

## A new model for spray interactions.

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Colliding jets Crossing jets

Conclusions

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### Introduction



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#### Context

- Diesel engines,
- Ariane boosters,
- Aerosols.

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#### Ø Goal :

- Having a test code able to deal with various applications,
  - Treating cases with numerous droplets of different sizes,
  - Establishing test cases.

#### The basic model



Droplets are injected into a gas.

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2 Euler equations are used for the motion of the gas.3 A kinetic model is set for droplets.

### Unknowns



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- u<sub>p</sub> : droplet velocity,
- $e_p, T_p$ : internal energy and temperature of a droplet,
- r : droplet radius,
- *ρ<sub>p</sub>* : droplet density,
- *m<sub>p</sub>* : droplet mass
- $f(t, x, u_p, e_p, r)$  : droplet density function ,
- Q : collision kernel,
- Q<sub>b</sub> : break-up kernel,
- ρ : gas density,
- u : gas velocity,
- e : gas internal energy,
- p : gas pressure,
- T : gas temperature,
- $\alpha$  : gas volume fraction,

### Constants

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- $\lambda$  : gas thermal conductivity,
- η : gas dynamic viscosity,
- C : gas specific heat,
- $Pr = \frac{\eta C}{\lambda}$  : Prandtl number ,
- Ma :Mach number of the gas,
- $Re = \frac{2r
  ho |u_{
  ho} u|}{\eta}$  : droplet Reynolds number,
- $D_p = \frac{1}{2}\rho\pi r^2 C_d |u_p u|$ : drag coefficient  $C_d(\alpha, Re, Ma)$ ,
- Nu(Re, Pr) : Nusselt number,  $(Nu = 1 + 0.3Re^{1/2}Pr^{1/3})$
- $\Gamma_p = \frac{\partial u_p}{\partial t}$  : droplet acceleration ,
- $\phi_p = \frac{\partial e_p}{\partial t}$  : droplet thermal flux.

#### Set of equations

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$$\partial_{t}(\alpha\rho) + \nabla_{x} \cdot (\alpha\rho u) = 0,$$
  

$$\partial_{t}(\alpha\rho u) + \nabla_{x} \cdot (\alpha\rho u \otimes u) + \nabla_{x}p = -\int_{u_{p}, e_{p}, r} m_{p}\Gamma_{p}fdu_{p}de_{p}dr,$$
  

$$\partial_{t}(\alpha\rho e) + \nabla_{x} \cdot (\alpha\rho eu) + p[\partial_{t}\alpha + \nabla_{x} \cdot (\alpha u)]$$

$$= \int_{u_{\rho},e_{\rho},r} \left[ (m_{\rho} \Gamma_{\rho} + \frac{m_{\rho}}{\rho_{\rho}} \nabla_{x} \rho) \cdot (u - u_{\rho}) - 4\pi r \lambda N u (T - T_{\rho}) \right] f du_{\rho} de_{\rho} dr,$$

$$\begin{split} \alpha &= 1 - \int_{u_{\rho}, e_{\rho}, r} \frac{4}{3} \pi r^{3} f du_{\rho} de_{\rho} dr = 1 - \int_{u_{\rho}, e_{\rho}, r} \frac{m_{\rho}}{\rho_{\rho}} f du_{\rho} de_{\rho} dr, \\ \partial_{t} f + u_{\rho} \cdot \nabla_{x} f + \nabla_{u_{\rho}} \cdot (f \Gamma_{\rho}) + \partial_{e_{\rho}} (f \phi_{\rho}) = Q(f, f) + Q_{b}(f), \end{split}$$

$$\begin{split} m_p \Gamma_p &= -\frac{4}{3} \pi r^3 \nabla_x p - D_p (u_p - u), \\ m_p \phi_p &= 4 \pi r \lambda N u (T - T_p), \\ p &= P(\rho, e), \\ e_p &= E(T_p). \end{split}$$

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## Motivations

#### Why a new model?

• Difficulties arise with small gas volume fractions.

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- Lagrangian/Eulerian simulations are costly and badly scalable on a parallelism level : we need to make computations on droplets as less as possible and choose properly the ones we keep.
- Methods of moments for the droplet density functions have proven to be efficient for some applications (work of M.MASSOT AND AL. :'Eulerian quadrature based moment models for dilute polydisperse evaporating sprays').

#### Some remarks on the current model

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- For small radii, droplets are rapidly at equilibrium with the gas (velocity/pressure/temperature) due to exchange terms : caracteristic times for droplets are proportionnal to  $r^2$ .
- Droplets can break up so obtaining small radii is frequent : there is always a caracteristic radius (depending on the flow) for which equilibrium can be taken into account.

### Basis of the new model



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- We separate the phase space of the droplet density function in two parts :
  - the first part is made of droplets at equilibrium with the gas (velocity, pressure and temperature),
  - the second one contains the remaining droplets.
  - Droplets at equilibrium are solved through a mix model.
- Others are still solved through a kinetic equation.

# Toy model

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$$\partial_t(\rho) + \nabla_x \cdot (\rho u) = 0,$$
  
$$\partial_t(\rho u) + \nabla_x \cdot (\rho u \otimes u) + \nabla_x p = -\int_{u_p, e_p, r} m_p \Gamma_p f du_p de_p dr,$$

$$\begin{aligned} \partial_t f + u_p \cdot \nabla_x f + \nabla_{u_p} \cdot (f \Gamma_p) &= Q_b(f), \\ m_p \Gamma_p &= -D_p (u_p - u), \\ p &= P(\rho). \end{aligned}$$

We split f in two parts :

$$f = f_1(t, x, v) + f_2(t, x, v).$$
 (1)

 $f_1$  (resp.  $f_2$ ) is a droplet density function for droplets of radius  $r_1$  (resp.  $r_2$ ).

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# Toy model (2)



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$$\begin{aligned} \partial_t f_1 + u_p \cdot \nabla_x f_1 + \nabla_{u_p} \cdot (f_1 \Gamma_1) &= -Ff_1, \\ \partial_t f_2 + u_p \cdot \nabla_x f_2 + \nabla_{u_p} \cdot (f_2 \Gamma_2) &= Ff_1 \left(\frac{r_1}{r_2}\right)^3, \\ \Gamma_1 &= \frac{D}{r_1^2} (u - u_p), \\ \Gamma_2 &= \frac{D}{r_2^2} (u - u_p). \end{aligned}$$

# Toy model (3)



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Let's define 
$$arepsilon=r_2/r_1$$
. We get

$$\begin{split} \partial_t(\rho^{\varepsilon}) &+ \nabla_x \cdot (\rho^{\varepsilon} u^{\varepsilon}) = 0, \\ \partial_t(\rho^{\varepsilon} u^{\varepsilon}) &+ \nabla_x \cdot (\rho^{\varepsilon} u^{\varepsilon} \otimes u^{\varepsilon}) + \nabla_x p^{\varepsilon} \\ &= \rho_p \int_{u_p} \left( \frac{D_3^4 \pi r_1^3}{r_1^2} f_1 + \frac{D_3^4 \pi \varepsilon^3 r_1^3}{\varepsilon^2 r_1^2} f_2 \right) (u_p - u^{\varepsilon}) du_p, \end{split}$$

$$\partial_t f_1 + u_p \cdot \nabla_x f_1 + \nabla_{u_p} \cdot (f_1 D \frac{u^{\varepsilon} - u_p}{r_1^2}) = -Ff_1,$$

$$\partial_t f_2 + u_p \cdot \nabla_x f_2 + \nabla_{u_p} \cdot (f_2 D \frac{u^{\varepsilon} - u_p}{\varepsilon^2 r_1^2}) = F f_2 \left(\frac{1}{\varepsilon}\right)^3,$$
  
$$\rho = P(\rho^{\varepsilon}).$$

### Kinetic energy : limit when $\varepsilon \rightarrow 0$ (1)

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$$\partial_{t} \left( \left(\frac{1}{2}\rho^{\varepsilon}(u^{\varepsilon})^{2}\right) + \frac{c}{\gamma - 1}\left(\rho^{\varepsilon}\right)^{\gamma} \right) + \nabla_{x} \cdot \left(\frac{1}{2}\rho^{\varepsilon}(u^{\varepsilon})^{2}u^{\varepsilon}\right) = \\\rho_{\rho}u^{\varepsilon} \left[ \int_{u_{\rho}} f_{1}\frac{D_{4}^{4}\pi r_{1}^{3}}{r_{1}^{2}}(u_{\rho} - u^{\varepsilon})du_{\rho} + \int_{u_{\rho}} f_{2}\frac{D_{4}^{4}\pi\varepsilon^{3}r_{1}^{3}}{\varepsilon^{2}r_{1}^{2}}(u_{\rho} - u^{\varepsilon})du_{\rho} \right], \\\partial_{t}\int_{u_{\rho}} f_{1}\rho_{p}\frac{u_{\rho}^{2}}{2}du_{\rho} + \nabla_{x} \cdot \left( \int_{u_{\rho}} f_{1}\rho_{p}\frac{u_{\rho}^{2}}{2}u_{\rho}du_{\rho} \right) = \\\int f_{1}\frac{D}{r_{1}^{2}}(u_{\rho} - u^{\varepsilon}) \cdot du_{\rho} - \int Ff_{1}\rho_{p}\frac{u_{\rho}^{2}}{2},$$

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#### Kinetic energy : limit when $\varepsilon \rightarrow 0$ (2)



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$$\partial_t \int_{u_p} f_2 \rho_p \frac{u_p^2}{2} du_p + \nabla_x \cdot \left( \int_{u_p} f_2 \rho_p \frac{u_p^2}{2} u_p du_p \right) = \int_{u_p} f_2 \frac{D}{\varepsilon^2 r_2^2} (u_p - u^\varepsilon) \cdot du_p + \frac{1}{\varepsilon^3} \int_{u_p} Ff_1 \rho_p \frac{u_p^2}{2}.$$

#### Kinetic energy : limit when $\varepsilon \rightarrow 0$ (3)



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$$\begin{split} \partial_t \left( \left(\frac{1}{2} \rho^{\varepsilon} (u^{\varepsilon})^2 \right) + \frac{c}{\gamma - 1} (\rho^{\varepsilon})^{\gamma} \right) + \nabla_x \cdot \left(\frac{1}{2} \rho^{\varepsilon} (u^{\varepsilon})^2 u^{\varepsilon} \right) + \\ \partial_t \int_{u_p} f_1 \frac{4}{3} \pi \rho_p r_1^3 \frac{u_p^2}{2} du_p + \nabla_x \cdot \int_{u_p} f_1 \frac{4}{3} \pi \rho_p r_1^3 \frac{u_p^2}{2} u_p du_p + \\ \partial_t \int_{u_p} f_2 \frac{4}{3} \pi \rho_p \varepsilon^3 r_1^3 \frac{u_p^2}{2} du_p + \nabla_x \cdot \int_{u_p} f_2 \frac{4}{3} \pi \rho_p \varepsilon^3 r_1^3 \frac{u_p^2}{2} u_p du_p = \\ -\rho_p \left[ \int_{u_p} f_1 \frac{D \frac{4}{3} \pi r_1^3}{r_1^2} (u_p - u^{\varepsilon})^2 du_p + \int_{u_p} f_2 \frac{D \frac{4}{3} \pi \varepsilon^3 r_1^3}{\varepsilon^2 r_1^2} (u_p - u^{\varepsilon})^2 du_p \right]. \end{split}$$

By letting tend  $\varepsilon$  to zero (at a constant mass for small droplets *i.e.*  $\int_{u_p} f_2 \frac{4}{3} \pi \rho_p \varepsilon^3 r_1^3 du_p = cte$ ), we must have  $\int_{u_p} f_2 \frac{D \frac{4}{3} \pi r_1^3}{r_1^2} (u_p - u^{\varepsilon})^2 du_p = O(\varepsilon^2)$ , in order to keep kinetic energy positive, so that  $f_2$  is a Dirac mass in velocity (the

gas velocity).

#### New set of equations

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Let's 
$$\tilde{\rho}(t, x)$$
 be defined by  $\int_{u_p} f_2 \frac{4}{3} \rho_p \varepsilon^3 r_1^3 du_p$  a partial droplet density, then we get

the following system :

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$$\partial_t(\tilde{\rho}) + \nabla_x \cdot (\tilde{\rho}u) = \rho_p \frac{4}{3} \pi r_1^3 \int_{u_p} Ff_1 du_p,$$

$$\partial_t((\rho+\tilde{\rho})u) + \nabla_x \cdot ((\rho+\tilde{\rho})u \otimes u) + \nabla_x p = -\rho_p \int_{u_p} \left( \frac{D_3^4 \pi r_1^3}{r_1^2} f_1 \right) (u-u_p) du_p,$$

$$+\int_{u_p} \left( F\frac{4}{3}\rho_p \pi r_1^3 f_1 \right) u_p du_p$$

 $\partial_t(\rho) + \nabla_x \cdot (\rho \mu) = 0.$ 

$$\partial_t f_1 + u_p \cdot \nabla_x f_1 + \nabla_{u_p} \cdot (f_1 D \frac{u - u_p}{r_1^2}) = -Ff_1,$$
  
$$p = P(\rho).$$

### Mix model

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Let's define  $\rho_m = \rho + \tilde{\rho}$ , the gas mass concentration  $c^+ = \frac{\rho}{\rho_m}$  and the small droplet concentration  $c^- = \frac{\tilde{\rho}}{\rho_m}$ . We get :

$$\partial_t(\rho_m c^+) + \nabla_x \cdot (\rho_m c^+ u) = 0,$$
  
$$\partial_t(\rho_m c^-) + \nabla_x \cdot (\rho_m c^- u) = \rho_p \frac{4}{3} \pi r_1^3 \int_{u_p} Ff_1 du_p,$$

$$\partial_t(\rho_m u) + \nabla_x \cdot (\rho_m u \otimes u) + \nabla_x p = -\rho_p \int_{u_p} \left( \frac{D_3^4 \pi r_1^3}{r_1^2} f_1(u - u_p) \right) du_p de_p dr$$

$$+\int_{u_p} \left( F\frac{4}{3}\rho_p \pi r_1^3 f_1 \right) u_p du_p$$

$$\begin{aligned} \partial_t f_1 + u_p \cdot \nabla_x f_1 + \nabla_{u_p} \cdot (f_1 D \frac{u - u_p}{r_1^2}) &= -Ff_1, \\ c^+ + c^- &= 1, \\ \rho &= P(\rho). \end{aligned}$$

### Hydrodynamic limit for thick sprays



Let's define :

$$\beta = \int_{u_p, e_p, r} \frac{4}{3} \pi r_2^3 f_2 du_p de_p dr,$$

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$$\partial_{t}(\alpha\rho) + \nabla_{x} \cdot (\alpha\rho u) = 0,$$
  

$$\partial_{t}(\beta\rho_{p}) + \nabla_{x} \cdot (\beta\rho_{p}u) = \int_{u_{p},e_{p},r} Ff_{1}\rho_{p}\frac{4}{3}\pi r_{1}^{3}du_{p}de_{p}dr,$$
  

$$\partial_{t}((\alpha\rho + \beta\rho_{p})u) + \nabla_{x} \cdot ((\alpha\rho + \beta\rho_{p})u \otimes u) + \alpha_{m}\nabla_{x}p = \int_{u_{p},e_{p},r} m_{1}\frac{D}{r_{1}^{2}}(u_{p} - u)f_{1}du_{p}de_{p}dr + \int_{u_{p},e_{p},r} Ff_{1}\rho_{p}\frac{4}{3}\pi r_{1}^{3}u_{p}du_{p}de_{p}dr,$$

## Hydrodynamic limit for thick sprays

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$$\partial_t (\alpha \rho \mathbf{e} + \beta \rho_p \mathbf{E}_p) + \nabla_x \cdot ((\alpha \rho \mathbf{e} + \beta \rho_p \mathbf{E}_p) \mathbf{u}) + p[\partial_t \alpha_m + \nabla_x \cdot (\alpha_m \mathbf{u})]$$

$$= \int_{u_{\rho},e_{\rho},r} \left[ (m_{\rho} \Gamma_{\rho} + \frac{m_{\rho}}{\rho_{\rho}} \nabla_{x} p) \cdot (u - u_{\rho}) - 4\pi r \lambda N u (T - T_{\rho}) \right] f_{1} du_{\rho} de_{\rho} dr$$

$$+\rho_{p}\frac{4}{3}\pi r_{1}^{3}\int_{u_{p},e_{p},r}Ff_{1}e_{p}du_{p}de_{p}dr+p\frac{4}{3}\pi r_{1}^{3}\int_{u_{p},e_{p},r}Ff_{1}du_{p}de_{p}dr,$$

$$\alpha_m = 1 - \int\limits_{u_p, e_\rho, r} \frac{4}{3} \pi r^3 f_1 du_p de_\rho dr = 1 - \int\limits_{u_p, e_\rho, r} \frac{m_\rho}{\rho_\rho} f_1 du_p de_\rho dr,$$

 $\partial_t f_1 + u_p \cdot \nabla_x f_1 + \nabla_{u_p} \cdot (f_1 \Gamma_1) + \partial_{e_p} (f_1 \phi_1) = -Ff_1 + Q_1(f_1, f_1),$ 

$$\Gamma_1 = -\frac{D}{r_1^2}(u_p - u) - \frac{m_1}{\rho_p} \nabla_x p$$

$$m_1\phi_1 = 4\pi r_1 \lambda N u(r_1)(T - T_\rho),$$
  

$$p = P(\rho, T),$$
  

$$E_\rho = E(T),$$

$$e_p = E(T_p).$$

### Mix model for thick sprays

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$$\partial_{t}(\alpha_{m}\rho_{m}c^{+}) + \nabla_{x} \cdot (\alpha_{m}(\rho_{m}c^{+}u)) = 0,$$
  

$$\partial_{t}(\alpha_{m}\rho_{m}c^{-}) + \nabla_{x} \cdot (\alpha_{m}\rho_{m}c^{-}u) = \rho_{p}\frac{4}{3}\pi r_{1}^{3}\int_{u_{p}}Ff_{1}(u_{p}-u)du_{p}de_{p}dr,$$
  

$$\partial_{t}(\alpha_{m}\rho_{m}u) + \nabla_{x} \cdot (\alpha_{m}\rho_{m}u \otimes u) + \alpha_{m}\nabla_{x}p =$$
  

$$\int_{u_{p},e_{p},r}m_{1}\frac{D}{r_{1}^{2}}(u_{p}-u)fdu_{p}de_{p}dr + \int_{u_{p},e_{p},r}Ff_{1}\rho_{p}\frac{4}{3}\pi r_{1}^{3}u_{p}du_{p}de_{p}dr,$$
  

$$\partial_{t}\alpha_{m}\rho_{m}e_{m}) + \nabla_{x} \cdot (\alpha_{m}\rho_{m}e_{m})u) + p[\partial_{t}\alpha_{m} + \nabla_{x} \cdot (\alpha_{m}u)]$$

$$= \int_{u_p,e_p,r} \left[ (m_p \Gamma_p + \frac{m_p}{\rho_p} \nabla_x p) \cdot (u - u_p) - 4\pi r \lambda N u (T - T_p) \right] f_1 du_p de_p dr$$
$$+ \int_{u_p,e_p,r} F \rho_p \frac{4}{3} \pi r_1^3 f_1 e_p du_p de_p dr + p \int_{u_p,e_p,r} F \frac{4}{3} \pi r_1^3 f_1 du_p de_p dr,$$

## Mix model



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$$\begin{aligned} \alpha_{m} &= 1 - \int_{u_{p}, e_{p}, r} \frac{4}{3} \pi r^{3} f_{1} du_{p} de_{p} dr = 1 - \int_{u_{p}, e_{p}, r} \frac{m_{p}}{\rho_{p}} f_{1} du_{p} de_{p} dr, \\ \partial_{t} f_{1} &= u_{p} \cdot \nabla_{x} f_{1} + \nabla_{u_{p}} \cdot (f_{1} \Gamma_{1}) + \partial_{e_{p}} (f_{1} \phi_{1}) = -Ff_{1} + Q_{1} (f_{1}, f_{1}), \\ \Gamma_{1} &= -\frac{D}{r_{1}^{2}} (u_{p} - u) - \frac{m_{1}}{\rho_{p}} \nabla_{x} p, \\ m_{1} \phi_{1} &= 4 \pi r_{1} \lambda N u(r_{1}) (T - T_{p}), \\ p &= P(\rho, T), \\ E_{p} &= E(T), \\ e_{p} &= E(T_{p}). \end{aligned}$$

### Some remarks on the mix model



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- The model is obtained for two sizes of droplet,
- Generally a transition radius r<sub>t</sub> is defined because the distribution in droplet sizes is continuous : droplets of radii larger than r<sub>t</sub> are dealt with the Boltzmann equation whereas others are put in the mix,
- Other criteria can be added : for instance in combustion at a given temperature droplets vaporize and can be put in the mix.

## First Test

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droplets moving in the air with the following properties :

We present a case of interactions between two jets of metallic

- the initial droplet radius is  $6\mu m$ ,
- the jet coming from the right is two times heavier than the one from the left,
- the jet coming from the right comes faster  $-2500m.s^{-1}$ ) than the one from the left  $(1800m.s^{-1})$ ,
- the gas is at rest,
- the gas volume fraction is set between 0.95 et 1 in each jet.

We test different transition radii for droplets and compare results

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### First Test : results(1)

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	PRESSION			
	1.165e+05			
	1.160e+05			
	1.155e+05			
	1.150e+05			
	1.145e+05			
	1.141e+05			
	1.1366+05			
Introduction	1.1310+05			
	1.1200+05			
	1.1216+05			
A new model	1 111e+05			
-	1.106e±05			
Context	1.101e+05			
Hydrodynamic	1.096e+05			
limit	1.091e+05			
IIITIIL	1.086e+05		=	
Hvdrodvnamic	1.082e+05			
limit	1.07/0+05			
	1.0/20105			
	1.062e+05			
lest case	1.057e+05			
	1.052e + 05			
Colliding jets	1.047e+05			
Crossing jets	1.042e+05			
crossing jees	1.037e+05			
	1.032e+05			
Conclusions	1.02/e+05			
	1.0180+05			
	1.013e+05			
	1.008e+05			
	1.003e+05			
	9.979e+04			
	9.930e+04			

#### First Test : results (2)

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### First Test : results (3)

CEC

Pressure for different radii of transition  $r_t$ ( $r_t = 0$  (without mix), 20*nm*, 80*nm*)



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#### First Test : results (4)







#### Second Test : crossing jets

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## Second Test : results(1)

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Location of droplets mass for the mix model on the top (strict criterium for radius of transition) and droplet model on the bottom

Introduction	1.182e-09 1.112e-09 1.043e-09 9.731e-10			
A new model	8.341e-10 7.646e.10			
Context	6.951e-10 6.256e-10			
Hydrodynamic limit	5.561e-10 4.866e-10 4.171e-10			
Hydrodynamic limit	3.475e-10 2.780e-10 2.085e-10			
Test case	1.390e-10 6.951e-11 0.000e+00			
Colliding jets	1.372e-09			
Crossing jets	1.292e-09 1.211e-09			
Conclusions	1.130e-09 1.049e-09 9.686e-10 8.879e-10 8.072e-10 7.265e-10 6.4588e-10			
	5.650e-10 4.843e-10 4.035e-10 3.229e-10 2.422e-10 1.614e-10 8.072e-11			
	0.000e+00			

### Second Test : results(2)

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Location of droplets mass for the mix model on the top (large criterium for radius of transition) and droplet model on the bottom

Introduction	1.029e-09 9.686e-10 9.081e-10 8.476e-10 7.870e-10			
A new model	7.265e-10			
Context	6.054e-10 5.449e-10		Carrier Contraction	
Hydrodynamic limit	4.843e-10 4.238e-10 3.632e-10		AND STORE	
Hydrodynamic limit	3.027e-10 2.422e-10 1.816e-10			
Test case	1.211e-10 6.054e-11 0.000e+00			
Colliding jets	1.372e-09			
Crossing jets	1.292e-09 1.211e-09			
Conclusions	1.130e-09 1.049e-09 9.686e-10 8.872e-10			
	8.072e-10 7.265e-10			
	6.458e-10 5.650e-10			
	4.843e-10 4.036e-10			
	3.229e-10 2.422e-10			
	1.614e-10 8.072e-11			
	0.000e+00			

## Conclusions and Perspectives



Introduction

- A new model
- Context Hydrodynamic limit
- Test case

Colliding jets Crossing jets

- The model can deal with various applications.
- More computations are needed to understand the transition towards mix.
- More realistic data should be used for tests.