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# Mechanism of Enhanced Late-Cycle Soot Oxidation

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# Project Description



- Lund University
  - Division of Combustion Engines
  - Division of Fluid Mechanics
- Politecnico di Milano
- Volvo GTT
- Volvo Cars
- Scania

# Background



In Compression Ignition (CI) engines the efficiency and soot emissions are linked to the level of mixing

- Mixing is controlled by turbulence
- Large scale motions
  - Swirl
  - Tumble
  - Squish
- Shear stresses created by spray
- Piston motion

Increasing the level of mixing will enhance the late-cycle oxidation

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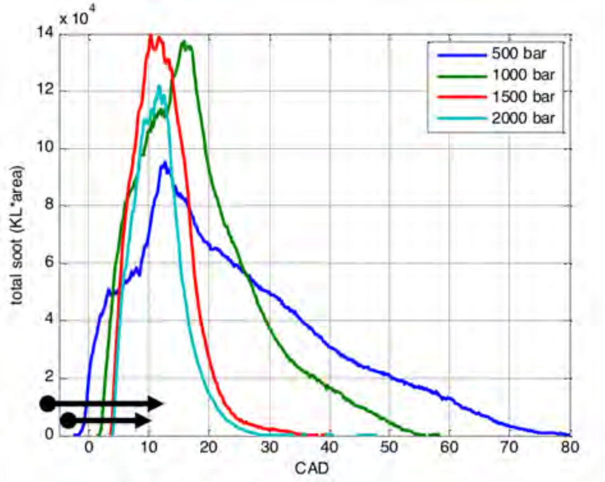
# Experimental observations

## Effect of injection pressure on the late-cycle soot oxidation

Experimental results from an optical engine

Measured at swirl number 1.7

Swirl number is defined as the ratio of air rotational velocity around cylinder center axis and engine rotational crankshaft velocity




[Dembinski, H.W.R., Doctoral Thesis in Machine Design, KTH, Stockholm (2013)]

# Experimental observations



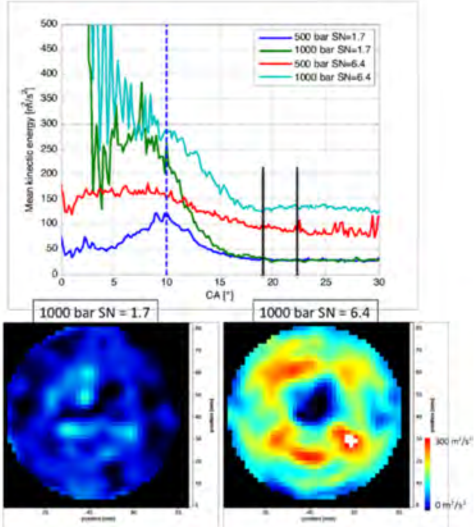
- As the injection pressure increases from 500 to 2000 bar, the soot oxidation is affected
- Despite the increase in maximum soot value, the final soot at late-cycle is drastically reduced
- Effect of turbulence generated by spray?
  - According to these measurements the turbulence of the spray dies within about 5 CAD
  - Energy stored in the large scale motion?

# Experimental observations



## Mean kinetic Energy at different swirl numbers

Experimental results from an optical engine
Measured at swirl number 1.7



# Experimental observations



**Comparing swirl number 6.4 to swirl number 1.7**

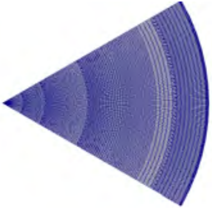
- Higher kinetic energy is stored in the flow due to the spray at higher swirl number
- Effect of injection pressure is pronounced at higher swirl number
- Doubling of the injection pressure increases the mean kinetic energy by 50% during expansion (red and light blue curve) for higher swirl number
- Despite this differences
  - The injection pressure increased late-cycle soot oxidation for both swirl numbers

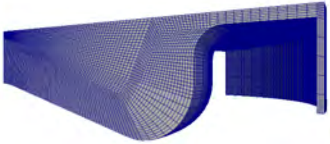
# Experimental cases



The experimental cases considered in this study are from an open-bowl, heavy duty direct ignition engine.

| | |
|---|---|
| Nominal compression ratio | 15.9 |
| RPM | 1200 |
| Bore diameter | 131.0 *mm* |
| Stroke | 158 *mm* |
| Clearance (Nominal) | 1.0 *mm* |
| Injection hole size | 212 $\mu m$ |
| Injection pressure | 1500 *bar* |
| Number of holes | 6 |





# Experimental cases



Details of the operating condition for the simulated cases; SOI: Start of injection, EOI, End of injection, $\lambda_{cyl}$: In cylinder air to fuel ratio, $CO_2$ ratio: ratio between in cylinder $CO_2$ and stoichiometric $CO_2$, HL: High Load, LL: Low Load.

| Load | 100% | 100% | 25% | 25% |
|---|---|---|---|---|
| SOI (CAD) | 355 | 355 | 357 | 357 |
| EOI (CAD) | 378 | 377 | 363.8 | 363.5 |
| Mass injected ($mg$) | 48.86 | 46.67 | 13.17 | 13.19 |
| $CO_2$ ratio | 0.232 | 0.191 | 0.198 | 0.291 |
| Intake temp. (K) | 404 | 404 | 390 | 390 |
| $\lambda_{cyl}$ | 1.17 | 1.3 | 1.49 | 1.74 |

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# Numerical cases

To understand the effect of swirl number and in-cylinder flow motions in the late cycle oxidation of soot, A sweep over swirl number, injection pressure and start of injection is performed.

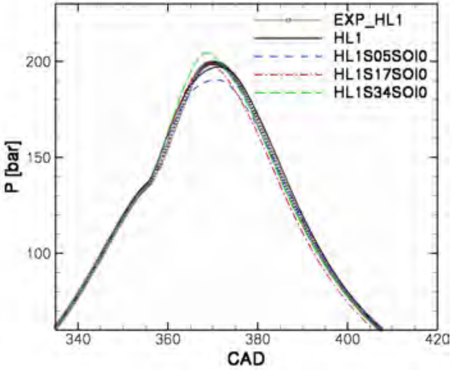
| Case reference | Load | Swirl Nr. | $\Delta P_{inj}$ | $\Delta SOI$ |
|---|---|---|---|---|
| HL1S0SOI0 | 100% | 0 | 0 | 0 |
| HL1S0SOI0Pinjm50 | 100% | 0 | -50% | 0 |
| HL1S0SOI0Pinjp50 | 100% | 0 | +50% | 0 |
| HL1S05SOI0 | 100% | 0.5 | 0 | 0 |
| HL1S17SOI0 | 100% | 1.7 | 0 | 0 |
| HL1S34SOI0 | 100% | 3.4 | 0 | 0 |
| HL1S34SOI0Pinjm50 | 100% | 3.4 | -50% | 0 |
| HL1S34SOI0Pinjp50 | 100% | 3.4 | +50% | 0 |
| HL1S34SOIm3 | 100% | 3.4 | 0 | -3 |
| HL1S34SOIp3 | 100% | 3.4 | 0 | +3 |
| HL2S0SOI0 | 100% | 0 | 0 | 0 |
| HL2S17SOI0 | 100% | 1.7 | 0 | 0 |
| HL2S17SOIm3 | 100% | 1.7 | 0 | -3 |
| HL2S17SOIp3 | 100% | 1.7 | 0 | +3 |
| HL2S34SOI0 | 100% | 3.4 | 0 | 0 |
| LL1S0SOI0 | 25% | 0 | 0 | 0 |
| LL1S17SOI0 | 25% | 1.7 | 0 | 0 |
| LL1S17SOIm3 | 25% | 1.7 | 0 | -3 |
| LL1S17SOIp3 | 25% | 1.7 | 0 | +3 |
| LL1S34SOI0 | 25% | 3.4 | 0 | 0 |
| LL2S0SOI0 | 25% | 0 | 0 | 0 |
| LL2S05SOI0 | 25% | 0.5 | 0 | 0 |
| LL2S17SOI0 | 25% | 1.7 | 0 | 0 |
| LL2S34SOI0 | 25% | 3.4 | 0 | 0 |
| LL2S34SOIm3 | 25% | 3.4 | 0 | -3 |

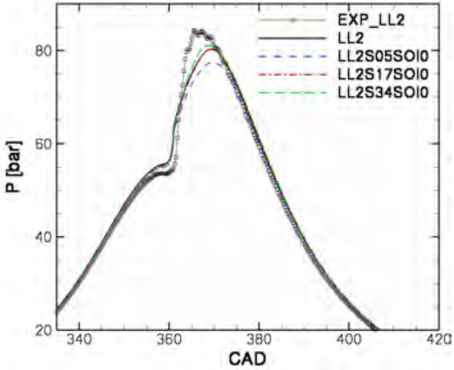
# Base-line case, Temperature



# Pressure traces

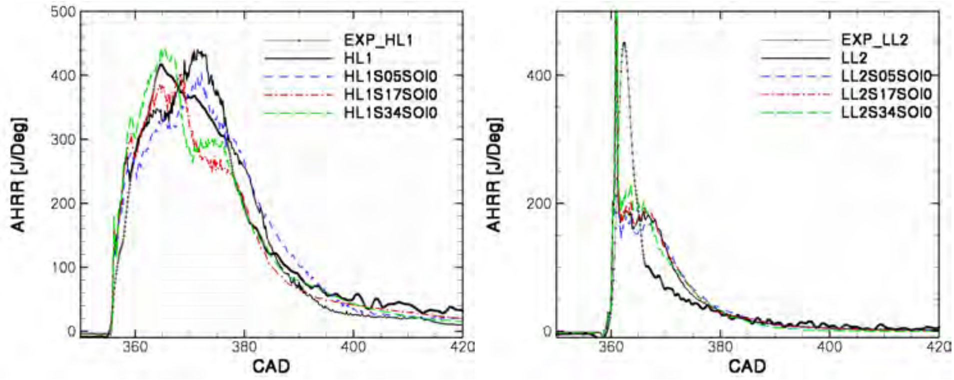




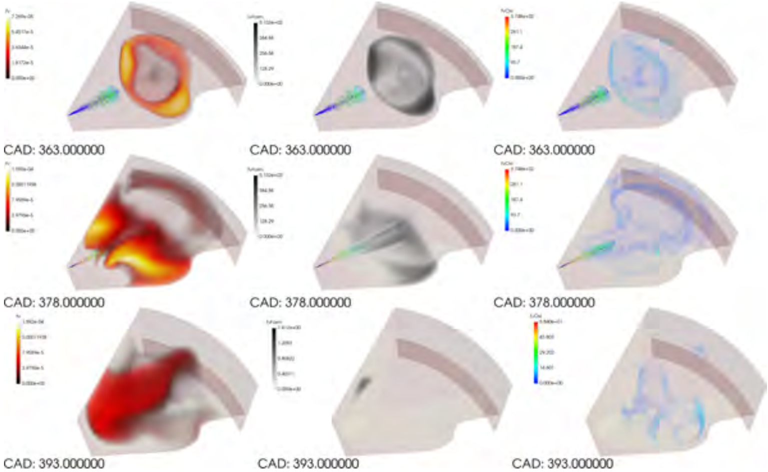
# Heat release rates





# Soot





CAD: 363.000000
CAD: 363.000000
CAD: 363.000000
CAD: 378.000000
CAD: 378.000000
CAD: 378.000000
CAD: 393.000000
CAD: 393.000000
CAD: 393.000000

# Effect of swirl number on soot

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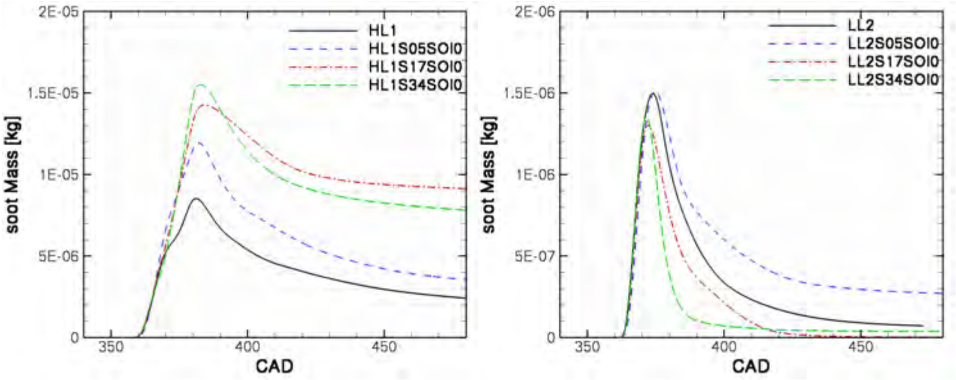
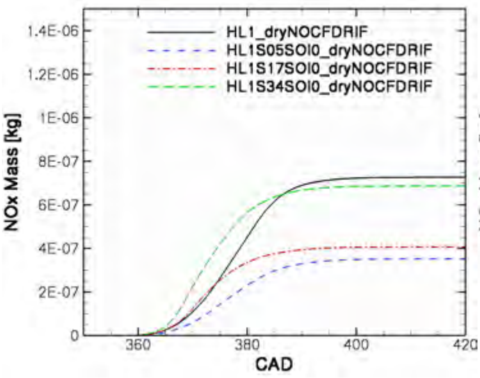
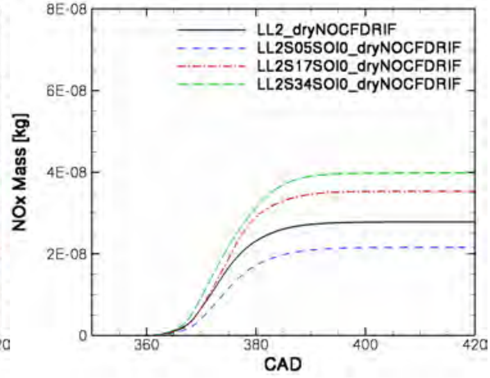


# Effect of swirl on NOx

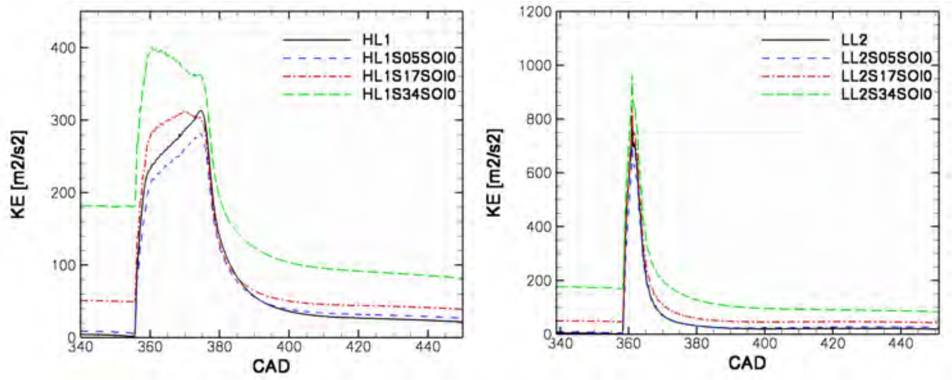




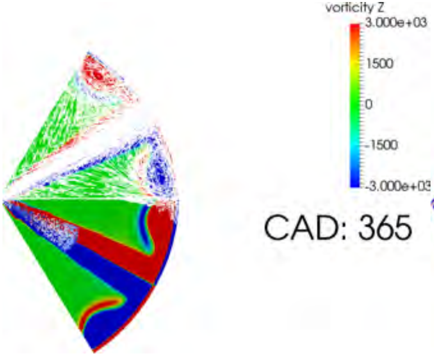
# Kinetic energy



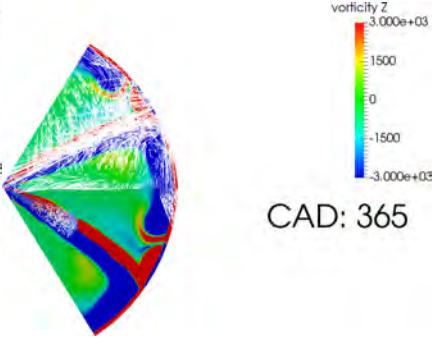


# Vorticity fields of no swirl and high swirl



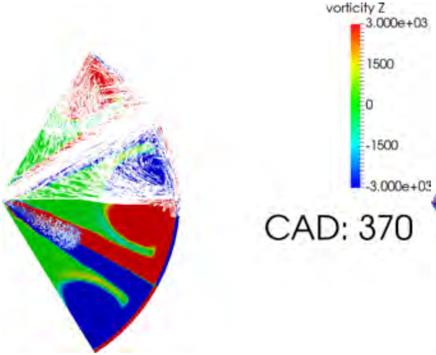



HL1 S=0

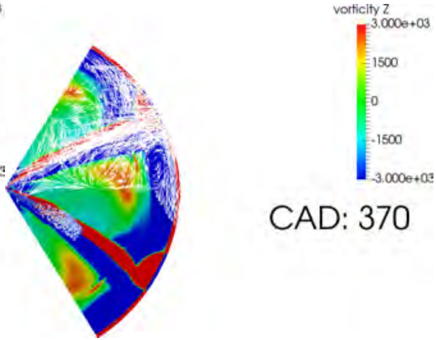



HL1 S=3.4

# Vorticity fields of no swirl and high swirl

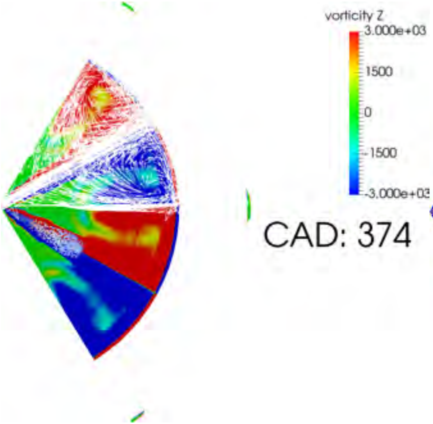



HL1 S=0

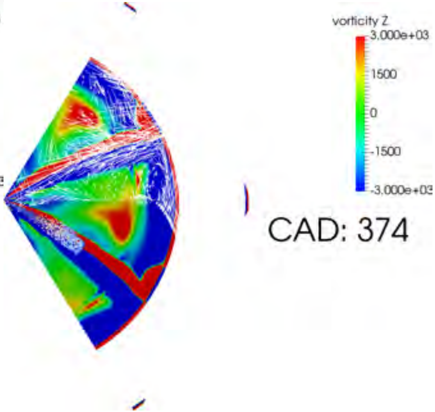



HL1 S=3.4

# Vorticity fields of no swirl and high swirl



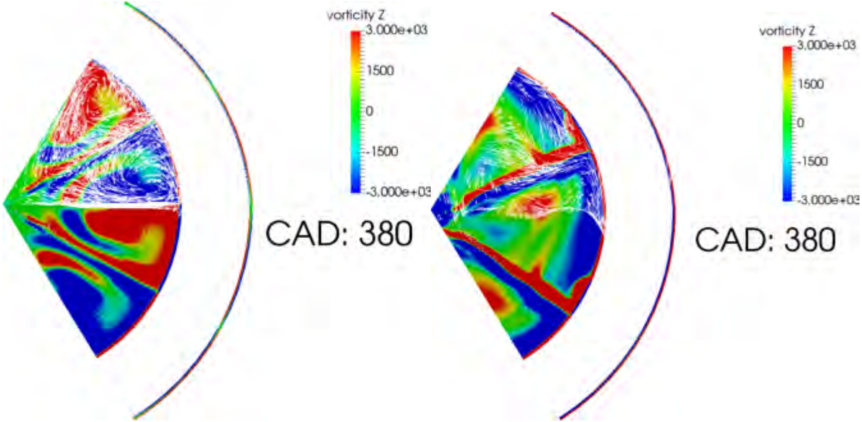

HL1 S=0




HL1 S=3.4

# Vorticity fields of no swirl and high swirl






HL1 S=0 HL1 S=3.4

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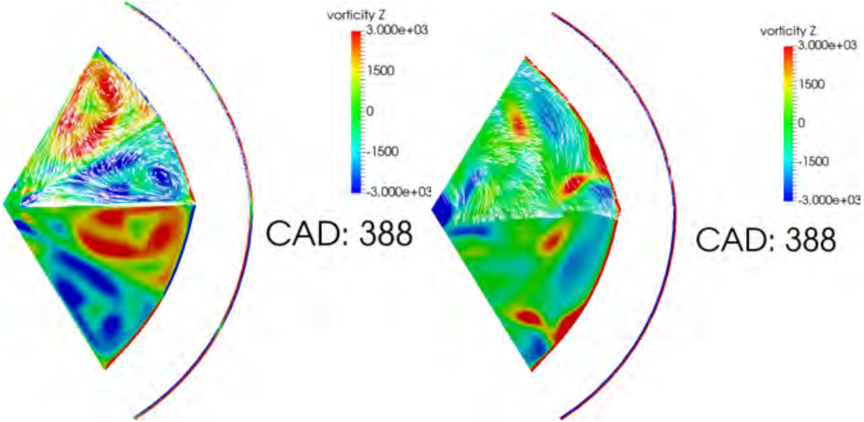
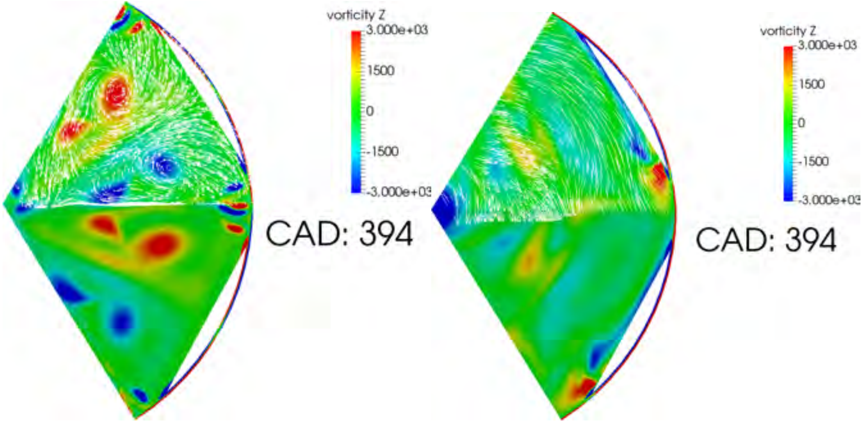



HL1 S=0

HL1 S=3.4

# Vorticity fields of no swirl and high swirl




HL1 S=0

HL1 S=3.4

# Soot distribution




HL1 S=0


HL1 S=3.4

# Soot distribution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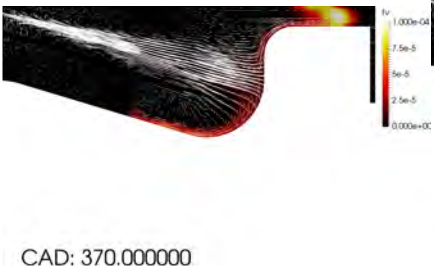
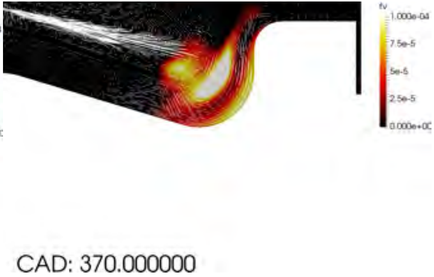



HL1 S=0




HL1 S=3.4

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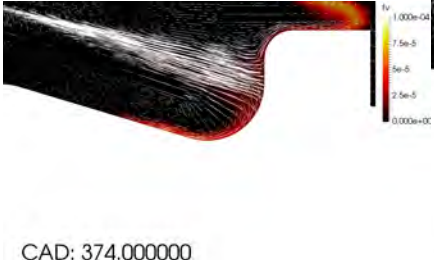


HL1 S=0


HL1 S=3.4

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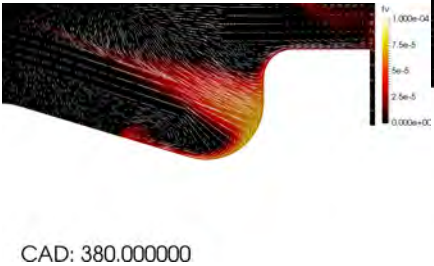
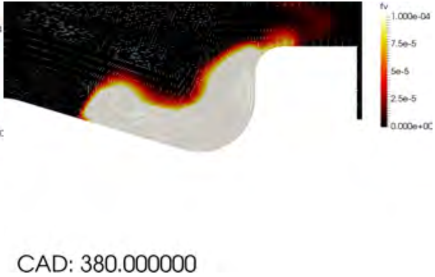


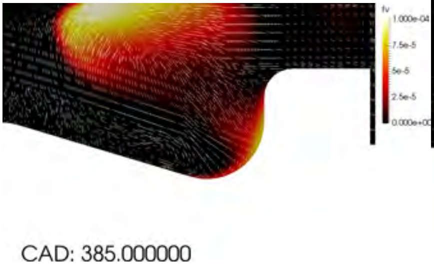

HL1 S=0



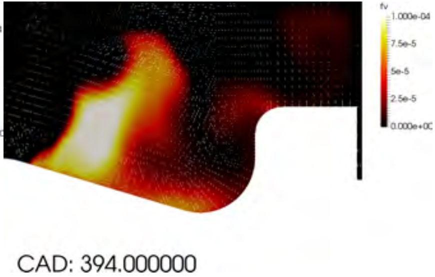

HL1 S=3.4

# Soot distribution






HL1 S=0




HL1 S=3.4

# Temperature Field




HL1 S=0


HL1 S=3.4

# Temperature Field




HL1 S=0


HL1 S=3.4

# Temperature Field




HL1 S=0


HL1 S=3.4

# Temperature Field




HL1 S=0


HL1 S=3.4

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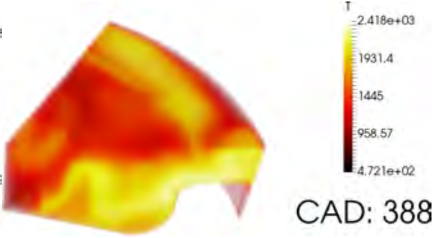
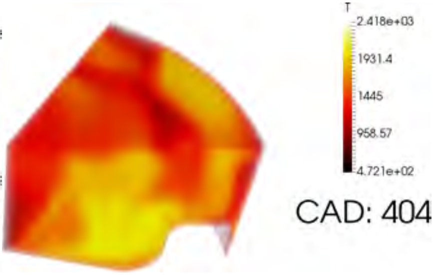
HL1 S=0




HL1 S=3.4

# Temperature Field


HL1 S=0




HL1 S=3.4

# Air entrainment



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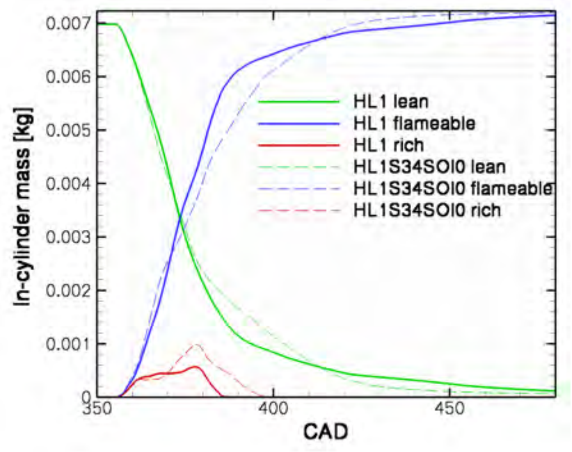
To quantify the effect of swirl number on the combustion behaviour, the mixture in the cylinder is divided to three groups:

- where equivalence ratio is less than 0.35$\rightarrow$ lean
- where equivalence ratio is between 0.35 and 2 $\rightarrow$ flameable
- where equivalence ratio is greater than 2$\rightarrow$ rich

# Air entrainment



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# Large scale structures



To see the large structure of the flow in the context of mixing:

**The relative motion of the flow field to the oxidisers concentration**

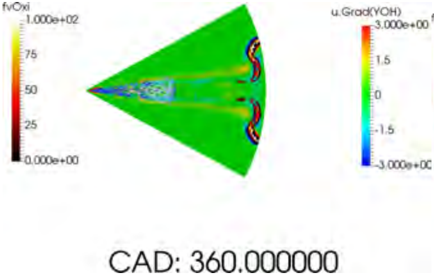
$\alpha_{O2} = u \cdot \nabla Y_{O2}$ and $\alpha_{OH} = u \cdot \nabla Y_{OH}$

The positive values of these fields represent the depletion of oxidisers towards the higher concentrations (red colors)

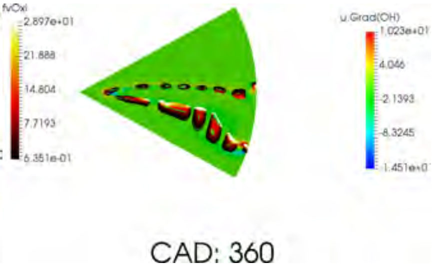
The negative values represents the mixing of oxidisers into the fuel rich regions (blue colors)

# Large scale structures






HL1 S=0




HL1 S=3.4

# Large scale structures

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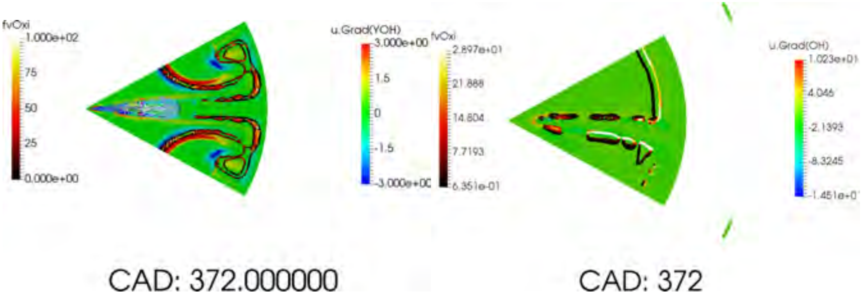
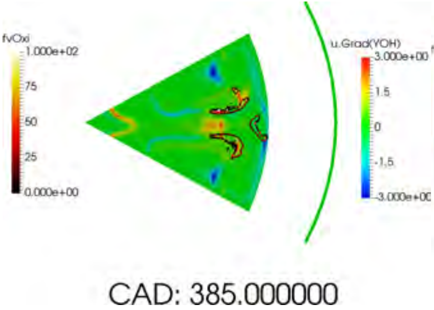


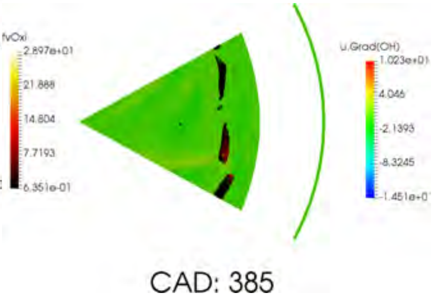

HL1 S=0 HL1 S=3.4

# Large scale structures






HL1 S=0




HL1 S=3.4

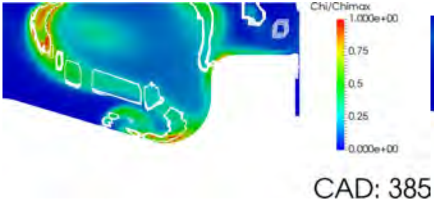
# Small scale mixing



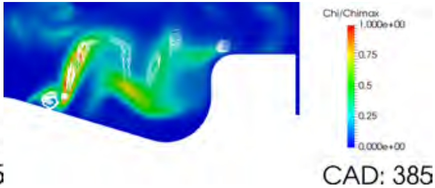
Correlation between the scalar dissipation rate and soot oxidation
Scalar dissipation rate is normalized by its maximum value

# Scalar dissipation rate and soot oxidation





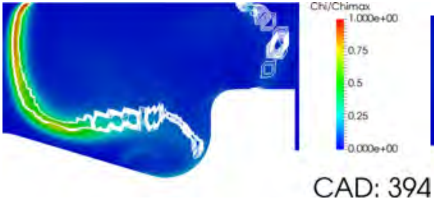

HL1 S=0



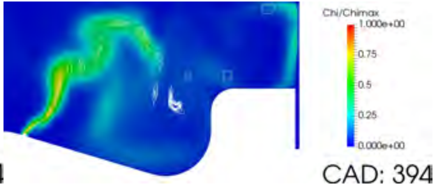

HL1 S=3.4

# Scalar dissipation rate and soot oxidation





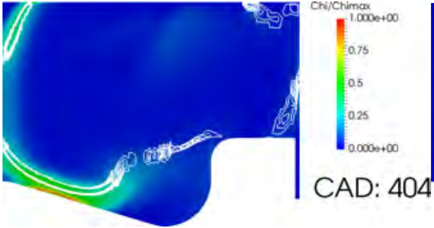

HL1 S=0



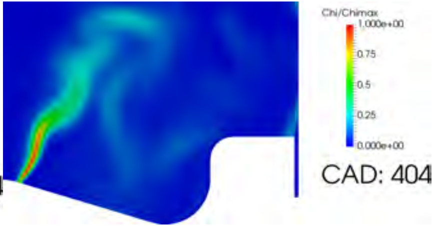

HL1 S=3.4

# Scalar dissipation rate and soot oxidation






HL1 S=0




HL1 S=3.4

# Thank you!



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We are grateful to Professor Tommaso Lucchini and Professor Gianluca D'Errico for providing LibICE package and supporting the numerical simulations.

## Questions?

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