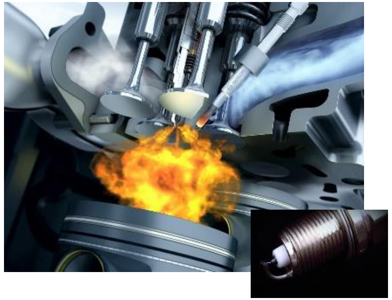
Application and validation of combustion models for SI engines operating with diluted mixtures



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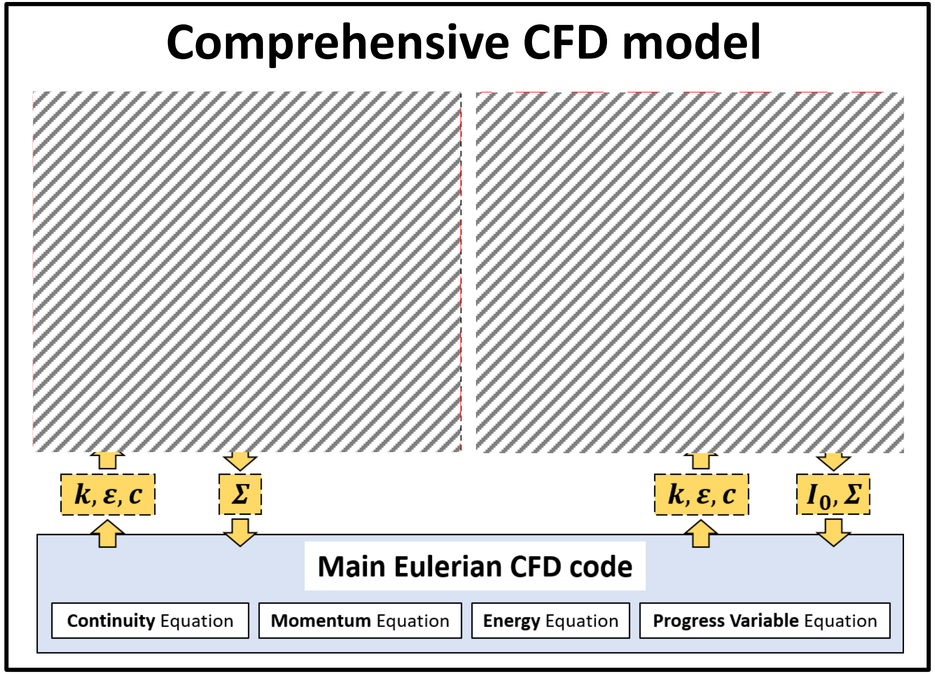
Outline

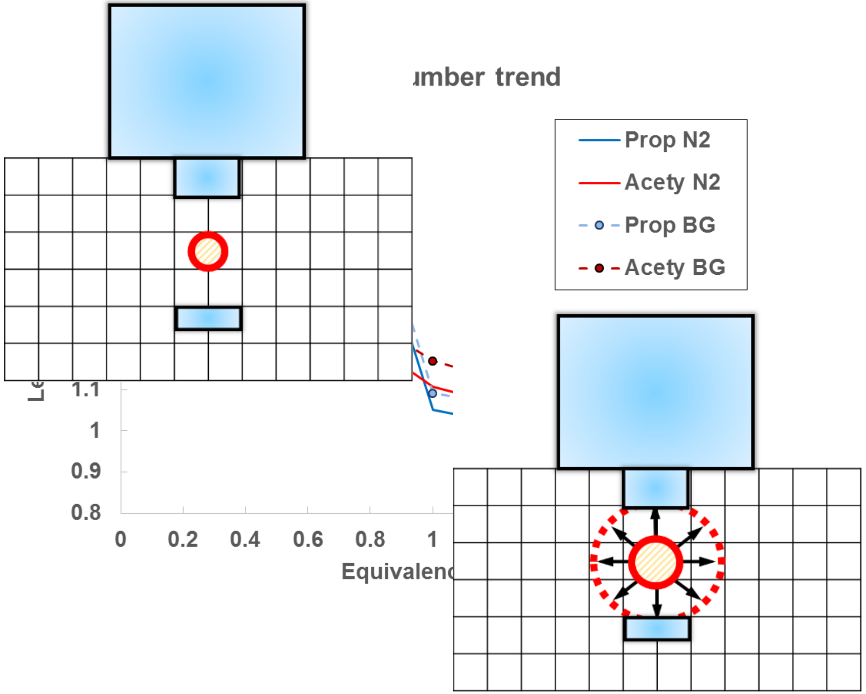
1) **Modeling approaches for SI combustion** developed using the Open-FOAM® technology
   a) *Eulerian-only*
   b) *Lagrangian-Eulerian*

2) **SI combustion simulation of diluted mixtures**
   a) *Applications*
   b) *Validations*

The *Eulerian-only* model for SI combustion

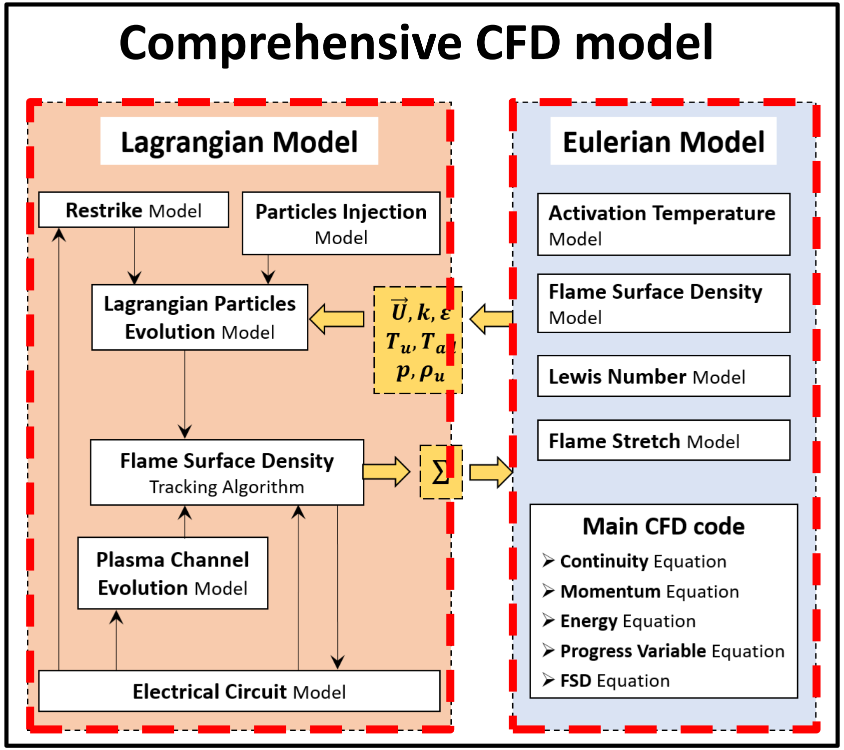
SI combustion engine modeling using the Open-FOAM® technology

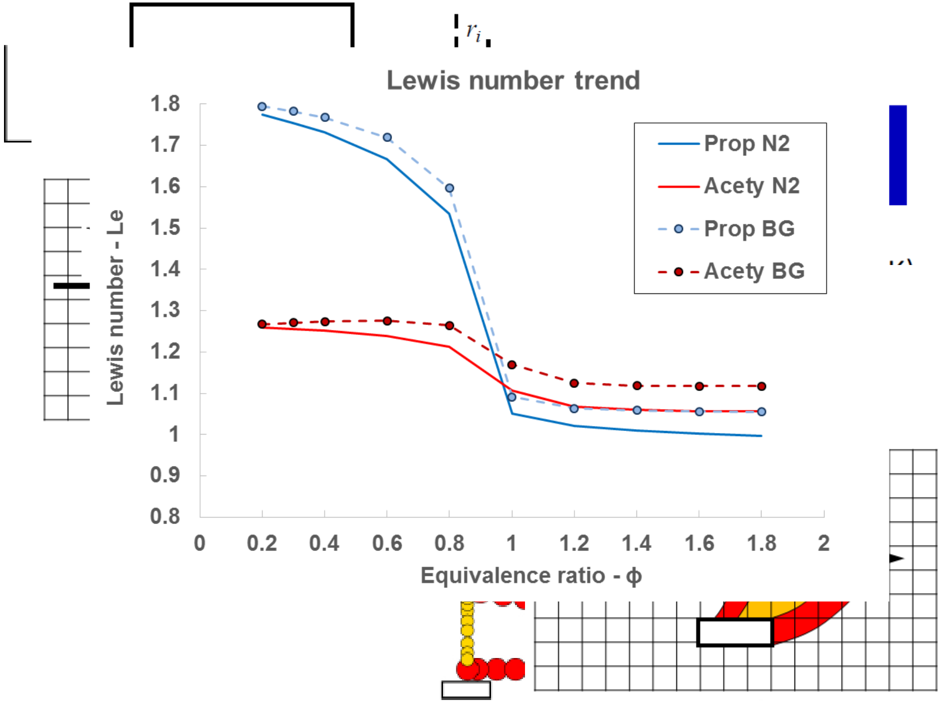




The *Lagrangian-Eulerian* model for SI combustion

SI combustion engine modeling using the Open-FOAM® technology





SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

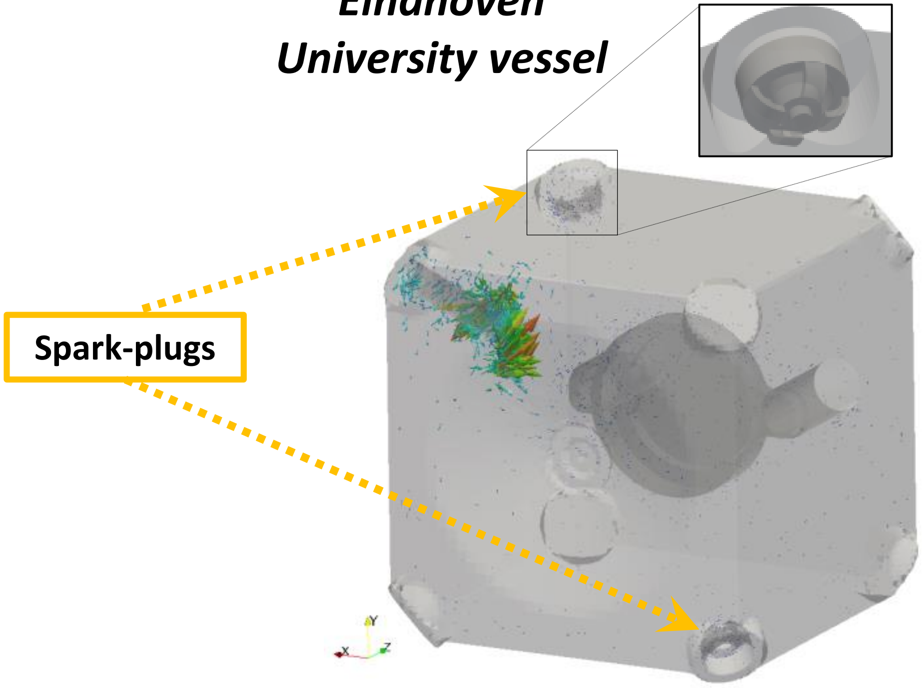
Applications

- Pressurized vessels
- Multi-ignition systems
- Fan-generated flow velocity and turbulence fields at the spark-gap
- Research engines

TU/e Technische Universiteit Eindhoven University of Technology

FPT POWERTRAIN TECHNOLOGIES

Eindhoven University vessel



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SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Applications

- Pressurized vessels
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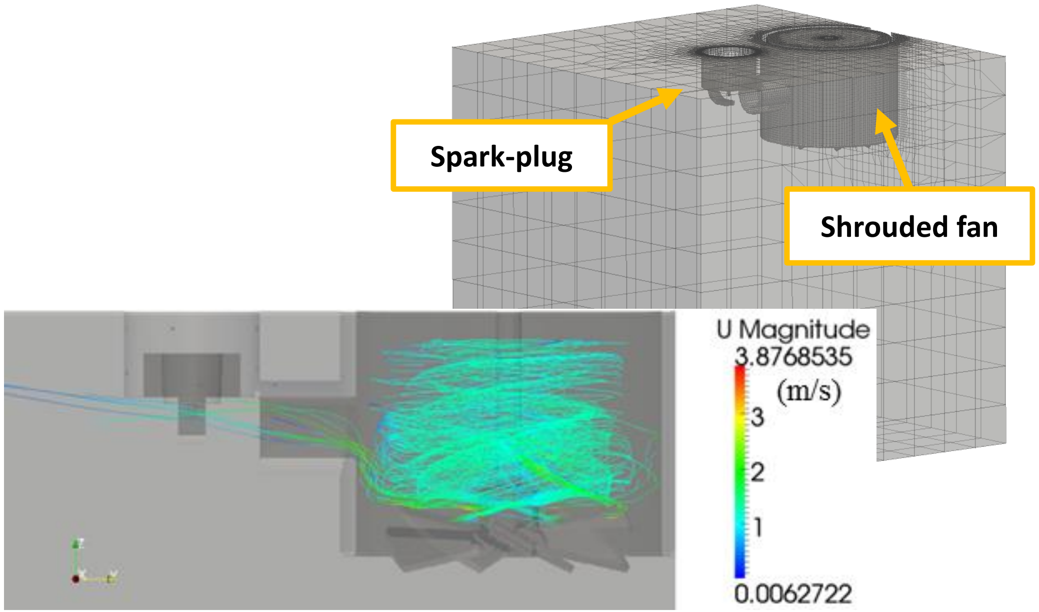
- Research engines

Michigan Technological University

Michigan Tech University vessel



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Applications

- Pressurized vessels
- Multi-ignition systems
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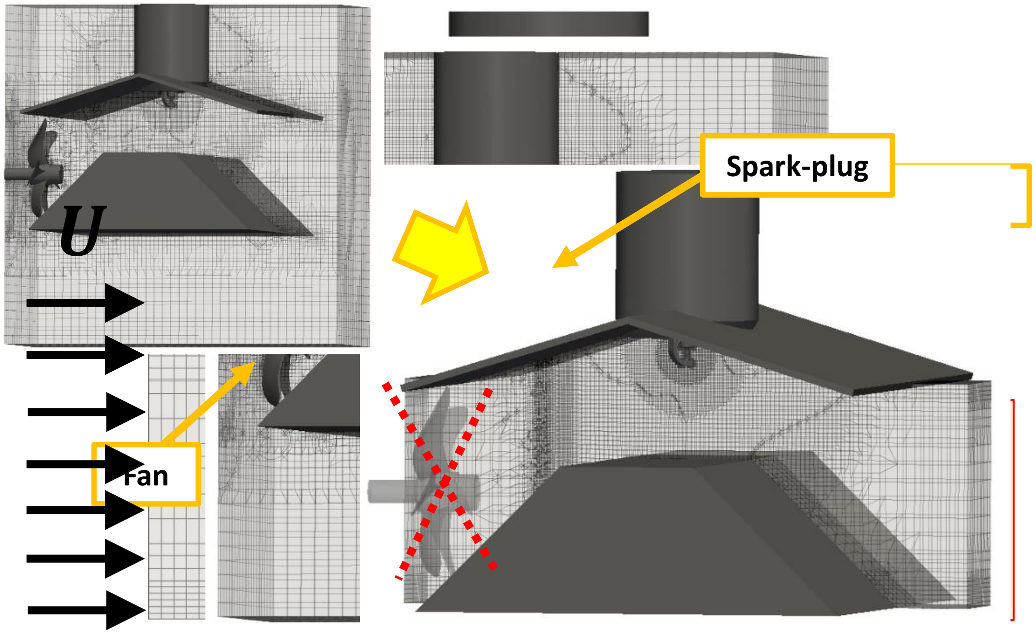
- Research engines

CHIBA UNIVERSITY

NISSAN

Chiba University vessel



SI combustion simulation of diluted mixtures

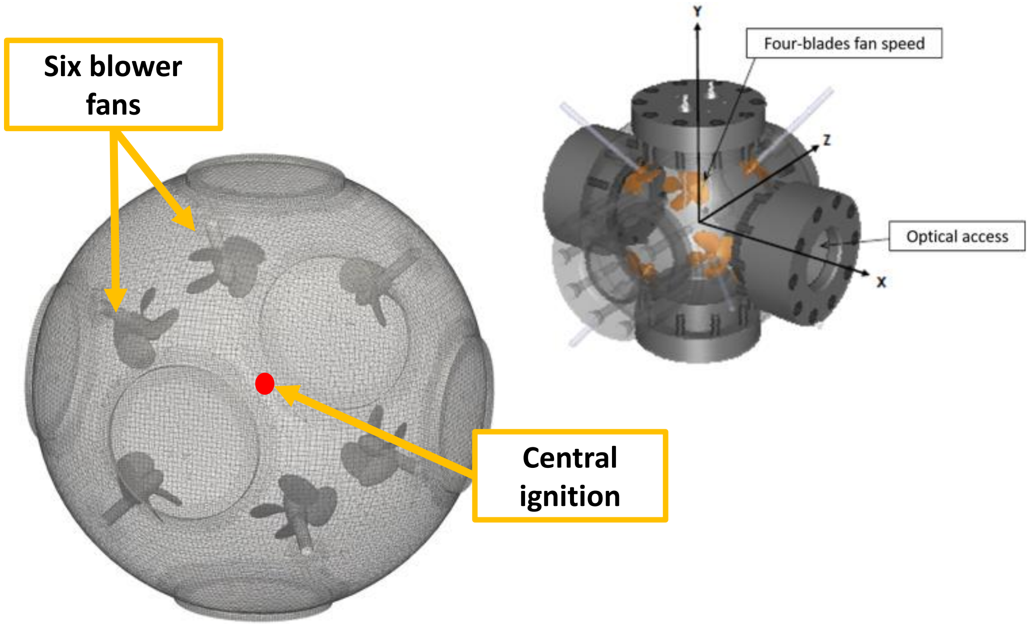
SI combustion engine modeling using the Open-FOAM® technology

Applications

- Pressurized vessels
- Multi-ignition systems
- Fan-generated flow velocity and turbulence fields at the spark-gap
- Research engines

UNIVERSITE D'ORLEANS

Orleans University vessel



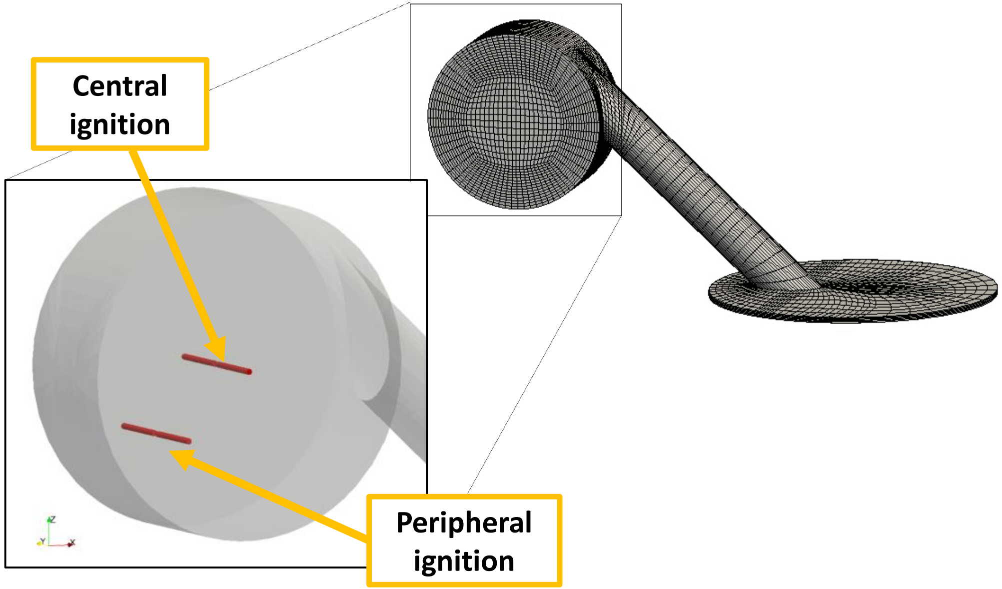
SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Applications

- Pressurized vessels
- Multi-ignition systems
- Fan-generated flow velocity and turbulence fields at the spark-gap
- Research engines

Herweg-Maly side chamber



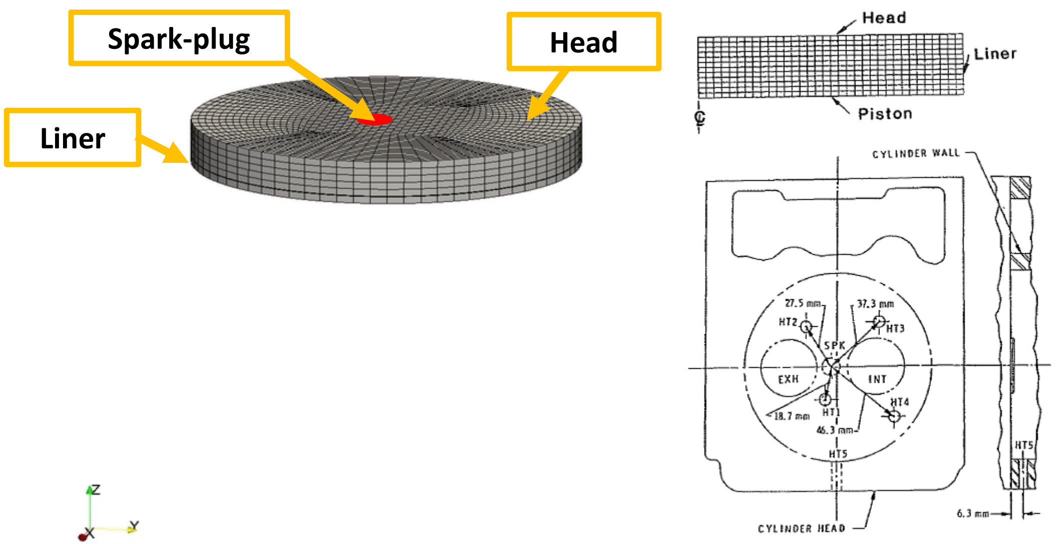
SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Applications

- Pressurized vessels
- Multi-ignition systems
- Fan-generated flow velocity and turbulence fields at the spark-gap
- Research engines

GM "pancake" engine



SI combustion simulation of diluted mixtures

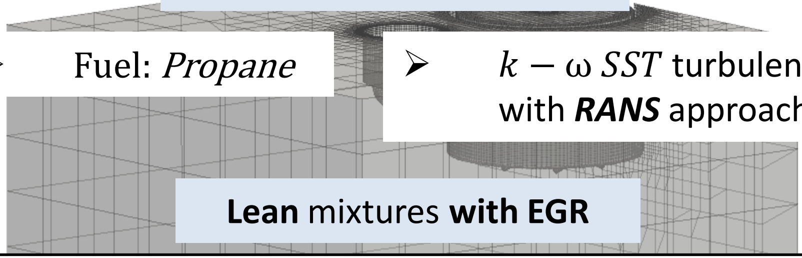
SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

***Lagrangian-Eulerian* model**
for SI combustion

Analyzed conditions



- Fuel: *Propane*
- $k-\omega\ SST$ turbulence model with ***RANS*** approach

Lean mixtures **with EGR**

Test	Charged gas	P (bar)	T (K)	ρ (kg/m3)	n (rpm)
2	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	3000
3	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	6000
6	$\Phi = 0.7$ $EGR = 20\%$	16	453	12.42	3000
9	$\Phi = 0.9$ $EGR = 20\%$	8	453	6.33	6000

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Analyzed conditions

Test	Charged gas	P (bar)	T (K)	ρ (kg/m3)	n (rpm)
2	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	3000
3	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	6000
6	$\Phi = 0.7$ $EGR = 20\%$	16	453	12.42	3000
9	$\Phi = 0.9$ $EGR = 20\%$	8	453	6.33	6000

Investigation target

Assessing the model behavior under **variations of**:

a) Turbulence intensity $\boldsymbol{u'}$

b) Equivalence ratio $\boldsymbol{\phi}$

c) Pressure $\boldsymbol{P}$

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Analyzed conditions

Test	Charged gas	P (bar)	T (K)	ρ (kg/m3)	n (rpm)
2	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	3000
3	$\Phi = 0.7$ $EGR = 20\%$	8	453	6.21	6000
6	$\Phi = 0.7$ $EGR = 20\%$	16	453	12.42	3000
9	$\Phi = 0.9$ $EGR = 20\%$	8	453	6.33	6000

Investigation target

Numerical investigation on:

a) Flame front position

b) Burnt mass

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Analyzed conditions

Test	Charged gas	P (bar)	T (K)	ρ (kg/m3)	n (rpm)
2	$\Phi = 0.7$ $EGR =$ [illegible]	8	453	[illegible]	3000
3	$\Phi =$ [illegible] $EGR =$ [illegible]	8	453	[illegible]	6000
6	$\Phi = 0.7$ $EGR = 20\%$	16	453	12.42	3000
9	$\Phi = 0.9$ $EGR = 20\%$	8	453	6.33	6000

↑ *flame speed*

↑ *flame speed*

Expected behaviors

Form experimental observations and well known knowledge, an ↑ **flame front velocity** is achieved under:

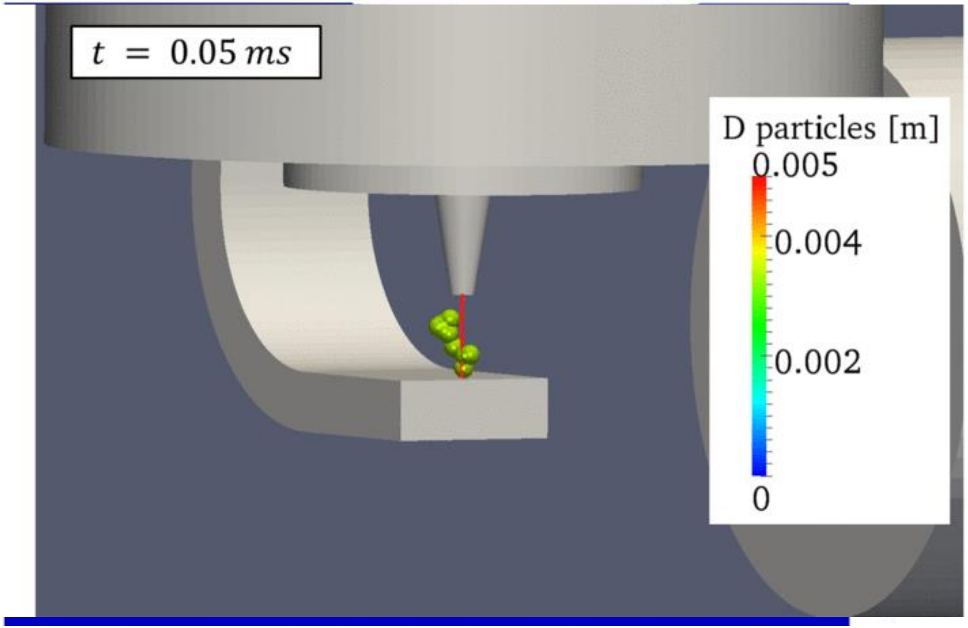
a) $\uparrow \boldsymbol{u'}$ b) $\uparrow \boldsymbol{\phi}$ c) $\uparrow \boldsymbol{P}$

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber



- Lagrangian particles dimension artificially decreased by a factor of 10 ... tion of elec

Chance to appreciate the **effects of local flow filed on channel geometry**

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

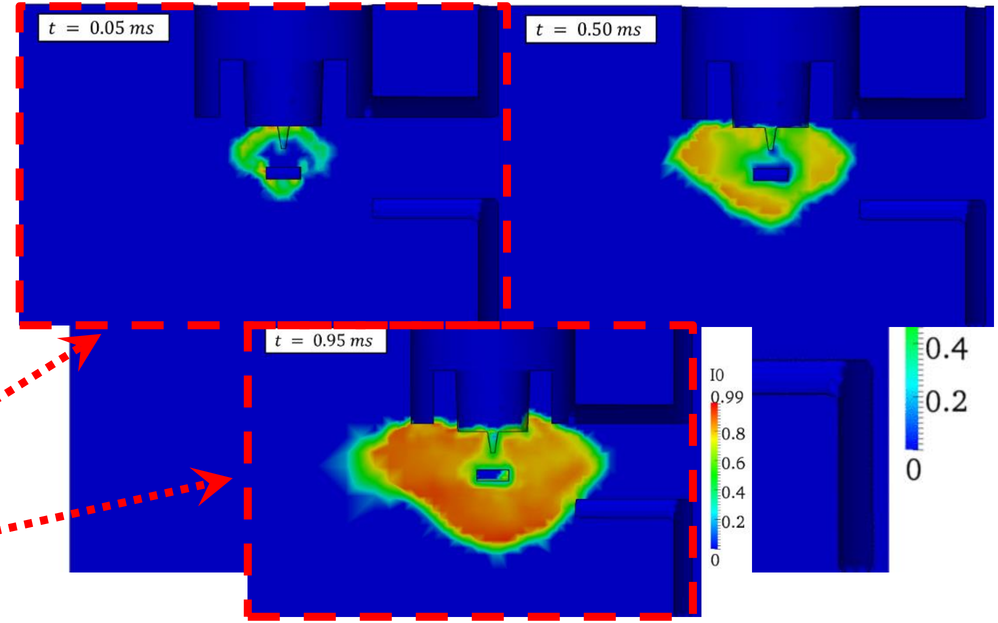
Definition

$$I_0 = \frac{s_u}{s_{u0}}$$

- Important contribution during f
- Self-sustained flame front

($I_{0,max} \approx 0.6$)

Flame stretch



SI combustion simulation of diluted mixtures

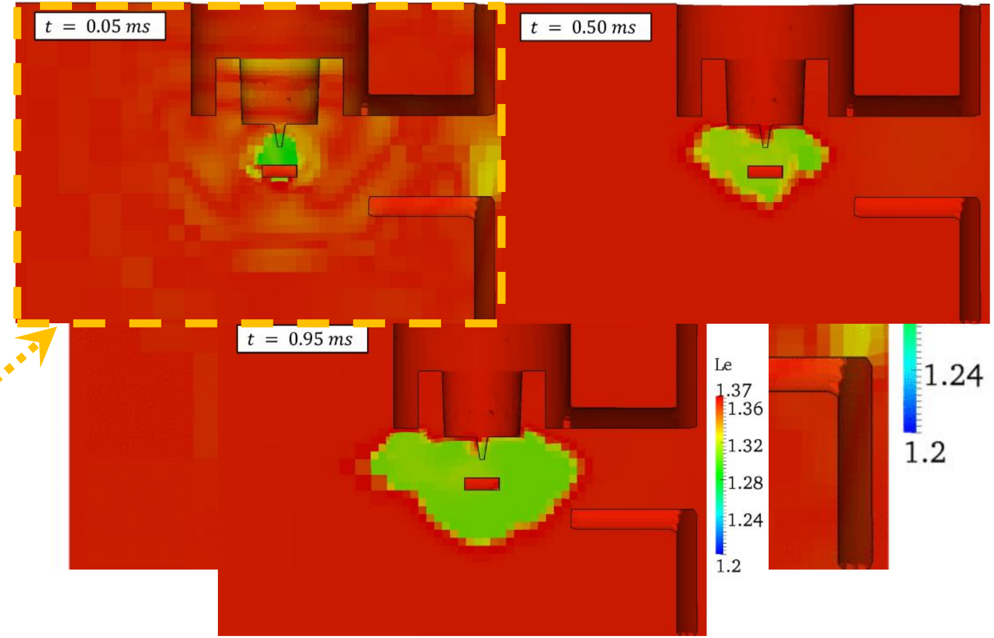
SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

- Intermediate values between
  a) $Le_{C_3H_8} \approx 1.8$
  b) $Le_{Air} \approx 1.0$

Lewis number



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

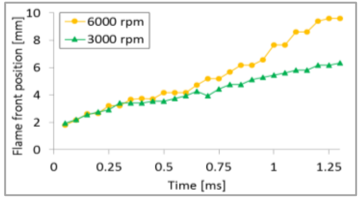
- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

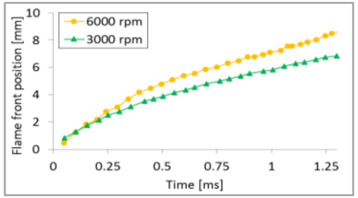
↑ ***flame speed*** is achieved with ↑ $\boldsymbol{u'}$, ↑ $\boldsymbol{\phi}$ and ↑ $\boldsymbol{P}$

Flame front position

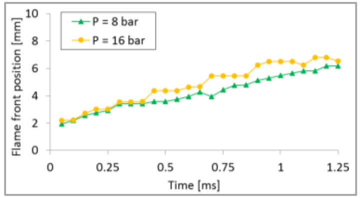
Numerical | *Experimental*

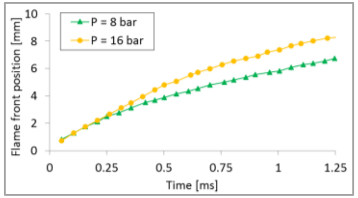
$\boldsymbol{u'}$ variation



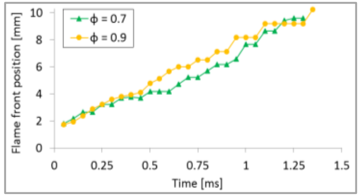


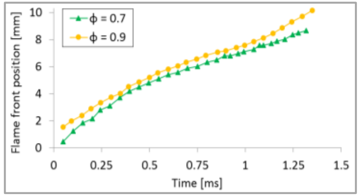
$\boldsymbol{P}$ variation





$\boldsymbol{\phi}$ variation





SI combustion simulation of diluted mixtures

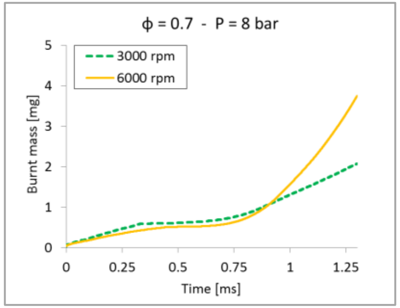
SI combustion engine modeling using the Open-FOAM® technology

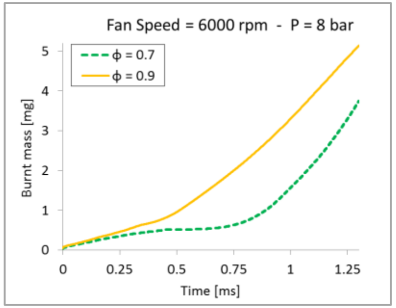
Burnt mass

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

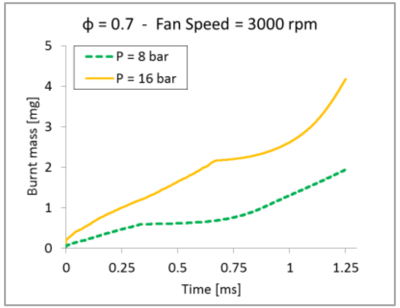
u' variation





ϕ variation

Numerical results only



P variation

Same trends are confirmed

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SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

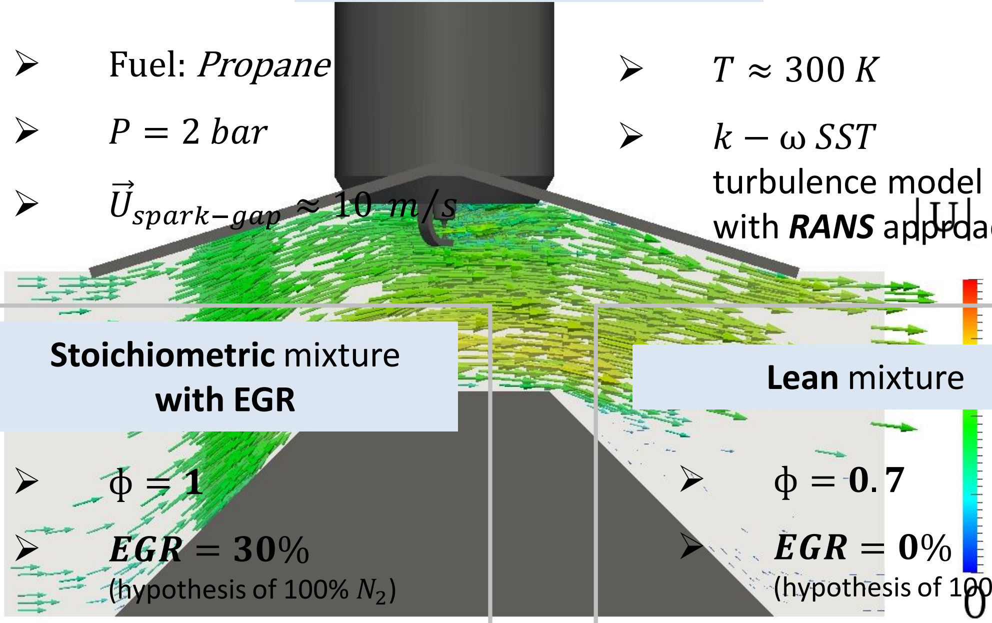
Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

***Lagrangian-Eulerian* model**
for SI combustion

Analyzed conditions

- Fuel: *Propane*
- $P = 2\ bar$
- $\vec{U}_{spark-gap} \approx 10\ m/s$
- $T \approx 300\ K$
- $k - \omega\ SST$ turbulence model with ***RANS*** approach



Stoichiometric mixture **with EGR**

- $\phi = 1$
- $EGR = 30\%$ (hypothesis of 100% N_2)

Lean mixture

- $\phi = 0.7$
- $EGR = 0\%$ (hypothesis of 100% N_2)

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Investigation target

Experimental imposition of:

a) the *secondary current* i_s *trend*

b) a ***variation*** in ***initial secondary current value*** i_s

⇨

Numerical prediction of:

a) Voltage V_s *trend*

b) Plasma channel shape

c) Flame area after $1\ ms$ from spark onset

Expected behaviors

From several experimental observations, an ↑ $\boldsymbol{i_s}$ corresponds to:

a) ↓ $\boldsymbol{dV_s/dt}$, with a consequent longer 1st discharge duration

b) ↑ $\boldsymbol{l_{channel}}$ and ↑ $\boldsymbol{d_{channel}}$

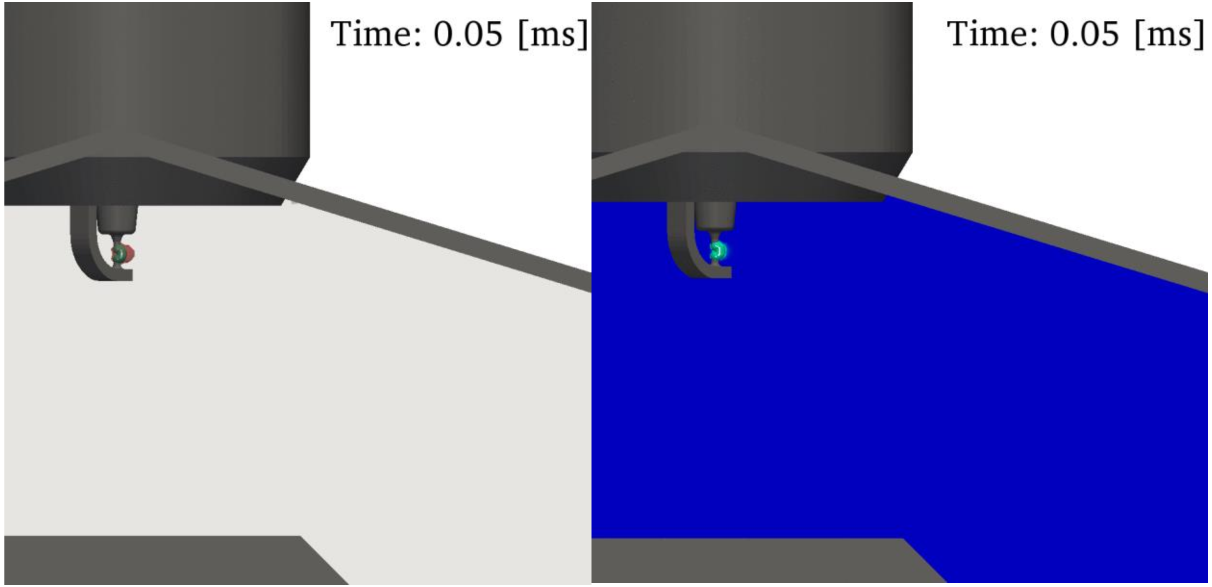
c) ↑ ***flame area*** after $1\ ms$ from spark onset

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
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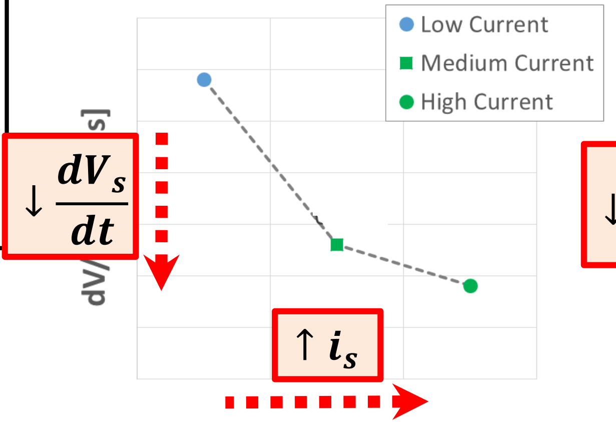
Stoichiometric mixture
with EGR

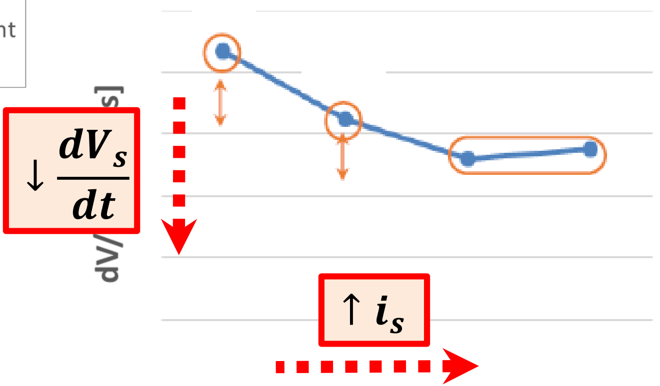
$\phi = 1$ $EGR = 30\%$
(hypothesis of 100% N_2)

Voltage trend

Numerical



Experimental



Initial $\uparrow i_s$ corresponds to $\downarrow dV_s/dt$

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

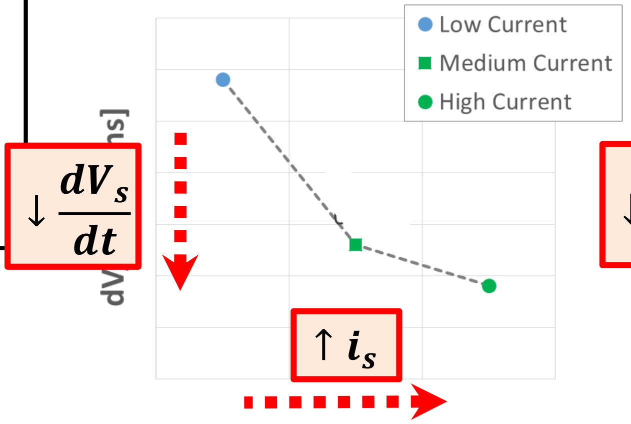
Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

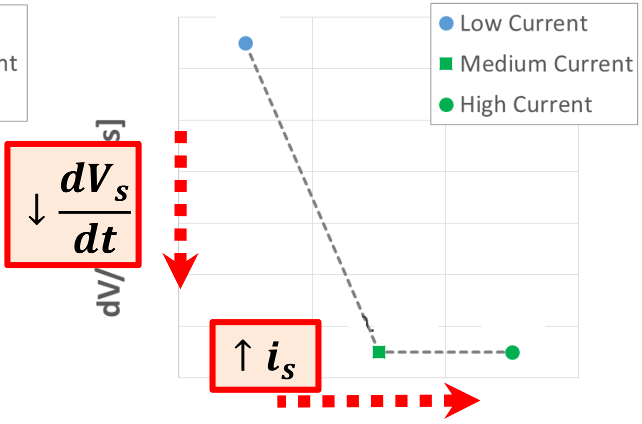
Numerical results

Voltage trend

Stoichiometric mixture with EGR



Lean mixture



Same trend is confirmed

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

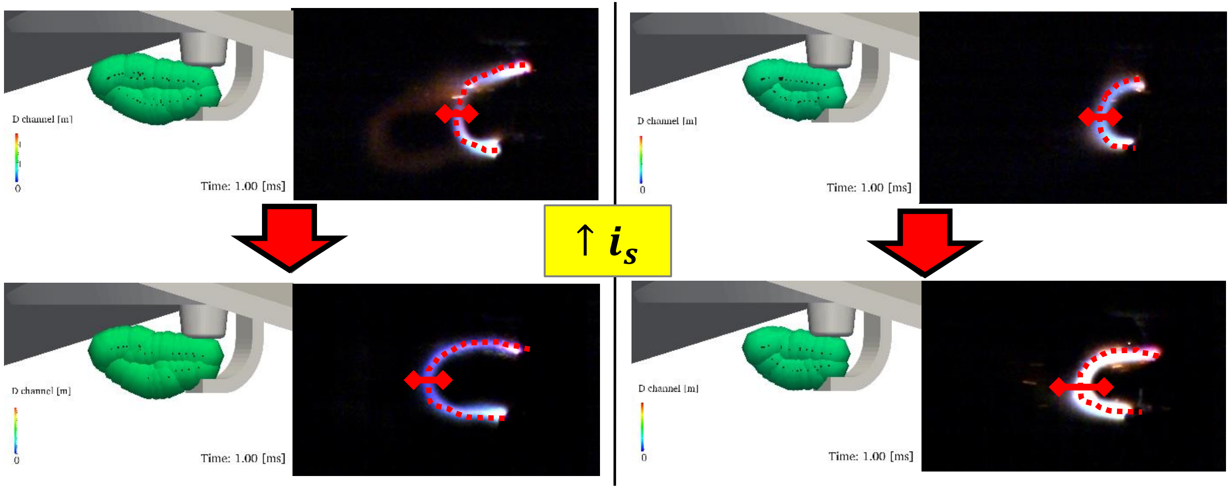
Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

$\uparrow l_{channel}$ and $\uparrow d_{channel}$

Plasma channel shape

Stoichiometric mixture with EGR | *Lean mixture*



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

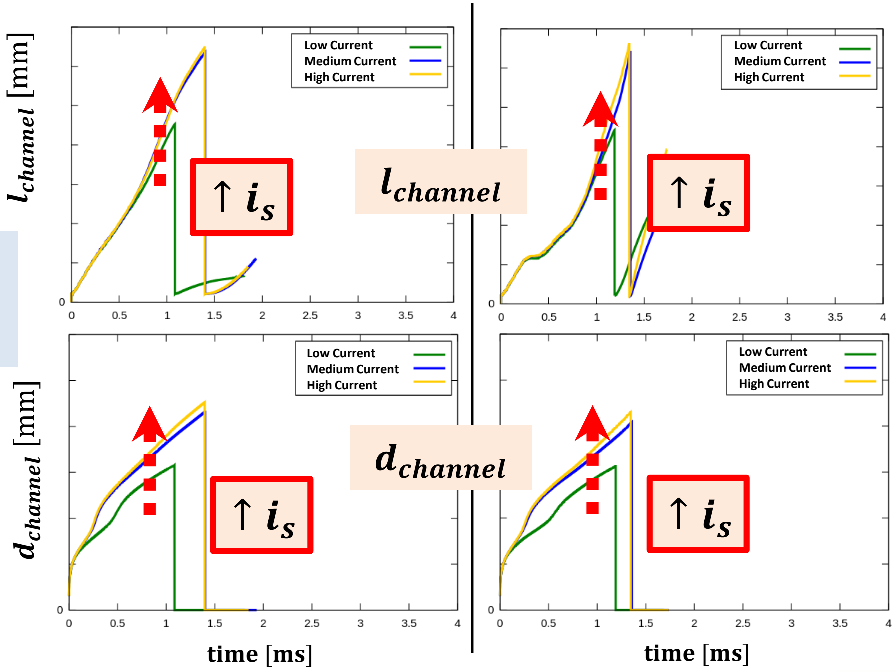
Numerical results

Initial ↑ i_s corresponds to ↑ $l_{channel}$ and ↑ $d_{channel}$

Plasma channel shape

Stoich. mixture with EGR

Lean mixture



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
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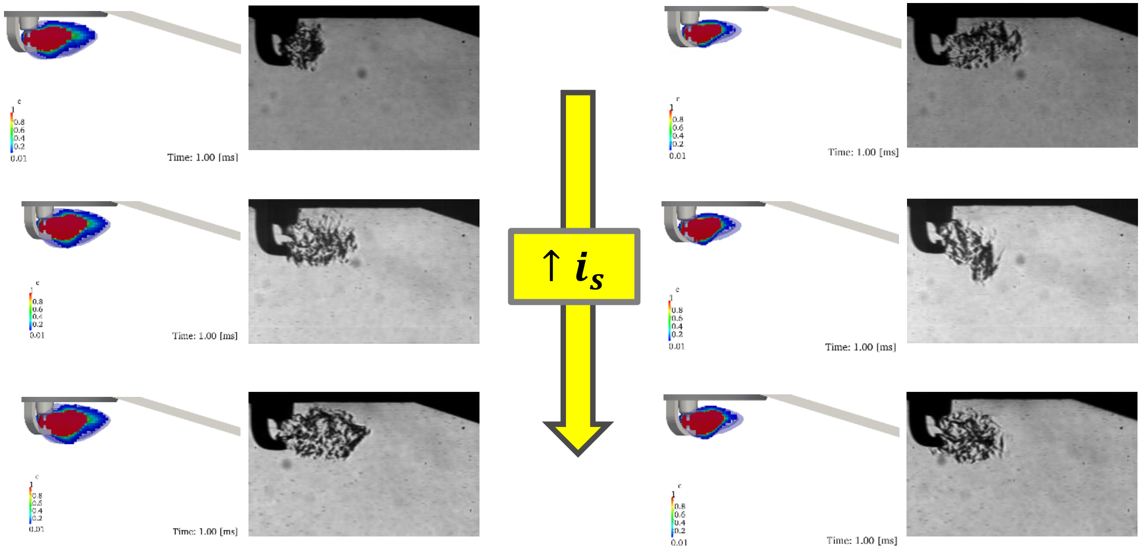
“Visual” comparison

Numerical results **seem to agree** with *experimental findings*

Flame area after 1 ms from spark onset

Stoichiometric mixture with EGR | *Lean mixture*



SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

$\uparrow i_s \rightarrow \uparrow$ ***released energy***

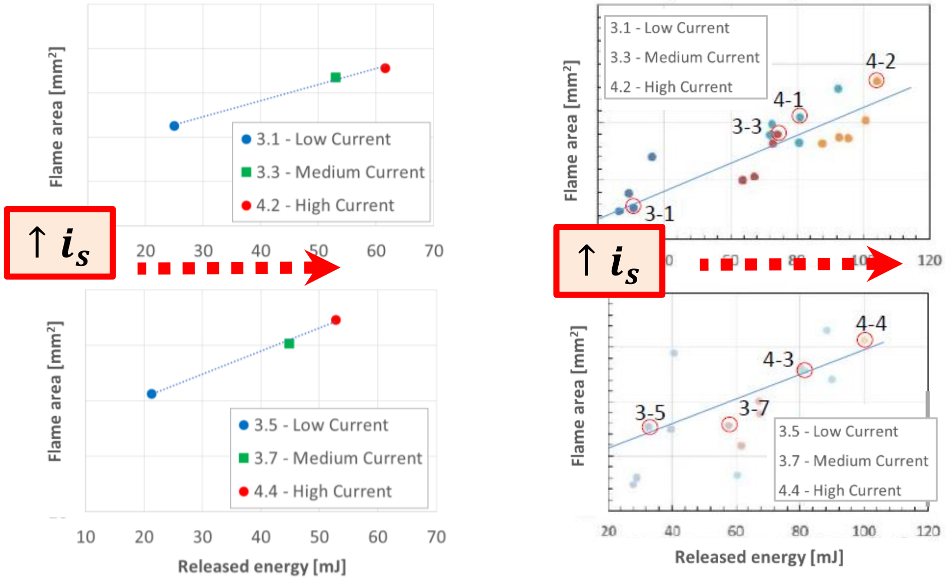
Initial $\uparrow i_s$ corresponds to
$\uparrow$ ***flame area*** after 1 ms from spark onset

Stoich. mixture with EGR

Lean mixture

Flame area after 1 ms from spark onset

Numerical | *Experimental*



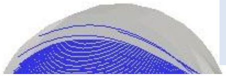
SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

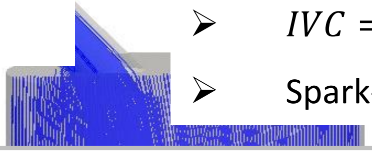
- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

***Eulerian-only* model**
for SI combustion



Analyzed conditions

- Fuel: *Propane*
- $P_{spark-timing} = 5\ bar$
- Ignition location: *central, peripheral*
- $T_{IVC} \approx 300\ K$
- $k - \omega\ SST$ turbulence model with ***RANS*** approach
- $IVC = -168\ CAD$
- Spark-timing $= -10\ CAD$



Lean to **stoichiometric** mixtures

- $\phi = 0.67,\ 0.77,\ 1$
- $EGR = 0\%$ (hypothesis of 100% N_2)
- $speed = 300,\ 500,\ 750,\ 1000,\ 1250\ rpm$

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Ing. Federico Clerici
M.Sc. thesis work

Investigation target

Assessing the model behavior under **variations of**:

a) Equivalence ratio $\boldsymbol{\phi}$

b) Turbulence intensity $\boldsymbol{u'}$

c) Ignition **location**

⇨

Numerical investigation on:

a) *Cold-flow*, in order to *evaluate* $\boldsymbol{U}$ and $\boldsymbol{u'}$ *prediction*

b) *Flame burnt volume*

Expected behaviors

Form experimental observations and well known knowledge, an ↑ **flame front velocity** is achieved under:

a) ↑ $\boldsymbol{u'}$ b) ↑ $\boldsymbol{\phi}$

SI combustion simulation of diluted mixtures

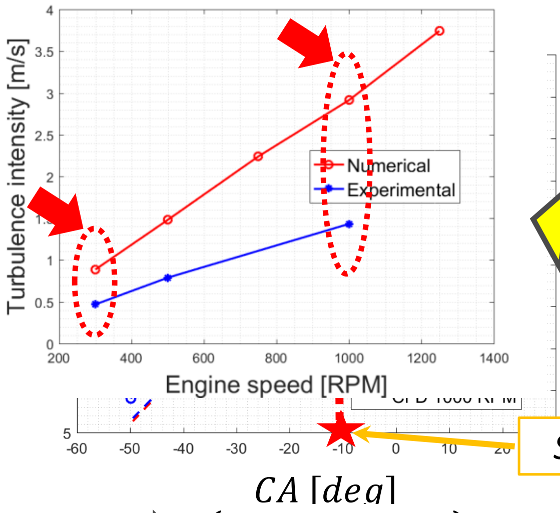
SI combustion engine modeling using the Open-FOAM® technology

Cold flow

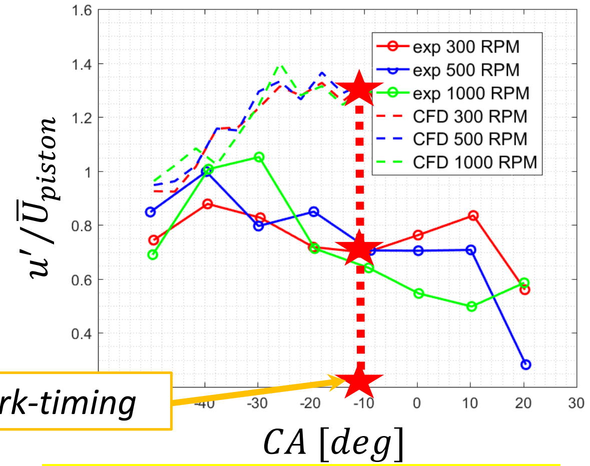
Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Ing. Federico Clerici
M.Sc. thesis work



Normalized $\boldsymbol{u'}$



Spark-timing

Legend:
- Num. data
- Exp. data

If $\uparrow \boldsymbol{rpm}$ ⇨ $(u'_{num} - u'_{exp}) \uparrow$ ⇨ **↑ numerical flame front speed**

If $\downarrow \boldsymbol{rpm}$ ⇨ $(u'_{num} - u'_{exp}) \downarrow$ ⇨ **↓ numerical flame front speed**

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

Validations

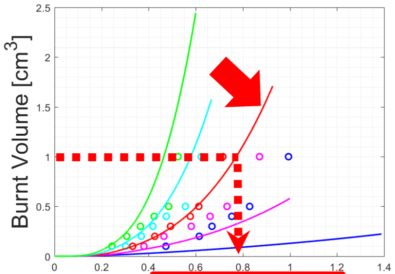
- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Ing. Federico Clerici
M.Sc. thesis work

Model calibration at:
$\phi = 1$ $\quad$ $speed = 750\ rpm$

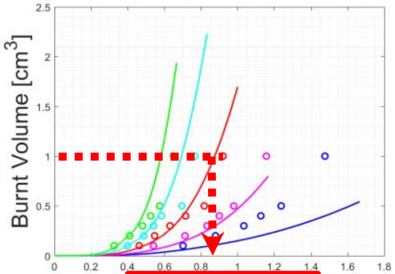
Flame burnt volume

$\phi = 1$



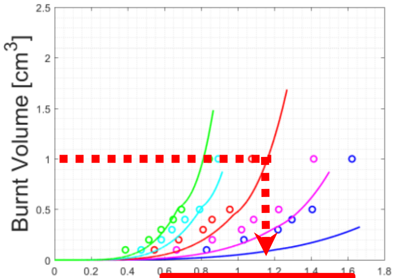
$\mathbf{0.79\ ms}$

$\phi = 0.77$



$\mathbf{0.83\ ms}$

$\phi = 0.67$



$\mathbf{1.15\ ms}$

Model calibration at:
$\phi = 1$ $\quad$ $speed = 750\ rpm$

ved
under an ↑ ϕ

SI combustion simulation of diluted mixtures

SI combustion engine modeling using the Open-FOAM® technology

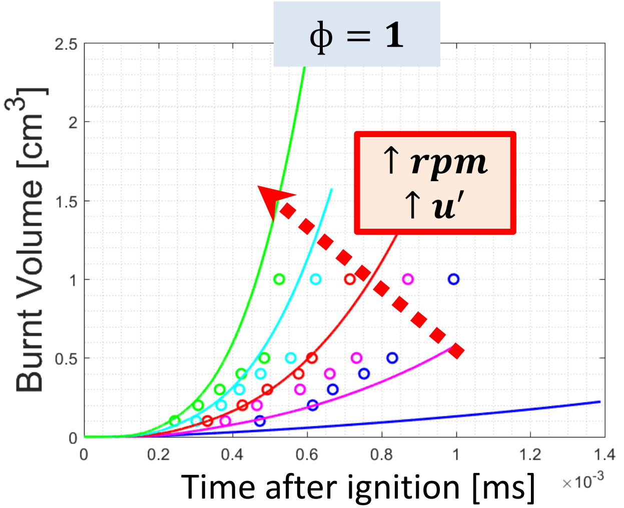
Validations

- Michigan Tech University vessel
- Chiba University vessel
- Herweg-Maly side chamber

Ing. Federico Clerici
M.Sc. thesis work

Legend:
- Num. data — red line
- Exp. Data — red circle
- 300 RPM — blue
- 500 RPM — magenta
- 750 RPM — red
- 1000 RPM — cyan
- 1250 RPM — green

Flame burnt volume



Model calibration at:
$\phi = 1$ $speed = 750\ rpm$

As expected, if $\uparrow rpm$

$\uparrow$ flame front velocity is a $\left(u'_{num} - u'_{exp}\right) \uparrow$ under an $\uparrow u'$

$\uparrow$ numerical flame front speed

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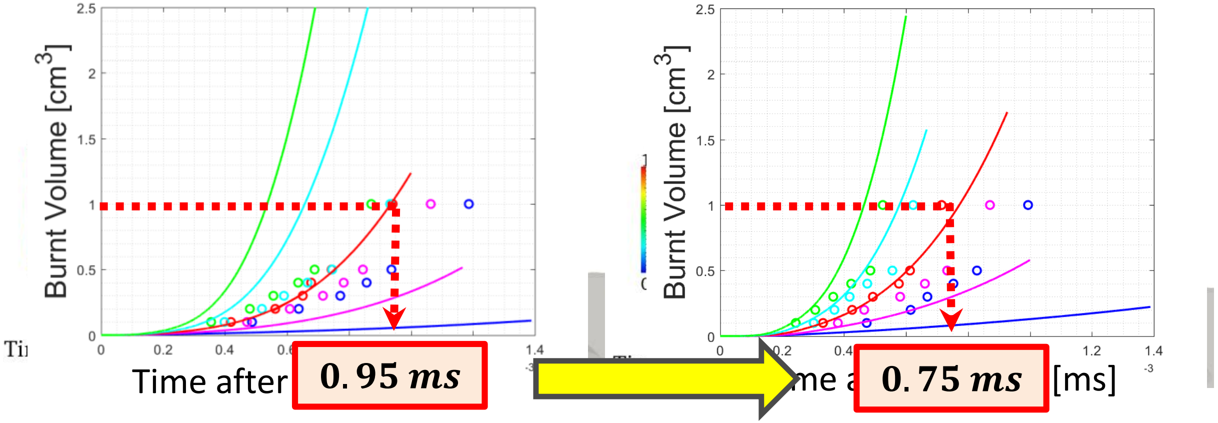
Model calibration at:
$\phi = 1$ $\quad speed = 750\ rpm$

Flame burnt volume

Central ignition | Peripheral ignition



↑ **flame front velocity** is achieved going to **peripheral ignition, because** ↑ u' when ↑ $r_{side\ chamber}$

Conclusions

SI combustion engine modeling using the Open-FOAM® technology

- The developed **modeling approaches** for SI combustion allow to **model with different complexities the ignition stage**

  a) ↓ detail → *Eulerian-only* model

  b) ↑ detail → *Lagrangian-Eulerian* model

  ⇨ Useful to fulfill different requests

- The proposed approaches are **validated** for **simulating diluted mixture conditions**

Future developments

SI combustion engine modeling using the Open-FOAM® technology

- The ***Lagrangian-Eulerian* model** is **ready** to be tested on research engines conditions, in order **to study innovative**:
  - *a) Ignition strategies*
  - *b) Combustion modes*

  ⇒ Strongly diluted and stratified mixtures

- The ***Eulerian-only* model** can be exploited to provide **more insight on innovative *Air-Fuel* mixtures combustion**:
  - a) with *low computational costs*
  - b) where the *first target* is to understand the *turbulent combustion stage*

  → Low-carbon fuels

Thank you for your attention!

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