Combined Effects of Flow/Spray Interactions and EGR on Combustion Variability for a Stratified DISI Engine

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Abstract

This study investigates combustion variability for a stratified-charge direct-injection spark-ignited (DISI) engine, operated with near-TDC injection of E70 fuel and a spark timing that occurs during the early part of the fuel injection. Using EGR, very low engine-out NO_x can be achieved, but at the expense of increased combustion variability at higher engine speeds. Initial motored tests at different speeds for liquid spray measurement reveal that the in-cylinder gas flow becomes sufficiently strong at 2000 rpm to cause significant cycle-to-cycle variations of the spray penetration. Meanwhile, in-cylinder flow measurements via swirl plane of view reveal that the swirl flow (before injection) contributes to the flow energy after the SOI, while the spray is the key to entrain and strengthen the swirl flow. To further understand how the spray entrains the flow, in-cylinder flow and spray measurements via tumble plane of view are implemented. These measurements are correlated with combustion thermodynamic measurements to reveal the effect of flow/spray interactions on the combustion variability. Here, the fired tests focus on operation at 2000 rpm with N_2 dilution ($[O_2]$ =19% and 21%) to simulate EGR.

Results reveal two types of flow/spray-interactions that predict the likelihood of a partial burn. 1) Proper flow direction before injection with a more collapsed spray leads to high kinetic energy of the flow during injection, thus generating a rapid early burn, which ensures complete combustion, regardless of the EGR level. 2) Improper flow direction and less collapsed spray generate low flow energy during the early phase of combustion. For this second type of flow/spray-interaction, application of EGR results in a partial-burn frequency of 30%, whereas without EGR, early combustion is shown to be insensitive to flow variations. Hence, having weak gas flow near the fuel spray during injection is thought to be one mechanism that contributes to the appearance of partial-burn cycles.

U.S. DEPARTMENT OF ENERGY

Office Vehicle Technologies
Program Manager: Kevin Stork

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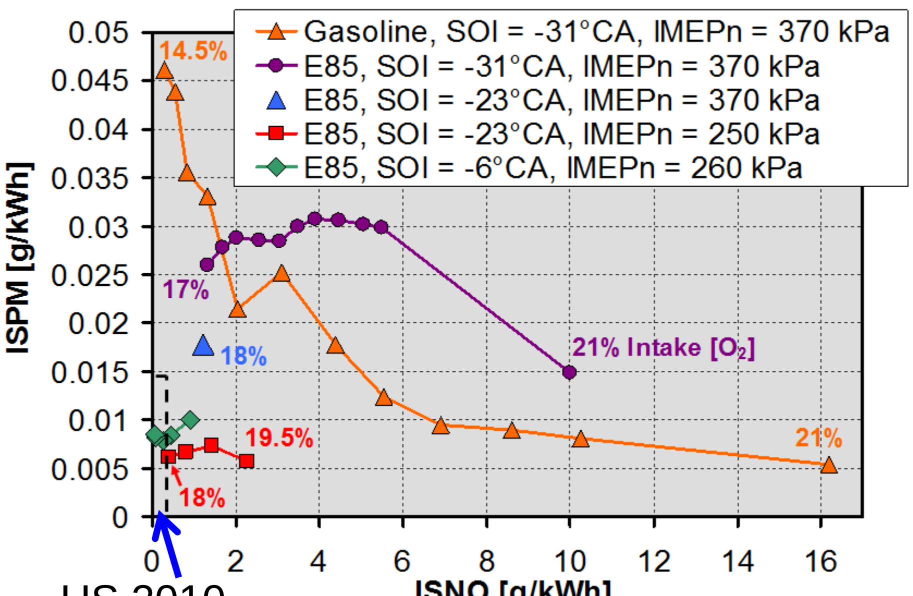
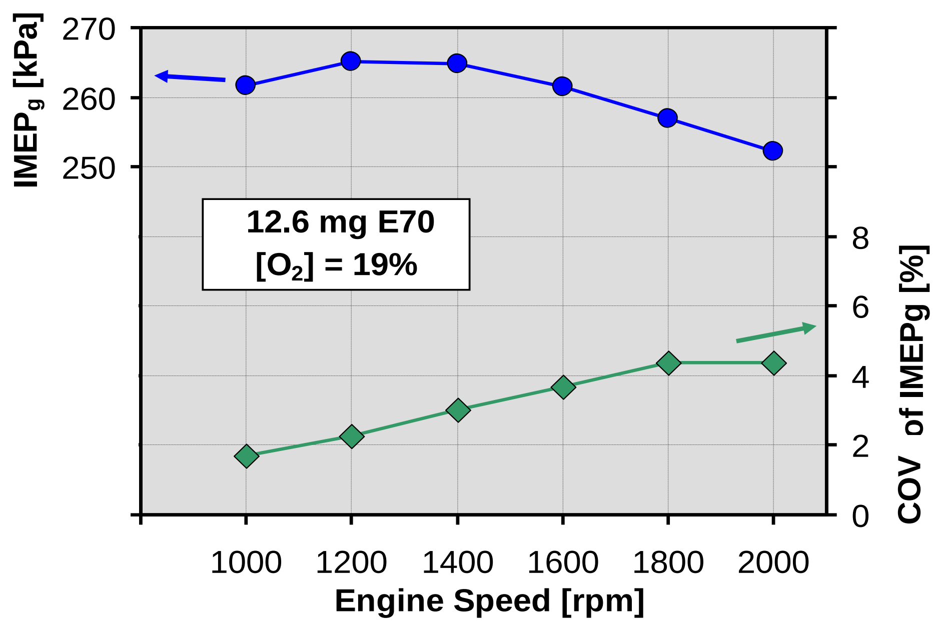
Introduction – Stratified DISI combustion with E85

- High efficiency can be achieved in spark-ignited engines using un-throttled stratified-charge combustion at low to moderate loads
- Inhibited by the need for lean-NO_x aftertreatment.
- Legislated levels of engine-out NO_x and soot can be achieved when using EGR combined with high ethanol fuels (SAE 2012, Proc. Comb. Inst 2013, AEC 2013)
  - *E85 allows near-TDC injection which enables closely coupled injection and combustion.*
  - This low NOx operation is challenged by increased engine speed (AEC 2013, SAE 2014).



US 2010 emission box



Introduction – Combustion variability

- With a goal of expanding operating range (from 1000 to 2000 rpm) and understanding the sources of combustion variability, PIV measurements (AEC 2013 August, SAE 2014-01-1237) revealed
  - The liquid spray does dominate the flow during injection (spray-induced-flow generated by flow/spray interactions) and the subsequent heat-release rate.
  - But the in-cylinder flow before injection contributes to the cycle-to-cycle variation, especially at 2000 rpm.

- Here, we focus on

  a) Correlating spray, flow and flame measurements with combustion variability for operation with EGR at 2000 rpm

  b) Revealing the role of the in-cylinder flow for liquid-spray structure

  c) Revealing the collapsing-spray impact on high-swirl gas-flow entrainment

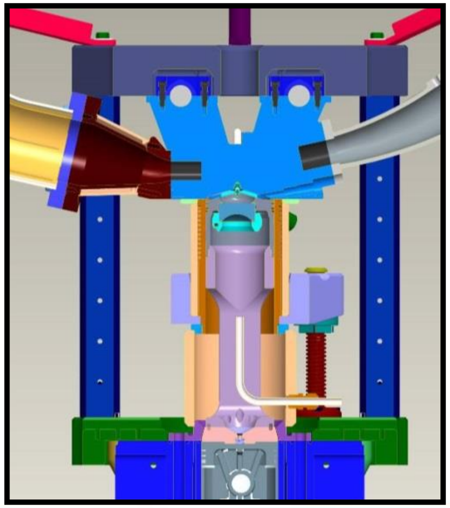
Single Cylinder DISI Engine

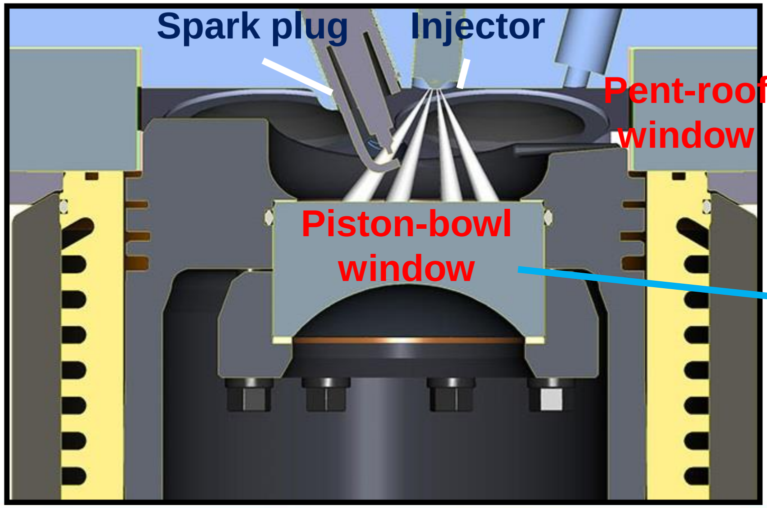
Two configurations

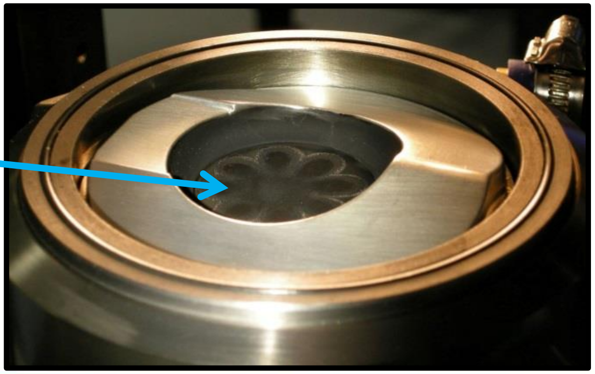
- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston.
- <u>Optical:</u> Pent-roof, piston-bowl, and 45° Bowditch mirror.
- Identical geometry for both configurations.
- 8-hole injector with 60°included angle
- Spark gap is in between two spray-plumes.

- Swirl/tumble generated by deactivating one of the intake valves
- Focus on stratified operation

Parameter	Current Study
CR	12
Bore/Stroke	86.0/95.1 mm
Swept volume	0.55 liter
Piston Bowl	∅ 46 mm
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Swirl/tumble Index	2.7/0.62
# of Injections	Single
Spark Energy	106 mJ
$T_{coolant}$	75°C
T_{in}	26-28°C
$P_{exhaust}$	100 kPa







All-metal engine experiments

- Quantify the effect of EGR on combustion and establish the conditions for optical experiments
  - 2000 rpm for strong flow variation
  - N_2 dilution to simulate EGR
  - Implement near-TDC injection
  - Maintain CA50 = 7-8°CA ATDC
- Constant injection pressure and mass injection rate
- High ethanol level fuel (E70)

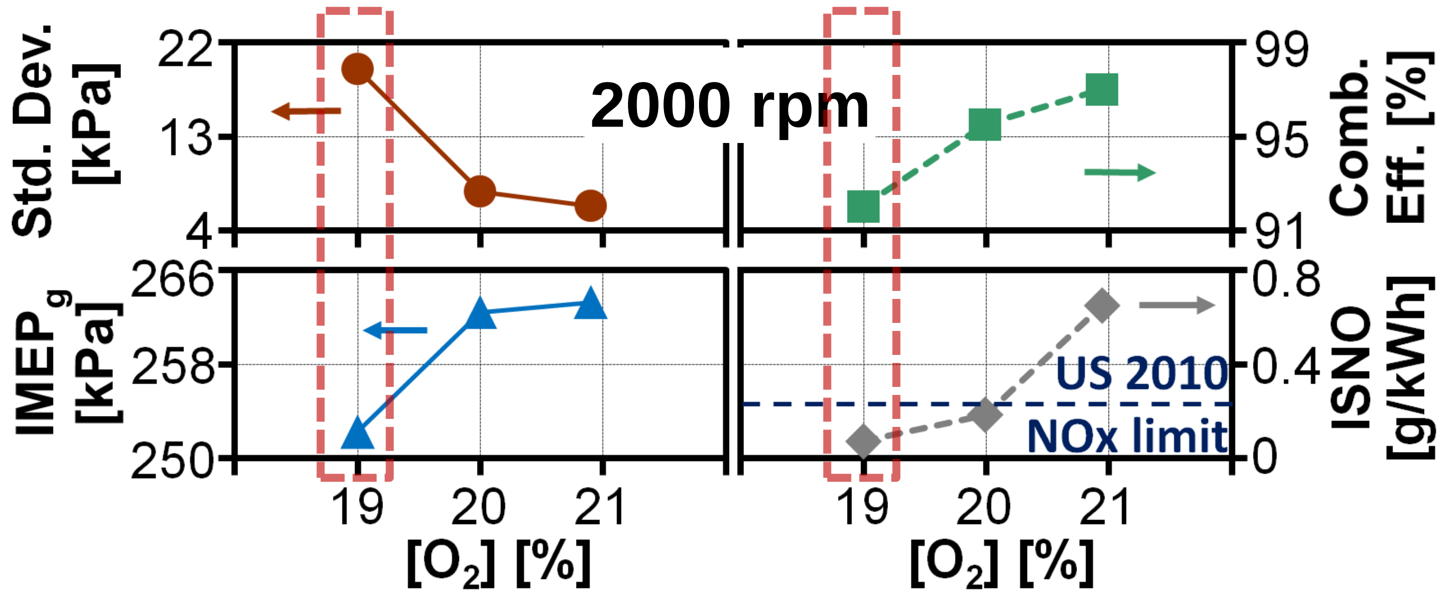
Test Configuration	$[O_2]$	SOI/ST(ºCA	RPM
1.All-metal	21%	-16/-14	2000
2.All-metal	20%	-18/-16	2000
3.All-metal	19%	-21/-19	2000

Injection-duration/Mass	0.925 ms /12.6 mg
Injection pressure/Fuel	17 MPa / E70

- Acquire in-cylinder pressure with 0.1° CA resolution for 500 consecutively cycles
- Compute apparent heat-release rate (AHRR) using a constant ratio of specific heats (γ)

EGR effect on engine combustion and emission

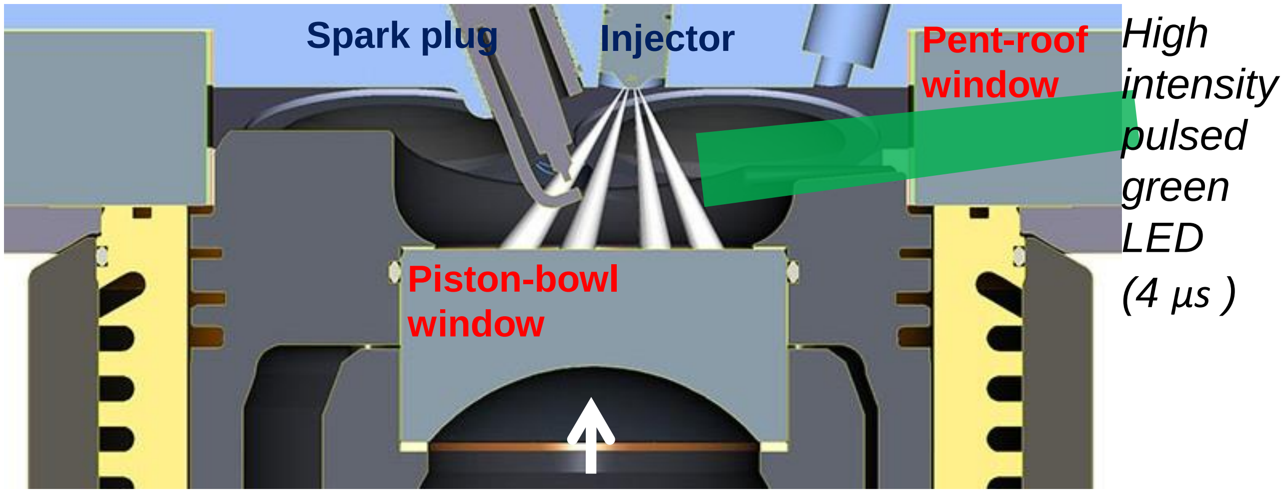
- For low [O_2] (high EGR rate), decreased NO, but elevated Std. Dev.
- Flow is much stronger at 2000 rpm (AEC 2013 fall, SAE 2014-01-1237 & 1241)
- Hypothesis: flame weakens sufficiently to the point of being susceptible to variations of flow/spray, degrading the Comb. Eff., thereby elevating the variability of $IMEP_g$
- Motivates the optical study: effects of flow/spray interactions on combustion variability with EGR ([O_2]=19%)



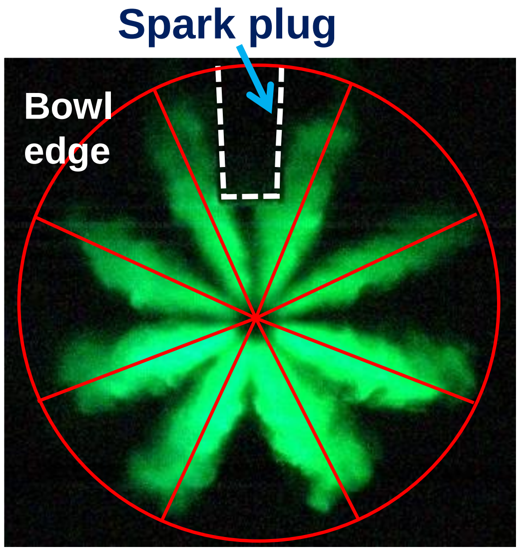
Liquid spray measurements

- To reveal the role of in-cylinder flow variability on liquid jets
- Disparate engine speeds (thus large differences of the flow variations)

Test Configuration	SOI (ºCA	RPM
4.Spray meas. (no ignition)	-22.8	2000
5.Spray meas. (no ignition)	-22.8	333



Camera (Phantom v6.11 color) view for spray



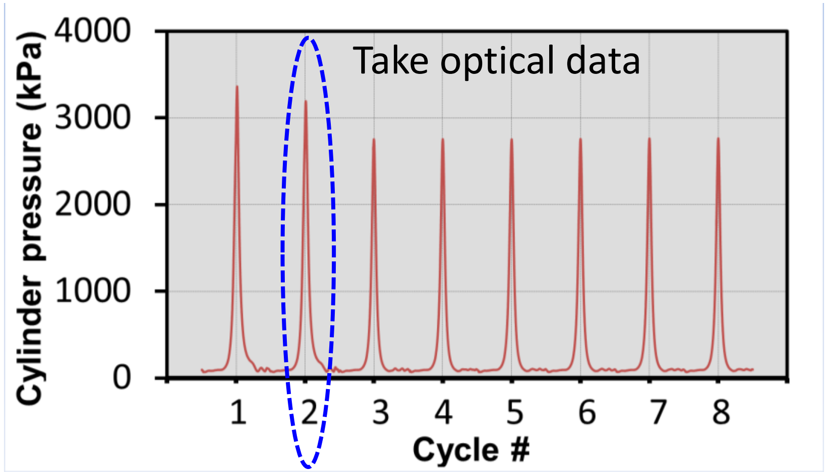
The overlay indicates the expected jet directions based on averaged images

Simultaneous flow, spray and flame measurements

- Combined effects of Flow/spray interaction and EGR on combustion variability

Test Configuration	$[O_2]$	SOI/ST(ºCA	RPM
6.PIV/flame/spray	21%	-21/-19	2000
7.PIV/flame/spray	19%	-21/-19	2000

- Fired optical engine operation,
  - Fire2-Skip6 sequence to reduce the heat load
  - Take data at the 2rd fired cycle of each sequence to ensure proper temperature and composition of the residual gases

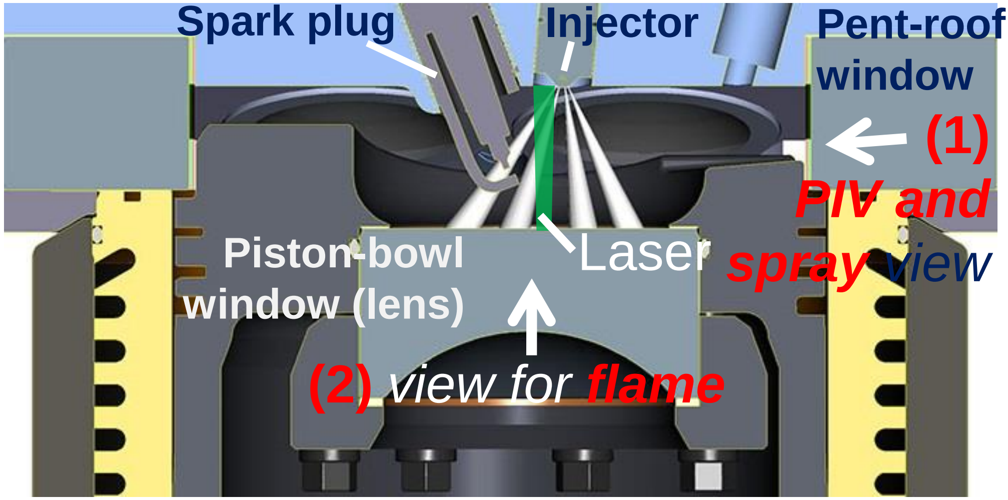


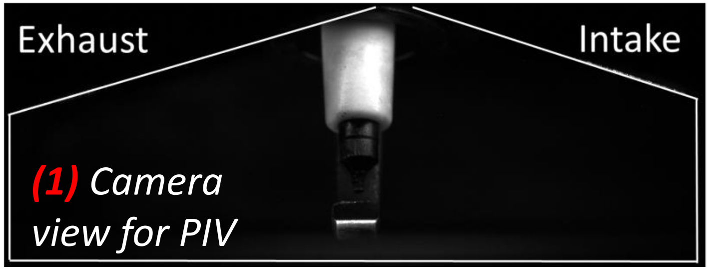
Fired optical engine operation

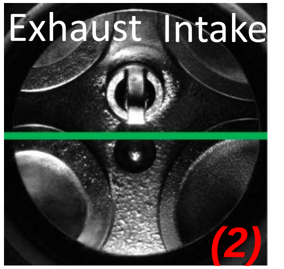
Optical setups for PIV

For vertical PIV (view of tumble plane)

- 532 nm laser
  - 120 ns pulse duration, 12 kHz
- Phantom v7.10 for flow and spray (pent roof)
  - 12 kHz (1200x440 resolution)
- Phantom v7.1 for flame natural emission (piston bowl)
  - 12 kHz (512x512 resolution)
  - 532 Notch filter to reject laser light.

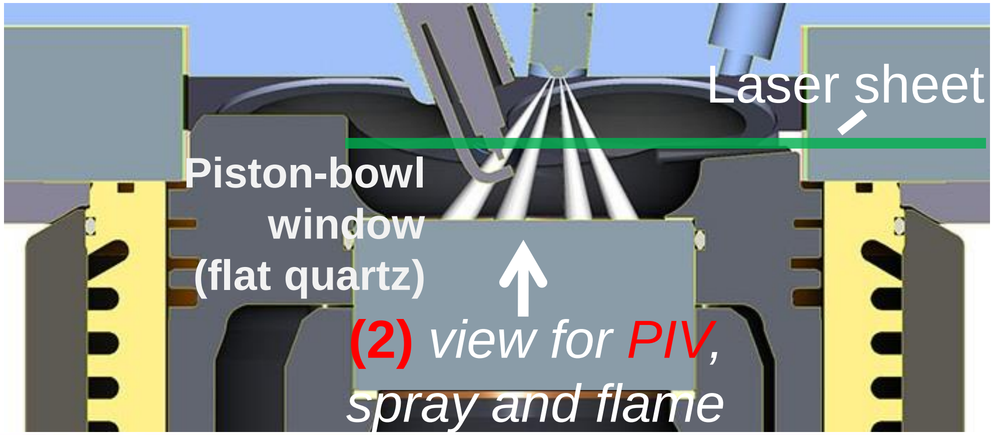






For horizontal PIV (view of swirl plane)

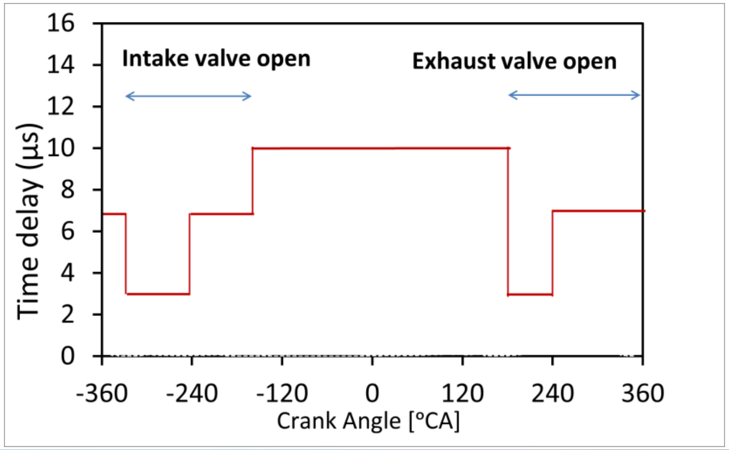
- V7.10 camera
  - 24 kHz (736x736 resolution)



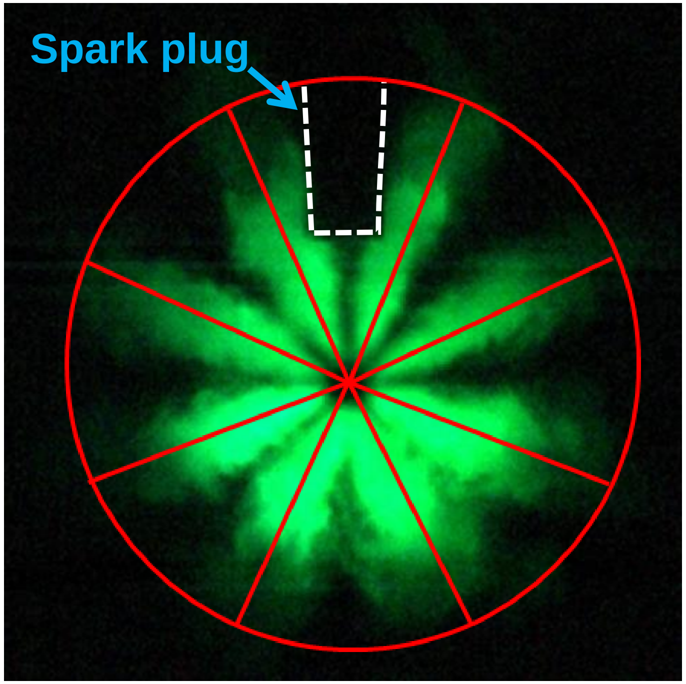
PIV measurement

- PIV setting and post-processing parameters (SAE 2014-01-1237)
  a) In-plane resolution of 1 mm
  b) Increased out-of-plane displacement due 2 mm laser sheet (perspective error, 10%)
  c) The valid-vector rate is greater than 85%
- Keep parameters constant, except the time delay between two image-frames (Δt)
- Varied Δt for different CA range due different dynamic range of velocity magnitude (SAE 2013-01-0542)
  a) X, Y displacements < 8 pixels (quarter of interrogation window size)
  b) 85% vectors > 0.15 RMS pixel displacement (PIV resolution)

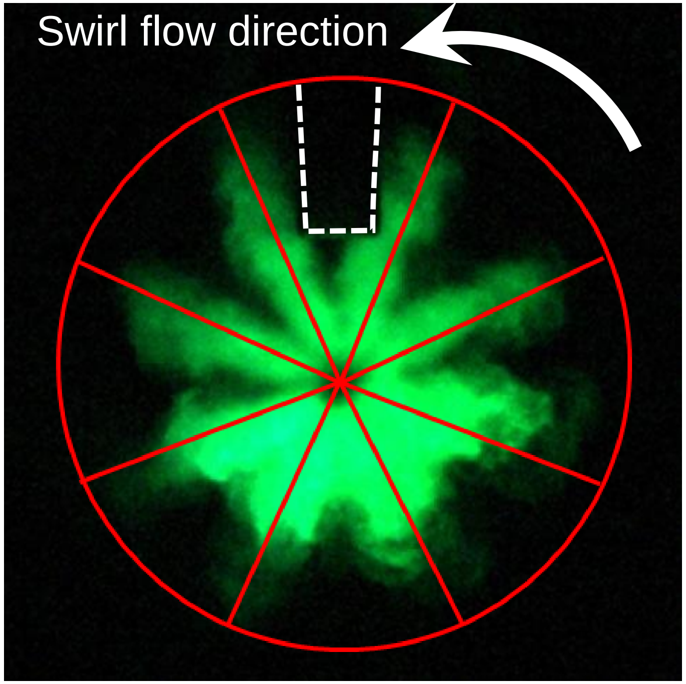
Key parameters	Current Study
Seed droplet diameter / laser sheet thickness	≈10~30 particles per window / 2 mm
Interrogation window size (Multi-pass)	128×128 to 32×32 with 50% overlap
Magnification for both horizontal and vertical PIV	0.7
Field of view (vertical PIV)	48×17.5 mm
Pixel resolution (vertical PIV)	1200×440
Field of view (horizontal PIV)	31×31 mm
Pixel resolution (horizontal PIV)	736×736
Spatial resolution for both horizontal and vertical PIV	≈ 0.96 mm < in-cylinder flow scales (1-10mm)



Spray development in individual cycles



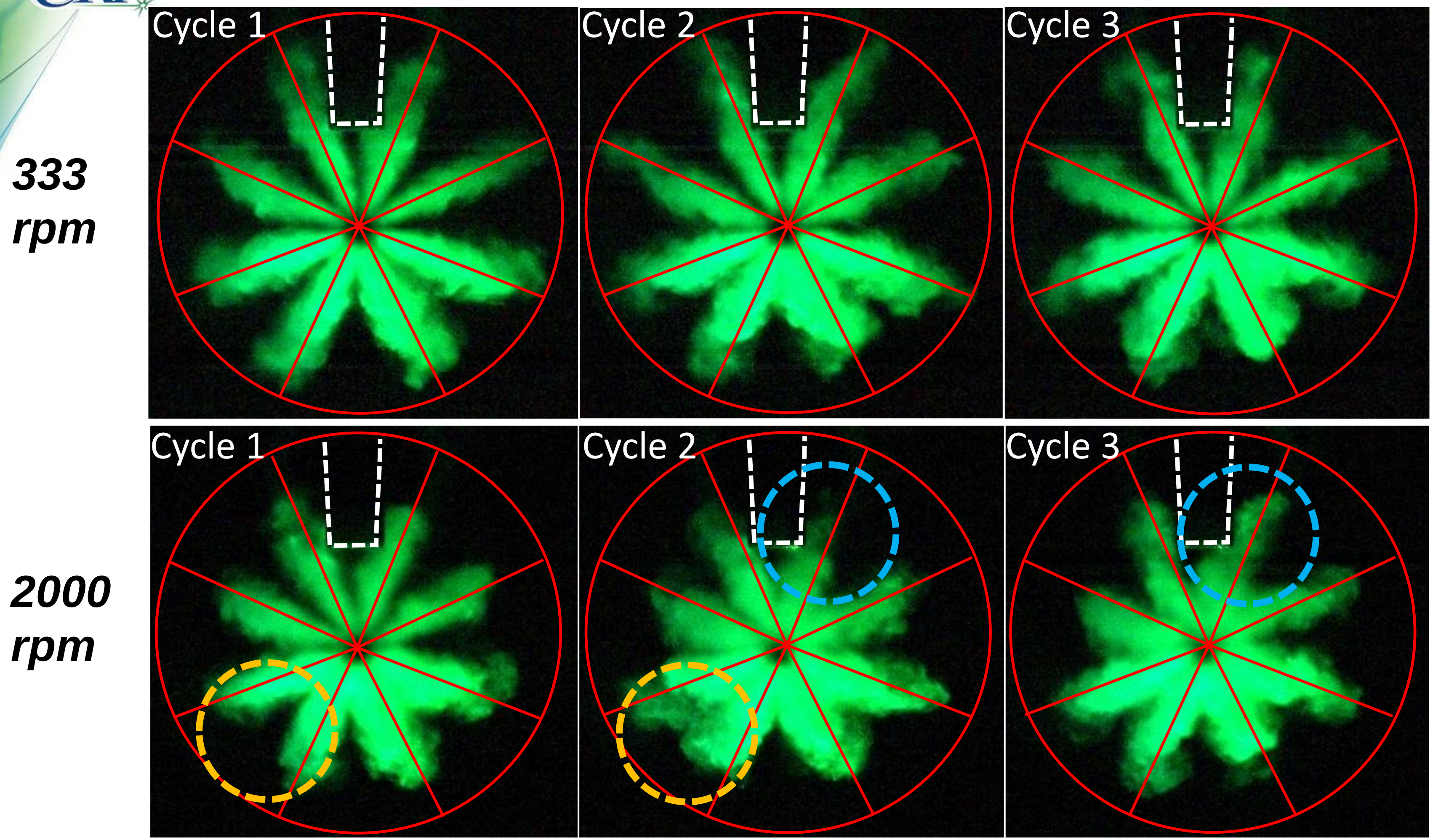
250 us ASOIa (-19.7 °CA)



250 us ASOIa (-15.6 °CA)

- A more collapsed spray at 2000 rpm
- At 2000 rpm, liquid jets start to rotate with the swirl flow at the very beginning of the injection duration

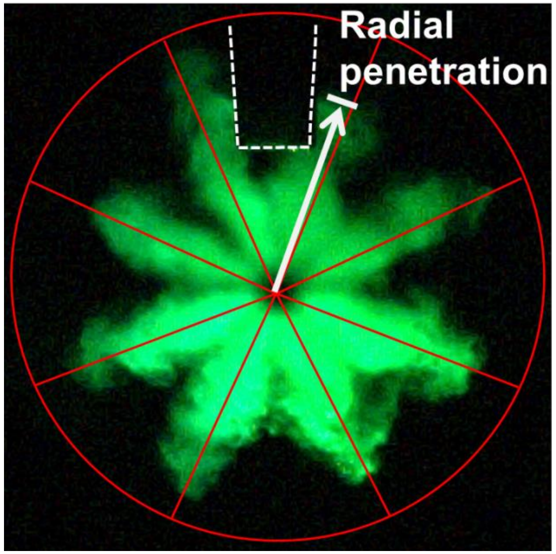
Spray variations at 20% injection duration

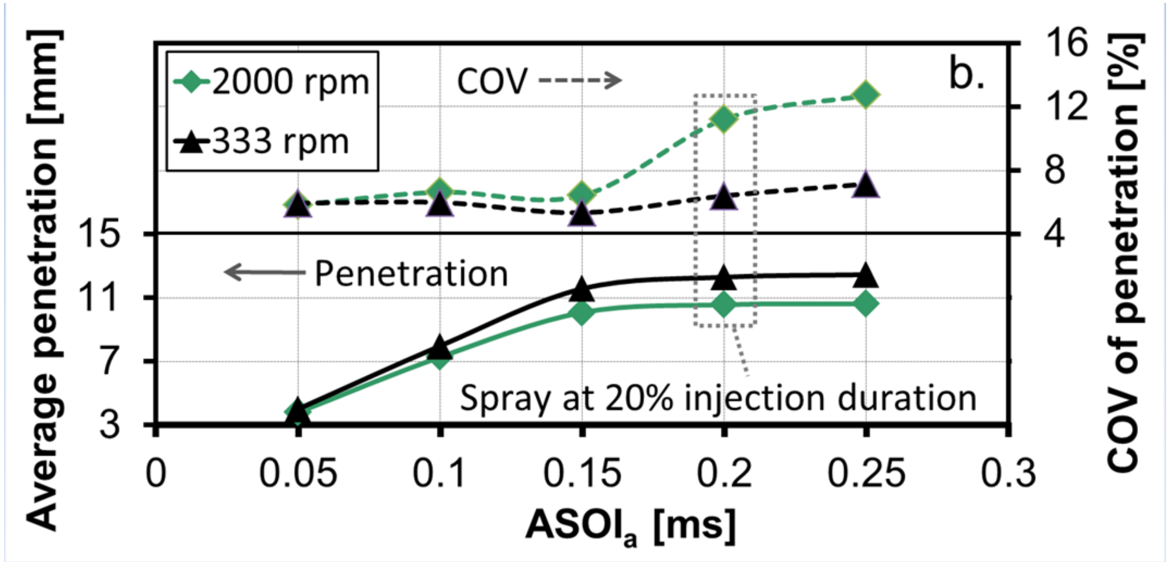


- Observe more significant variations in plume spread and jet penetration at 2000 rpm

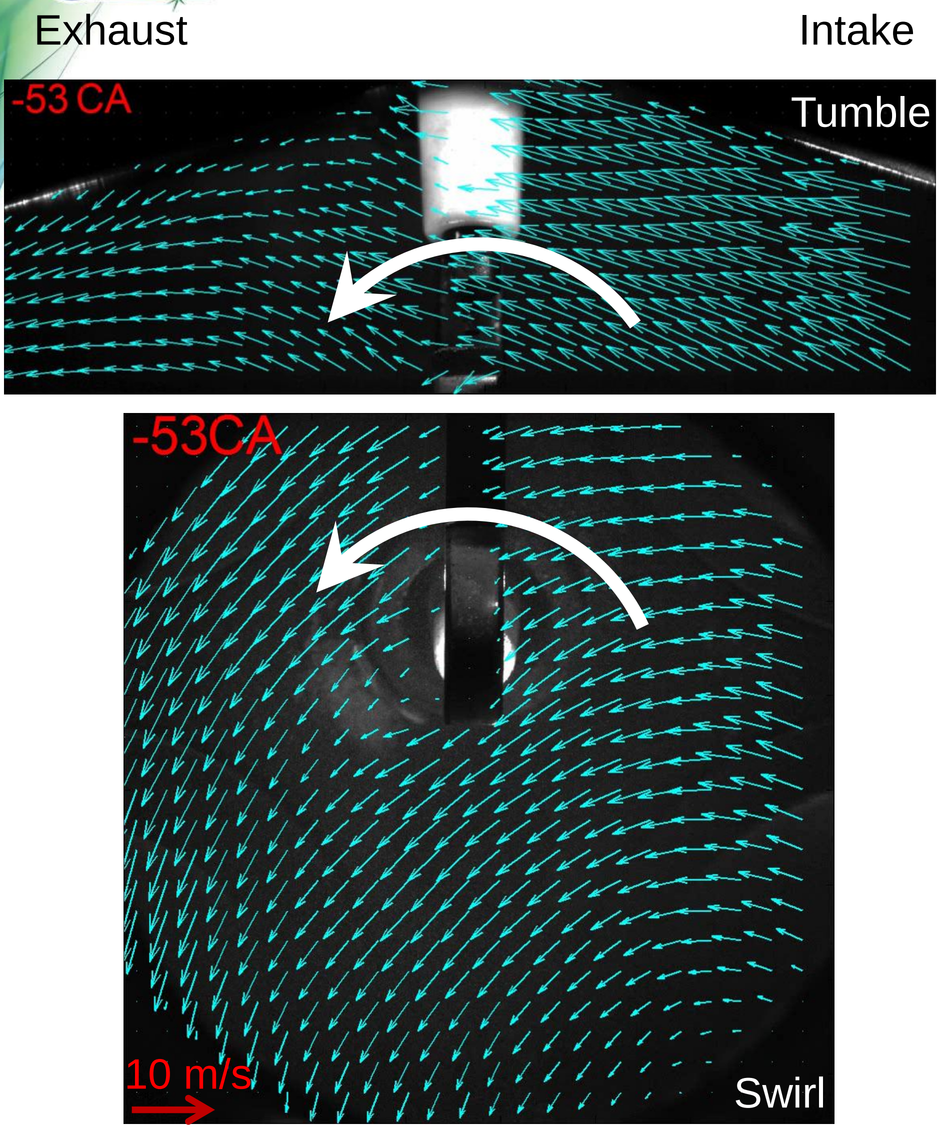
Jet penetration variations

- At 0.2 ms ASOI, the COV doubles at 2000 rpm.
- The in-cylinder flow becomes sufficiently strong to impact the liquid jet at 2000 rpm.
- Higher density at 2000 rpm may contribute (short penetration at 0.2 ms ASOI), while density only increases 14%.

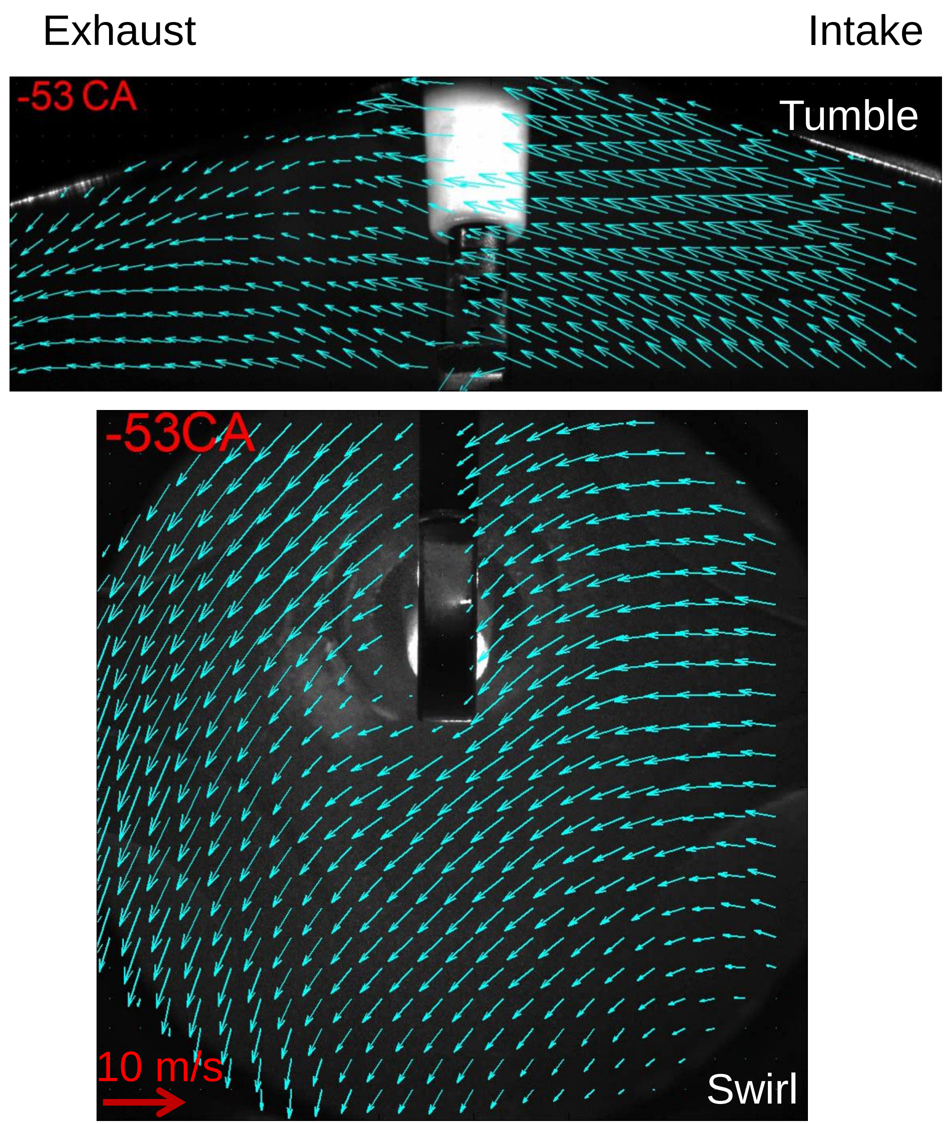




Injection effect on mean flow evolution



Without injection

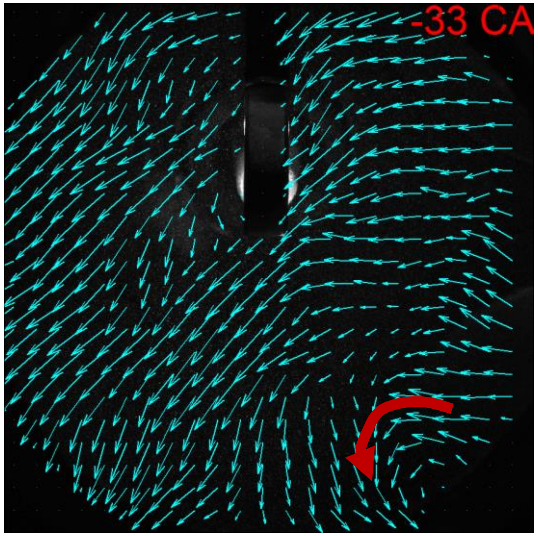


With injection

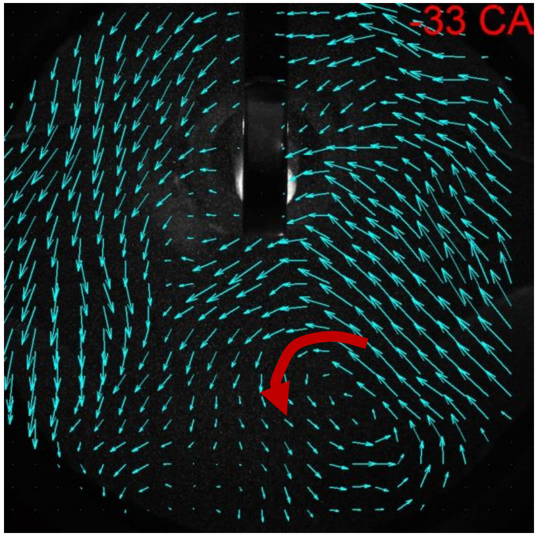
Individual cycles via swirl plane of view

Just before liquid enters chamber

No injection

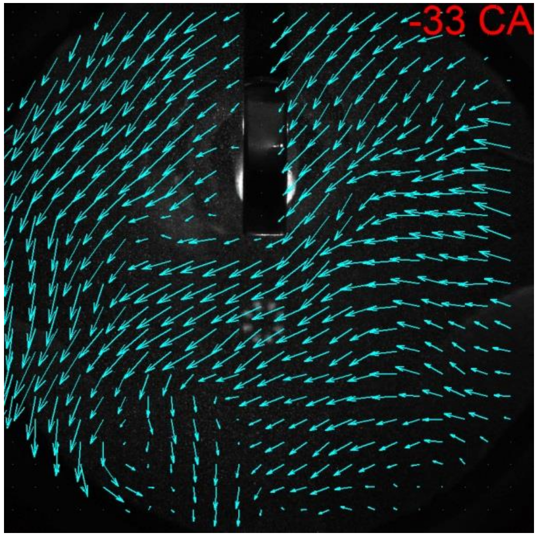


Case 1

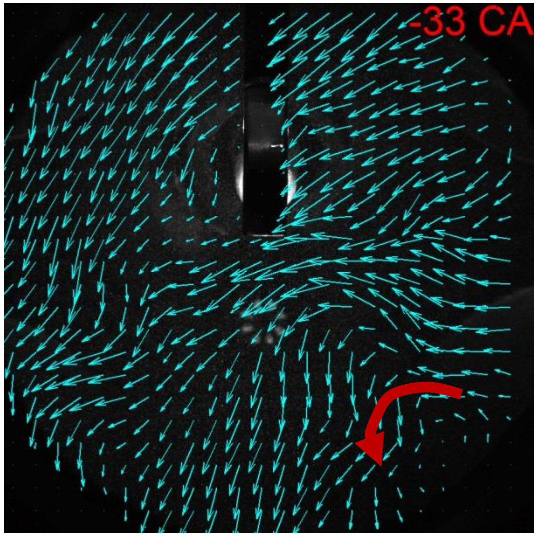


Case 2

Injection



Case 1



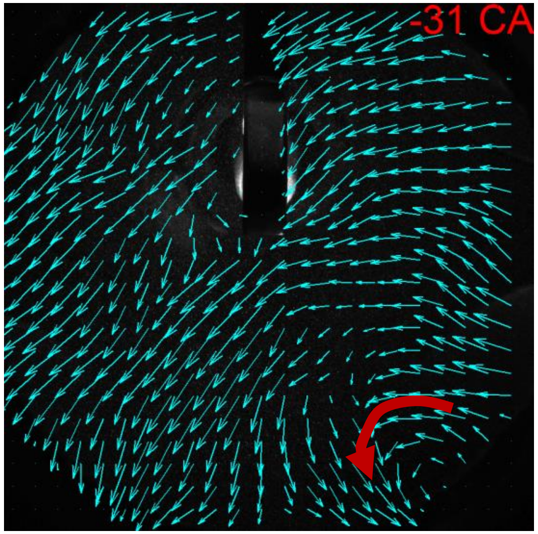
Case 2

- Location of swirl center is random

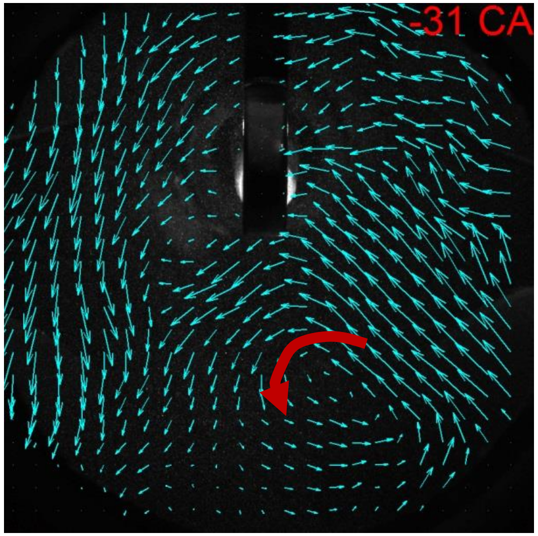
Individual cycles via swirl plane of view

About 20% injection duration

No injection

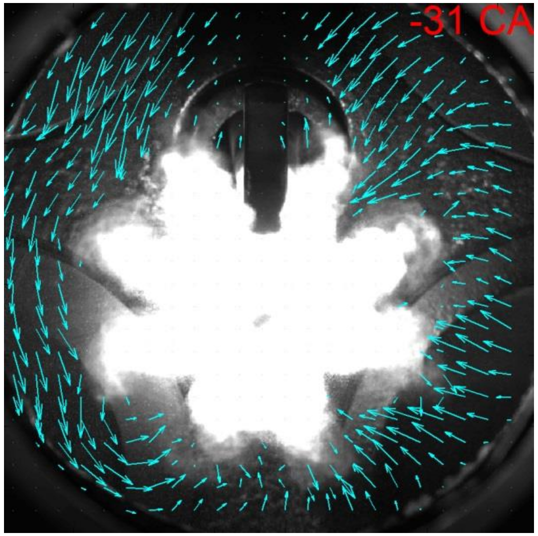


Case 1

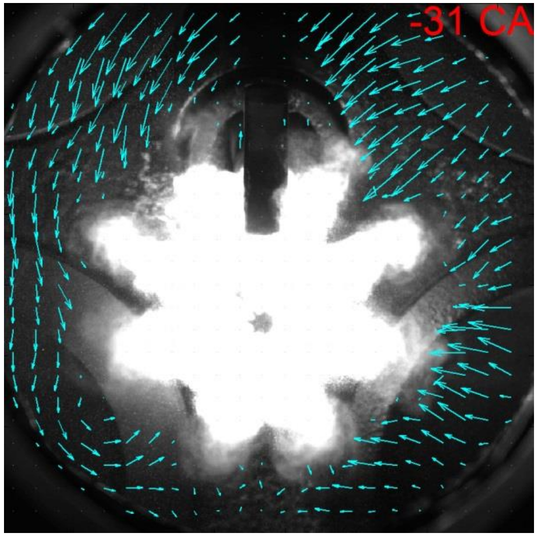


Case 2

Injection



Case 1



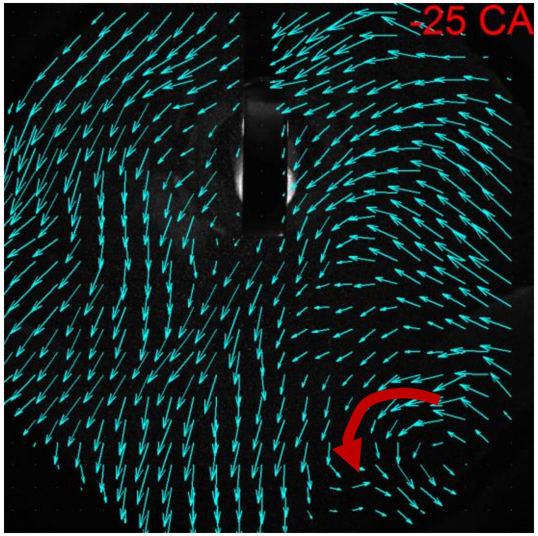
Case 2

- Random swirl center for no-injection case
- Only show gas-flow vectors

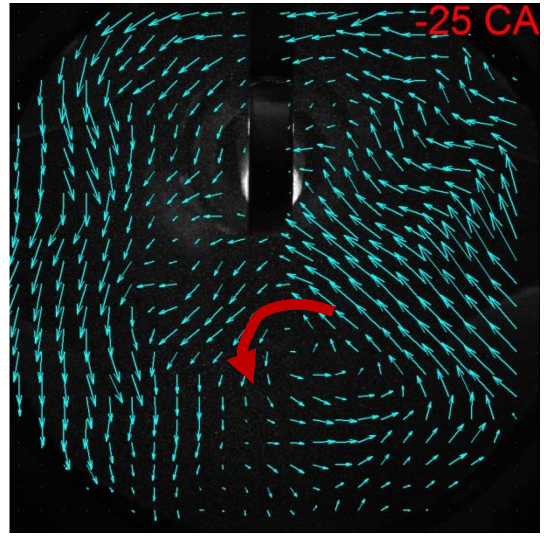
Individual cycles via swirl plane of view

About at the end of injection

No injection

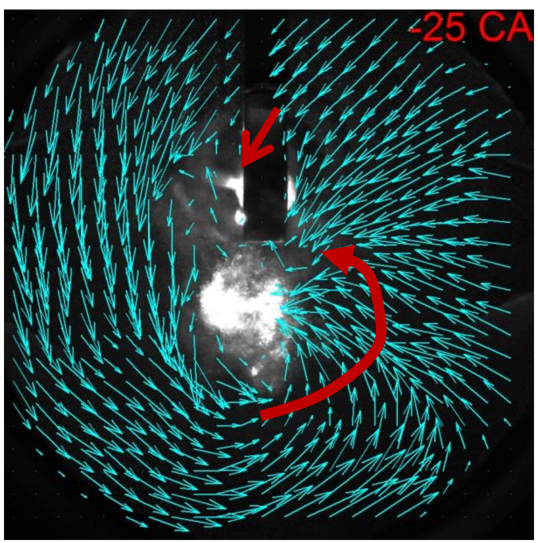


Case 1



Case 2

Injection



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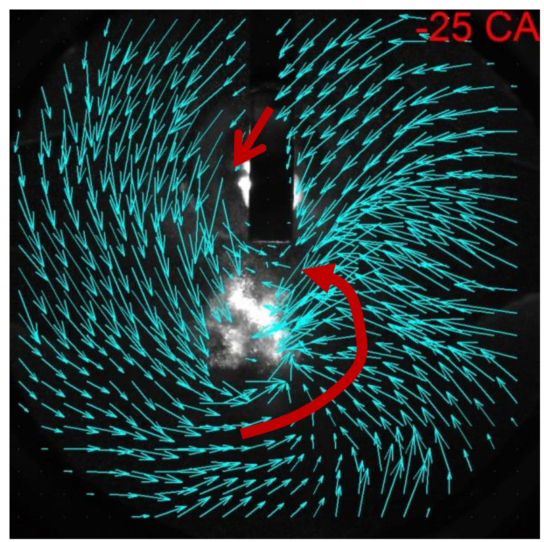


Case 2

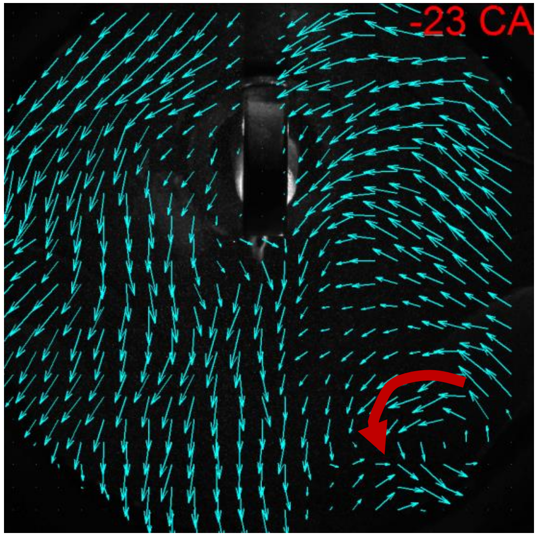
- Gas entrainment by spray moves gas radially outwards and downwards
- Gas with higher angular momentum near bowl rim flows to center to replace the spray-displaced gas.
- Causes high rotational speed near spray centerline
- Swirl center perfectly exists at the spray centerline for all cycles

Individual cycles via swirl plane of view

About at the end of injection

- Early kernel

No injection



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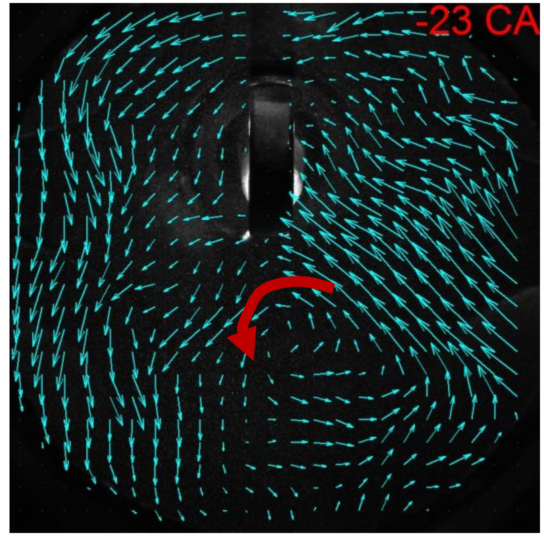
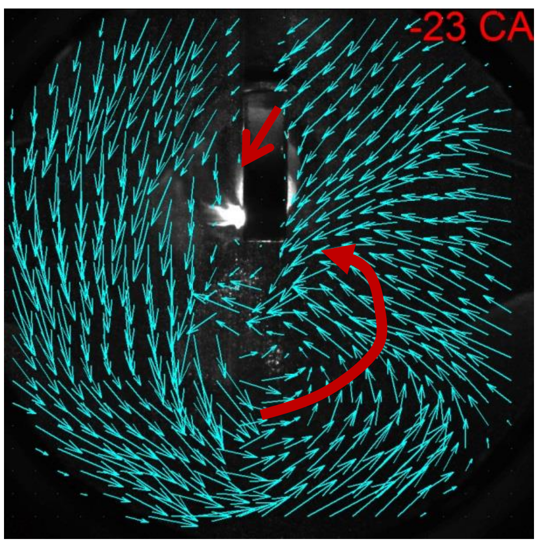
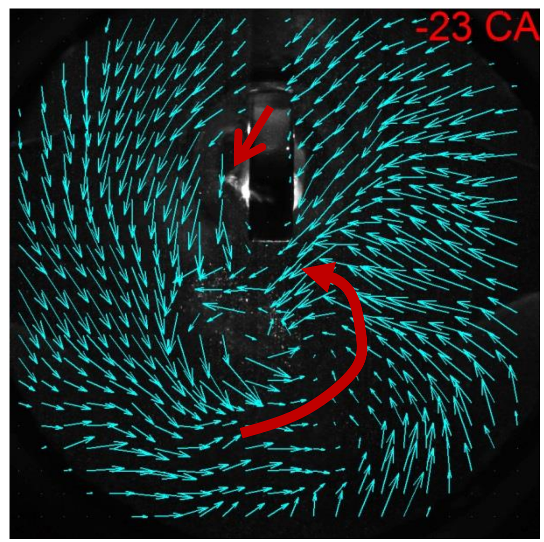


Case 2

Injection



Case 1

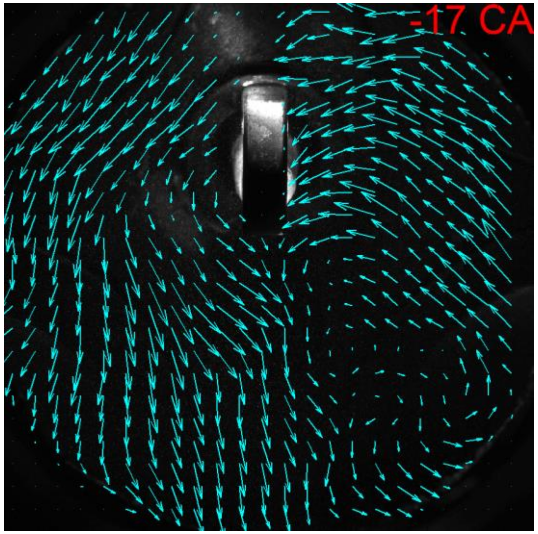


Case 2

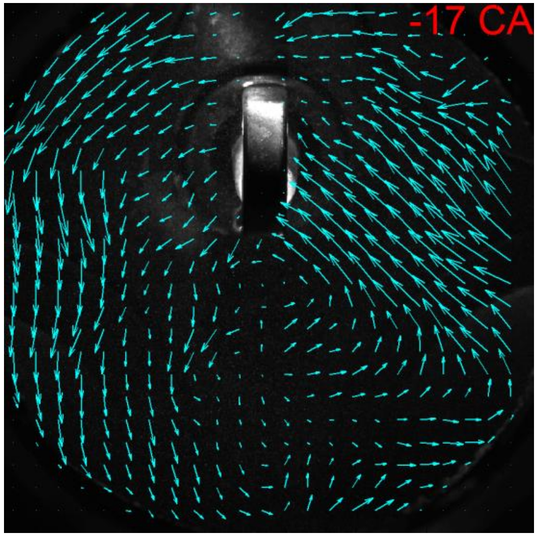
Individual cycles via swirl plane of view

After injection

No injection

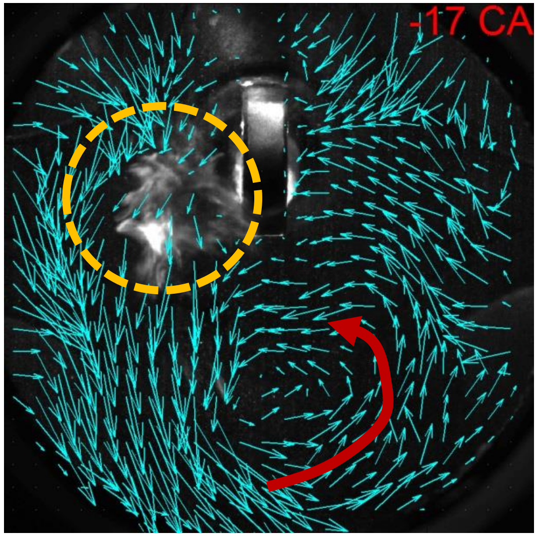


Case 1

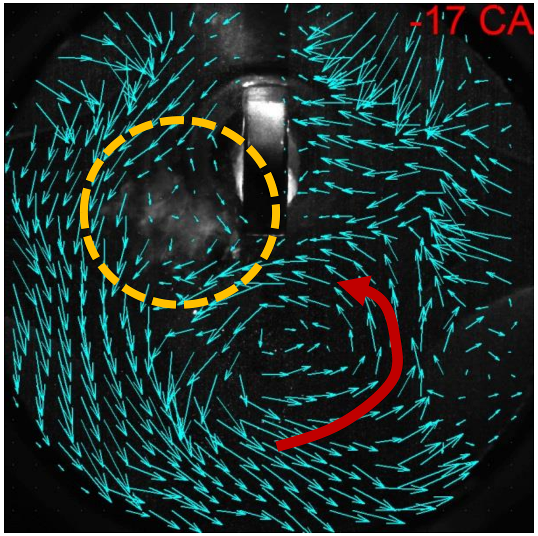


Case 2

Injection



Case 1

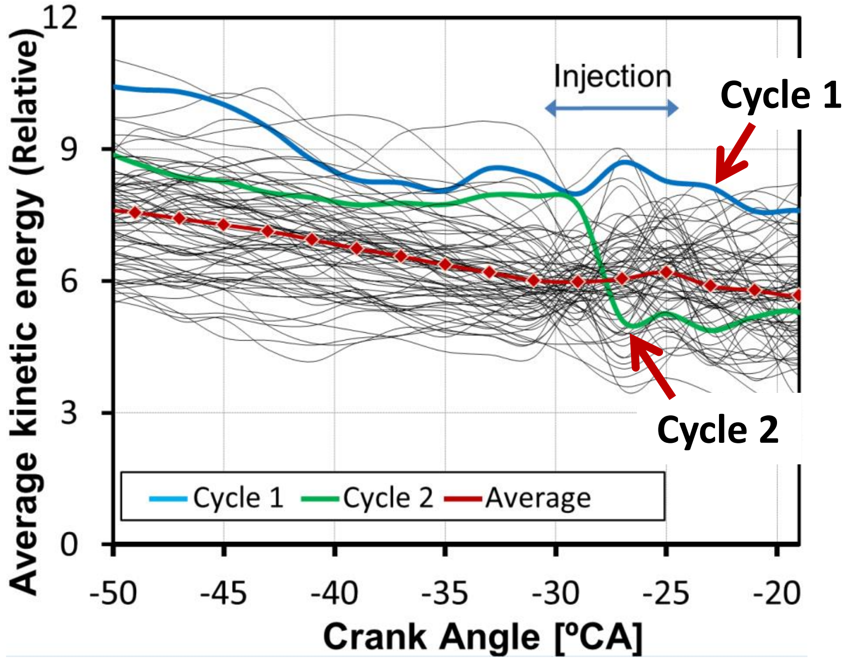


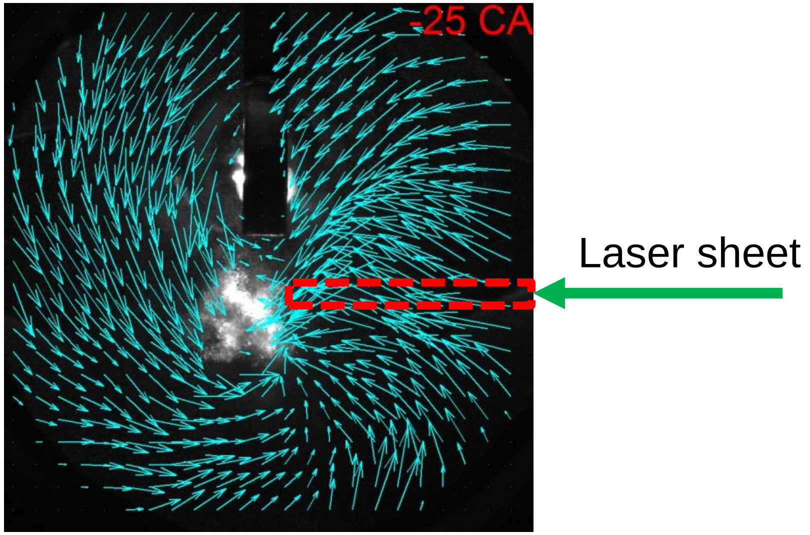
Case 2

- Injection-enhanced swirl flow directs the flame propagation

Swirl flow energy after injection

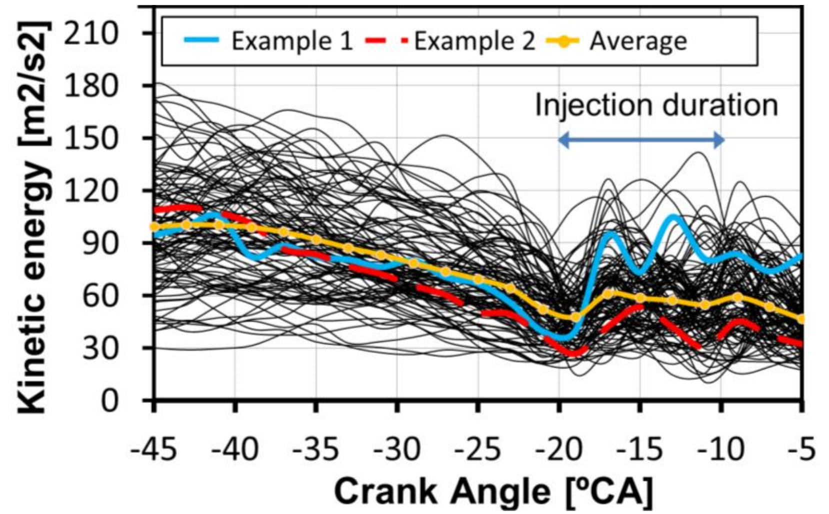
- Supports
  - Gas-flow entrained by spray is the key factor
  - In-cylinder swirl flow (before injection) contributes to the flow energy after the SOI and directs the flame propagation
- Kinetic energy plots for swirl flow
- Two examples
  - Cycle 1: high KE persists after the SOI
  - <u>Cycle 2: KE reduces after the SOI (why?), perhaps relies on flow entrainment</u>
- How does the spray entrain the flow?
  - Examine the flow/spray interactions via tumble plane of view

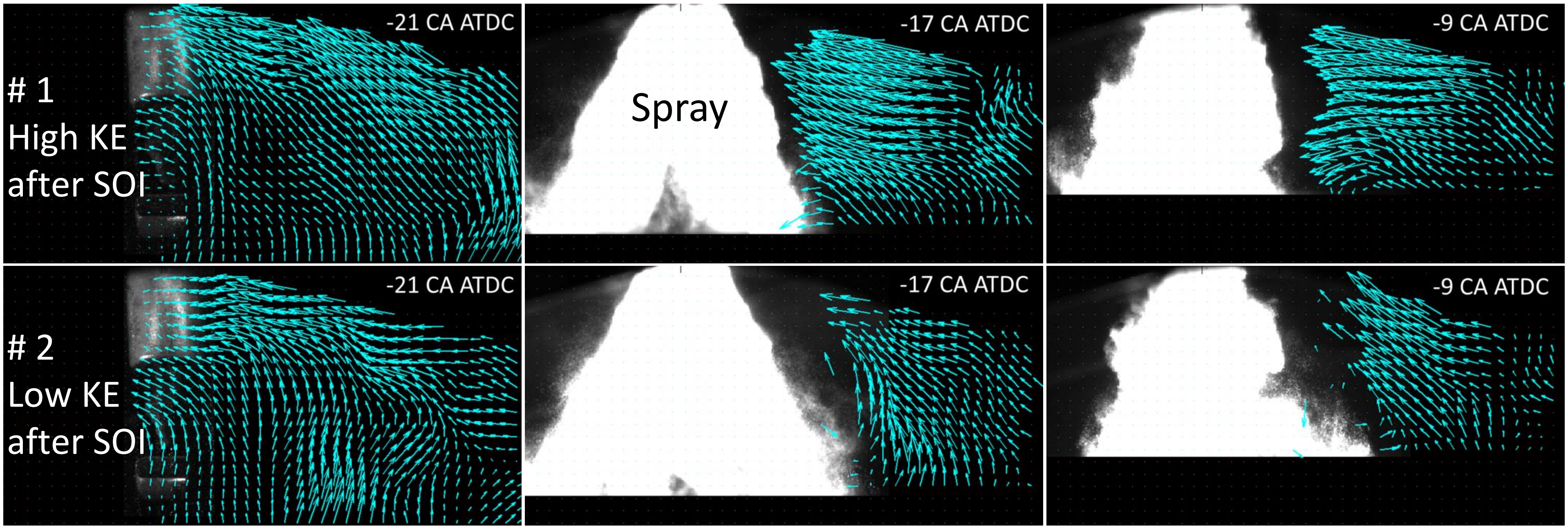




Flow/spray interactions via tumble plane of view

- Selected individual cycles to demonstrate the flow/spray interactions on flow energy
  - Similar kinetic energy (KE) level before injection
  - Different KE level after the SOI

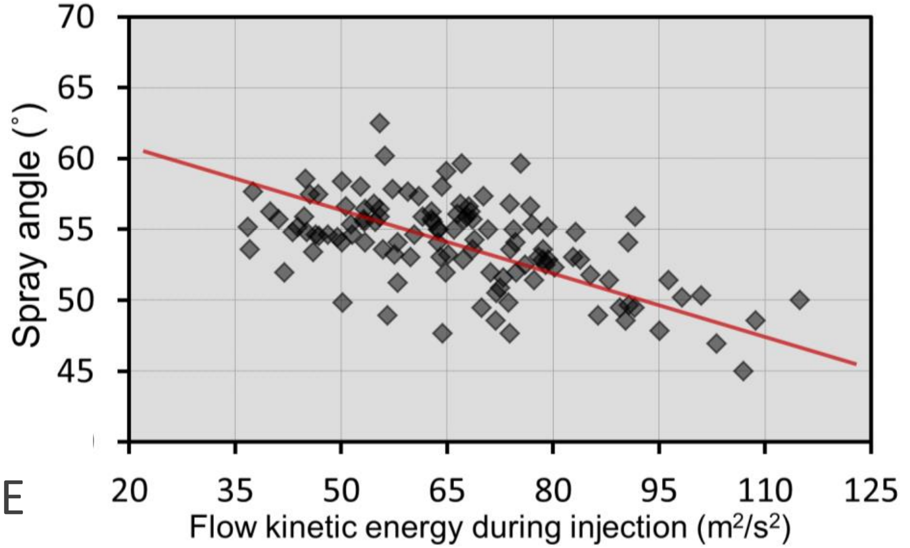


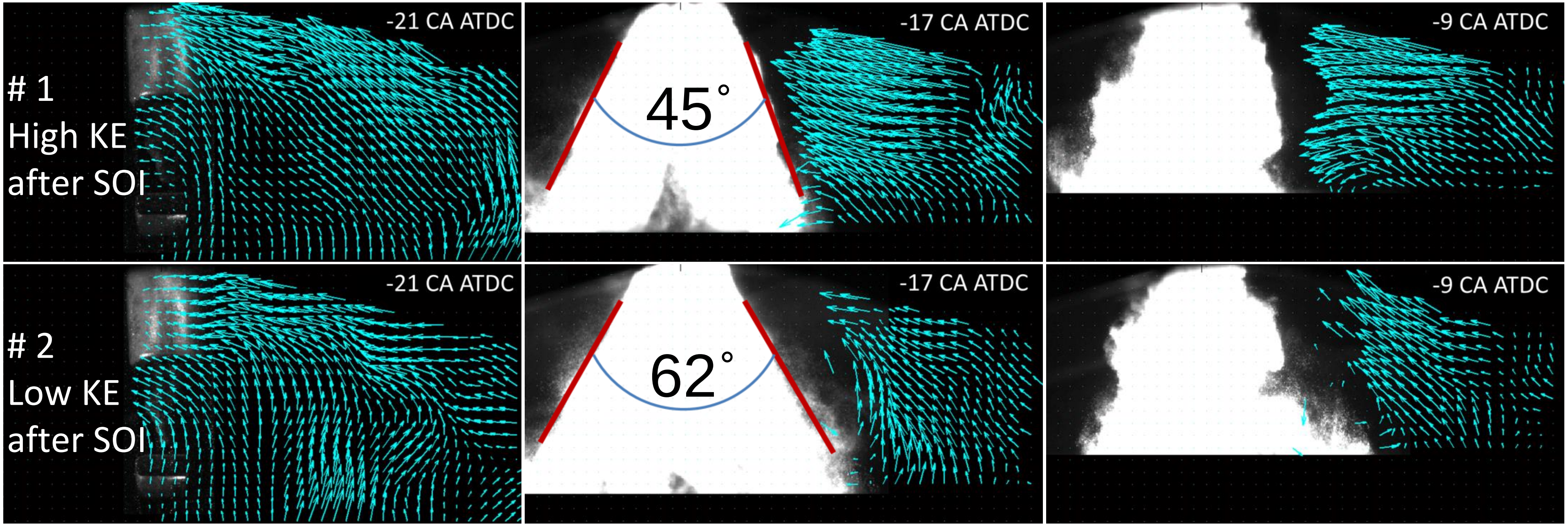


Right before injection *20% at injection duration* *The end of injection*

Sources for flow variations

- Observation 1: spray angle
  - Collapsed spray (spray angle less than injector included angle (60°))
  - Large variation in spray angle (flow variation should be one of the causes)
  - Small angle corresponds to high KE
- Hypothesis: more collapsed spray, more intense flow entrainment, thereby higher KE

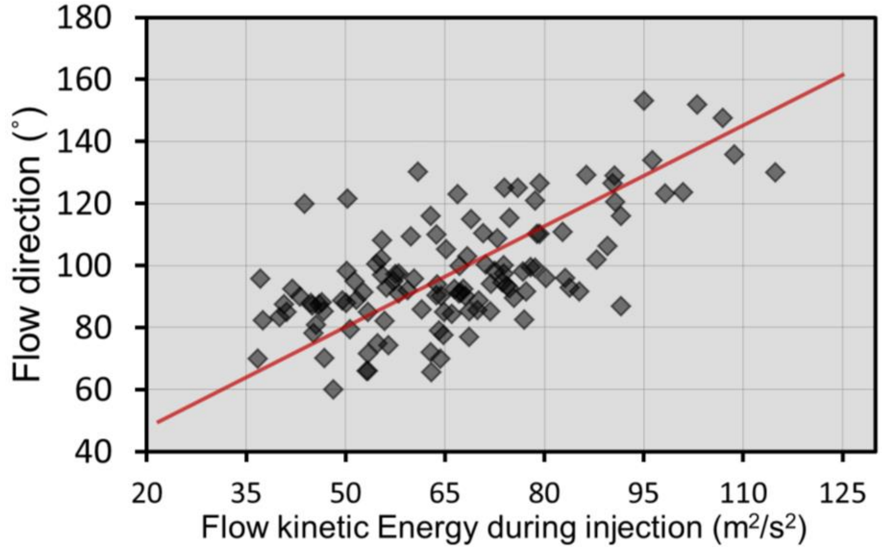


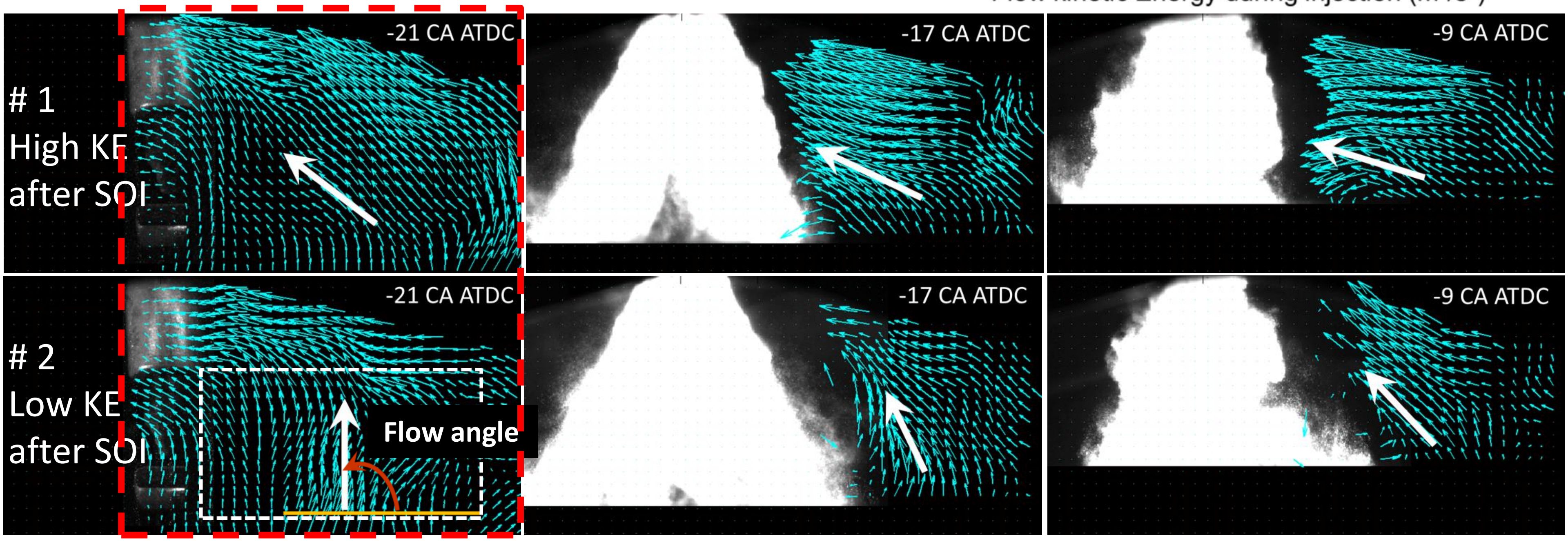


Right before injection *20% at injection duration* *The end of injection*

Sources for flow variations

- Observation 2: flow structure
  - Different flow direction is due to different tumble center
  - Flow angle is defined to capture the tumble flow direction
  - Large flow angle corresponds to high KE
- Hypothesis: larger flow angle promotes gas entrainment into spray

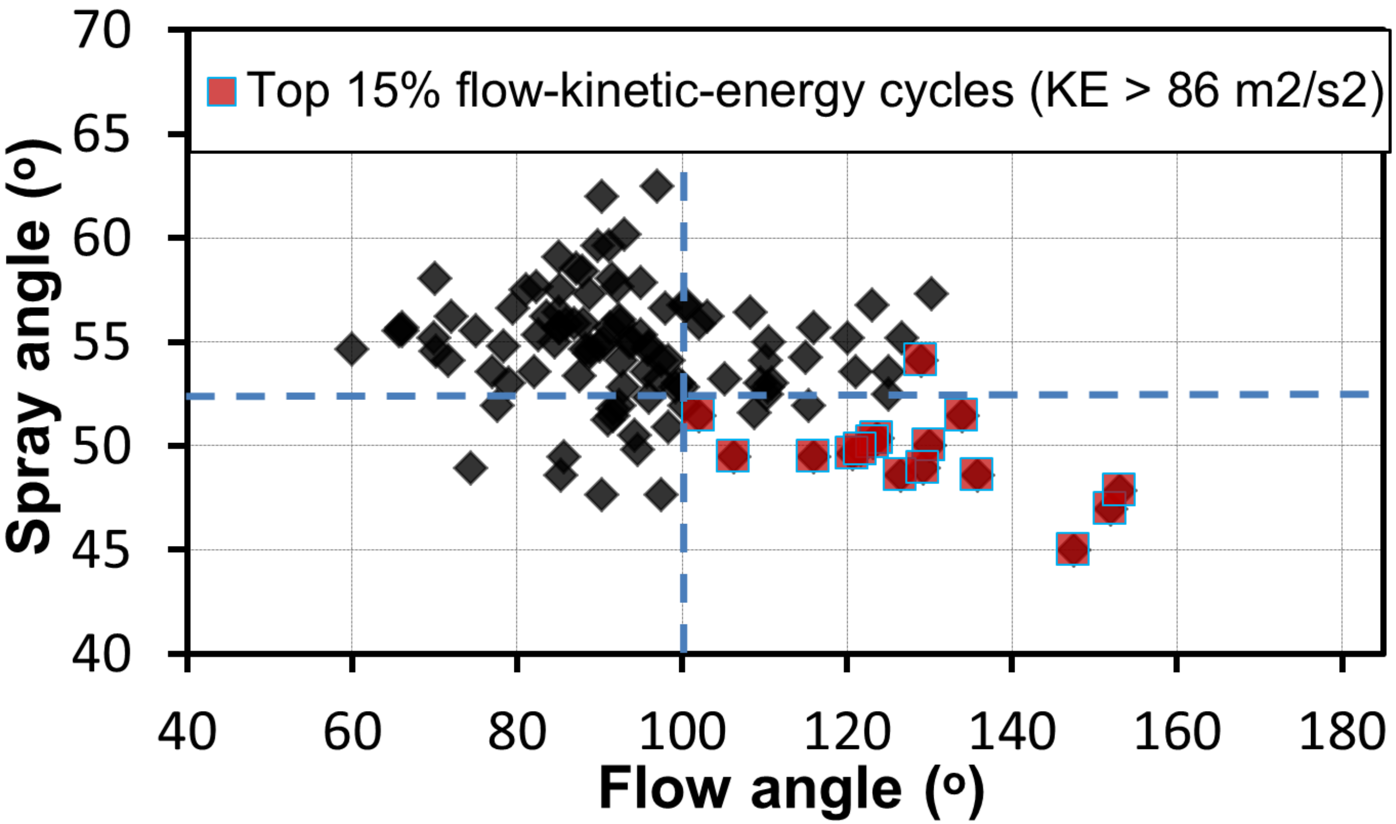




Right before injection *20% at injection duration* *The end of injection*

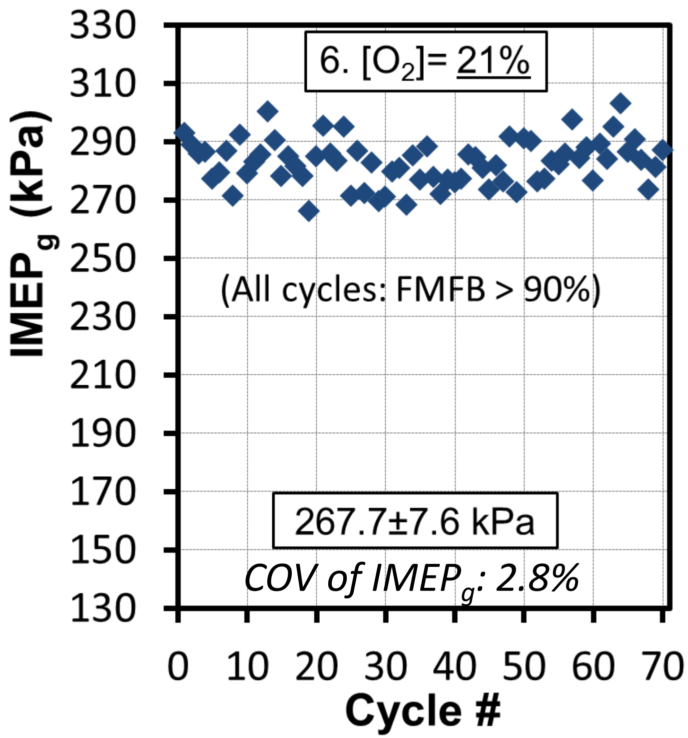
Predictor for flow energy during injection

- A combination of flow and spray angles is a predictor of the flow energy
- Large flow direction angle combined with a more collapsed spray ensures high KE of the flow during injection, indicating intense flow/spray interactions



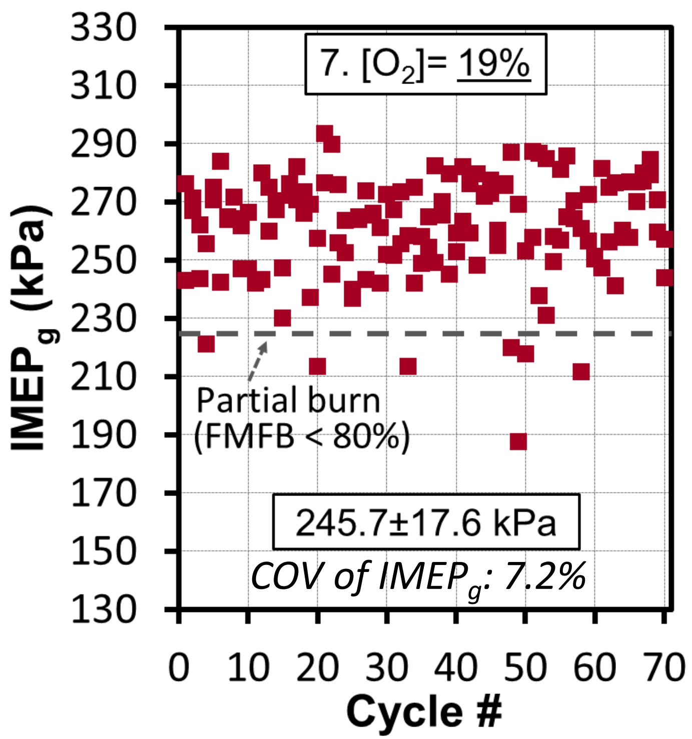
Correlations with combustion variability

$[O_2]$	SOI/ST(ºCA	RPM
21%	-21/-19	2000



Reference point: stable combustion (without EGR)

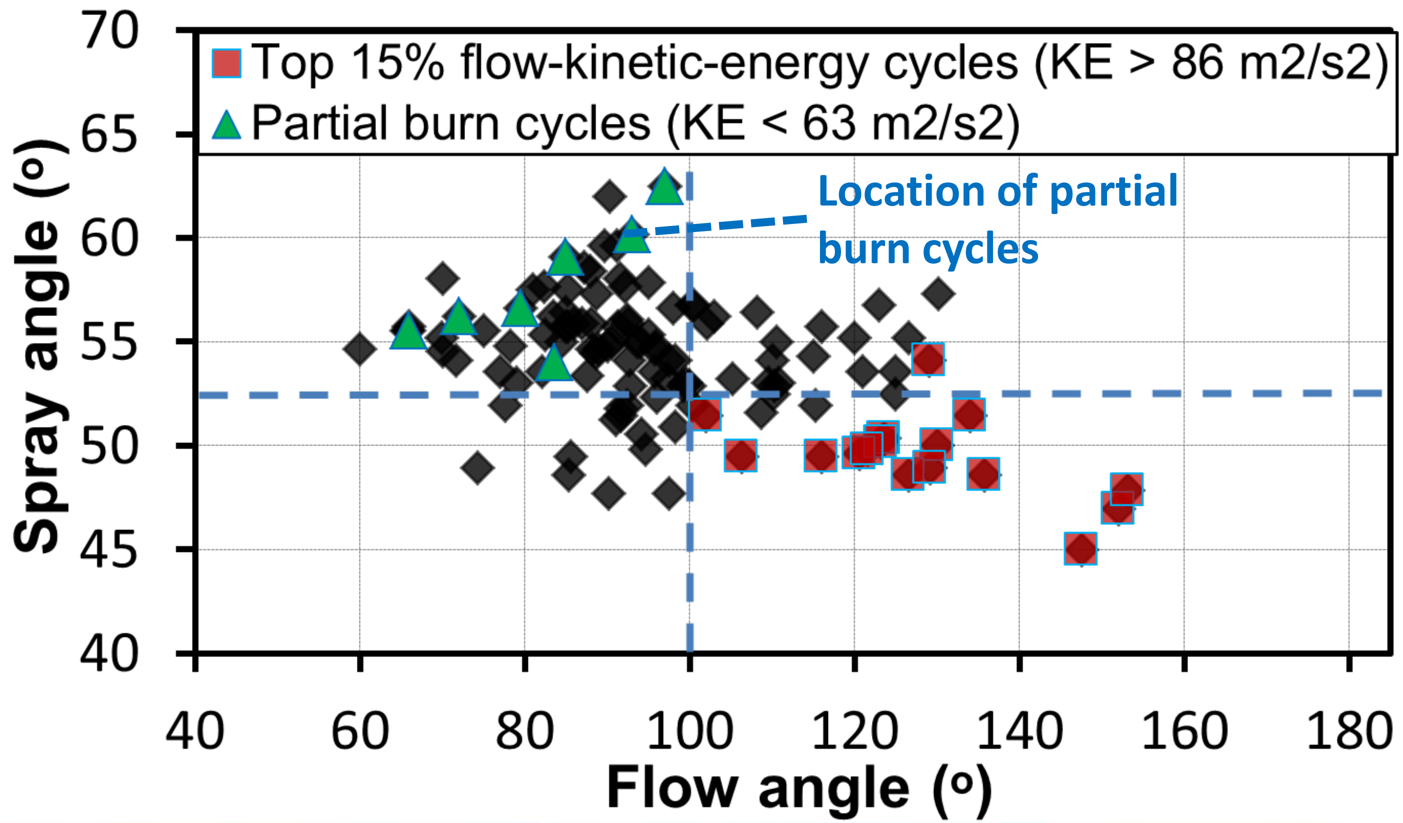
$[O_2]$	SOI/ST(ºCA	RPM
19%	-21/-19	2000



7 partial burns (with EGR) among 140 cycles

Correlations with combustion variability

- Observation 1: cycles characterized by small spray angles with large flow angles exhibit high KE and burn well (the top 15% KE cycles).
- Observation 2: all partial-burn cycles (KE below 63 m^2/s^2) are biased towards large spray angles (>52.5°, less collapsed) and small flow angles (<100°).
  – Low flow energy during injection is ***one*** of the causes for poor burns.

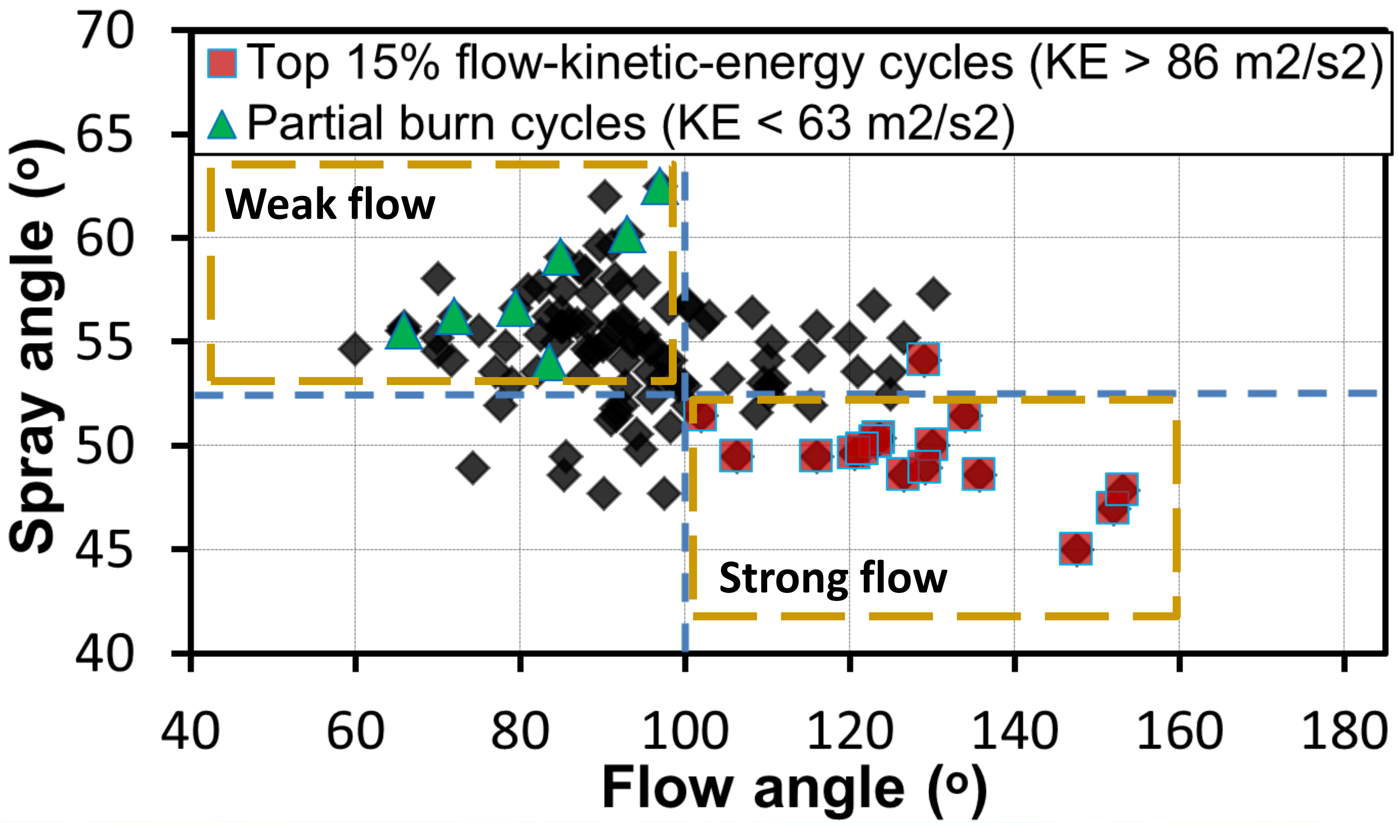


Classification of flow/spray interaction

- Classified into two types, based on spray-induced flow via tumble plane of view

	KE (during injection)	Flow angle	Spray angle
Strong flow	> 86 m^2/s^2	> 100º	< 52.5º
Weak flow	< 63 m^2/s^2	< 100º	> 52.5º

- All strong-flow cycles burn well, 30% of all weak flow cycles develop into partial burns.

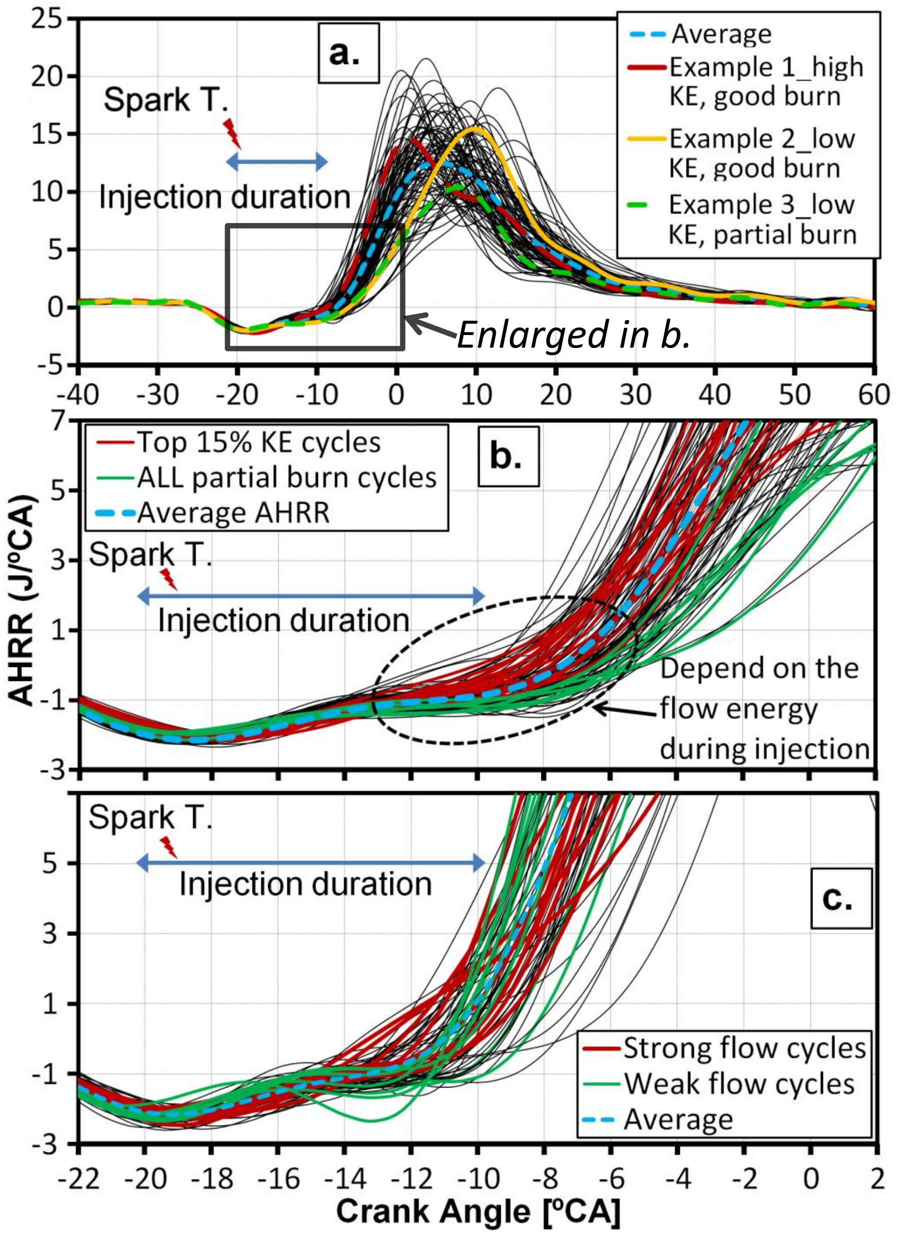


AHHR comparison using conditional analysis

- Three examples for $[O_2]$=19% (EGR)

1	Well burn	High KE	Fast early burn
2	Well burn	Low KE	Slow early burn
3	Partial burn	Low KE	Slow early burn

- Hypothesis for flow during injection:
  - High KE results in fast early burn, ensuring complete combustion
  - Low KE leads to slow early burn, occasionally causing partial burn cycles
- Enlarged AHRR curves (b) show all strong flow and all weak flow (partial burn) cycles to support the hypothesis
- High low energy is a predictor for good early burn
- AHRR curves (c) for $[O_2]$ =21% (no EGR)
  - 10 strong-flow cycles and 10 weak-flow cycles among the 70 cycles
  - Higher $[O_2]$ level makes the early burn insensitive to flow variations



Summary

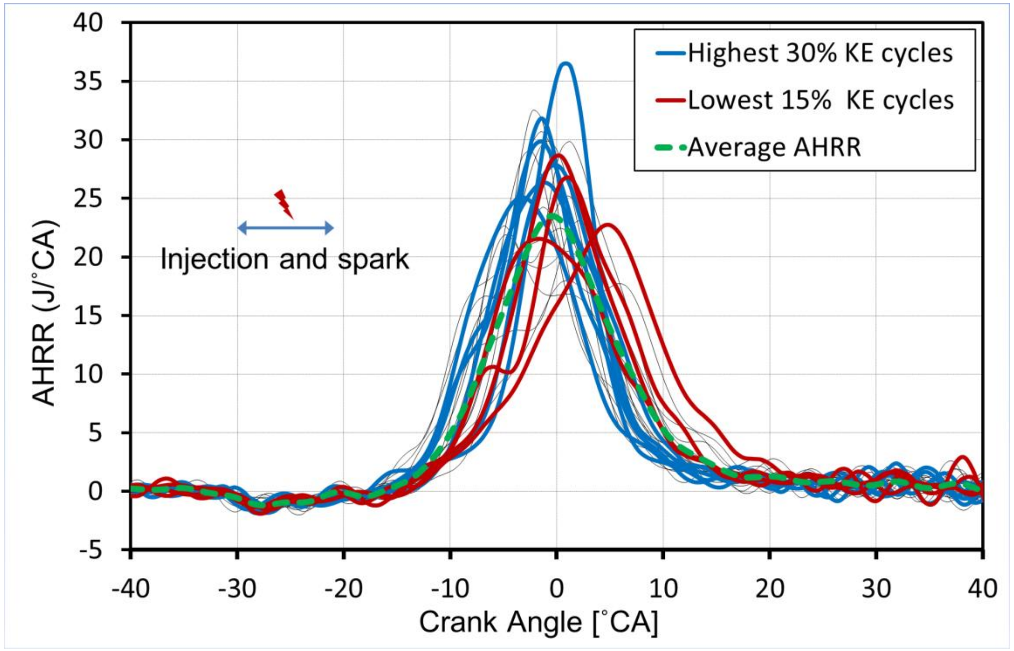
- Flow and spray measurements are correlated with combustion variability.
- Conditional analysis reveals two types of flow/spray-interactions (strong and weak flows), predicting likelihood for a cycle to develop into a partial burn,
    - 1) A proper flow direction before injection with a more collapsed spray causes strong flow/spray interactions, ensuring high kinetic energy of the flow during injection. This leads to a ***fast early*** burn, which ensures complete combustion, even for operation with EGR ([O_2]=19%).
    - 2) When EGR ([O_2]=19%) is applied, an improper flow direction and a less collapsed spray generate low flow energy during injection. For this type of flow/spray-interaction, 30% of the cycles exhibit ***weak early*** heat release and develop into partial burns.
- For spray-guided stratified DISI engine, flow is also important.

Thank you for your attention!

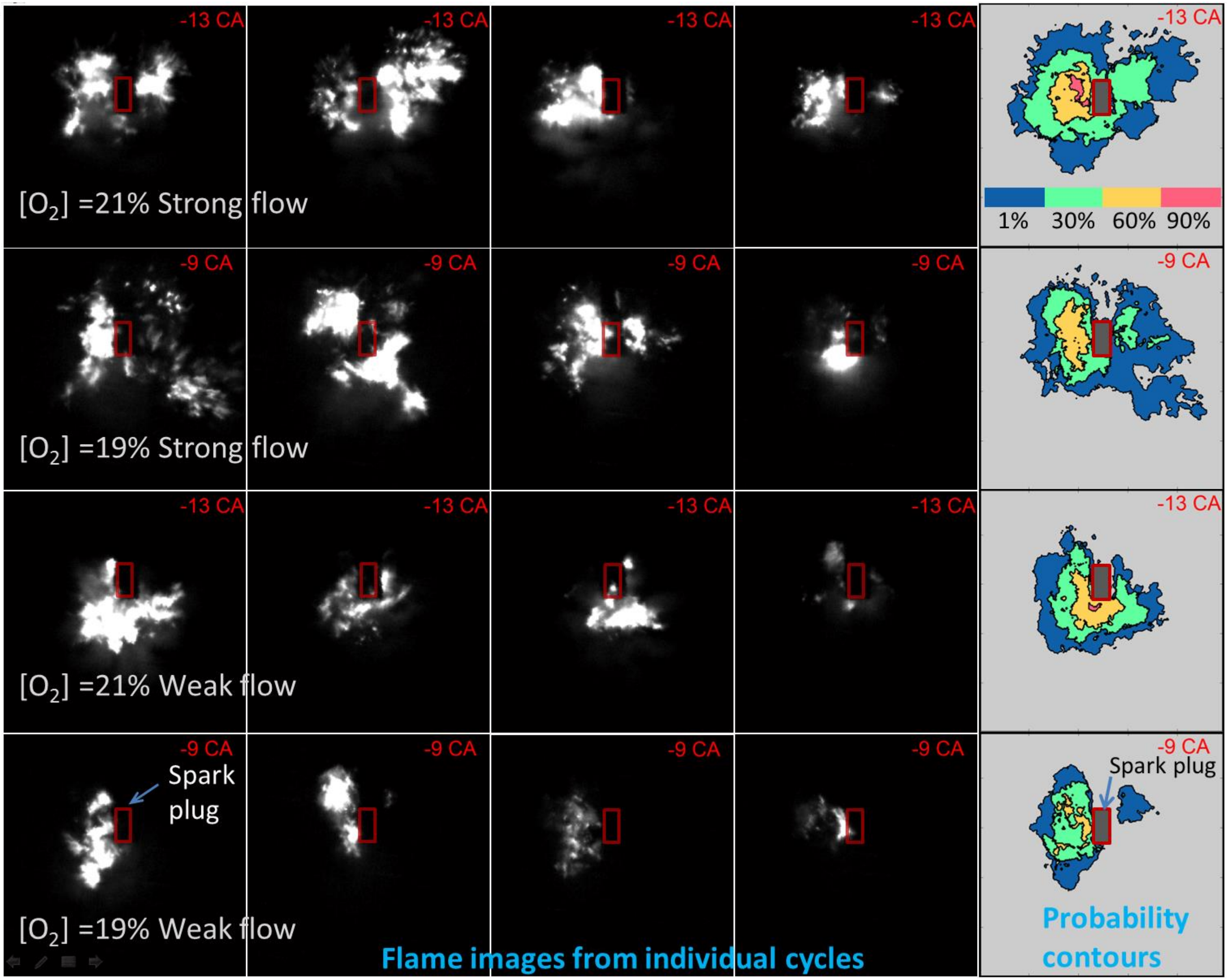
On-going…

- With the aims at understanding the sources of combustion variability

- Simultaneous flow, spray, spark plasma and flame measurements via views of both tumble and swirl planes (**Preliminary results for swirl flow**)
- Equivalence ratio measurement
- Focuses on the effects flow/spray interactions on changes in the transition from the spark plasma to early flame kernel



Correlation between swirl strength with AHRR


-13 CA
[O2] =21% Strong flow
-9 CA
[O2] =19% Strong flow
[O2] =21% Weak flow
[O2] =19% Weak flow
Spark plug
1% 30% 60% 90%
Flame images from individual cycles
Probability contours