A computational investigation of the effects of swirl ratio and injection pressure on mixture preparation in a light-duty diesel engine

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ERC Student Seminar – 01/22/2013

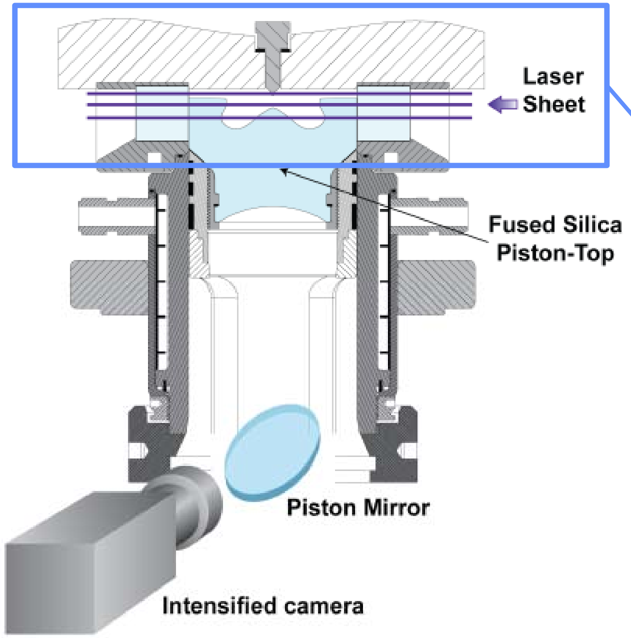
Outline

- **Experimental vs. Numerical study details**
  - **Motivation and problem setup**
- **Model improvement**
  - **Compressible connecting rod assembly**
- **Local mixture preparation study**
  - **Non-reacting conditions**
- **Model accuracy impact on fired operation**
  - **Wall heat transfer**
  - **sensitivity to swirl ratio and injection pressure**

Optical engine experimental setup

- **cf. ASME ICES2012-81234**

Side View



Engine specifications

Bore x stroke [mm]	82.0 x 90.4
Unit disp	
Compres	
Squish h	

Bosch C

Sac volu	
Number	
Included	
Hole dia	
Hole pro	

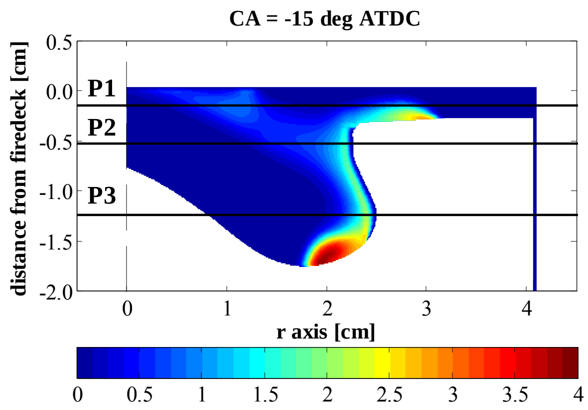
Fuel pro

Compos	H_{16}
	H_{18}
Fluorescent tracer [mass fraction]	0.5% C_7H_8
Equivalent Cetane Number	47

P1 = Half of squish region

P2 = Piston bowl rim

P3 = Inner bowl region



- 266 nm UV horizontal laser sheet
- Images at (degrees ATDC):

  CA = [-17.5:2.5:-5.0]

Optical engine experimental setup II

- **7 Diesel PPCI cases**

  (ASME ICES2012-81234)
  - **Low-load**
  - **Highly dilute**
  - **Slightly boosted**
  - **R_s and p_{inj} sweeps**

- Very low PM and NO_x
- Significant UHC and CO

  ← incomplete oxidation of bulk gas mixtures

  → comb. efficiency ↓
- Crucial role of mixing and chemical kinetics

	Non-reacting mixture	Reacting mixture
Intake charge composition [mole fractions]	100% N_2	10% O_2 81% N_2 9% CO_2
Intake pressure [bar]	1.5	
Intake temperature [K]	300	372
Engine speed [rpm]	1500	
IMEP [bar]	---	3.0
Global equiv. ratio [-]	---	0.3
Injected fuel mass [g]	0.0088	0.0088
Start of Injection [deg]	-23.0 ± 0.1, -23.3 ± 0.1	
Parameter sweeps: - swirl ratio, R_s [-] - injection pressure, p_{inj} [bar] *baseline case	R_s = 1.55, *R_s = 2.20, R_s = 3.50, R_s = 4.50, R_s = 2.20, R_s = 2.20,	*p_{inj} = 860 bar p_{inj} = 860 bar p_{inj} = 860 bar p_{inj} = 860 bar p_{inj} = 500 bar p_{inj} = 1220 bar

Computational model setup

- The ERC version of KIVA3v-R2 is employed
- Improvements to:

Spray (Spray breakup, Near-nozzle flow, Droplet collision, Wall film)

Fuel → (Evaporation)

Chemistry (Combustion, Reaction kinetics)

Phenomenon	Submodel
Spray breakup	KH-RT instability, Beale and Reitz
Near-nozzle flow	Gas-jet theory, Abani et al.
Droplet collision	O'Rourke model with ROI (radius-of-influence)
Wall film	O'Rourke and Amsden
Evaporation	Discrete multi-component fuel, Ra and Reitz
Turbulence	RNG k- ε, Han and Reitz
Combustion	Detailed chemical kinetics with sparse analytical Jacobian, Perini et al.
Reaction kinetics	Reduced PRF mechanism, Ra and Reitz

- Grid from resolution study (SAE 2012-01-0143)

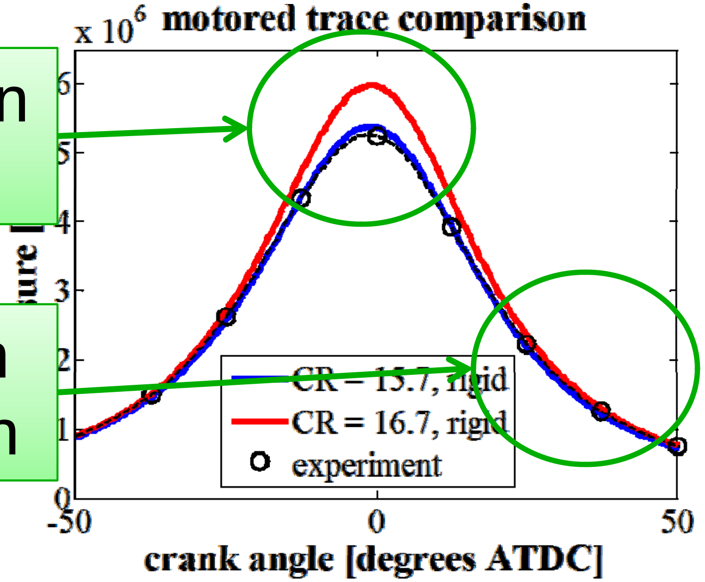
Compressible connecting rod model I

Motivation

- Motoring pressure tra model calibration
  - Incomplete piston/head geometry modeling
  - Charge blow-by to the crankcase
  - Compressibility i is not negligible

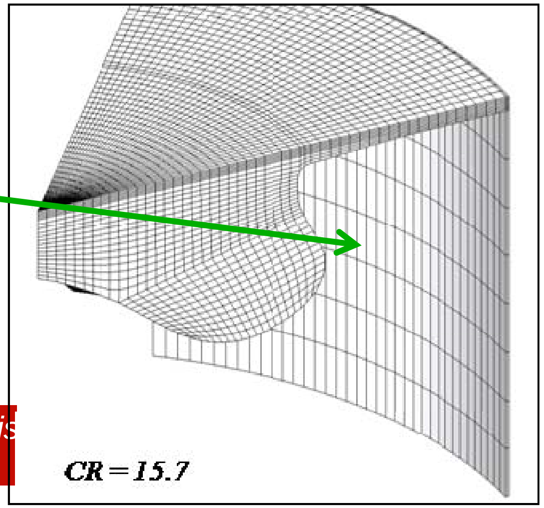
over-prediction around TDC

under-prediction during expansion

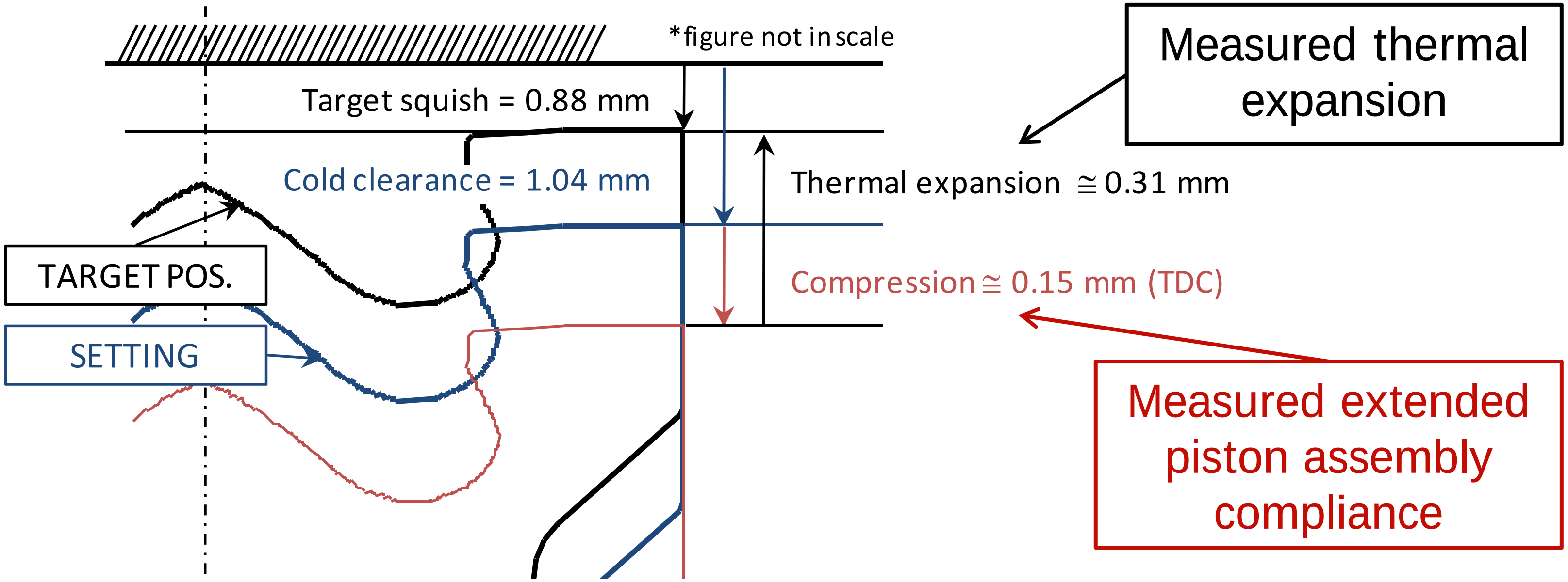


➔ Using Geometrical CR leads to **significant pressure overprediction** in the model

➔ Engine grid's CR typically reduced by artificially increasing crevice volume
  - Affects trapped mass, wall heat transfer, pollutants
  - Still difficult to match pressure trace shape

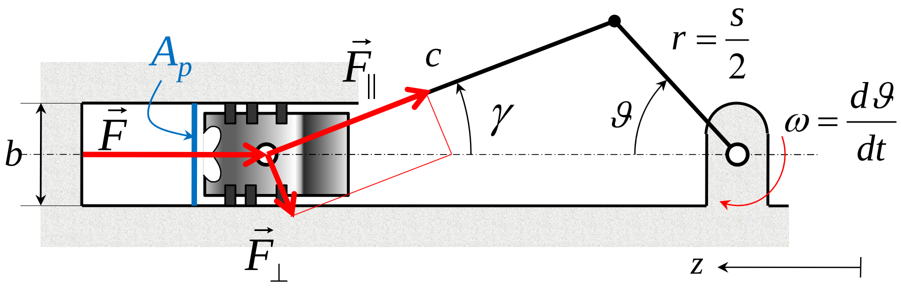


Compressible connecting rod model II



- **Experimental setup** ➔ accounts for **deviations from rigid slider-crank**
  ➔ does not consider bearing and crankshaft clearances
- **Thermal expansion <u>less affected</u>** by engine operation
  - <u>Ring friction</u> is dominant 🡐 scarcely reached by hot gases
- **Dynamic squish height can improve modelling** → <u>pollutants</u>

Compressible connecting rod model III



$$\frac{dz_P}{[illegible]} = \frac{s}{[illegible]}\omega \sin\vartheta\left(1+\frac{\tan\gamma}{\tan\vartheta}\right)+\frac{dc}{dt}\cos\gamma.$$

MODEL DETAILS

- **Static** → intertial forces are neglected
- Global compliance is modeled as an **effective connecting rod length, *c***

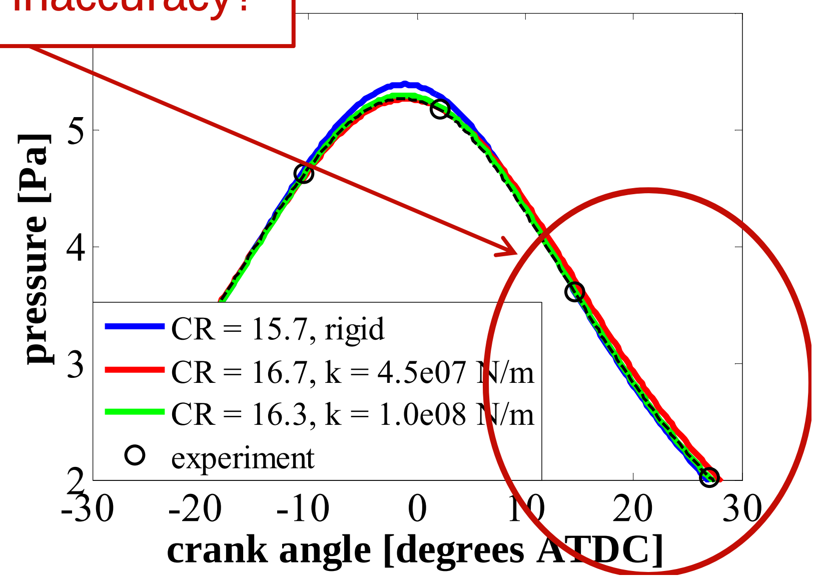
➔ Extended piston + bearings

Need to reduce CR:
Wall heat transfer
modeling inaccuracy?

MODEL CALIBRATION

- **“Rigid” grid**: CR= 16.7, squish = 0.73 mm (cold height+thermo)
  ➔ very low compliance (k = 4.5e4 N/mm)
  (5 times lower than measured)
- **“Calibrated” grid:** CR=16.3, sq = 0.73 mm
  ➔ k = 1.0e5 N/mm (~half than measured)

tored trace match

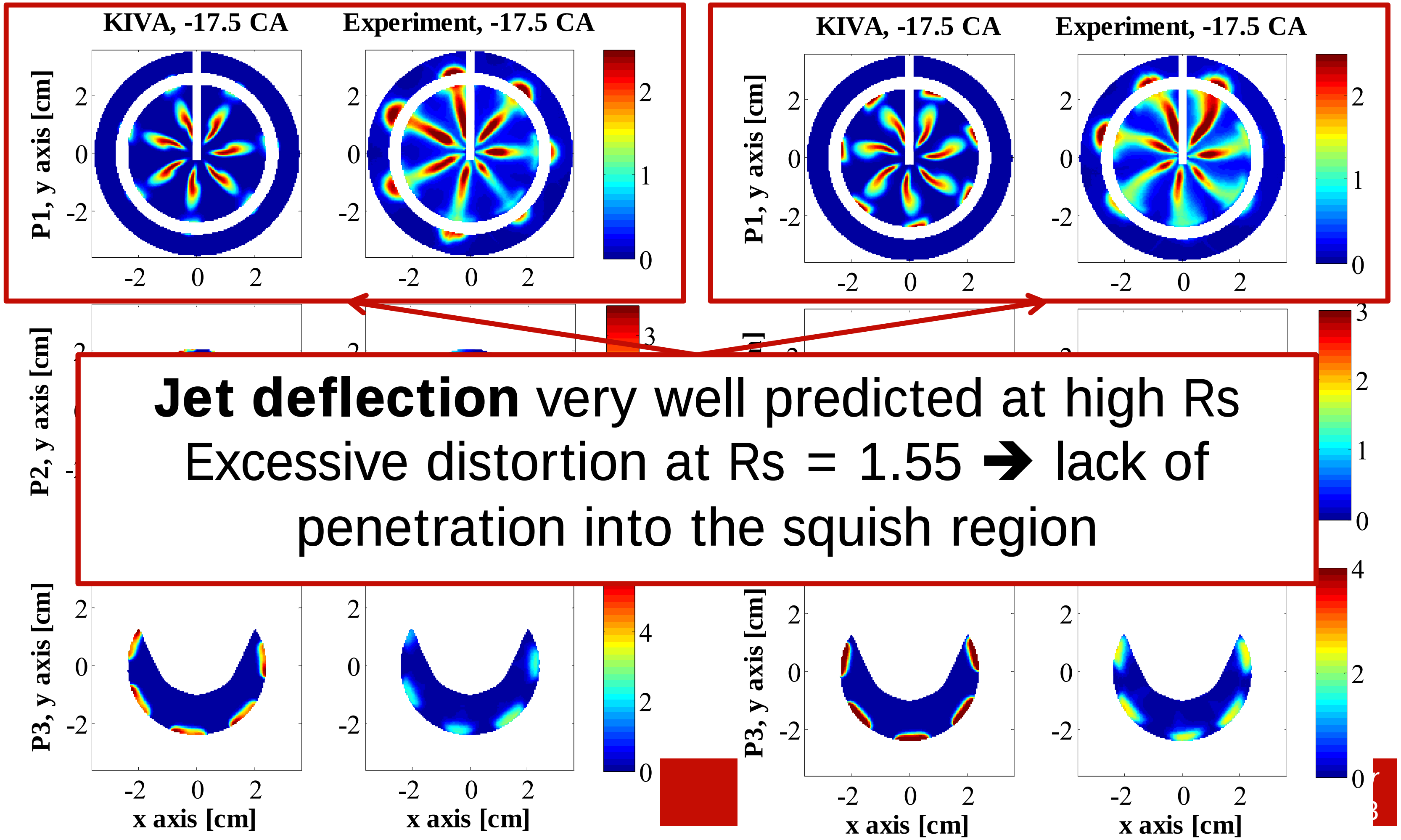


Local equivalence ratio prediction

Swirl ratio effects I – CA = -17.5 deg

Rs = 1.55, pinj = 860 bar

Rs = 4.5, pinj = 860 bar

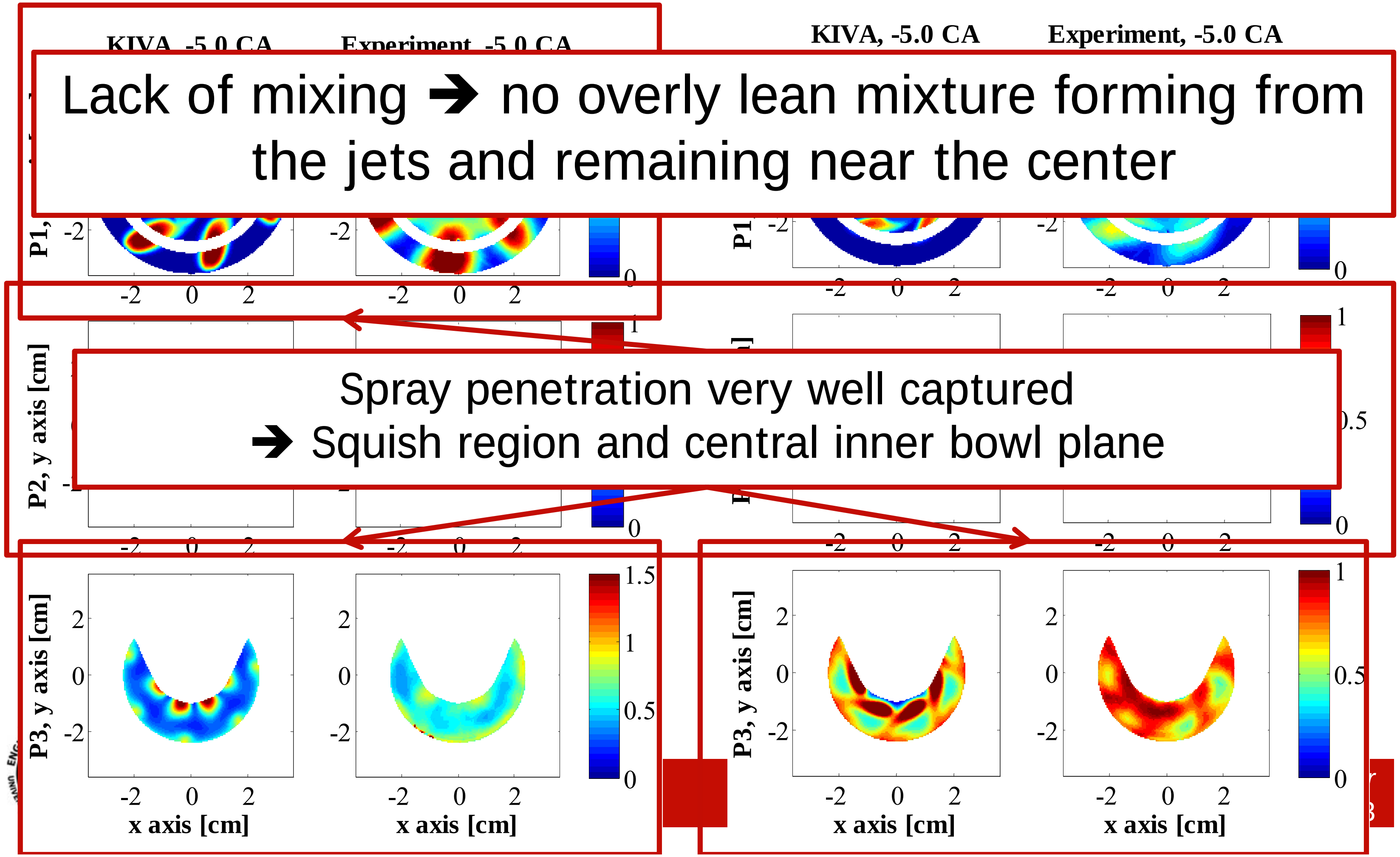


Jet deflection very well predicted at high Rs
Excessive distortion at Rs = 1.55 ➔ lack of penetration into the squish region

Swirl ratio effects II – CA = -5.0 deg

Rs = 1.55, pinj = 860 bar

Rs = 4.5, pinj = 860 bar

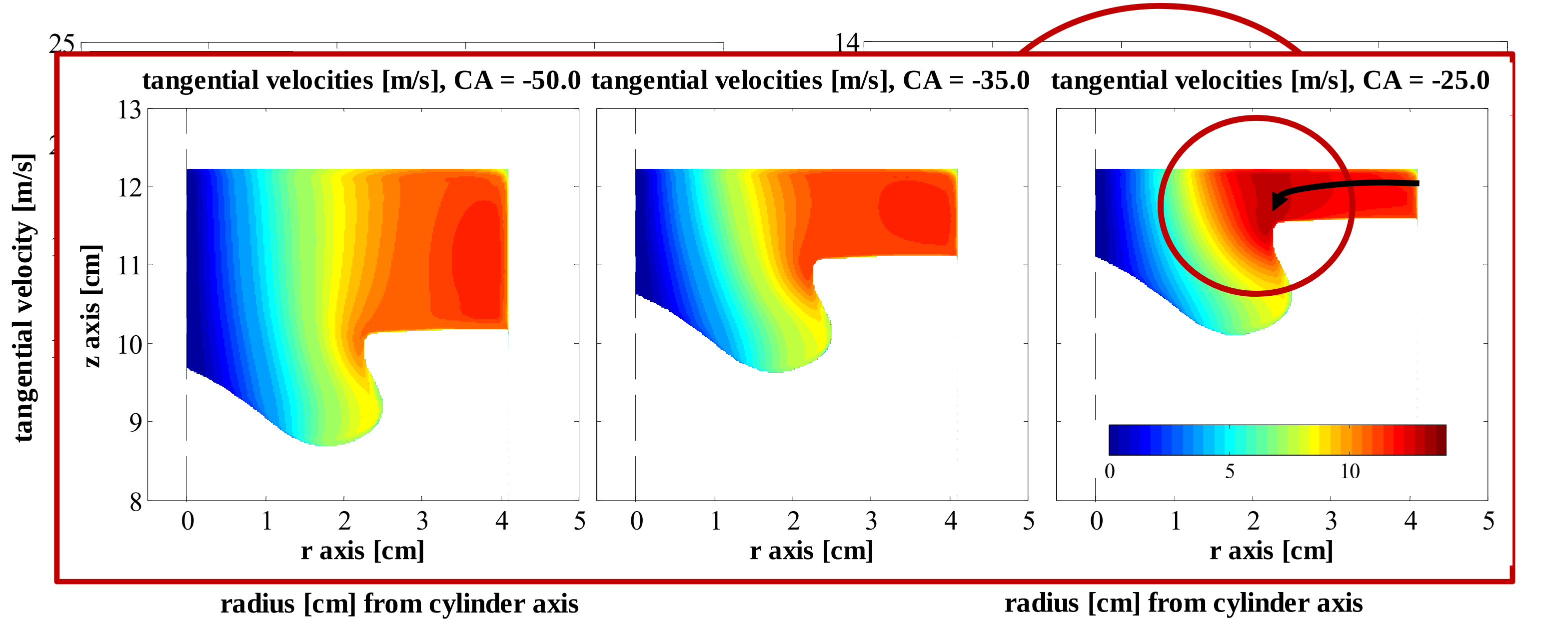


Lack of mixing ➔ no overly lean mixture forming from the jets and remaining near the center

Spray penetration very well captured
➔ Squish region and central inner bowl plane

Swirling flow structure

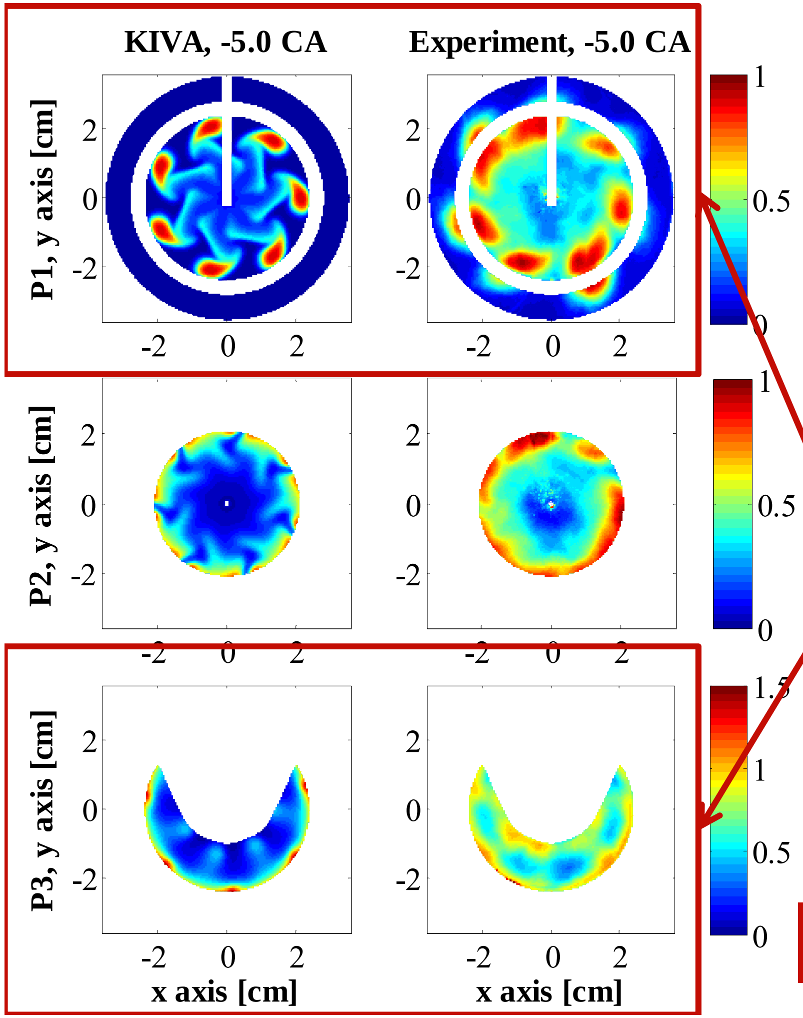
- Comparison with PIV measurements by Petersen (SAE 2011-01-1285)



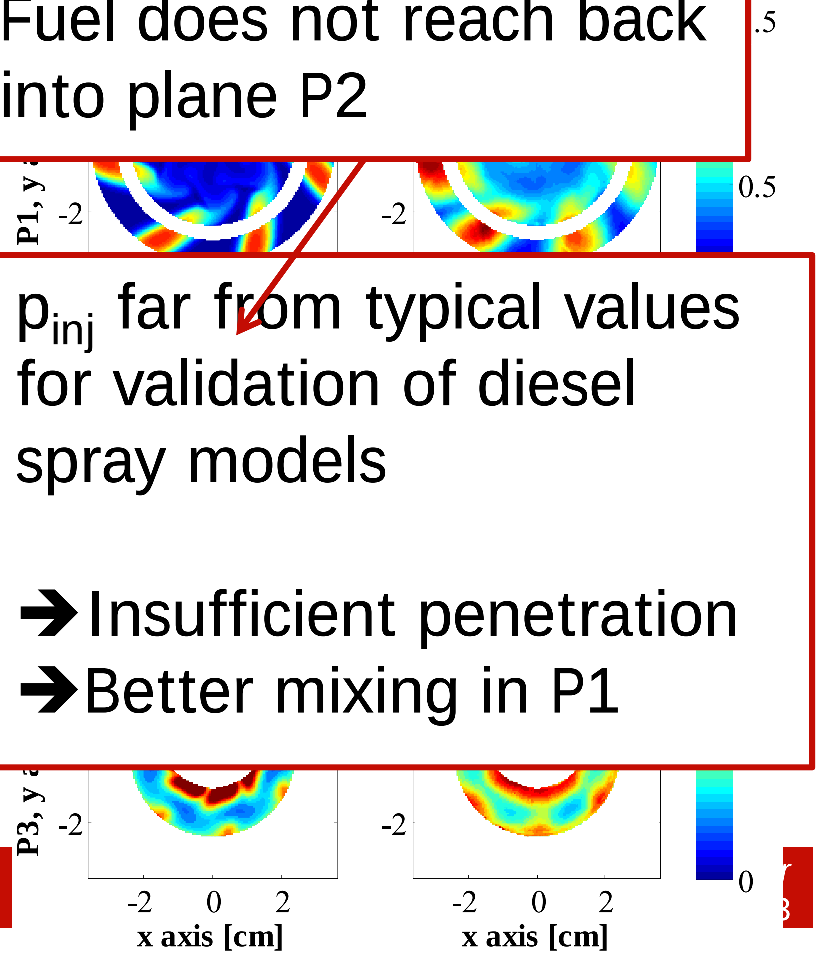
- Predicted velocity profile accuracy deteriorates when approaching TDC
  - ➔ high angular momentum from the squish volume **forced inward**
  - ➔ OK with the model's geometry but <u>not seen in the experiments</u>
    - \- impact of **valve recesses** in the head and cut-outs on the piston

Injection pressure effects I – CA=-5.0

Rs = 2.2, pinj = 500 bar



Rs = 2.2, pinj = 1220 bar



Fuel does not reach back into plane P2

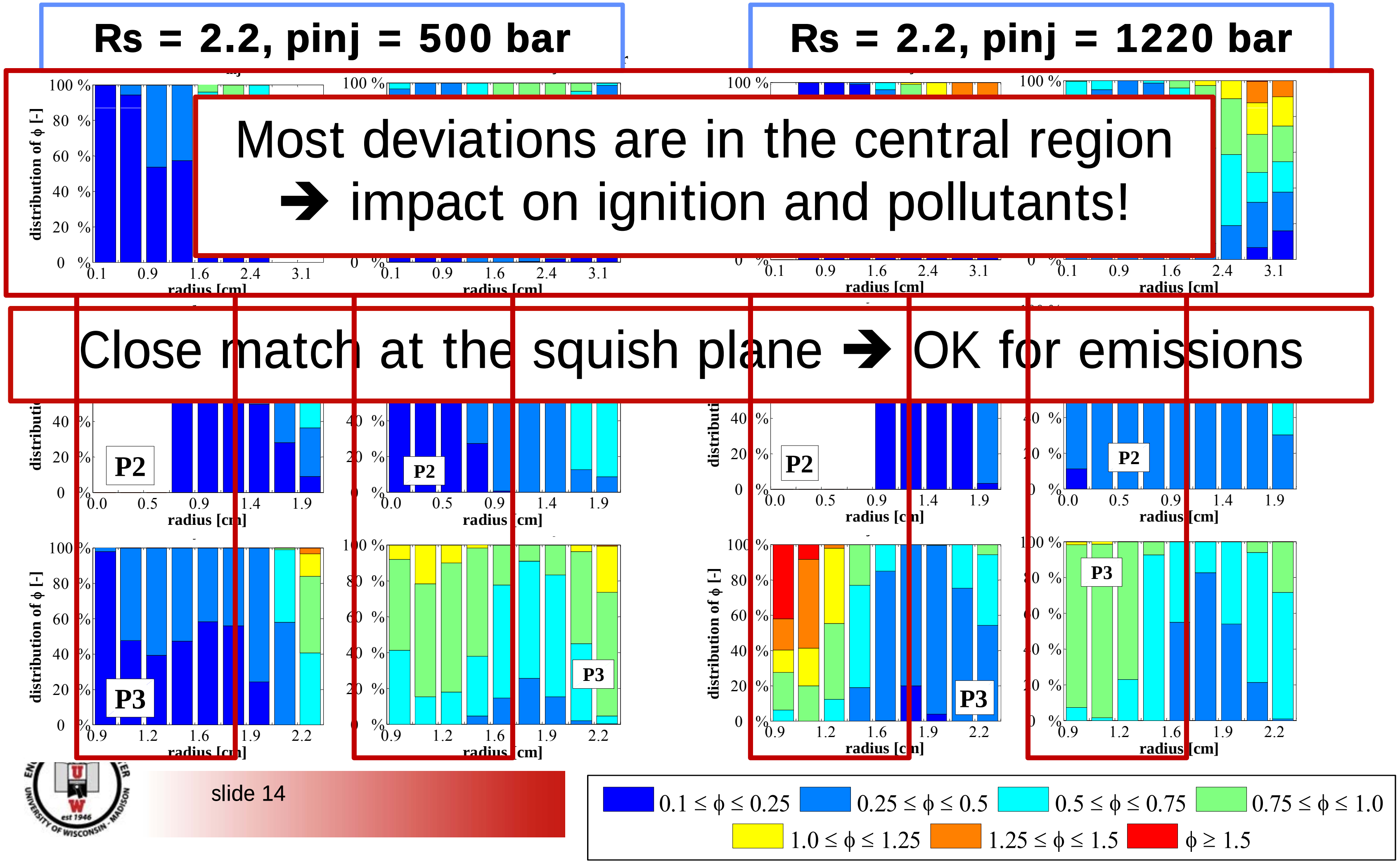
p_{inj} far from typical values for validation of diesel spray models

➔ Insufficient penetration

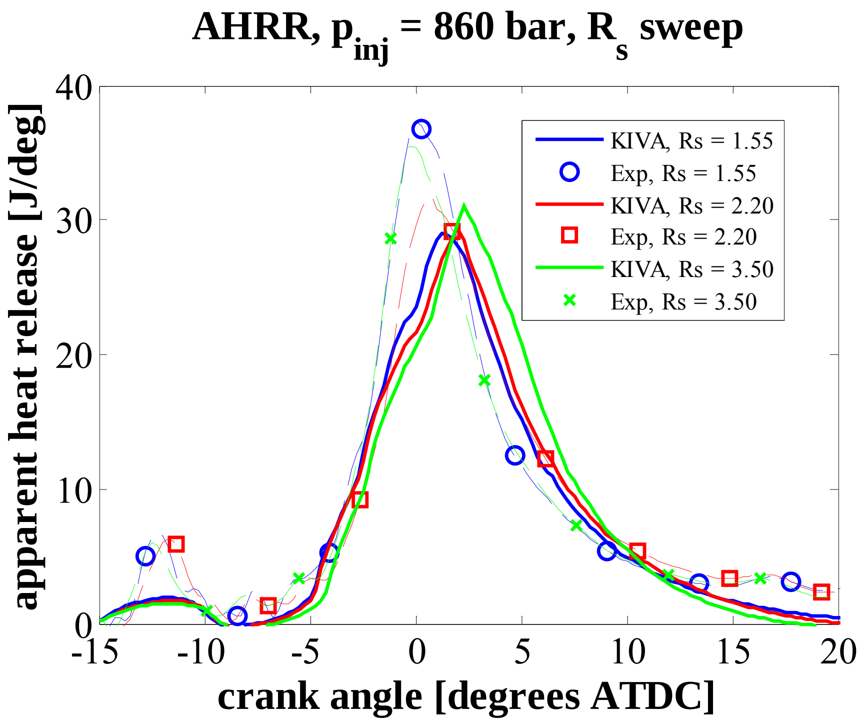
➔ Better mixing in P1

Injection pressure, mixture stratification

- Cumulative azimuthal equivalence ratio distributions
- Histograms at fixed distances from cylinder axis



Fired engine operation I – R_s sweep

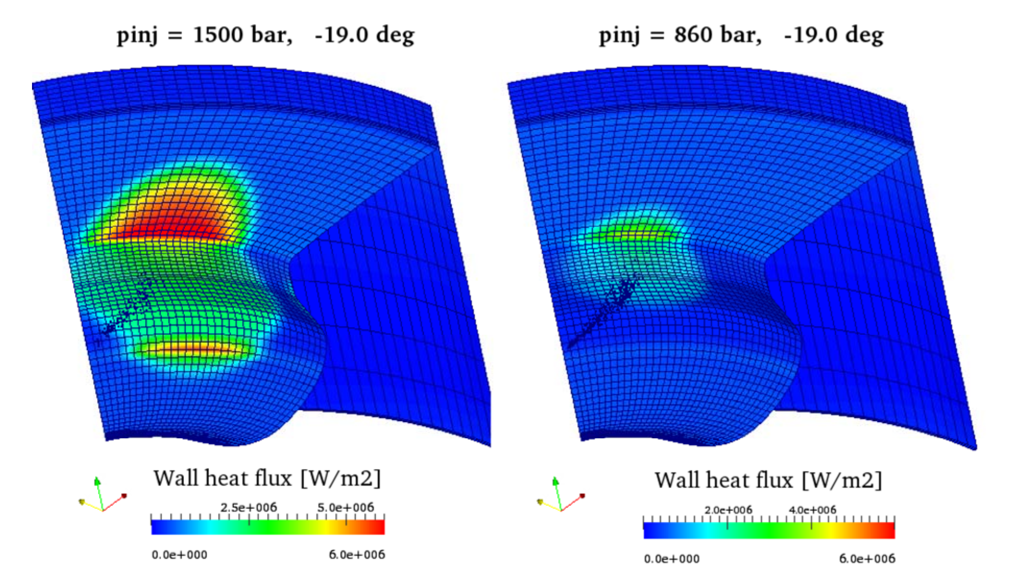


Experiment: ignition advances at Rs = 1.55
➔ **richer mixtures in the squish region**

At higher Rs, richer mixtures are due to fuel more strongly confined to the bowl

KIVA:
- similar ignition timings ➔ good average match
- inverse ignition behavior at Rs↑ ➔ under investigation:
  1) Wall heat transfer.
  2) over-predicted jet deflection ➔ more homogeneous and leaner mixtures ➔ longer ignition delay

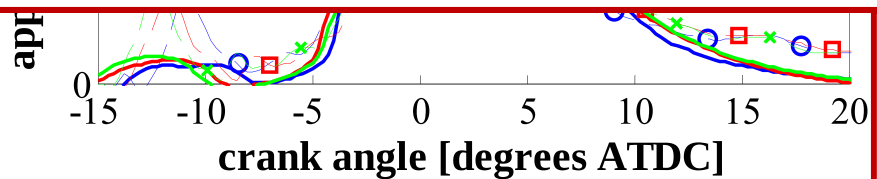
Fired engine operation II – p_{inj} sweep

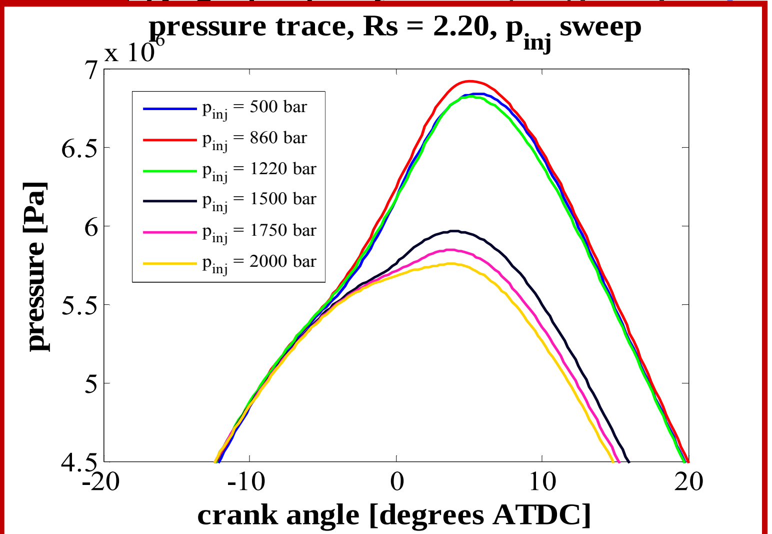


HR timing well captured at
he experimental pressures

T HRR peaks well captured
➔ Wall heat transfer

Lower and delayed AHRR
peak at p_{inj}=500 bar in





Computational Investigation at higher injection pressures
➔ Misfiring conditions at p_{inj} ≥ 1500 bar
🡅 Wall heat transfer

Concluding Remarks I

- **Aim: <u>assess+improve the accuracy of KIVA modelling</u>** of an optical light duty diesel engine operated in LTC (PPC) mode, with respect to:

  ➔ **<u>quantitative</u> equivalence ratio distributions** provided by the experiments at three in-cylinder planes

  ➔ **understanding and exploring** the role of **<u>mixing and wall heat transfer</u>** on combustion development

↓

<u>Non-reacting operation and equivalence ratio distribution</u>

- Elastic extended piston – connecting rod assembly model
  - Significantly improved motored pressure curve match
  - Need to lower geometrical CR ➔ wall heat transfer?

Concluding Remarks II

Non-reacting operation and equivalence ratio distribution

- Mixture dynamics and equivalence ratio stratification before ignition
  - **Very accurate penetration** is predicted with a refined grid
  - **Over-predicted swirl** when approaching TDC
    ➔ jet deflection and under-predicted penetration at $\mathbf{p_{inj}}$ ↓
  - **Under-predicted turbulent mixing**, crucial to emissions

Fired engine operation

- At increasing Rs: **predicted** HTHR timing **delays**
  measured HTHR timing **advances**

➔ The model responds to wall heat transfer and over-predicted spray deflection

➔ the experiments instead show that mixing rules over ignition timing

Concluding Remarks III

<u>Fired engine operation</u>

- Injection pressure plays a major role on combustion development
  - Increased impact area + greater spray jet momentum
  - ➔ Delayed ignition timing can lead to misfire at very high pressures

Future Work

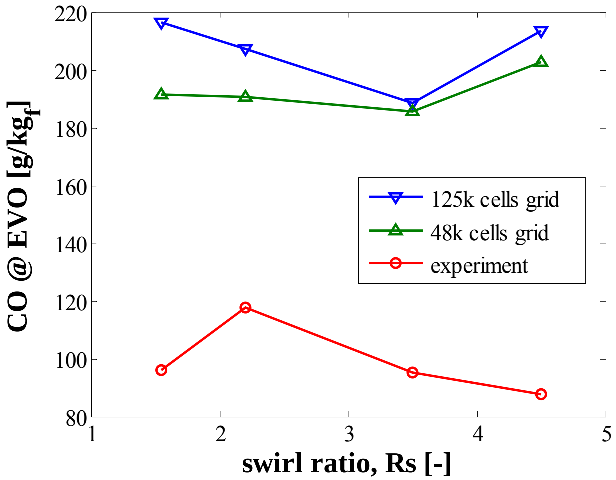
<u>CFD model impact on mixing and ignition</u>

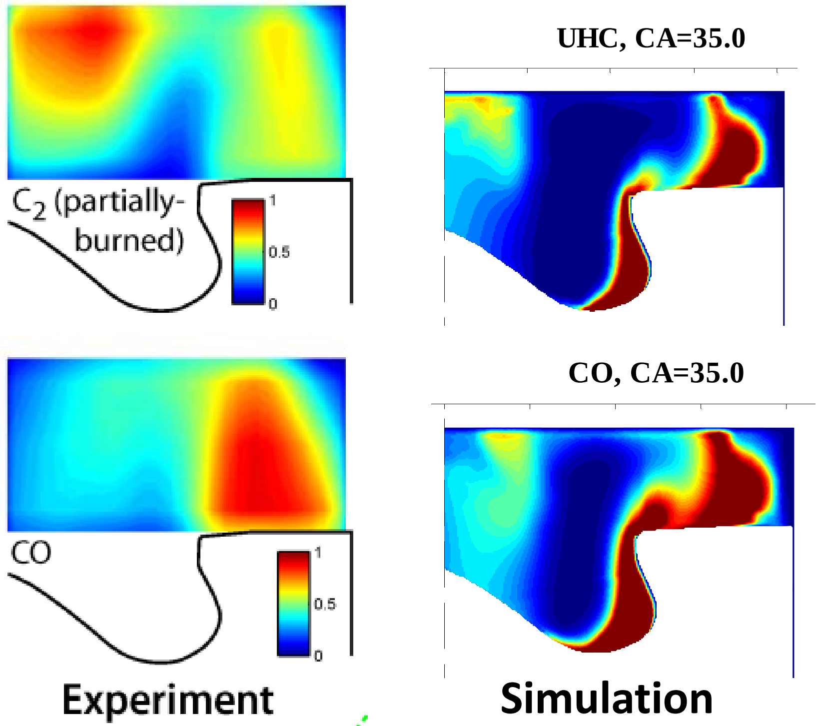
- Turbulent <u>transport</u> ➔ generalized RNG k- ε model
- Fluid flow solver <u>accuracy</u> ➔ solution tolerances and numerics
- Wall <u>heat transfer</u> ➔ Impact of wall temperatures
  ➔ Conjugate heat-transfer

Future Work

UHC and CO emissions

- Investigate impact of the reaction mechanism on predicted emissions



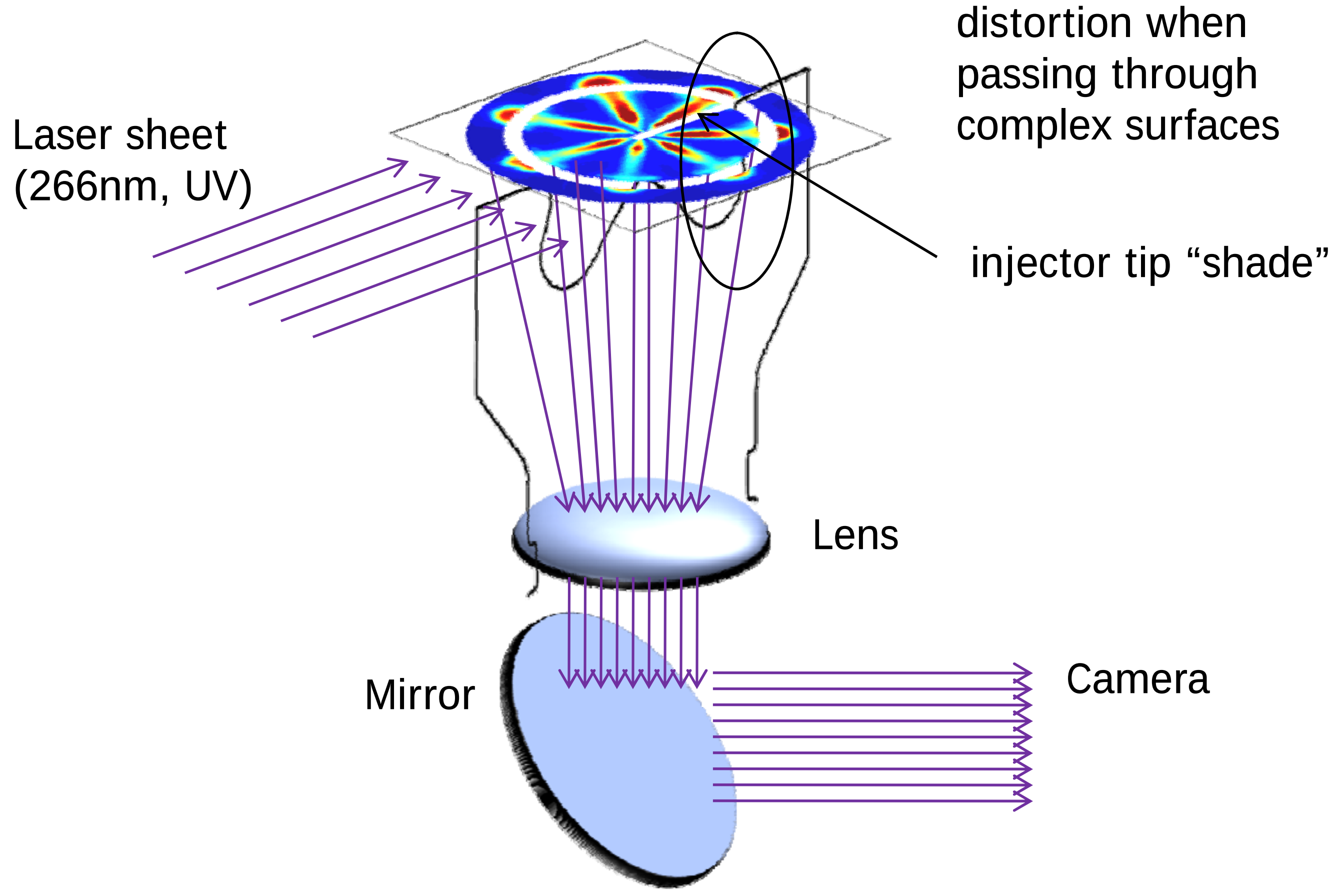


- Identify and validate in-cylinder emission sources

Thanks for your attention!
Questions?

Back-up slides

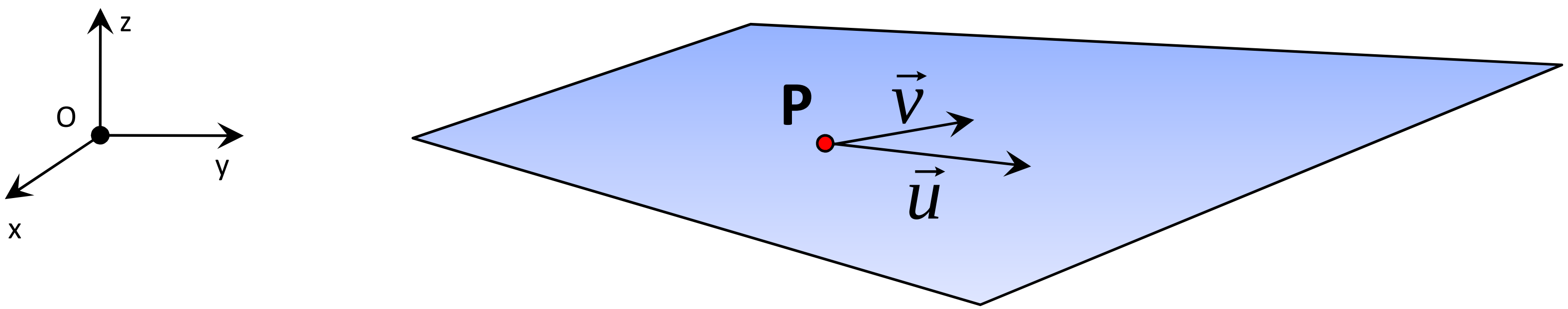
Laser sheet imaging – missing zones



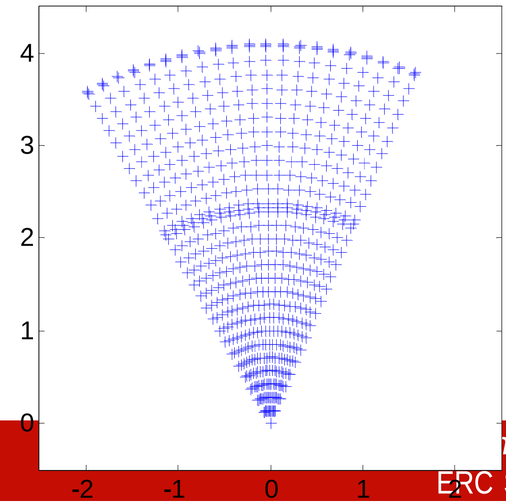
KIVA plane slices reconstruction

- **Generate a plane representation:**

$$plane = \lfloor x_P \quad y_P \quad z_P \quad u_i \quad u_j \quad u_k \quad v_i \quad v_j \quad v_k \rfloor$$



- **Compute intersecting points of KIVA mesh with plane**



KIVA plane slices reconstruction

- **Reconstruct data at those values using Delaunay Triangulation (left)**
- **Pursue <u>cubic spline interpolation</u> at a more refined grid, using point positions from the laser sheet images (right)**