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A Virtual Gasoline Particle Sensor (vGPS) for Direct Injection Spark Ignition Engines

Dr. Christophe Barro — LAV ETH Zürich / Vir2sense

Prof. Dr. Konstantinos Boulouchos — LAV ETH Zürich

Outline

- Introduction
  - EU Paregen Project
  - Particles in GDI Engines
- Model Concept
- Results
- Conclusions and Outlook

Introduction

PaREGEn

- International European consortium of 17 large industry and research organisations
- New generation of gasoline direct injection engine vehicles achieving a 15% reduction in CO_2 emissions through the optimal combination of advanced engine and robust aftertreatment technologies.
- Modelling and simulation software will be verified and used to improve the design and the capability of the engines.
- Two demonstration vehicles, one Mercedes E180 and one Jaguar XE, will comply with upcoming Euro 6 RDE limits with particle number emissions measured to a 10 nm dia. size threshold.

www.paregen.eu

Introduction

Origin of (soot)-particles in GDI engines

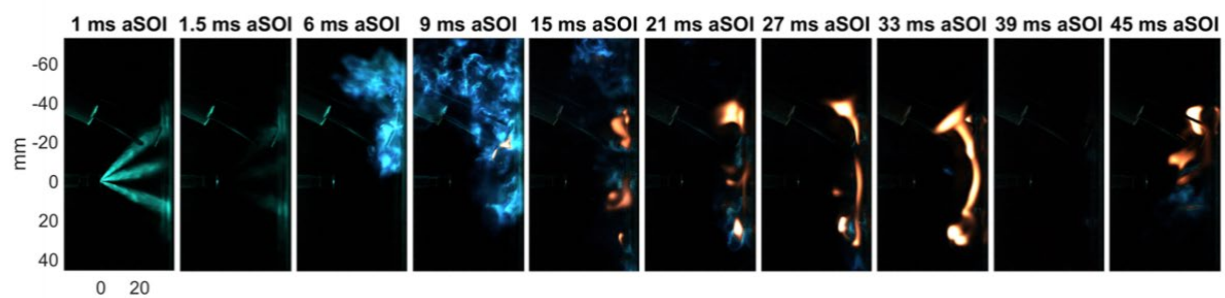
$$\frac{dm_s}{dt} = \frac{dm_{s,form}}{dt} - \frac{dm_{s,ox}}{dt}$$

$$\frac{dm_{Formation}}{dt} = A_f \cdot m_{fc} \cdot p^{0.5} \cdot e^{-\left(\frac{E_{sf}}{R \cdot T}\right)}$$

$$\frac{dm_{Oxidation}}{dt} = A_o \cdot m_s \cdot \frac{p_{O_2}}{p} \cdot p^{1.8} \cdot e^{-\left(\frac{E_{so}}{R \cdot T}\right)}$$

Homogeneous Operation:
Early injection -> low density -> wall / piston impingement -> **fuel rich pool fires**

Stratified Operation:
Late injection -> poor mixing -> **fuel rich combustion portion**



High-speed color imaging of fuel injection, ignition, flame propagation, and soot formation: University of Duisburg Essen, www.paregen.eu

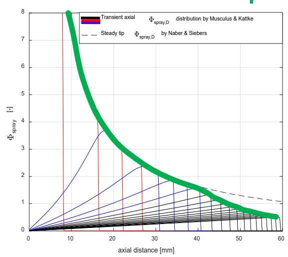
vGPS: Model Concept and Goal

Requirements:
Applicable on an ECU in real-time

model inputs (from ECU)

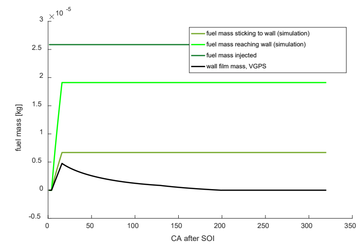
p_{intake}
$p_{injection}$
ρ_{air}
ρ_{liquid}

Modified Musculus-Kattke / Naber Siebers Spray model



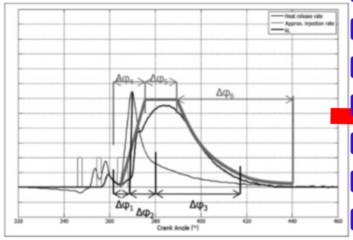
$S_{tip}(t)$
$v_{tip}(t)$
$\phi_{tip}(t)$

Impingement model
Wall film evaporation model



$m_{critical}$

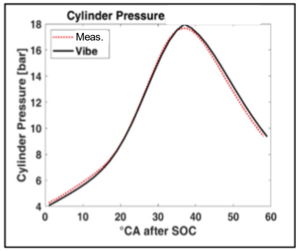
Soot model



PM/PN

LHV
n_{engine}
m_{fuel}
T_{intake}
p_{intake}

Vibe model for combustion
HTR Model for cylinder pressure



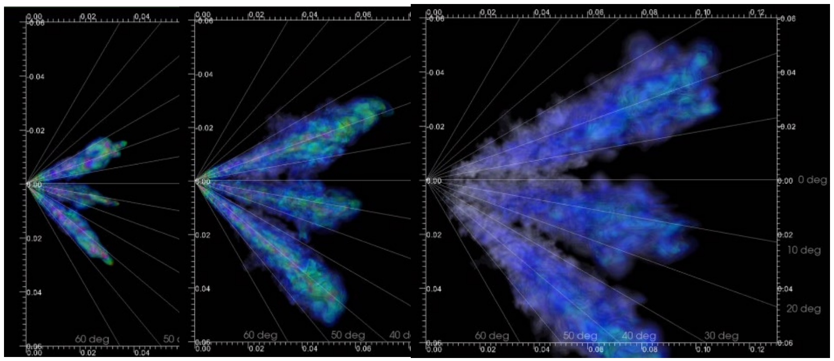
T_{burned}, p
O_2

model calibration

model parameter

Spray Model Simplificaiton

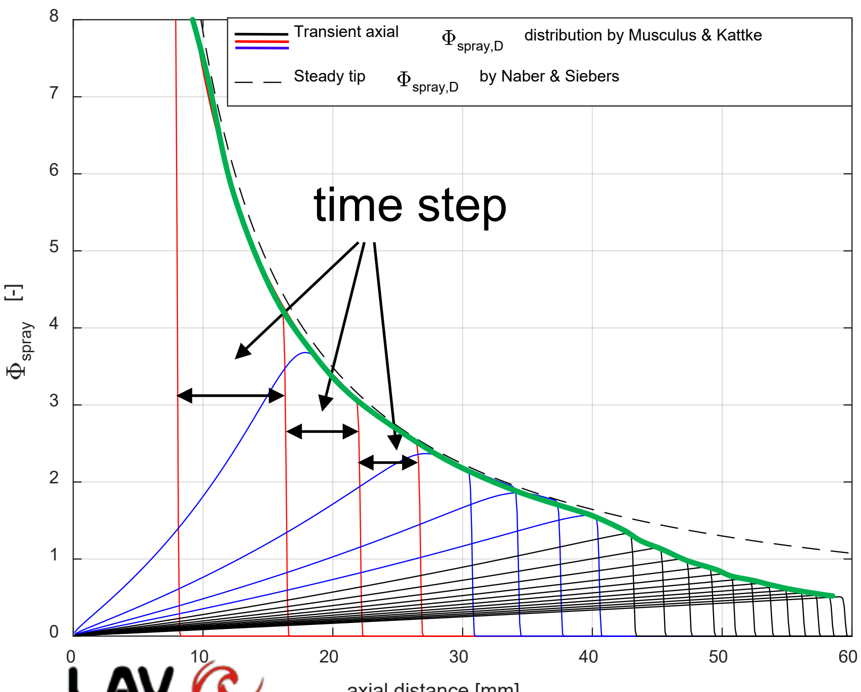
Simplification of quivalence ratio history $\phi(t)$



comparison of Musculus & Kattke model (1D) with Naber & Siebers (tip only, steady state)

Naber & Siebers (steady state spray)

$$\phi(t) = \frac{2 \cdot \phi_{stoich}}{\sqrt{1 + 16 \cdot \widetilde{S(t)}^2} - 1}$$



During injection

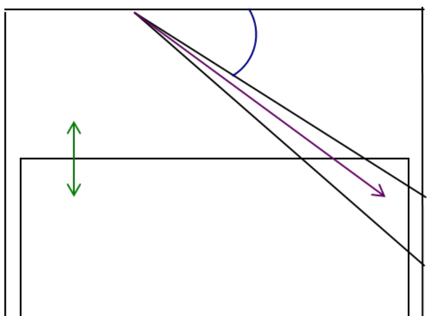
Short after end of injection

Long after end of injection

Line of interest

Impingement / Evaporation model

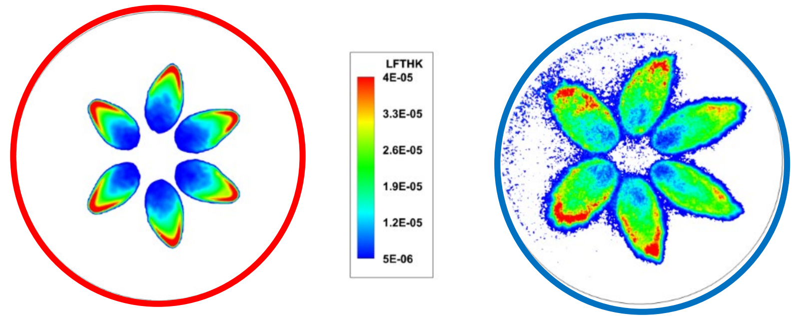
- **Spray impingement (wall / piston)**
  - Piston Position = f(CA)
  - Penetration length S(t)
  - Spray angle, valve position

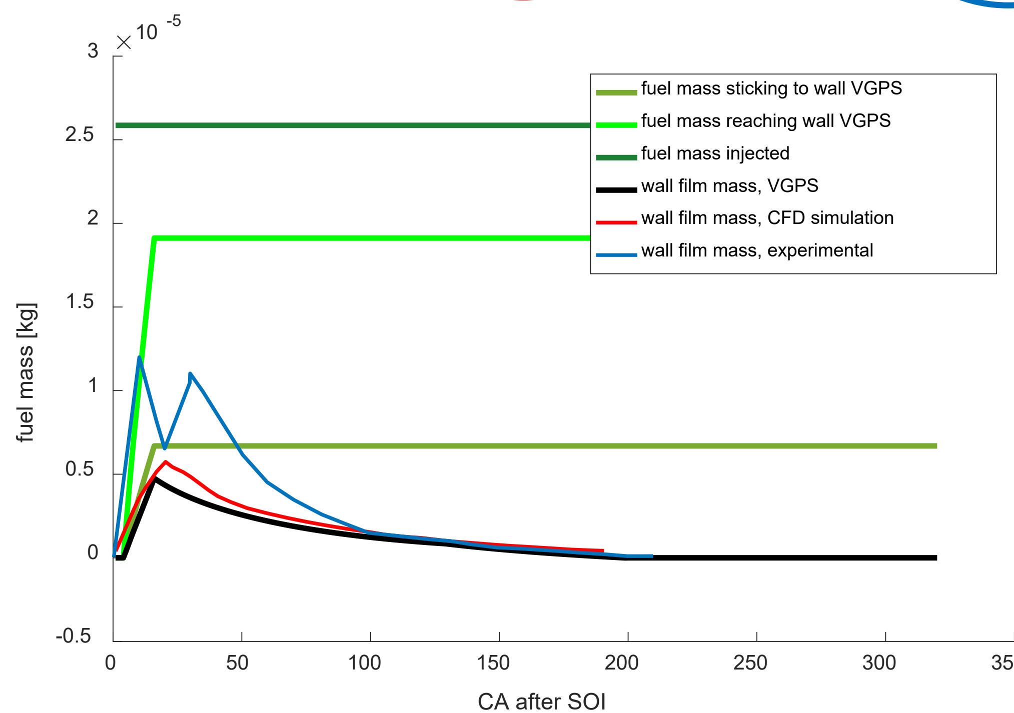


Sketch of spray in cylinder

- Behaviour at the wall[6]
  - *Stick:* $We \leq 2$
  - *Rebound:* $2 < We \leq 20$
  - *Spread:* $20 < We \leq We_c$
  - *Splash:* $We_c < We$

- **Evaporation**
  - $m_{wall\ film}(t)$
  - Power (T_{wall})
  - N_{engine})turbulence)
  - $\phi(t)$

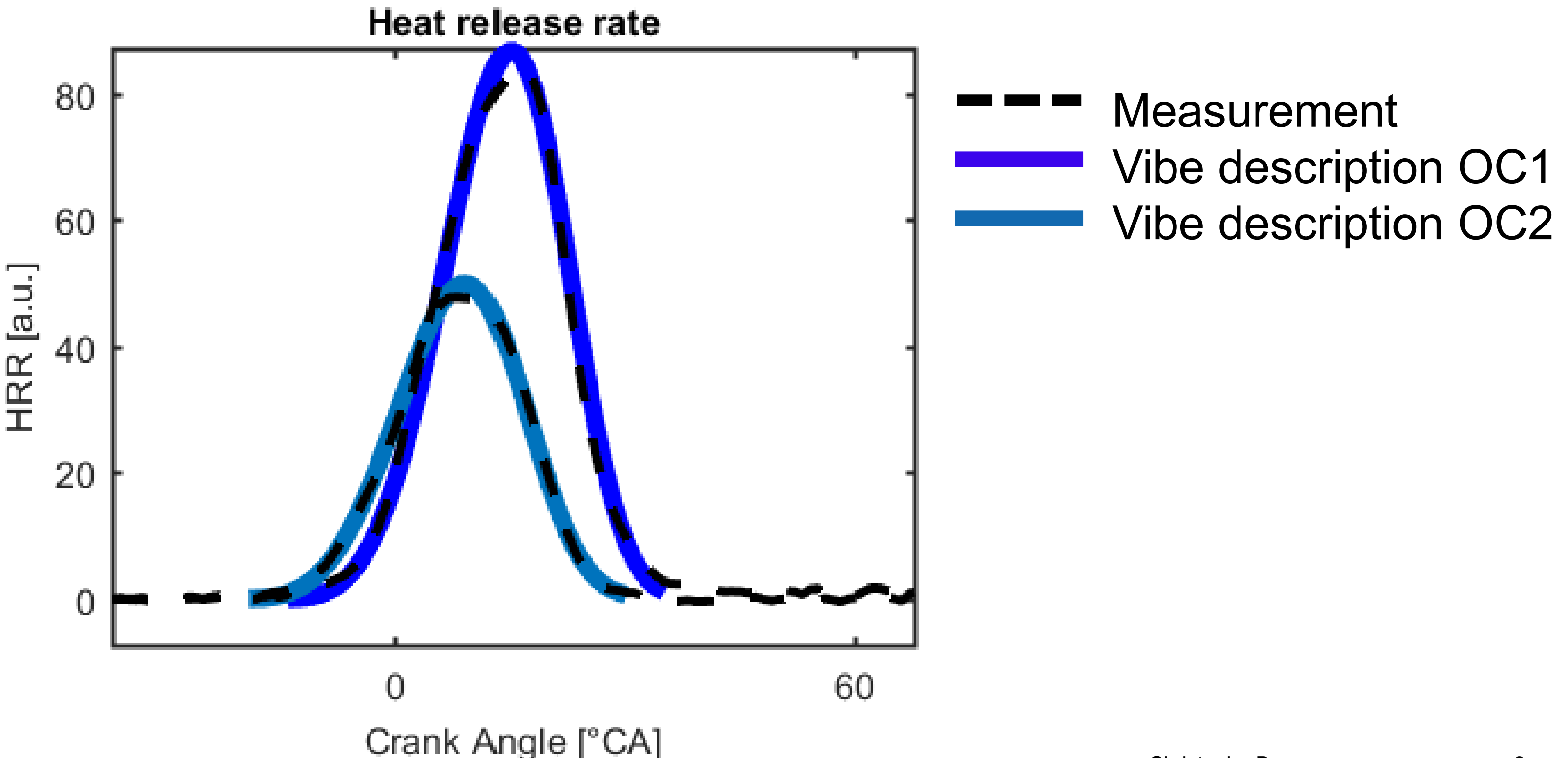




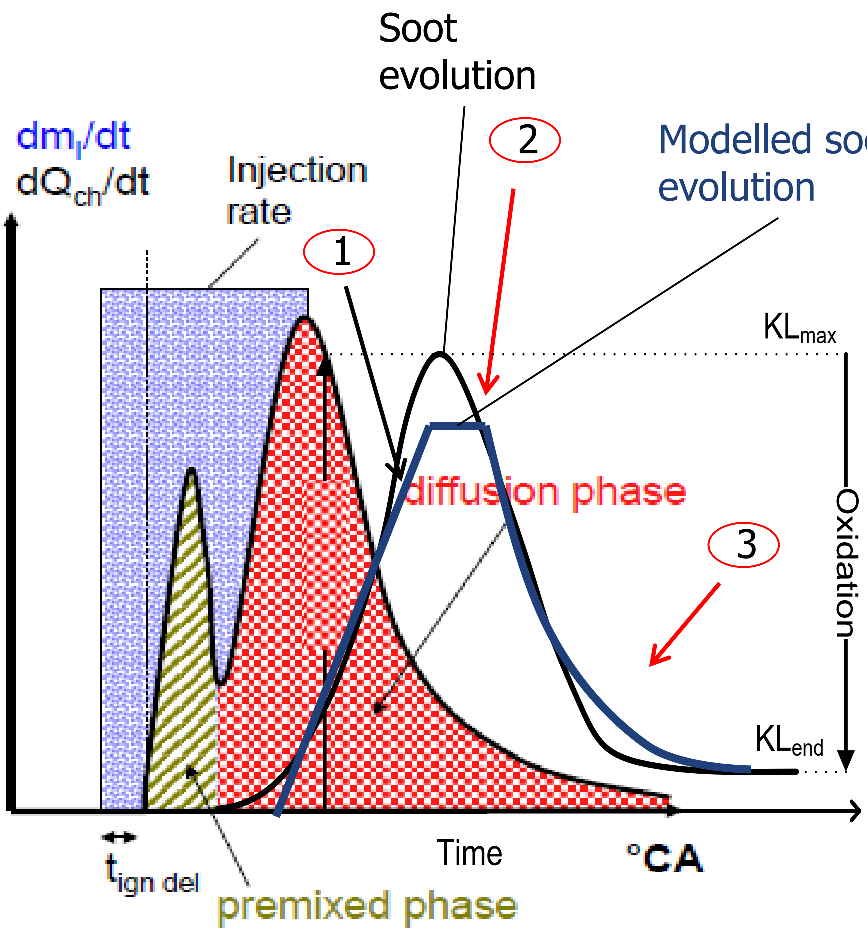
6: Bai and Gosman (1996)

Combustion

- Simple formulation using Vibe (resp. Wiebe) functions
  - Computationally very efficient
  - Only 2 parameters to characterize a *HRR*



Soot Model («stolen» from Diesel Engine Application)



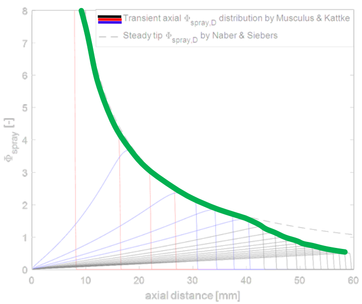
Parts:

1 •Soot formation
-f($dQ_{B_{diff}}/d\varphi$, p, T)

2 •Balance: formation, oxidation

3 •Soot Oxidation
Exponential decrease, f(conc. O_2, T and turbulence)

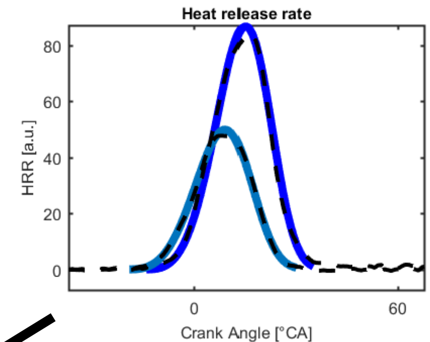
Virtual Gasoline Particle Sensor VGPS

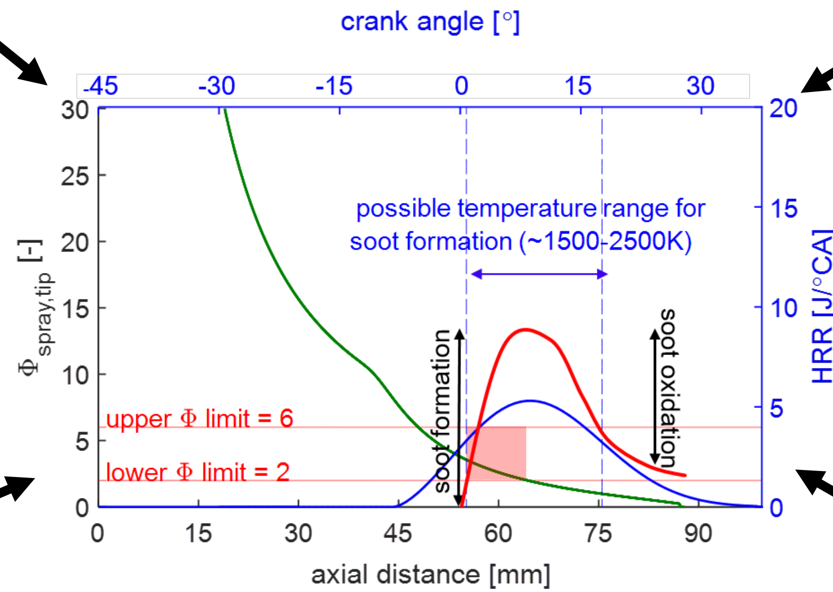


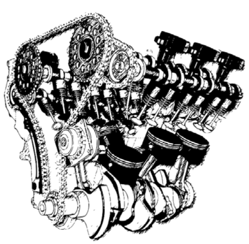
Spray

Combustion

Soot

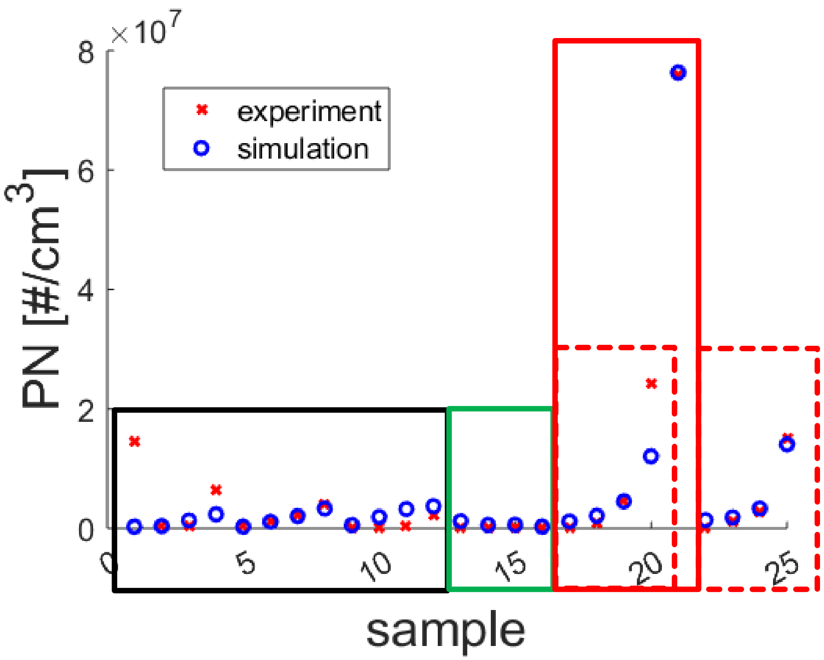






$$m_s = \left.\frac{dm_s}{dt}\right|^{*}_{form}\tau_{form} - \left.\frac{dm_s}{dt}\right|^{*}_{ox}\tau_{ox}$$

Results: Soot emissions, model calibration



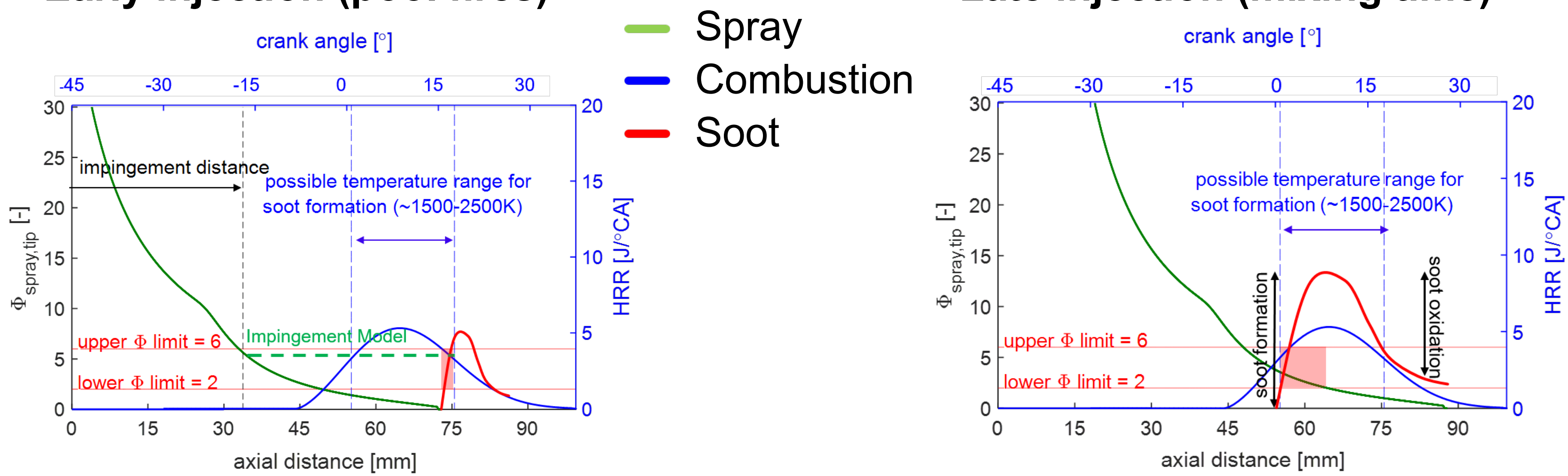
- Calibration on single cylinder naturally aspirated research engine
- Good Agreement with experiment (except first OC) $r^2 = 0.97$
- First OC: possible phenomena
  - Intake valve impingement
  - Flash boiling
- Only few measurements for calibration available

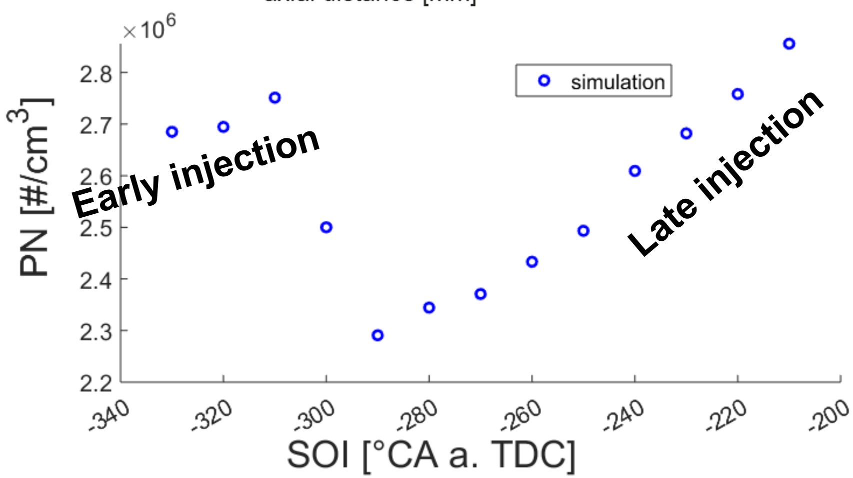
Stoichiometric operation
(1200-2500 rpm, 2-8 bar BMEP)
Lean operation
Rich operation
Injector tip cleaned

Computation time:
~5 ms per cylce

Results: Soot emissions, model validation

Early injection (pool fires) Late injection (mixing time)





- Validation with data from literature
- Similar behaviour for SOI variation
- Model behaviour without any calibration for SOI variation

Conclusions & Outlook

- Conclusions
  - Phenomenological virtual gasoline particle sensor has been developed using sub-models for spray, impingement, evaporation, combustion and soot formation
  - Good agreement with measurements under stoichiometric, rich and lean operation
  - Ability to distinguish between soot formation from pool fires and from insufficient mixing
- Outlook
  - Calibration on a multi-cylinder turbocharged engine under stoichiometric and lean operation
    - Preliminary results are very promising
    - Final results available on www.paregen.eu