Engine Combustion System Design with CAESES
A Passive Pre-Chamber Case Study

ANQI ZHANG
ARAMCO AMERICAS: ARAMCO RESEARCH CENTER - DETROIT

MAR 31, 2026

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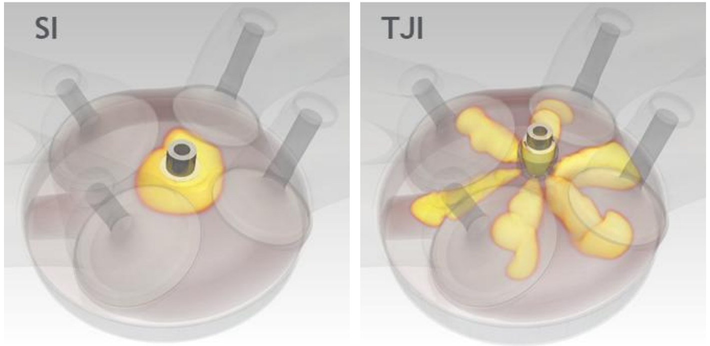
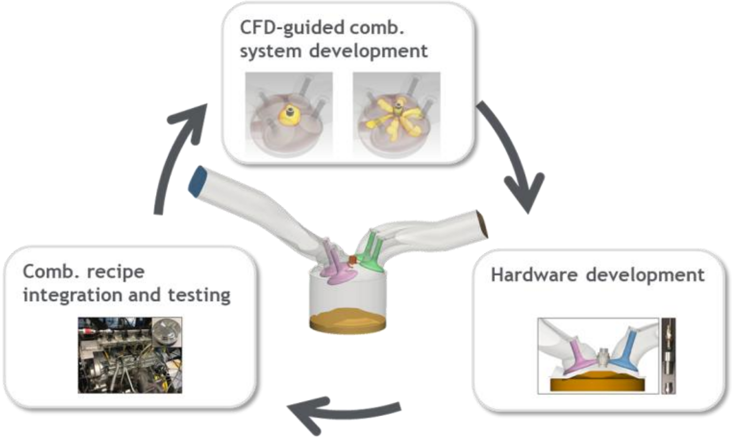
Background and Motivation

Pre-Chamber Ignition: enabling technology for engine efficiency improvement

- Extending dilution tolerance: spatially-distributed ignition sources
- Mitigating knock at elevated loads: accelerated combustion





Pre-Chamber Combustion Research at Aramco

- Physics-based 3D CFD combustion model
- Closely-coupled analytical and experimental campaigns
- Extensive design exploration and analysis

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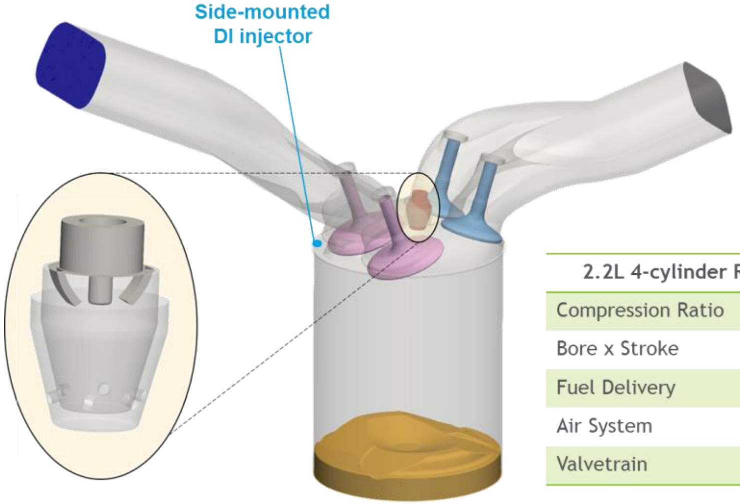
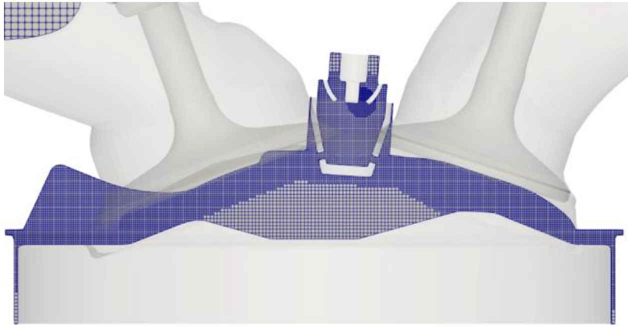
Open-cycle Engine CFD Model for Pre-chamber Combustion



2.2L 4-cylinder Research Engine	
Compression Ratio	14
Bore x Stroke	86 x 94.6 mm
Fuel Delivery	Side-mounted GDI
Air System	Turbo-charged
Valvetrain	LIVC, Dual VVT



CFD Model Setup in CONVERGE™		
Turbulence	RNG k-ε RANS	
GDI Spray	Lagrangian liquid parcels with KH-RT break-up; PRF surrogate fuel	
Spark Ignition	Spherical energy deposition	
Combustion	SAGE (multi-zone well stirred reactor with detailed mechanism)	
Boundary Condition	Dynamic intake/exhaust pressure waveforms	
Mesh	AMR + Fixed Embedding	
	Base	4mm
	Cylinder(gas exchange)	1mm
	Cylinder(combustion)	0.5mm
	Pre-chamber and Jet	0.25mm
	Spark gap	0.125mm

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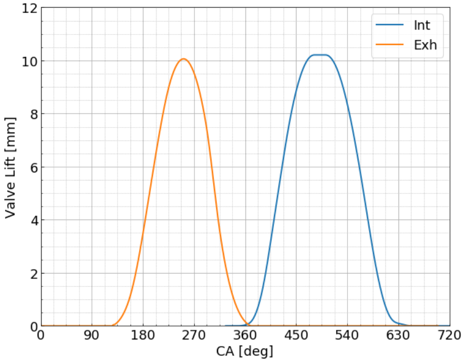
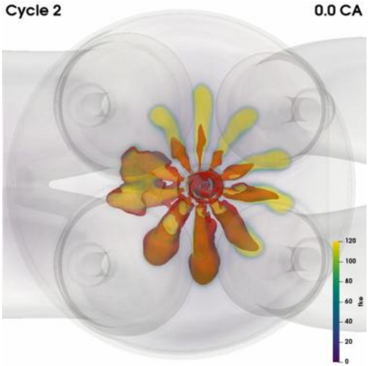
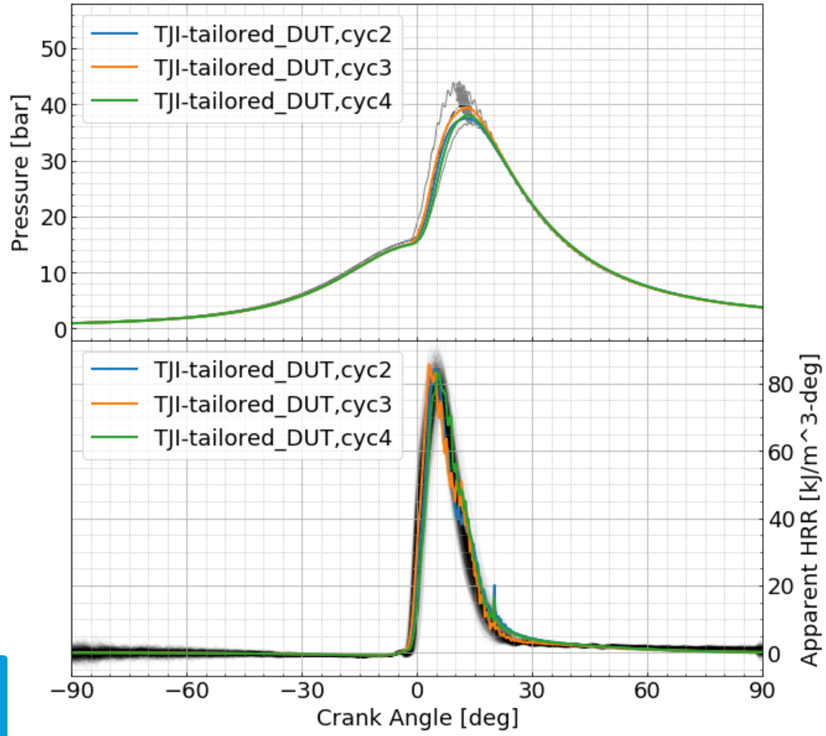
Base Combustion Model Validation at Part Load

- Engine test condition
  - 1500 RPM, 5 bar BMEP
  - Spark timing at -8 deg aTDC
  - Early GDI with SOI at -300 deg aTDC, λ=1
  - Passive pre-chamber with 10 nozzles
  - LIVC cam minimum valve overlap







Engine combustion simulations achieve satisfactory agreement with experimental measurements over multiple cycles

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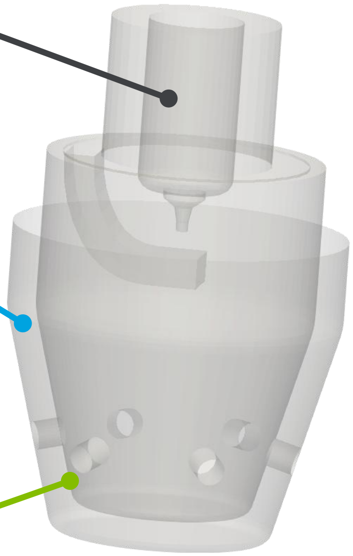
Design Space of a Passive Pre-Chamber

Spark Plug
- Essential component for ignition
- Delivers an electrical spark to ignite the fuel-air mixture within the engine's primary combustion chamber

Pre-chamber body
- A rotational solid forming a housing around the spark plug
- Key design considerations:
  - Pre-chamber shape
  - Pre-chamber volume

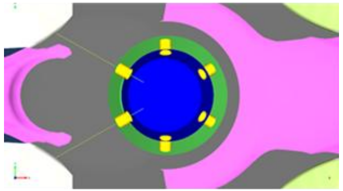
Pre-chamber nozzles
- Nozzles evenly positioned and drilled close to the base of the pre-chamber housing
- Key design considerations:
  - Number of nozzles
  - Size of each nozzle
  - Configuration of nozzle placement



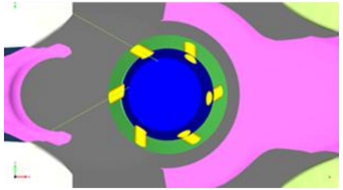
Nozzle Placement Variants

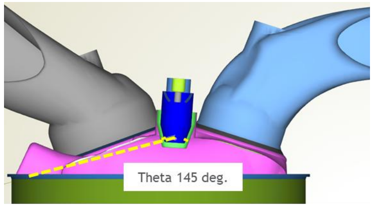
Non-swirl
vs.
Swirl

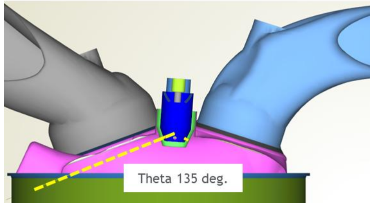
Non-swirl Nozzles



Swirl Nozzles



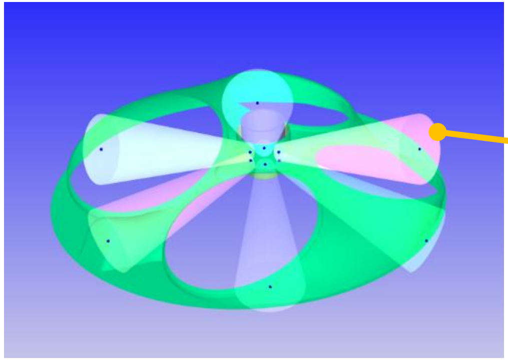




Wide vs. narrow inclusion angle

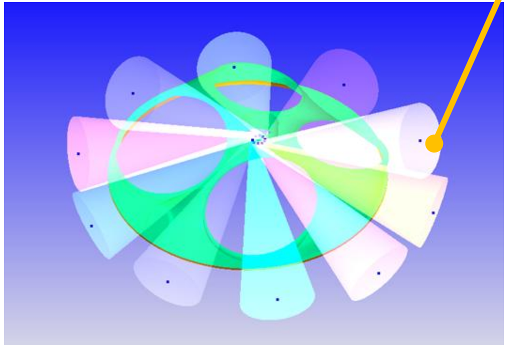
Effectively modeling subtle changes in geometric features and generating CFD-compatible surface geometries continues to be a practical challenge.

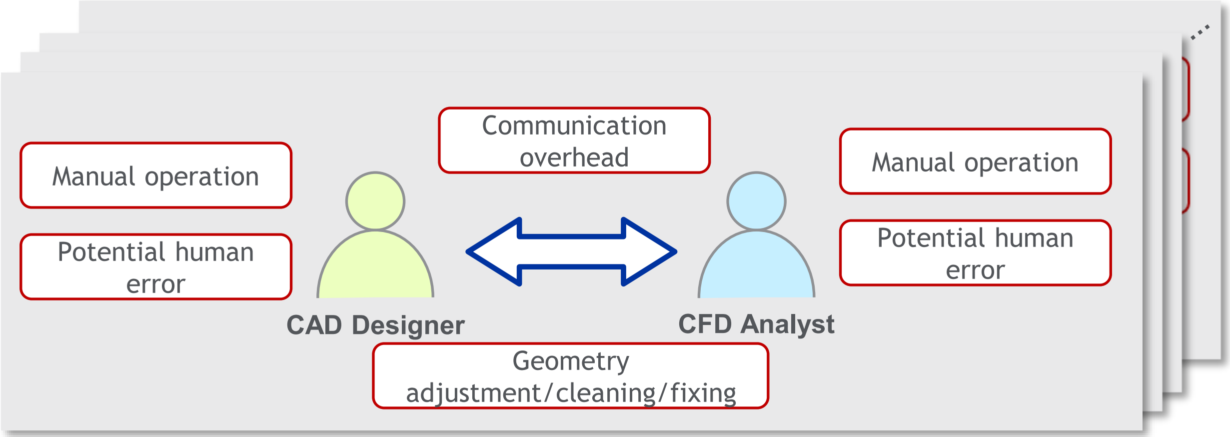
Challenges in Setting Up CFD Cases for Batch Analyses



CFD Mesh Refinement Zones

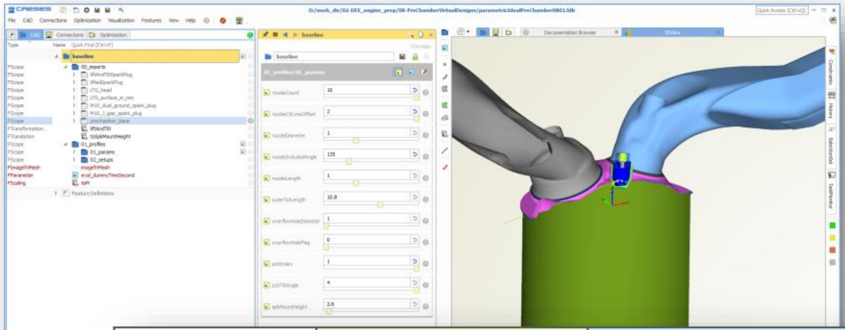
- Each nozzle has designated mesh refinement zones to encompass the associated turbulent jet flow and combustion areas.
- These refinement zones are cone-shaped, specified by their start and end positions in global coordinates.
- Updating these zones became a time-consuming process whenever the pre-chamber design was modified.



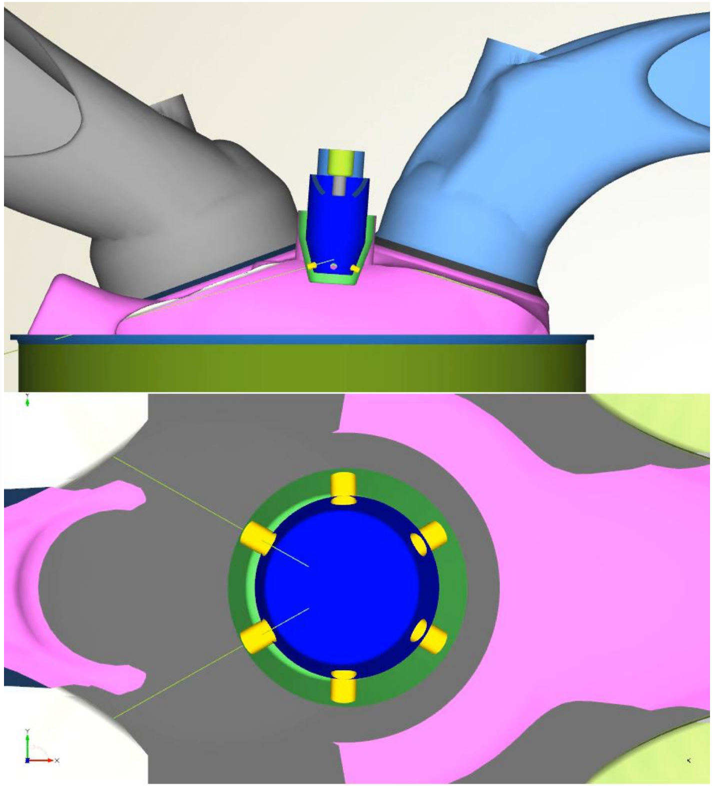


Traditional workflows can quickly become impractical for conducting batch CFD analyses.

Streamlined Automation Enabled by CAESES



		A/V = 5.0 [m^{-1}]			A/V = 6.5 [m^{-1}]			A/V = 8.0 [m^{-1}]	
145° inclusion	Non-swirl	6 noz	8 noz	10 noz	6 noz	8 noz	10 noz	8 noz	10 noz
	Swirl	6 noz	8 noz	10 noz	6 noz	8 noz	10 noz	8 noz	10 noz
135° inclusion	Non-swirl	6 noz	8 noz	10 noz	6 noz	8 noz	10 noz	8 noz	10 noz
	Swirl	6 noz	8 noz	10 noz	6 noz	8 noz	10 noz	8 noz	10 noz



- Parametric pre-chamber model developed
- Case-specific CFD inputs preparation automated
  - Ignition source location
  - Mesh refinement regions

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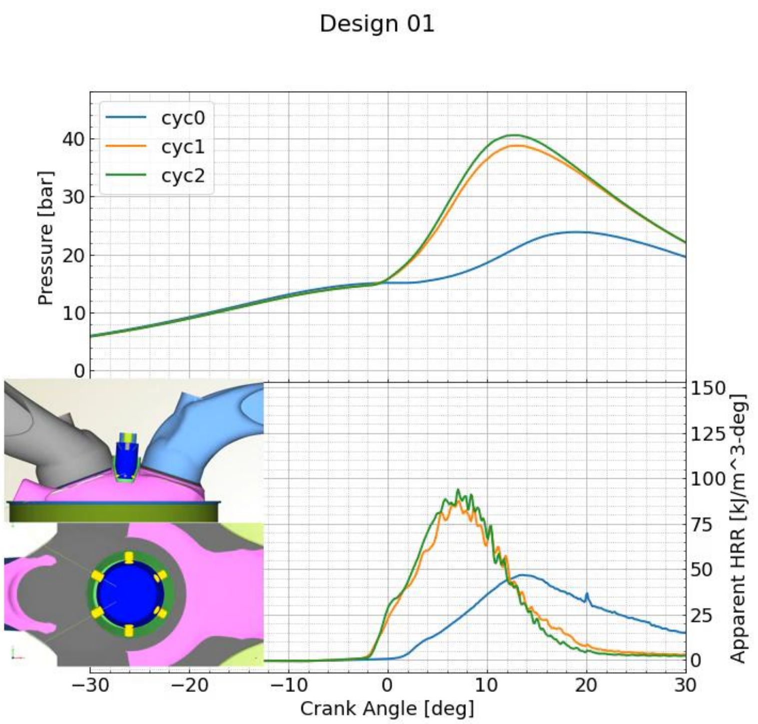
Multi-cycle Engine CFD Results

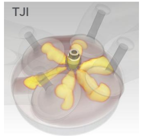
- Multi-cycle engine combustion simulation results
  - 3 consecutive cycles performed for each design
  - The first cycle always suffers from unrealistic initial conditions and should be excluded
  - The two effective cycles largely resemble each other in heat release profiles, and represent different features between different designs

- Limitation of numerical evaluation
  - For the batch CFD simulations, intake pressure, fuel flow rate, and spark timing are fixed for all designs



- **Consistent behavior between effective cycles increase confidence of the numerical results**
- **Multi-cycle combustion simulations are essential when realistic initialization is not available**

Pre-Chamber Engine Combustion Analysis



Turbulence Enhancement during Combustion

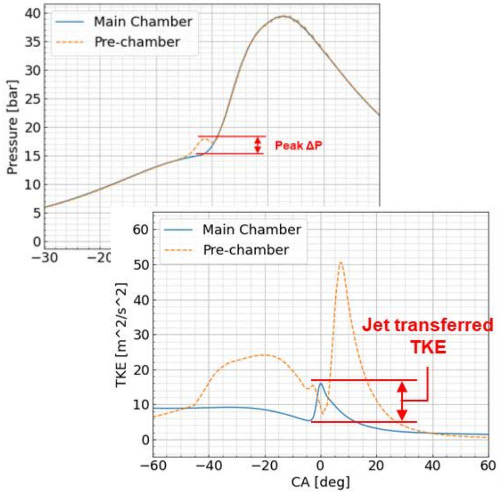
Effects of added turbulence?

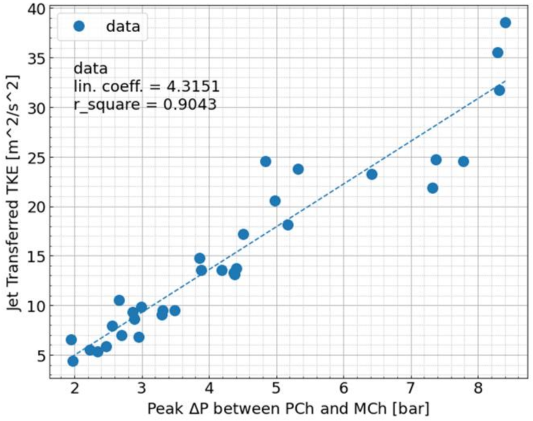
- **Fast combustion**
  - Shorter combustion duration to reduce exhaust heat loss
- **Increased combustion efficiency**
  - Release more chemical energy

- **Increased peak pressure and temperature**
  - Potential increase of heat transfer loss
- **Higher turbulence near walls**
  - Increase heat transfer coefficient and enhance heat transfer loss

Trade-offs exist between accelerated combustion and enhanced heat transfer

How to quantify added turbulence?





The peak ΔP is an effective performance metric that reflects combined effects of pre-chamber designs

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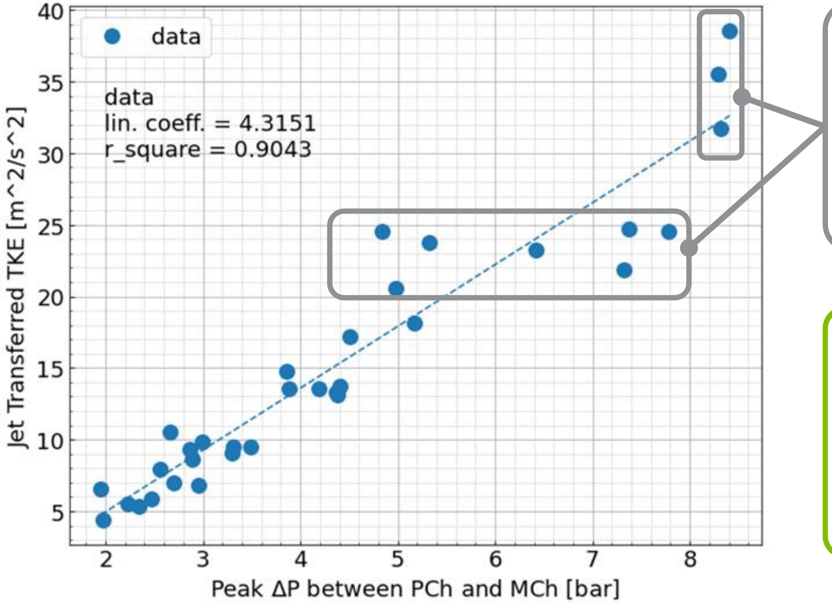
Advantages of Batch Analysis



Potential challenges with limited dataset

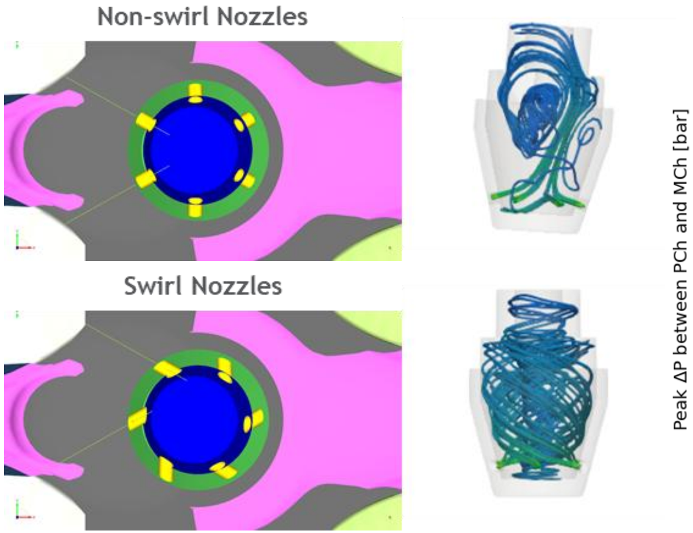
- Model uncertainty could compromise interpretation of data trend
- Unclear or misleading trend interpretation for extreme situations

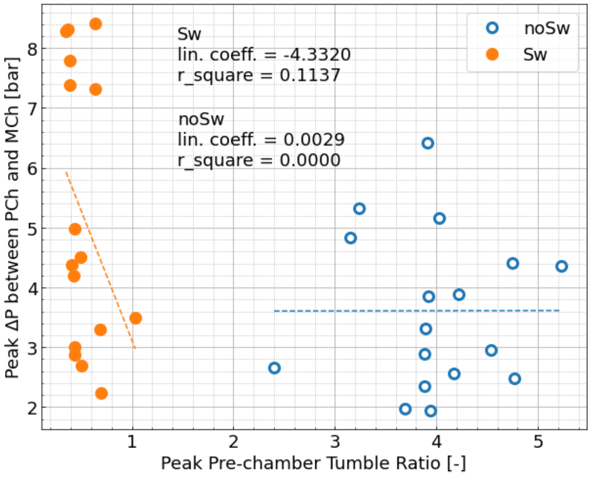
Benefits of a large dataset

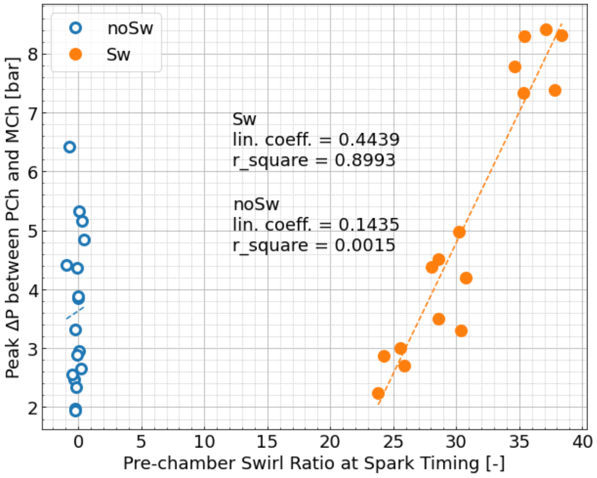
- Complete picture of data trend
- Possible to understand/evaluate model uncertainty level

Large, well-structured datasets are essential to reveal true trends and avoid misleading conclusions in batch CFD analysis.

Nozzle Arrangement Effects (1/4): Peak ΔP and Charge Motion







- **Strong tumble motion does not necessarily accelerate pre-chamber combustion**
- **Peak ΔP can be consistently enhanced with stronger swirling charge motion within the pre-chamber**

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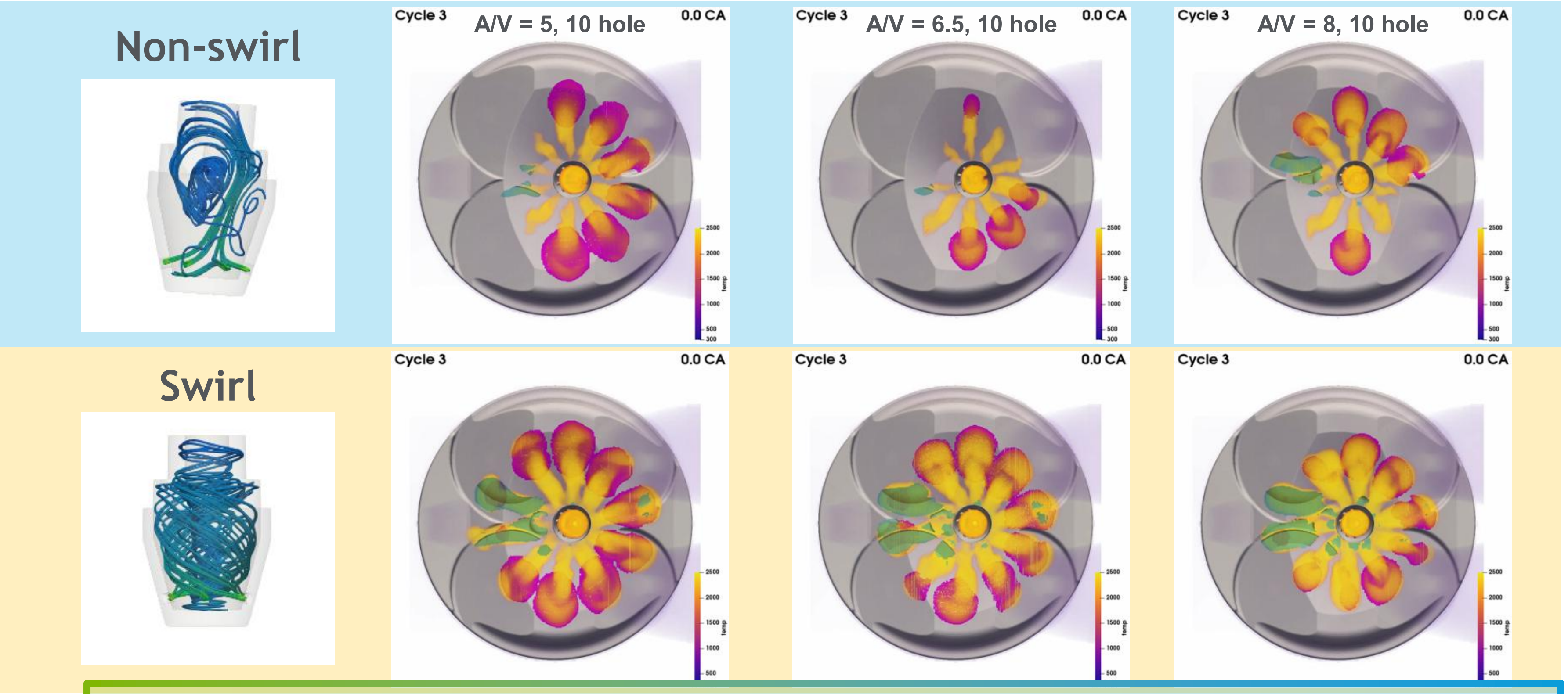
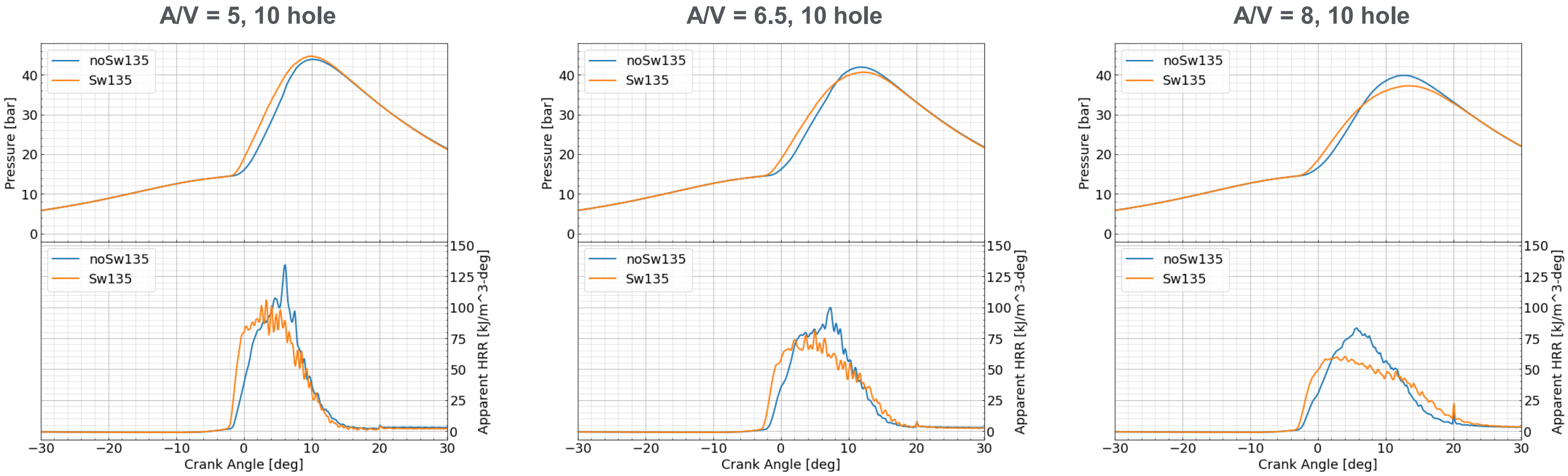
Nozzle Arrangement Effects (2/4): Jet Structure



The swirl nozzle design is more likely to generate evenly-distributed Jets

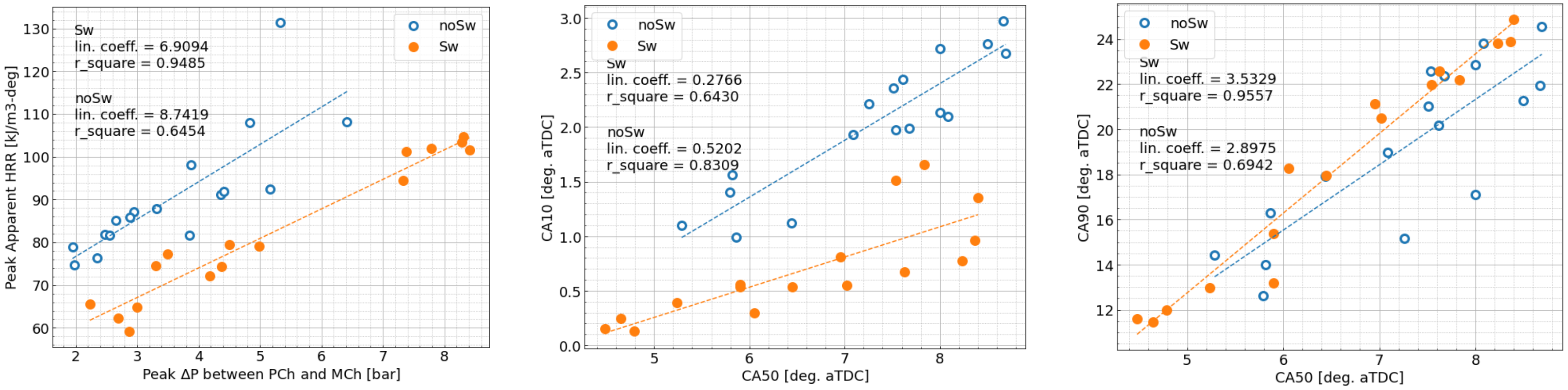
Nozzle Arrangement Effects (3/4): Combustion Profile



Swirl pre-chamber designs yield:

- Faster early heat release
- Lower peak heat release rate in the main chamber
- Reduced peak main chamber pressure
- Slightly extended combustion duration

Nozzle Arrangement Effects (4/4): Combustion Characteristics

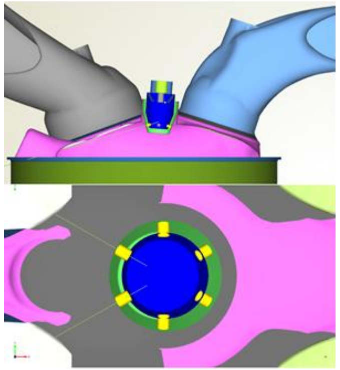


On reviewing the complete dataset:

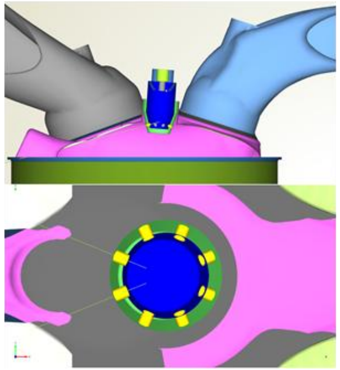
- The swirl design leads to consistently **reduced peak AHRR**, which could contribute to reduced heat transfer and combustion noise
- The swirl design features **faster early combustion**, but similar end of combustion. As a result, combustion duration is likely longer using a swirl design

Area-to-Volume Ratio (AVR) Effects

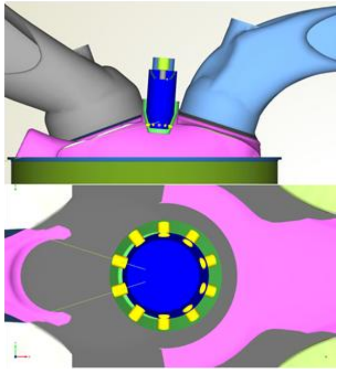
AVR = 6.5, 6 nozzle

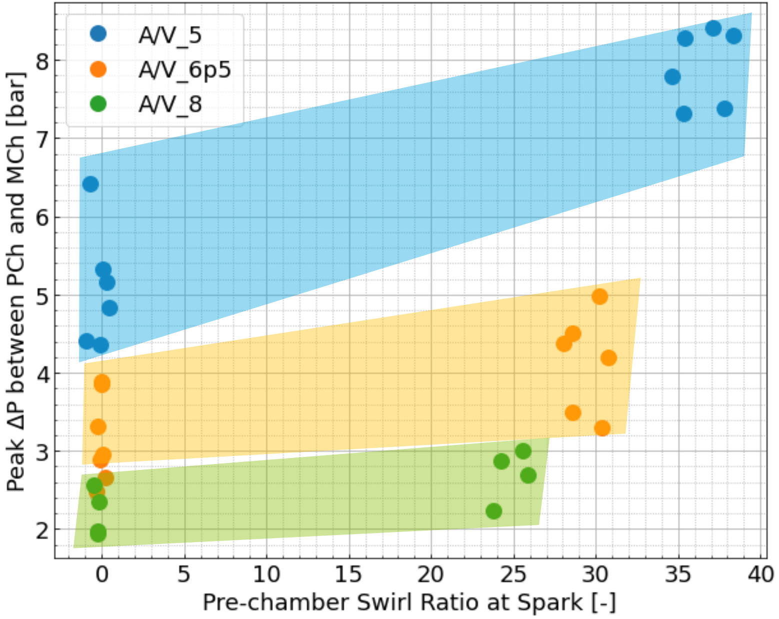


AVR = 6.5, 8 nozzle



AVR = 6.5, 10 nozzle





- Pre-chamber volume is adjusted simultaneously with the nozzle outlet area to achieve controlled AVR
- Obvious grouping found for evaluated configurations, in general, peak ΔP increases as AVR reduces
- Peak ΔP is a strong function of AVR, and other design parameters also contribute to peak ΔP variation

Pre-chamber AVR is the major knob to dial the resulting ΔP for desired engine combustion performance

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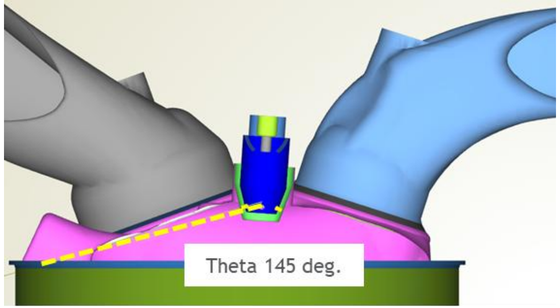
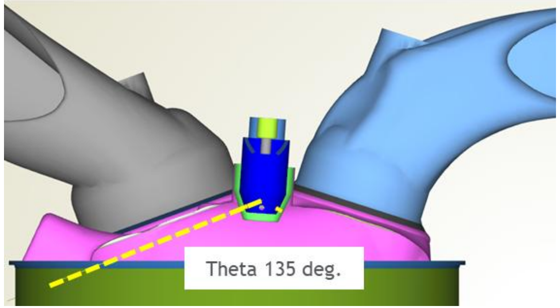
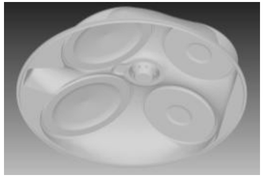
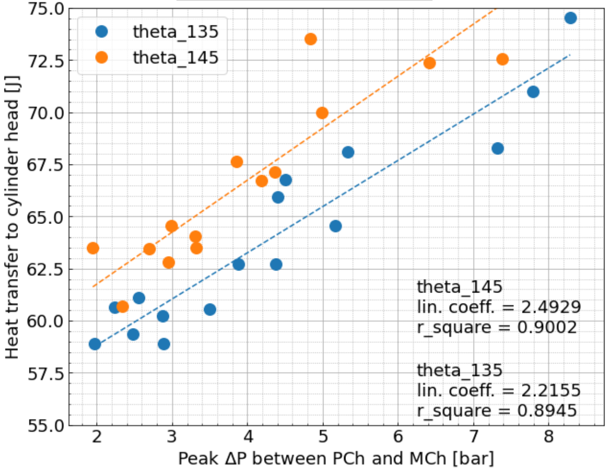
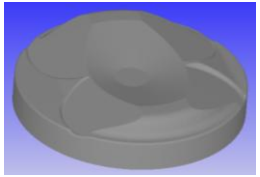
Nozzle Inclusion Angle Effects

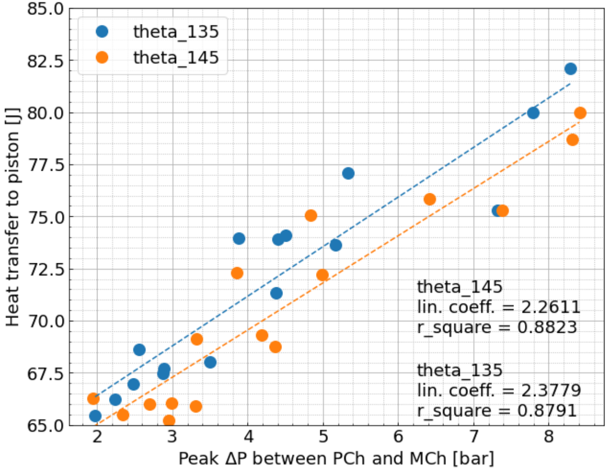






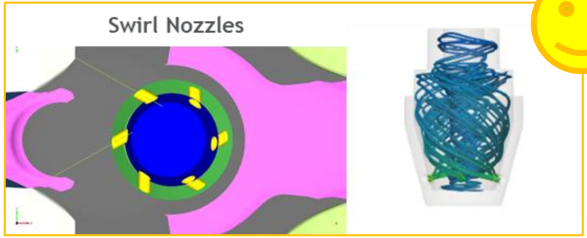






- The wider included angle design causes more heat loss to cylinder head that cannot be offset with the reduced piston heat transfer
- Optimization of piston shape can be pursued to further reduce piston heat transfer

Verdict regarding Swirl Nozzle Design



- The swirl nozzle design is recommended for passive pre-chamber
  - **Higher ΔP between pre- and main chambers**
    - For a given AVR, swirl designs could generate higher ΔP between pre-chamber and the main chamber, which will benefit dilute combustion when unburned loss becomes more severe
  - **Better controllability**
    - Swirl designs create repeatable flow patterns
    - Swirl designs yield better regression performances (with R^2 values closer to unity)
    - The swirl behavior could be effectively controlled by adjusting area-to-volume ratio
  - **More evenly-distributed combusting jets**
    - The swirl motion transports the flame kernel to pre-chamber outlets at similar times
    - The tumble motion inside non-swirl designs usually transports the flame kernel to one corner of the pre-chamber and causes uneven jet distribution

Concluding Remarks

- **Reliable numerical approach for pre-chamber design analysis**
  - Validated combustion CFD model accurately representing key physical processes in TJI combustion
  - Implemented automated workflows to ensure consistent simulation and evaluation
  - Gained valuable analytical understanding through systematic batch processing

- **Key factors in pre-chamber design**
  - Swirl versus non-swirl nozzle configurations produce different flow and combustion characteristics
  - The area-to-volume ratio serves as a primary parameter to adjust combustion ΔP for optimal performance
  - The included angle directly influences heat transfer losses caused by jet impingement on various combustion chamber surfaces

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Thanks for your attention!

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Please contact anqi.zhang@aramcoamericas.com for questions/comments.