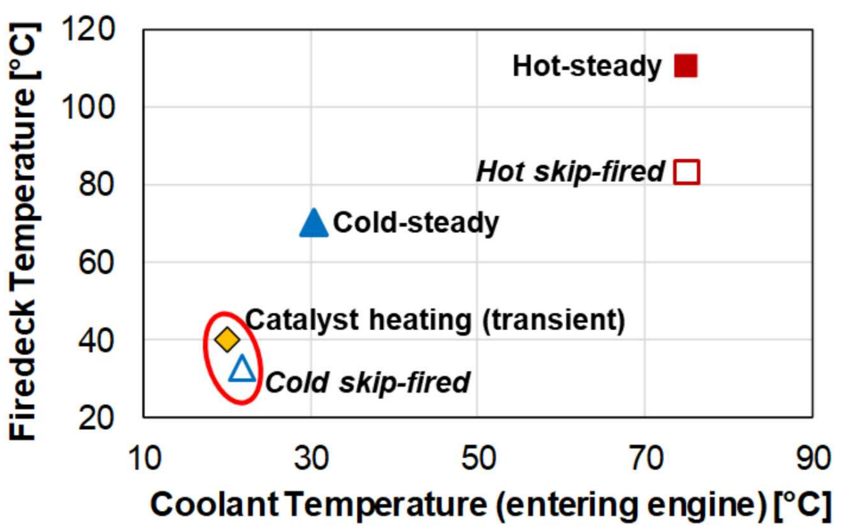


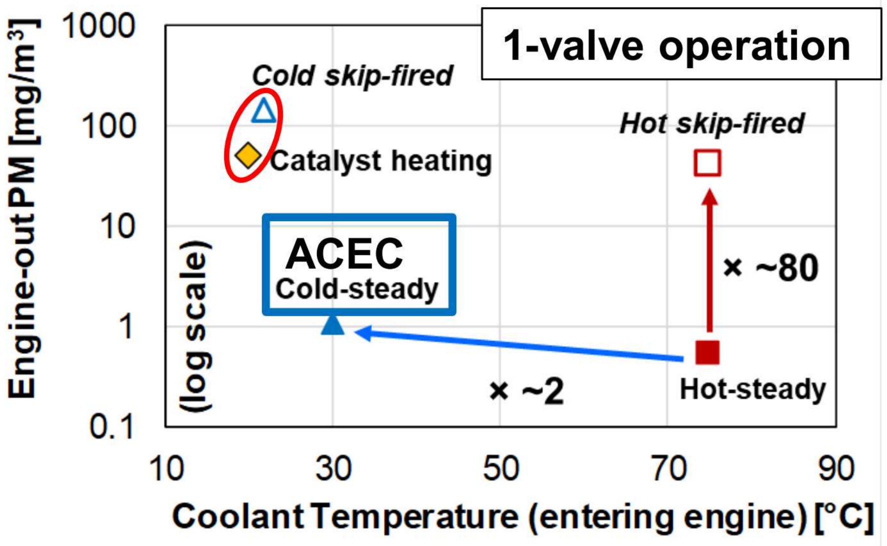


20/80 Skip-firing Strategy

- ACEC cold-start protocol does not reveal the true challenges of transient cold-start PM emissions.
  - Continuous firing (100% duty cycle) leads to high combustion chamber temperatures.
- Skip-firing reduces surface temperatures.
  - Provides PM challenges similar to transient cold-starting.
- What is "the best" skip-firing strategy?
  - Hot or cold? # cycles in each batch?
- Do all fired cycles contribute equally to PM/PN emission?

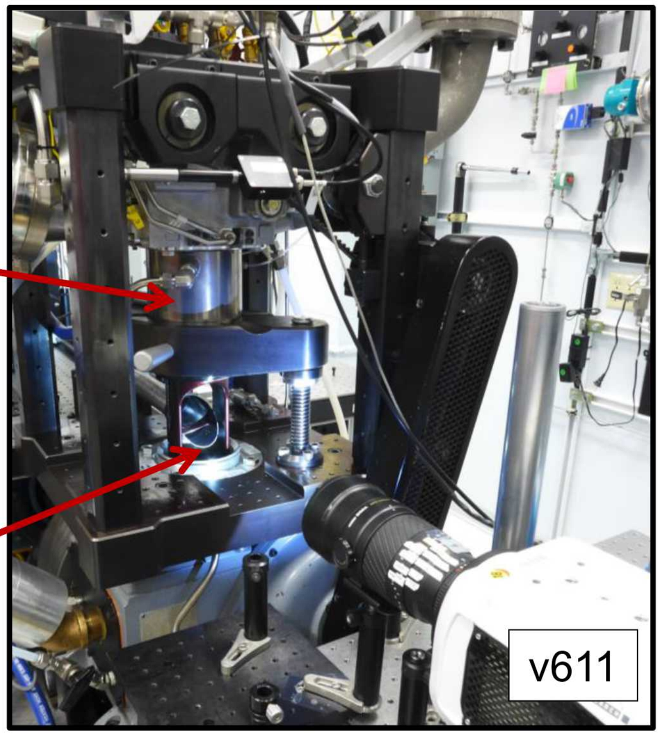


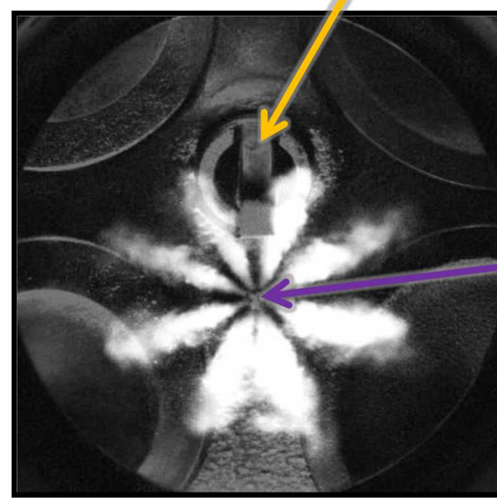




Optical Setup for Natural Luminosity Imaging

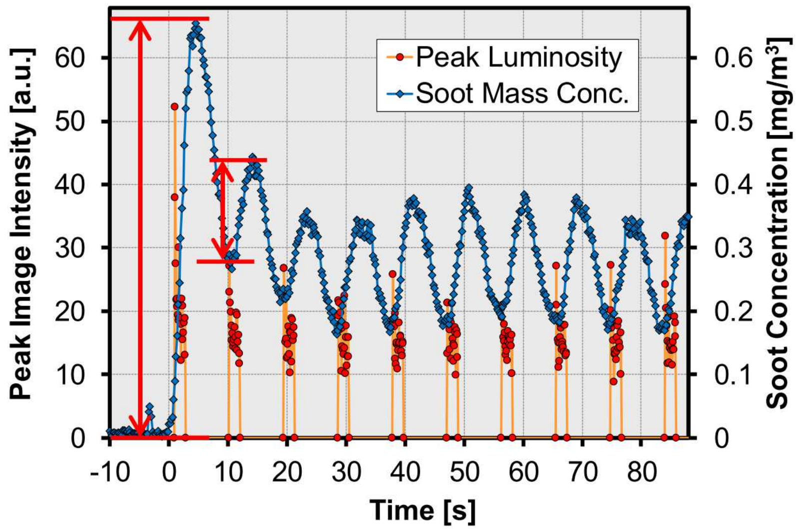
- Natural luminosity images from 20/80 skip-fired operation with $T_{coolant} \approx 20$ & 90°C .
- Variable image acquisition rate: 3.9 – 0.39 kHz (2° - 20°CA). 240 μs exposure.
- 512 x 512 pixel resolution. Aperture = f/8.

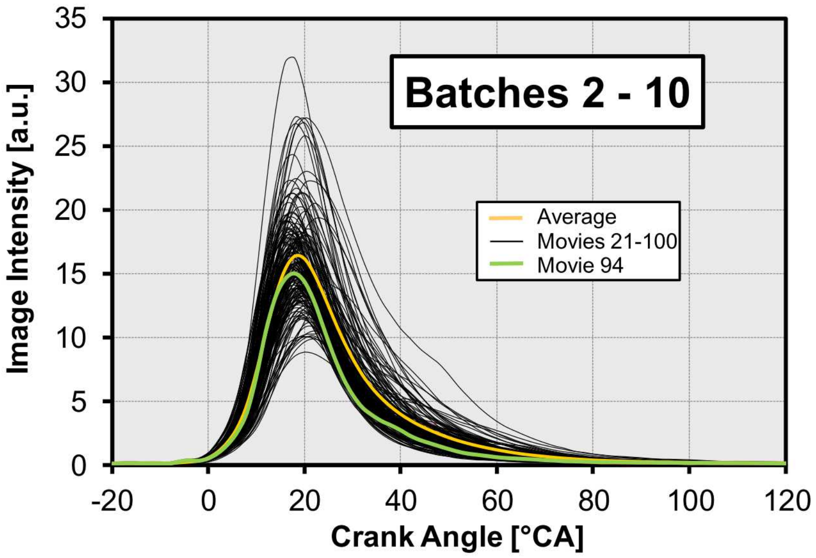


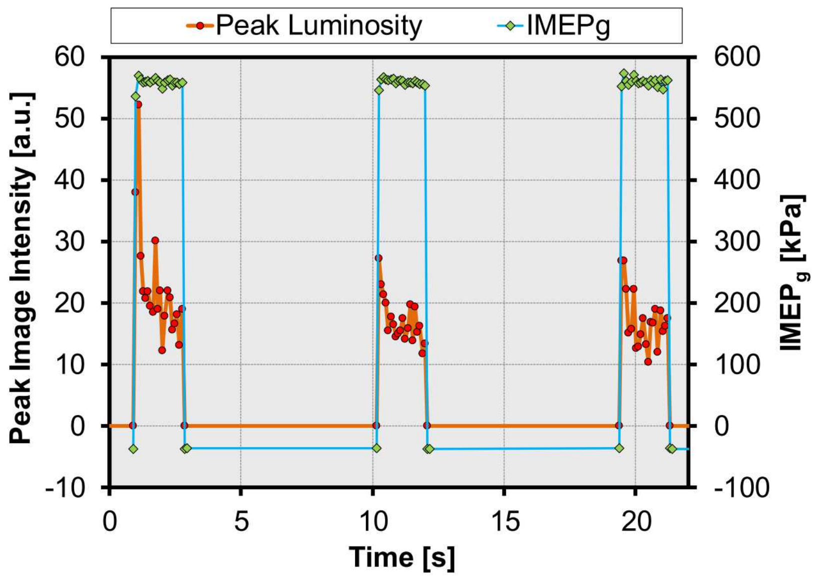


20/80 Operation with Imaging, $T_{coolant}$ = 90°C

- Tumble plate installed. Minimal motoring before data acquisition.
- Stable IMEP, except for first cycle.
- First batch of 20 fired cycles has excessive soot PM contribution.
- Subsequent batches are stable.
- Moderate variability of luminosity.

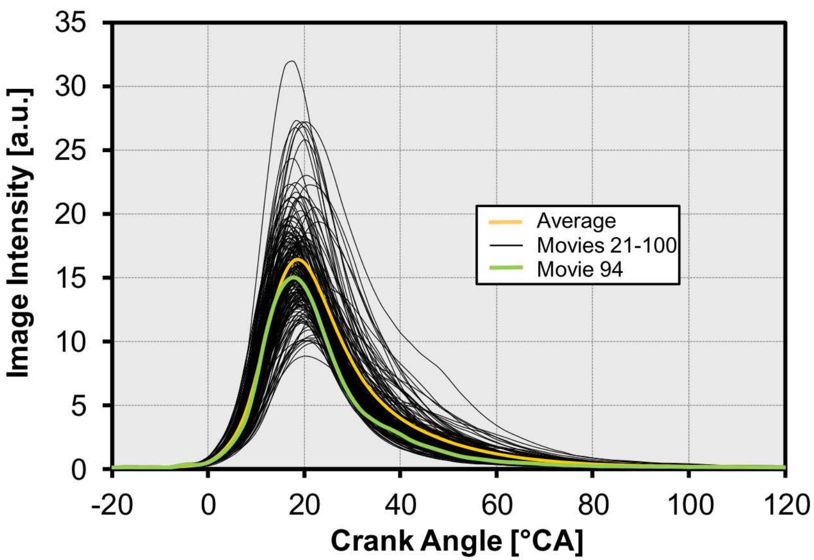


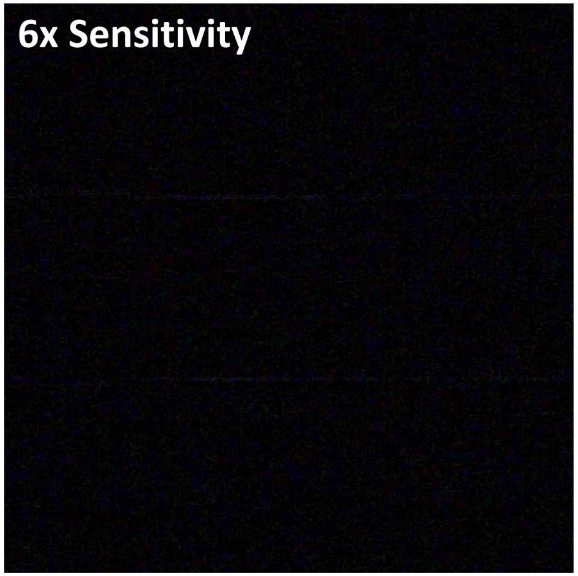


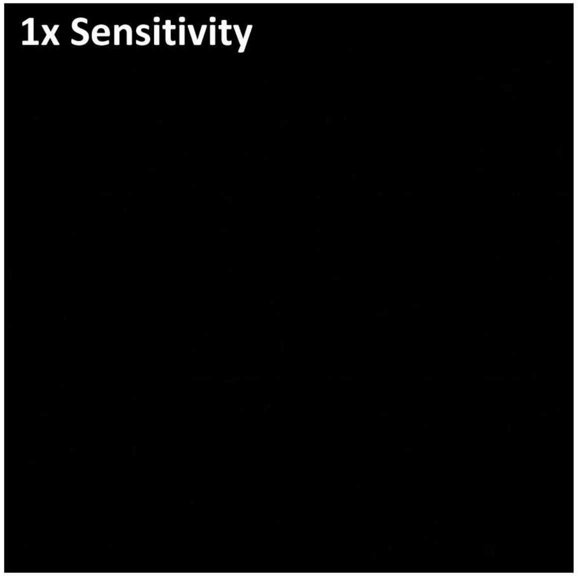


20/80 Operation with Imaging, $T_{coolant}$ = 90°C

- Mostly blue flame development.
- Scattered sooting flames.
- Diffusion flame attached to injector tip.

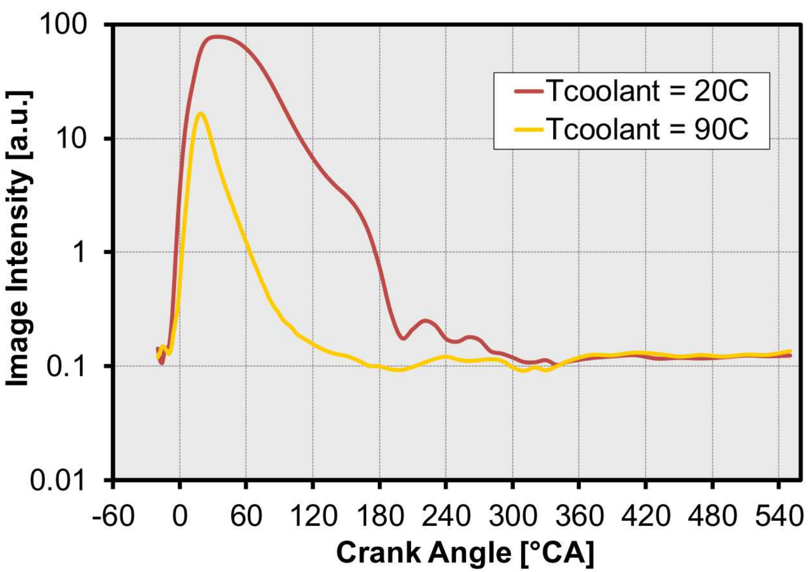


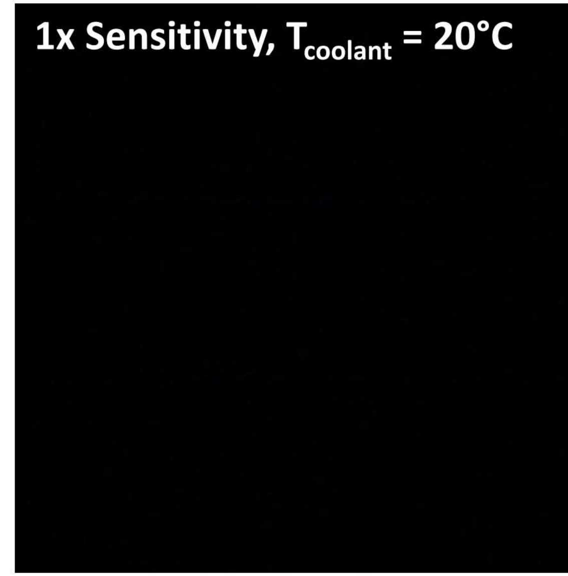


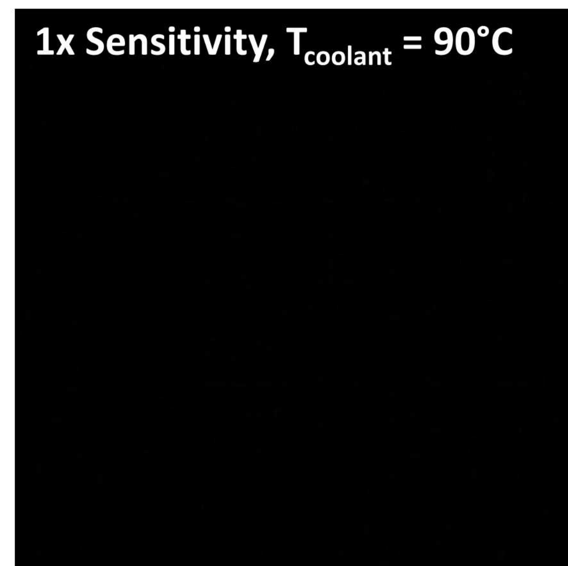


20/80 Operation with Imaging, $T_{coolant}$ = 20° vs. 90°C

- A reduction of $T_{coolant}$ leads to drastically increased soot luminosity.
  - Bulk-soot formation.
  - Persistent diffusion flames.
- Tumble flow convects flames near piston top across window.
  - Pool-fires along rim?

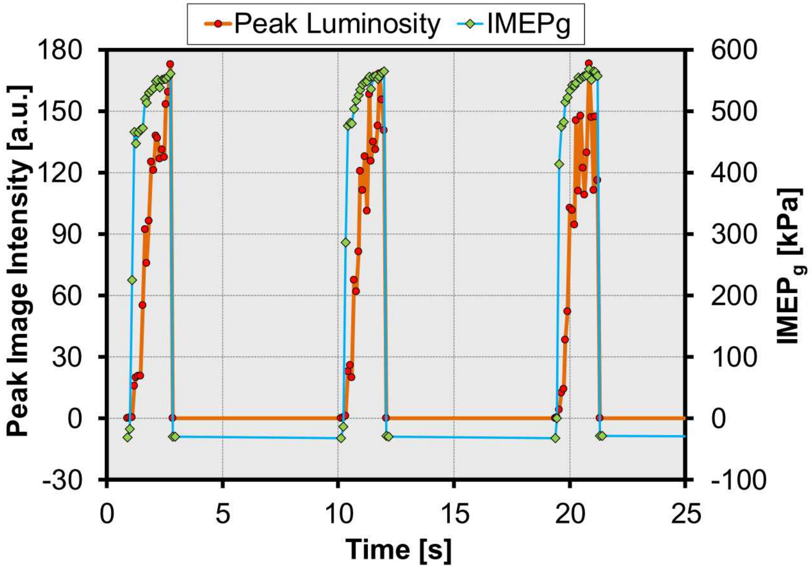


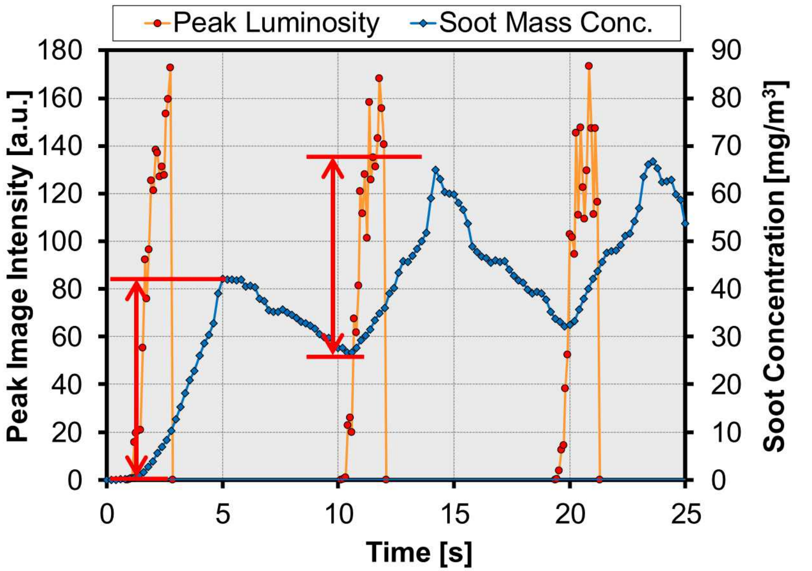




20/80 Operation with Imaging, $T_{coolant}$ = 20°C

- Ramp up of IMEP and luminosity for each batch.
  - Less soot PM contribution from early cycles in each batch of 20?
- Effect of poor fuel vaporization.
- Wall films may carry fuel from cycle to cycle. (See E30 example that follows.)
- Overfueling is required to match engine-out CO emissions expected for $\lambda = 1$ operation.
- Indicates loss to fuel to:
  - Lubricating oil on cylinder.
  - Leftover fuel after each batch of 20 cycles.
- Overall messy operation, but…
- …soot PM production is fairly consistent from batch to batch.

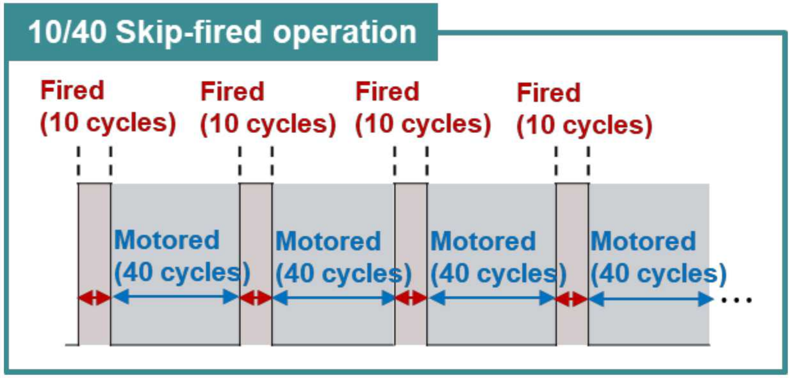


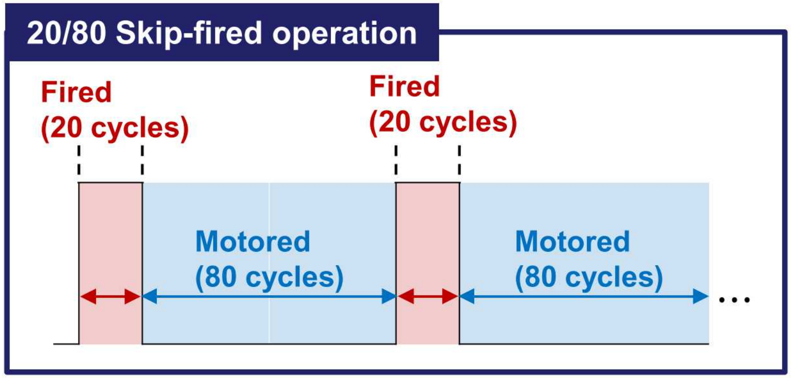


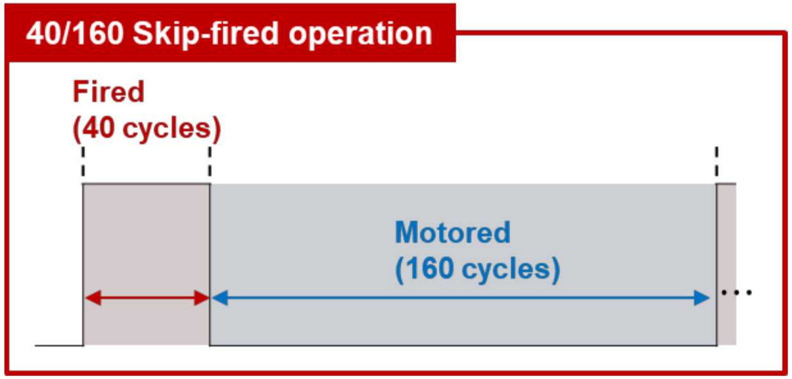
Alternative Skip-firing Strategies

- To confirm the trend of change in flame luminosities over cycles, additional skip-firing strategies were tested.
- 10/40 or 40/160 skip-fired operation has the same duty ratio, but different period of each batch.

Strategy	Duty ratio	Period
10/40		~ 4.62 sec
20/80	20%	~ 9.23 sec
40/160		~ 18.46 sec

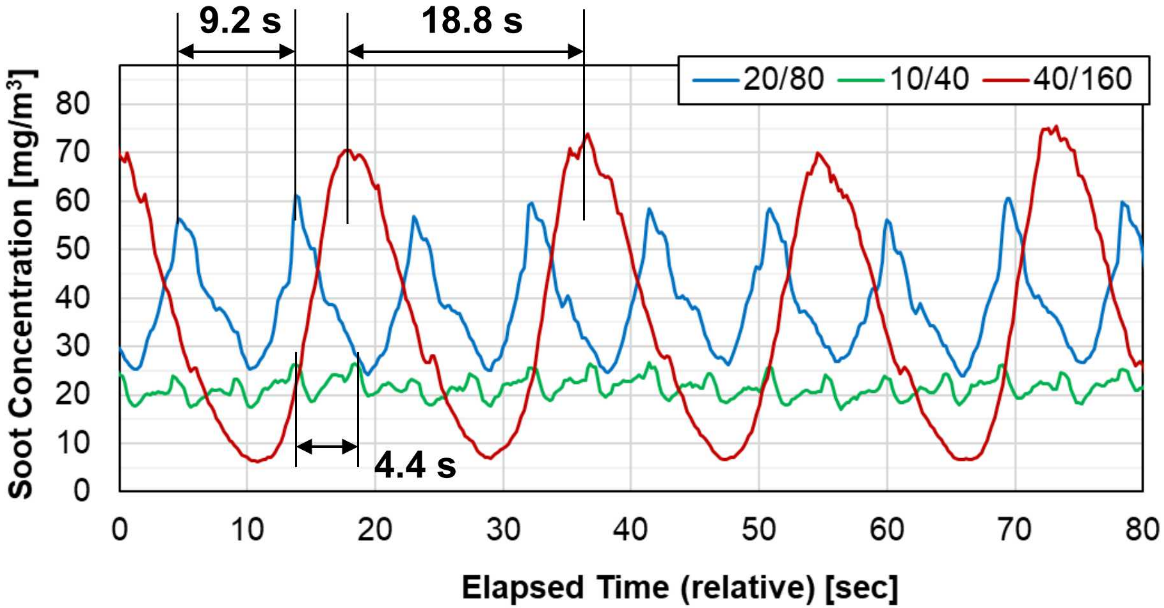


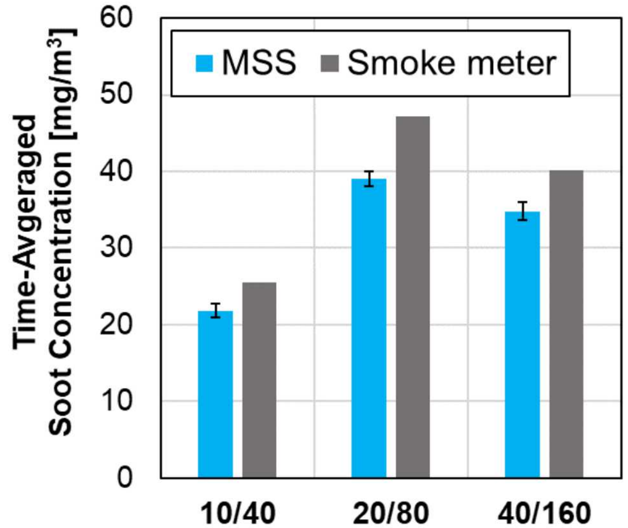




PM from Various Skip-firing Operations

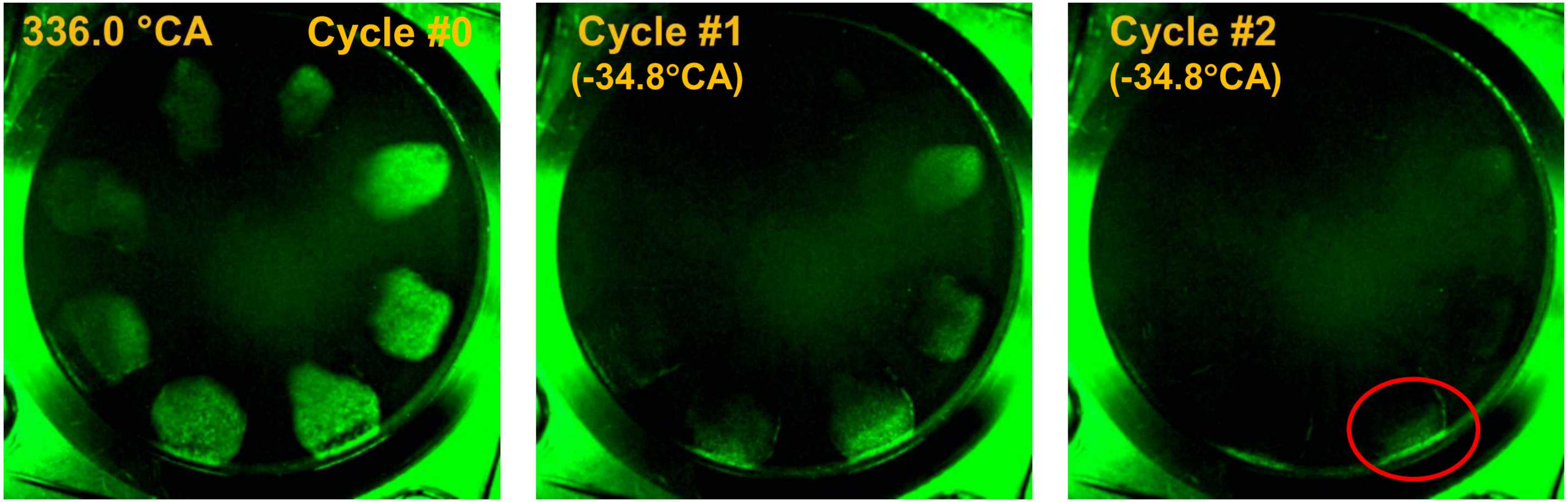
- $T_{coolant}$ = 22~25°C.
- The time-averaged PM indicates that use of 10/40 skip-firing strategy results in reduced PM level.
  - Smoke meter read-outs corresponds well with time-average of AVL Micro-Soot Sensor.
- Agrees with optical data from $T_{coolant}$ = 20°C case.
  - First few cycles of each batch burn poorly and do not produce soot much.





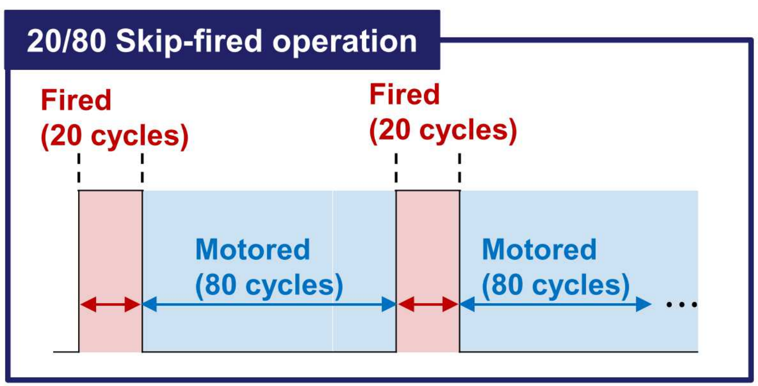
Cool Walls Promote Cycle-to-Cycle Interaction

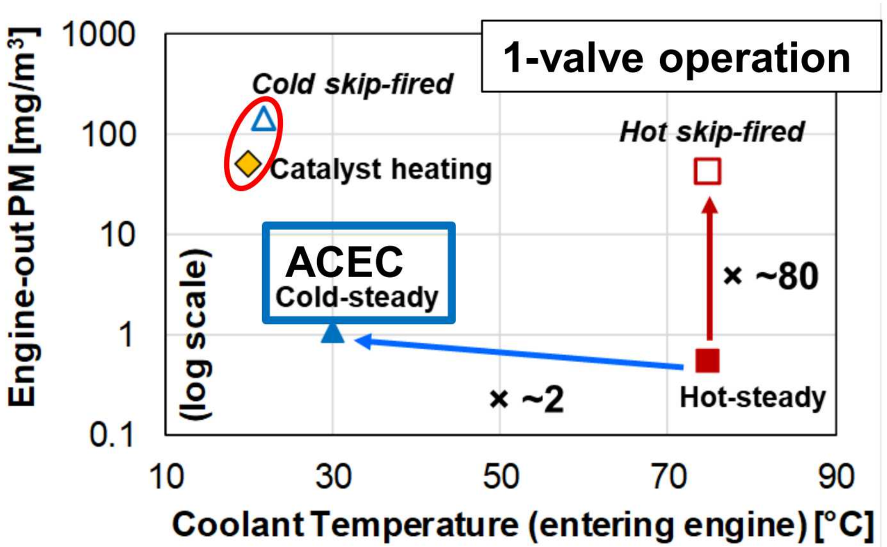
- $T_{coolant}$ = 20°C.
- Persistent wall films may carry fuel from cycle to cycle.
- E30 example for stratified-charge operation illustrates this.



Selecting a Skip-Firing Strategy

- ACEC cold-start protocol does not reveal the true challenges of transient cold-start PM emissions.
  - Continuous firing (100% duty cycle) leads to high combustion chamber temperatures.
- Skip-firing reduces surface temperatures.
  - Provides PM challenges similar to transient cold-starting.
- What is “the best” skip-firing strategy?
- 20/80 operation with $T_{coolant}$ in the 75°C range may be a reasonable compromise for our current research purposes.
  - Reduces challenges with persistent fuel films and associated cycle-to-cycle interactions.





Conclusions

- CFD modeling indicates that the selected intake-port blockage plate strongly increases the in-cylinder tumble level.
- The increased tumble has only a modest effect on the combustion for stoichiometric operation.
- The spark-plug protrusion has a very small effect on the inflammation and combustion stability for stoichiometric operation.
- PM and PN soot emissions with tumble plate were generally higher than for 1-valve operation.
  - Could indicate an effect on the fuel sprays from an altered cross flow.
  - However, a higher injector and/or combustion chamber fouling level may be responsible.
- Existing spray data highlight the importance of the intake-generated flow.
- Combustion stability, in-cylinder soot, and soot PM/PN exhaust levels are highly dependent on $T_{coolant}$ for skip-fired operation.
- For a low $T_{coolant}$ = 20°C, optical operation highlighted soot-production pathways:
  - 1. Bulk-gas soot.
  - 2. Piston-rim wall-wetting and pool fires.
  - 3. Diffusive combustion off fouled and wetted injector tip.

Future Work

- Clean the injector tip and investigate the role of injector fouling.
- Install Spray-G injector and repeat key operating conditions.
- Examine the use of 20/80 operation with $T_{coolant}$ = 75°C.
- Test multi-component surrogate of RD5-87.
- Acquire additional optical data, including side imaging.
  - Spray, wall-wetting, flame and combustion luminosity.
- Use PIV to quantify velocities in cross-flow field of the fuel spray.
- Modify piston to allow transient piston temperatures to be monitored.

Acknowledgements

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