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Using PIV Measurements to Determine the Role of the in-cylinder Flow Field for Stratified DISI Engine Combustion

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Abstract

This study seeks to determine the role of the in-cylinder flow field for spray-guided stratified-charge combustion using particle image velocimetry (PIV) measurement in a tumble plane in the central part of the piston bowl. Here, "in-cylinder flow field" includes the tumble flow field generated by the intake system and the flow effects generated by the fuel injection conducted during the latter part of the compression stroke. The roles of these flows for stratified combustion at 1000 and 2000 rpm are examined and compared.

E70 fuel is used for this study. Utilizing "head ignition" of E70 generally allows misfire-free stratified operations, so it is selected as the spark-timing strategy. Head-ignition of the fuel sprays occurs when the spark timing coincides with the arrival of the head of the fuel spray at the spark gap. Such spark timing strategy leads to closely-coupled injection and combustion processes, and allows good CA50 control. Start of injection (SOI) is advanced to maintain CA50 = 8°CA as speed increases. The fuel mass per injection is held constant for both engine speeds, presumably resulting in a similar spray-momentum impact on the flow evolution.

On average, as engine speed is doubled, the peak HRR increases only by 20%. This small increase is close to the 24% increase of flow velocities of the spray-generated flow, indicating that the combustion rate scales with the strength of spray-generated-flow. Here, the spray-generated flow refers to the flow field after the SOI. These findings support the hypothesis that the combustion rate for spray-guided stratified combustion that utilizes "head ignition" is primarily controlled by the mixing of fuel and air associated with spray-generated flow. Furthermore, PIV data show that the absolute magnitude of the cyclic variations of the flow increases significantly with engine speed, and this is consistent with the observed increased variability of combustion. A weak correlation between poor burns and spray-generated-flow energy is found, showing that the spray-generated-flow is one of several important factors responsible for cyclic variations of stratified combustion. Large cycle-to-cycle fluctuations of flow energy before injection (flow generated by intake system) are observed, together with large variations of flow direction and spray structure. These are potential to cause cyclic variation of the spray-generated flow and then affect the stratified combustion. Observations based on 140 individual cycles reveal that good burns have a proper flow direction before injection and narrow spray, leading to a large energy of the spray-generated flow.

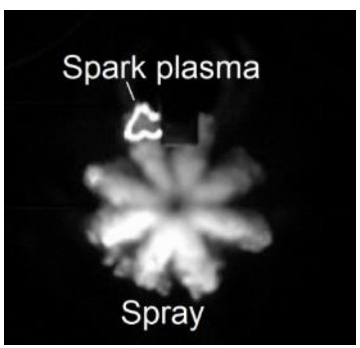
Acknowledgement

This work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Support was provided by the U.S. Department of Energy, Office of Vehicle Technologies via Fuels Technologies program manager Kevin Stork. Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

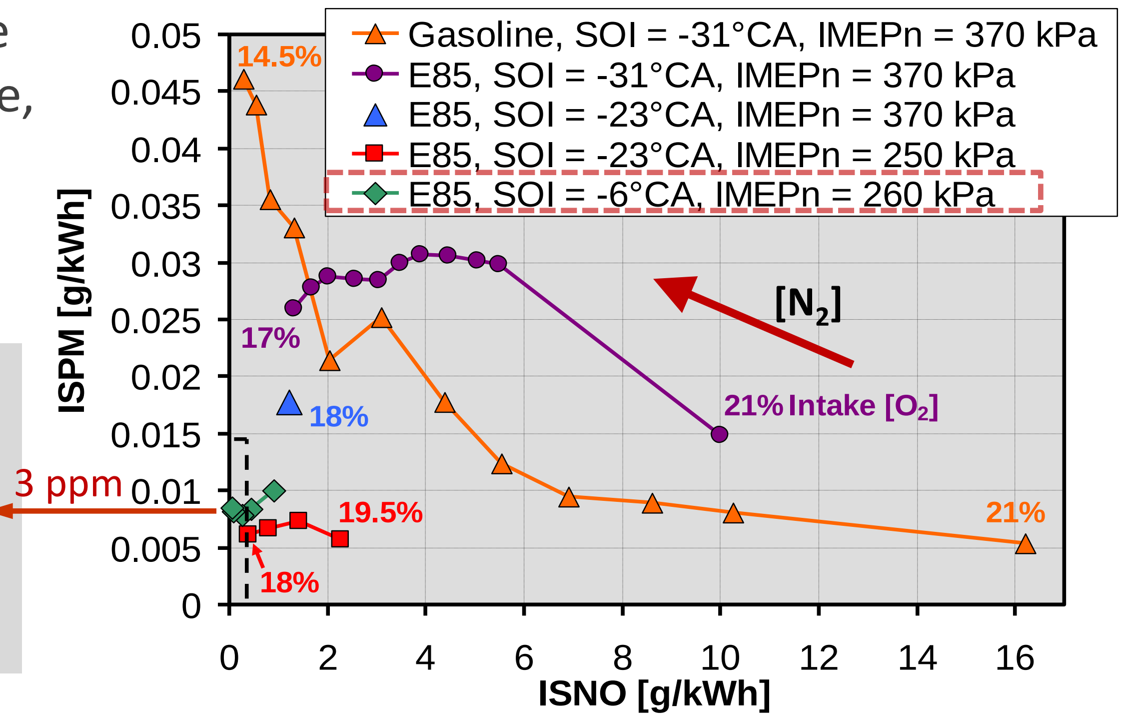
Introduction - Reaching Inside the NO/PM Box

- Stratified combustion can improve fuel economy because of **overall lean**
- Challenging to ensure **stable combustion** with low engine-out **NOx** and **PM** across load and speed ranges.
- Especially challenging to do this for flex-fuel vehicles.
  - **0% to 85% ethanol** in the tank at any instant time.

- With E85, can reach inside the US2010 NO/PM box and stable, **Using near-TDC injection**



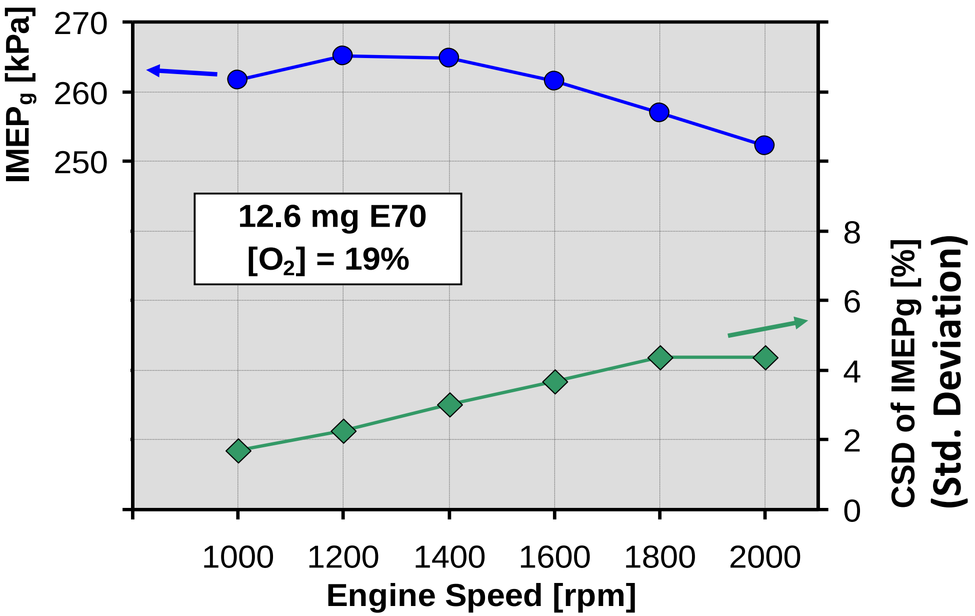
For SOI = -6˚CA, ST = -12˚CA ⇒ most stable “**Ignition of the spray leading edge**”



Objectives – Engine speed effects

- Near-TDC injection still reduces NO and PM when increasing engine speed. However, the cyclic variability **increases.**
  - Shows need to manage stochastic processes (flow) for better engine performance

- **Objectives:** Use PIV to determine the **role** of the in-cylinder flow field for stratified-charge combustion
  - Under **various engine speeds**
  - Via **tumble plane of view**
  - Both on **average**, and on a **cycle-to-cycle** basis



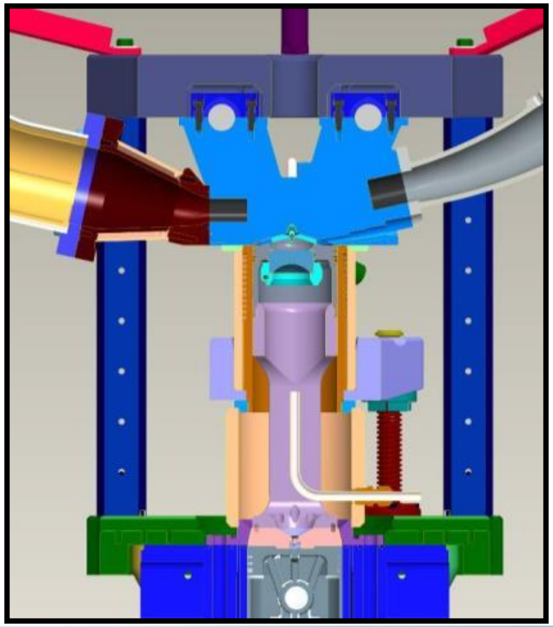
Research Engine

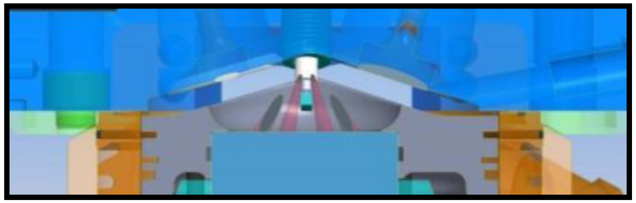
Two configurations

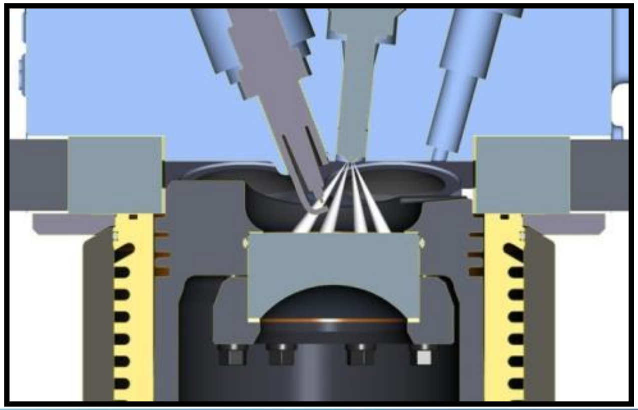
- <u>All-metal:</u> Metal-ring pack and air/oil-jet cooling of piston.
- <u>Optical:</u> Pent-roof, piston-bowl, and 45° Bowditch mirror.
- Identical geometry for both configurations.
- 8-hole injector with 60°included angle
- Spark gap is in between two spray-plumes.

- <u>Swirl/tumble generated by deactivating one of the valves</u>

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
Injection Pressure	170 bar
# of Injections	Single
Spark Energy	106 mJ
$T_{coolant}$	60°C
T_{in}	26-28°C
$P_{exhaust}$	100 kPa

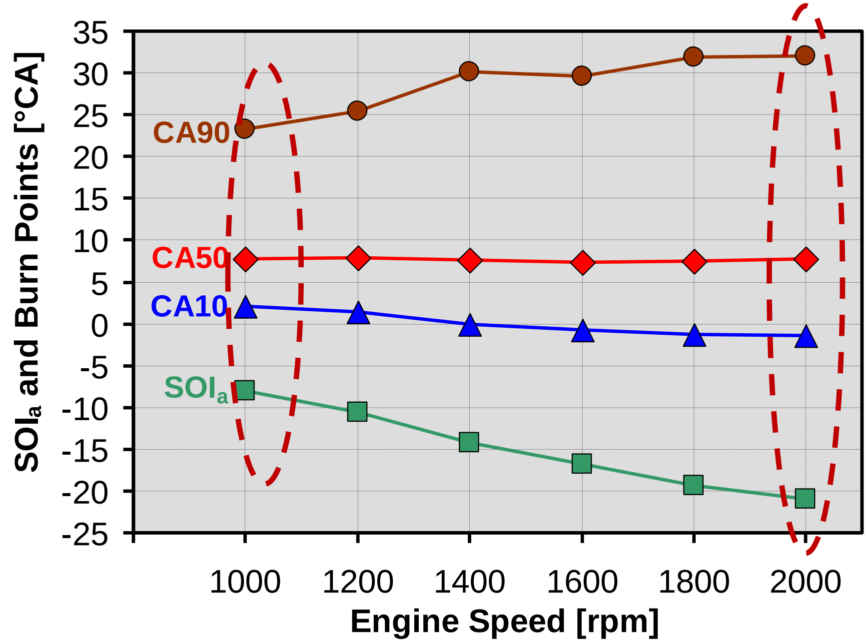




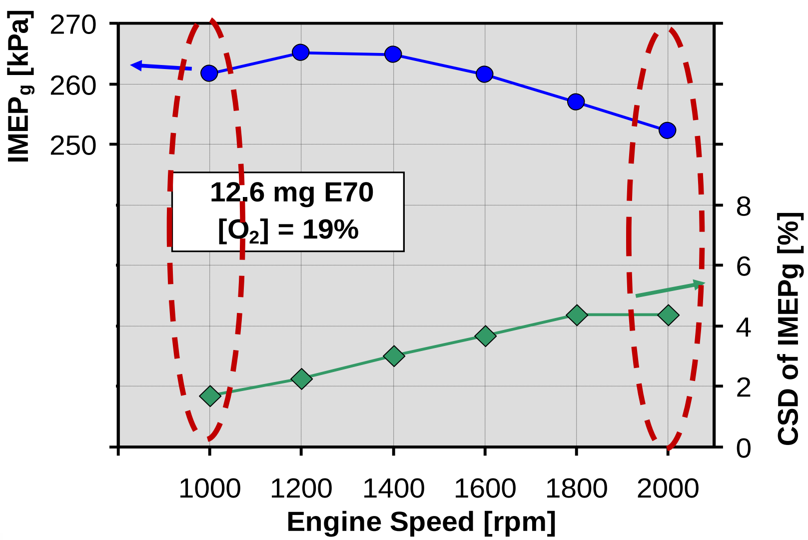


Operation conditions for PIV measurements

- 2 operation conditions (1000, 2000 rpm)
- Constant mass injection rate for both engine speeds
  - A similar spray momentum is expected.
- Designed spray-ignition strategies
  - Implement near-TDC injection
  - Maintain CA50 at about 9.0˚CA ATDC

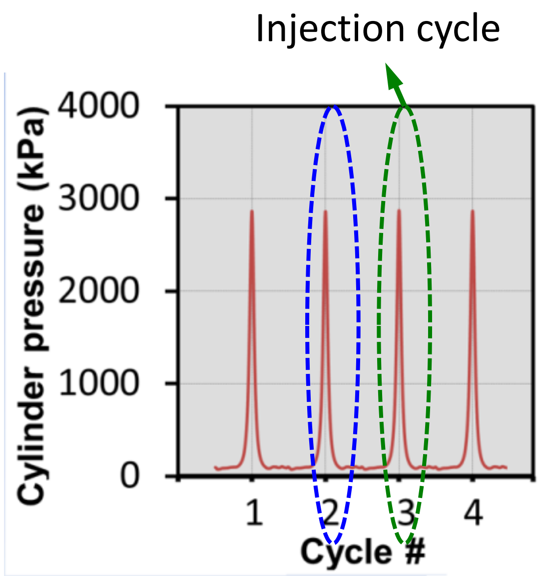


Fuel type	E70	
EGR/$[O_2]_{in}$	19%	
Injection duration	**0.925 ms (12.6 mg fuel mass)**	
Engine speed	1000 rpm	2000 rpm
Start of injection	-8˚CA	-21˚CA
End of injection	-2˚CA	-9˚CA
Spark timing	-7˚CA	-19˚CA

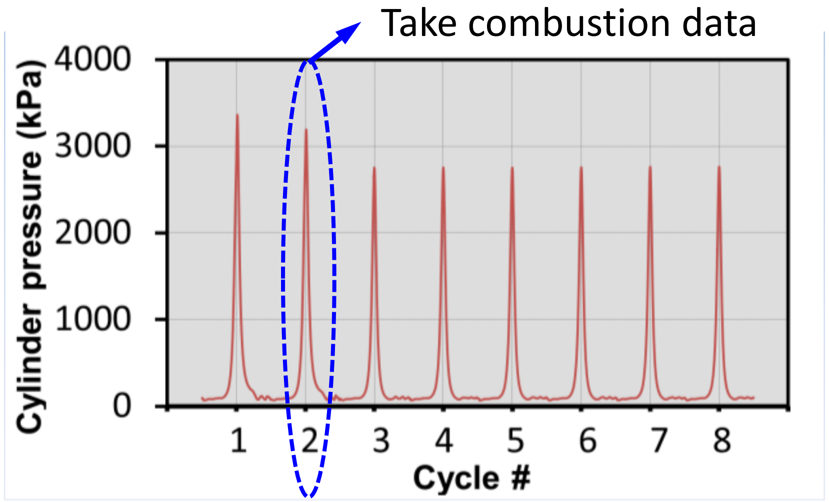


Operations for optical engine

- Combined motored and fired operations in each test condition
- Motored operations,
  - Skip2-Injection1-Skip1 strategy
  - Take data at the 2nd and 3rd cycles
  - 100 cycles for w & w/o injections each
- Fired operations,
  - 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 (100 cycles)
- Focus on -69˚CA to 29˚CA ATDC
  - Covers late compression and early expansion strokes



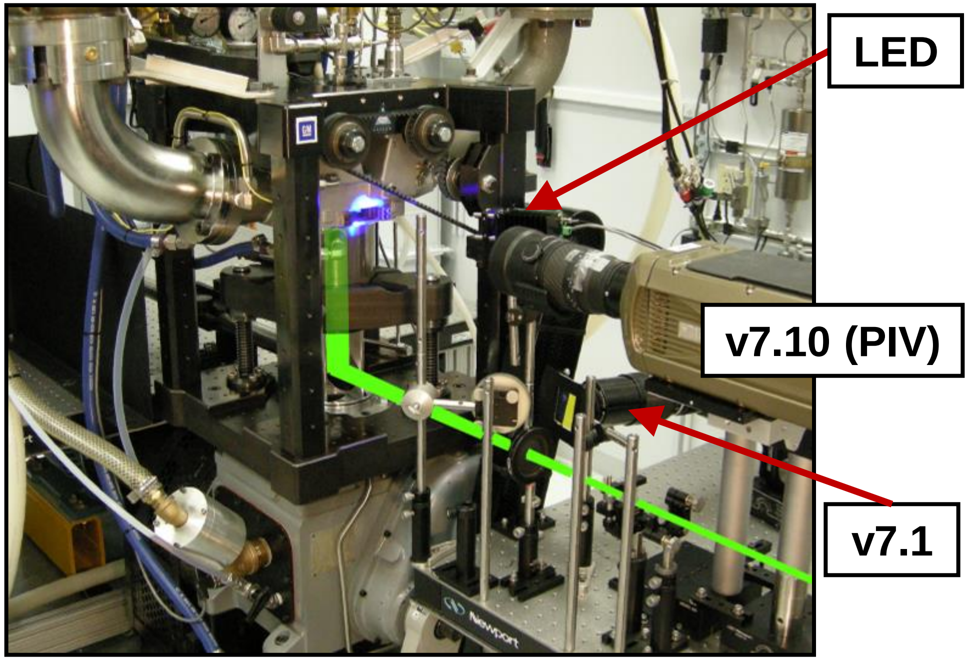
Motored operations

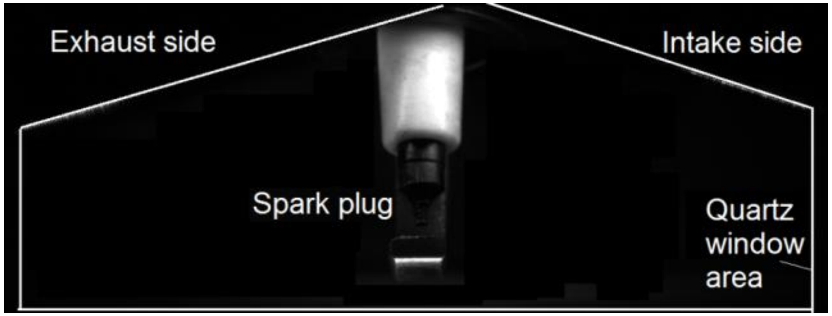


Fired operation

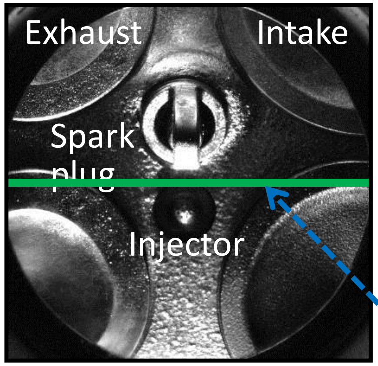
Optical Diagnostics Setups

- Phantom v7.10 for PIV (pent-roof)
  - 12 kHz (1200x440) for 2000 rpm
- 532 nm laser
  - 120 ns pulse duration
  - 12 kHz for 2000 rpm
- Pulsed high-intensity blue LED (4 µs) for liquid spray.
- Phantom v7.1 for Mie & natural luminosity imaging (piston bowl)
  - 12 kHz (512x512) for 2000 rpm
  - 532 Notch filters to reject laser light.

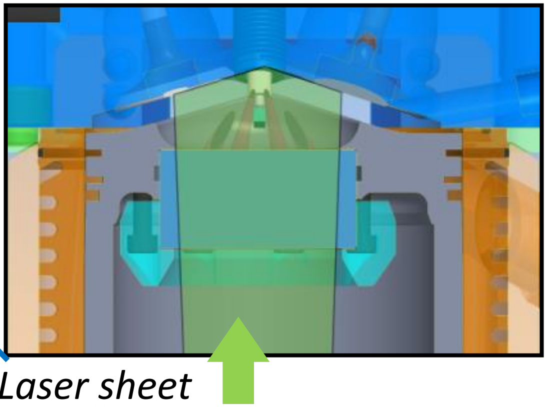




Pent-roof window Piston-bowl window



Piston-bowl window



Laser sheet

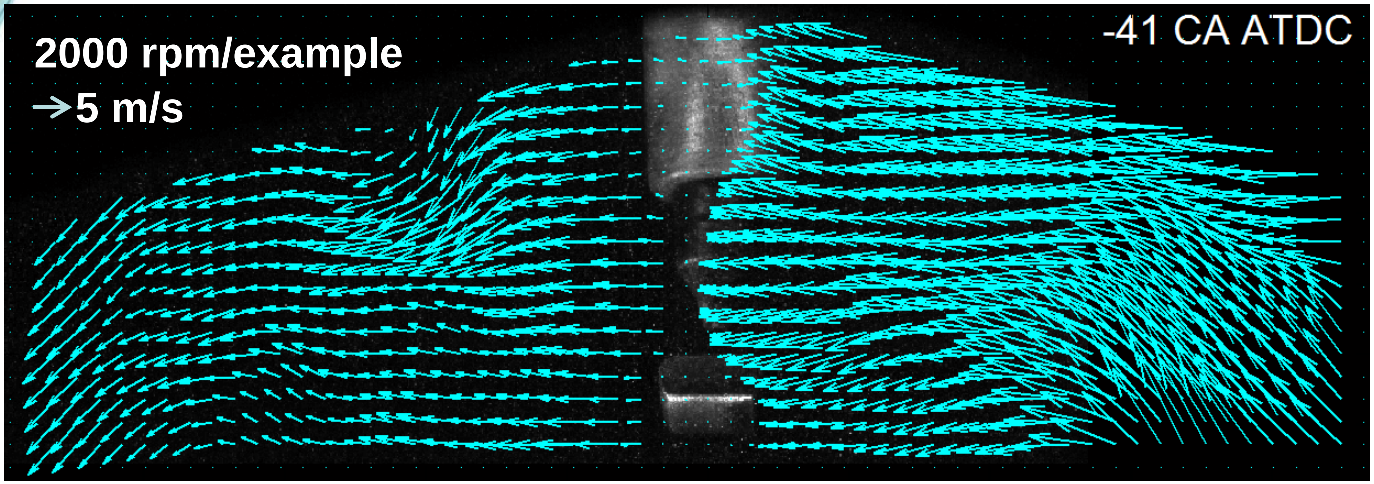
PIV measurement

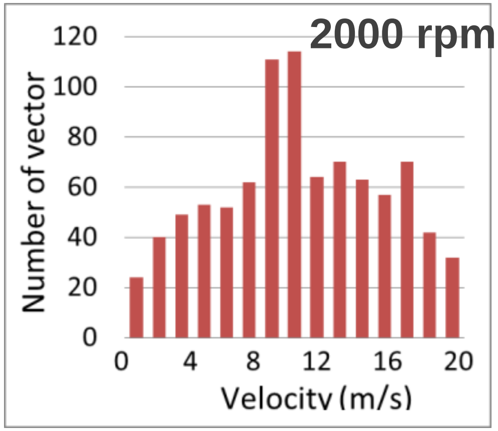
- The accuracy of PIV measurement depends on PIV setting and post-processing parameters.
- Keep most of them **constant** for two engine speeds for reasonable comparison
  - Constant Time delay between two image-frames (Δt) means constant dynamic range
- However, **constant Δt** for both 1000 and 2000 cases can cause uncertainties because of different velocity range

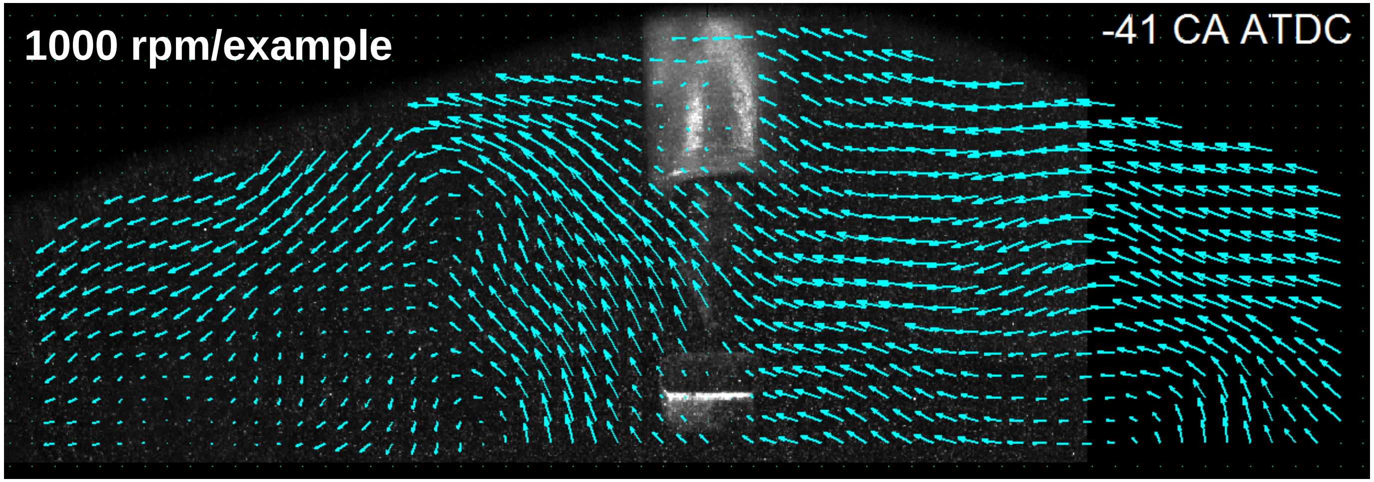
Parameter	Current Study
Light sheet thickness	2 mm
Interrogation window size	128×128 to 32×32
Spatial resolution	0.98 mm
Magnification	0.75
Field of view	46.9×17.2
Frame resolution (pixel)	1200×440
Frame resolution (size)	1 µm
Seed droplet diameter	≈15 particles per 32×32 pixels
Time delay between two frames (Δt)	10 µs
Camera lens aperture	f/16
Laser energy for 1000 rpm	7 mJ/pulse
Laser energy for 2000 rpm	4 mJ/pulse
PIV crank angle range	-69˚CA to 29˚CA
PIV crank angle resolution	2.0˚CA

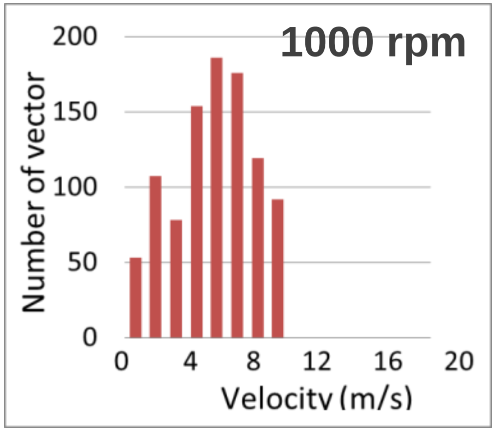
PIV setting and post-processing parameters

Difference in velocity range between speeds









PIV measurement

- The accuracy of PIV measurement depends on PIV setting and post-processing parameters.
- Keep most of them **constant** for two engine speeds for reasonable comparison
  - Constant Time delay between two image-frames (Δt) means constant dynamic range
- However, **constant Δt** for both 1000 and 2000 cases can cause uncertainties because of different velocity range
- Uncertainty (noise) estimation based on an approach from previous study (Abraham, Ruess & Sick)

Parameter	Current Study
Light sheet thickness	2 mm
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Spatial resolution	0.98 mm
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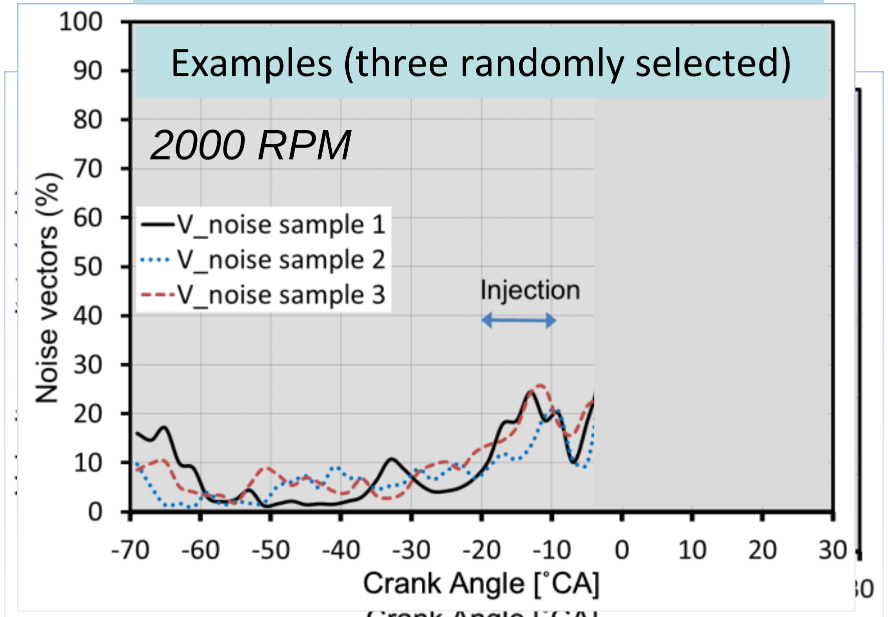
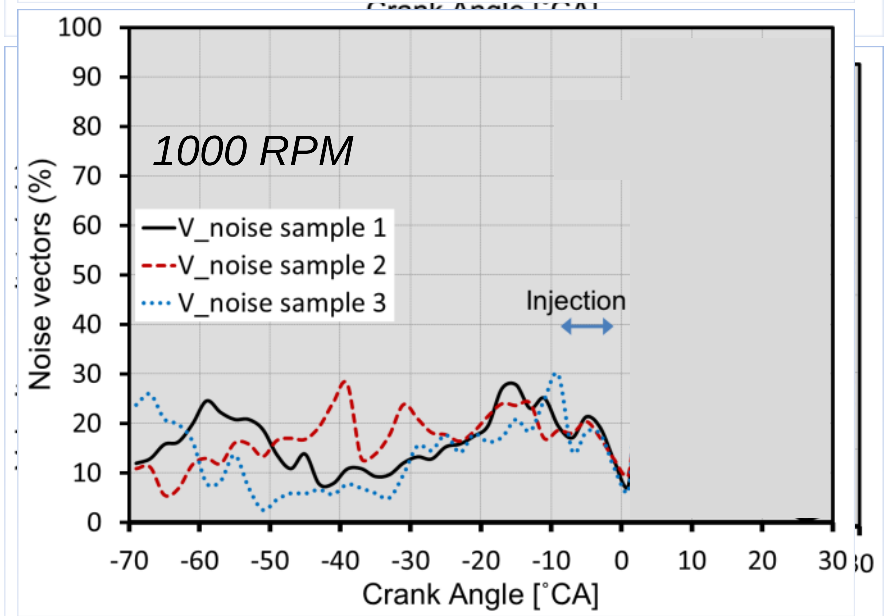
PIV setting and post-processing parameters

Measurement noise estimation

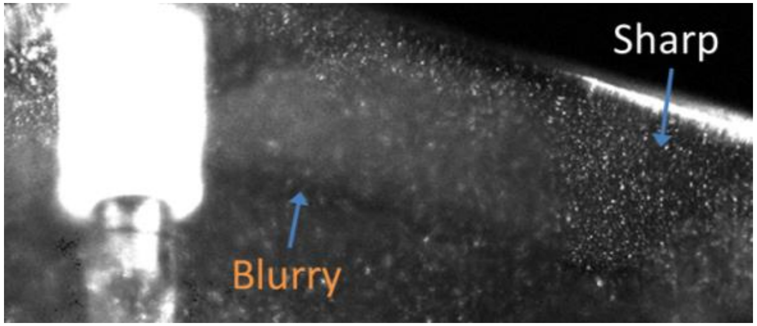
- Dynamic range based on 10 μs Δt
  - (0.58 – 31.3 m/s)
- Vectors outside this range are potential noise
- Three randomly selected cycles
- Δt (10 μs) is big
- However, it reduces noise for spray generated flow
- And large vectors dominate flow energy
- Moreover, Number of small vectors is small

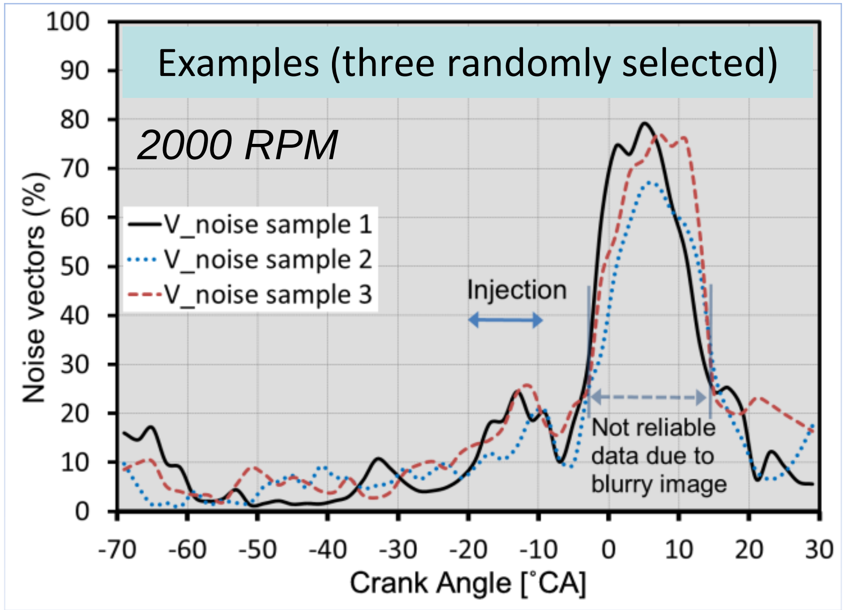


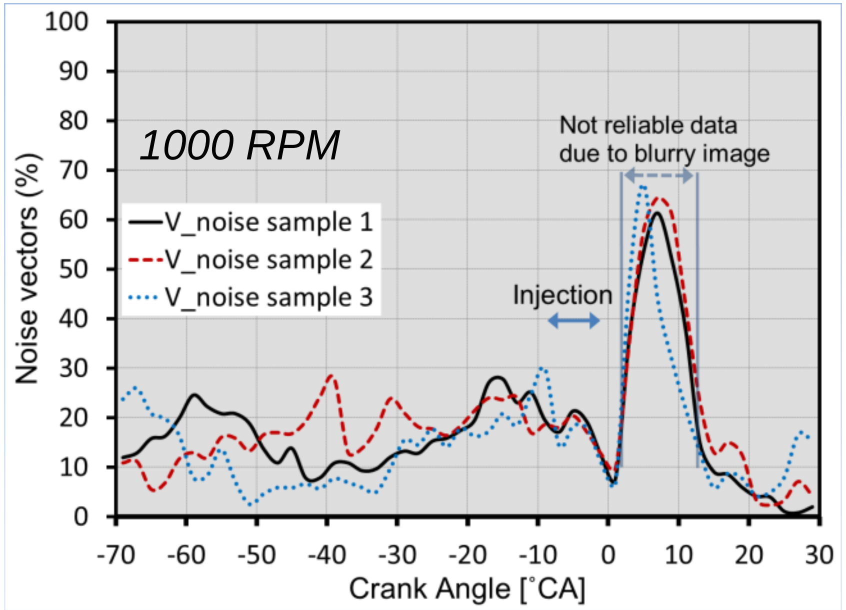


Real errors due to spray evaporation

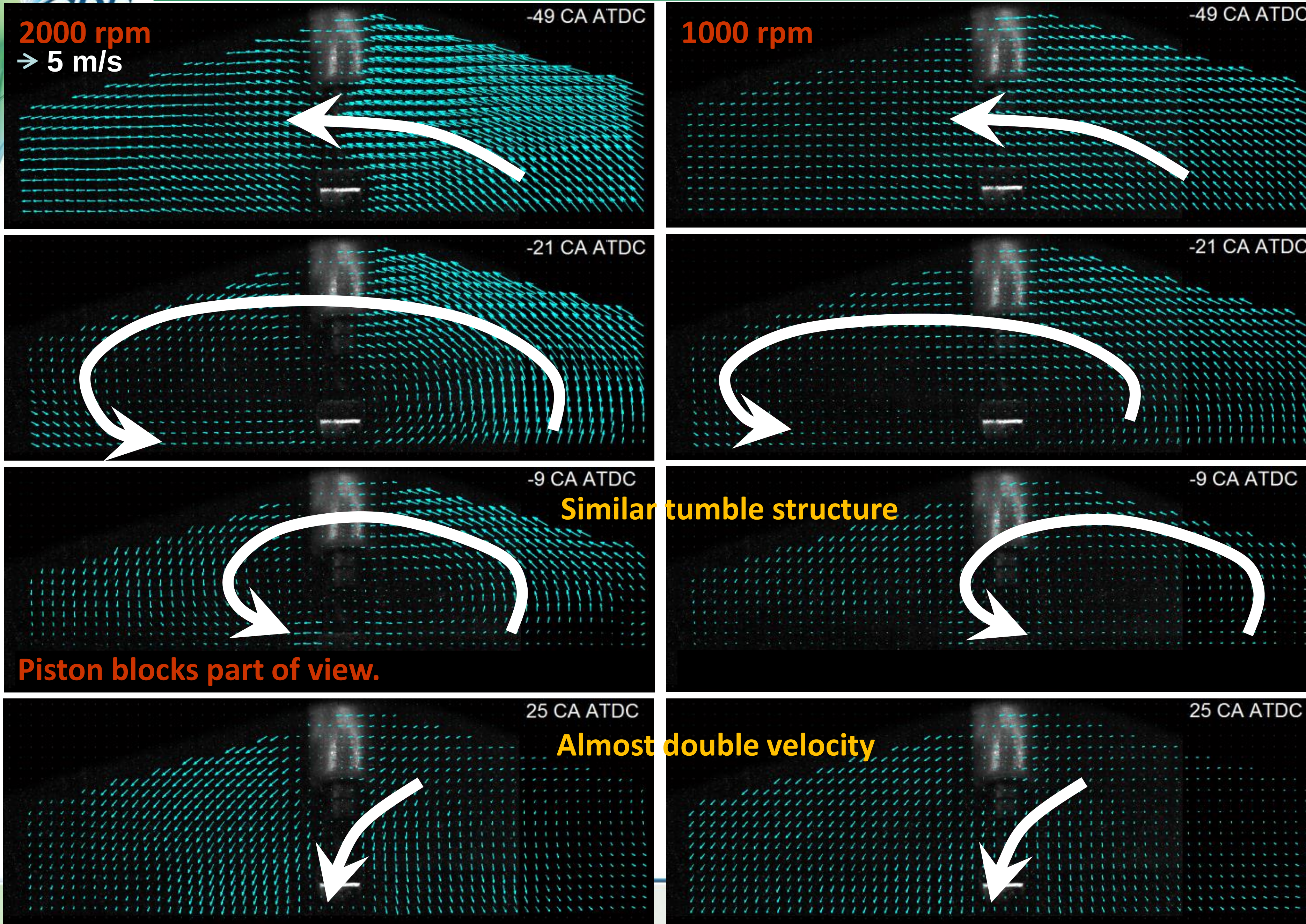
- After EOI, very high noise (in fact it is error)
  - Additional reason: Blurry particle image. (Likely caused by the prompt thermal stratification and density changes due to spray evaporation)
  - Causes PIV software to assign vectors near-zero values, so it introduces real errors, not only noise.



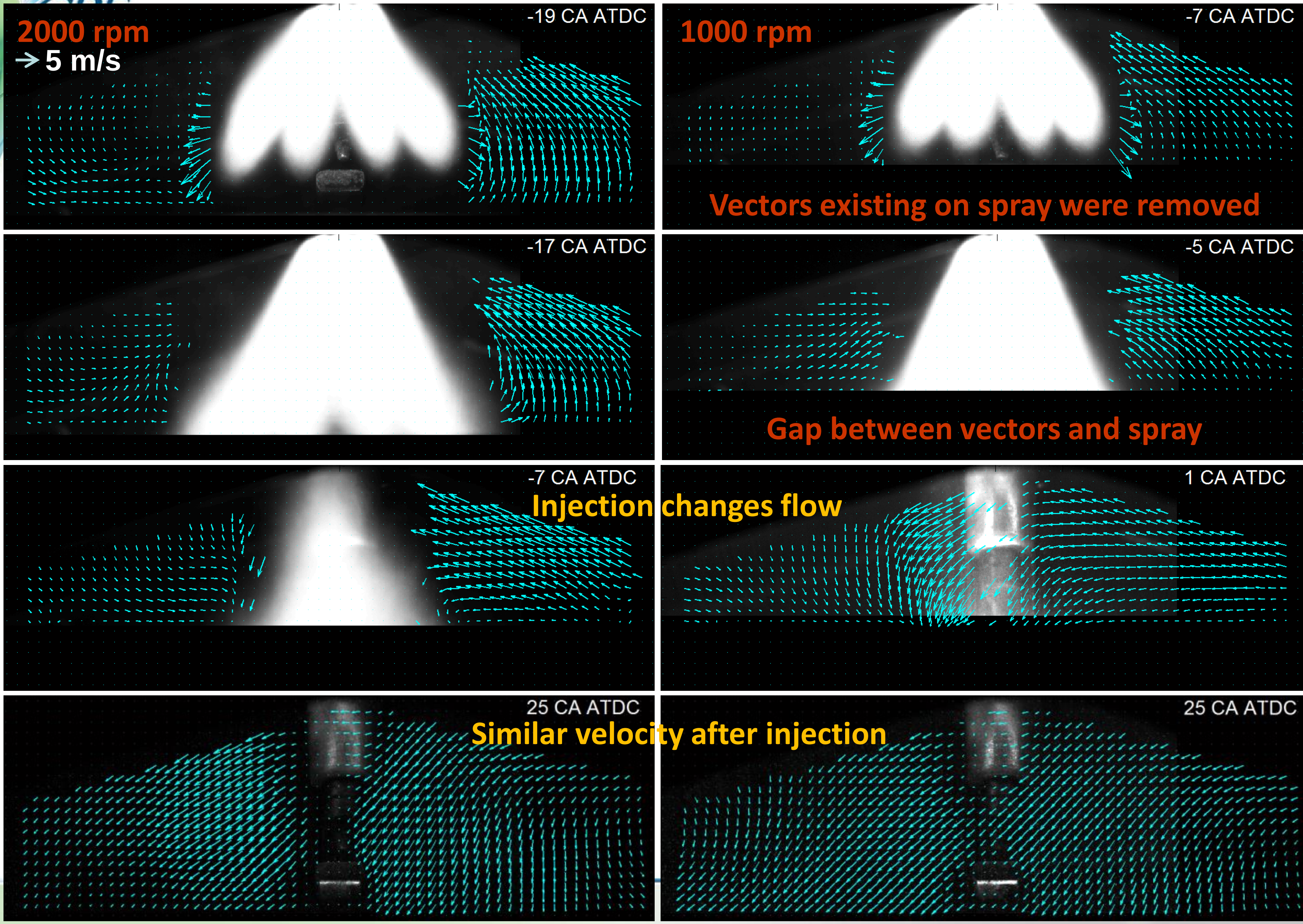




Mean flow structure (motored no injection)



Mean flow structure (motored with injection)

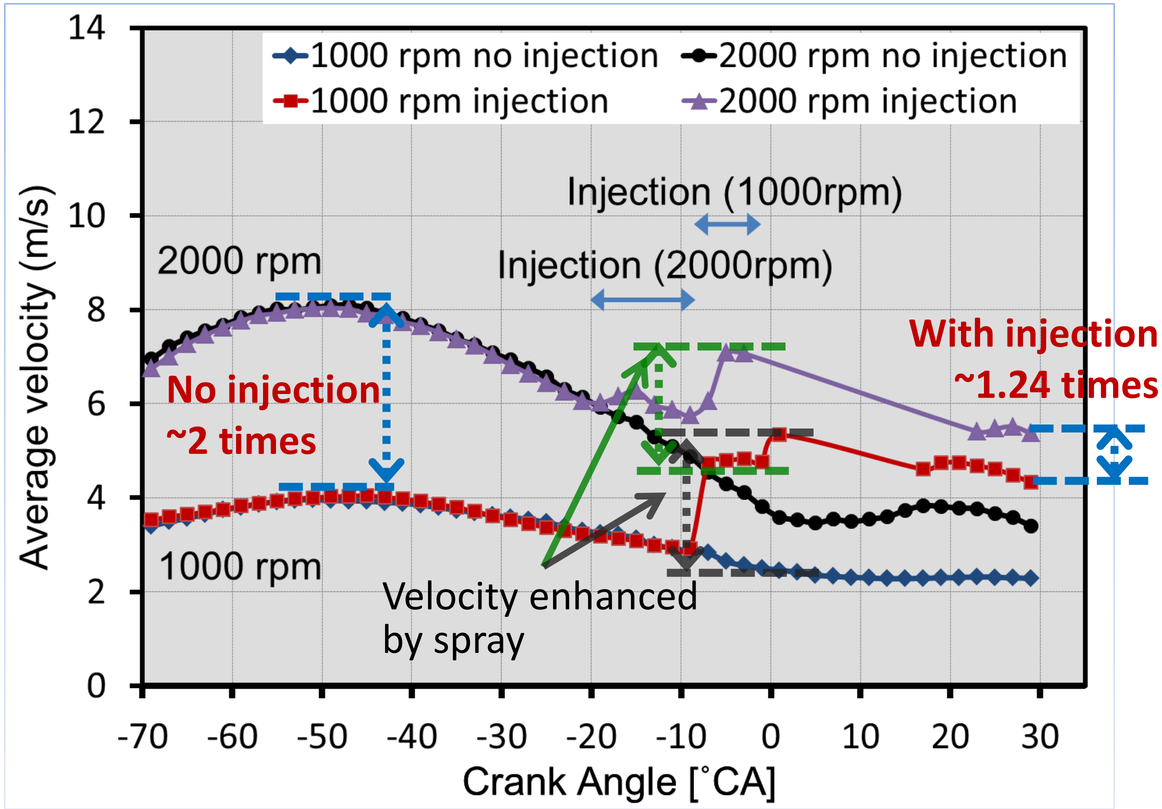


Average velocity evolution

- First average all vectors in each vector-field and then average over all cycles.

- **For no injection cases**, in-cylinder flow field significantly strengthens with engine speed (average flow velocity scaling of engine speed).
- **When injection occurs**, the velocity increased by spray is near-constant for both speeds
- **After injection**, the strength of the spray-generated flow remains only slightly variant with engine speed (1.24 times)

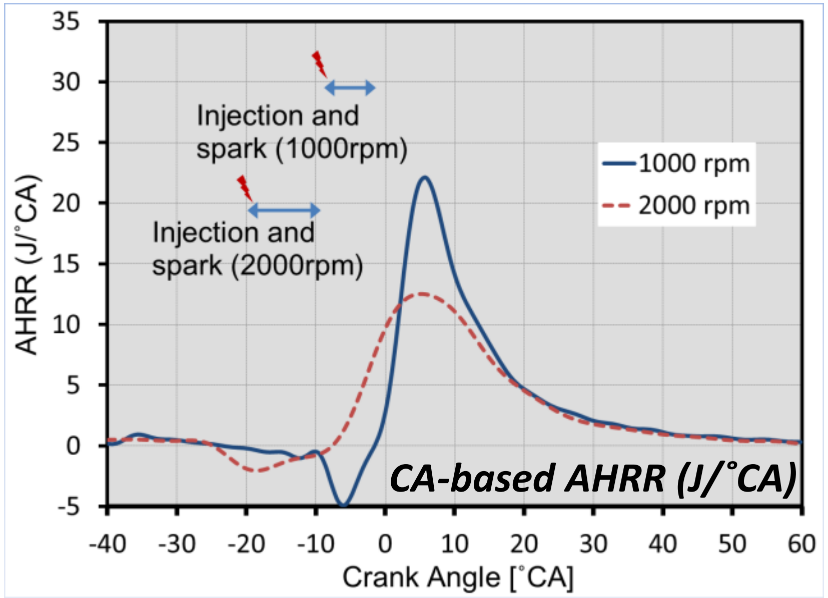
$$U = \frac{1}{c}\sum_{k}^{c}((\frac{1}{n \times m}\sum_{i}^{n}\sum_{j}^{m} U_{i,j,k})\ )$$

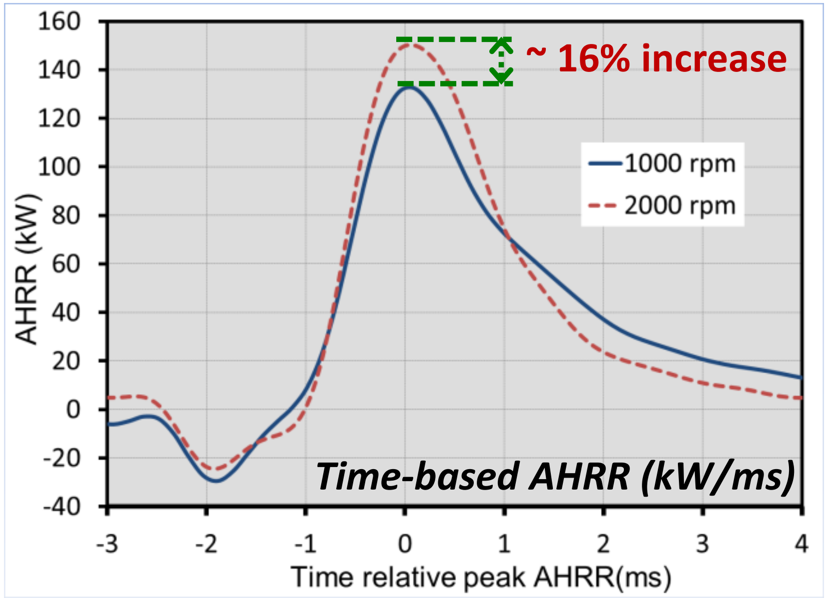


Injection: real liquid appears in the chamber

Speed effect on combustion performance

- Study <u>ensemble-averaged heat-release</u>, **AHRR spreads out in J/˚CA**
- Comparison of CA-based (J/˚CA) to **time-based (kW/ms)** AHRR

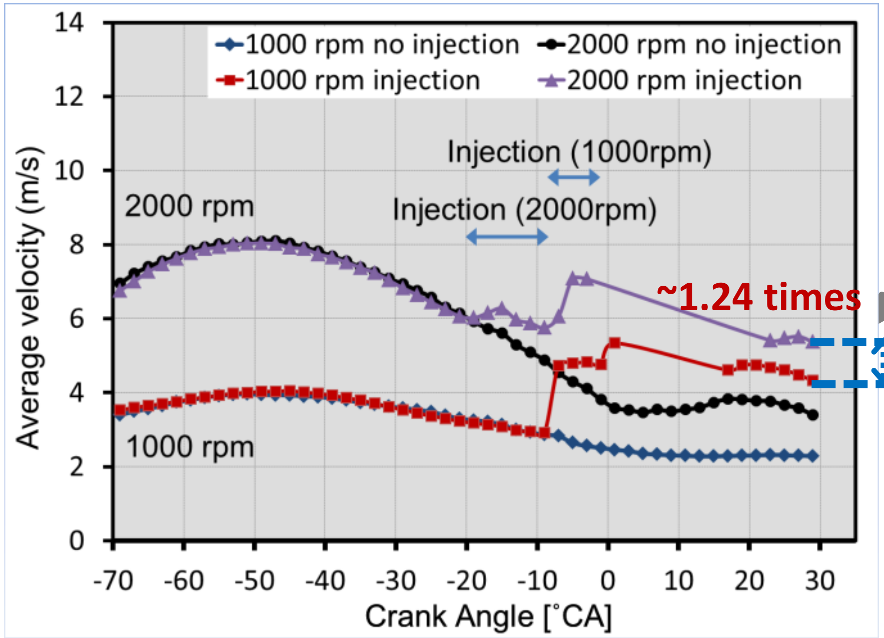


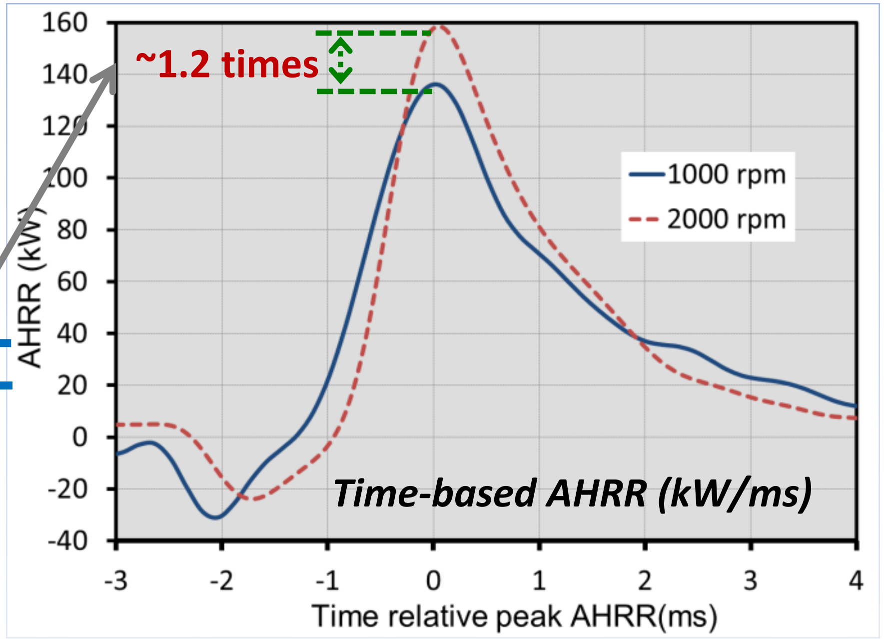


- Slightly increased as engine speed increases (about 16%)
  - No engine speed scaling of combustion duration observed, different from well-mixed operation

Flow velocity scaling of combustion duration

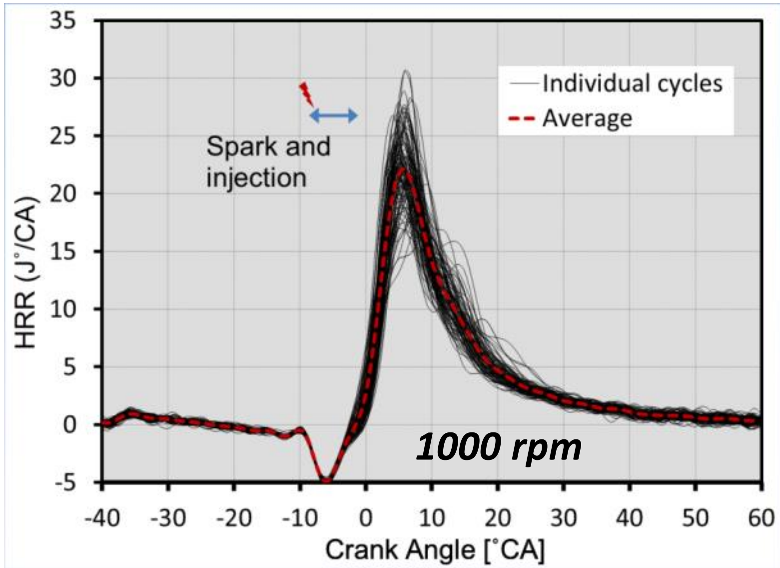
- Correlate difference in flow velocity ratio with difference in AHRR ratio
  - AHRR ratio is based on statistically selected individual cycle (from 100 cycles)
- Flow (spray generated flow) velocity scaling of combustion duration is found
- Spray generated flow affects the evaporation and subsequent mixing
  - Supports the hypothesis that the combustion rate is primarily governed by fuel/air mixing associated with spray generated flow
- **Swirl effect** and **fuel-air stratification effect** need to be examined in the future

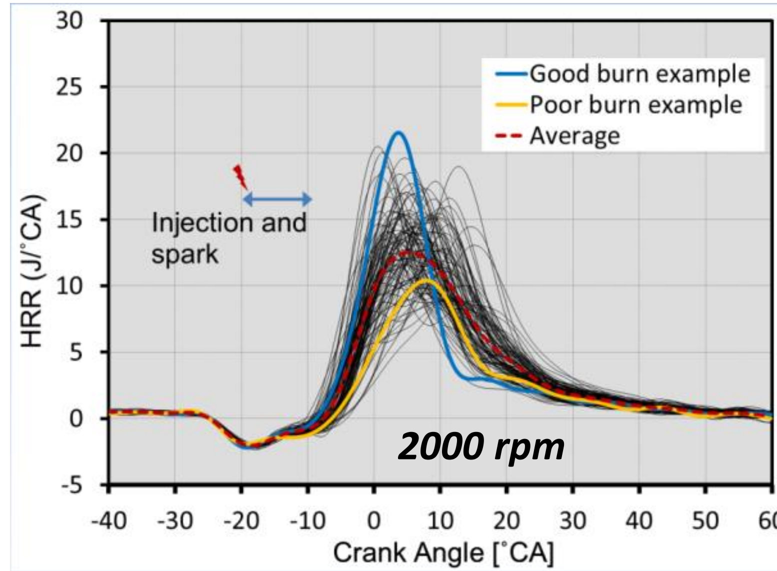




Speed effect on cyclic variability

- **Cyclic variation of the stratified combustion increases significantly with speed**

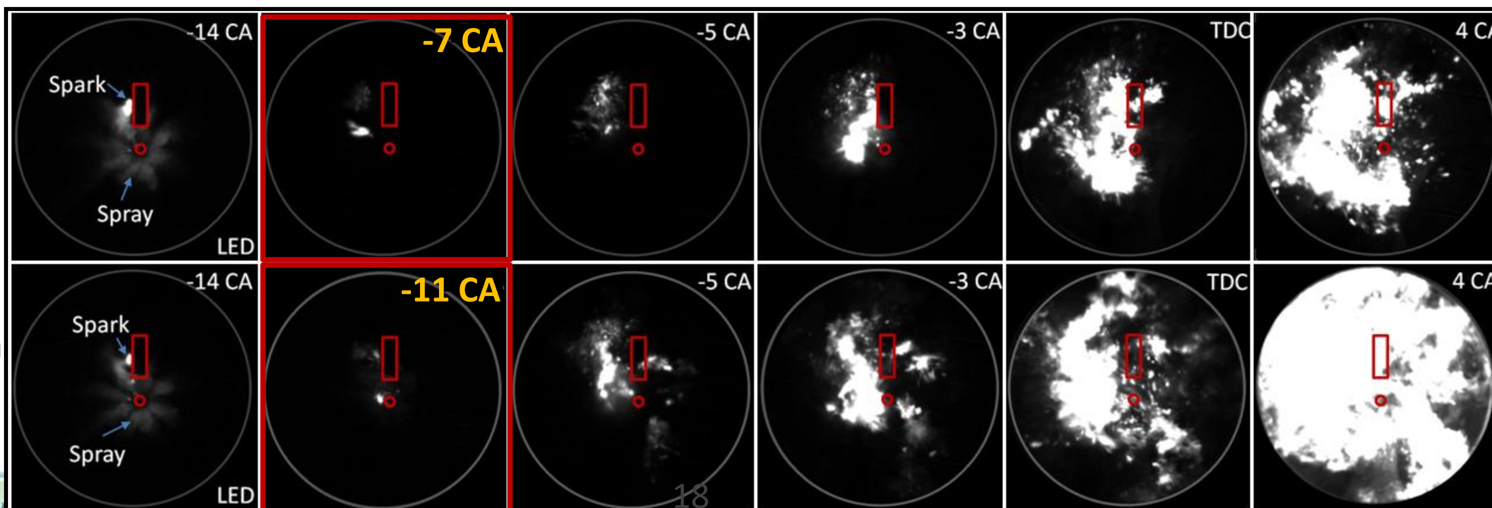




- **Early flame propagation delays for poor burn (stochastic processes)**
  - One major aspect is the flow effect

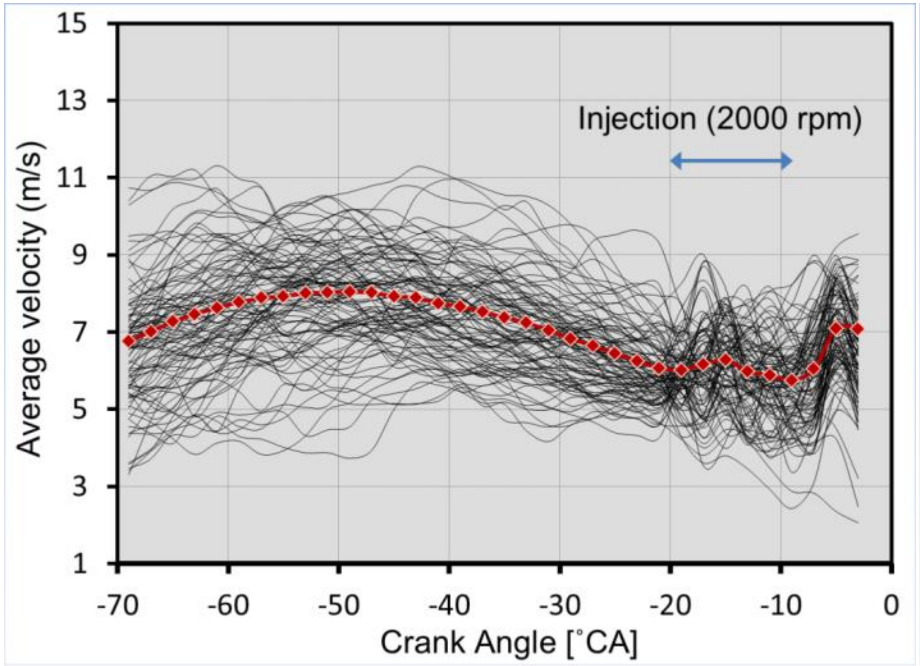
Poor burn /2000

Good burn /2000

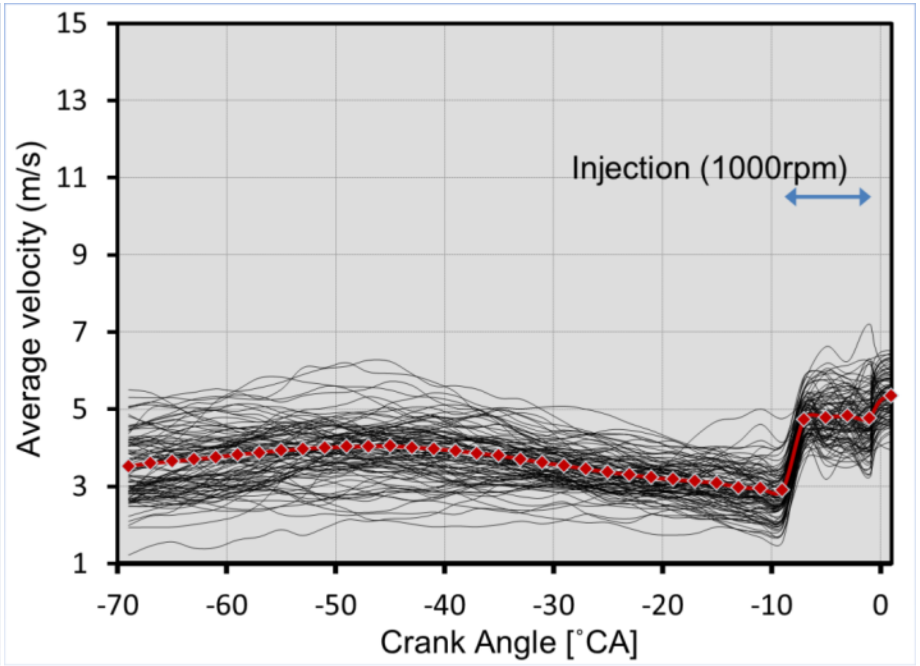


Cyclic variation of flow field

- Plot spatial average velocity over entire vector field for 100 individual cycles (with injection cases)
- Cyclic variation of the flow field increases significantly with speed
- Consistent with the cycle-to-cycle variations of HRR



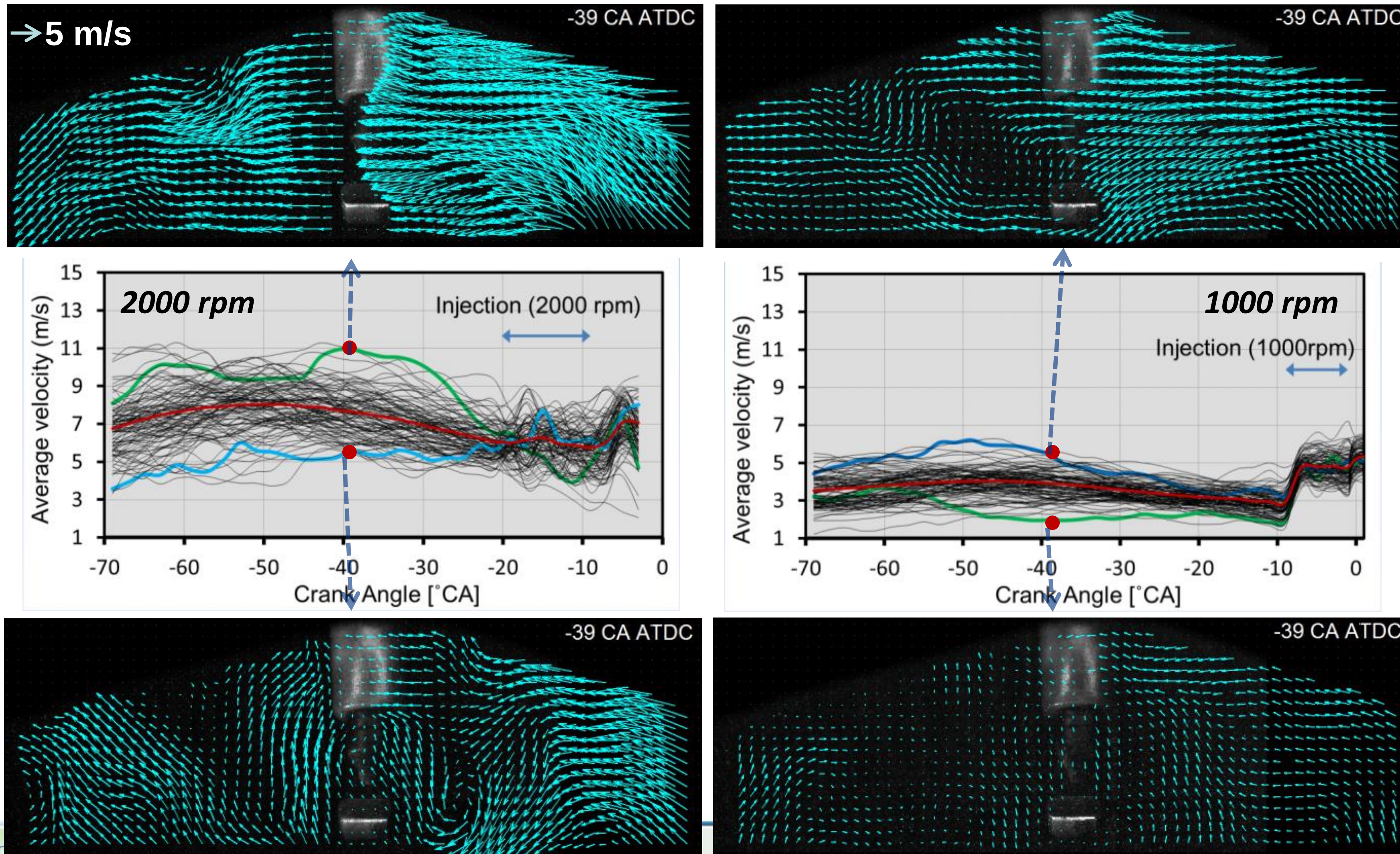
2000 rpm



1000 rpm

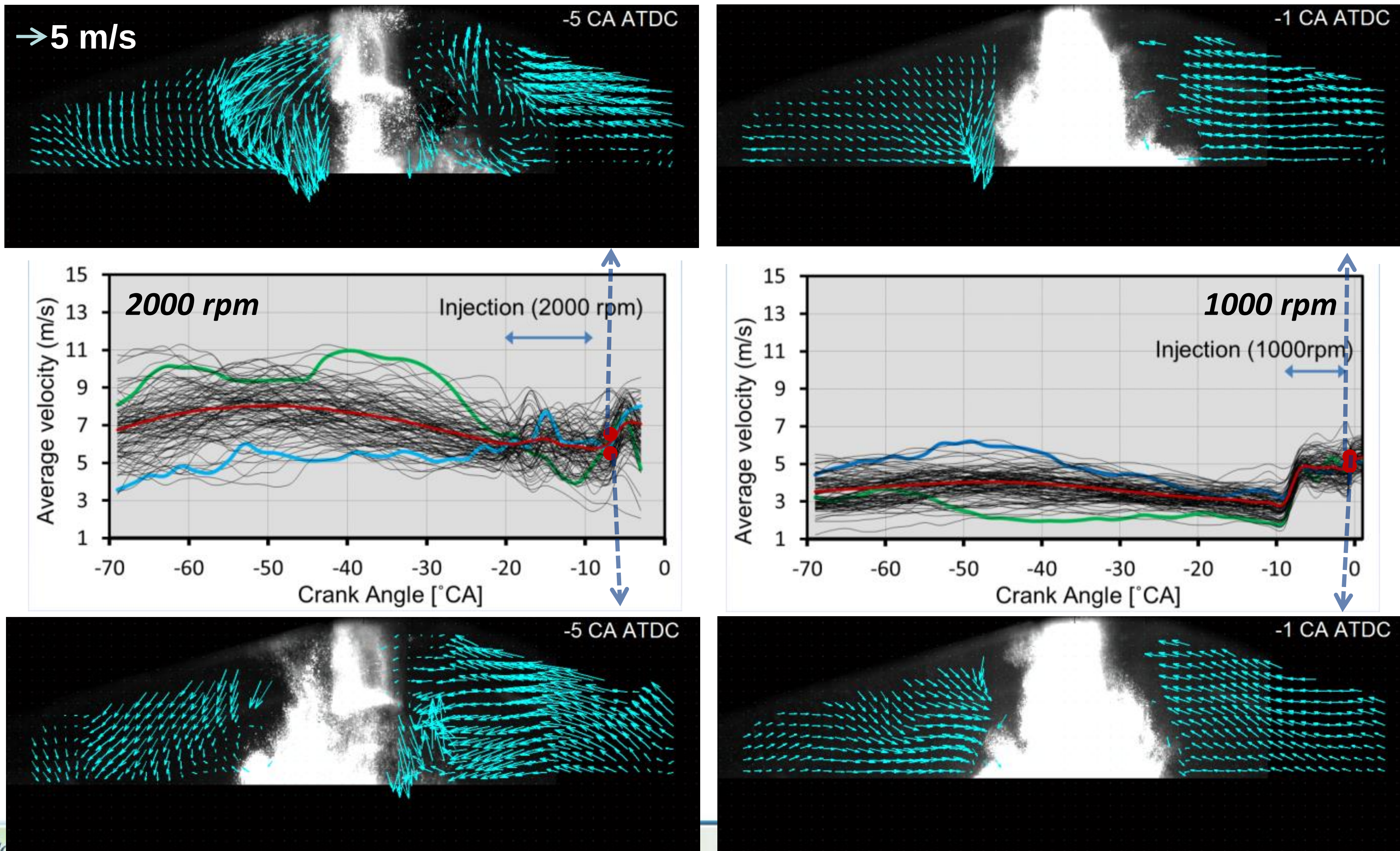
Cyclic variation of flow field

- Trend of flow development is changed by fuel injection process.
  - **Before injection (flow field generated by intake system)**



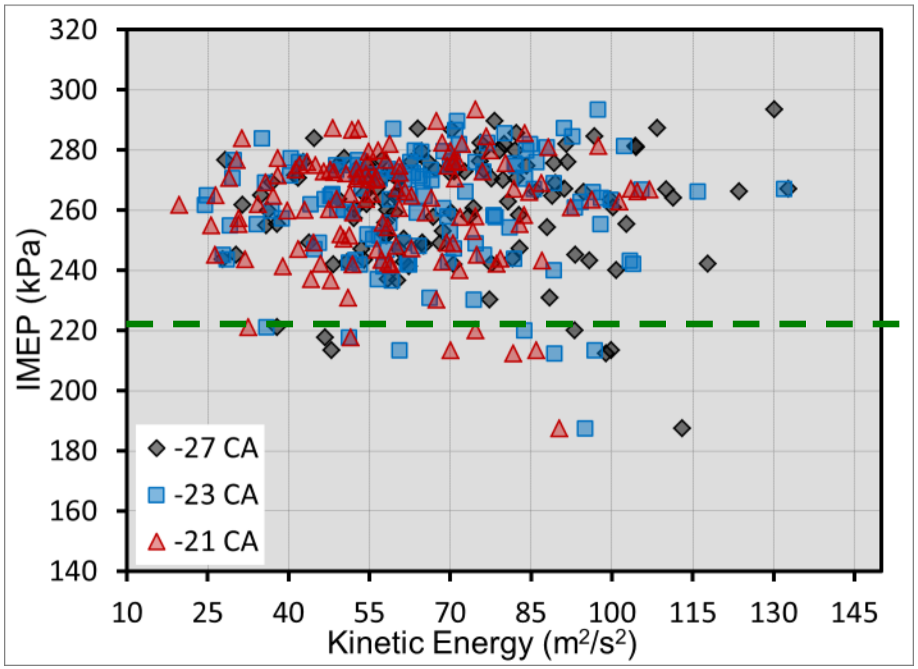
Cyclic variation of flow field

- Flow development is changed by fuel injection process.
  - **After the SOI (spray generated flow)**
- Examine the roles of flows before and after the SOI to stratified combustion

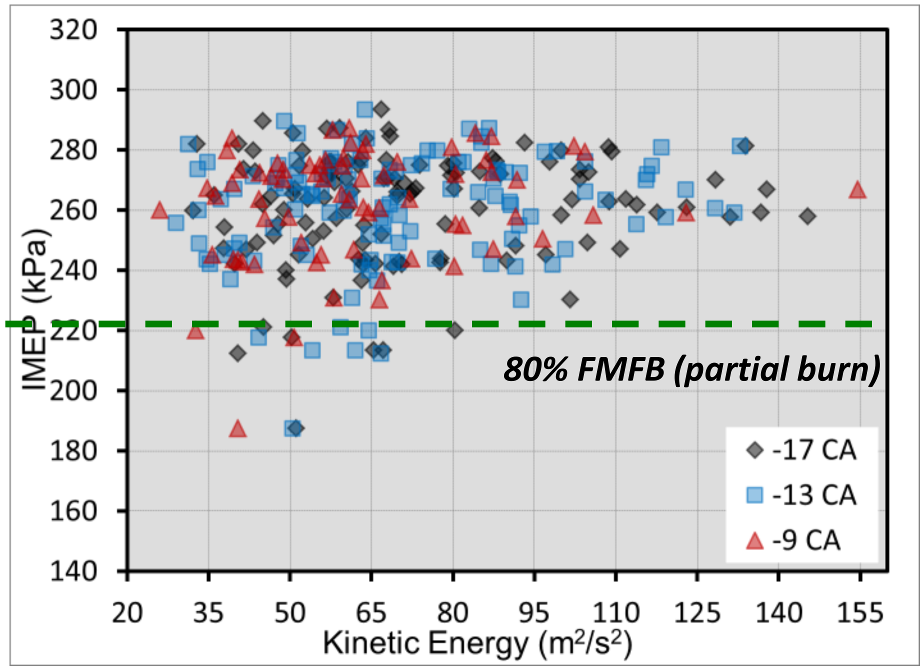


Flow effect on combustion performance

- **Examine the influence on combustion of flow fields before and after SOI**
- By correlating IMEP with spatial average kinetic energy (AKE) for 140 individual cycles
- First, **2000 rpm**, before injection, correlation does not exist
- After injection, relatively high AKE show normal IMEP, poor burns have low AKE values.
- However, many cases with large IMEP also indicate small AKE
- Exists under various crank angles before and after SOI **(spatial evolution)**
  - **There is perhaps a correlation of partial burns with spray generated flow energy**
  - The spray generated flow is not the only attributor



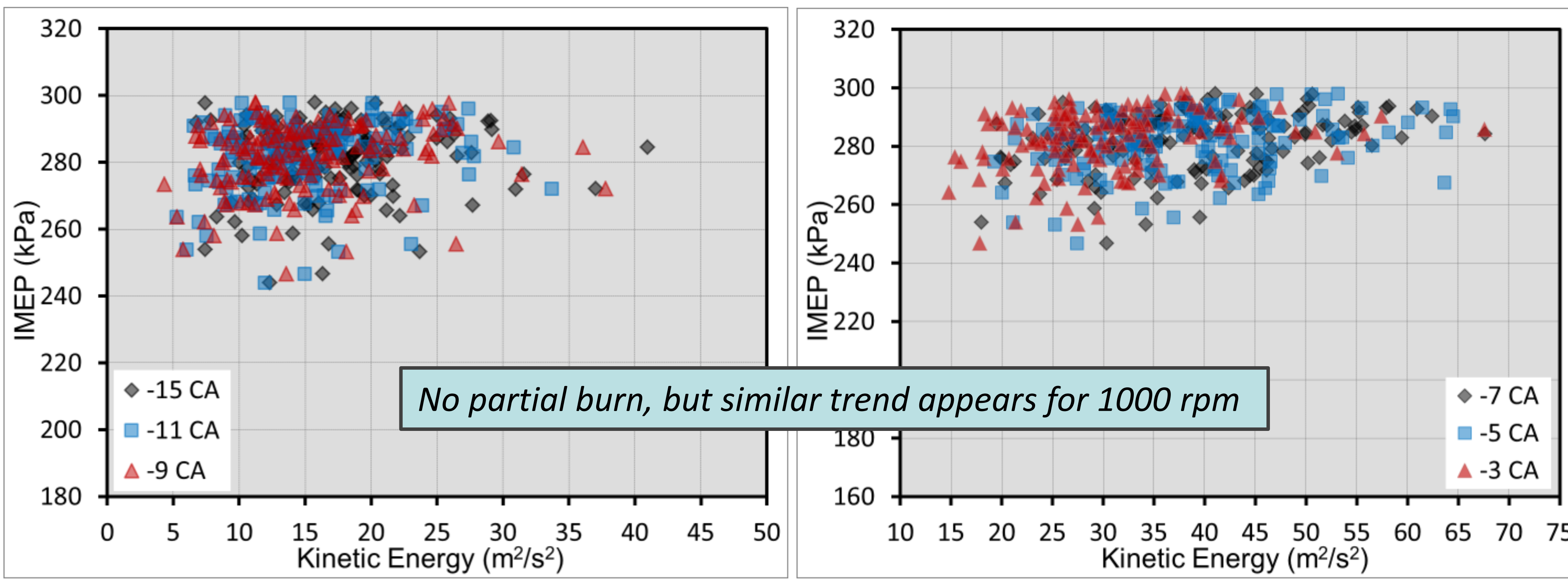
Before injection (spray appears at -19 CA) /2000 rpm



During and after injection /2000 rpm

Flow effect on combustion performance

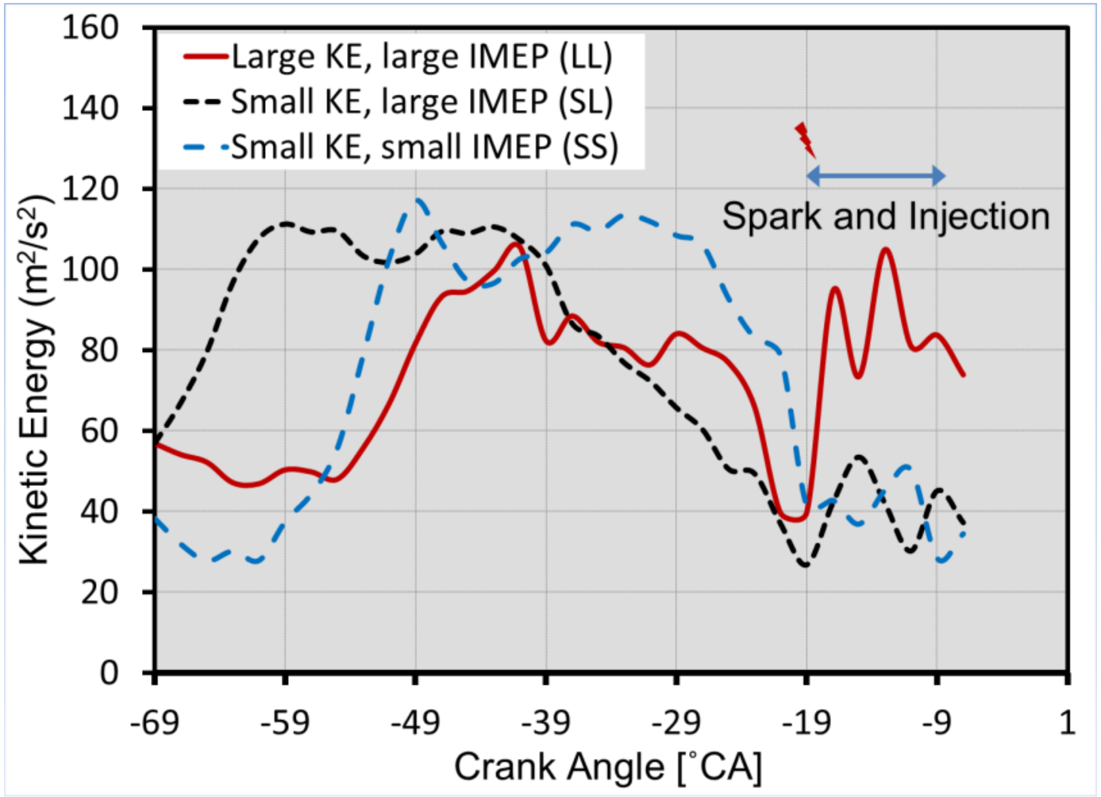
- **Examine the influence on combustion of flow fields before and after SOI**
- Correlate IMEP with Kinetic Energy for 140 individual cycles
- **<u>1000 rpm</u>**, before injection, no-correlation
- After injection, relatively high AKE show normal IMEP, poor burns have low AKE values.
- However, many cases with large IMEP also indicate small AKE
- Exists under various crank angles before and after SOI (**spatial evolution**), then conclusions
  - There is **perhaps a weak correlation of relatively poor burns with flow energy**
  - The spray generated flow is not the only attributor



Before injection (spray appears at -8 CA) /1000 rpm *During injection /1000 rpm*

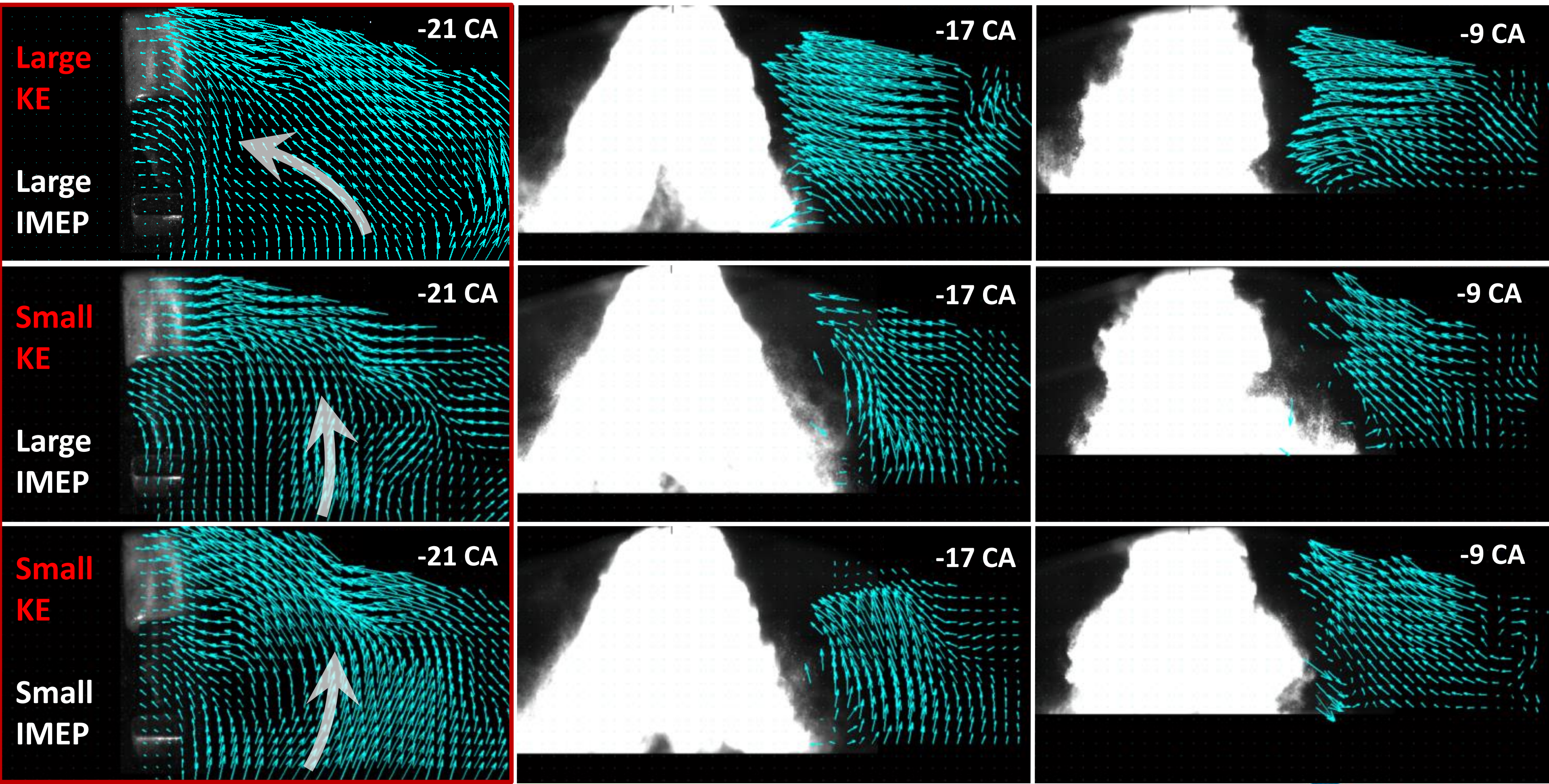
Potential reasons for cyclic variation

- Demonstrate the variations of fuel injection impact on flow development
- Three examples,
  - Large flow kinetic energy (KE) Large IMEP
  - Small KE large IMEP
  - Small KE small IMEP



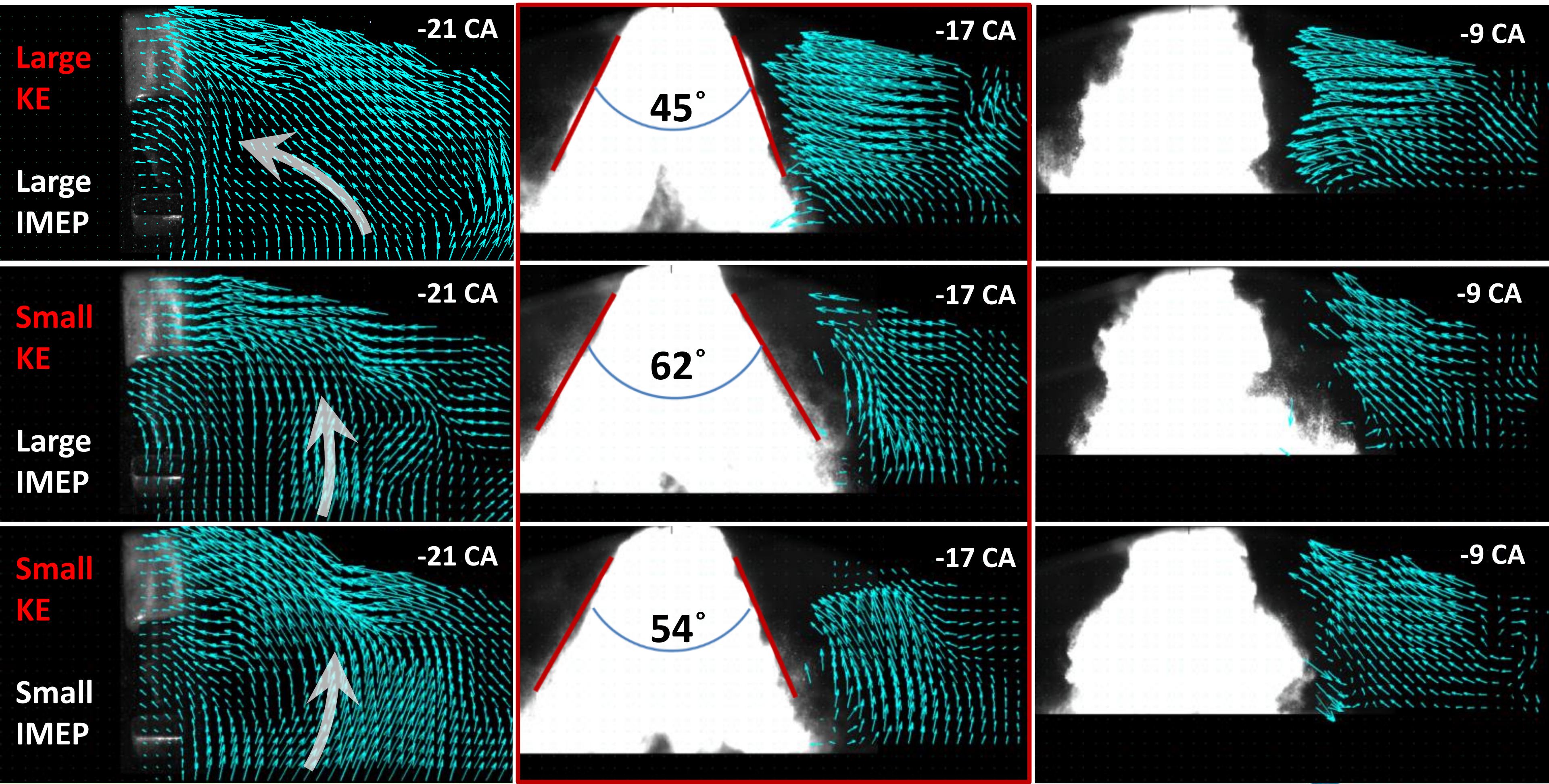
Preliminary result – flow direction

- The left half of vector field is not shown due to the low signal-to-noise level
  - Strong energy attenuation as a result of soot deposit on piston-bowl window.
- **First, flow direction before injection** (relies on flow generated by intake system)
  - Left-to-right direction is easier to be entrained by the spray, then large KE



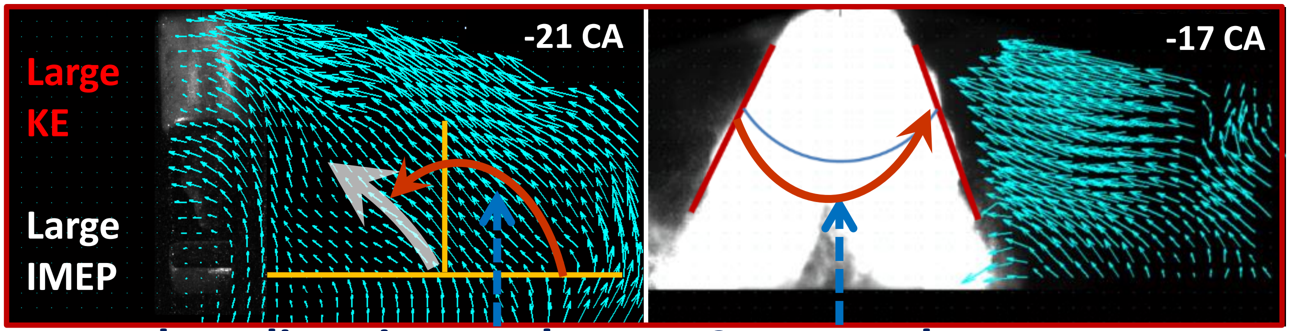
Preliminary result – spray structure

- **Second, large fluctuations in spray structure** (17CA) from cycle to cycle, different from previous studies (small spray-plume angle variation)
  - Because of spray collapsing -- small included angle (60˚) and near-TDC injection (high density and temperature)
  - More collapse, larger flow energy



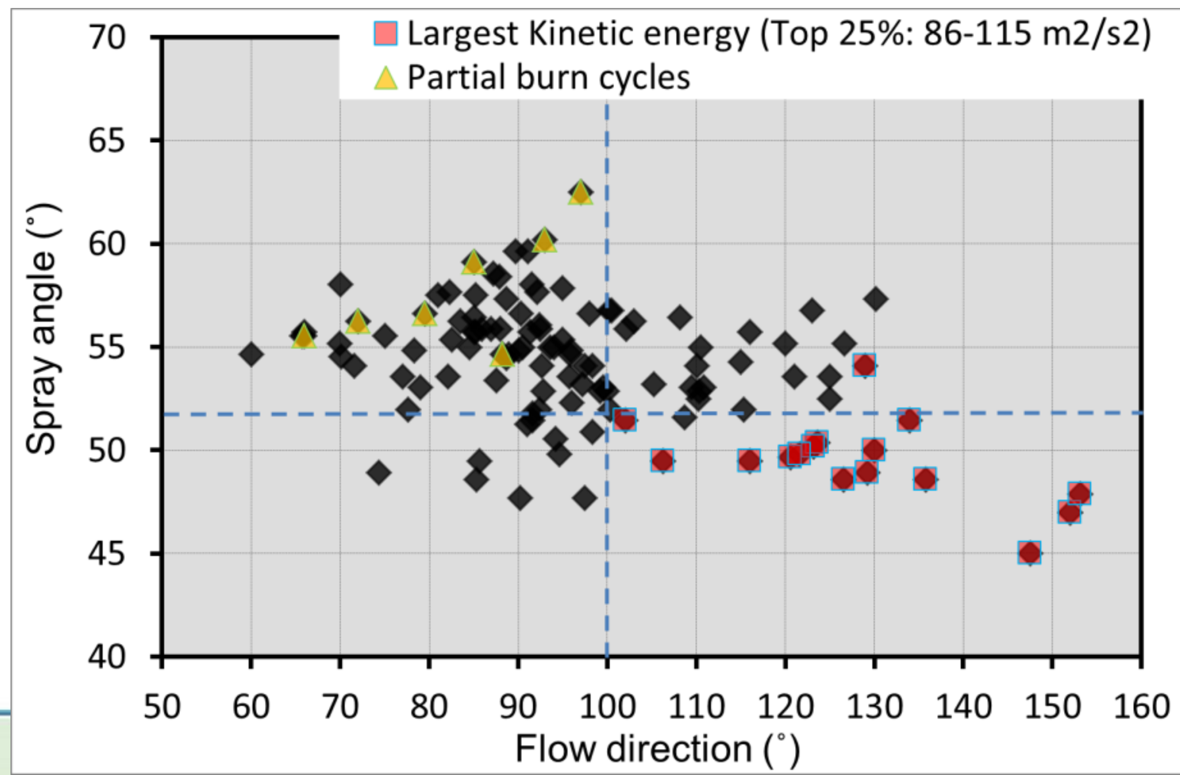
Flow direction and spray structure

- Combined effects of flow direction and spray structure on flow energy
  - Flow direction angle and spray angle



Flow direction angle **Spray angle**

- Observation based on 140 cycles: <u>large flow direction angle with small spray angle corresponds to large flow energy, then good burns</u>
- Consistent with the correlation of partial burns with spray generated flow energy
- <u>Further investigation is necessary</u>



Summary

- Use PIV to determine the roles of the flows before and after SOI to stratified combustion
- On average, energy of spray-generated-flow does not change with speed.
- **Spray-generated-flow velocity scaling of combustion duration is found**
  - **Combustion rate is primarily governed by fuel/air mixing associated with spray-generated-flow**
- Cyclic variation of the flow field increases with speed, consistent with the cyclic variation of combustion performance.
- **A weak correlation of partial burns with spray-generated-flow energy is found**
  - **Spray-generated-flow is important, but not the only attributor for cyclic variation**
- Large fluctuations in flow structure before injection and spray structure are found, having potential to cause cyclic variation of spray generated flow
  - **Large flow direction angle before injection with small spray angle lead to large flow energy (stratified combustion with near-TDC injection), then good burns**
  - **Indicates combined effects of tumble flow and spray control the flow generated by spray, then affect combustion**
- Further work: swirl flow, fuel-air stratification, interaction between spray and flow