# Aluminium Combustion Model

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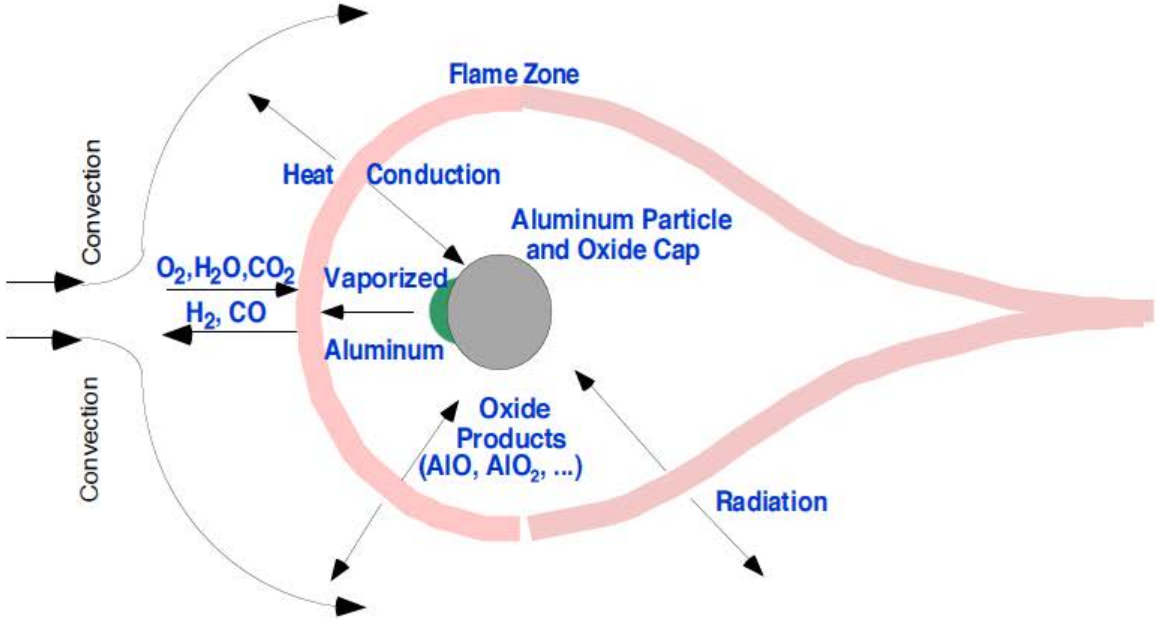
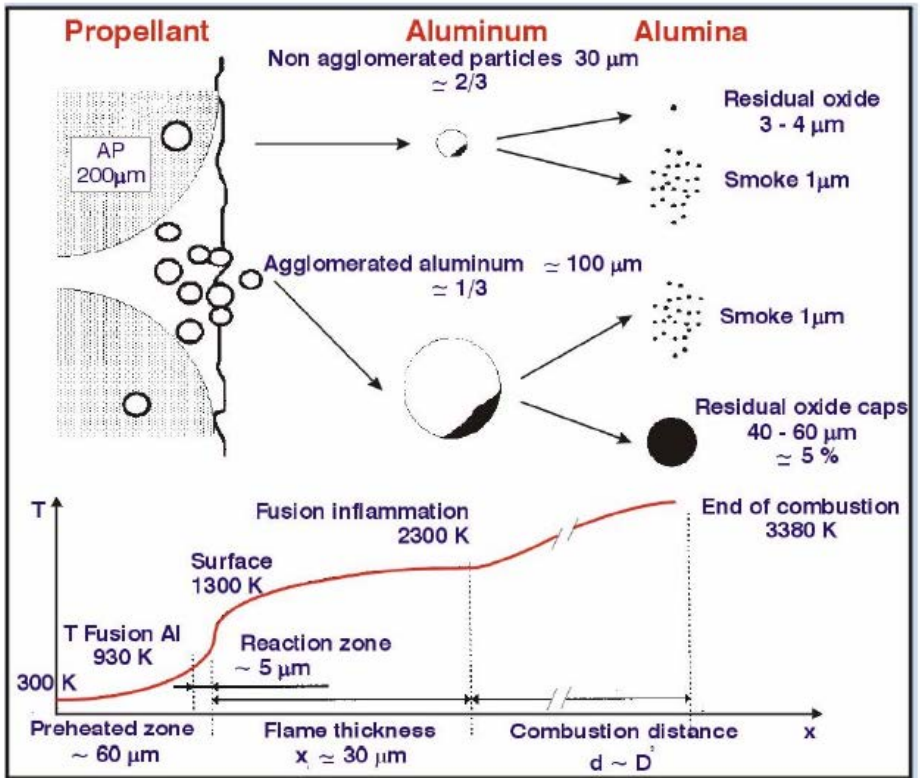



# PHYSICAL PHENOMENON

# Aluminum in a Composite Propellant

✓ Typically two families of particle leave the propellant surface:



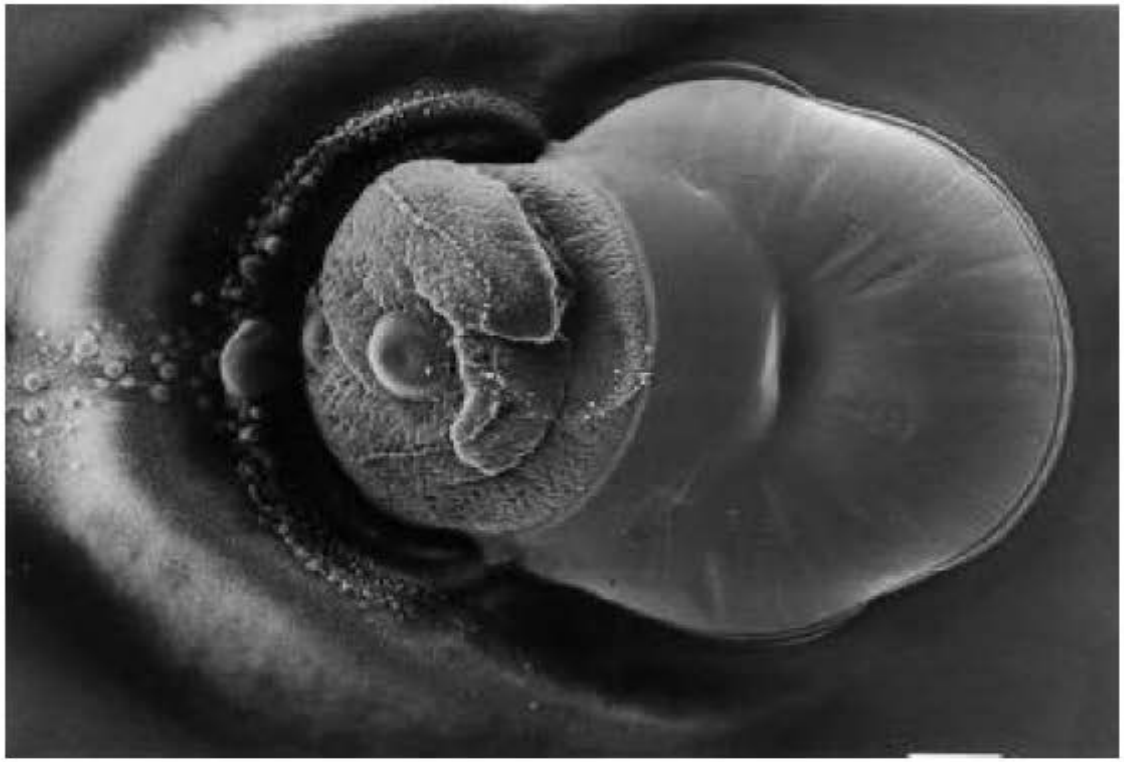

- small, non –agglomerate particles (i.e. ≈30µm)
- large agglomerate (i.e.≈100µm)

✓ The above size distribution is the most commonly investigated.

✓ Actual values change with propellant composition, granulometry, operative pressure and temperature.

* G. Lengellé et al. (2004).

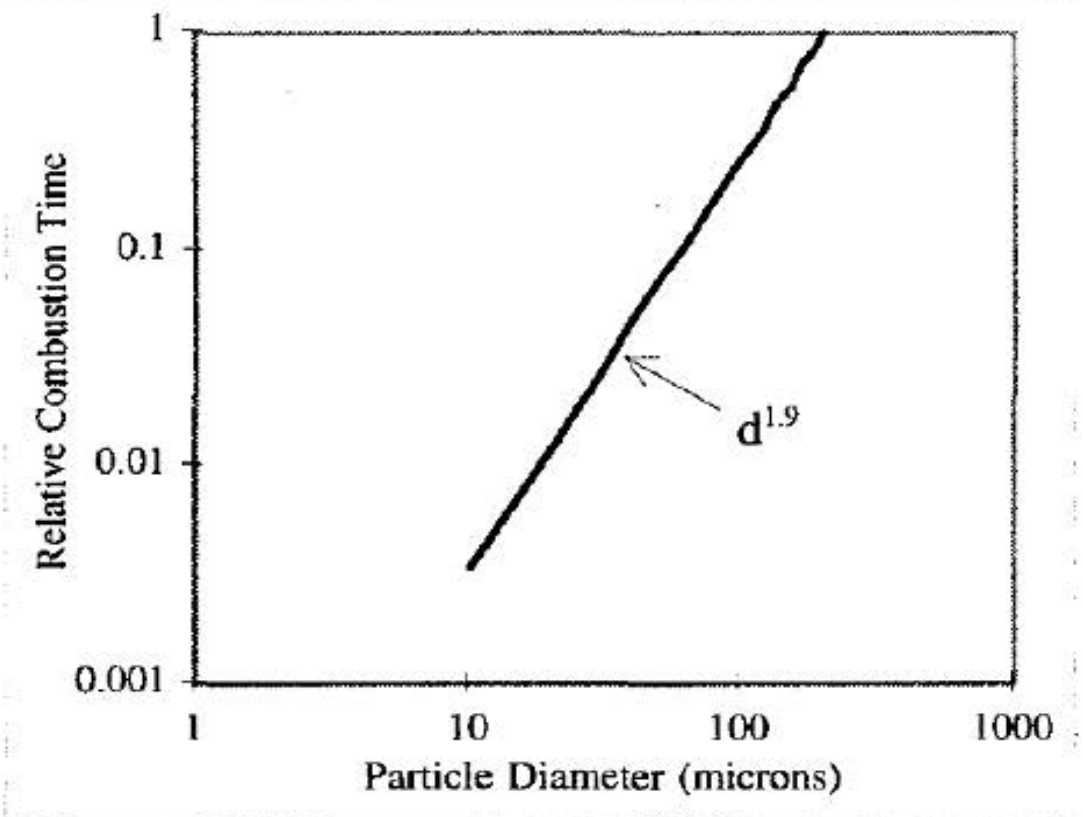
# Agglomerated Particles

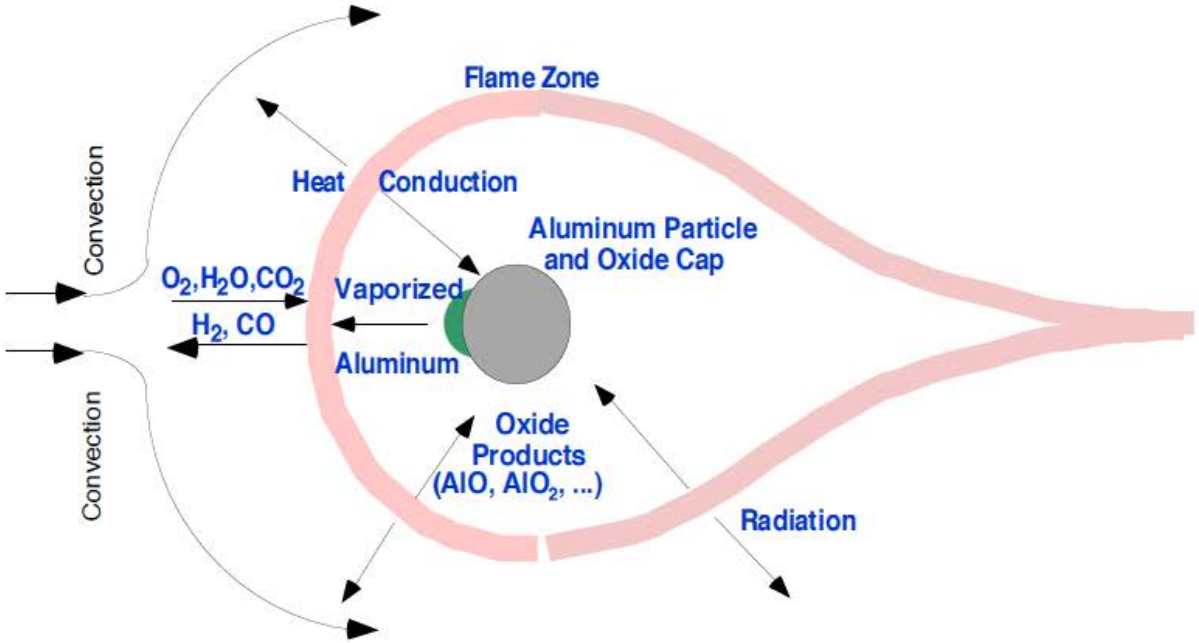


- ✓ The agglomerated particles (about 1/3 of the original Al mass) have a longer life time and burn away from surface.
- ✓ This requires an explicit treatment during their transport through the cc (Lagrangian Approach).
- ✓ Due to the formation of $Al_2O_3$ caps, a small residual part of Al (about 5% -Bekstead 2002- ) remains unburnt.

# Burning-rate law

❑ Widener and Beckstead (1998) have shown that dependence of aluminum particle burn time on diameter is proportional to $d^{1.9}$.




Flame Zone
Heat
Conduction
Aluminum Particle
and Oxide Cap
Convection
$O_2, H_2O, CO_2$
Vaporized
$H_2$, CO
Aluminum
Convection
Oxide
Products
(AlO, $AlO_2$, ...)
Radiation

# MODELING

# Modeling

1. Agglomerates (typically ≈100 μm) with Lagrangian approach.
2. Aluminum combustion model
3. Smoke particles (≈1μm) treatment.
4. Coupling  between agglomerates  and gas.
5. Break-up model.

# Modeling: 1 - Agglomerates

✓Lagrangian model for large particles

*Droplet velocity evolution*

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p, \qquad \frac{d\boldsymbol{v}_p}{dt} = \frac{1}{\tau_p}[\boldsymbol{u}(\boldsymbol{x}_p) - \boldsymbol{v}_p]$$

*Droplet velocity time scale*

$$\tau_p = \frac{\rho_p d_p^2}{18\mu f(Re_p)}$$

*Droplet temperature evolution*

$$\frac{dT_p}{dt} = \frac{1}{\tau_{p,\theta}}[T(\boldsymbol{x}_p) - T_p]$$

*Droplet temperature time scale*

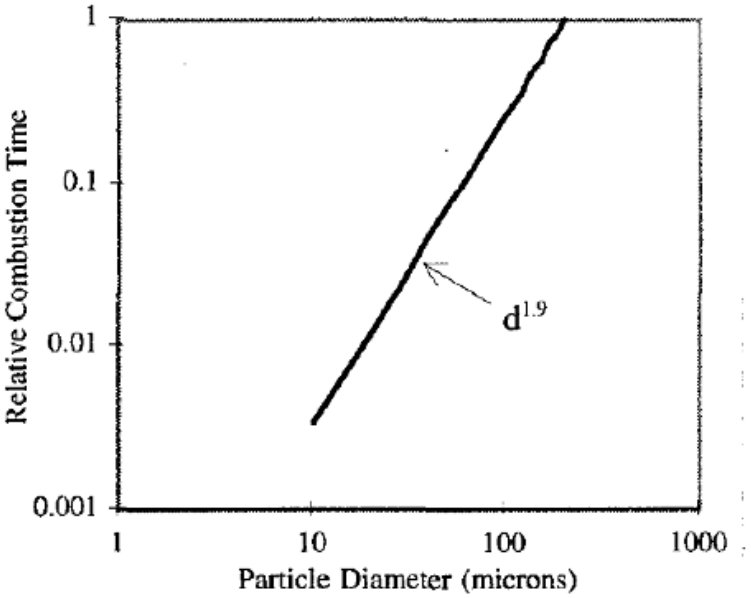
$$\tau_{p,\theta} = \frac{C_{p,p}\rho_p d_p^2}{12kf_\theta(Re_p)}$$

# Modeling: 2 – Aluminum combustion model

✓ Burn rate model

$$\dot{m}_{bu} = c\rho_{Al} T^{1.57}(x_p) p^{0.2}(x_p) \chi_{eff}^{0.39} \mathcal{D}_{rel} d_p^{1.1} \psi_{Al}$$

$$\dot{m} = \frac{mass}{comb.time} \approx f\left(\frac{d^3}{d^{1.9}}\right) \approx f\left(d^{1.1}\right)$$




The burn time depends on the diameter with the 1.9 power law.

* Widener and Beckstead (1998), Najjar et al. J. of Spac. and Rockets (2006).

# Modeling: 3 – smoke particles

- An eulerian approach is adopted

- Gaseous combustion products from propellant and smoke particles are considered as two components of the gas mixture

- Gas properties are modified to account for the presence of smoke and kept constant.

# Modeling : 4 -Coupling gas – $Al/Al_2O_3$ agglomerates (1/2)

❑ $Al/Al_2O_3$ agglomerates → gas

- Production of “smoke” particles (~ 1μm)
- A number of source terms is included into equations

✓ Mass source term in continuity equation

$$S^p_{\rho,l} = L\dot{m}_{\mathrm{bu},l}(1 - M_R)$$

✓ Momentum source term in momentum equation:

$$\boldsymbol{S}^p_{\rho u,l} = L\boldsymbol{F}_{p,l} + L\dot{m}_{\mathrm{bu},l}\boldsymbol{v}_{p,l} + S^p_{\rho,l}\boldsymbol{u}(\boldsymbol{x}_{p,l})$$

✓ Energy source term:

$$S^p_{e,l} = \boldsymbol{S}^p_{\rho u,l} \cdot \boldsymbol{u}(\boldsymbol{x}_{p,l}) + L\dot{m}_{\mathrm{bu},l}h_b + L\dot{m}_{\mathrm{cond},l}h_c$$

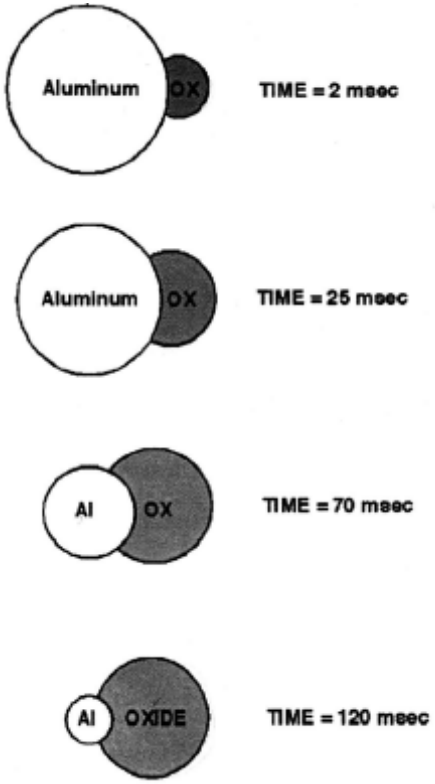
# Modeling : 4 -Coupling gas – $Al/Al_2O_3$ agglomerates (2/2)

❑ gas → $Al/Al_2O_3$ agglomerates

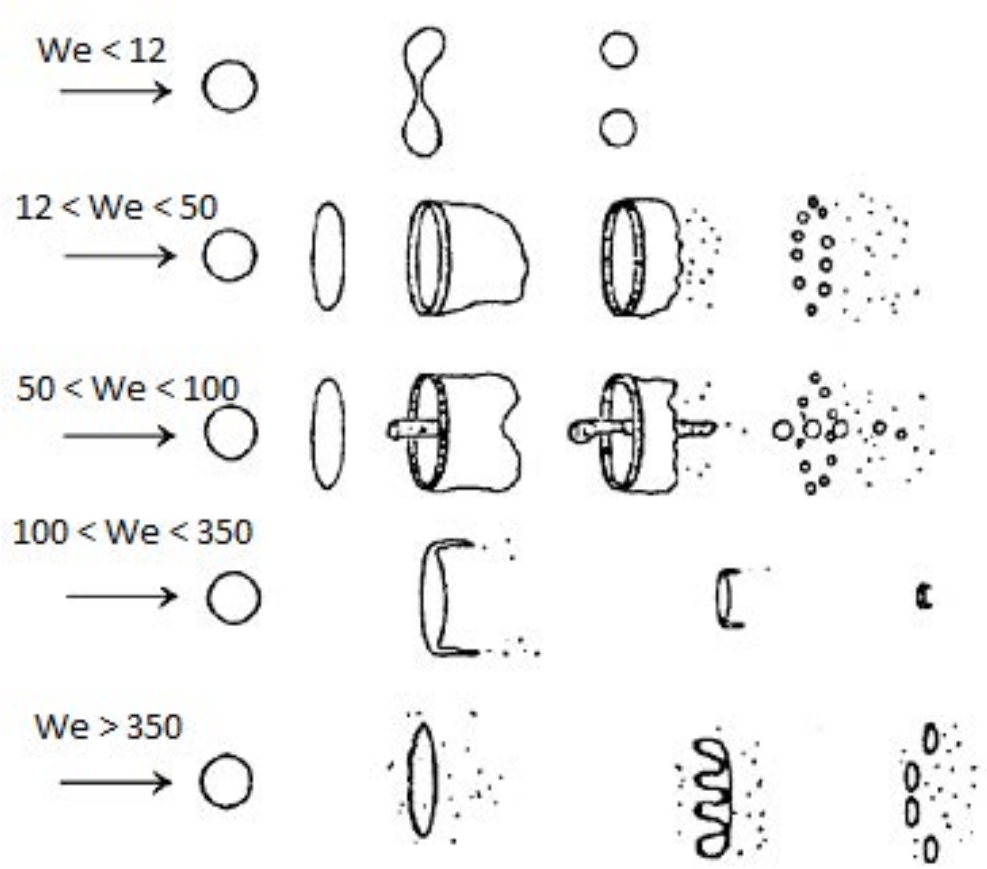
• The oxide cap grows because the particle collides with the oxide smoke in the combustion chamber.

• Experimental data show that 30% of burned Al is re-collected from agglomerates

• This corresponds to a “mass recover” of 57% of $Al_2O_3$



# Modeling: 5 - Break-up




Average predicted effect of initial particle diameter on burn time

# Modeling: 5 - Break-up model

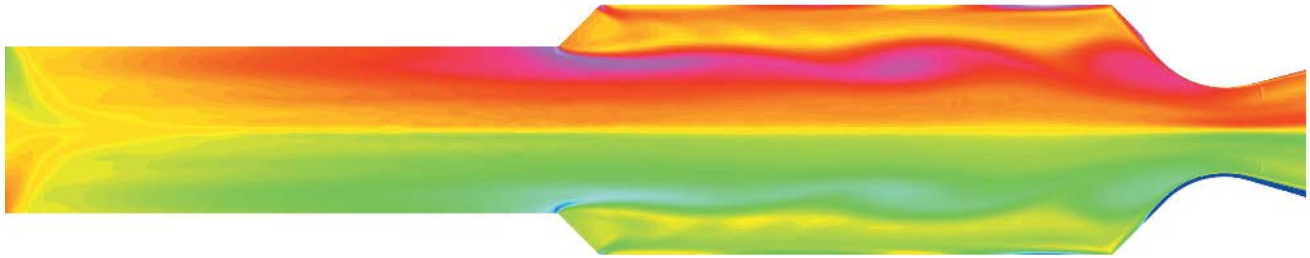
- ✓ Break-up is due to relative velocity between gas and droplets.

- ✓ The non dimensional parameter, most suitable to describe the droplet break-up is the Weber number :

$$We = \frac{\rho_{gas} u_{rel}^2 \phi_p}{\sigma}$$

- ✓ Break-up occurs when We > $W_{cr}$ : single particle going through break-up is replaced with 2 particles.

- ✓ $W_{cr}$=14 has been assumed.



# TEST CASES

# TEST CASE 1

- ✓ Evaluation of burning time using the adopted combustion model
- ✓ Comparison with the large review/synthesis of experiments made by Beckstead
- ✓ Wide range different diameters
- ✓ Large range of different conditions


- Beckstead, A summary of Aluminum Combustion (VKI 2002)
- Beckstead Correlating Aluminum Burning Times (2005)
- Widener Beckstead, Aluminum Combustion Modeling in Solid Propellant Combustion Products (1998)

# TEST CASE 1

| | | | Ambient T | | Gas Concentrations (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | Date | Do (μm) | To (K) | P(atm) | H2O | O2 | CO2 | CO | N2 | Ar | HCl |
| Friedman & Macek[33,34] | 1962 -3 | 15-67 | 2510 | 1 | 17 to 18 | 5 to 6 | 12 to 14 | 0 | 63 to 65 | 0 | 0 |
| Davis[35] | 1963 | 60-96 | 2200-3200 | 1-204 | .5 to 50 | 0 to 27 | 9 to 50 | 9 to 41 | 9 to 41 | 0 | 0 -21 |
| Macek[36] | 1967 | 32-49 | 2500 | 1 | 0 to 17 | 8 to 16 | 13 to 43 | 0 | 40 to 58 | 0 | 0 |
| Hartman[37] | 1971 | 23-94 | 3000-3189 | 25.5 | 27 to 34 | 0 to 4 | 17 to 23 | 9 to 30 | 13 to 20 | 0 | 0 - 8 |
| Wilson & Williams[38] | 1971 | 24-74 | 298 | 2 - 5 | 0 | 10 to 30 | 0 | 0 | 70 to 90 | 90 | 0 |
| Prentice[39] | 1974 | 250-400 | 298 | 1 | 0 to 3 | 15 to 75 | 0 to 50 | 0 | 0 to 80 | 0 - 85 | 0 |
| Turns and Wong[40,41] | 1987 | 300-760 | 1809-1827 | 1 | 29 to 31 | 10 to 25 | 27 to 30 | 15 to 49 | 46 to 64 | 0 | 0 |
| Roberts, et al[42] | 1993 | 20 | 2225-2775 | 85.-34 | | 99 | | | 1 | | |
| Marion[43,44] | 1995 | 35-40 | 298 | 1 - 39 | 0 | 21 | 0 | 0 | 79 | 0 | 0 |
| Olsen & Beckstead[45] | 1996 | 40-70 | 3000 | 1 | 66 to 89 | 11 to 16 | 0 to 18 | 0 | 0 | 0 | 0 |
| Melcher, et al[46] | 1999 | 106 | 2300 | 13-22 | 41 to 38 | 0 to 11 | 12 to 16 | 9 to 2 | 10 | 0 | 18 |
| Dreizin[47,48] | 1999 | 90,200 | 298 | 1 | | 5-100 | | | 5-90 | 0-95 | ** |
| Zenin[49,50] | 2000 | 185-500 | 298 | 1 - 40 | 0 | 0 to 20 | 0 to 100 | 0 | 0 to 80 | 0 - 80 | 0 |

# Model setup

$$\dot{m}_{\mathrm{bu}} = c\rho_{\mathrm{Al}} T^{1.57}(\boldsymbol{x}_p)\, p^{0.2}(\boldsymbol{x}_p)\, \chi_{\mathrm{eff}}^{0.39} \mathcal{D}_{\mathrm{rel}} d_p^{1.1} \psi_{\mathrm{Al}}$$

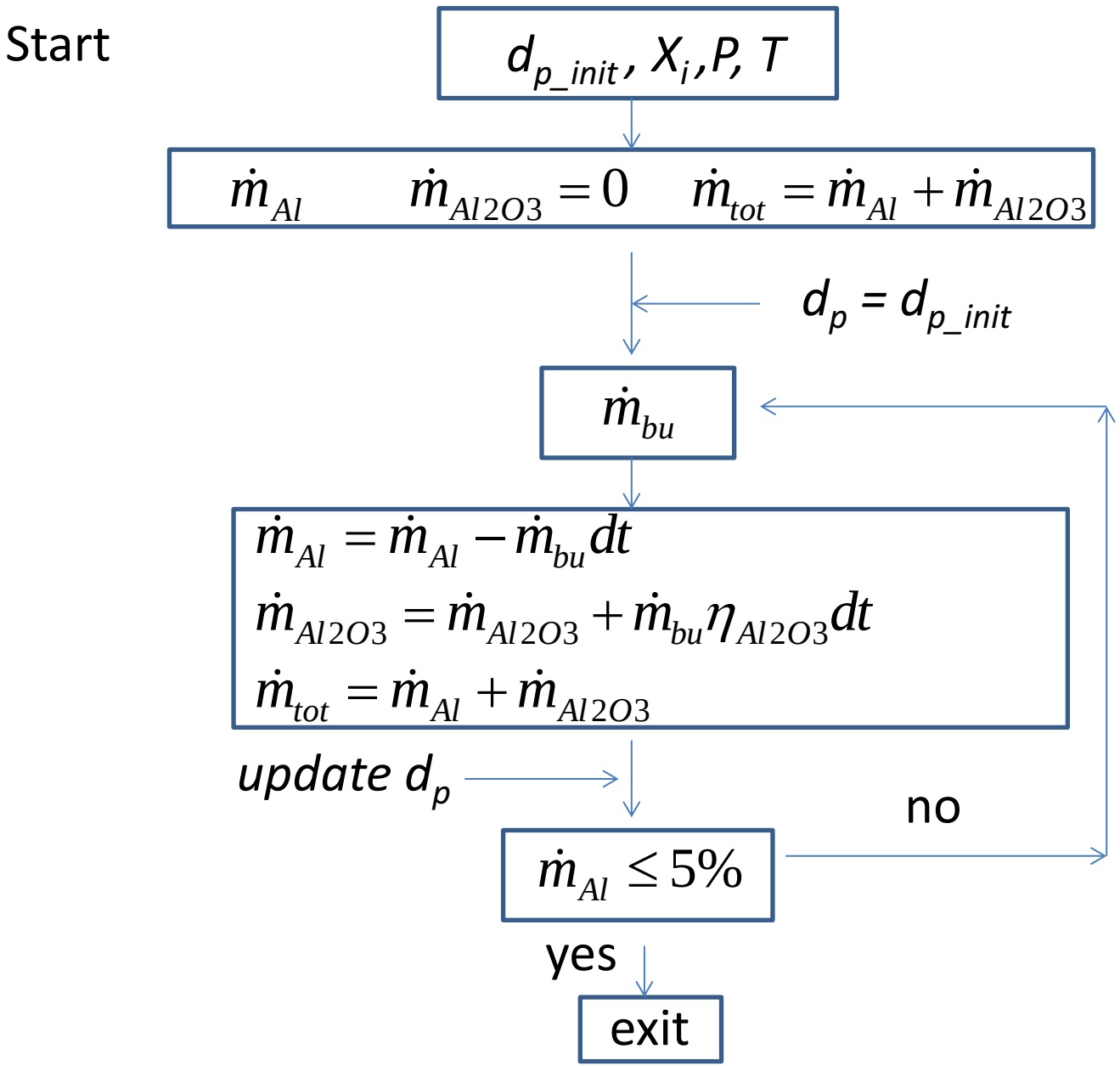
$$\chi_{\mathrm{eff}} = \chi_{\mathrm{O_2}} + 0.58\chi_{\mathrm{H_2O}} + 0.22\chi_{\mathrm{CO_2}}$$

$$\mathcal{D}_{\mathrm{rel}} = 1 + 2.7\chi_{\mathrm{H_2}}$$

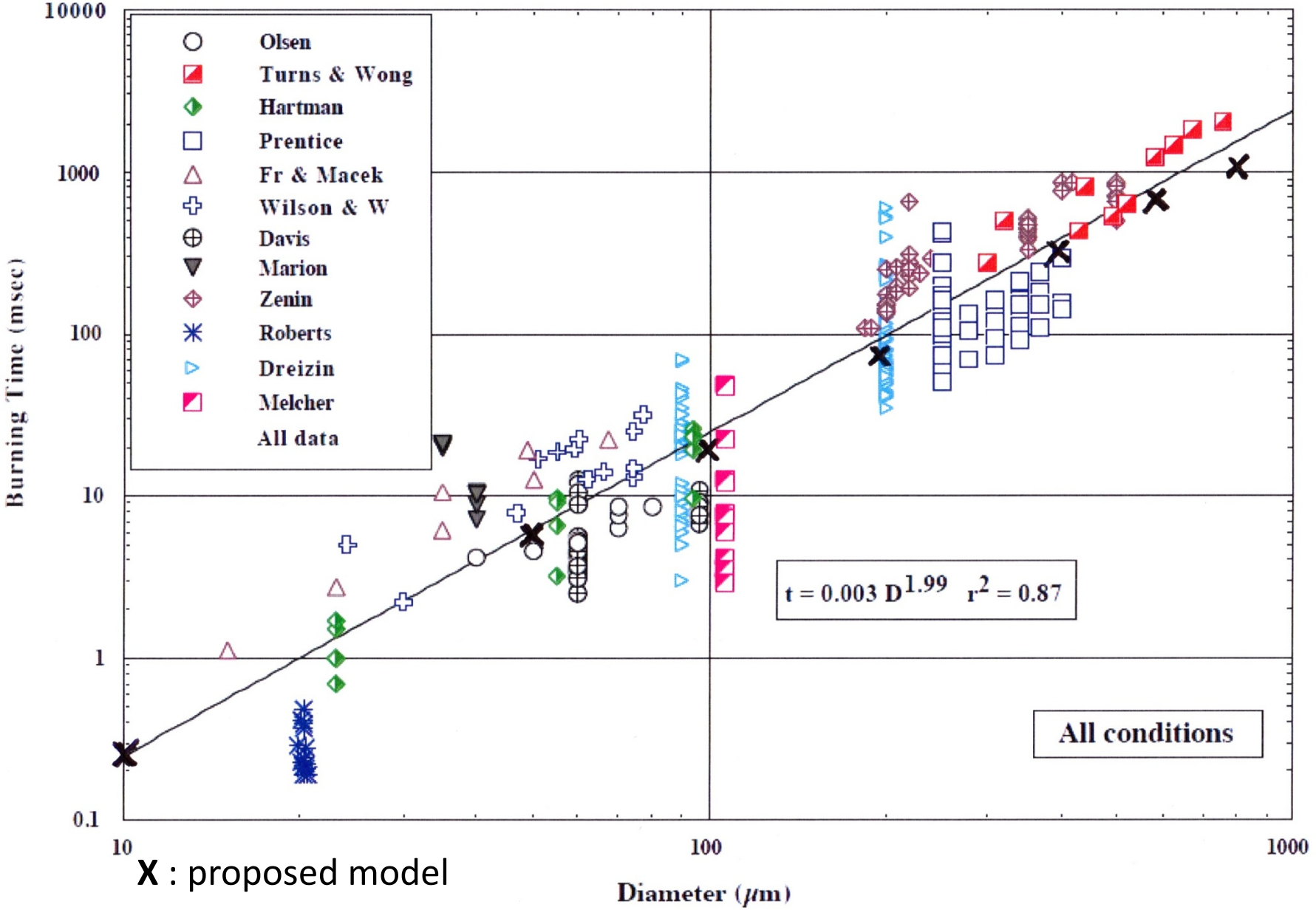
$$\chi_{\mathrm{H_2}} = 0.4$$
$$\chi_{\mathrm{O_2}} = 0.013$$
$$\chi_{\mathrm{H_2O}} = 0.42$$
$$\chi_{\mathrm{CO_2}} = 0.14$$

* Cai et Al. “A MODEL OF AP/HTPB COMPOSITE PROPELLANT COMBUSTION IN ROCKET-MOTOR ENVIRONMENTS”, (2008)

# Implementation



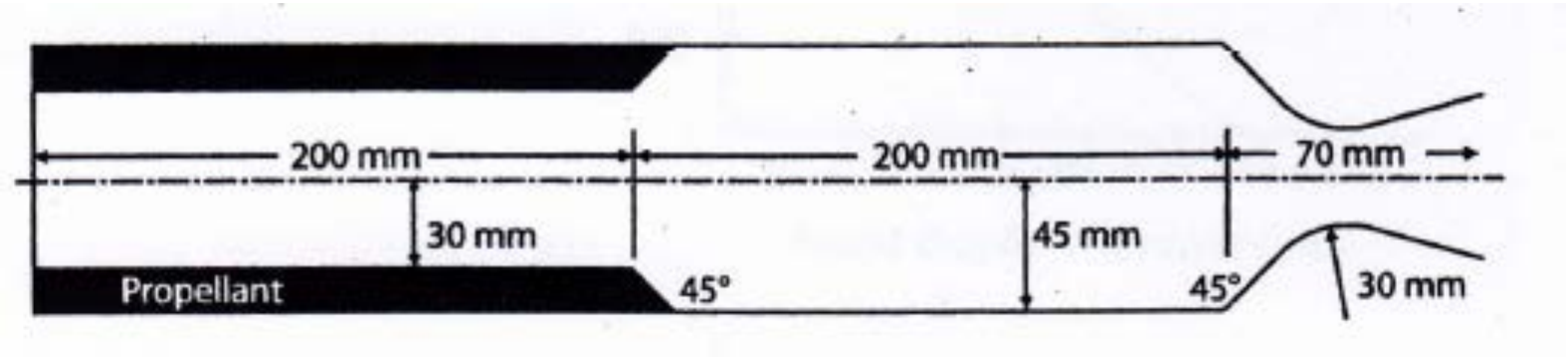
# Test case 1: comparison with experimental results




**X** : proposed model

# TEST CASE 2

✓ Onera C1 configuration: investigation of distributed combustion



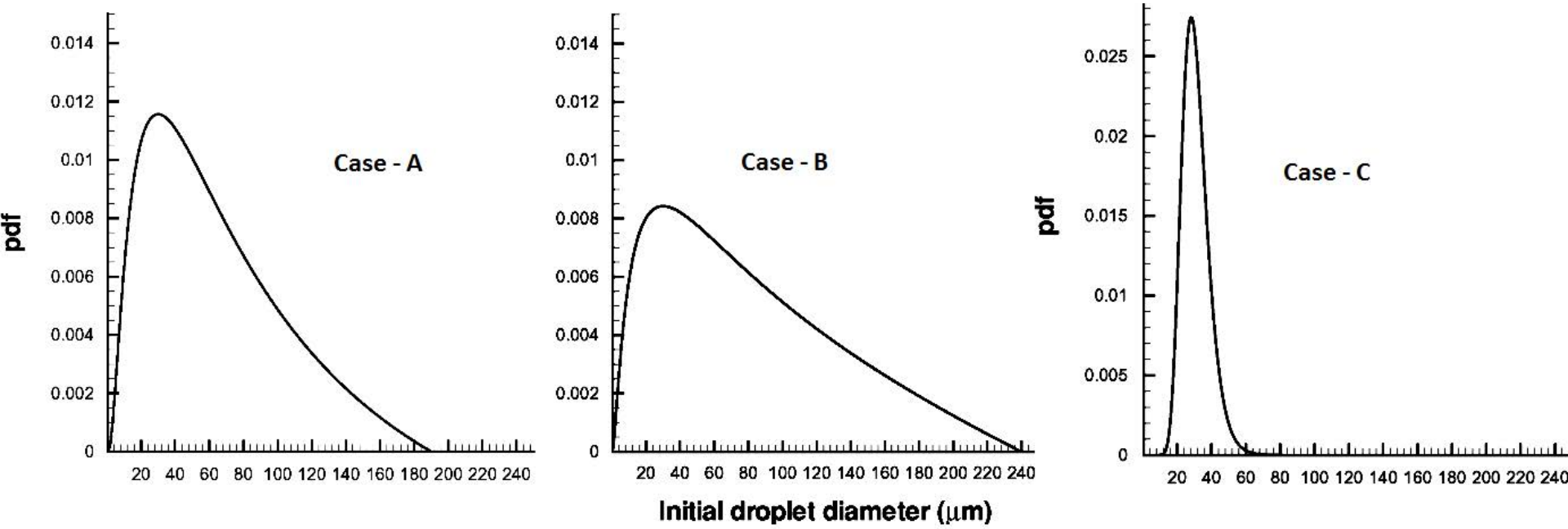

- **Najjar et al. J. of Spac. and Rockets (2006)**

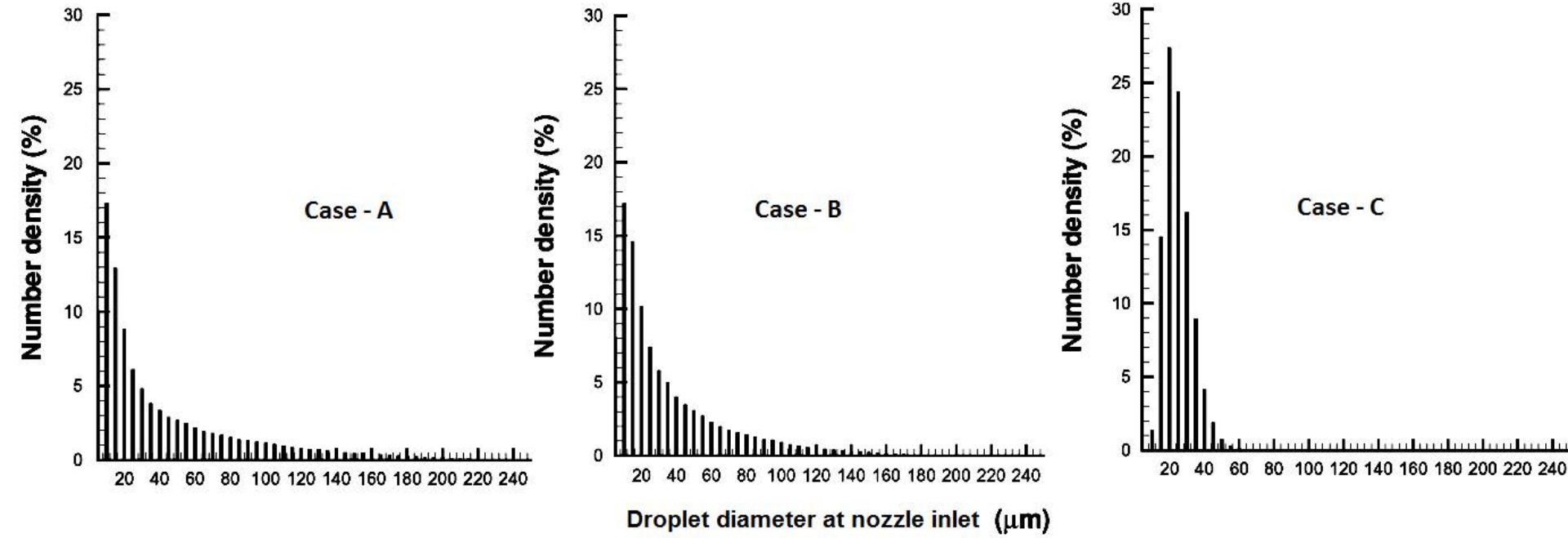
✓ Vuillot (1995)

✓ Kourta (1999)

✓ Lupoglazoff and Vuillot (1992; 1996)

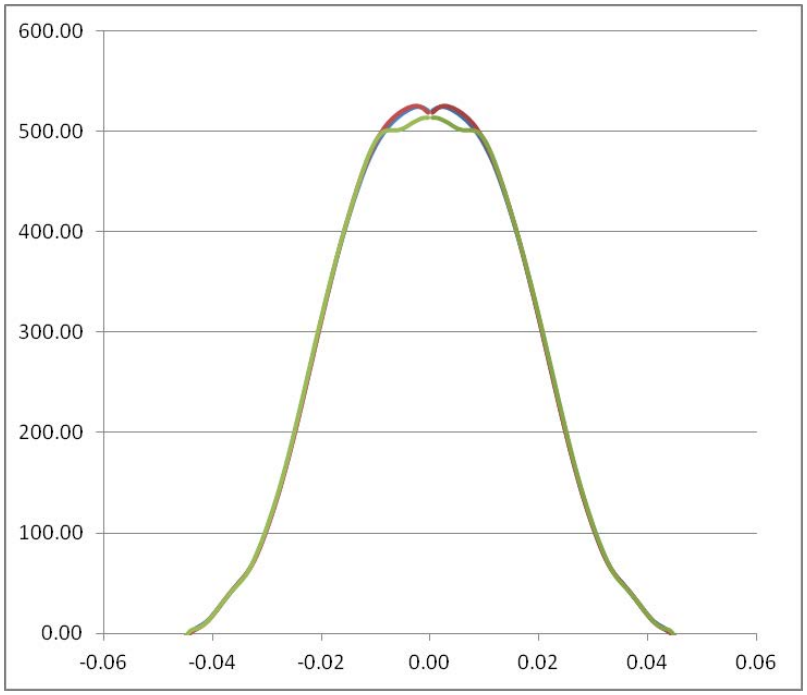
# TEST CASE 2


pdf
Case - A
Case - B
Case - C
Initial droplet diameter (μm)

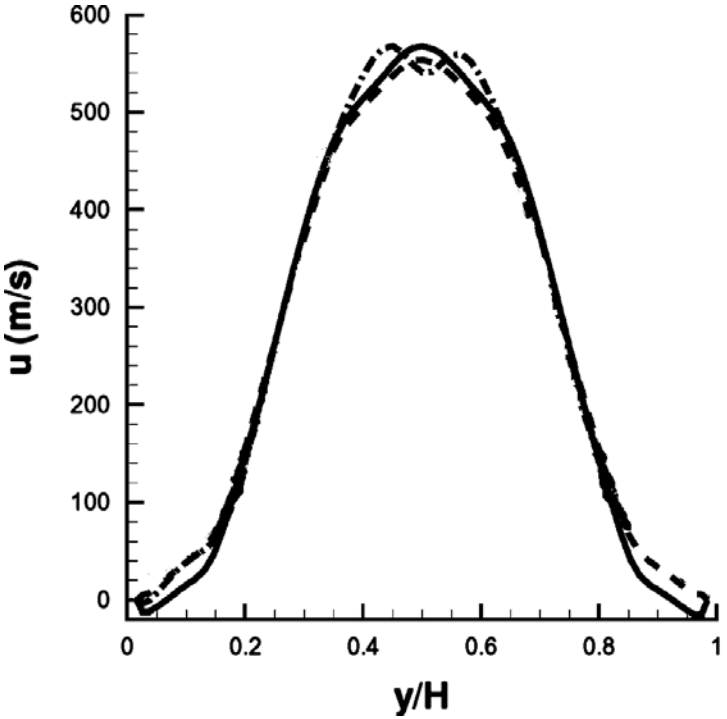

Number density (%)
Case - A
Case - B
Case - C
Droplet diameter at nozzle inlet (μm)

# RESULTS

Velocity profiles at nozzle inlet (gas phase)



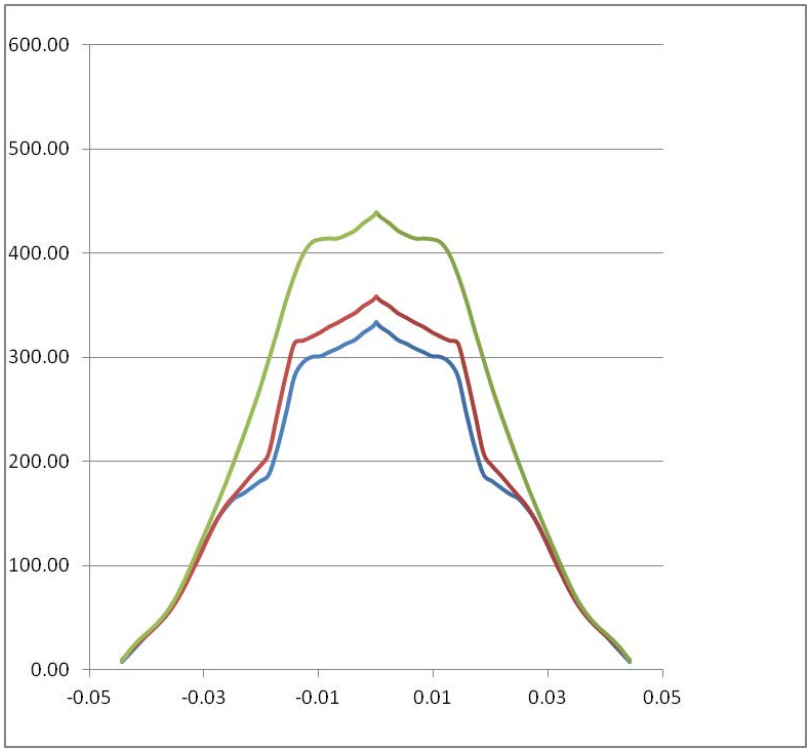

Present



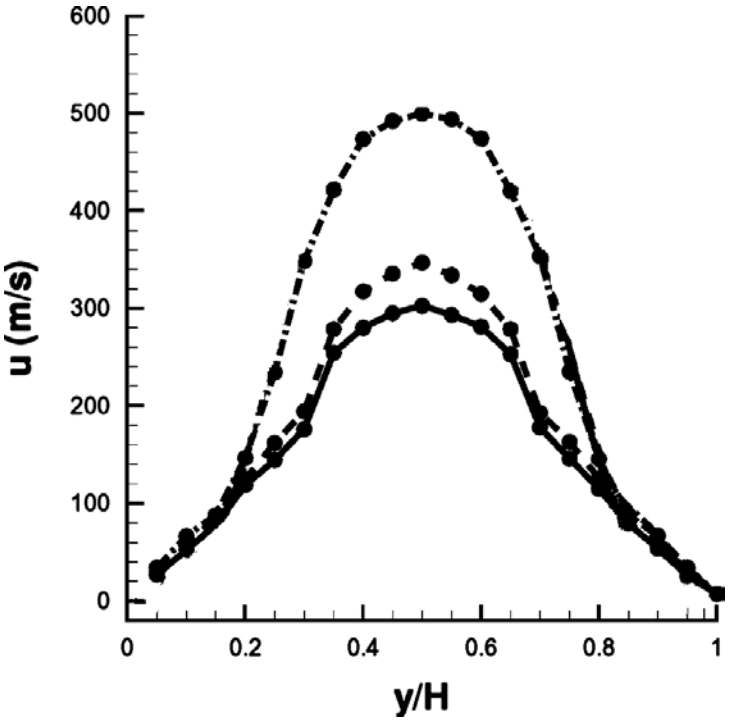

*Najjar et al. (2006).

# RESULTS

Velocity profiles at nozzle inlet (particles)



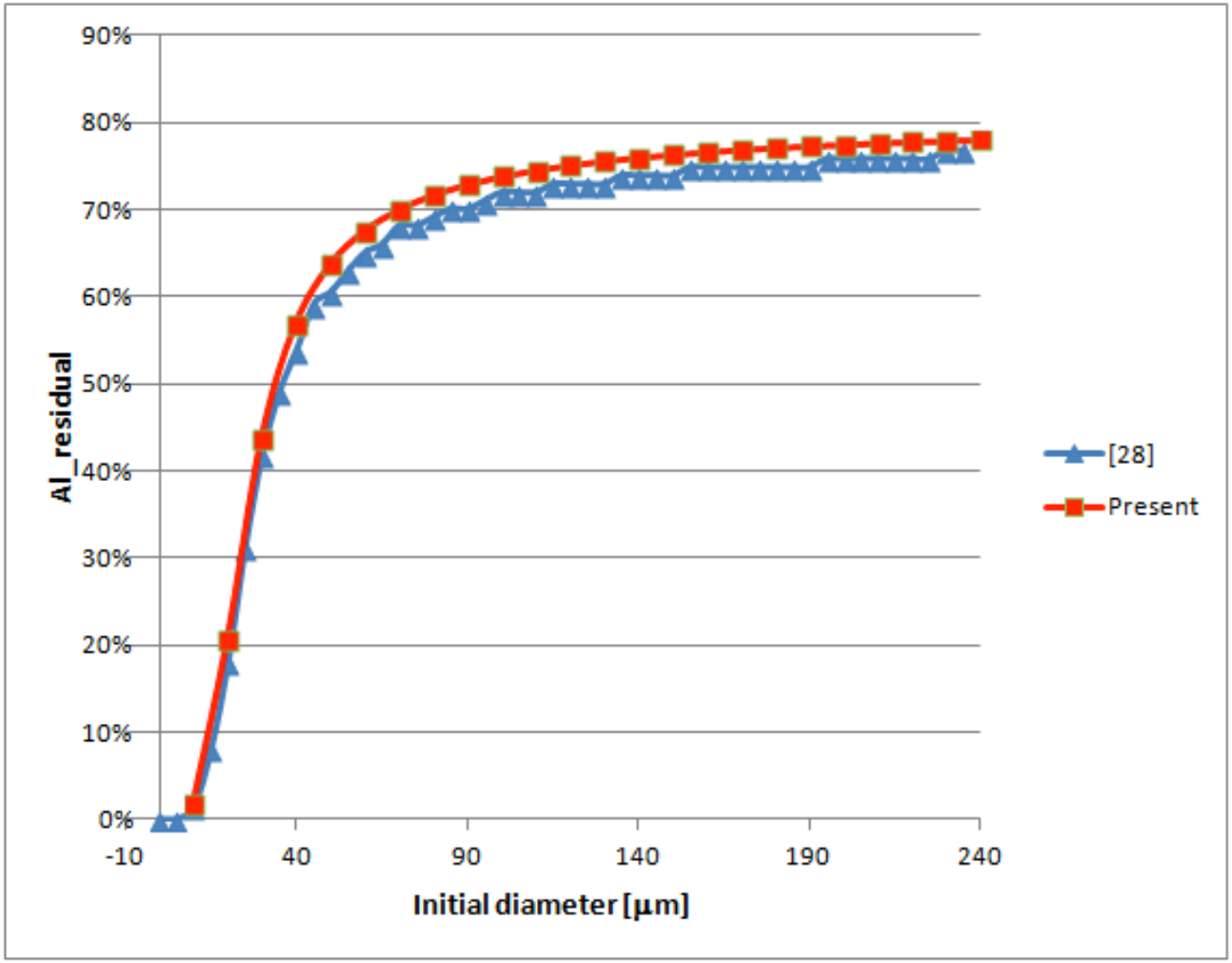

Present




*Najjar et al. (2006).

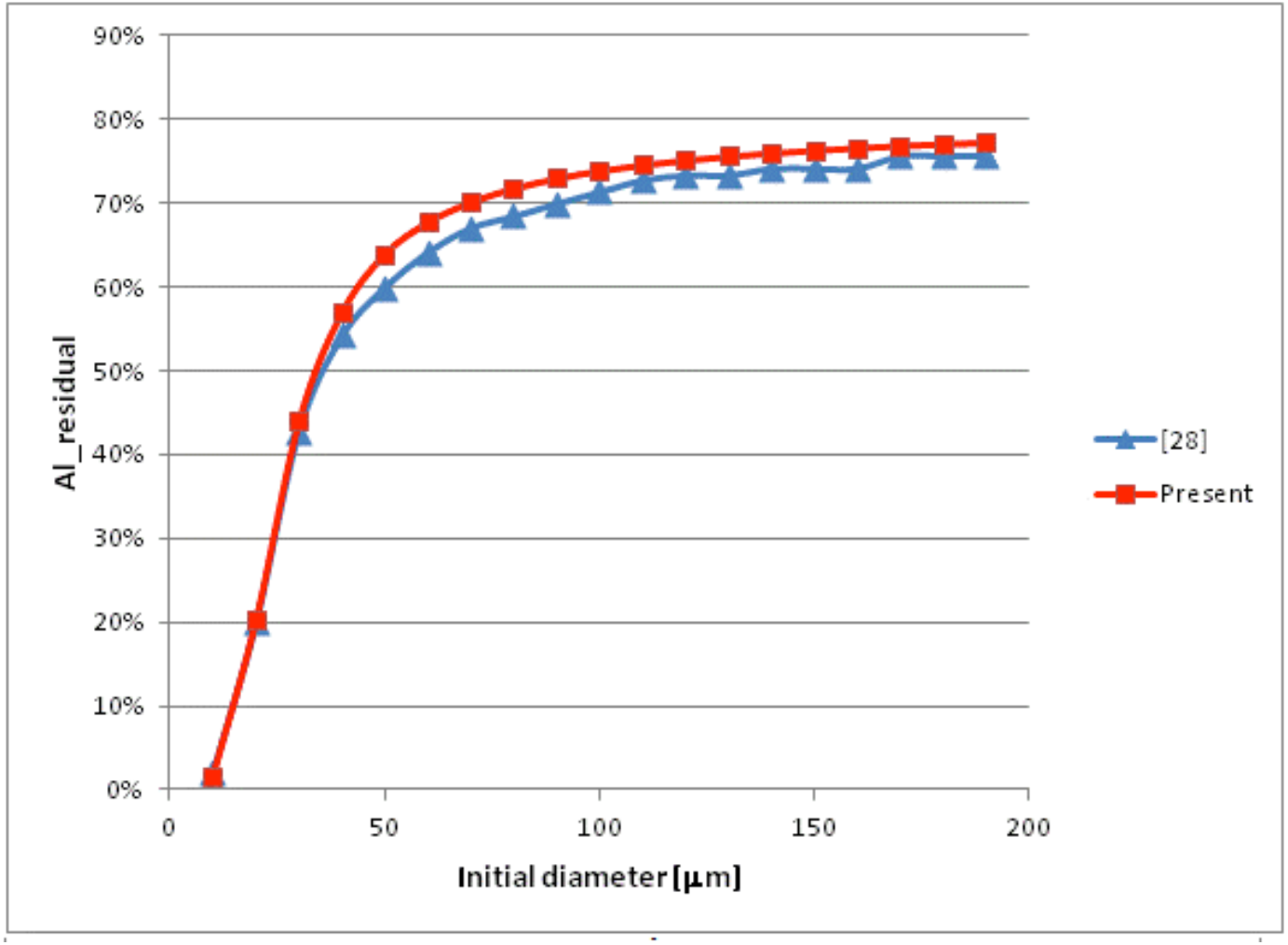
# RESULTS

Fraction of  Al residual as function of initial diameter DB (Case A)



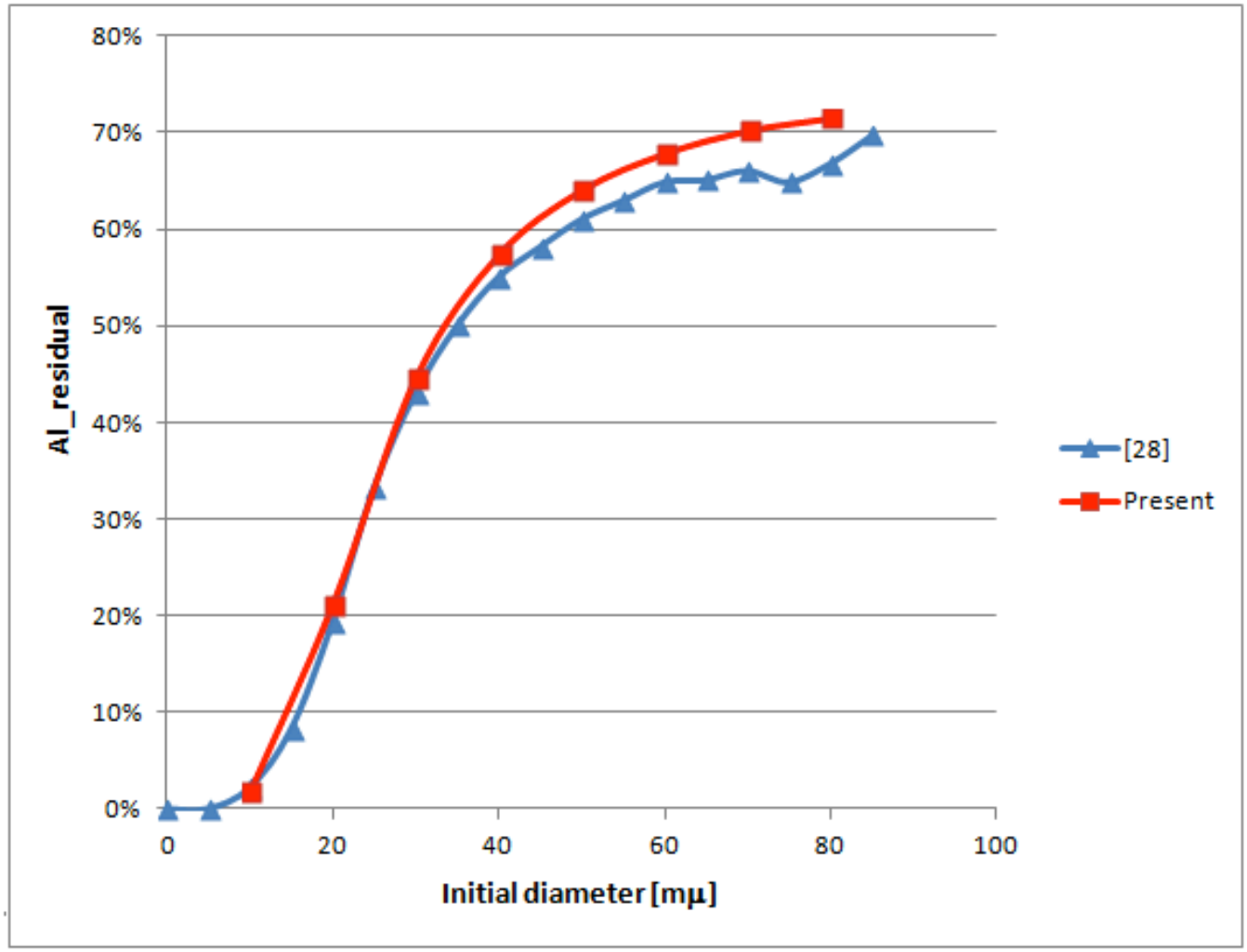
# RESULTS

Fraction of Al residual as function of initial diameter DB (Case B)



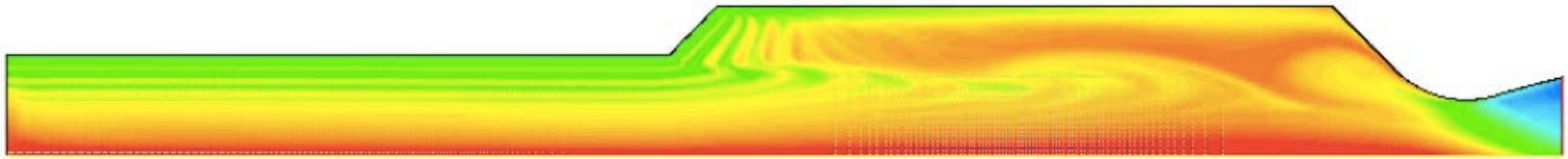
# RESULTS

Fraction of  Al residual as function of initial diameter DB (Case B)



# Comparisons

TEMPERATURE

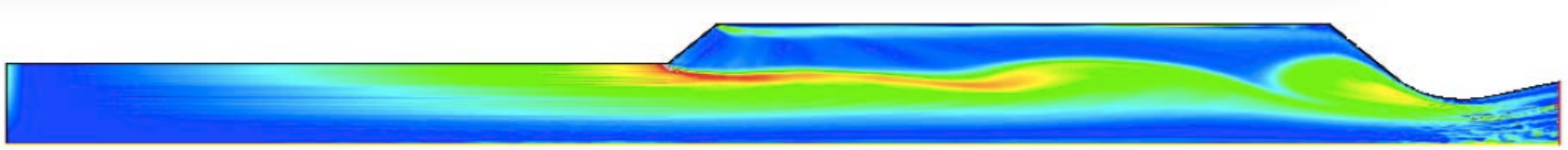


With distributed combustion

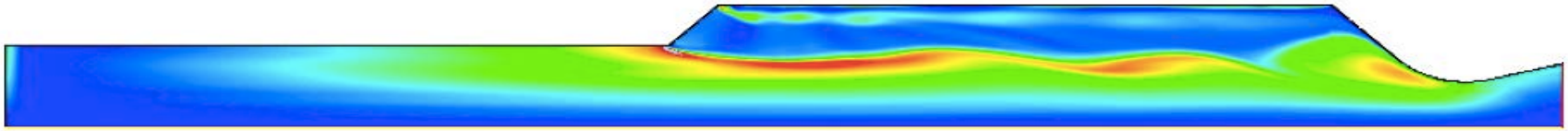
Without distributed combustion

# Comparisons

VORTICITY



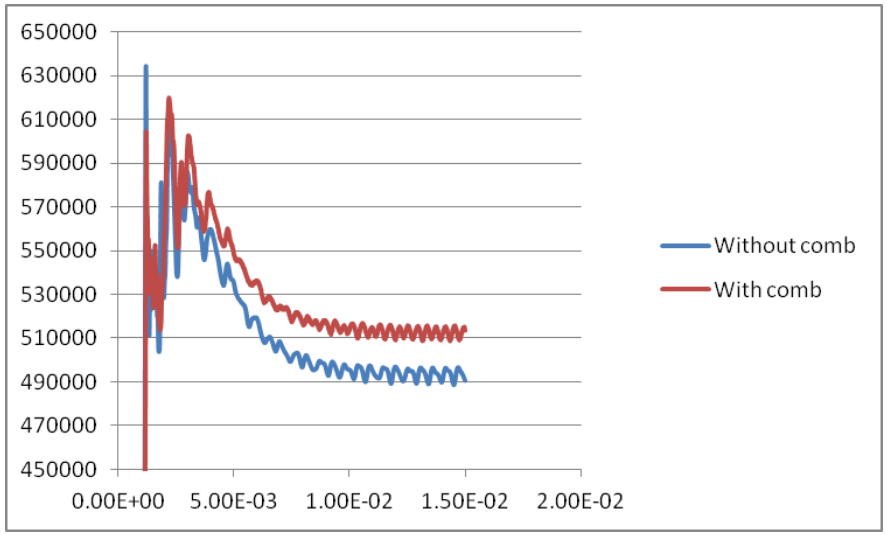
With distributed combustion

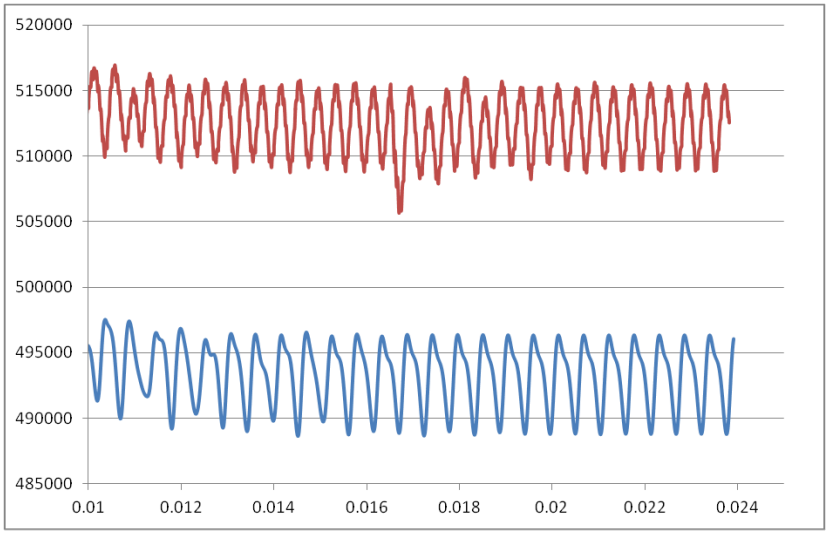


Without distributed combustion

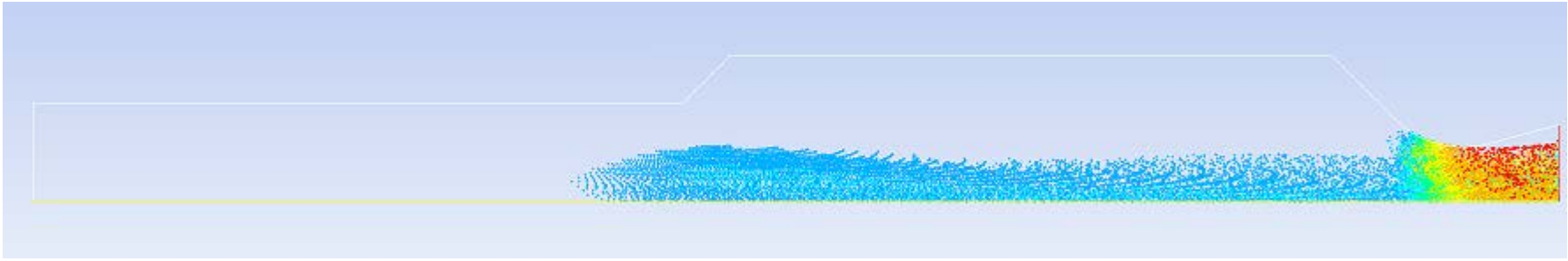
# Comparisons

Pressure

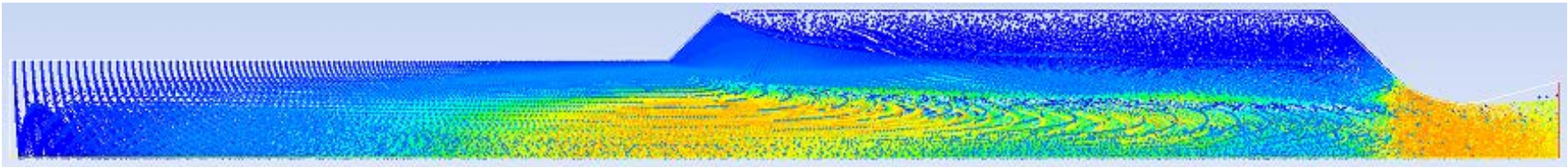


# BREAK-UP ($W_{cr}$=12)

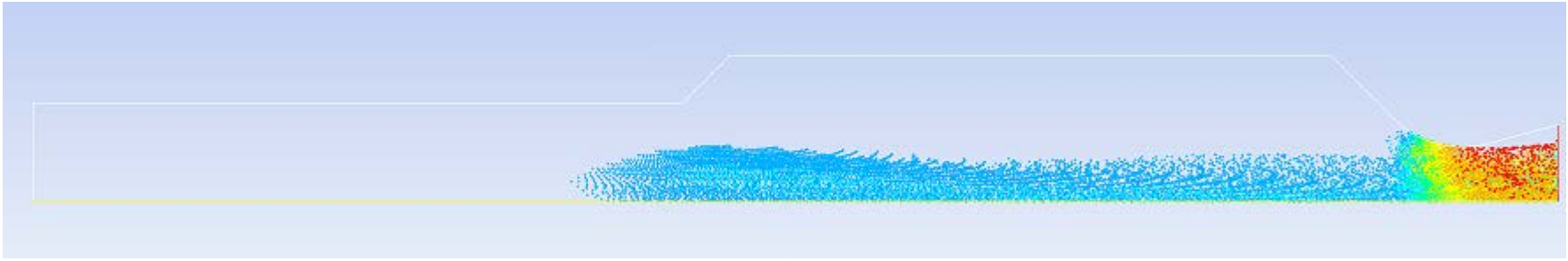


Breakup events (from 1 to 7)

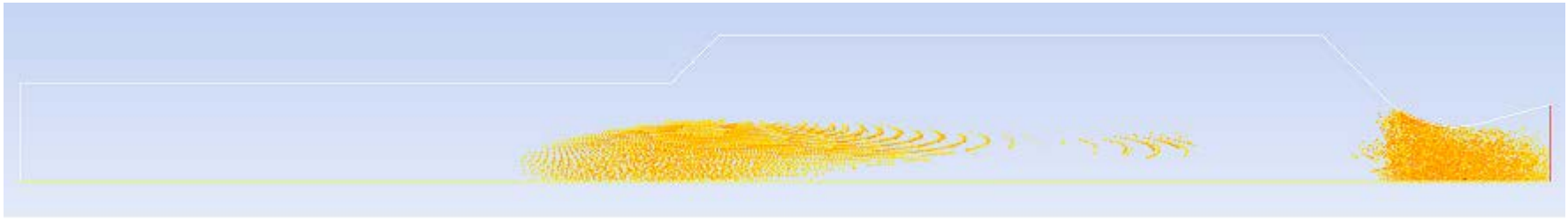


Weber contour ( 0 < We < 14)

# BREAK-UP ($W_{cr}$=12)

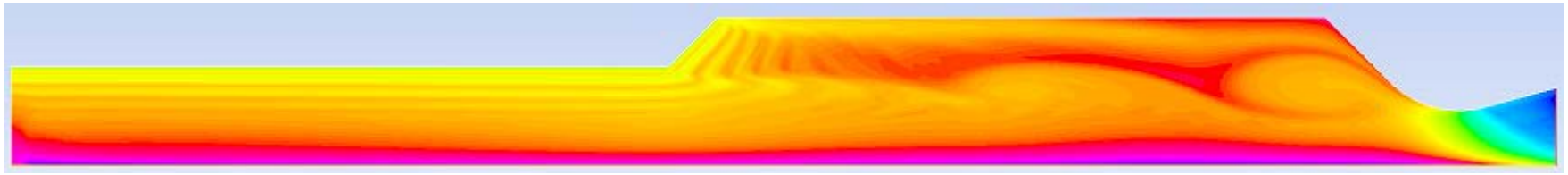


Breakup events (from 1 to 7)

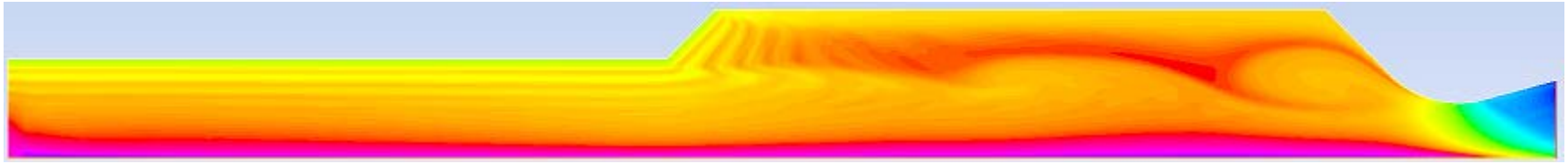


Weber contour ( 10 < We < 14)

# BREAK-UP ($W_{cr}$=12)

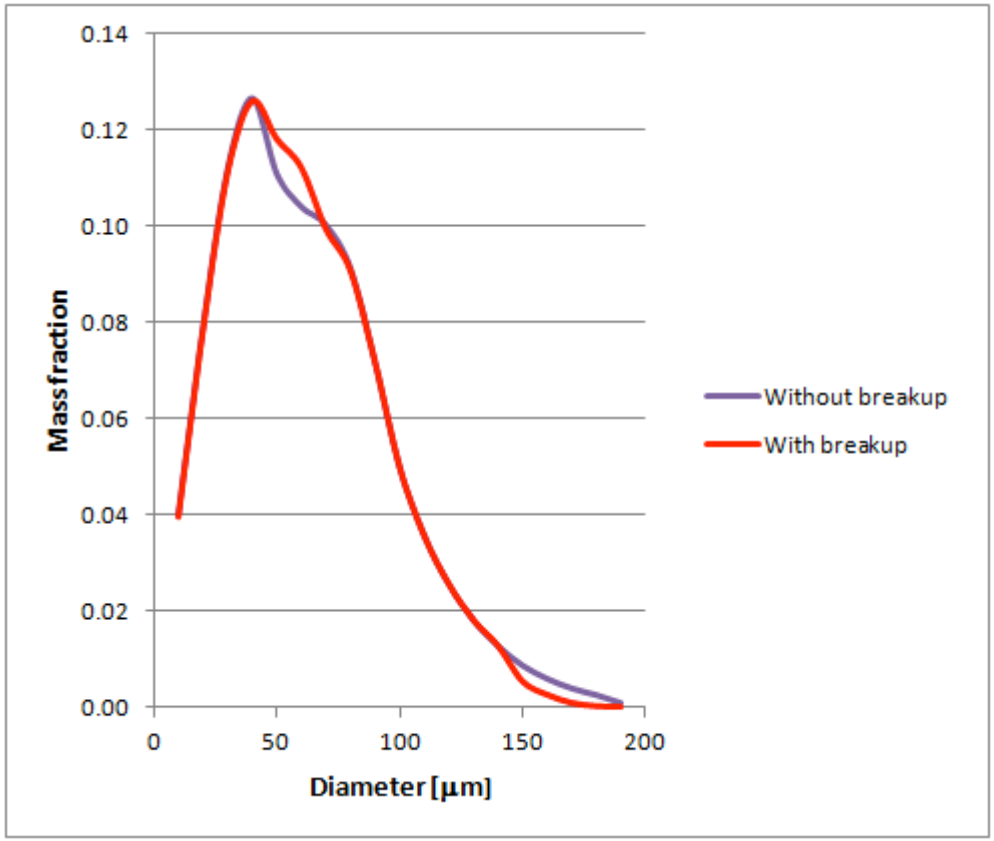


Temperature with breakup



Temperature without breakup

# BREAK-UP



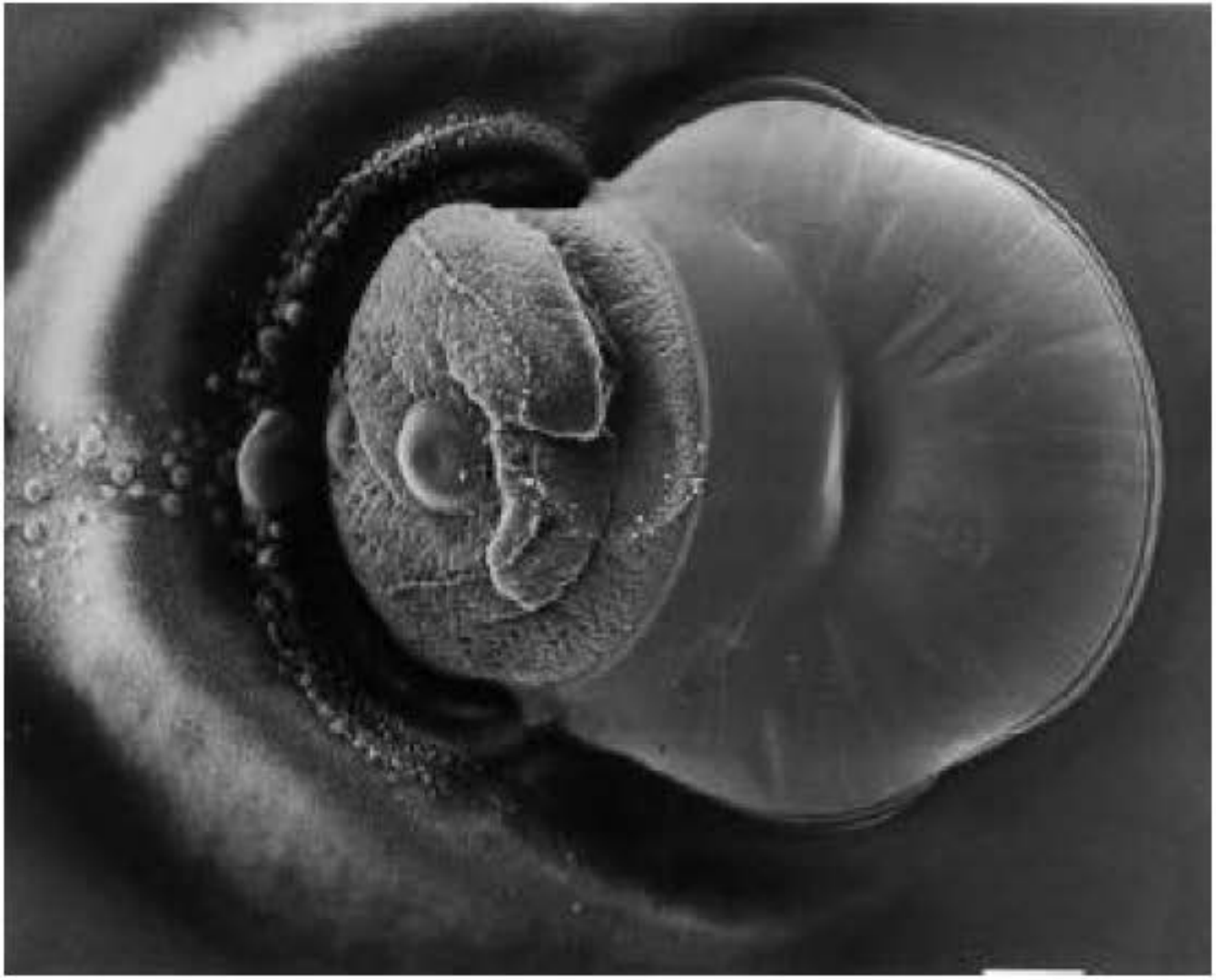

Mass fraction as function of diametr

# Open points and improvements

- Initial distribution of particles
- Concentration of chemical species
- Gas properties
- Finer tuning of combustion model using *ad hoc* experiment
- $We_{cr}$

Other points

- Determination of smoke/particle ratio
- Evaluation of $Al_2O_3$ collecting mechanism
- Model of particle release (actual V=0)



# THANKS FOR ATTENTION!