MTL 2018

UNL

CONICET

CIMEC

UTN SANTA FE

Desarrollos y aplicaciones de cálculo CFD para análisis y optimización de sistemas de combustión en motores

II Jornadas Iberoamericanas de Motores Térmicos y Lubricantes
29-31 Agosto, 2018
Santa Fe, Argentina

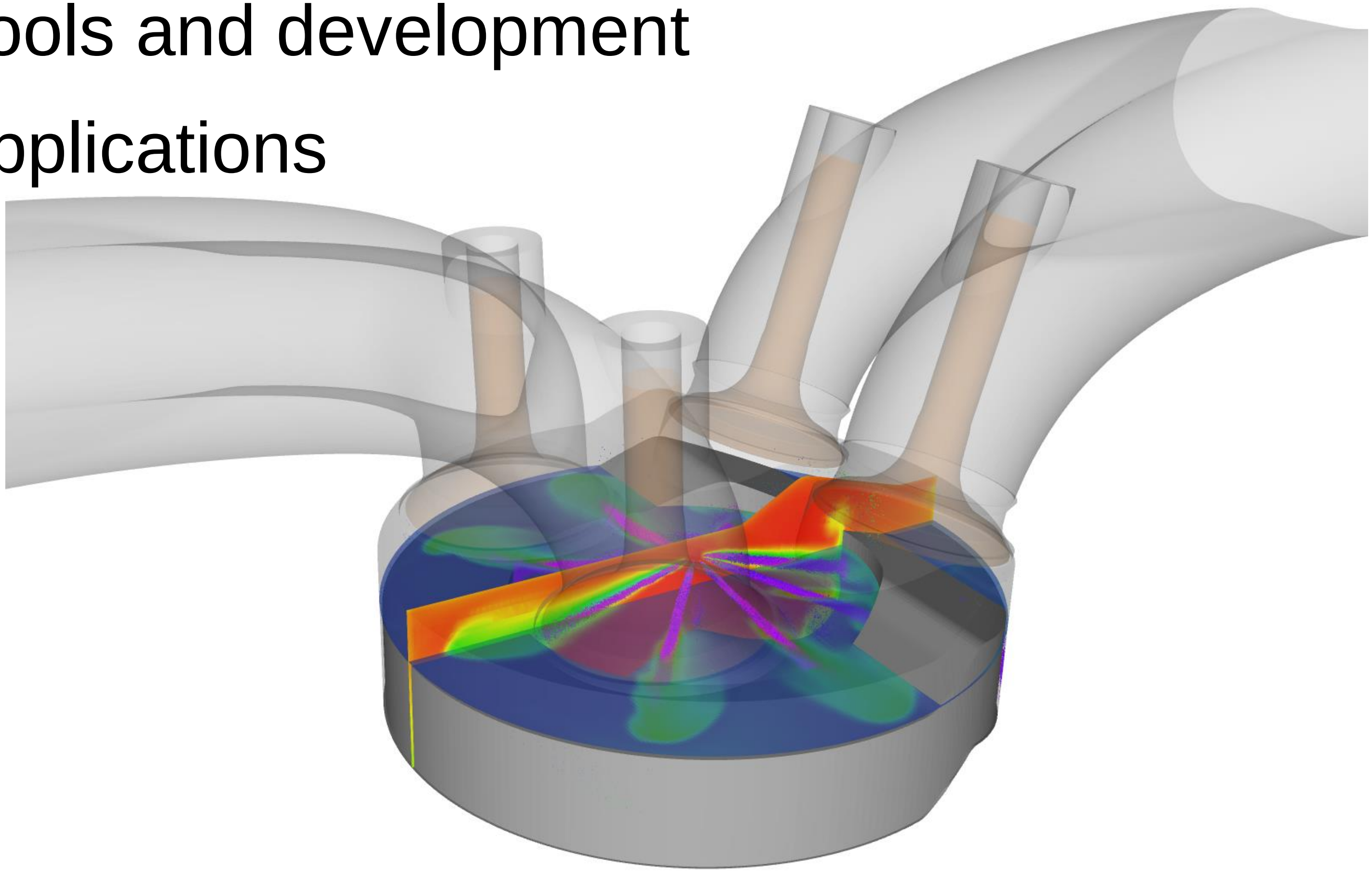
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

CMT motores térmicos

José M. Pastor, Ph.D.

CONTENTS

- Background and approach
- Tools and development
- Applications



BACKGROUND

Motivation

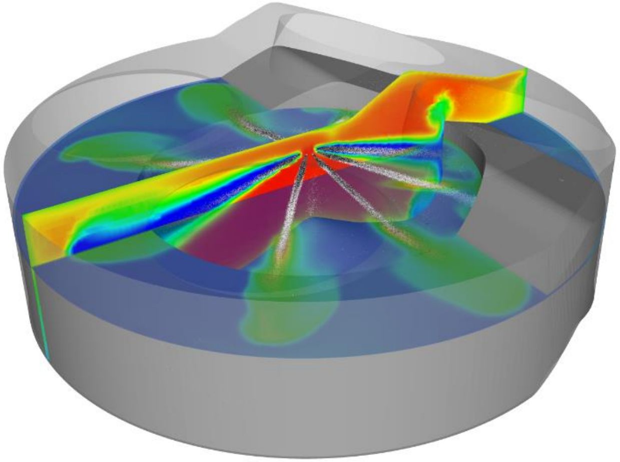
- Energy conversion by combustion processes
  - Today about 80% of total primary energy supply (TPES) from fossil fuels
  - In 2035 TPES increases by 7%-29% with about 70% fossil fuels
- Need for efficient combustion systems
  - ICEs are main power source in transportation sector
  - Increasingly stringent pollutant regulation for passenger cars and trucks
  - Demand on new low-consumption & pollutants aircraft engines
- Design of combustion devices is challenging task
  - Complex multi-physics and chemical process
  - Development by means of experiments (empirical approach)
  - Support design process with simulation tools
  - Numerical models to improve understanding

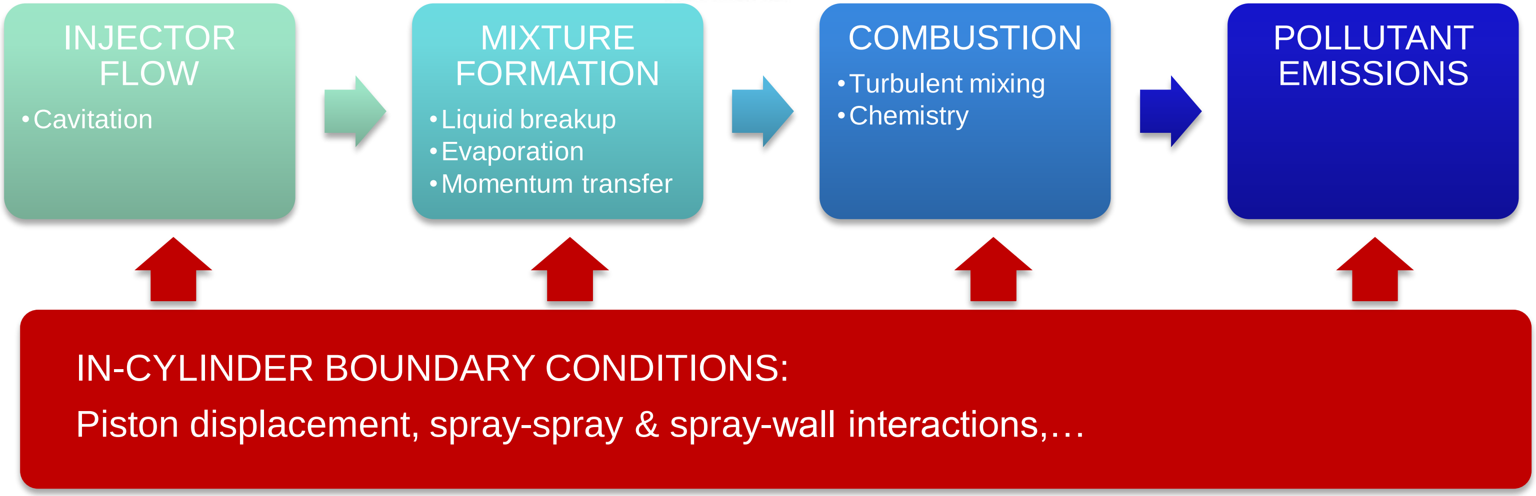
} Gaining attention in the latest decades

BACKGROUND

CFD of combustion in IC engines still a challenge:

- Complexity of the physical and chemical fundamental processes in a highly transient environment





INJECTOR FLOW
- Cavitation

MIXTURE FORMATION
- Liquid breakup
- Evaporation
- Momentum transfer

COMBUSTION
- Turbulent mixing
- Chemistry

POLLUTANT EMISSIONS

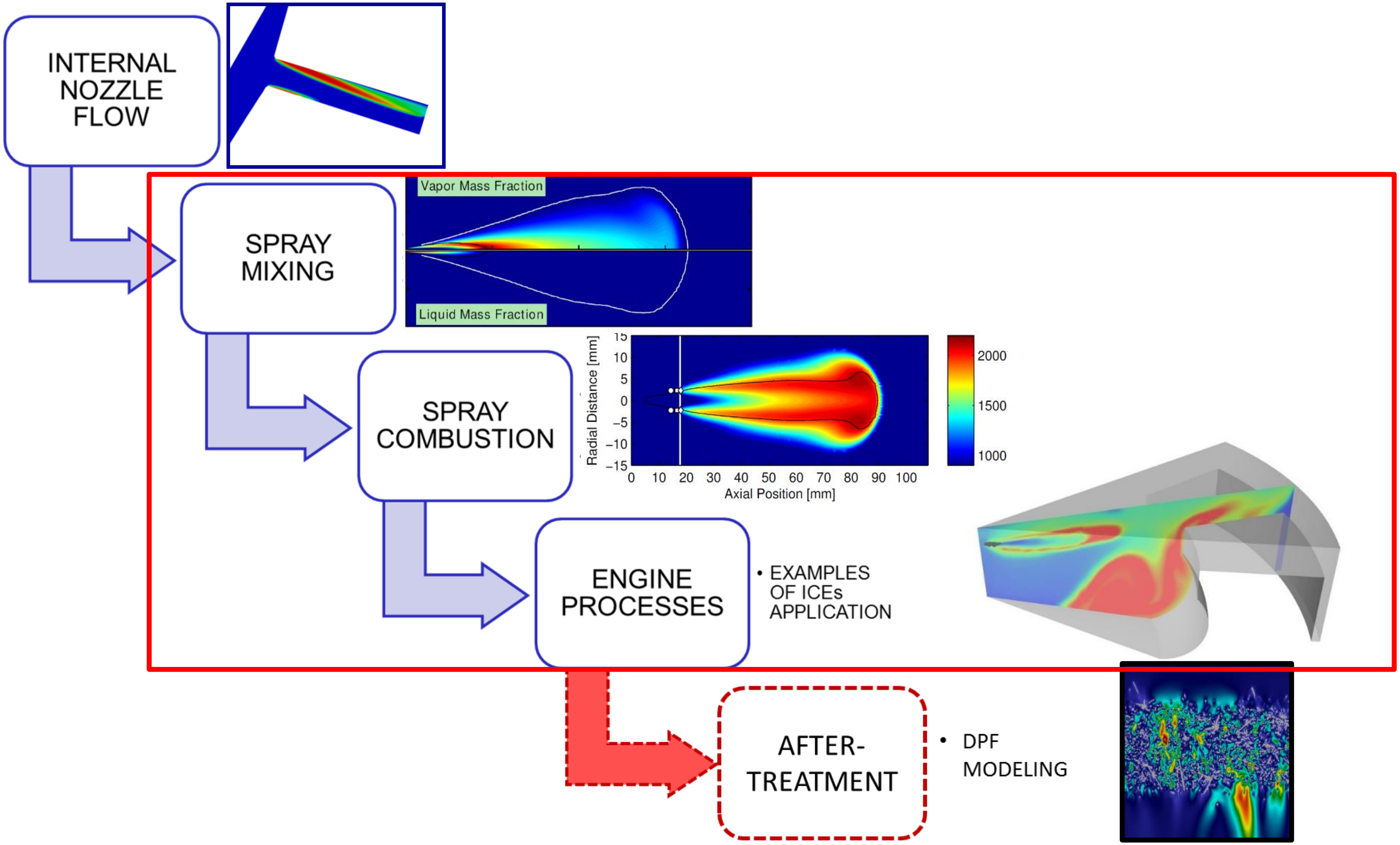
IN-CYLINDER BOUNDARY CONDITIONS:

Piston displacement, spray-spray & spray-wall interactions,…

APPROACH

Modelling steps for RICEs CFD simulations

- <u>Focused in Compression Ignited engines</u>



INTERNAL NOZZLE FLOW

SPRAY MIXING

SPRAY COMBUSTION

ENGINE PROCESSES

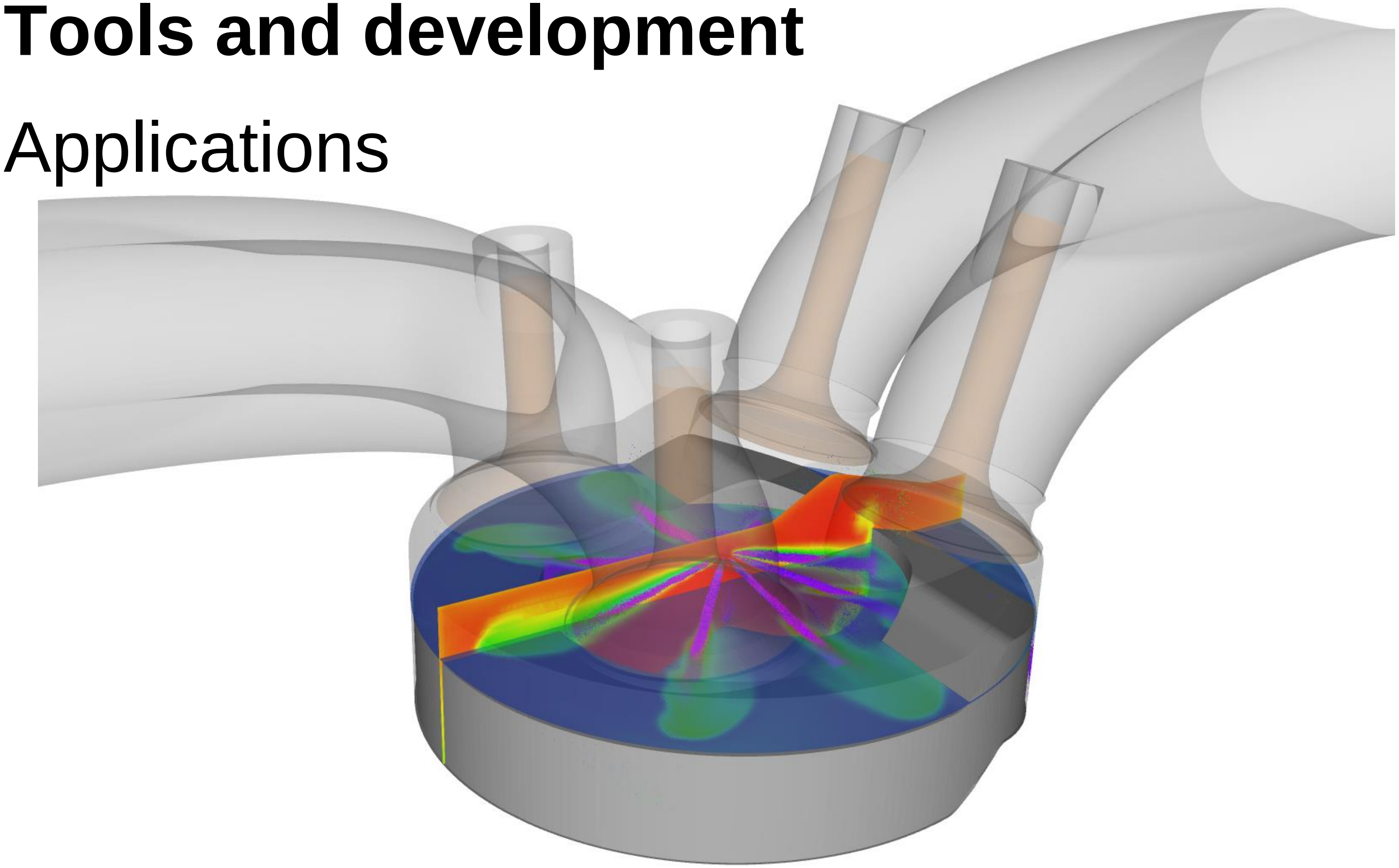
- EXAMPLES OF ICEs APPLICATION

AFTER-TREATMENT

- DPF MODELING

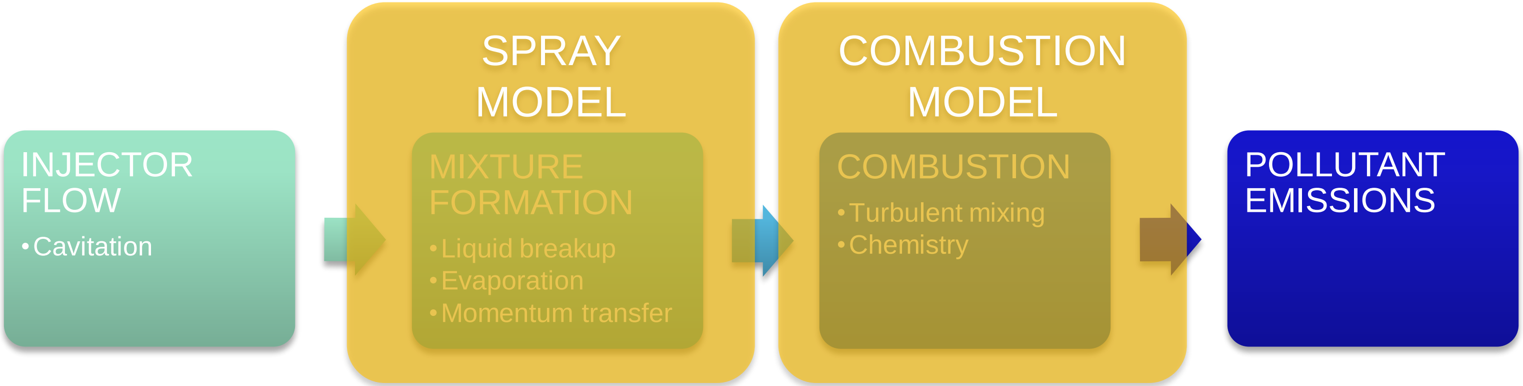
CONTENTS

- Background and approach
- **Tools and development**
- Applications



CFD of multiphase reacting flows

- State-of-the-art and research directions



SPRAY MODEL

COMBUSTION MODEL

INJECTOR FLOW
- Cavitation

MIXTURE FORMATION
- Liquid breakup
- Evaporation
- Momentum transfer

COMBUSTION
- Turbulent mixing
- Chemistry

POLLUTANT EMISSIONS

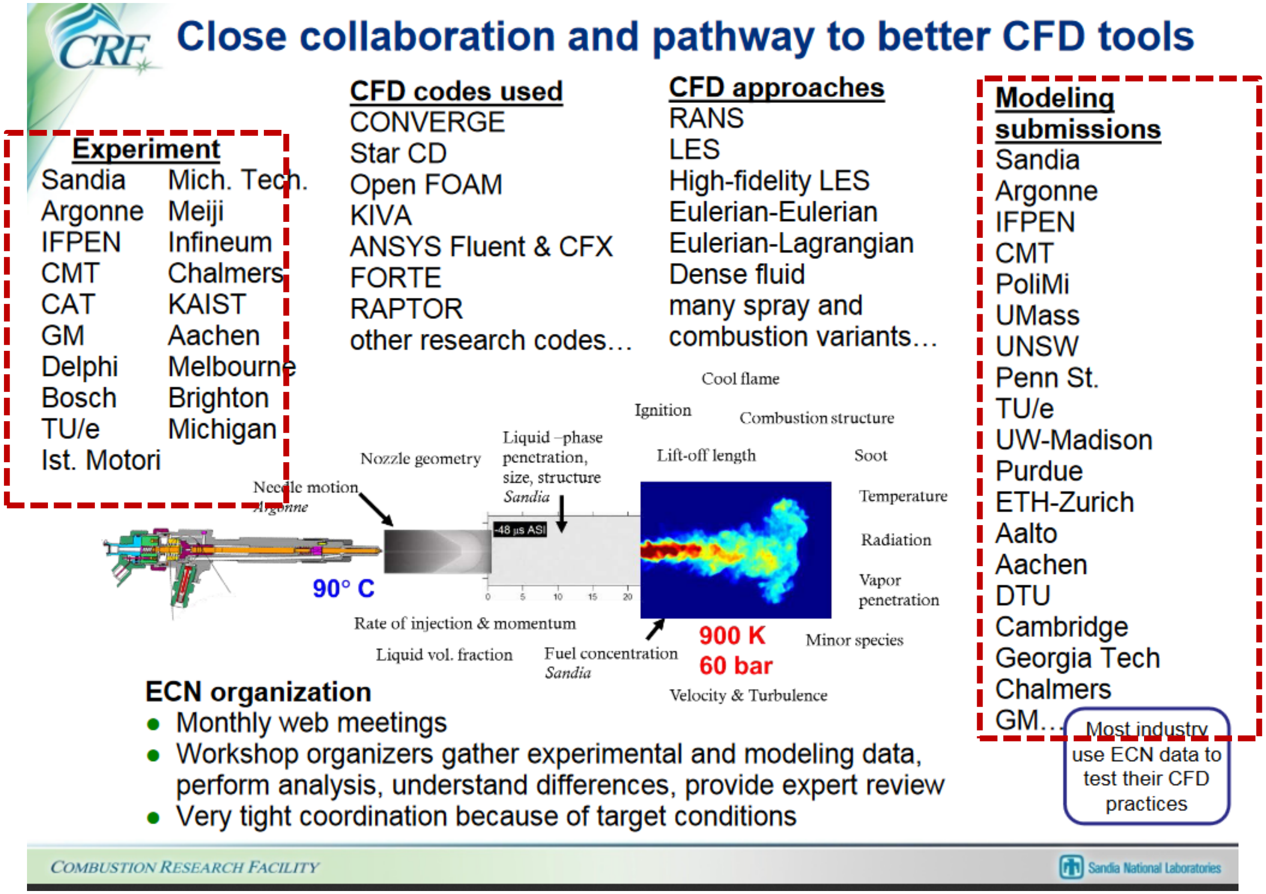
	SPRAY	COMBUSTION	TURBULENCE
CONVENTIONAL	LAGRANGIAN (DDM)	SIMPLIFIED KINETICS + TCI	RANS
ADVANCED	EULERIAN +LAGRANGIAN	DETAILED KINETICS + TCI	RANS → LES

TOOLS & DEVELOPMENT

Engine Combustion Network (ECN)

- Necessary dialogue between research efforts

Experiments Calculations



Close collaboration and pathway to better CFD tools

Experiment

Sandia
Argonne
IFPEN
CMT
CAT
GM
Delphi
Bosch
TU/e
Ist. Motori

Mich. Tech.
Meiji
Infineum
Chalmers
KAIST
Aachen
Melbourne
Brighton
Michigan

CFD codes used

CONVERGE
Star CD
Open FOAM
KIVA
ANSYS Fluent & CFX
FORTE
RAPTOR
other research codes…

CFD approaches

RANS
LES
High-fidelity LES
Eulerian-Eulerian
Eulerian-Lagrangian
Dense fluid
many spray and
combustion variants…

Modeling submissions

Sandia
Argonne
IFPEN
CMT
PoliMi
UMass
UNSW
Penn St.
TU/e
UW-Madison
Purdue
ETH-Zurich
Aalto
Aachen
DTU
Cambridge
Georgia Tech
Chalmers
GM…

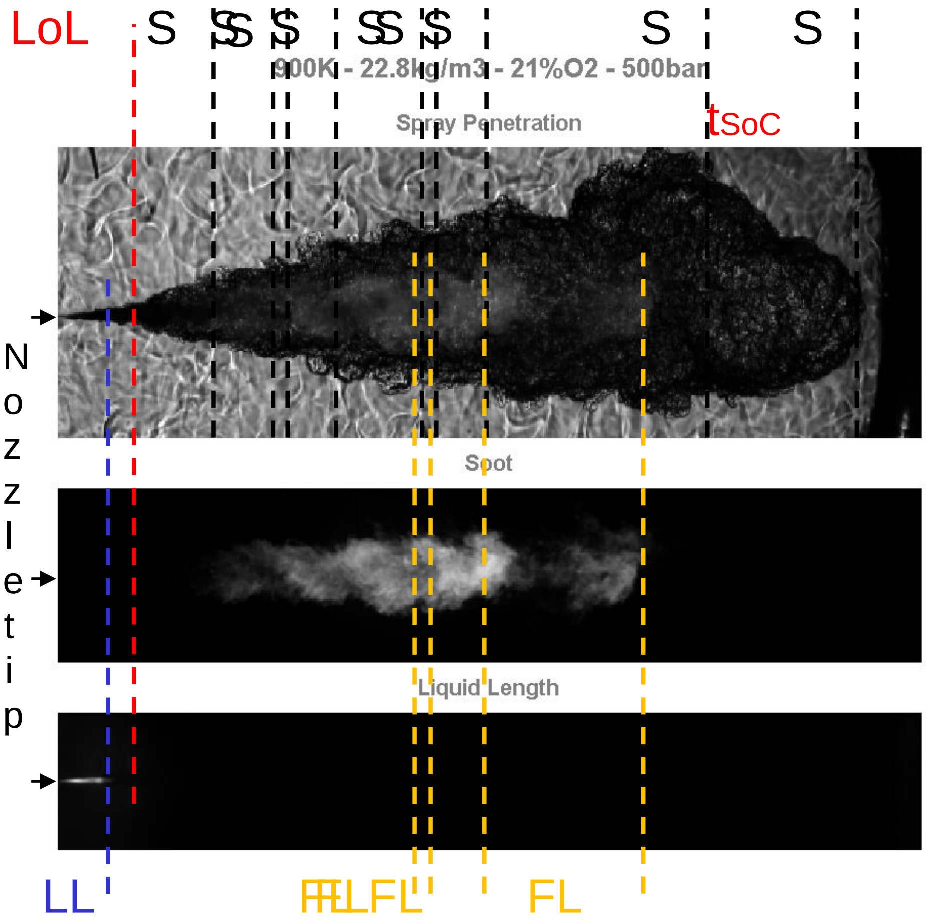
ECN organization

- Monthly web meetings
- Workshop organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review
- Very tight coordination because of target conditions

Most industry use ECN data to test their CFD practices

COMBUSTION RESEARCH FACILITY
Sandia National Laboratories

Diesel spray combustion, a highly transient process

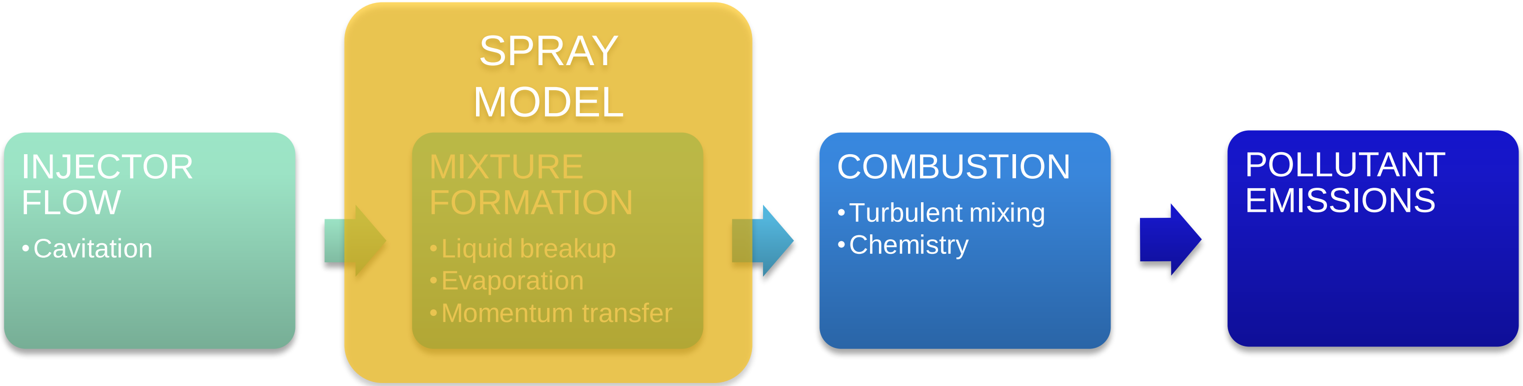


- Inert phase
  - Tip penetration (S)
  - Liquid stabilization (LL)

- Auto-ignition and diffusion flame
  - Tip penetration (S)
  - Ignition delay (t_{SoC})
  - Lift-off length (LOL)
  - Flame stabilization (FL)

CFD of multiphase reacting flows

- State-of-the-art and research directions



SPRAY MODEL

INJECTOR FLOW
- Cavitation

MIXTURE FORMATION
- Liquid breakup
- Evaporation
- Momentum transfer

COMBUSTION
- Turbulent mixing
- Chemistry

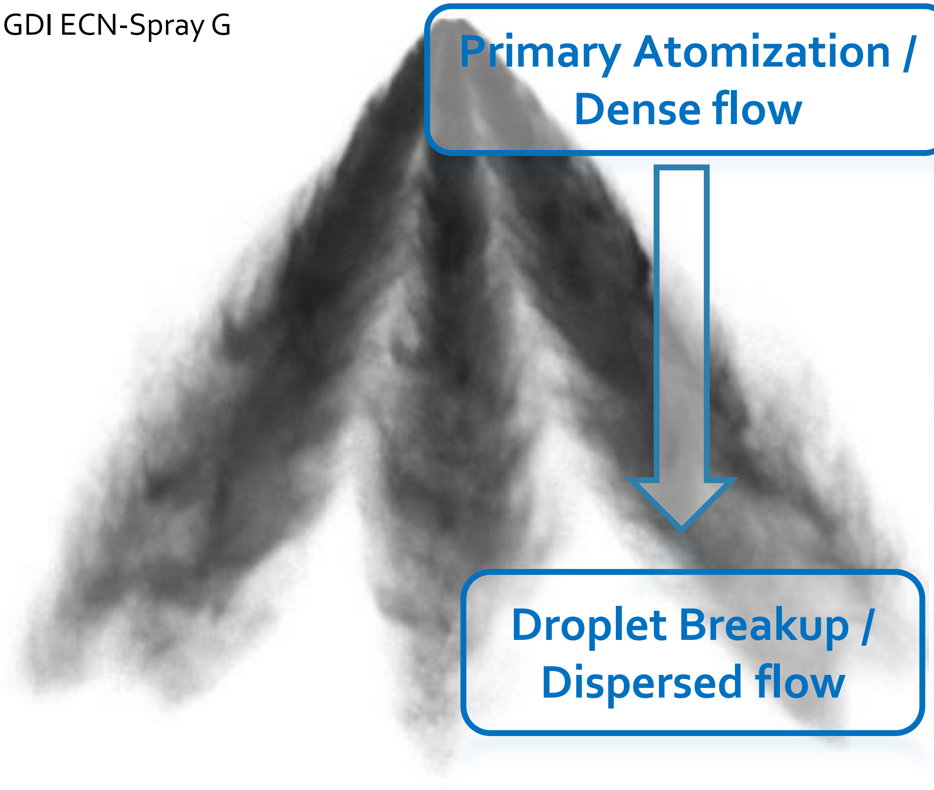
POLLUTANT EMISSIONS

	SPRAY	COMBUSTION	TURBULENCE
CONVENTIONAL	LAGRANGIAN (DDM)	SIMPLIFIED KINETICS + TCI	RANS
ADVANCED	EULERIAN (+LAGRANGIAN)	DETAILED KINETICS + TCI	RANS → LES

Spray modelling

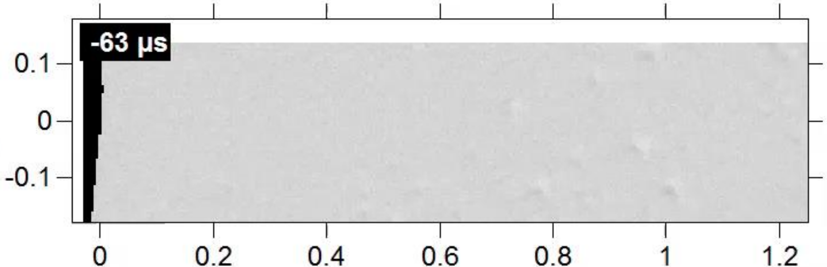
Engine sprays comprises wide range of two-phase flow regimes:

GDI ECN-Spray G

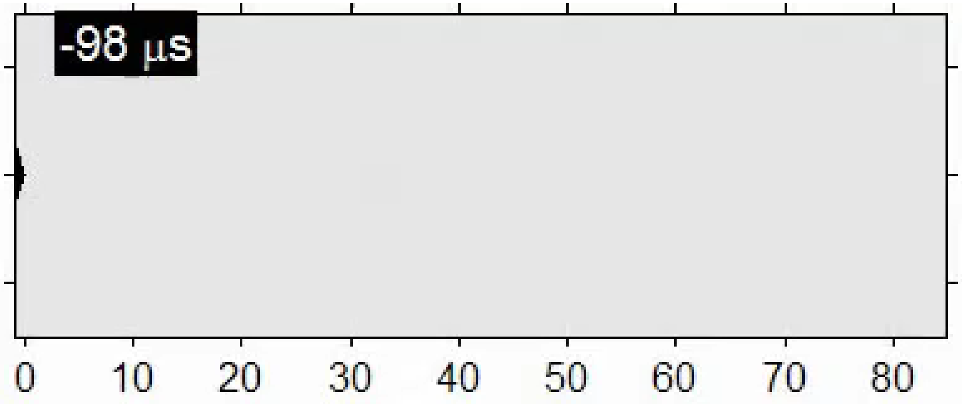


Primary Atomization / Dense flow

Droplet Breakup / Dispersed flow



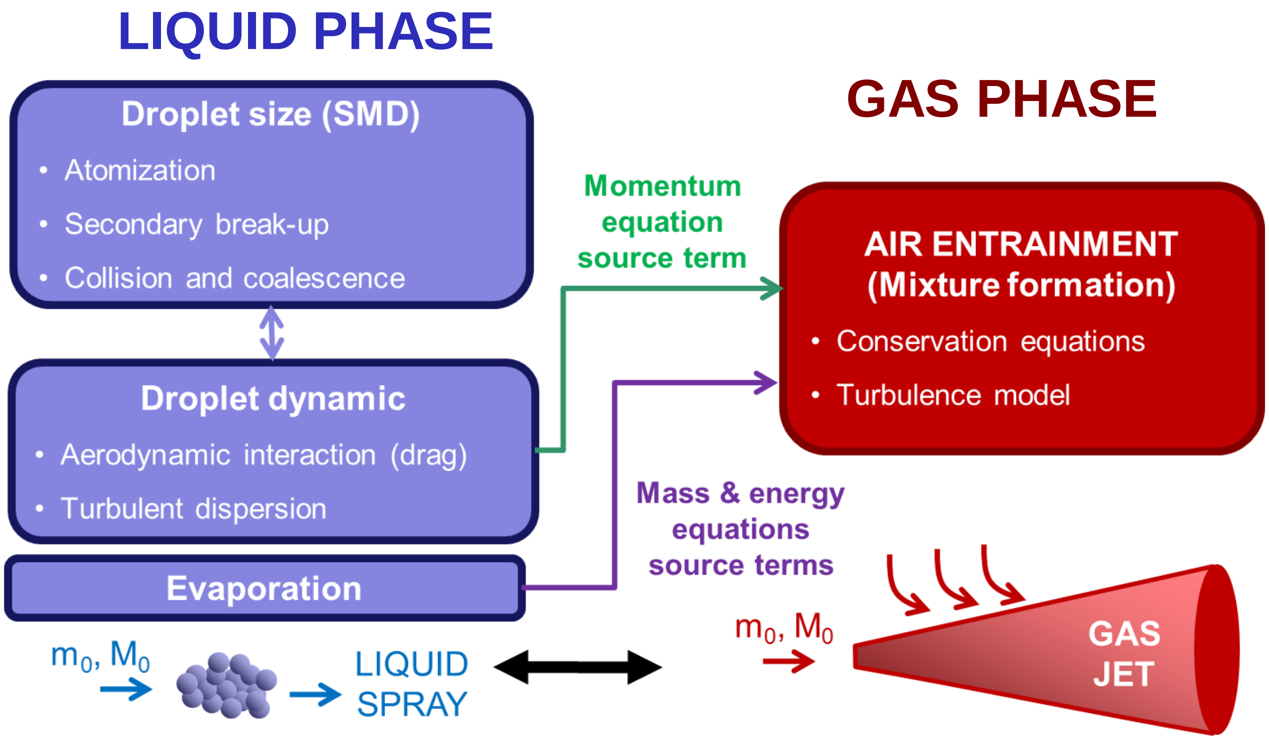
Diesel ECN-Spray A



Spray modelling

Discrete Droplet Model:

- Standard approach for engine spray CFD simulations
  - Two-fluid lagrangian liquid /eulerian gas framework
  - Phase coupling by source/sink terms between gas phase and spray eqs.



LIQUID PHASE

Droplet size (SMD)
- Atomization
- Secondary break-up
- Collision and coalescence

Droplet dynamic
- Aerodynamic interaction (drag)
- Turbulent dispersion

Evaporation

m_0, M_0 → → LIQUID SPRAY

Momentum equation source term

Mass & energy equations source terms

GAS PHASE

AIR ENTRAINMENT (Mixture formation)
- Conservation equations
- Turbulence model

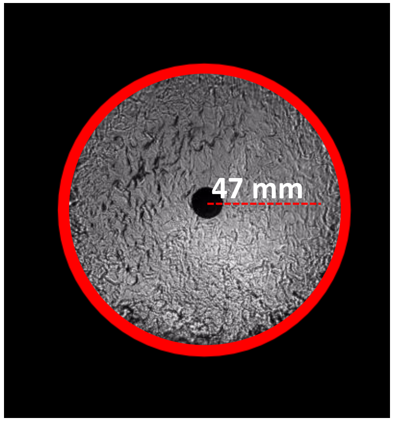
m_0, M_0 → GAS JET

Spray modelling

Discrete Droplet Model:

- Example of application

- Experimental (raw image)

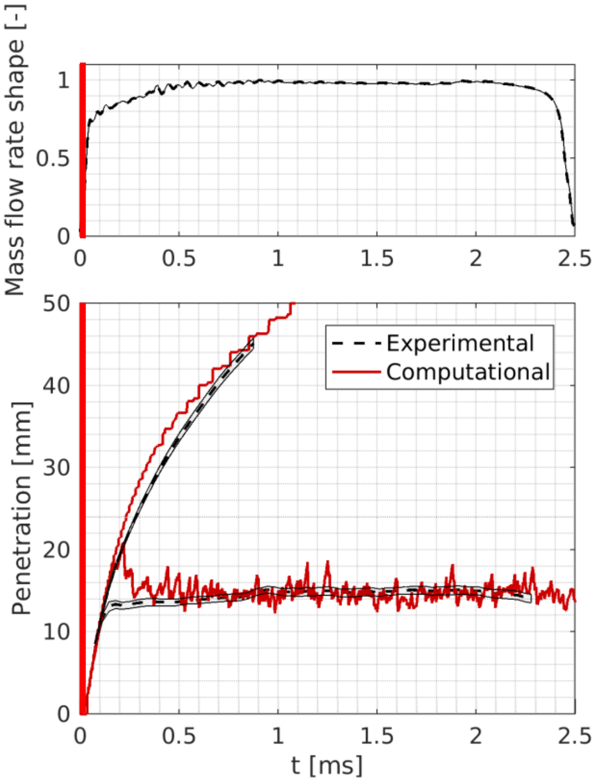


- CFD model

Benajes et al., FEV Diesel Powertrains 3.0 (2017)

Model calibration

- Target: error < 5% for all testing points

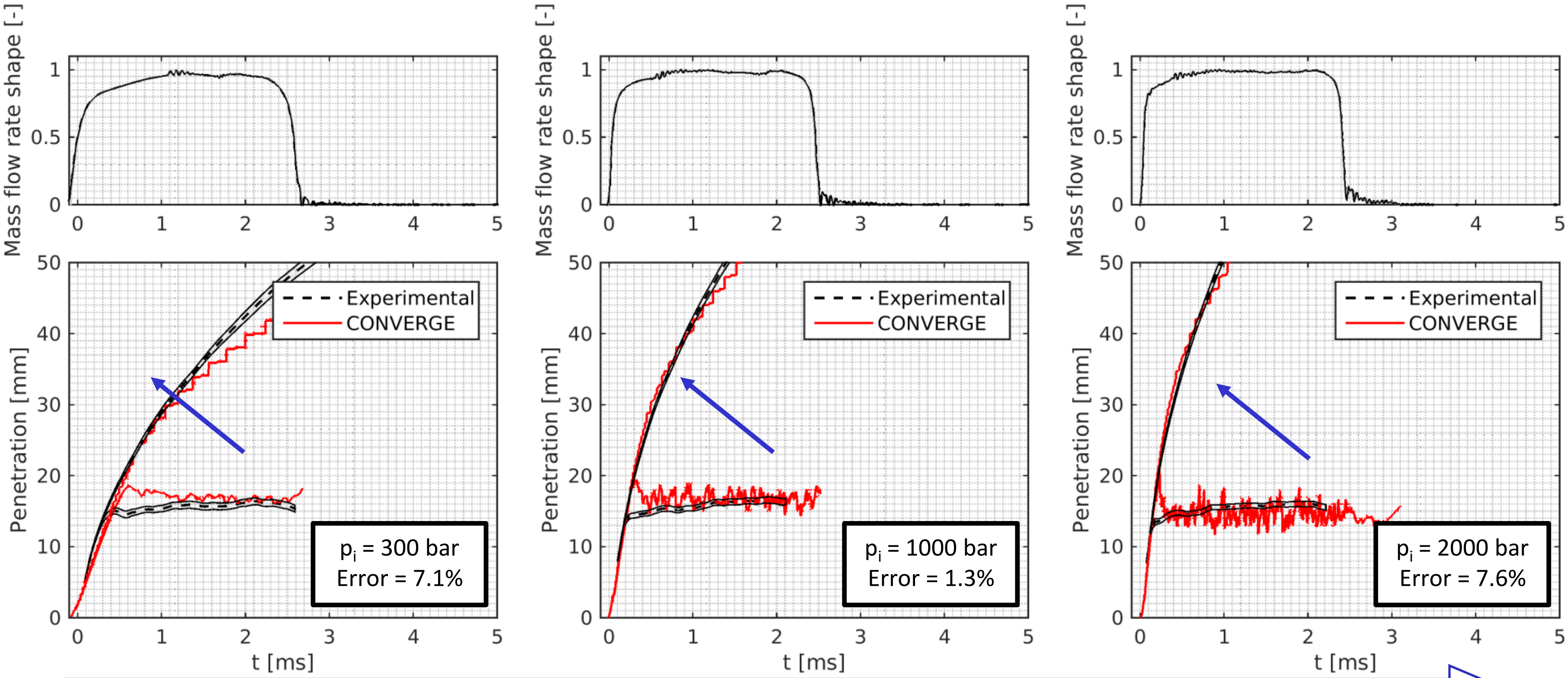


Nozzle A
$T = 900$ K
$p_i = 2500$ bar
$p_b = 50$ bar
Error = 1.7%

Spray modelling

Discrete Droplet Model:

- Fair accuracy after calibration using exp. data
  - Example: break-up model constants (time and size) depend on P_{inj}.



Benajes et al., Diesel Powertrains 3.0 (2017)

Increasing injection pressure

p_b = 50 bar, T_b = 900 K

Spray modelling

Discrete Droplet Model:

- Fair accuracy after calibration using exp. data
  - Example: break-up model constants (time and size) depend on P_{inj}.

		Size cnst KH	Time cnst KH	Size cnstRT	Time cnst RT
p_i [bar]	**p_b [bar]**	**B_0**	**B_1**	**cnst3rt**	**rtcnst2b**
300	30	0.80	5	0.5	1.0
300	50	0.80	5	0.5	
300	70	0.80	5	0.5	1.5
1000	30	1.34	11.4	0.5	1.0
1000	50	1.34	11.4	0.5	
1000	70	1.34	11.4	0.5	1.5
1800	30	2.00	18.6	0.5	1.0
1800	50	2.00	18.6	0.5	
1800	70	2.00	18.6	0.5	1.5
2500	30	5.00	25	0.5	1.0
2500	50	5.00	25	0.5	
2500	70	5.00	25	0.5	1.5

Increasing injection pressure

Increasing ambient pressure

Benajes et
Powertrains

KH model

$$\frac{dr_p}{dt} = -\frac{(r_p - r_c)}{\tau_{KH}}$$

$$r_c = B_0 \cdot \Lambda_{KH}$$

$$\tau_{KH} = \frac{3.726 \cdot B_1 \cdot r_p}{\Lambda_{KH} \cdot \Omega_{KH}}$$

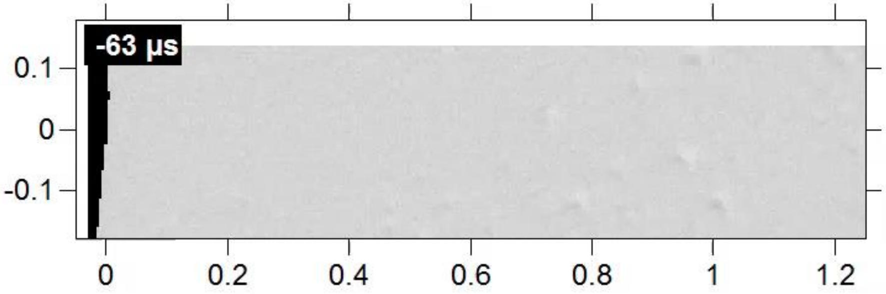
Spray modelling

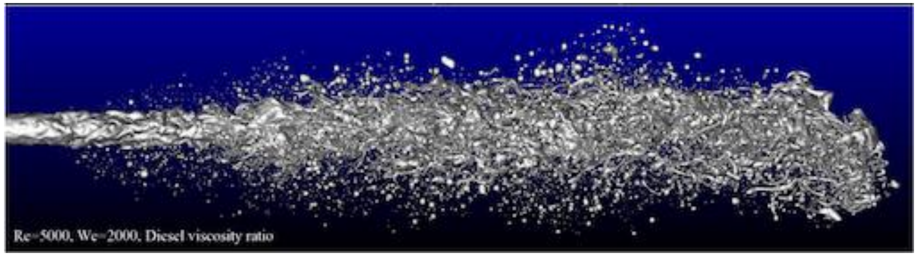
Near-nozzle flow:

- Complex liquid-gas interface
- Modeling *(and experiments)* should move away from the droplet concept within the spray dense core
  - DDM not well suited for this region
  - ICM unfeasible (↑↑ *Re* & *We*)

→

Diffuse-interface eulerian methods arises as an interesting option





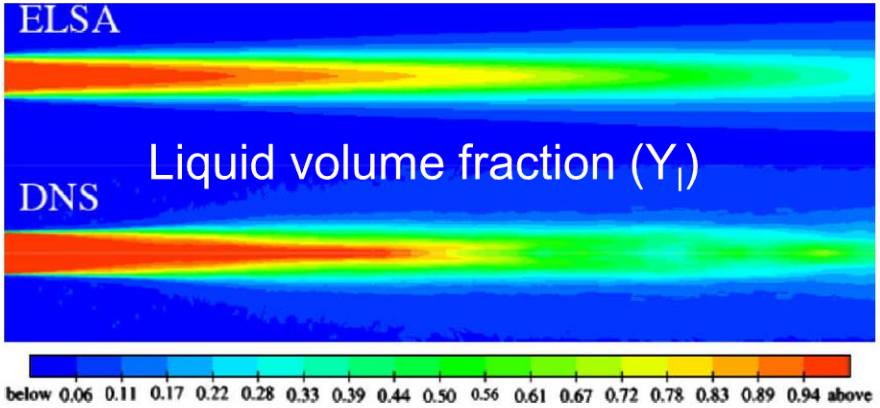
ECN –SprayA near-nozzle (https://ecn.sandia.gov/)

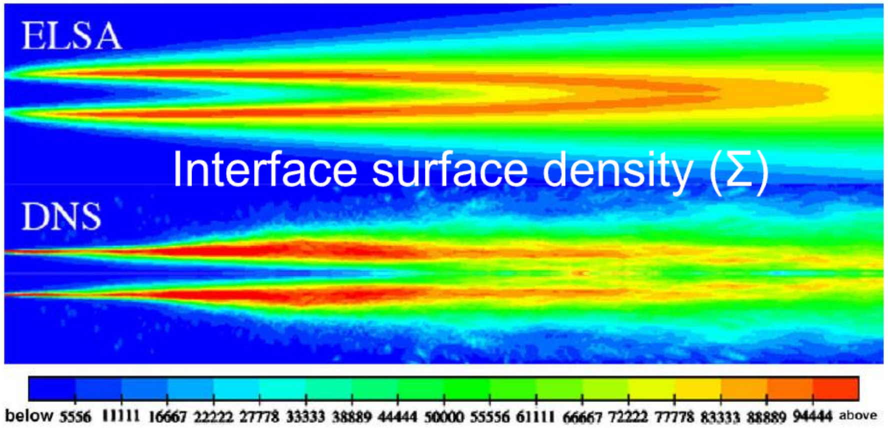
Liquid jet atomization under Diesel-like conditions, simulated on 400 million cells
https://ctflab.mae.cornell.edu/research.html

Spray modelling

Eulerian diffuse-interface approach (Vallet & Borghi, AAS (2001))

- Flow scales separation at ↑↑ *Re* & *We*
  - Liquid dispersion independent from atomization processes occurring at smaller scales
- Mean velocity field
  - Liquid/gas mixture considered as a single velocity pseudo-fluid
- Liquid mass dispersion
  - Modeled as turbulent mixing of variable density fluid by means of liquid mass fraction (Y) transport eq.
- Atomization process
  - Mean liquid geometry modeled by surface area of the liquid-gas interphase (Σ)



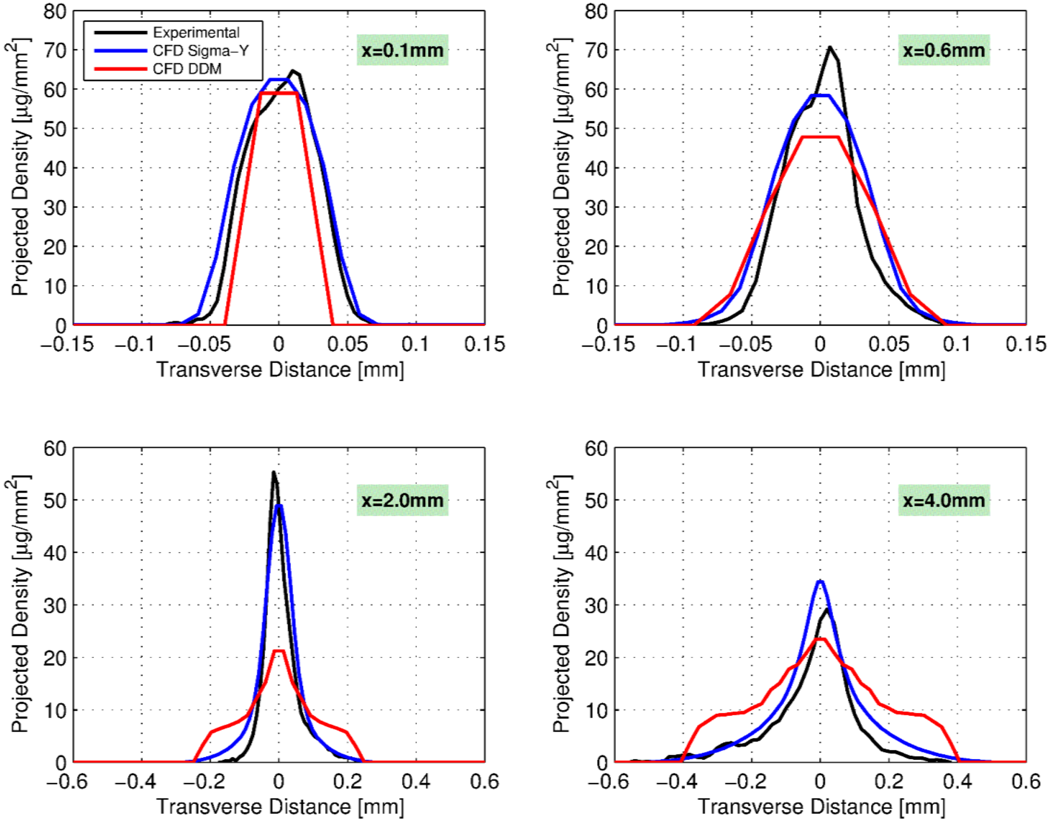


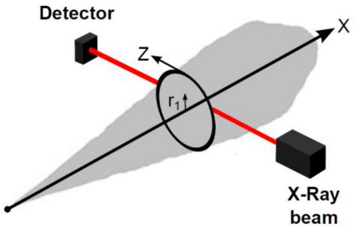
Lebas et al., IJMF (2009)

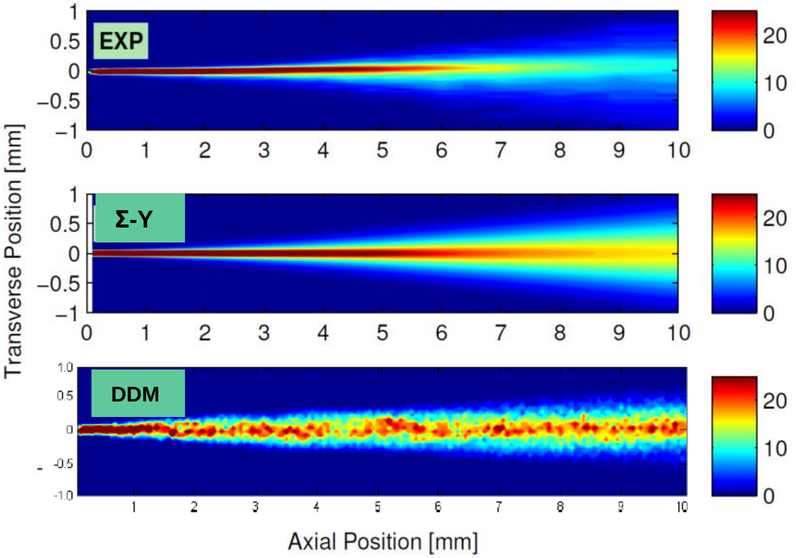
Eulerian spray modelling

Near-field

- Improved near-nozzle liquid dispersion compared to DDM





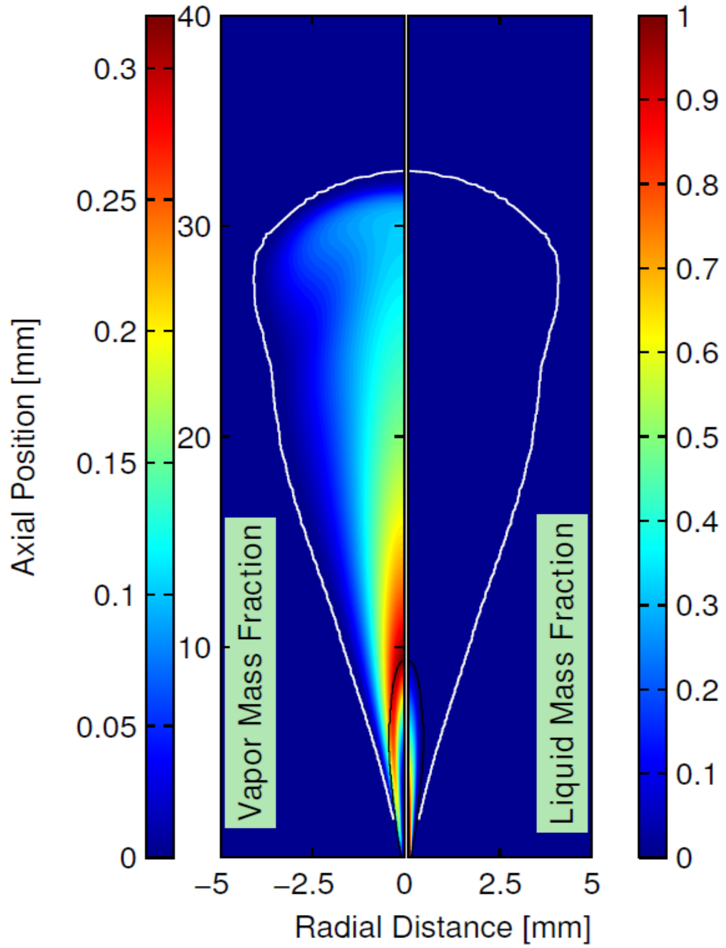


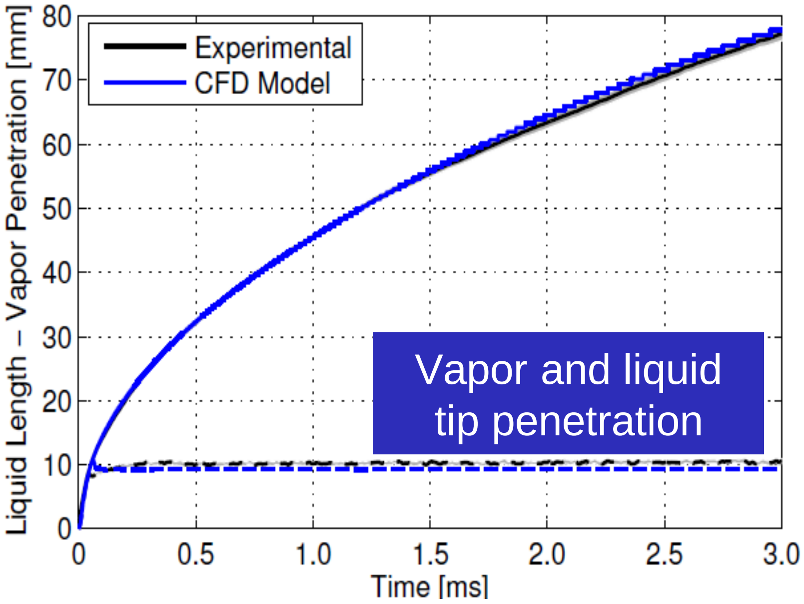
Desantes et al., AAS 26 (2016):713-737

Eulerian spray modelling

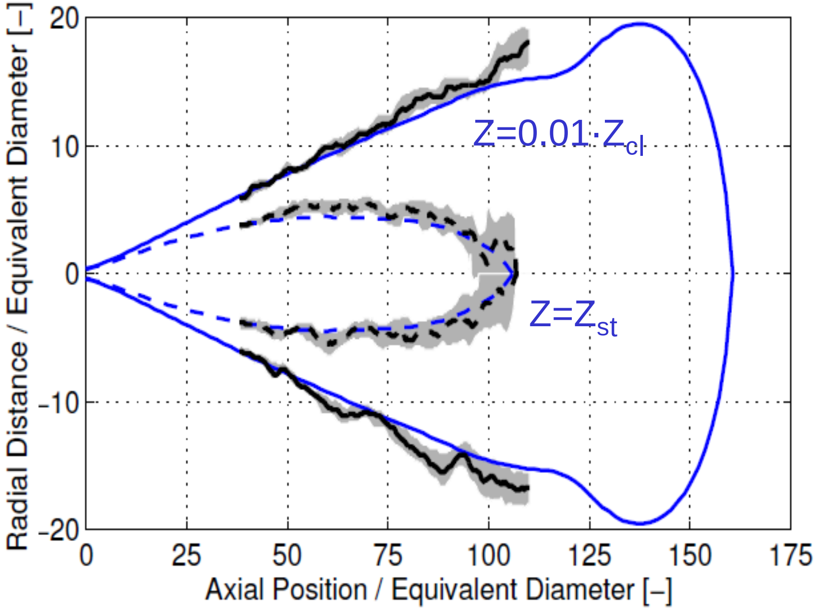
Far-field

- Consistent results downstream





Vapor and liquid tip penetration

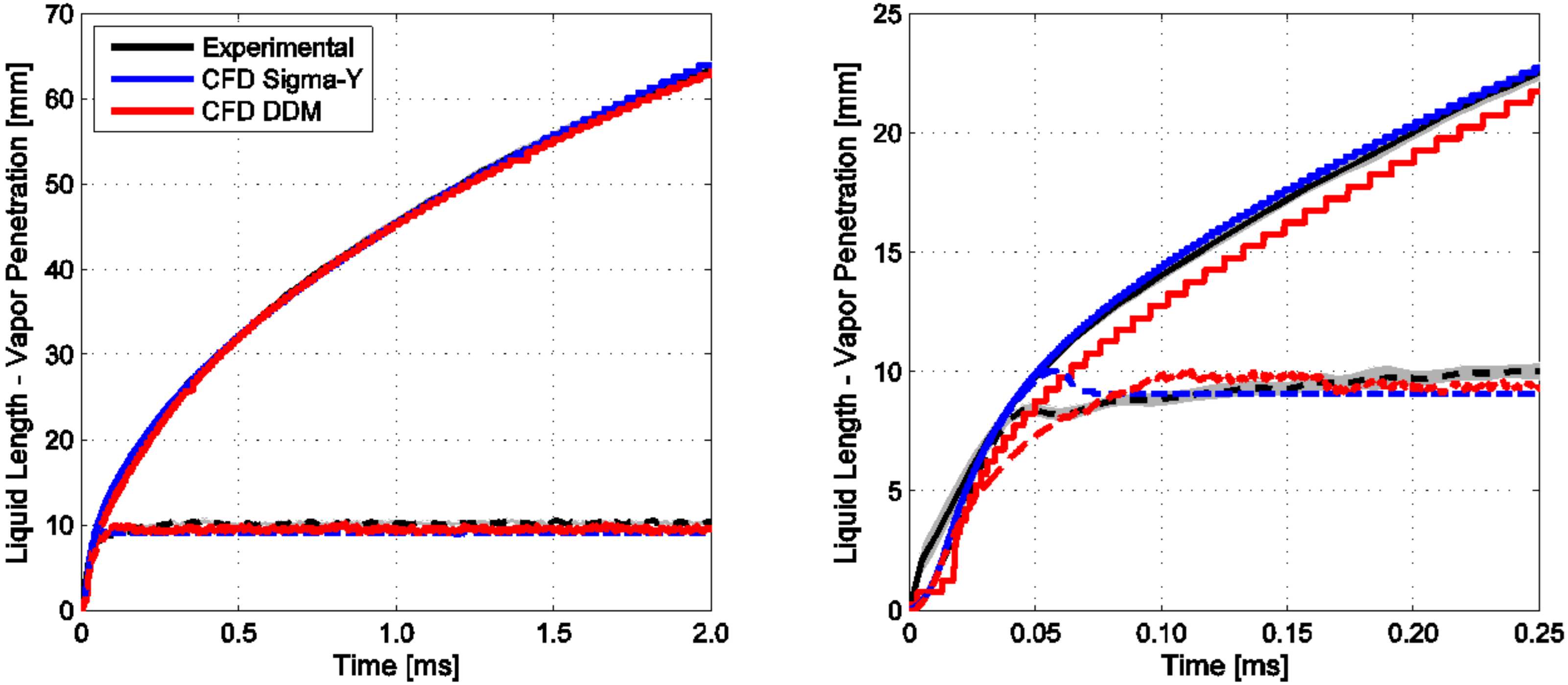


García-Oliver et al., AAS 23 (2013):71–95

Eulerian spray modelling

Far-field

- Improved predictions compared to calibrated DDM
  - Liquid and vapor tip penetration

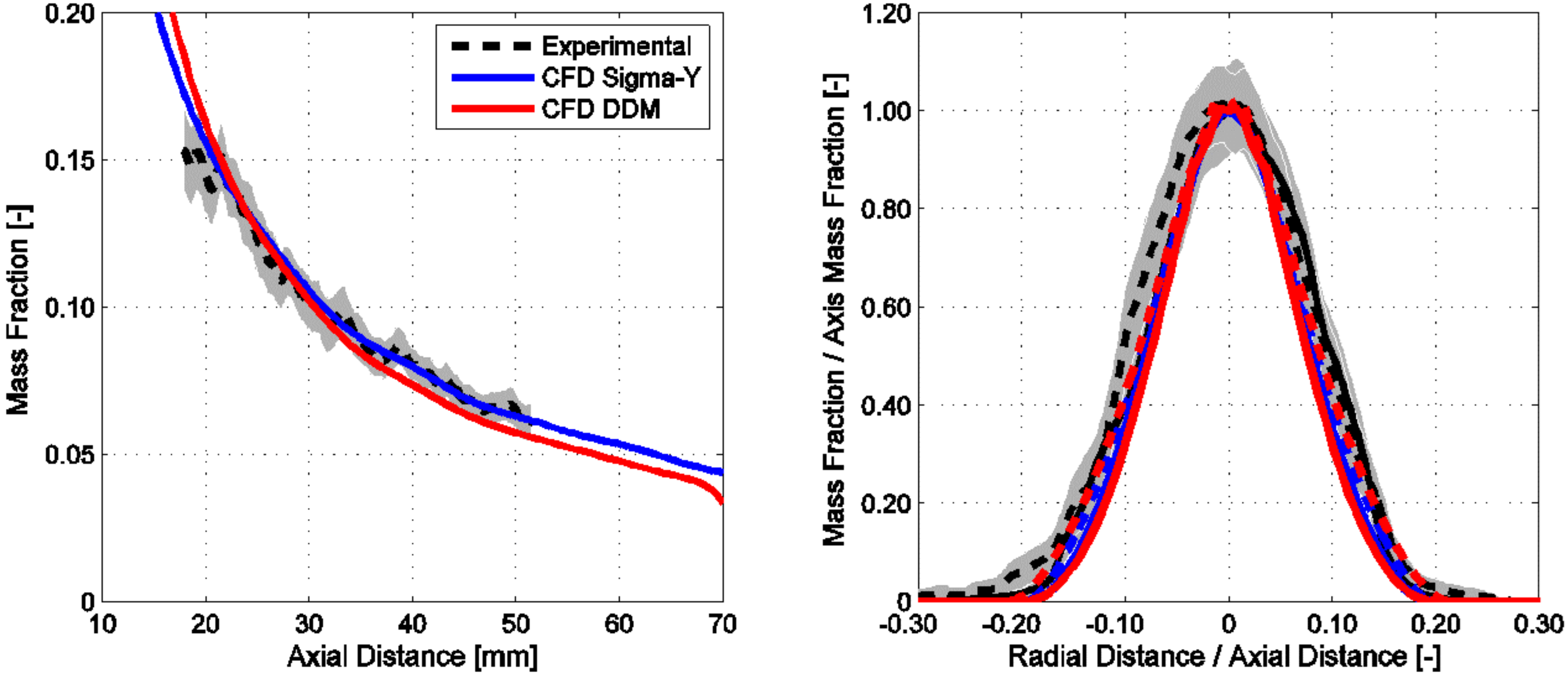


Desantes et al., AAS 26 (2016):713-737

Eulerian spray modelling

Far-field

- Improved predictions compared to calibrated DDM
  - Mixing field

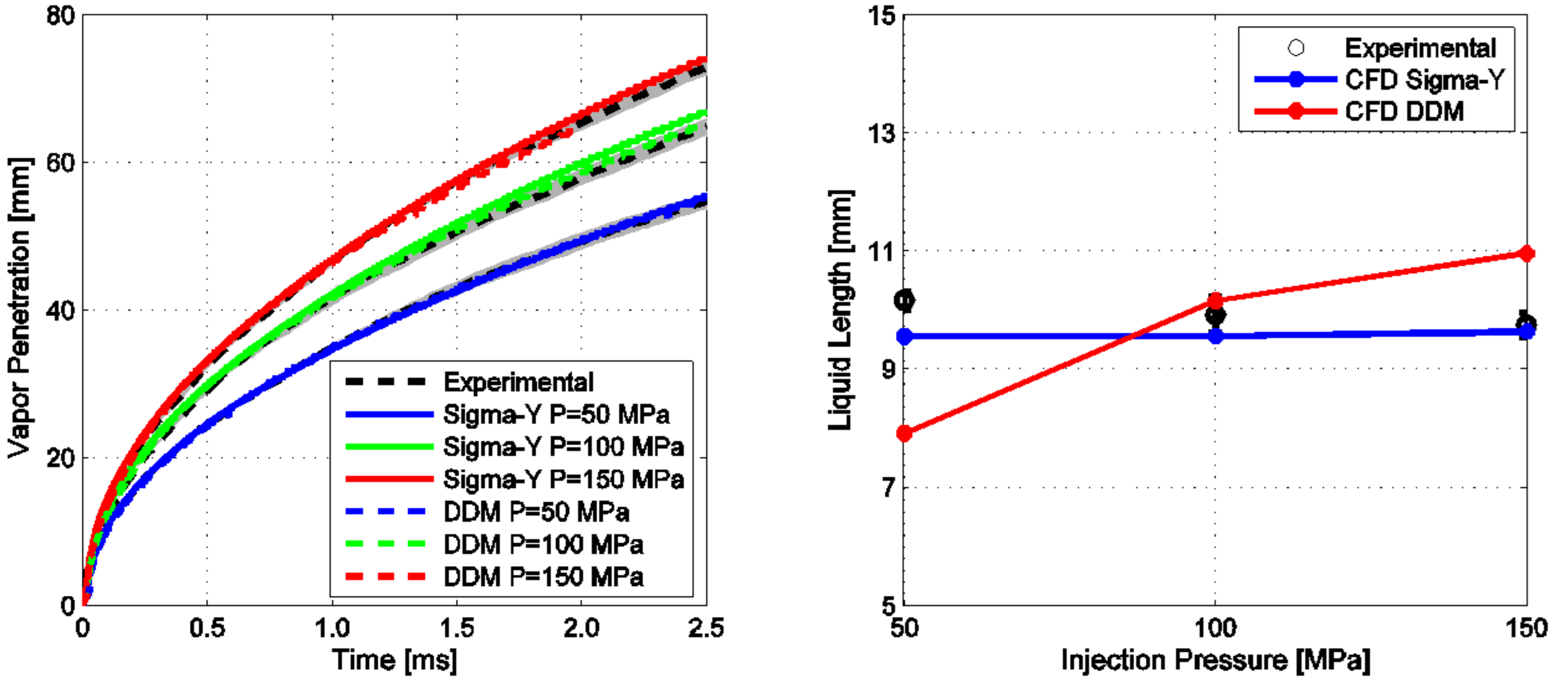


Desantes et al., AAS 26 (2016):713-737

Eulerian spray modelling

Far-field

- Proper trends on parametric variations w/o additional calibration, unlike DDM

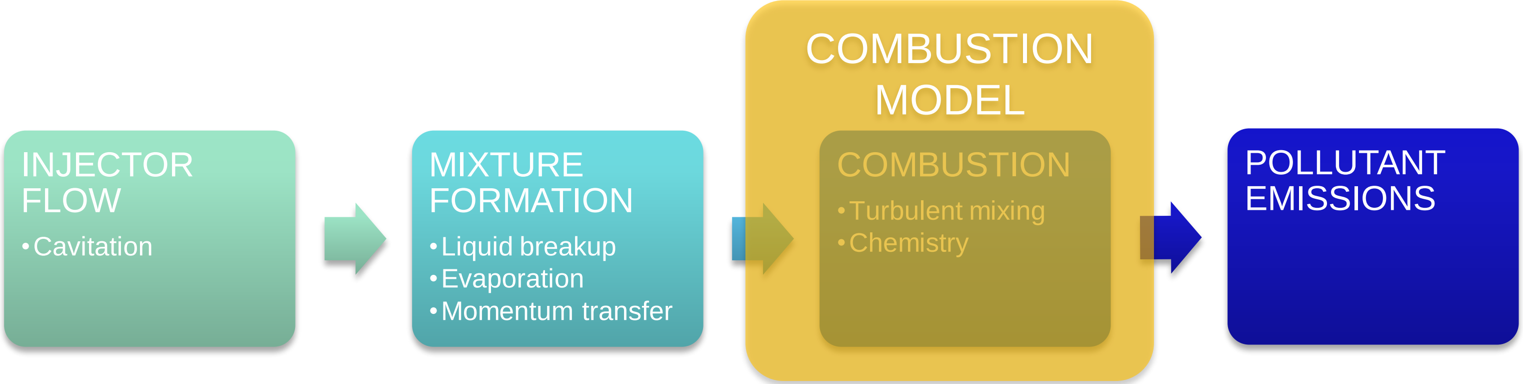


Desantes et al., AAS 26 (2016):713-737

TOOLS & DEVELOPMENT

CFD of multiphase reacting flows

- State-of-the-art and research directions



INJECTOR FLOW
- Cavitation

MIXTURE FORMATION
- Liquid breakup
- Evaporation
- Momentum transfer

COMBUSTION MODEL

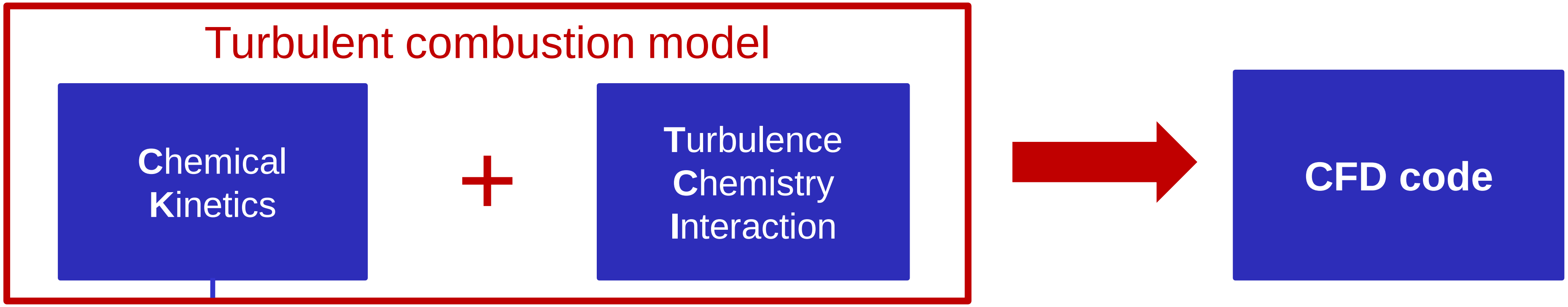
COMBUSTION
- Turbulent mixing
- Chemistry

POLLUTANT EMISSIONS

	SPRAY	COMBUSTION	TURBULENCE
CONVENTIONAL	LAGRANGIAN (DDM)	SIMPLIFIED KINETICS + TCI	RANS
ADVANCED	EULERIAN (+LAGRANGIAN)	DETAILED KINETICS + TCI	RANS → LES

Combustion modelling

CFD of reacting flows



Turbulent combustion model

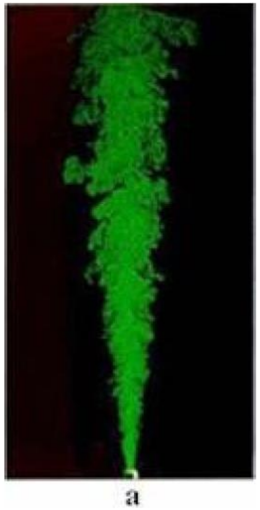
Chemical Kinetics

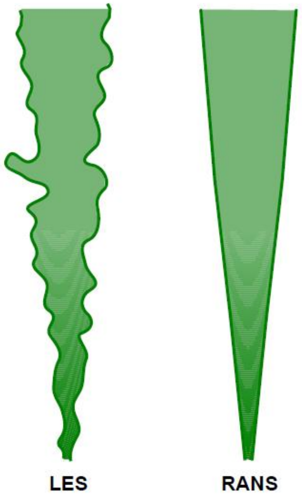
+

Turbulence Chemistry Interaction

CFD code

Fuel oxidation + Pollutant (NOx,soot,…)





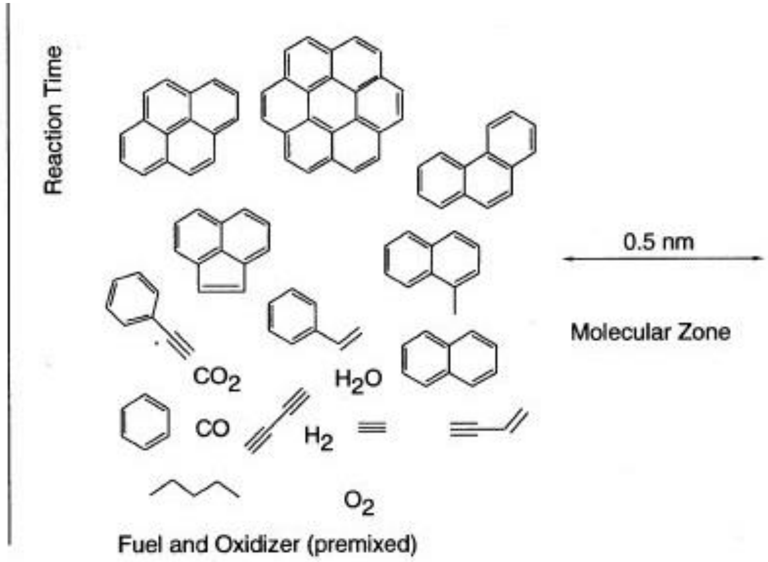
$\widetilde{\dot{w}_i}$?

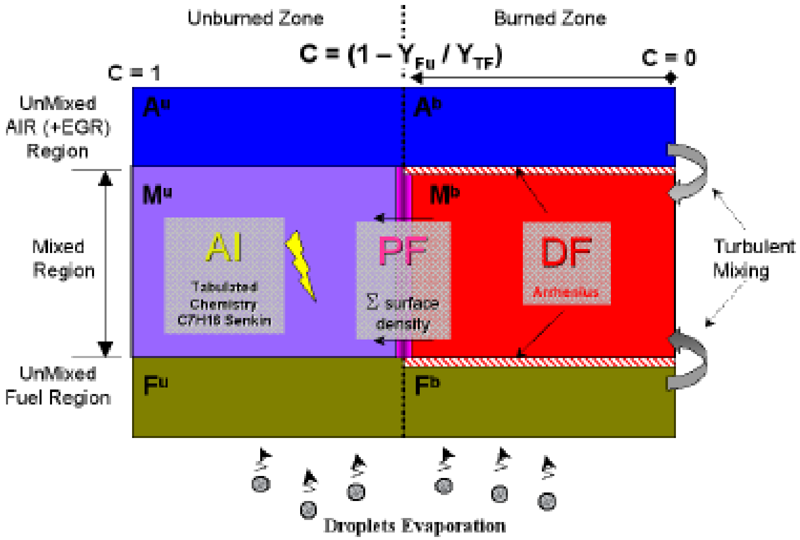
Combustion modelling

CFD of reacting flows

- Chemical Kinetics
  - From simple (1 reaction) to detailed (1000’s of reactions) mechs.

- TCI approaches
  - Direct integration (‘no model’, delta-PDF,…)
  - Phenomenological (CTC,PaSR,ECFM, …)
  - Scale separation + pPDF (RIF, UFPV, CMC,…)
  - Transported PDFs,..

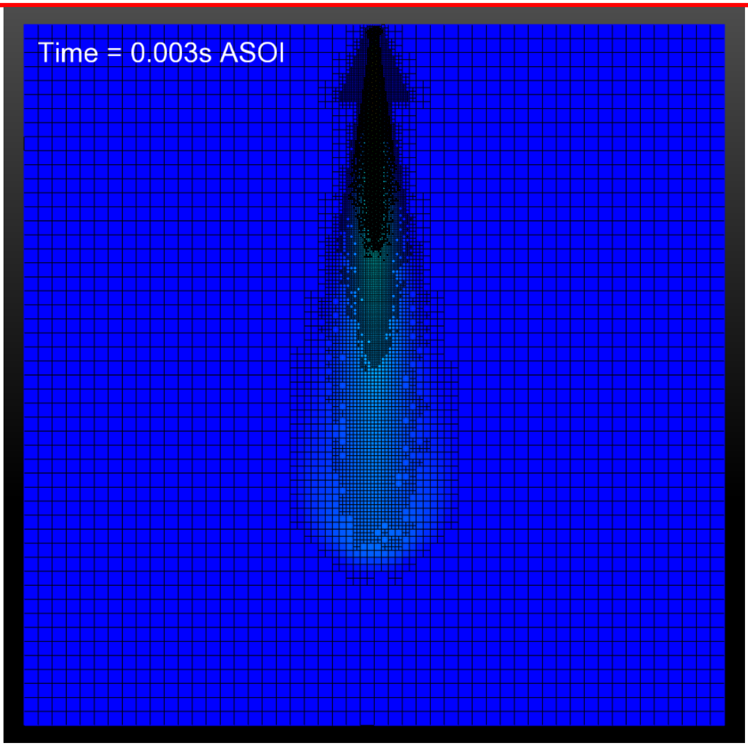




Combustion modelling

ECN-Spray A application

- Set-up:
  - *RANS:* std k-ε + $C_{1\varepsilon}$=1.55
    - ~1 Mcells
    - Min cell size 125 μm
  - *LES:* dynamic Structure
    - ~4 Mcells
    - Min cell size 62.5 μm
- DDM spray:
  - KH + RT atomization & break-up



- Chemical mechs. (n-C12H26)
  - Yao et al, Fuel, 2017
    - 54 species / 269 reactions
  - Narayanaswamy et al, Comb.Flame 2014
    - 255 species / 2289 reactions

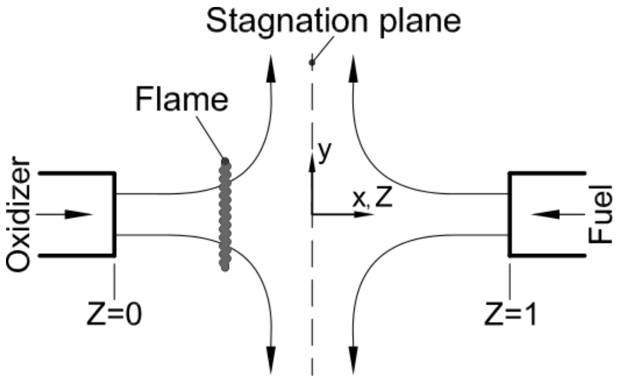
Combustion modelling

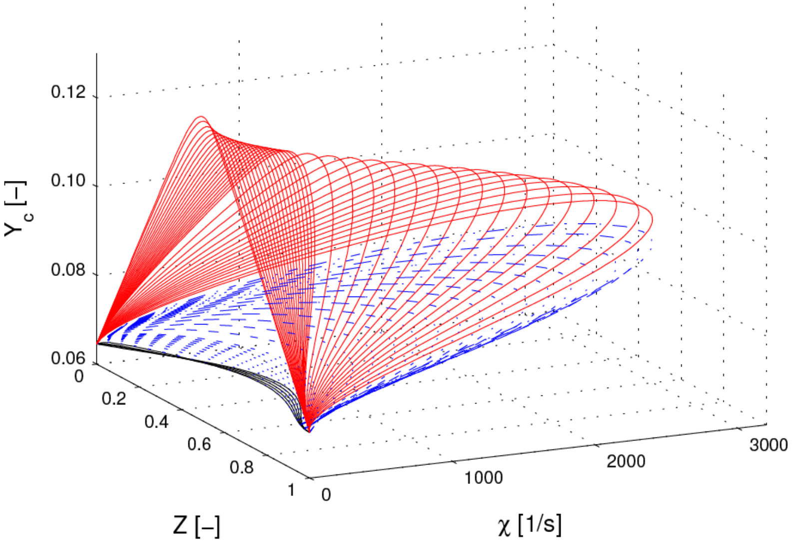
TCI impact

- SAGE (Senecal et al., 2003, SAE)
  - ➢Detailed Chemical Kinetics Solver
  - ➢Direct integration ('no model')
- UFPV (Unsteady Flamelet Progress Variable)
  - ➢Unsteady Flamelet Model (USFM)

    (Naud et al, CAF, 2014)
  - ➢Tabulated chemistry → Large chemical mechanisms
  - ➢Detailed Flamelet calculations (DF)

    (Payri et al., AppMathModel, 2017)

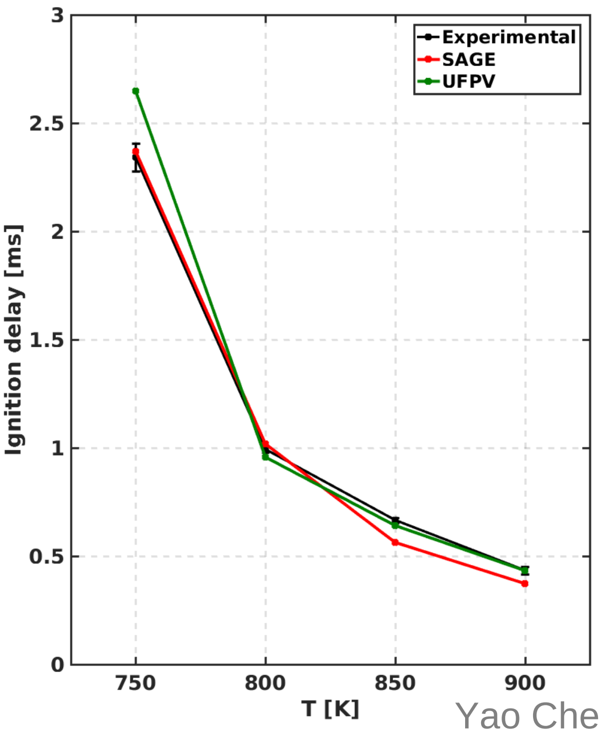


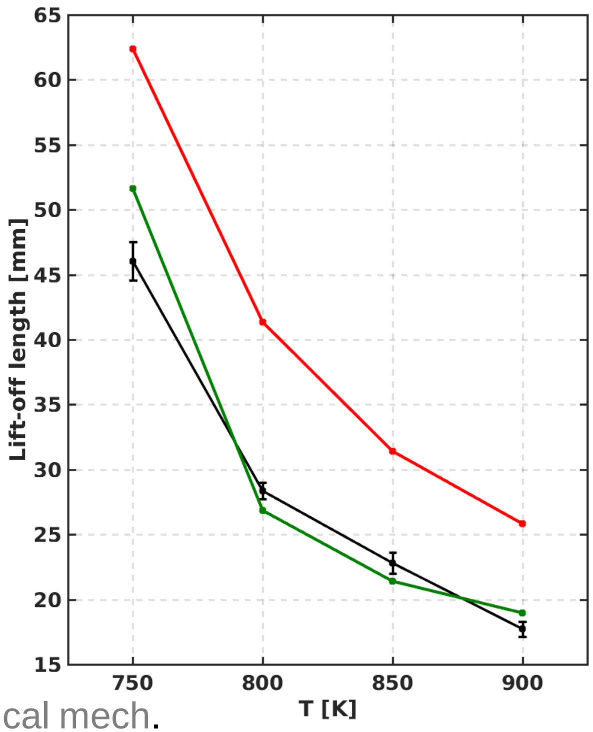


Combustion modelling

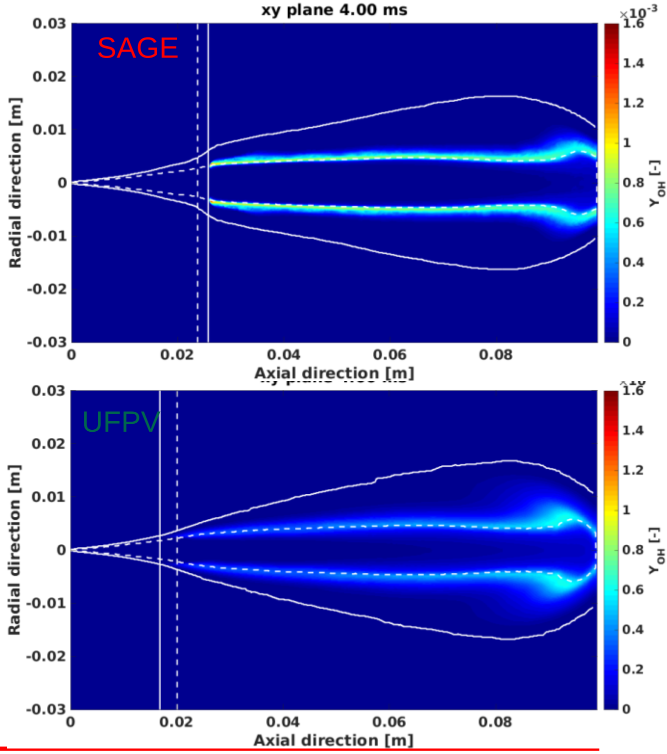
TCI impact

- Both models are able to capture trends
- Overall good agreement for both models in terms of ID
  - Yao mech. calibrated for reacting spray !!
- Better agreement in terms of LOL using UFPV





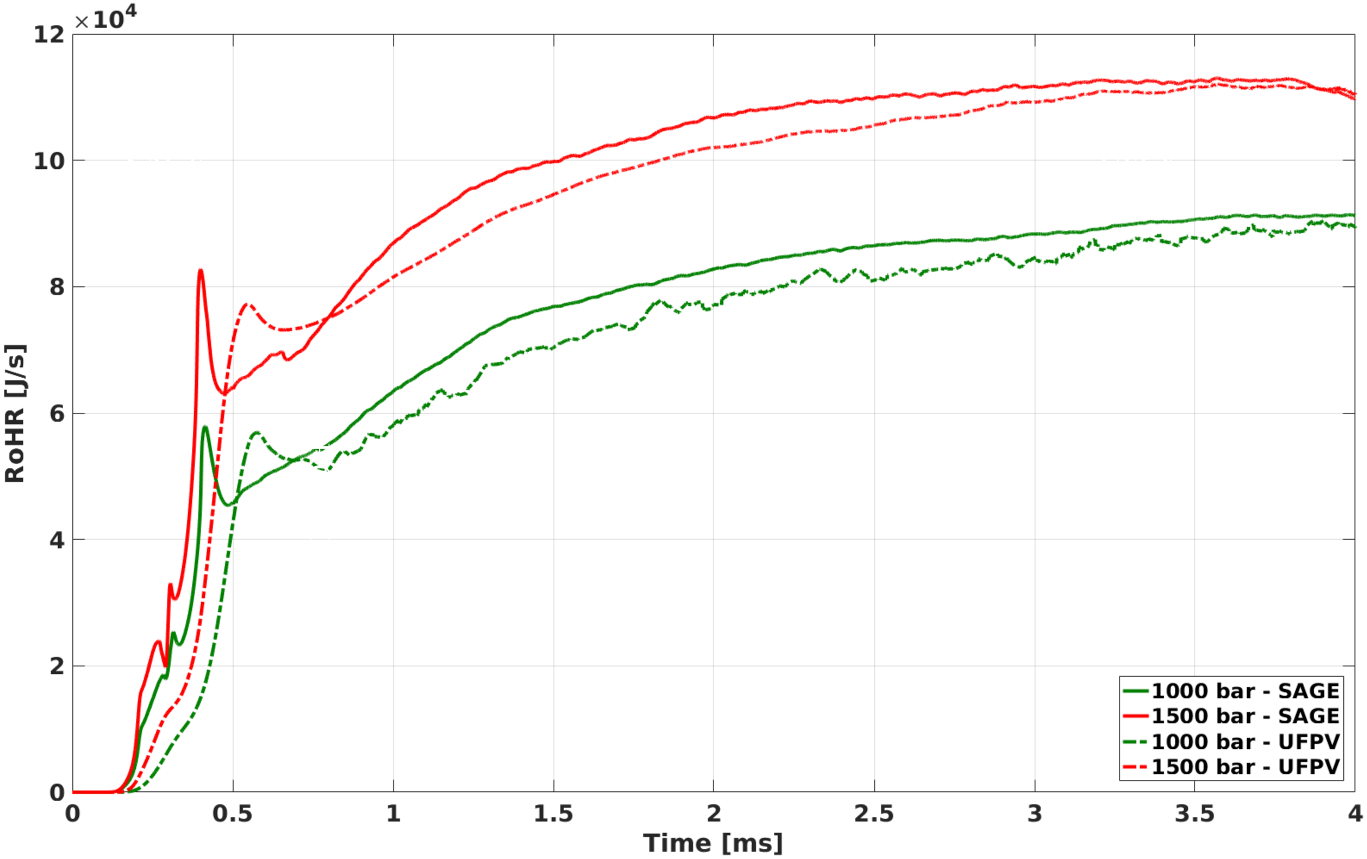
Yao Chemical mech.

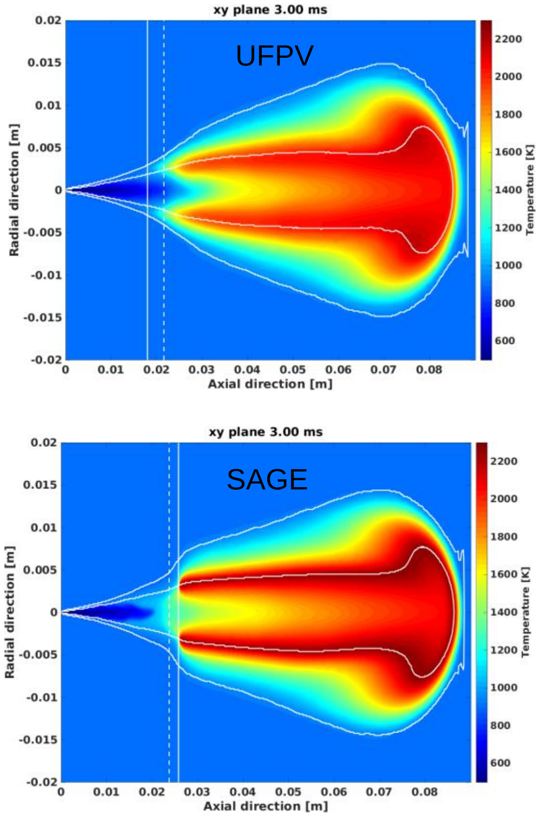


Combustion modelling

TCI impact

- Heat Release
  - ➢ Difference during premixed phase, closer during diffusion due to similar flame structure.

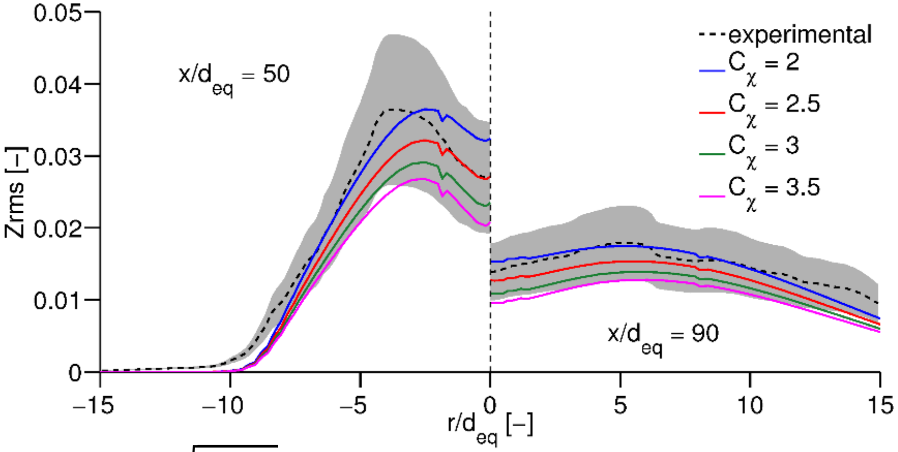


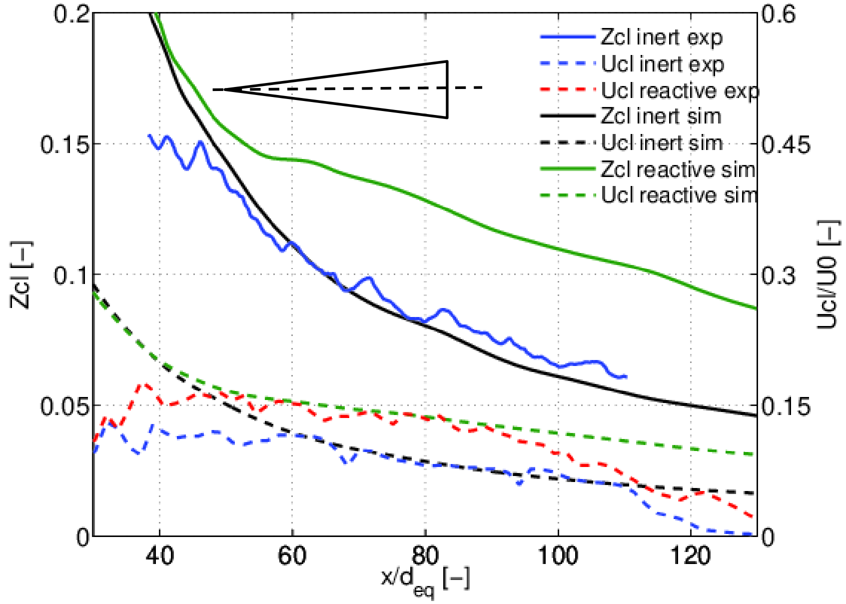


Combustion modelling

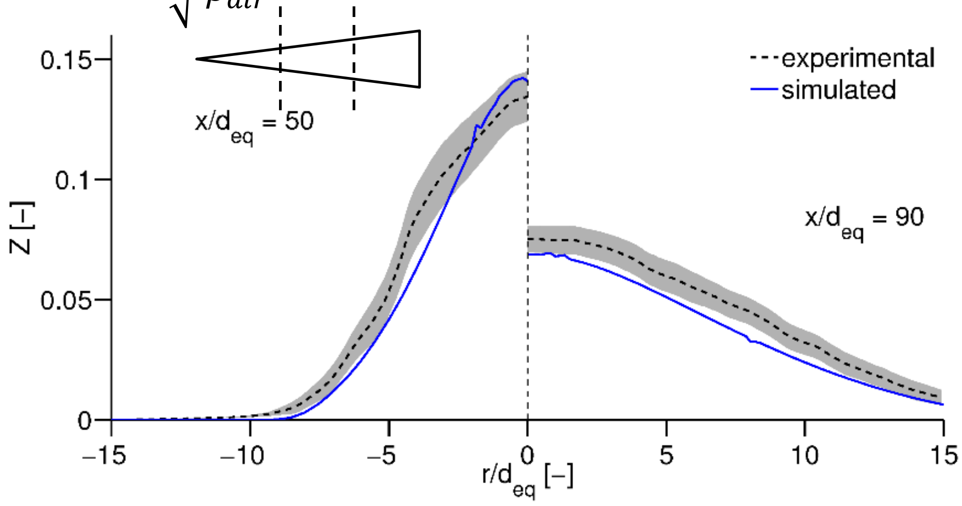
RANS → LES

- Spray mixing assessment
  - ➢Fair agreement of avg. fields with RANS requires turbulence model constant adjustment





$$d_{eq} = d_0 \sqrt{\frac{\rho_{fuel}}{\rho_{air}}}$$

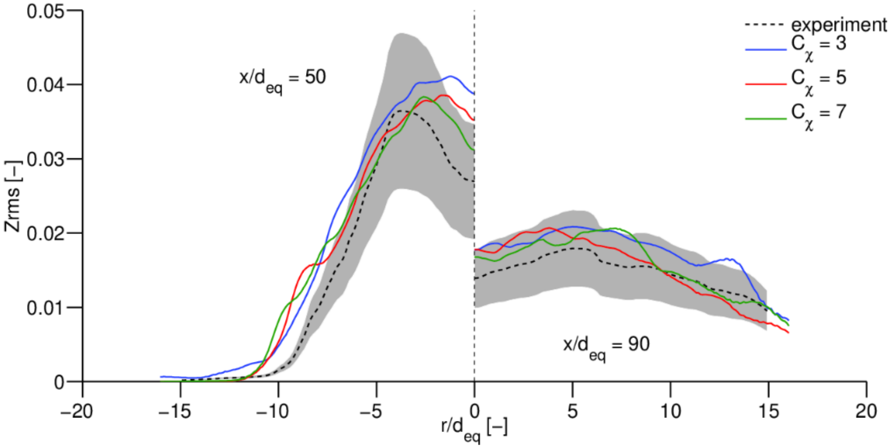


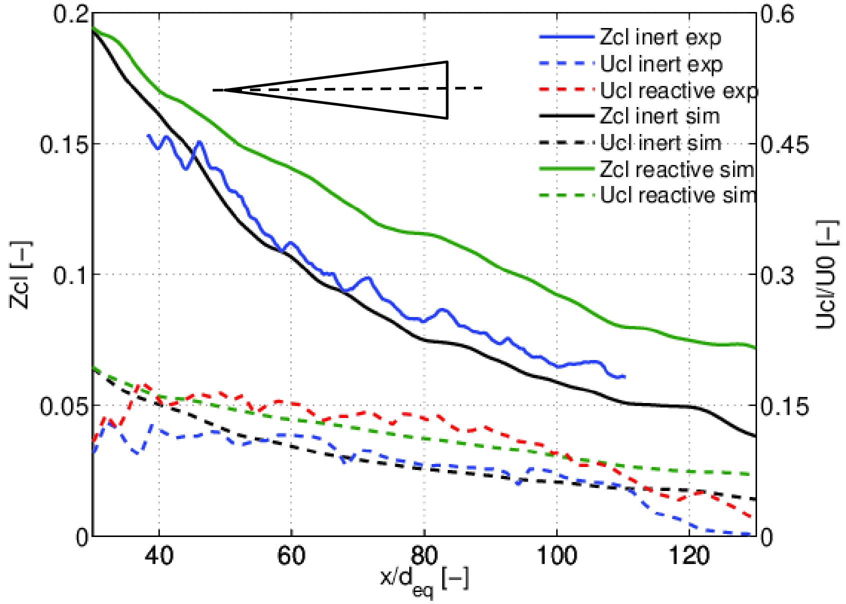
Desantes et al., Applied Thermal Engineering 117 (2017): 50–64

Combustion modelling

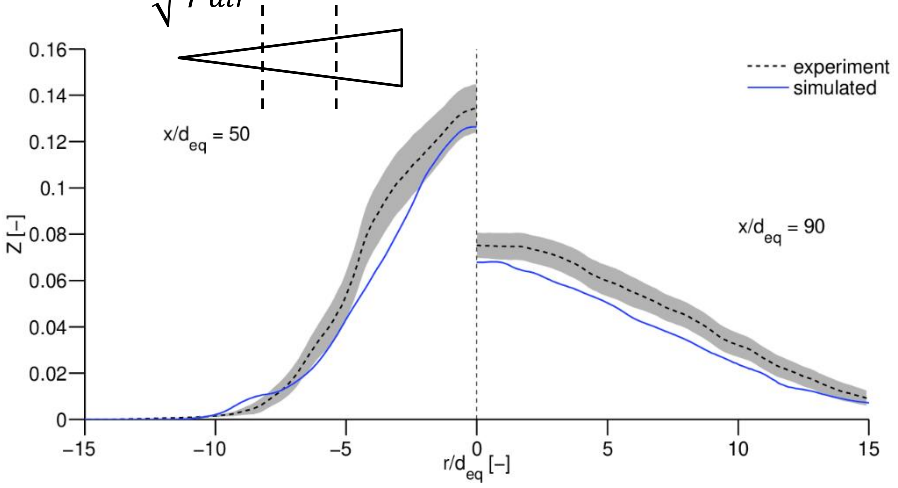
RANS → LES

- Spray mixing assessment
  - LES provides good averaged values and lower model constant impact on fluctuations





$$d_{eq} = d_0 \sqrt{\frac{\rho_{fuel}}{\rho_{air}}}$$

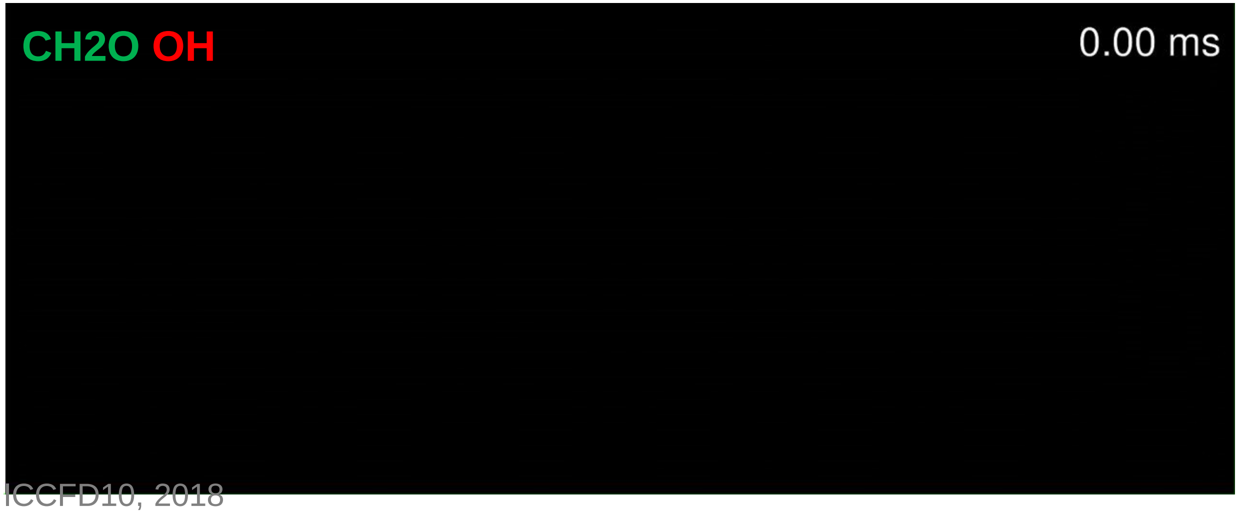


Desantes et al., ICCFD10, 2018

Combustion modelling

RANS → LES

- Spray flame

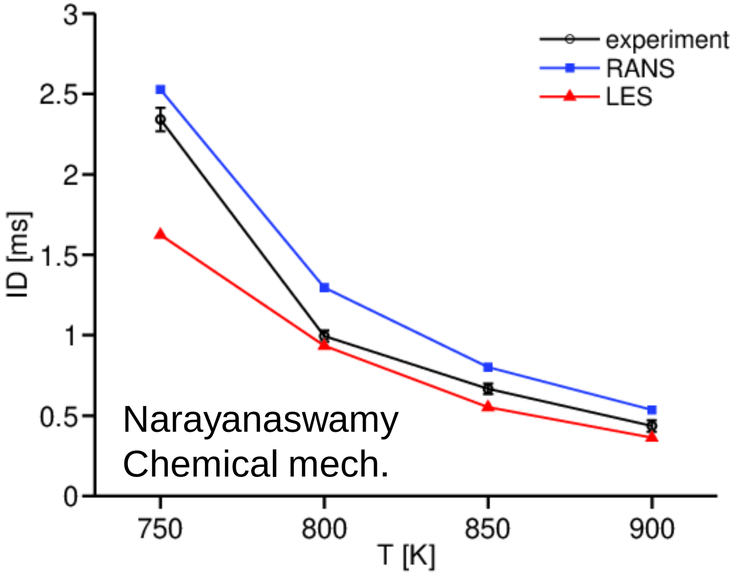


Desantes et al., ICCFD10, 2018

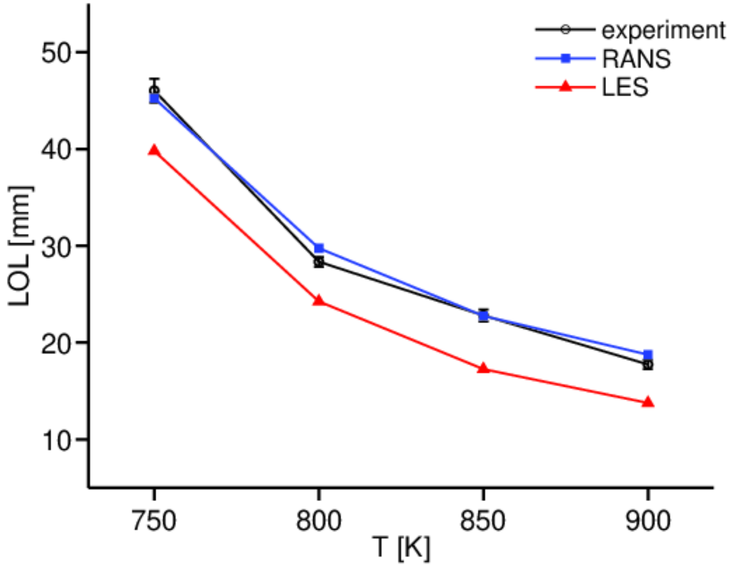
Combustion modelling

RANS → LES

- Global combustions indicators
  - ➢Both ID and LOL predictions are affected by turbulence modelling approach
    - – Improved ID for LES using detailed mechanism, but LOL underpredcition though trends are captured.



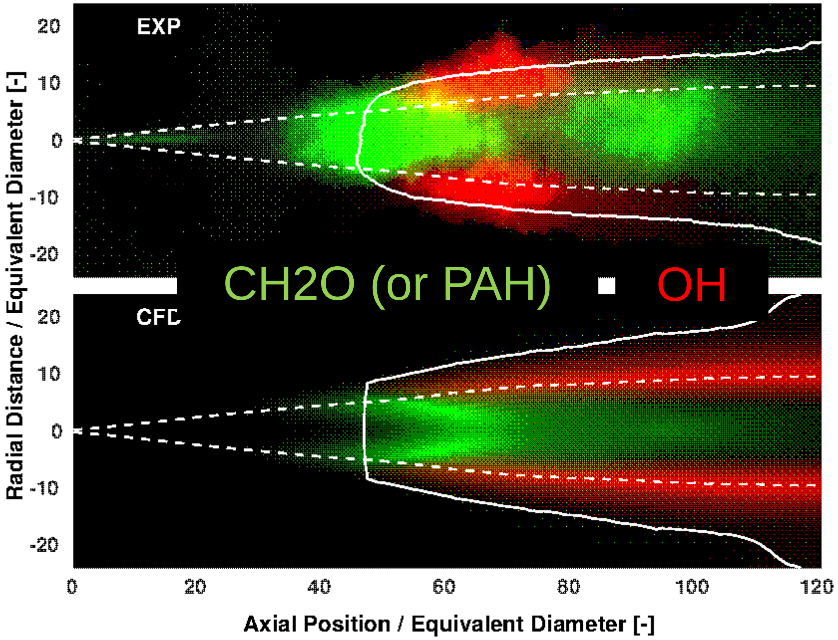
Narayanaswamy
Chemical mech.



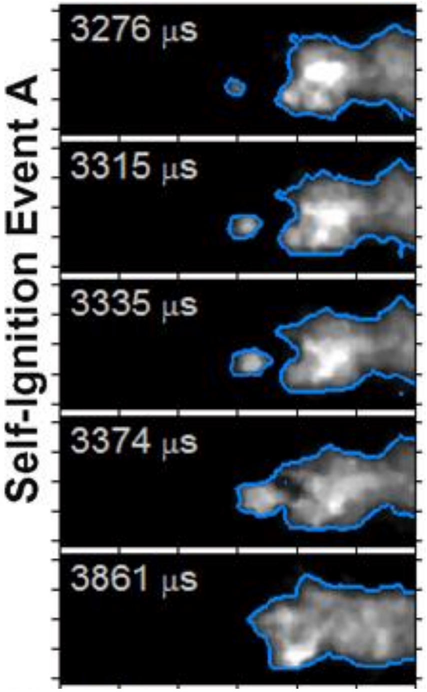
Combustion modelling

RANS → LES

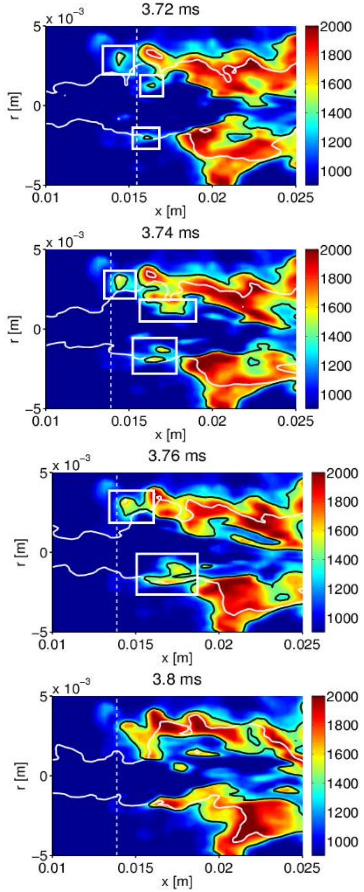
- Flame structure
  - ➢Both RANS and LES simulations produce meaningful results



➢LES is able to capture transient phenomena such as detached ignition kernels and LOL stabilization, observed in experiments.

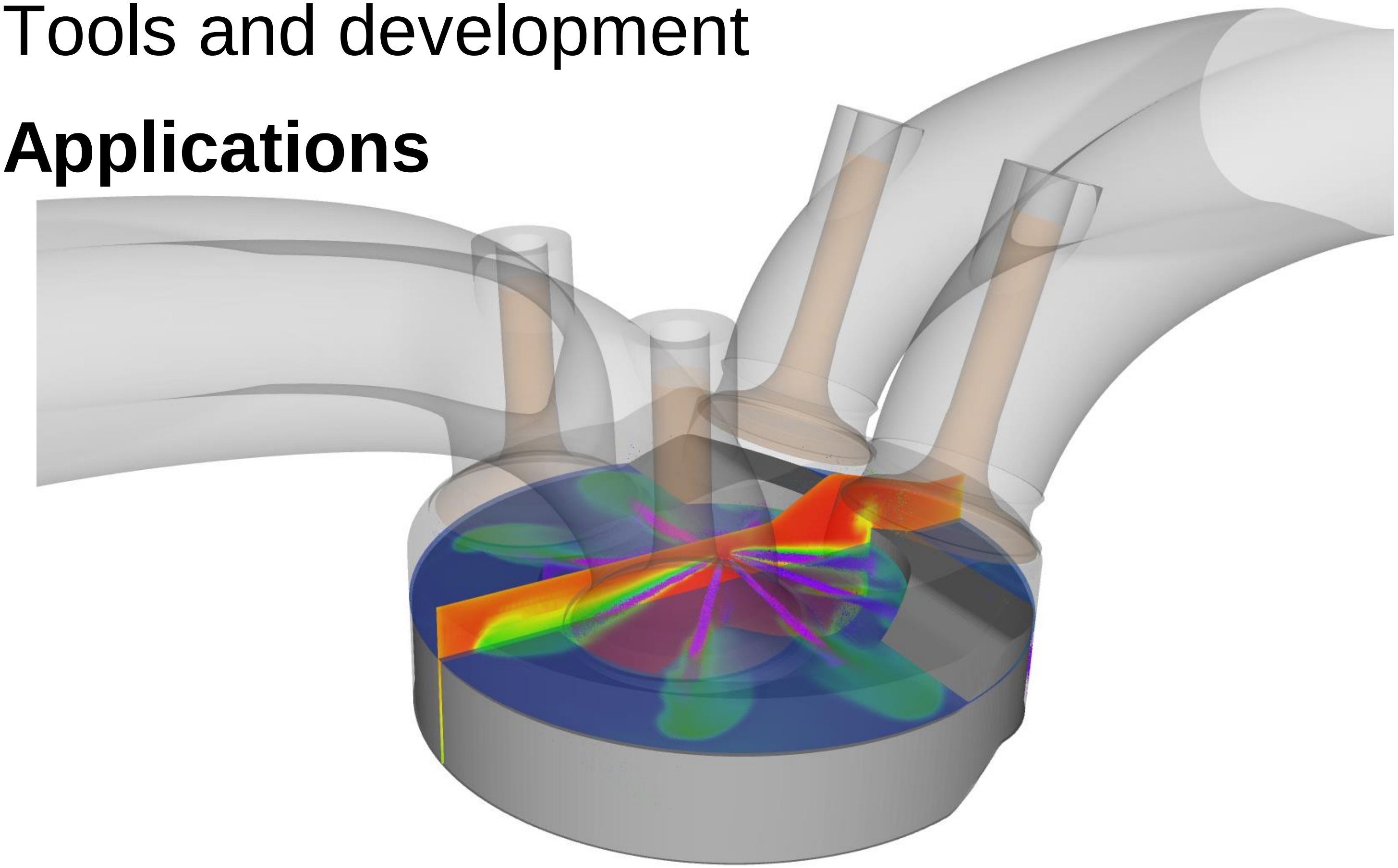


Pickett et al., PCI,32 (2009)



CONTENTS

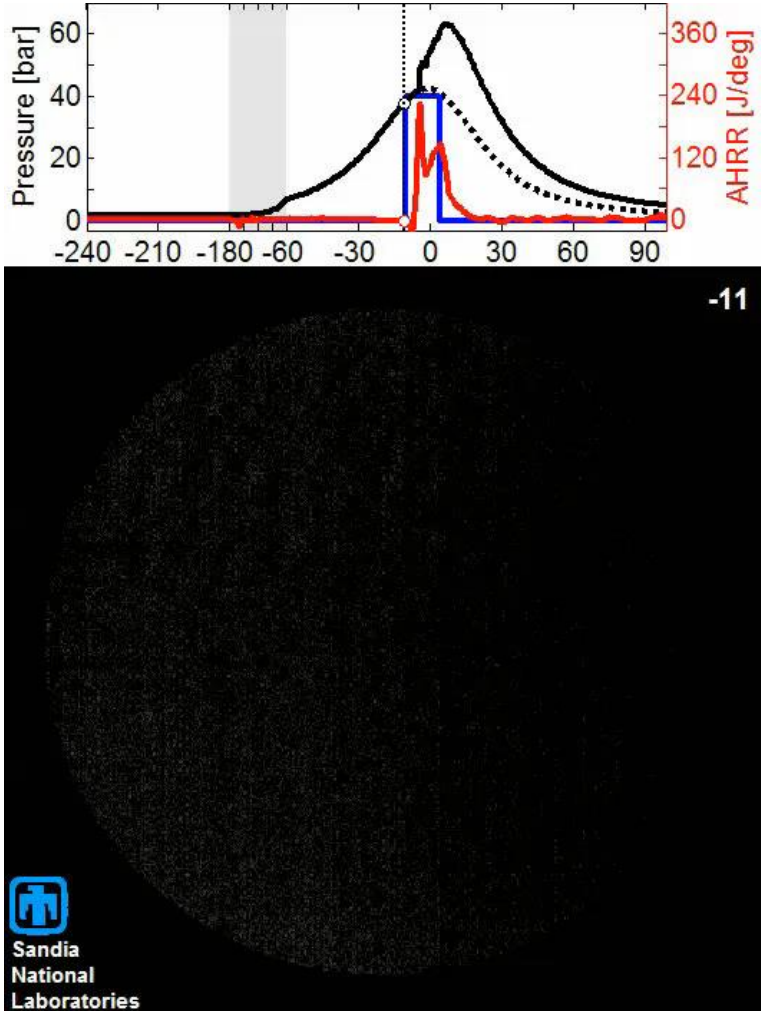
- Background and approach
- Tools and development
- **Applications**



APPLICATIONS

Framework

- **C**onvention **D**iesel **C**ombustion
  - Widely used due to high efficiency and reliability.
  - Difficult to simultaneously reduce fuel consumption and emissions (NOx-Soot trade-off) without complex after-treatment.
  - Alternative CI strategies (PPC,HCCI,…) still limited application due to ignition control issues.



APPLICATIONS

Framework

- Optimization strategies for CDC

Hardware

Comb. system geometry

- Compression ratio
- Piston bowl shape
- Injector spray angle

Settings

Air management

- Swirl
- Intake pressure
- Exhaust Gas Recirculation

Injection system

- Injection pressure
- Nozzle design
- Star of Injection

Others

Alternative fuels

- BioDiesel
- DME

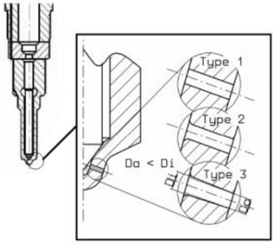
After-treatment

- Diesel Particle Filter
- Lean NOx Trap
- Selective Catalytic Reduction
- Three Way Catalyst

APPLICATIONS

Micro-orifice nozzles and high injection pressure

- Objective:
  - Evaluating the potential of integrating the micro-orifice nozzle technology together with a high injection pressure system for passenger car diesel engine applications



Injector Nozzle	Do [µm]	Nominal Flow [cm3/min]	Inj Pressure [bar]			
			Part load 1	Part load 2	Full Load1	Full Load 2
Nozzle A	REF	REF	620	1380	1980	2000
Nozzle B	-5 µm	REF-10%	737	1644	2360	2384
Nozzle C	-10 µm	REF-20%	973	2177	3128	3160

↓Øout

↑IP

In combination with

Benajes et al.,FEV Diesel Powertrains 3.0 (2017)

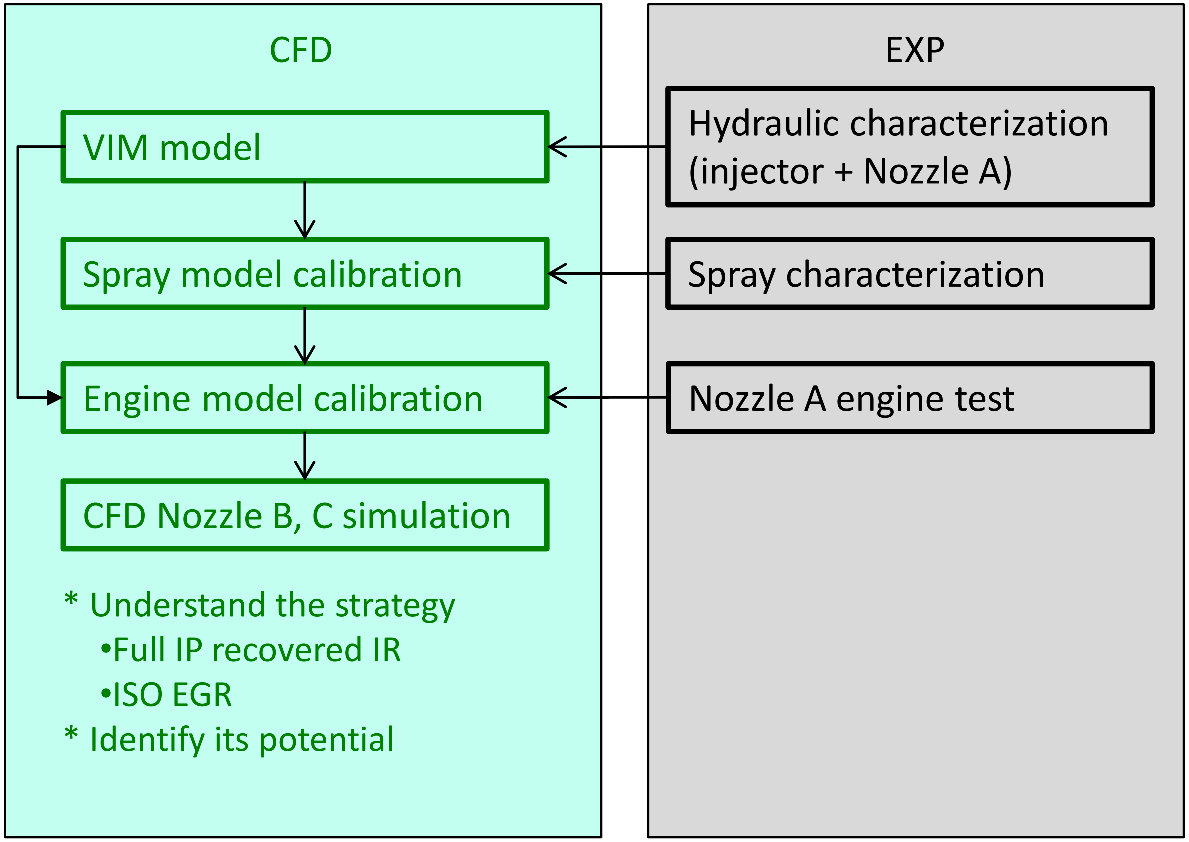
Tools & Methodology

CFD software: **CONVERGE v2.3**

Model approach: **DDM**
Injection model: Blob
Atomization model: **KH-RT**

Fuel: Diesel surrogate
- N-C10H22 (71%)
- C11H22O2-MD (23%)
- A2CH3 (6%)

Other submodels
- Drag: dynamic drop
- Evaporation: Frosling
- Collision model: O'Rourke



CFD

VIM model

Spray model calibration

Engine model calibration

CFD Nozzle B, C simulation

* Understand the strategy
  •Full IP recovered IR
  •ISO EGR
* Identify its potential

EXP

Hydraulic characterization (injector + Nozzle A)

Spray characterization

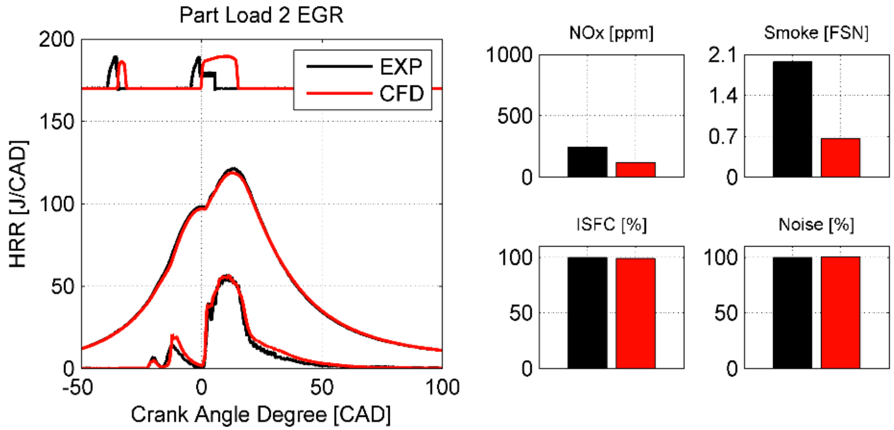
Nozzle A engine test

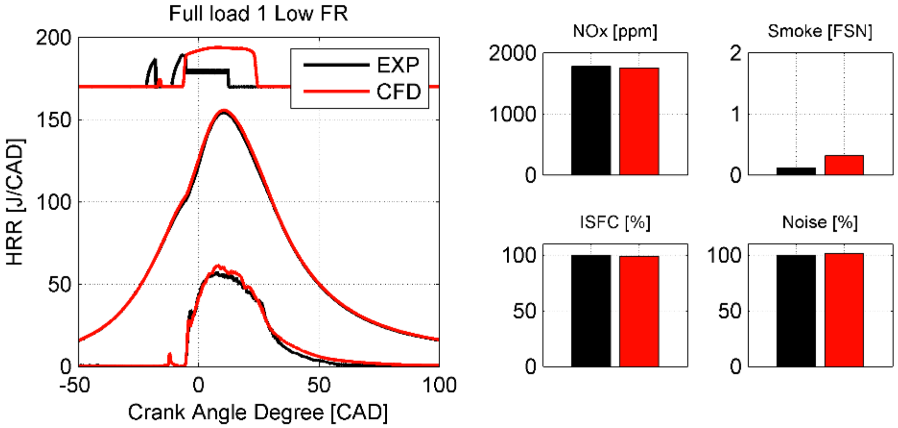
Benajes et al.,FEV Diesel Powertrains 3.0 (2017)

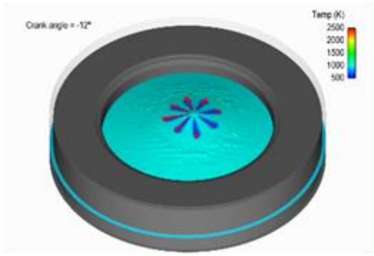
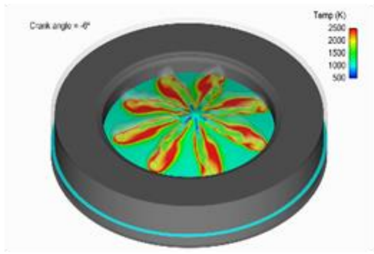
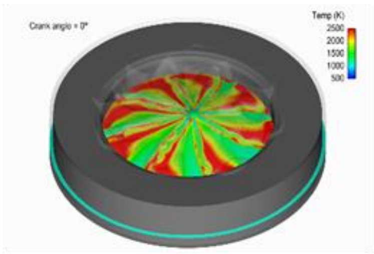
Micro-oriffices & high inj. pressure

Engine model calibration & assessment

- Part- and full-load





	Nozzle A
-12 CAD	
-6 CAD	
0 CAD	

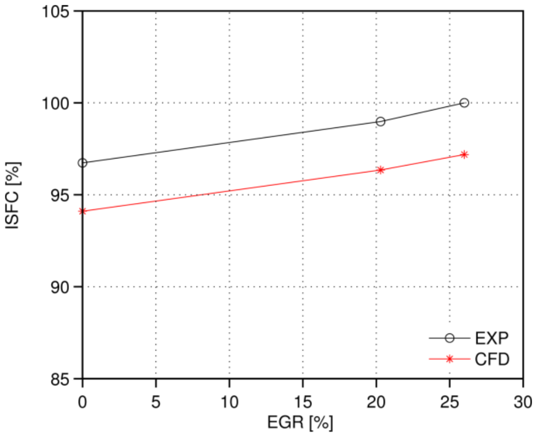
Benajes et al.,FEV Diesel Powertrains 3.0 (2017)

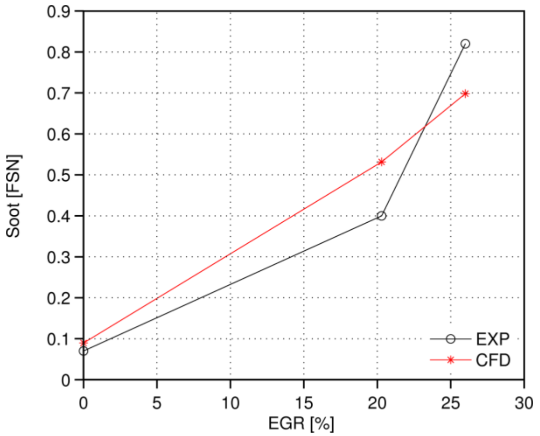
Micro-oriffices & high inj. pressure

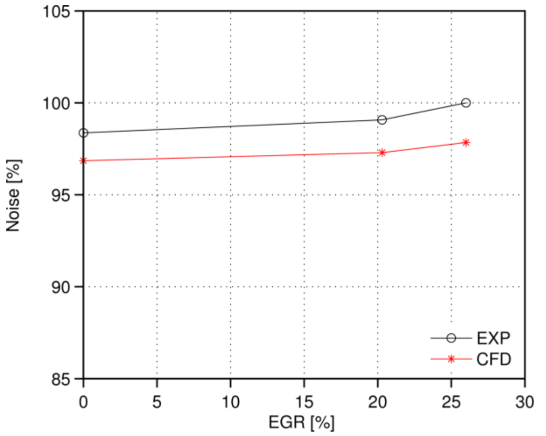
Engine model calibration & assessment

- Part- and full-load

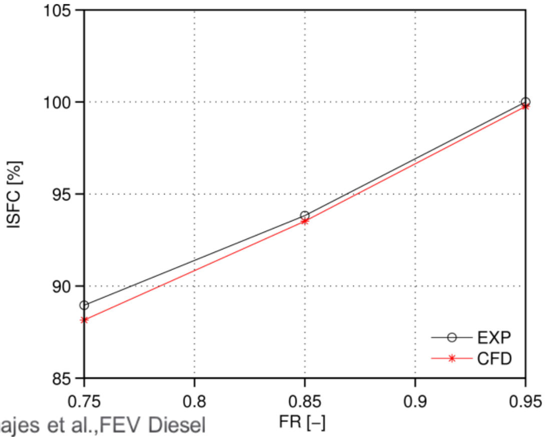
Part load

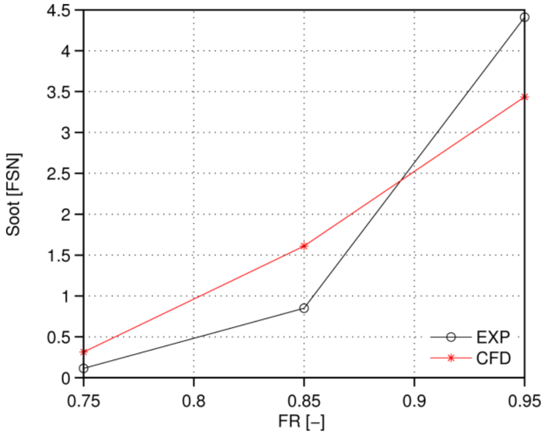


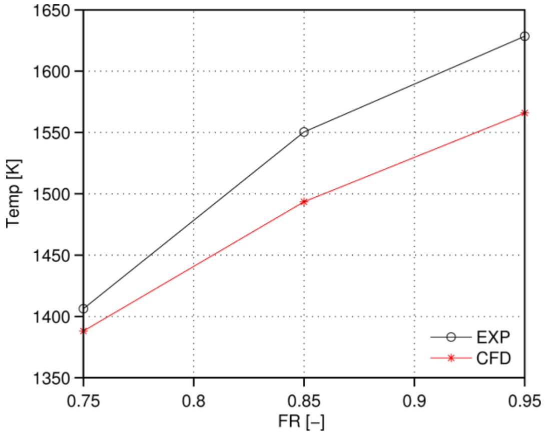




Full load





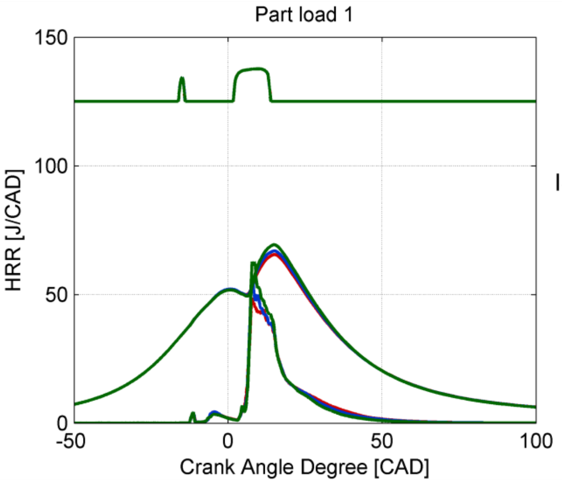


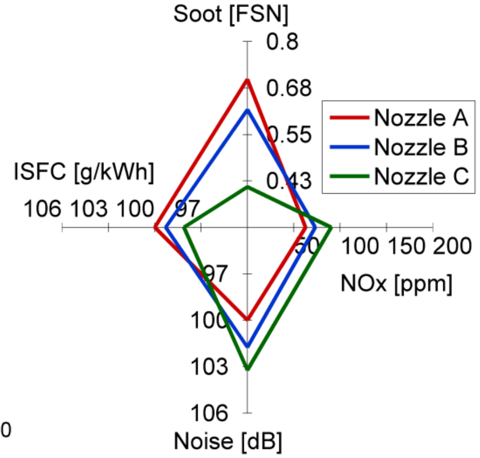
Benajes et al.,FEV Diesel
Powertrains 3.0 (2017)

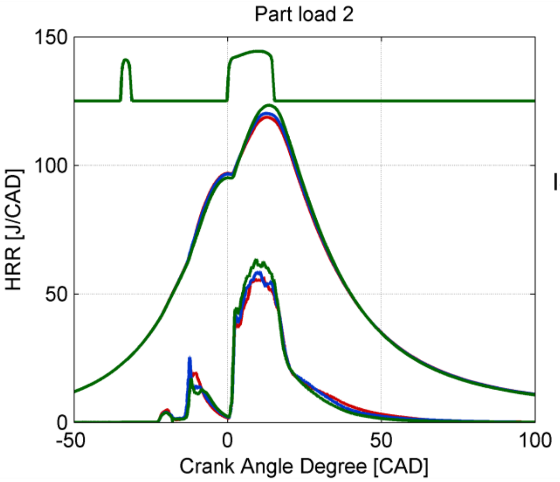
Micro-oriffices & high inj. pressure

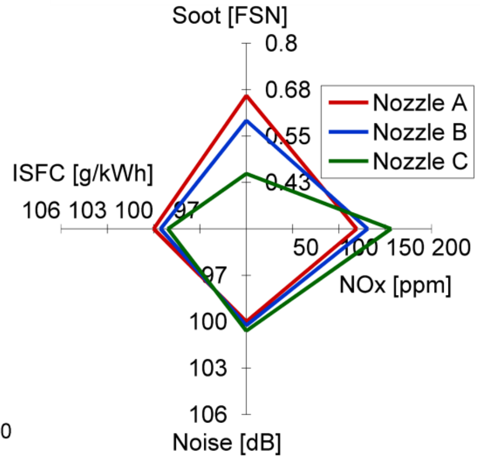
Model application

- Part-load
  - Enhance the mixing process
    - Positive impact on combustion duration (ISFC) and soot emission
    - Negative impact on NOx
  - Promote the premixed combustion stage
    - Negative impact on combustion noise particularly at low loads & low speeds









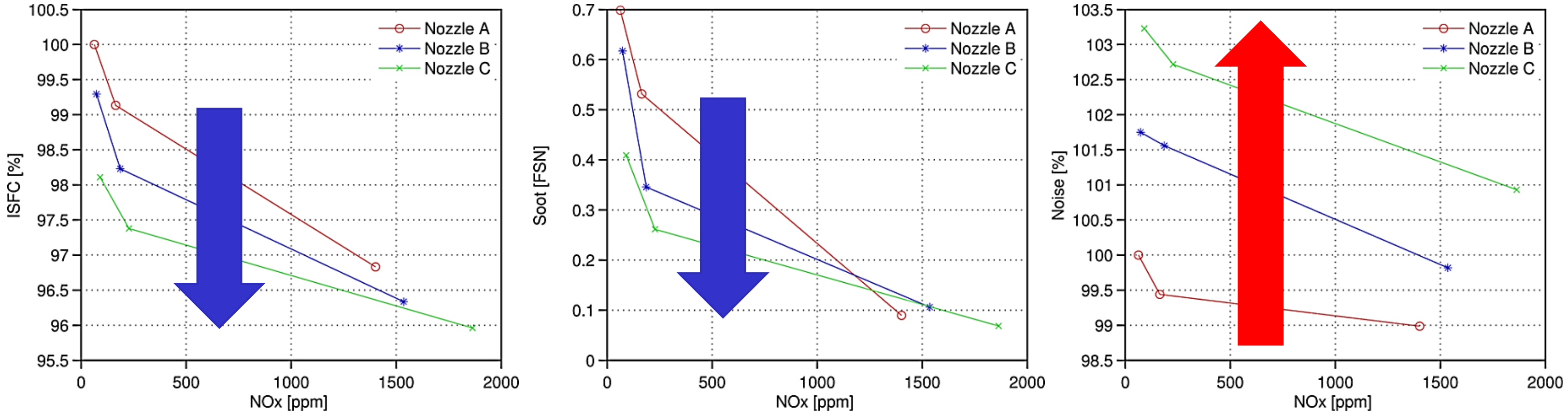
Benajes et al.,FEV Diesel Powertrains 3.0 (2017)

Micro-oriffices & high inj. pressure

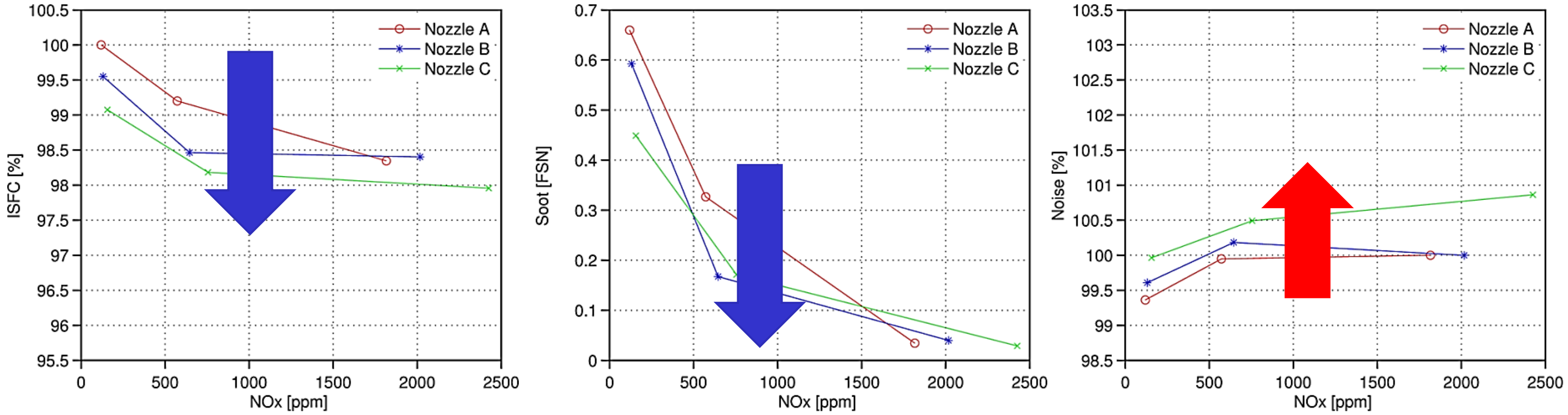
Model application

- Part-load
  - ➢Better NOx-soot & NOx- ISFC trade-offs

Part load 1



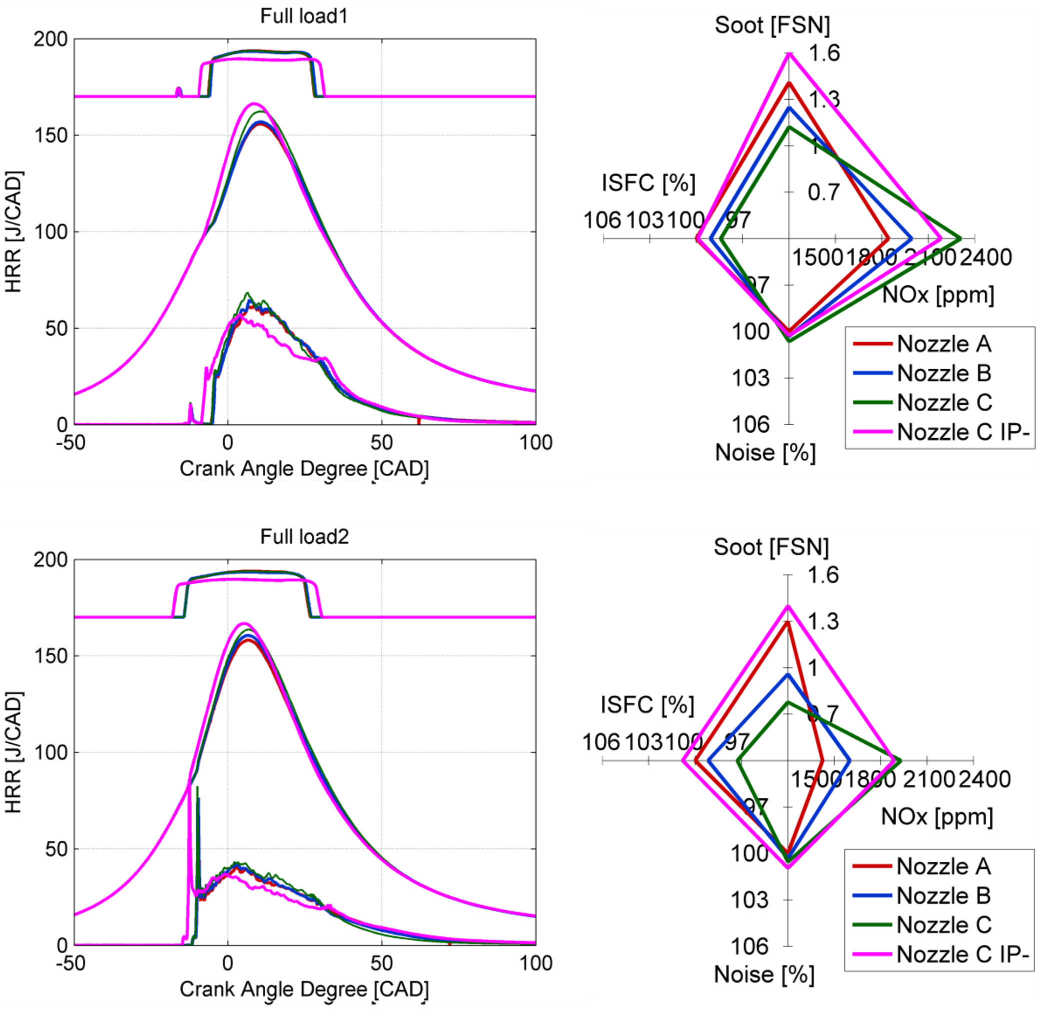
Part load 2



Micro-oriffices & high inj. pressure

Model application

- Full-load
  - ➢Enhance the mixing process, but the impact is slightly noticeable in HRR
    - – Positive impact on combustion duration (ISFC) and soot emission
    - – Negative impact on NOx
    - – Noise not critical
  - ➢If Nozzle C is evaluated limiting the injection pressure
    - – All benefits are LOST and this configuration is clearly the worst



Benajes et al.,FEV Diesel Powertrains 3.0 (2017)

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

APPLICATIONS

motores térmicos

Framework

- Optimization strategies for CDC

Hardware

Comb. system geometry
- Compression ratio
- Piston bowl shape
- Injector spray angle

Settings

Air management
- Swirl
- Intake pressure
- Exhaust Gas Recirculation

Injection system
- Injection pressure
- Nozzle design
- Star of Injection

Others

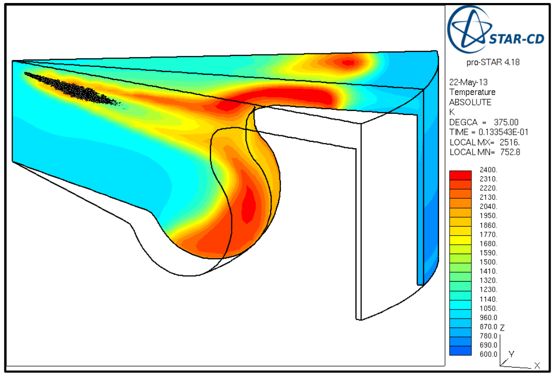
Alternative fuels
- BioDiesel
- DME

After-treatment
- Diesel Particle Filter
- Lean NOx Trap
- Selective Catalytic Reduction
- Three Way Catalyst

APPLICATIONS

CDC system optimization

- Objective:
  - Defining the combustion chamber geometry & key engine settings focusing on engine efficiency while keeping emission levels for a medium-duty diesel engine
- Tools

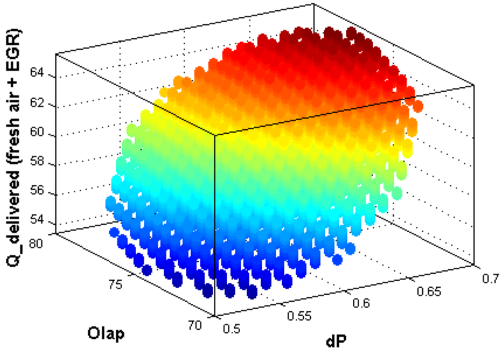


STARCD CFD code

- ✓ Combustion model → ECFM-3z
- ✓ Spray atomization and breakup→ Huh-Gosman and Reitz-Diwakar
- ✓ Turbulence model → RNG k-ε

+

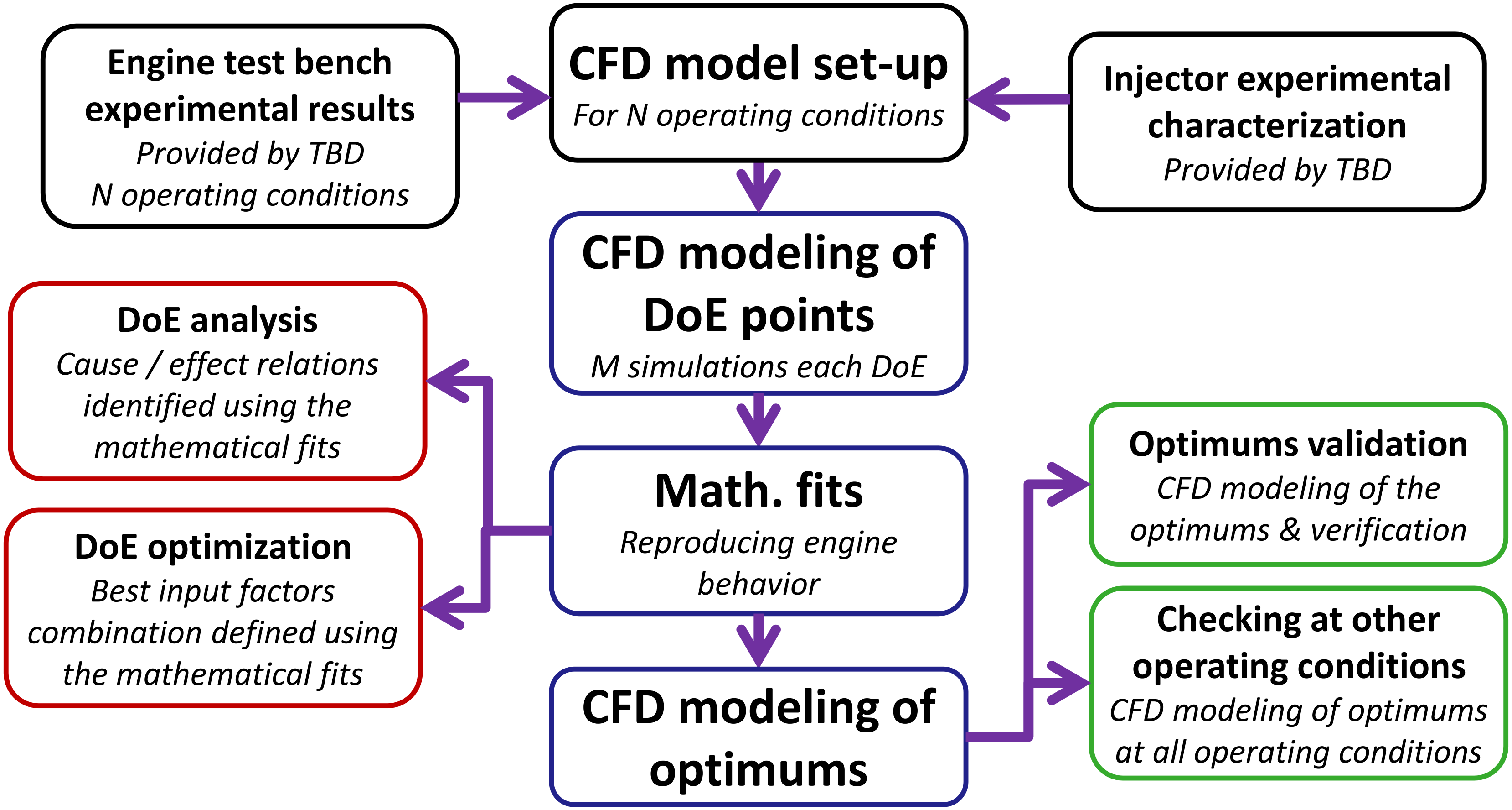
Response Surface Methods



CDC system optimization

Methodology

- Based on Design Of Experiments:



Engine test bench experimental results
Provided by TBD
N operating conditions

CFD model set-up
For N operating conditions

Injector experimental characterization
Provided by TBD

CFD modeling of DoE points
M simulations each DoE

DoE analysis
Cause / effect relations identified using the mathematical fits

DoE optimization
Best input factors combination defined using the mathematical fits

Math. fits
Reproducing engine behavior

Optimums validation
CFD modeling of the optimums & verification

CFD modeling of optimums

Checking at other operating conditions
CFD modeling of optimums at all operating conditions

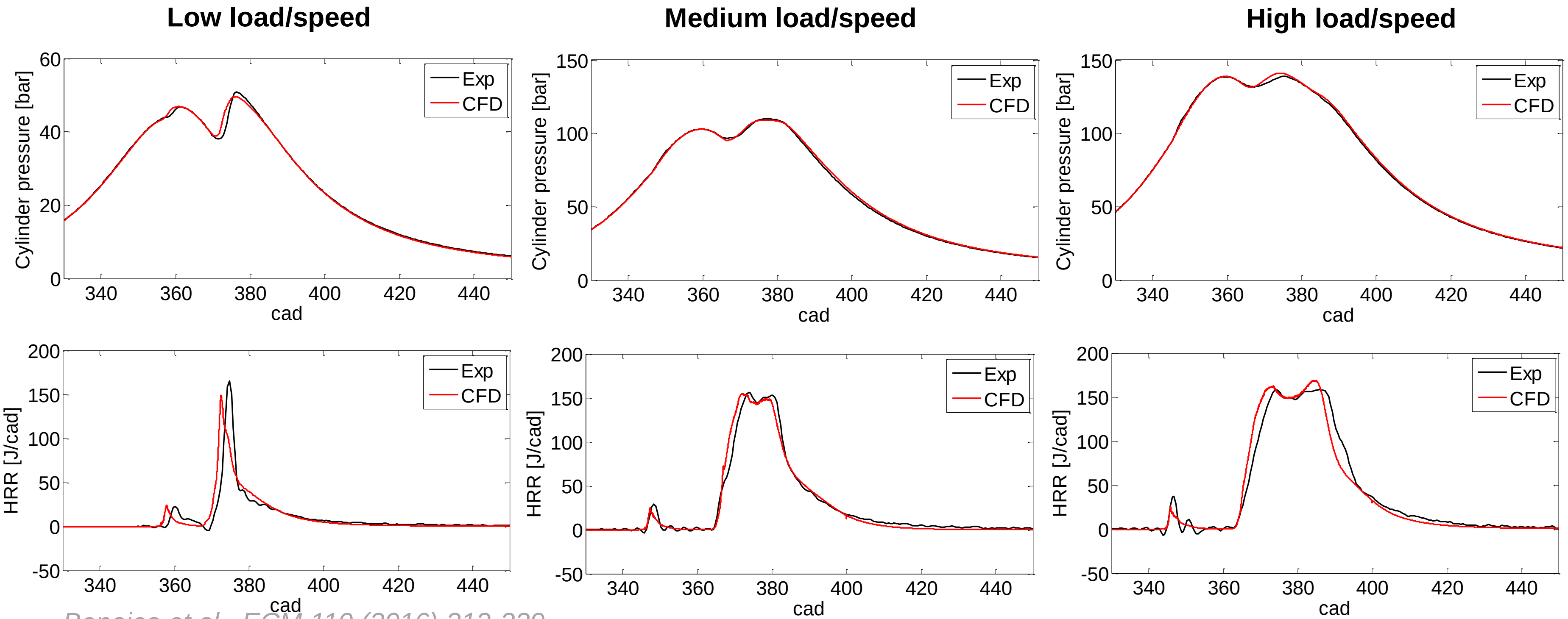
Benajes et al., ECM 110 (2016) 212-229

CDC system optimization

CFD model set-up

- Overall fair agreement wit exp.
    - ➢NOx overprediction at high load/speed, but the quality of CFD was considered suitable

Case		ISFC [g/kWh]	IMEP [bar]	NOx [g/h]	Soot [FSN]
1200 rpm	Exp	201.5	6.5	28.6	0.29
	CFD	203.1	6.2	27.6	0.24
1600 rpm	Exp	188.8	17.7	213.3	0.078
	CFD	186.3	18.3	218.6	0.08
1800 rpm	Exp	194.3	24.7	249.16	0.4
	CFD	193.7	24.96	368.4	0.42

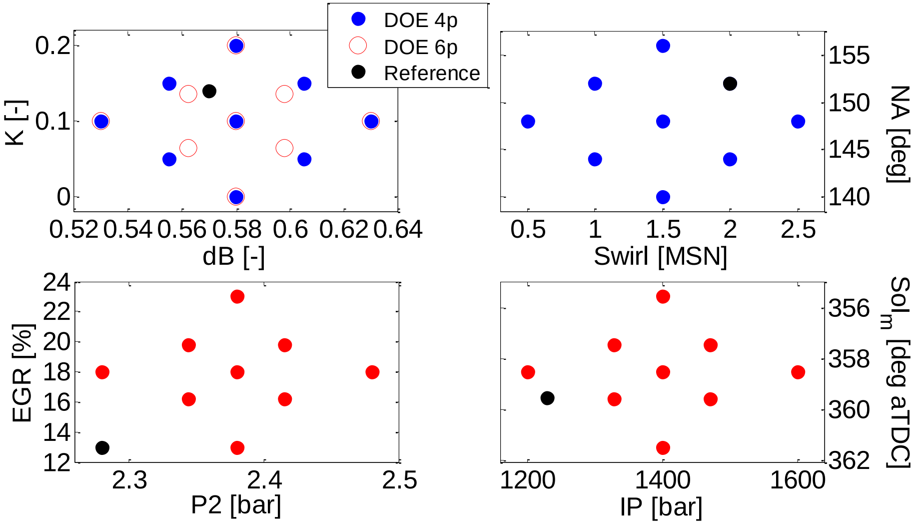


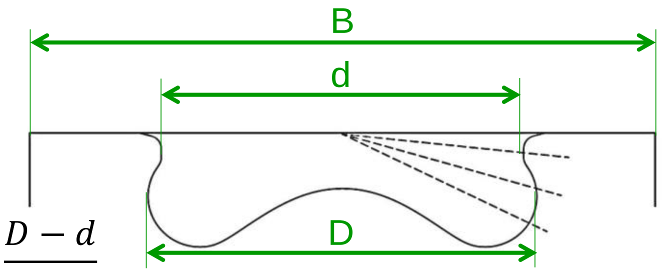
Benajes et al., ECM 110 (2016) 212-229

CDC system optimization

DoE - RSM

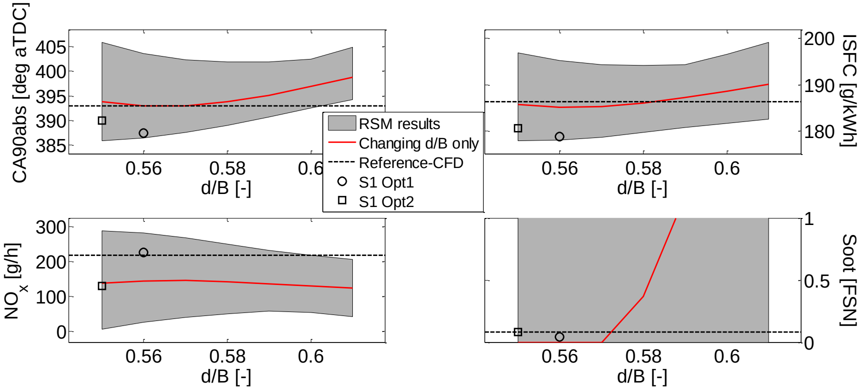
DoE definition

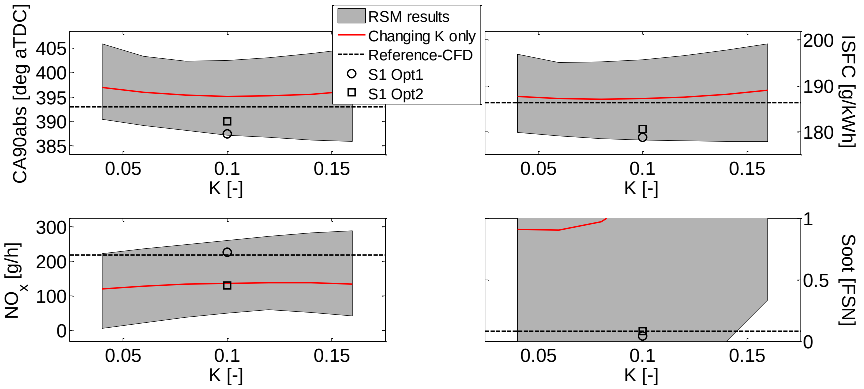




$$K = \frac{D - d}{B - d}$$

Input factor effect analysis



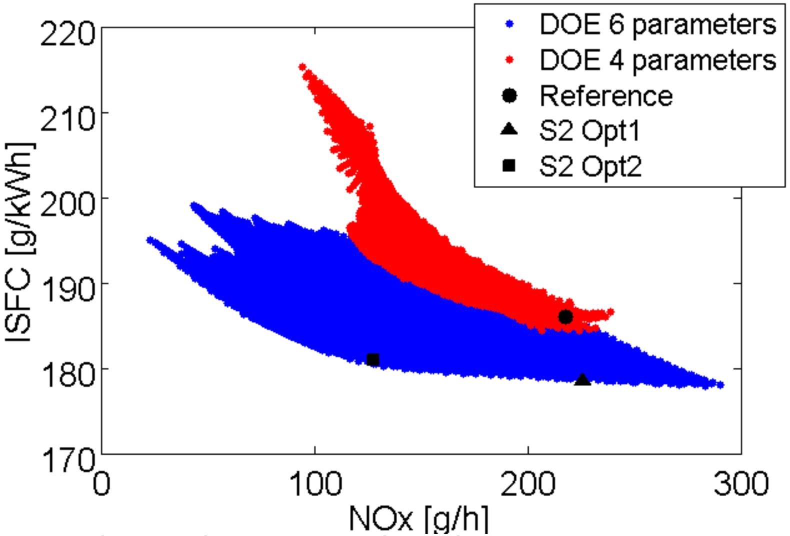


Benajes et al., ECM 110 (2016) 212-229

CDC system optimization

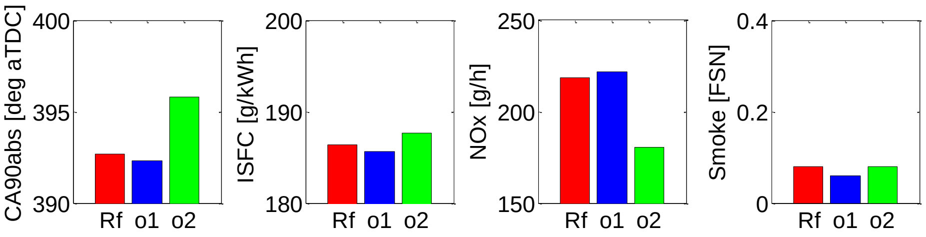
DoE - RSM: Optimum selection and validation

- 2 optimum configuration: min ISFC (o1) and min pollutants (o2)
  - CFD validation of RSM results
- With RSM method it is easy to analyze trade-off between parameters
  - More inputs (settings) → more potential of the combustion system → ISFC-NO_X trade-off still present
  - Geometry, air management and injection settings are not able to break the trade-offs

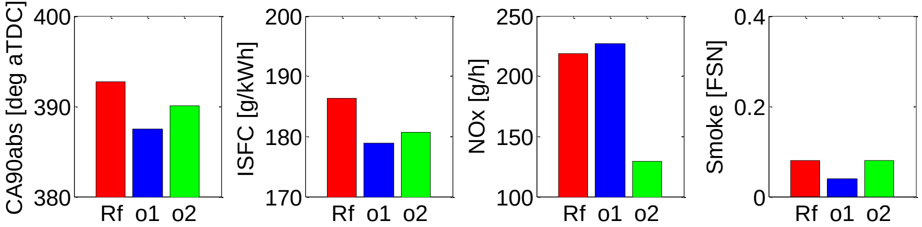


Benajes et al., ECM 110 (2016) 212-229

CFD validation DoE 4 p



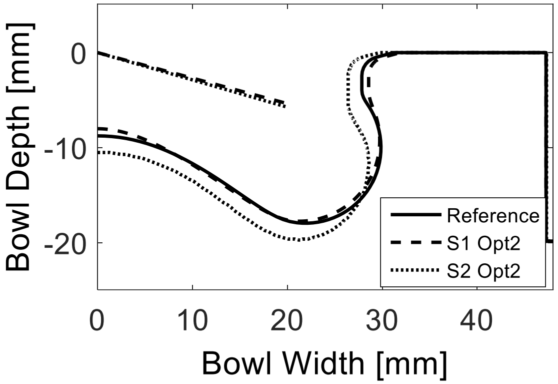
CFD validation DoE 6p

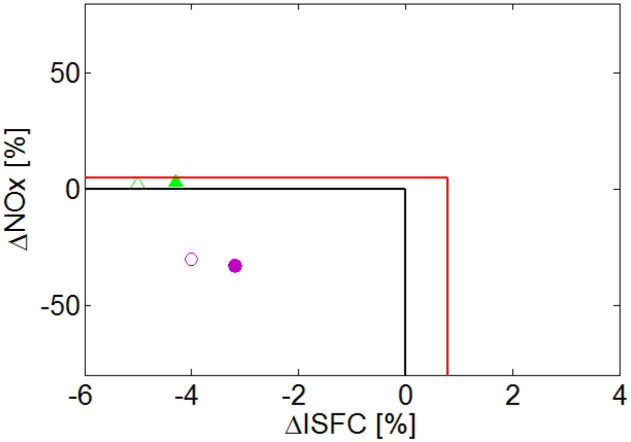


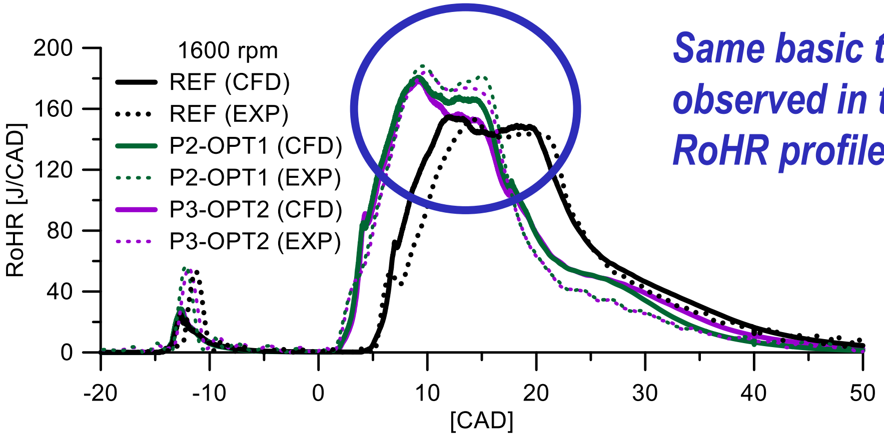
CDC system optimization

Experimental assessment

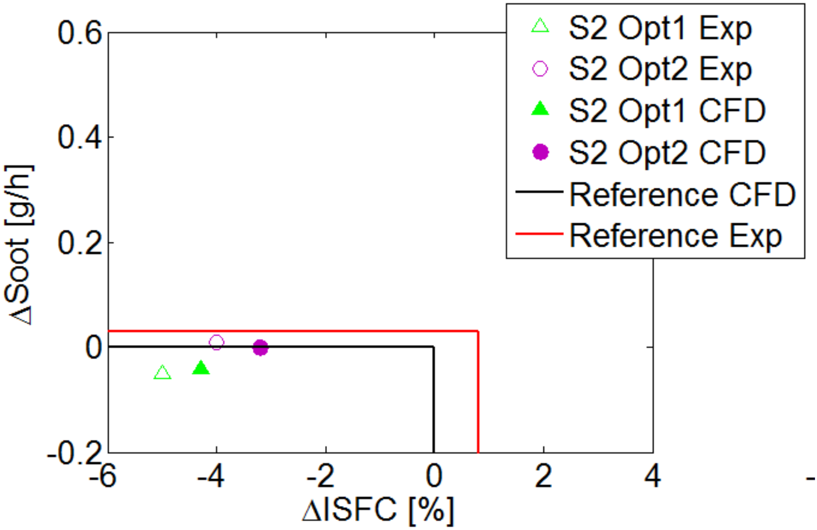
- SCE test using machined pistons according CFD results







Same basic trends observed in the RoHR profiles



Benajes et al., ECM 110 (2016) 212-229

APPLICATIONS

Framework

- Optimization strategies for CDC

Hardware

Comb. system geometry

- Compression ratio
- Piston bowl shape
- Injector spray angle

Others

Alternative fuels

- BioDiesel
- DME

After-treatment

- Diesel Particle Filter
- Lean NOx Trap
- Selective Catalytic Reduction
- Three Way Catalyst

Settings

Air management

- Swirl
- Intake pressure
- Exhaust Gas Recirculation

Injection system

- Injection pressure
- Nozzle design
- Star of Injection

APPLICATIONS

Alternative fuel combustion system

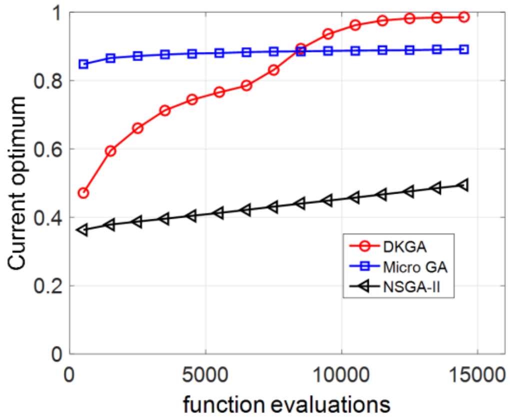
- Background: Main characteristics of the DME fuel
  - Easy to produce from different primary sources
  - Similar combustion properties than diesel fuel
    - Slightly higher cetane number (60), shorter ignition delay
    - Lower heating value (28.8 KJ/kg) but also lower stoichiometric air/fuel ratio (9)
  - Its non-sooting nature opens the possibility of optimization paths
  - It is gaseous in ambient conditions, liquefied by compressing it at 6 bar

- Objective
  - Evaluating in detail the potential of the CDC process using a synthetic fuel with better suited properties than the conventional diesel fuel → Keeping **ALL** the benefits of the CDC improving NOx/soot emissions and efficiency

Alternative fuel combustion system

Methodology & Tools

- Unexplored behavior requires complete combustion redefinition (hardware + settings)→Evolutionary methods better suited for large number of parameter optimization
- Genetic Algorithm
  - Mimics the mechanism of natural selection and evolution: Selection, Crossover and Mutation
  - Very effective with large number of inputs and also when the problem includes non-linear trends
  - Difficult to avoid local optimums
- GA selection →DK-GA (developed at the UWM)
  - Outperformed the other evaluated well-known GA
  - It finds the global optimum
  - It finds it after reasonable number of evaluations



Alternative fuel combustion system

Methodology & Tools

Multicylinder engine

- ✓ 6-cyl TC HDDI engine – 15 liters (2.5 l/cyl)
- ✓ SOI sweep for validation at the target OC

Key characteristics	
Bore [mm]	137
Stroke [mm]	171
Comp. Ratio [-]	17:1
Injection system	CR
Nozzle holes [-]	6
Hole diam. [mm]	0.214
Spray angle [deg]	130

Operating condition	
Speed [rpm]	1800
Fuel mass [Kg/s]	2.2e-2
IMEP [bar]	18
EGR [%]	25
Intake temp. [K]	333
Boost press. [bar]	3.1
MSN [-]	0.7

CFD platform → KIVA 3v

- ✓ Turbulence model → RNG k-ε
- ✓ Spray model → DDM approach
  - Improved grid dependency: Gas-Jet model
  - Atomization & break-up: KH-RT
  - Improved O'Rourke collision model
- ✓ Combustion model → DIC (SpeedCHEM)
- ✓ DME + NOx chem. model → 29 spec. + 66 reac.
- ✓ Soot model → *Not required*
- ✓ Cores per simulation → 1 core
- ✓ Number of cells → ~35000

} **~20 h/sim**

REMARK: Around 25K sim/optimization

Benajes et al., SAE WCX 2018

Alternative fuel combustion system

Results and discussion

- Optimization parameters and setup

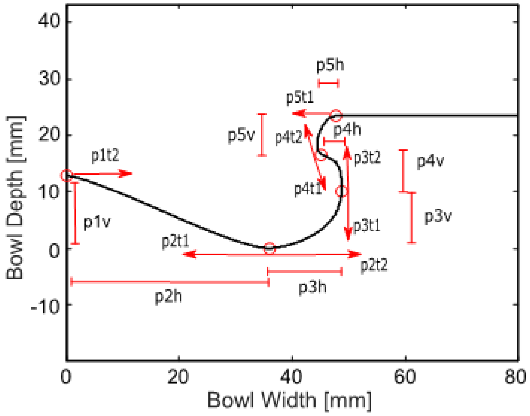
Input parameters

	G1-G4	G5	G6-G15	Dnoz	NA	SOI	IP	EGR	PIVC	swirl
	[-]	[-]	[-]	[µm]	[deg]	[cad]	[bar]	[%]	[bar]	[-]
Min.	0.01	-0.99	0.01	200	45	-35	500	2	2.5	0.1
Max	0.99	0.99	0.99	350	90	5	2600	62	4	3
	Geometry			Injection			Air management			

Restrictions

NOx	PP	maxPRR
[g/kWh]	[bar]	[bar/deg]
0.268	200	15

Geometry parameters



KEY ASPECTS

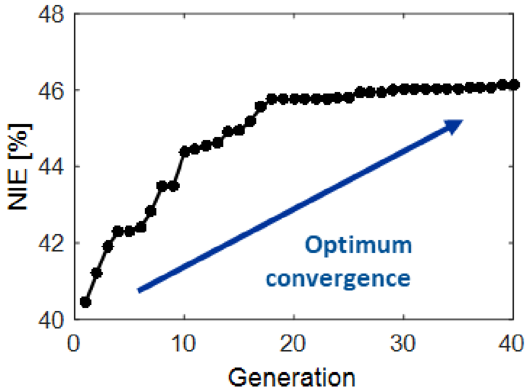
- ✓ Extended number of input parameters → All key inputs are included → 15 geometry parameters
- ✓ Wide ranges for the selected input parameters
- ✓ Objective function is optimized → high PP, NOx or maxPRR penalizes the objective function output

Benajes et al., SAE WCX 2018

Alternative fuel combustion system

Results and discussion

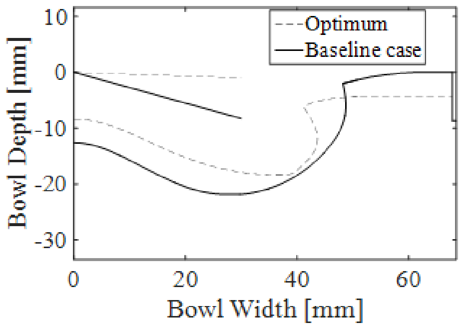
- Optimum performance description



KEY ASPECTS

- ✓ Geometry changed significantly (keeping CR)→ more reentrant, narrower and less depth piston
- ✓ Process converged to an optimum with a 3.3% NIE improvement reducing drastically NOx
- ✓ All restrictions are satisfied by the optimum

Optimum vs baseline geometry



Optimum settings

	Dnoz [μm]	NA [deg]	SOI [cad]	IP [bar]	EGR [%]	PIVC [bar]	swirl [-]
Baseline DME	300	65	-13	1800	25	3.1	0.7
Opt. Case	300	86.7	-8.19	2500	40	3.25	2.82

Optimum vs baseline outputs

	NIE [%]	maxPRR [bar/deg]	NOx [g/kWh]	PP [bar]
Baseline DME	42.8	6.1	2.81	193.9
Opt. Case	46.1	6.6	0.26	199.4

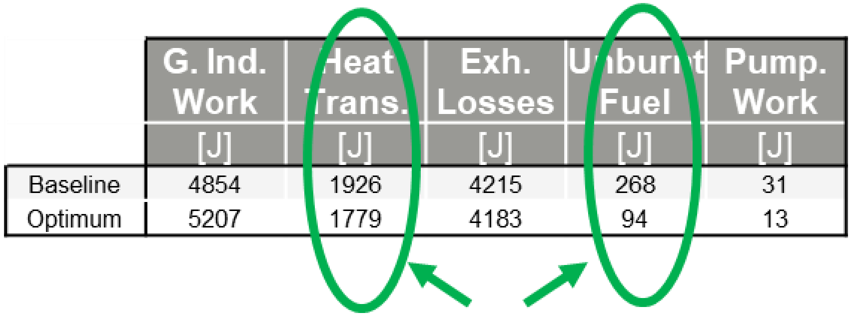
Benajes et al., SAE WCX 2018

Alternative fuel combustion system

Results and discussion

- Optimum performance description

Energy balance

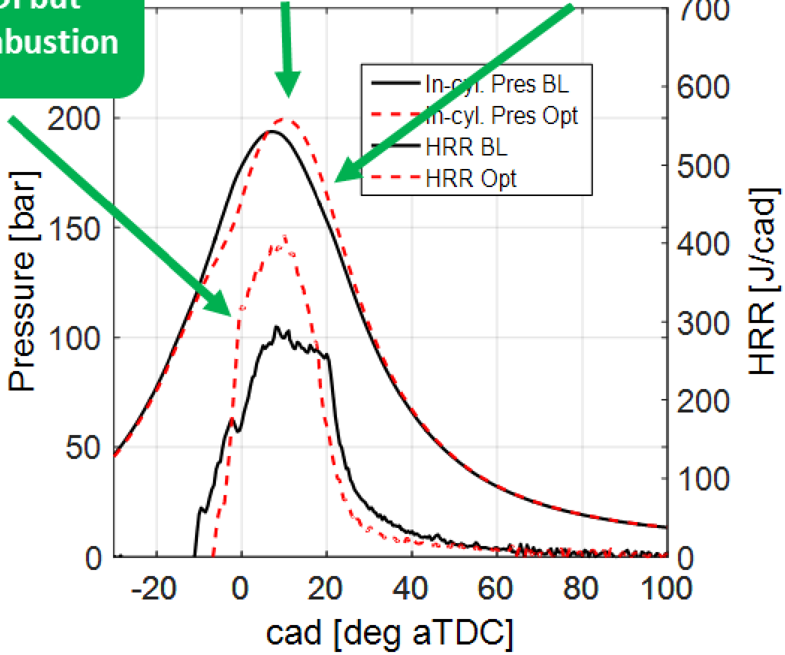


	G. Ind. Work [J]	Heat Trans. [J]	Exh. Losses [J]	Unburnt Fuel [J]	Pump. Work [J]
Baseline	4854	1926	4215	268	31
Optimum	5207	1779	4183	94	13

Main differences

Later SOI but faster combustion

Higher NIE



KEY ASPECTS

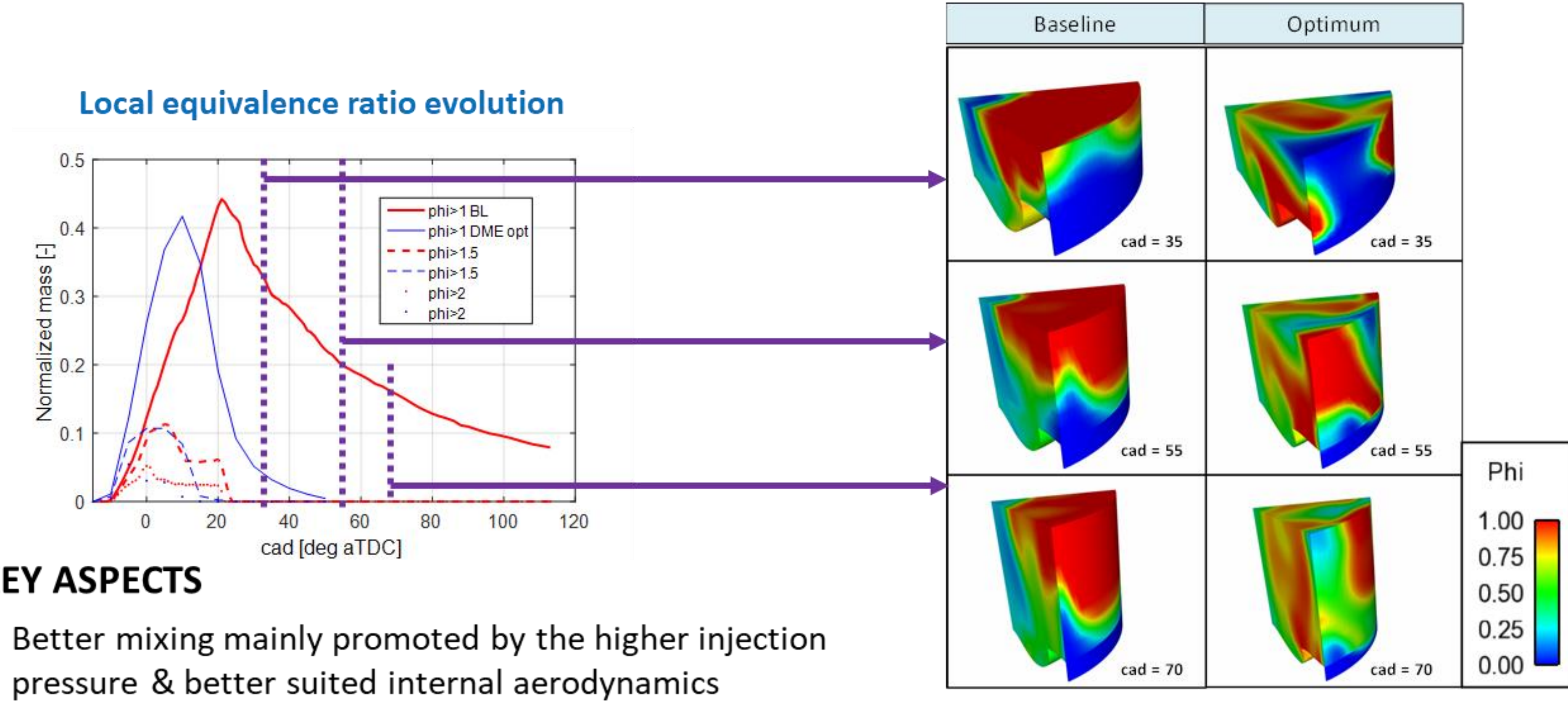
- ✓ Reduced HT → Optimum bowl geometry decreases piston surface area by 20%
- ✓ Better mixing → Faster combustion & higher combustion efficiency (less unburnt HC emissions)

Benajes et al., SAE WCX 2018

Alternative fuel combustion system

Results and discussion

- Optimum performance description



KEY ASPECTS

- ✓ Better mixing mainly promoted by the higher injection pressure & better suited internal aerodynamics

Benajes et al., SAE WCX 2018

Results and discussion

- Optimization path analysis

Reduces HT increasing GIE

Worsens spray-to-spray interaction decreasing GIE

Improves mixing and then increases GIE (low effect)

Improves mixing and then increases GIE (high effect)

NOx control but PIVC limited by pumping losses, GIE decreases

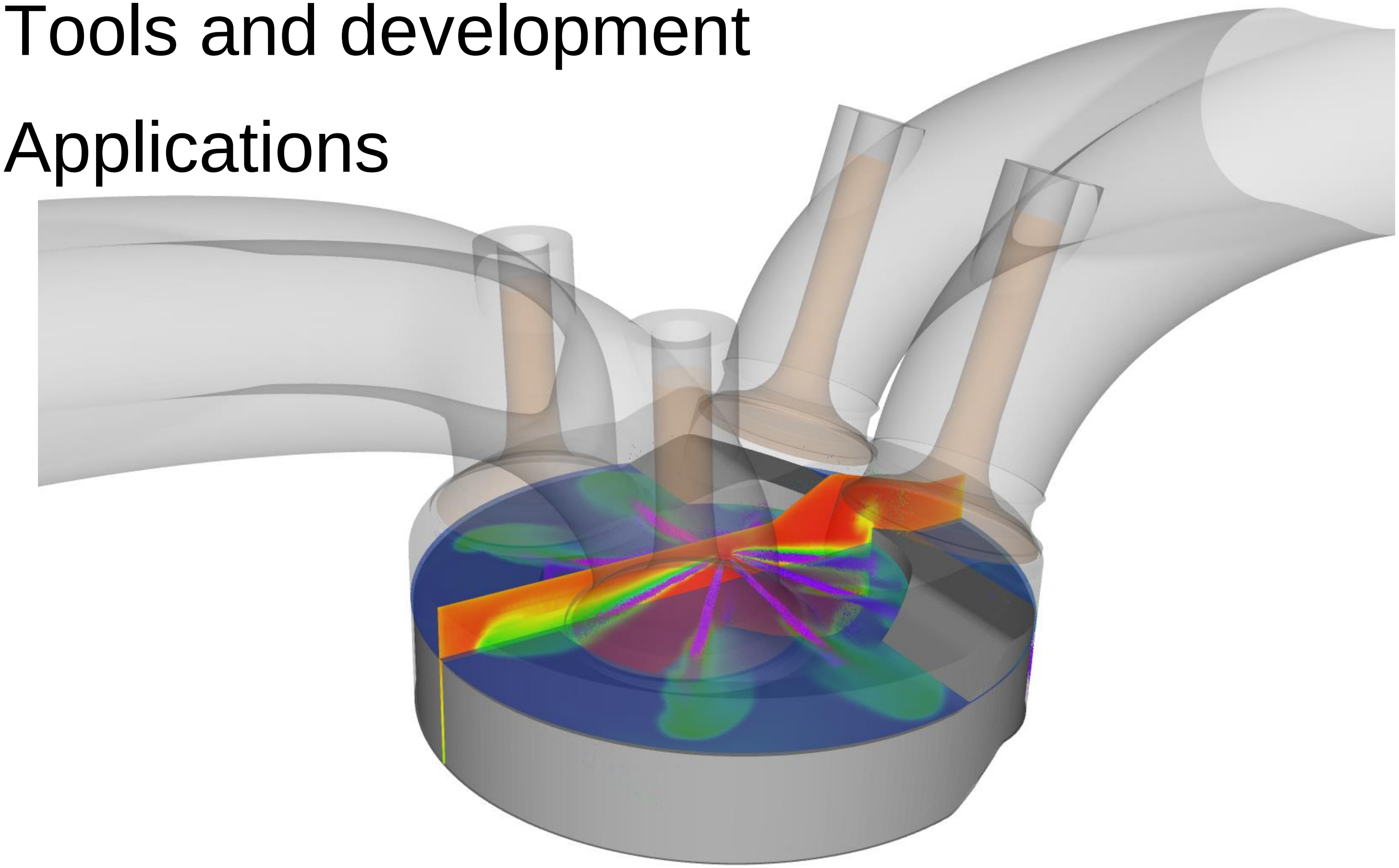
Further improves GIE until reaching the PP limit

	Baseline	Add Piston	Add Swirl	Add Injector	Add IP	Add EGR/PIVC	Add SOI
SOI [deg aTDC]	-13	-13	-13	-13	-13	-13	-8.19
Swirl Ratio [-]	0.7	0.7	2.82	2.82	2.82	2.82	2.82
EGR [%]	25	25	25	25	25	40	40
PIVC [bar]	3.1	3.1	3.1	3.1	3.1	3.25	3.25
Nozzle Diameter [µm]	300	300	300	300	300	300	300
Injection Pressure [bar]	1800	1800	1800	1800	2500	2500	2500
Injector Geometry [deg]	65	65	65	86.7	86.7	86.7	86.7
Piston	Baseline	Optimum	Optimum	Optimum	Optimum	Optimum	Optimum

Benajes et al., SAE WCX 2018

CONTENTS

- Background and approach
- Tools and development
- Applications



ACKNOWLEDGEMENTS

- CFD combustion group members and collaborations
  - Prof. JM García-Oliver and Prof. R. Novella
  - J. Gomez-Soriano, E.J. Perez, A. Hernández-Lopez, L. Pachano, …
  - Dr. A. Pandal & Dr. J.F. Winklinger (former CMT PhD Students)
- CMT combustion research manager Prof. J. Benajes

Gracias por su atención !