On the Polydisperse spray flames in turbulent flows using the 3D Euler-Euler approach

L. Fréret[⋆], O. Thomine[♢], J. Réveillon[♢]

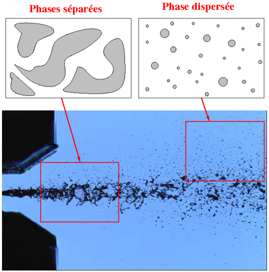
S. de Chaisemartin[♮], F. Laurent[♯], M. Massot[♯]

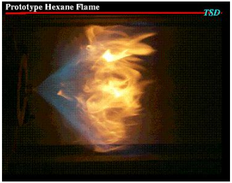
[⋆] Laboratoire LIP - UMR 7623
[♢] Laboratoire CORIA, UMR 6614
[♮] Institut Français du pétrole
[♯] Laboratoire EM2C - Ecole Centrale Paris, UPR 288

New combustion chamber concepts ⇒ unsteadyness

Dispersed liquid phase
+
Large size spectrum

- Mixing of fuel vapor mass fraction and gazeous air
- stabilization
- combustion regimes

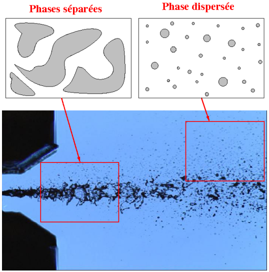


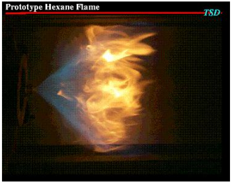


Modeling of the polydisperse spray

- Droplet / gas interactions
  ⇒ evaporation, drag and heat transfer
- Droplet / droplet interactions
  ⇒ Coalescence, break-up

Key parameter : size





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$f^{\Phi}(t, x, \Phi, u_l, T_l)$: droplet density number (NDF)

Transport Equation of Williams-Boltzmann type

$$\underbrace{\partial_t f^{\Phi} + \partial_x.(u_l f^{\Phi})}_{\text{free transport}} + \underbrace{\partial_{\Phi}(R_{\Phi} f^{\Phi})}_{\text{evaporation}} + \underbrace{\partial_{u_l}.(F f^{\Phi})}_{\text{drag}} + \underbrace{\partial_{T_l}.(E f^{\Phi})}_{\text{heat transfer}} = \Gamma$$

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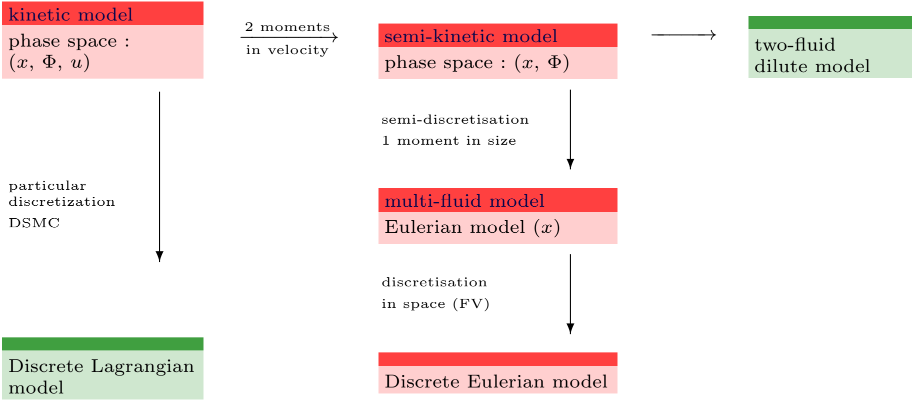
Modeling of the polydisperse spray



kinetic model

phase space : $(x,\ \Phi,\ u)$

$\xrightarrow[\text{in velocity}]{\text{2 moments}}$

semi-kinetic model

phase space : $(x,\ \Phi)$

$\longrightarrow$

two-fluid dilute model

particular discretization
DSMC

Discrete Lagrangian model

semi-discretisation
1 moment in size

multi-fluid model

Eulerian model (x)

discretisation
in space (FV)

Discrete Eulerian model

Advantages & drawbacks

Lagrangian model :

- Modelisation
- Implementation
- gas-liquid coupling
- MPI parallelization

Eulerian model :

- Modelisation
- Implementation
- gas-liquid coupling
- MPI parallelization

Eulerian multi-fluid model

Conservation equations for each size interval :

$$\begin{aligned}
\partial_t m^{(j)} + \partial_x.(m^{(j)} u_d^{(j)}) &= -(E_1^{(j)} + E_2^{(j)}) m^{(j)} + E_1^{(j+1)} m^{(j+1)} \\
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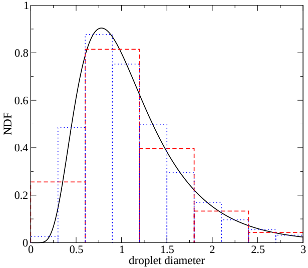

Eulerian multi-fluid model

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- Discretization of the size phase space is first order of accurate *(Laurent 2001)*
  number of sections (j) = number of equation systems
  number of sections increases dimension problem
- Recent developments of high order size moments
  (PhD Thesis of D. Kah, 2010)

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- Recent developments of high order size moments
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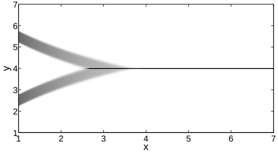
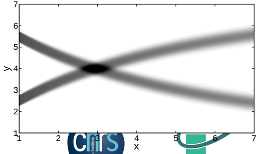
- mono-kinetic assumption at a given size, location and time
  Equivalent to pressureless gas dynamics

multi-fluid model



multi-velocity model



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Strang splitting algorithm :

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  - ODE equation

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- Transport in physical space during Δt
  - weakly hyperbolic equation

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- Transport in phase space during $\Delta t/2$ (evaporation, drag)
    - ODE equation
- Transport in physical space during Δt
    - weakly hyperbolic equation
- Transport in phase space during $\Delta t/2$
    - ODE equation

- divide problems into small sub-problems
- second order in time and space

II) ODE resolution

stiffness :

- evaporation, heat : temperature gradient
- drag : $F = \dfrac{1}{St}(\mathbf{U}_g - \mathbf{u}_l)$

RadauIIA method *(Hairer)*

5$^{\text{th}}$ order in time, implicit RK, adaptative time step

III) Transport scheme

Strang dimensional splitting :

$$\Delta t \text{ transport} \Longrightarrow \begin{cases} \text{transport in x-direction during } \Delta t/2 \\ \text{transport in y-direction during } \Delta t/2 \\ \text{transport in z-direction during } \Delta t \\ \text{transport in y-direction during } \Delta t/2 \\ \text{transport in x-direction during } \Delta t/2 \end{cases}$$

Equations equivalent to pressureless gas systems $\Longrightarrow \begin{cases} \partial_t \rho + \partial_x(\rho v) = 0 \\ \partial_t(\rho v) + \partial_x(\rho v^2) = 0 \end{cases}$

- Burger equation on velocity :
  - delta-shocks creation, vacuum density formation
- finite volume kinetic scheme *(Bouchut 2003)*
  - able to deal with delta-shocks and vacuum density
  - properties conservation
    - positivity of density
    - maximum principle on velocity

III) Transport scheme

Strang dimensional splitting :

transport scheme in 1D, CFL=1

very limited numerical diffusion

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Muses3D code

- MUlti-fluid Solver for Eulerian Spray *(S. de Chaisemartin, L. Freret)*
- http ://www.projet-plume.org/relier/muses3d
- multi-dimensional : 1D, 2D, 2D-axi, 3D
- multi-solver
    - multi-fluid model
    - mutli-fluid multi-velocity model
    - multi-fluid multi-size model
- gas/droplet interactions
    - evaporation
    - drag
    - heat transfer
- droplet/droplet interactions
    - collisions

I) 3D Non-evaporating spray dispersion in a HIT gas flow

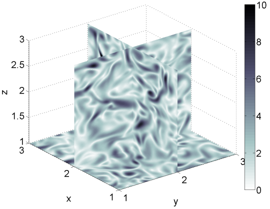
Goals

- Spray repartition study in a 3d instationnary context
- Comparisons between Eulerian and Lagrangian liquid phase
- Coupling multi-fluid with Euler-Lagrange code Asphodele (J. Réveillon, Coria)

(Fréret & al., ICMF 2010)

Gas phase

- Homogeneous isotropic turbulent instationnary flow
- Re=1000, turbulence forcing method
- Spatial discretization 129^3

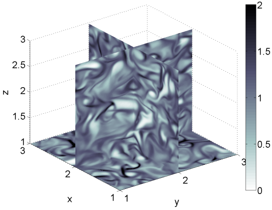


vorticity field

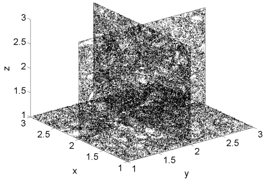
I) 3D Non-evaporating spray dispersion in a HIT gas flow

Liquid phase

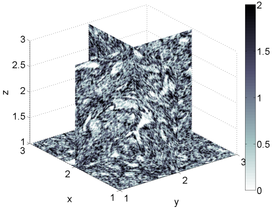
- Homogeneous repartition of the spray liquid phase
- Non-evaporating mono-dispersed droplets, Stokes=0.2
- only 1 section for MF model
- 1 droplet per mesh cell $\simeq$ total particle number 2,150,100



Eul. density



Lag. position

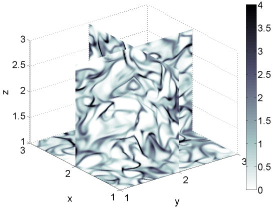


Lag. density

I) 3D Non-evaporating spray dispersion in a HIT gas flow

Liquid phase

- Homogeneous repartition of the spray liquid phase
- Non-evaporating mono-dispersed droplets, Stokes=1
- only 1 section for MF model
- 1 droplet per mesh cell $\simeq$ total particle number 2,150,100



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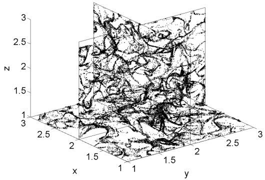

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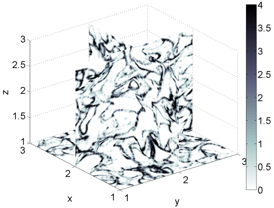

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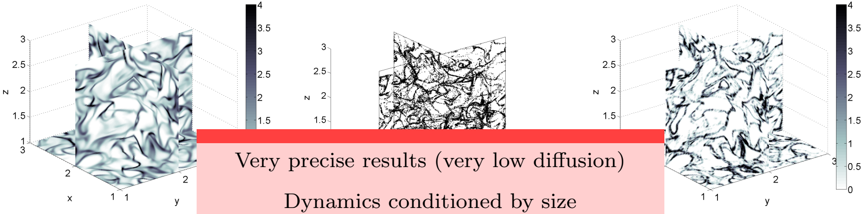


Very precise results (very low diffusion)

Dynamics conditioned by size

I) 3D Non-evaporating spray dispersion in a HIT gas flow

Scientific computing

- Entire gas velocity field known on each core
- No evaporation / no collision $\Longrightarrow$ droplets are independent
- Equivalent to Monte Carlo simulations
  - no communication between cores
  - optimal parallelization for the Lagrangian liquid phase
- 32 cores $\Longrightarrow$ total particule number / 32 = 65,000 per core

II) Flame propagation from a hot spot in a monodispersed spray 2D

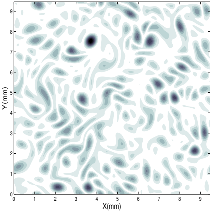
Goals

- Capacity of the multi-fluid method to simulate combustion process
- Influence of segregation onto evaporation and combustion process
- Cool flame configuration (no heat transfer)
- Comparisons between Eulerian and Lagrangian liquid phase

(Fréret & al., CTR 2010)

Gas phase

- Homogeneous isotropic turbulent instationnary flow
- Re=1000, turbulence forcing method
- Spatial discretization 256^2
- Hot spot in the domain center



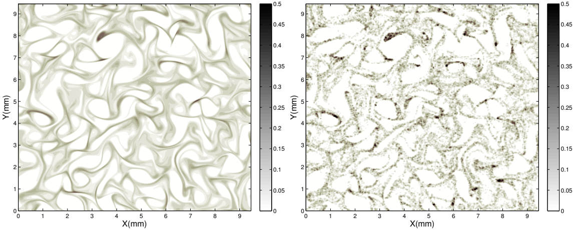
vorticity field

II) Flame propagation from a hot spot in a monodispersed spray 2D

Liquid phase

- Heterogeneous repartition of the spray liquid phase
- Evaporating initially mono-dispersed droplets, Stokes=0.2
- 20 sections for MF model (discretization : 512^2)
- 1 droplet per mesh cell $\simeq$ total particle number 70,000

Eul. density Lag. density



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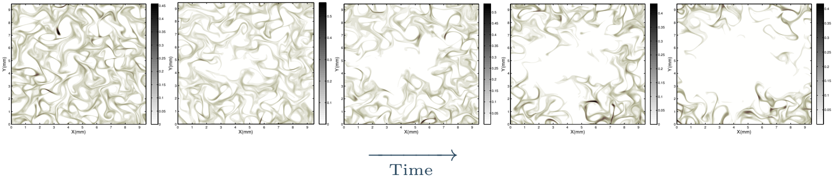
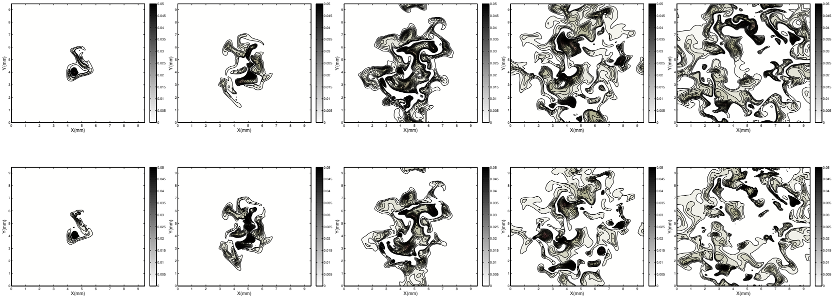
Evolution of Eulerian mass density repartition



II) Flame propagation from a hot spot in a monodispersed spray 2D

Fuel mass fraction comparison (top : Eulerian, bottom : Lagrangian)



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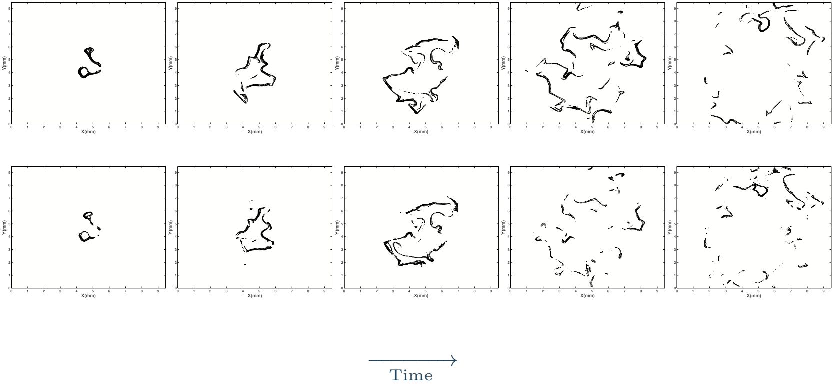
Front flame propagation (top : Eulerian, bottom : Lagrangian)



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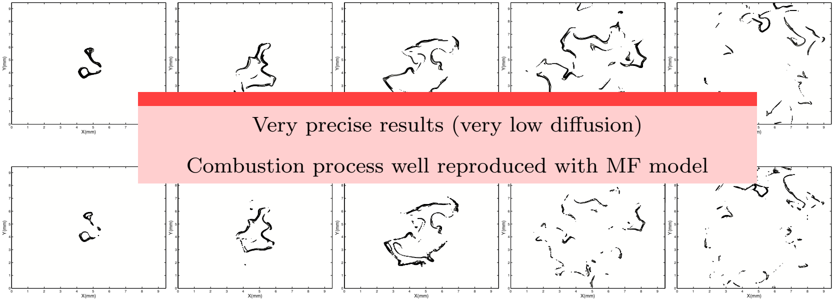

Very precise results (very low diffusion)

Combustion process well reproduced with MF model

$\longrightarrow$

Time

II) Flame propagation from a hot spot in a monodispersed spray 3D

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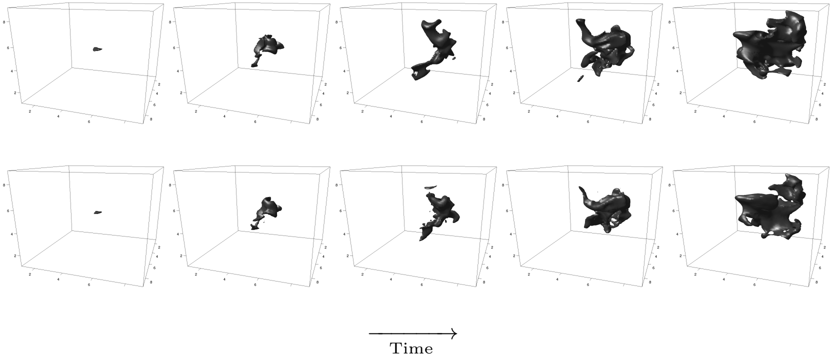

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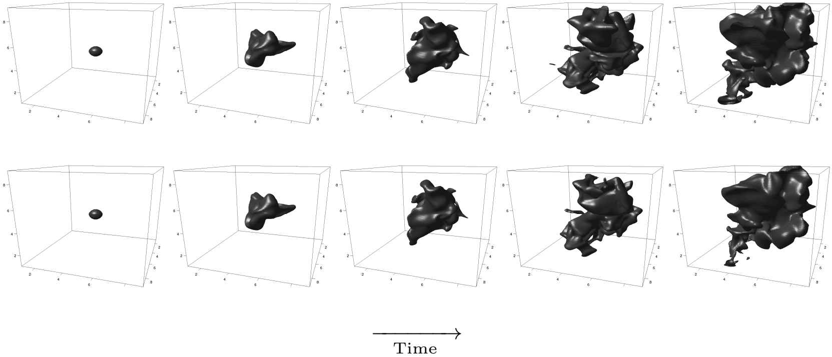
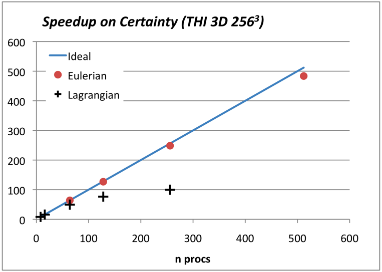


II) Flame propagation from a hot spot in a monodispersed spray 3D

Scientific computing

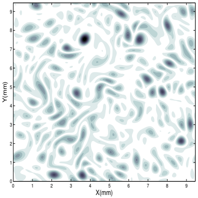
- Evaporation process $\Longrightarrow$ exchange between gas and liquid phase
- Classical spatial domain decomposition
  - a lot of communication between cores for the Lagrangian liquid phase
- 512 cores $\Longrightarrow$ total particule number / 512 $\simeq$ 5,000 per core



III) Flame propagation from a hot spot in a polydispersed spray 2D

Liquid phase

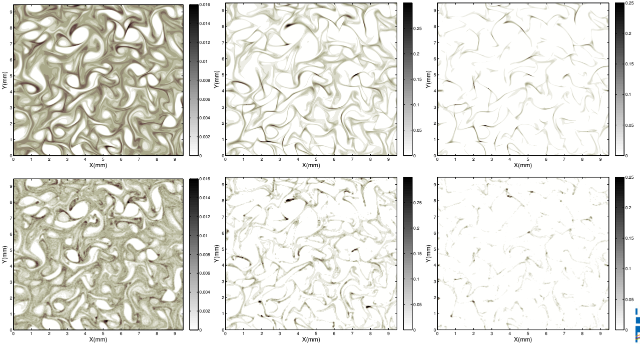
- Heterogeneous repartition of the spray liquid phase
- Evaporating initially poly-dispersed droplets, Stokes $= 0 \longrightarrow 1.32$
- 20 sections for MF model / 100 droplets per mesh cell $\simeq$ total $> 6{,}500{,}000$



vorticity field

Eul. density

$0 < St < 0.1$ $0.25 < St < 0.42$ $0.9 < St < 1.32$



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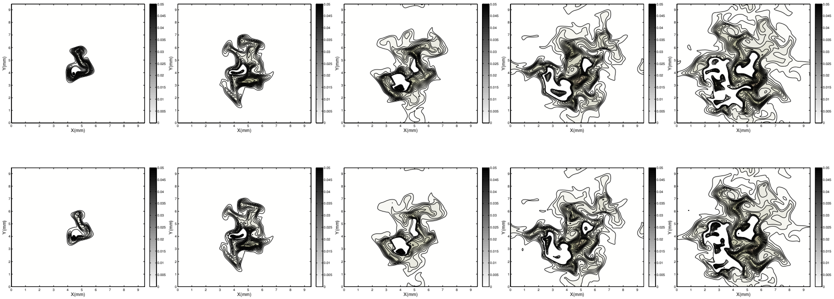

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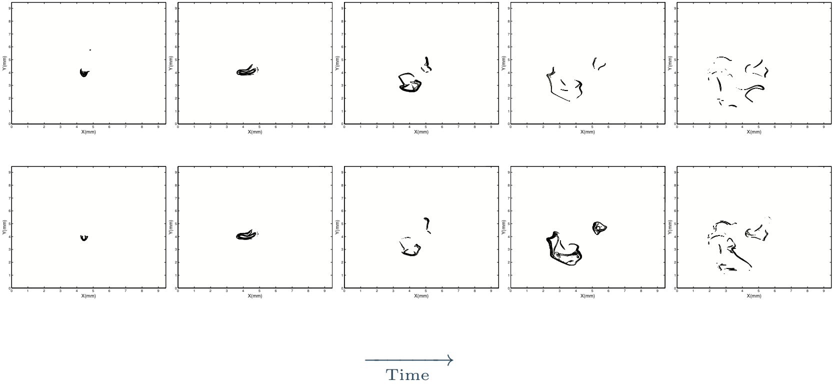

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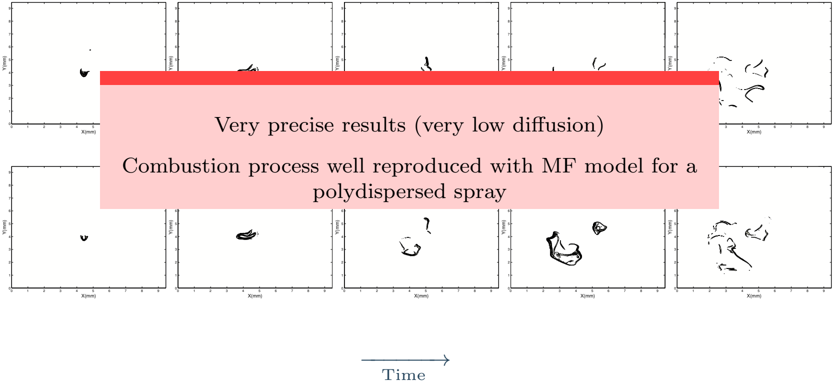


Very precise results (very low diffusion)

Combustion process well reproduced with MF model for a polydispersed spray

Introduction

Numerical methods

Numerical simulations

Conclusions & Perspectives

Conclusions

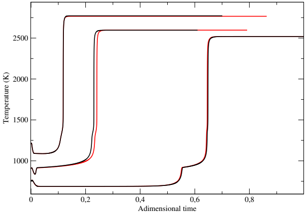
- Capacity of the multi-fluid method to deal with 3d configurations
- Comparison of combustion process between Lagrangian & Eulerian description
- Qualitative & quantitative comparisons between Eul. and Lag. model
- Use of numerical method adapted to parallel computing
- Splitting algorithm
  - Transport in phase space / Transport in physical space
  - Dimensional splitting
- Very good scaling

Perspectives

- 3D combustion process with a polydispersed evaporating spray
- Take into account heat tranfer
- Comparison of auto-ignition delay (PhD. of Zakaria Bouali)

First results

- Homogeneous spray liquid repartition
- Quiescent atmosphere
- Complex kinetic
- Heat transfer
- Initial temperature gas : 750K, 900K et 1200K



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