Numerical simulation of flake orientation during droplet impact on substrates in spray painting processes

Q. Ye[1], M. Dreher[1], Bo Shen[2]

[1]Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany

[2]University of Applied Sciences Esslingen, Esslingen, Germany

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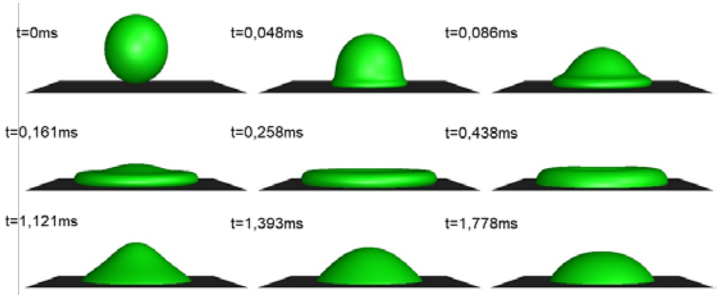

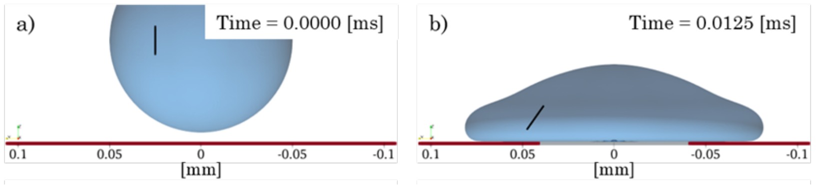

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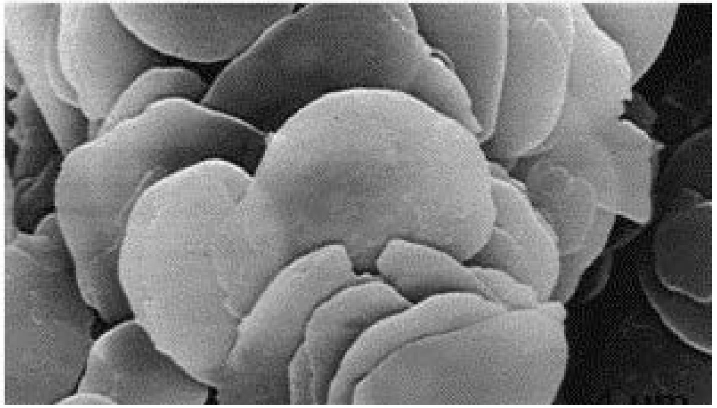
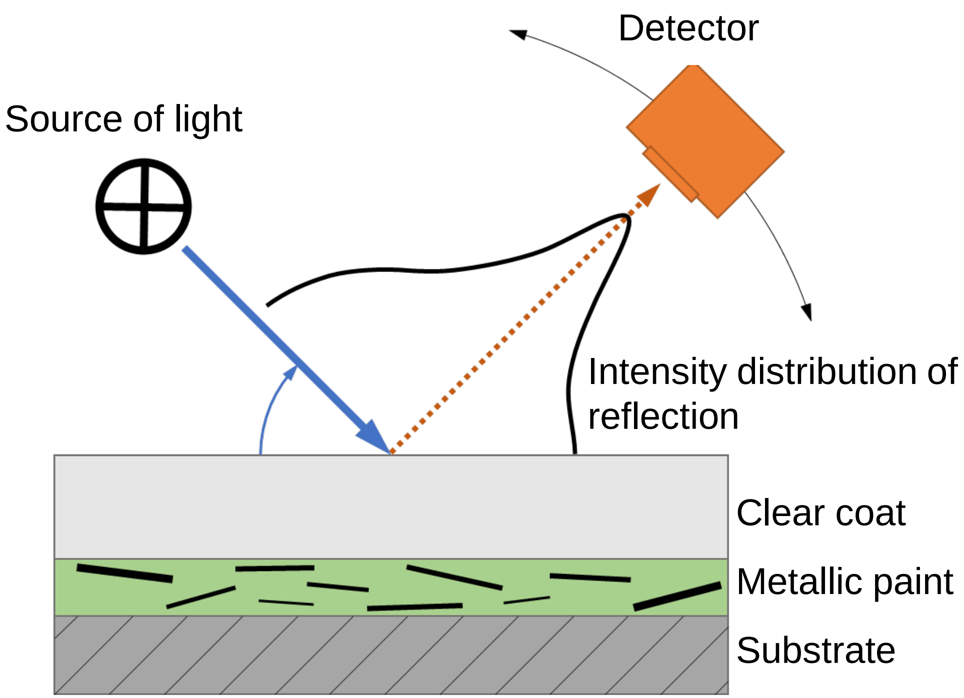


Metallic pigment



Optical impression of a metallic effect paint

Aim of the Research :

- How do flakes/pigments orientate themselves and how can this be controlled
- Investigation of flake orientation by droplet impact processes

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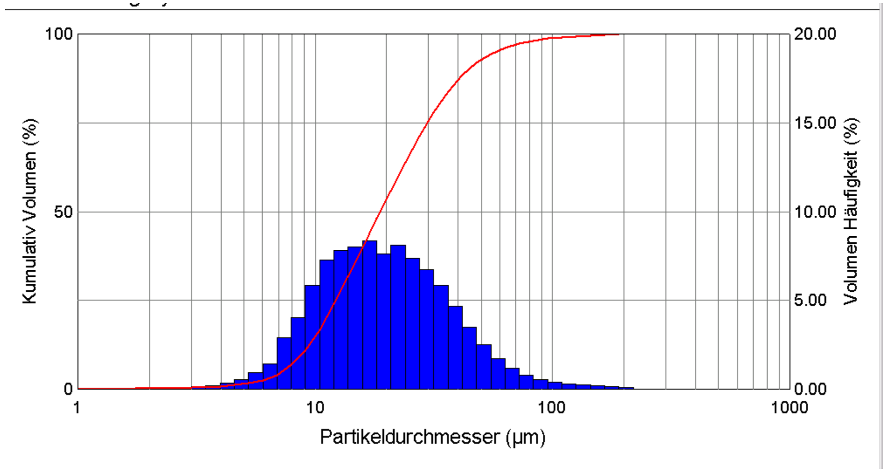
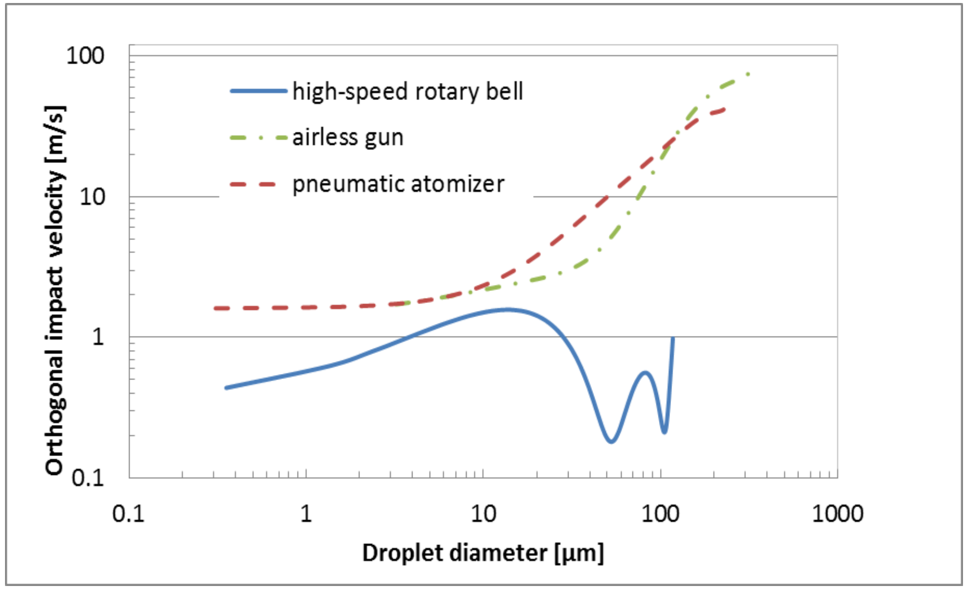
Information about droplet size and impact velocity in spray painting processes

atomizer	D_{32} (µm)	Impact velocity U (m/s)
Airless	68	10
pneumatic	8	2
Rotary bell	17	1.5



Typical paint droplet size distribution



Ref. Q. Ye , J. Domnick, Analysis of droplet impingement of different atomizers used in spray coating processes, J. Coat. Technol. Res., 14 (2) 467–476, 2017

- Fine droplets with pneumatic gun
- For droplet D < 50µm, impact velocity U < 10 m/s
- Important parameter for the current study should be:

  U < 10 m/s, D = 50µm (if so, 20µm, 100µm and 300µm)

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- 3D time-dependent VOF simulation (Ansys_Fluent CFD code was applied)
- Dynamic contact angle model validated by measurement

$$\theta_D = \begin{cases} v_{cl} > 0 & \theta_A(120°) \\ \overline{v_{cl}} < |\delta| \cap v_{cl} < \delta & \theta_{int} = 90° \\ \theta_{\nabla\phi} < \theta_A & \theta_{\nabla\phi} \\ \theta_{\nabla\phi} \leq \theta_E & \theta_E \end{cases} \quad \text{where } \delta = -0.1$$

- Rigid body motion equations for calculating flake movement (user-defined functions)

$$\vec{F}_p = \int_A p(\vec{r})\,\vec{n}\,dA \cong \sum^{n_f} p_c \vec{A}_f \quad \text{wobei} \quad \vec{A}_f = \vec{n}_f A_f$$

$$\vec{F}_\tau = \int_A \vec{\tau}\,dA \cong \sum^{n_f} \vec{\tau}_f A_f$$

$$\vec{M} \cong \sum^{n_f} (\vec{r}_f - \vec{r}_s) \times \left(\vec{F}_p + \vec{F}_\tau\right)_f$$

Calculating forces and moments

$$\Delta\vec{v} = \int_t^{t+\Delta t} \dot{\vec{v}}\,dt = \int_t^{t+\Delta t} m^{-1}\left(\vec{F}_p + \vec{F}_\tau + m\vec{g}\right) dt$$

$$\Delta\vec{\omega} = \int_t^{t+\Delta t} \dot{\vec{\omega}}\,dt = \int_t^{t+\Delta t} \mathbf{I}^{-1}\left(\vec{M} - \vec{\omega} \times \mathbf{I} \cdot \vec{\omega}\right) dt$$

Time integration using Adams-Moulton algorithm of 4th order

I ~1.6×10^{-23} [kg·m²] that is too small for 6DOF motion solver by ANSYS

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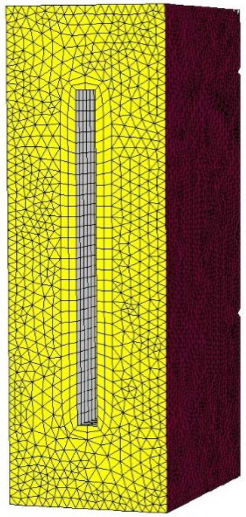
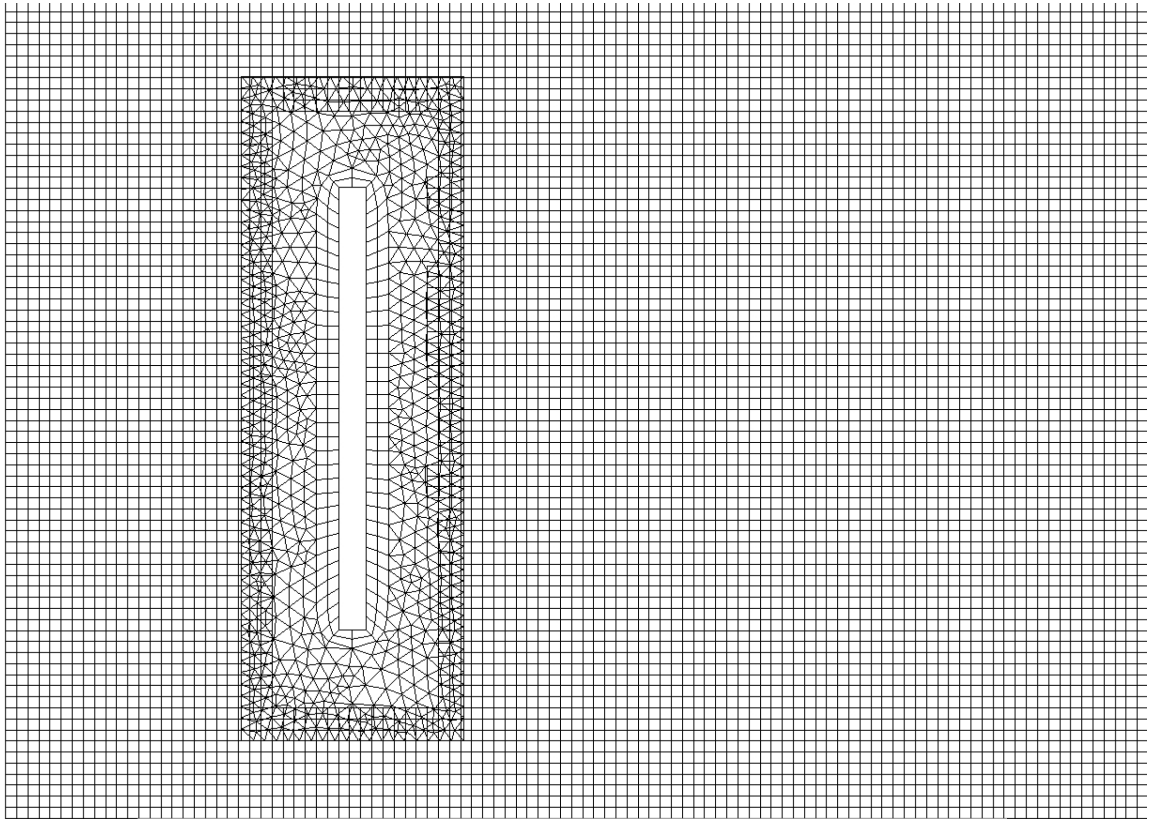
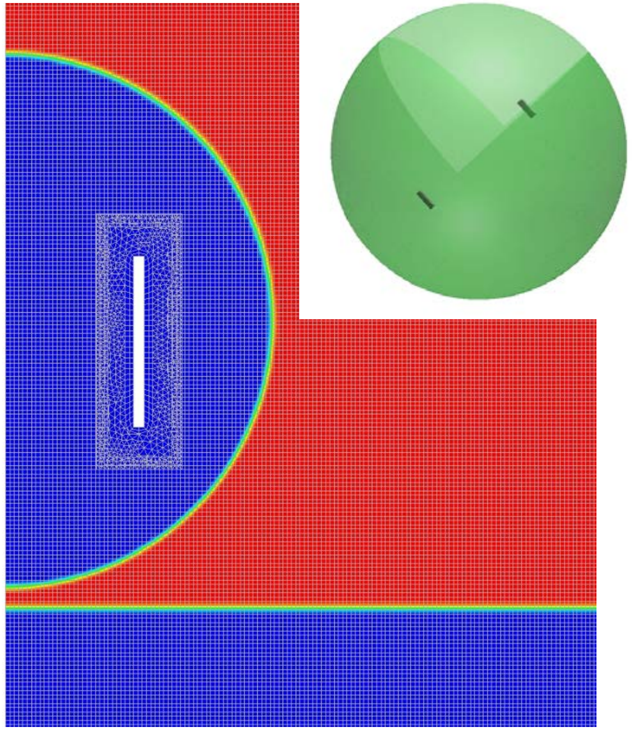
- Dynamic mesh with overset-method, 3-dimentional model with symmetry boundaries, the maximum computational domain: 8D × 8D × 3D



Component mesh with flake 1x16x16 µm³



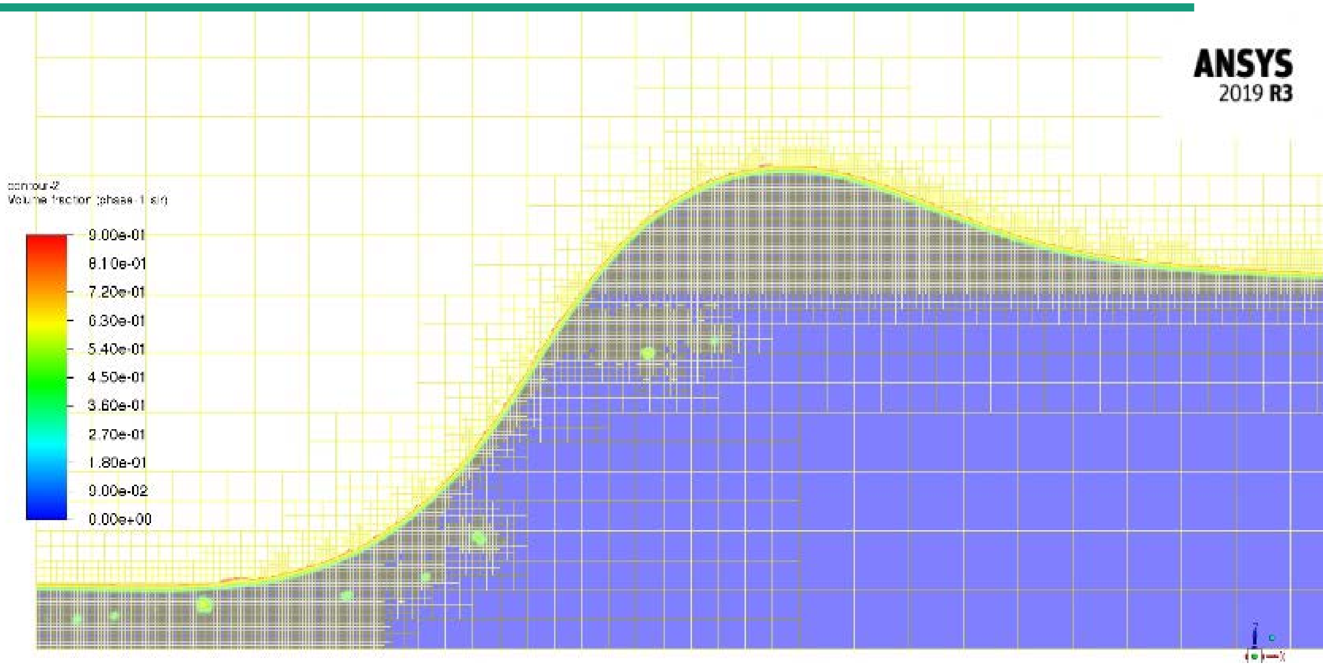
Domain mesh overlaid with component mesh



Contours of VOF overlaid with mesh at t = 0 s, blue: liquid, red: air

- $D/\Delta x = 150$ obtained after the study of grid independence
- Dynamic mesh adaption
- Typical time steps of 0.01 – 0.1 µs
- Parameters

Droplet diameter D (µm)	50, 100, 300
Droplet velocity U (m/s)	0.5 - 10
Liquid viscosity η (Pas)	0.01 – 0.04 and shear thinning viscosity
Surface tension σ (N/m)	0.025, 0.063
Liquid density ρ (kg/m³)	1020,1200
Static contact angle (°)	50 - 60



Mesh distribution using dynamic mesh adaption

Height of film (µm)	30, 60, 100
Flake size (µm³)	1×16×16
Flake density (kg/m³)	3200
Re-number, $Re = \rho UD/\eta$	5 – 100
We-number, $We = \rho U^2 D/\sigma$	3 – 1200
Oh-number, $Oh = \eta / \sqrt{(\sigma D \rho)}$	0.1 – 2.2

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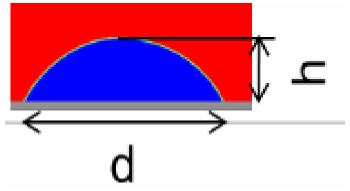
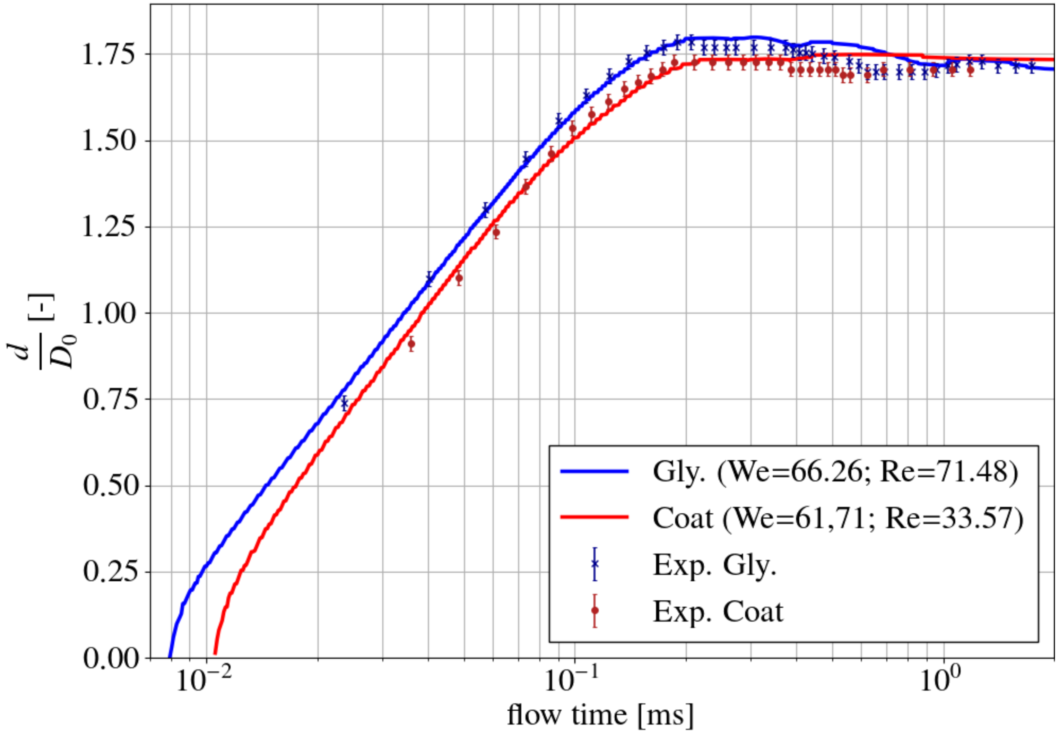
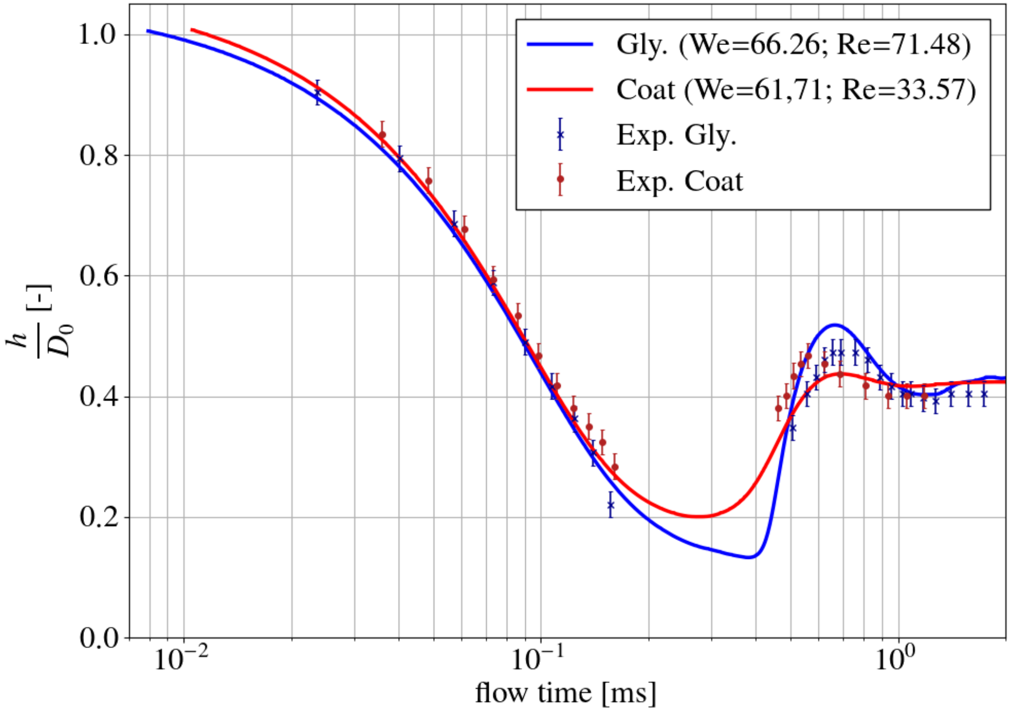
- Droplet impact on dry surfaces using dynamic contact angle model







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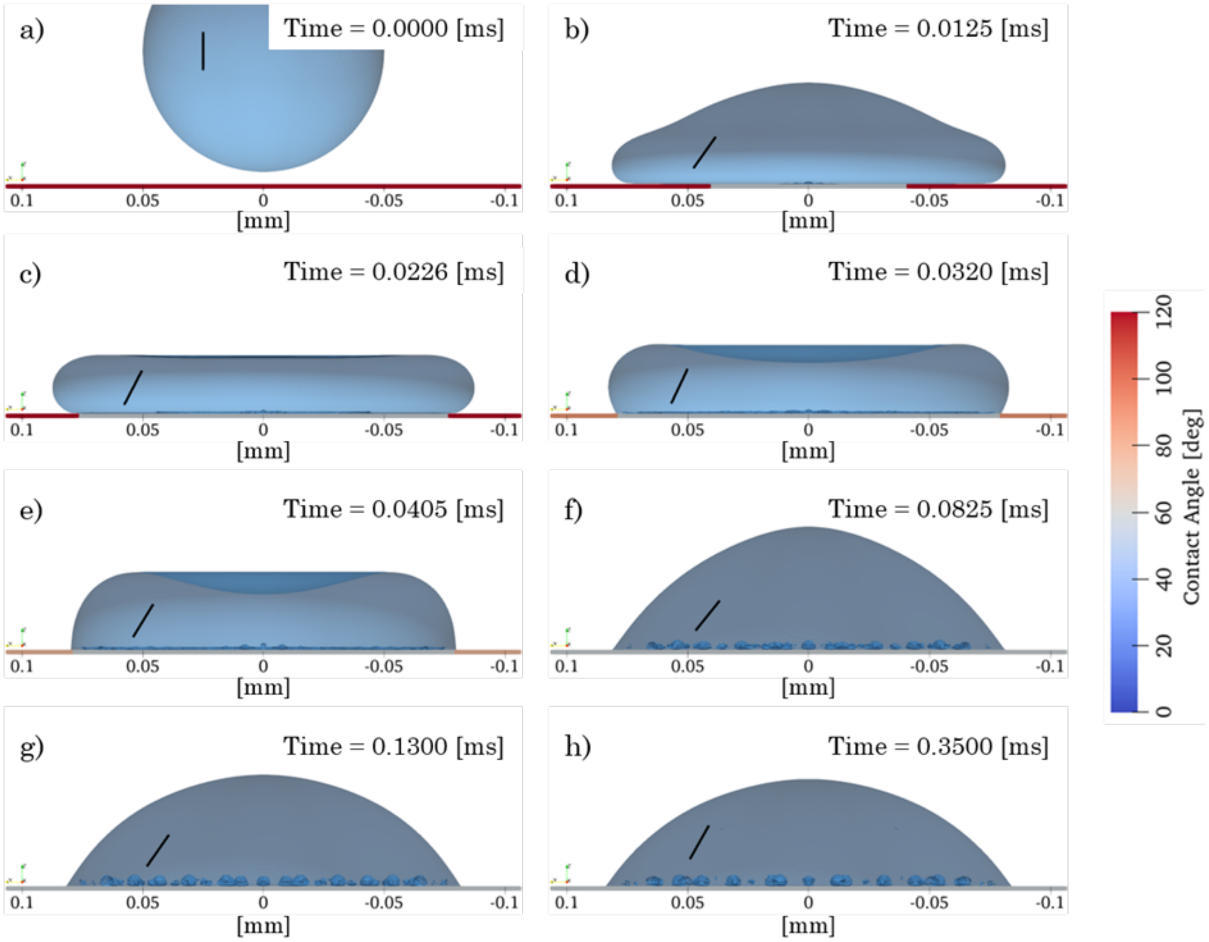
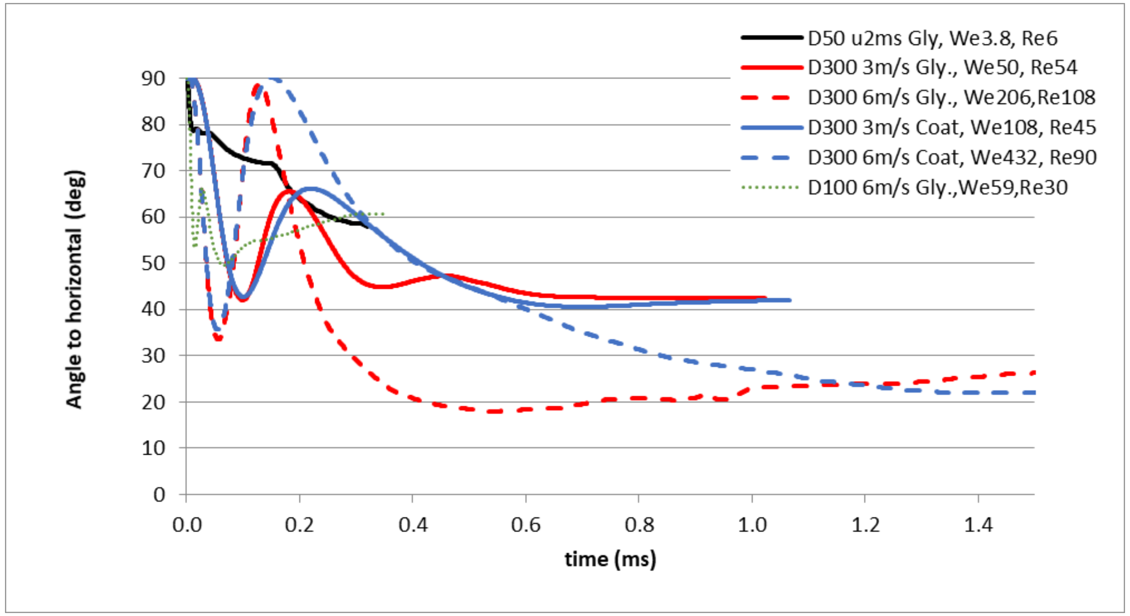


Evolution of the droplet contour and flake orientation (D= 100µm, η = 20 mPas, U = 6m/s, σ = 0.063 N/m)

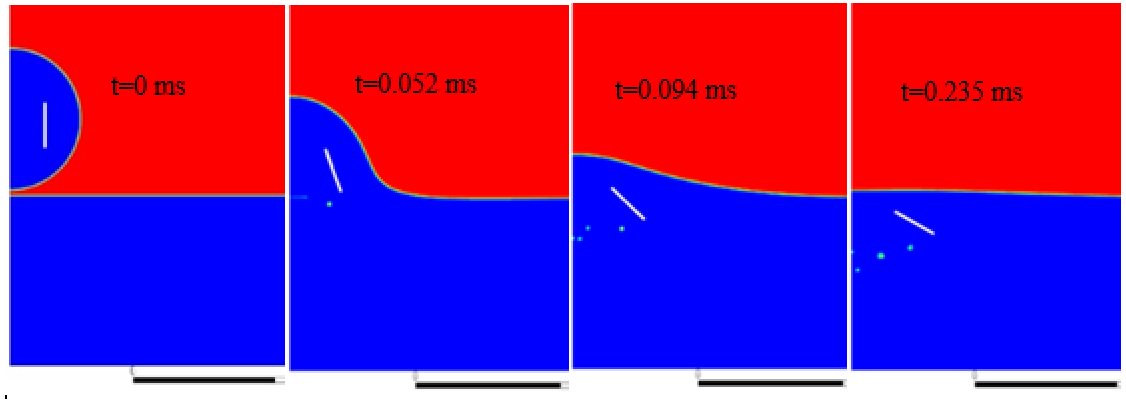


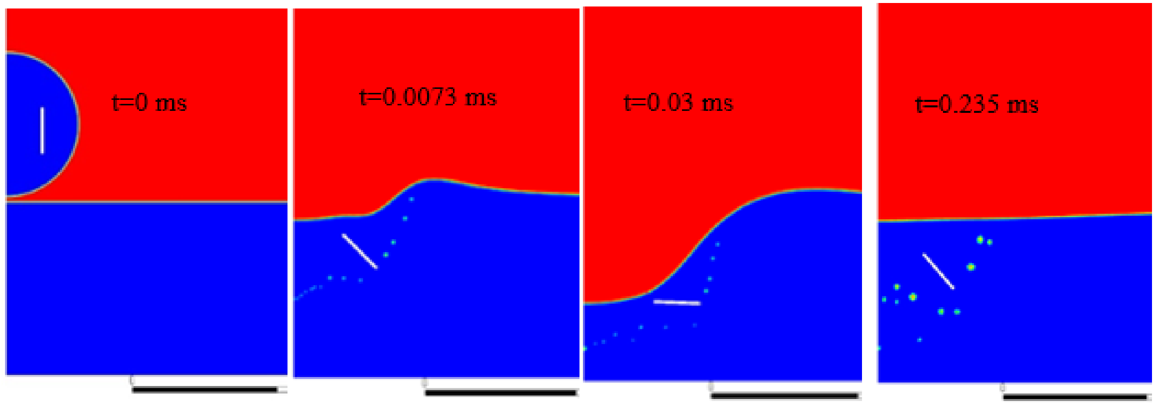
Comparison of flake orientation with different viscous droplets.

- Newtonian droplet: D=50µm, σ = 0.025 N/m, η = 20 mPas, h_film = 60µm

Impact velocity U = 0.5 m/s

Impact velocity U = 10 m/s





Droplet deposition, final angle = 32°

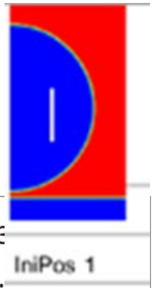
Cratering, final angle = 49.3°

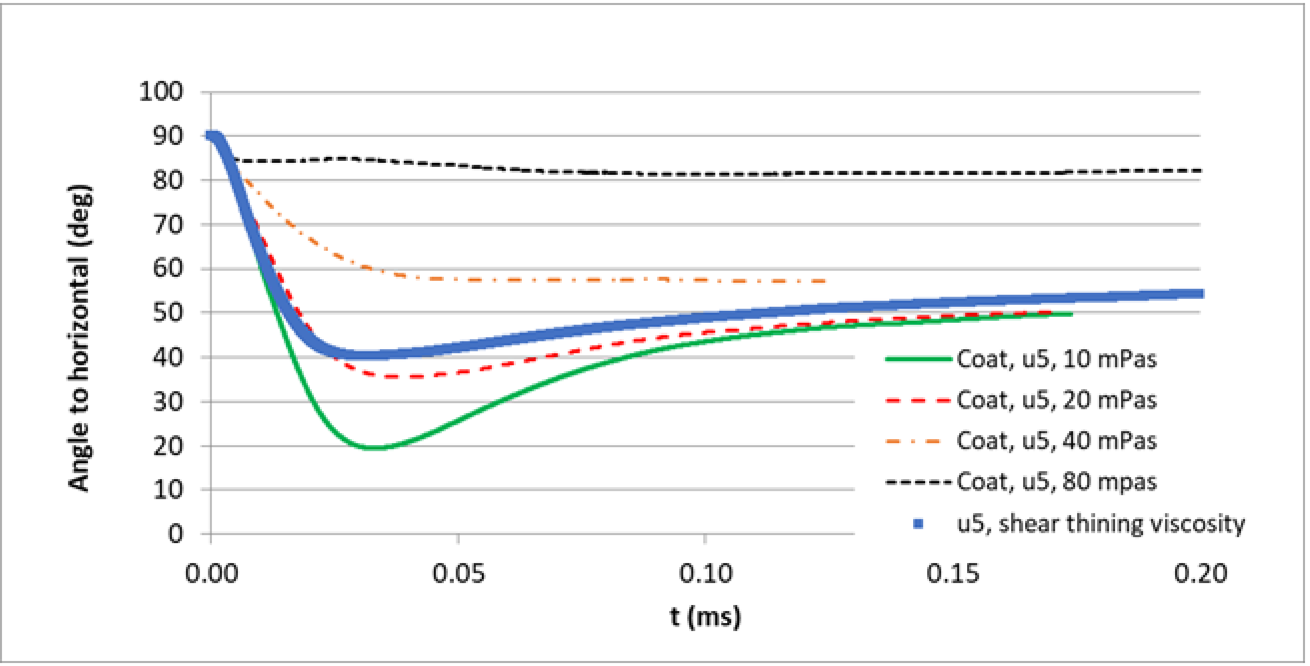
Outcome of droplet impact on wet surface by spray paintng:

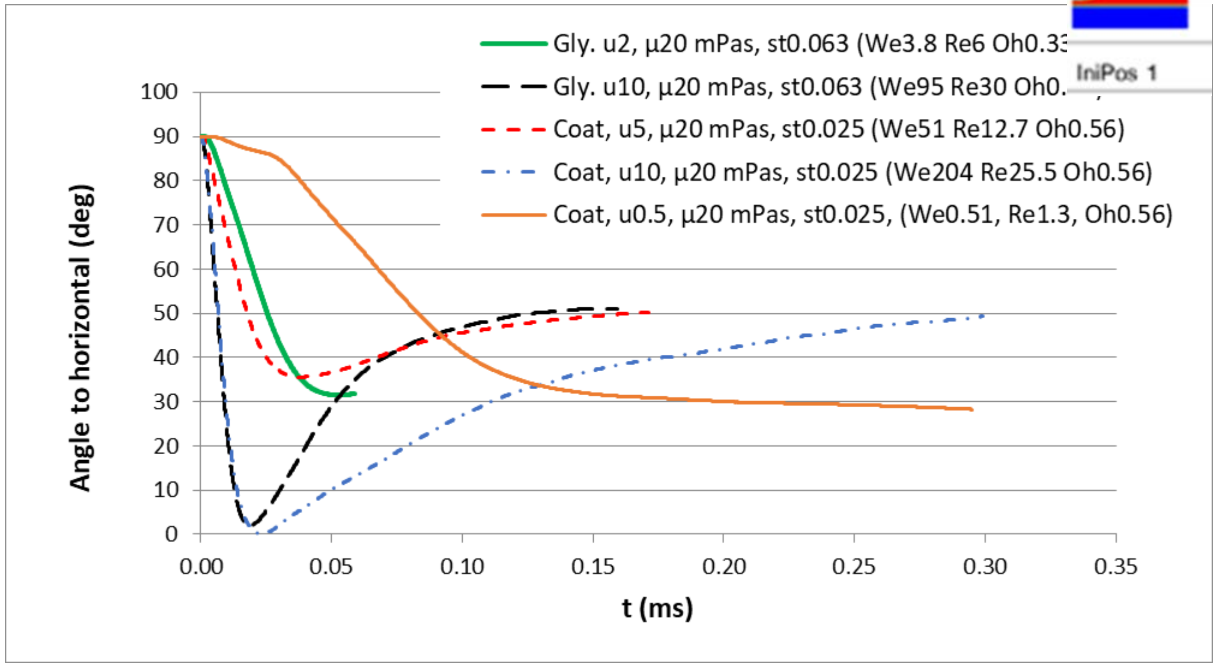
- Deposition
- Cratering
- Crater/crown

- Comparison of flake orientations by droplet impact on the wet solid surface using different viscous droplets (H_f = 60µm, D = 50 µm)

Initial position ☞







At quasi-static state:

- Viscosity ↑ → Angle ↑
- For lower viscosity, U ↑ → Angle ↑

- Effect of surface tension is weak for the final angle
- Effect of film thickness (H/D > 0.5) is weak

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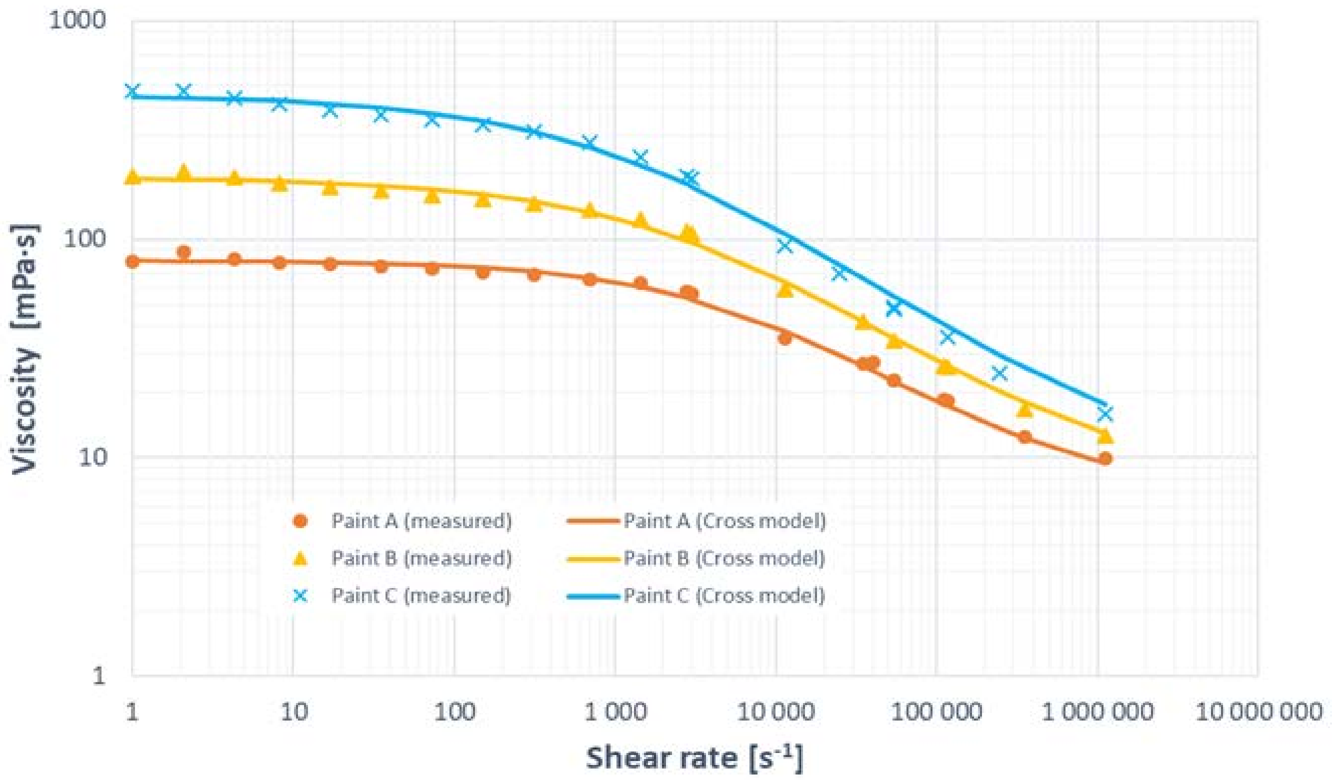
- Simulation with shear thinning viscosity (D = 50 µm, U = 5m/s, σ = 0.025 N/m, h_film = 60µm)



Measured after painting application

Characteristic shear rate by droplet impact:

$$\dot{\gamma}^* = \frac{2 \cdot u}{D} \rightarrow \eta^*$$

For example:

$u = 5, \dot{\gamma}^* = 2e5, \quad \eta^* = 14 \text{ mPas}$

$u = 0.5, \dot{\gamma}^* = 2e4, \quad \eta^* = 30 \text{ mPas}$

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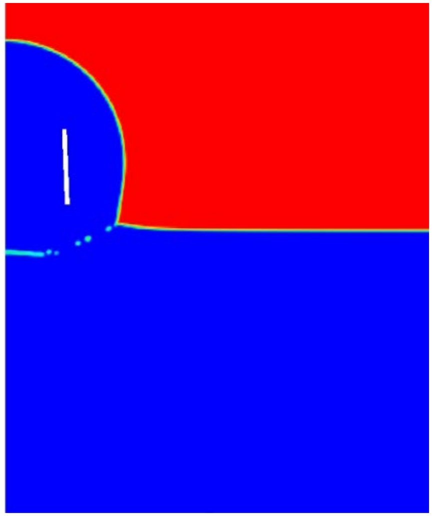
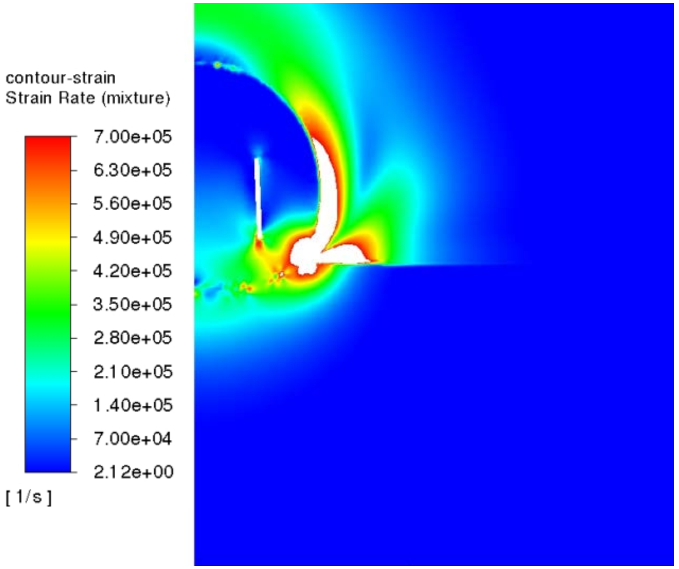
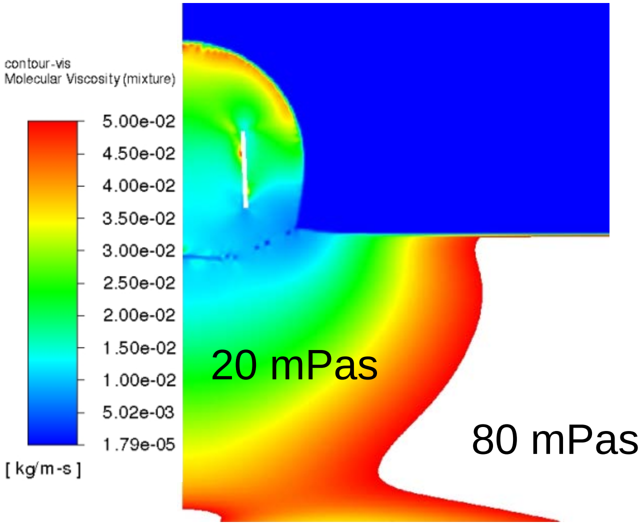
- Simulation with shear thinning viscosity (D = 50 µm, U = 5m/s, σ = 0.025 N/m, h_film = 60µm)



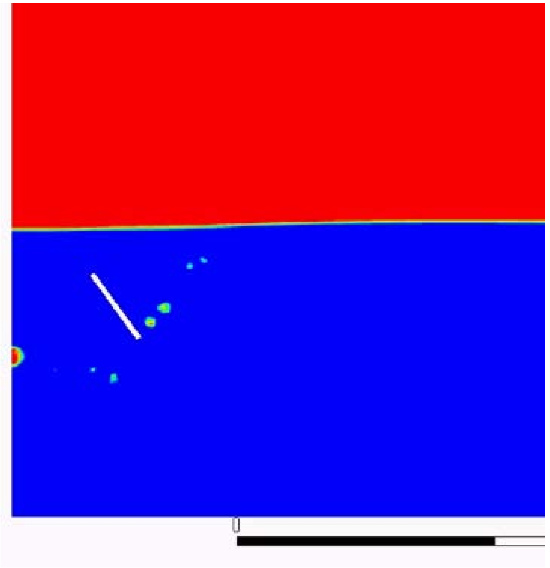
VOF contours



Shear rate: 2-7e5(1/s)



Viscosity: 10 – 50 (mPas)



Angle_static: 55°

- Comparison of above results, e.g. angle_static, with that using droplet with a constant viscosity
  - Using shear thinning viscosity, angle_static = 55°
  - η^* ~ 14 mPas by the characteristic shear rate (γ^* = 2e5 (1/s)), angle_static = 50°

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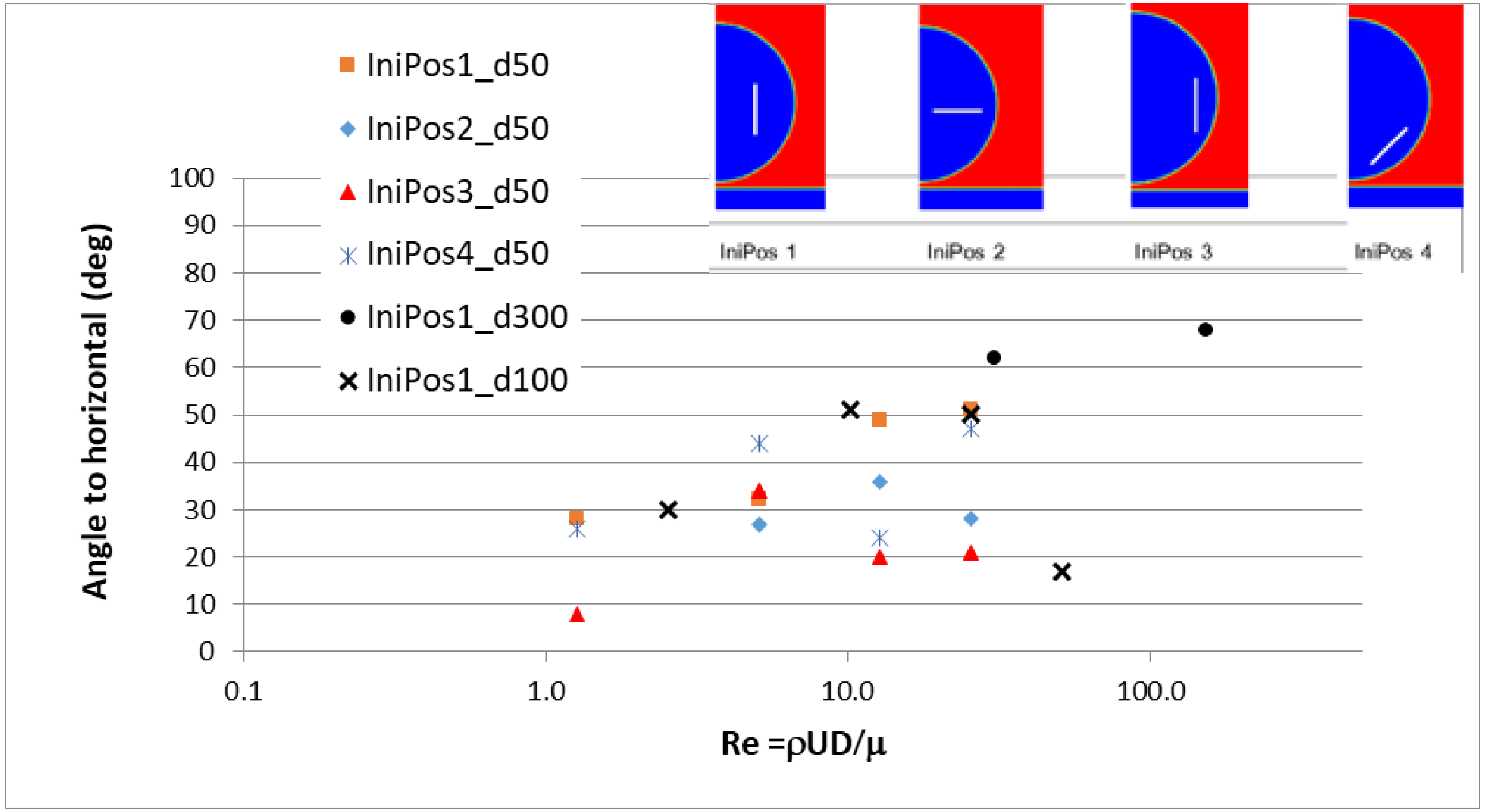
Effects of initial positions of flake on the final orientation (h_film = 60µm, η = 20 mPas)



- lower angle to horizontal for IniPos. 2&3
- For D = 50µm and a given low viscosity, angle increases with increasing of Re-Number
- For large droplets D >= 100µm, situations are complicated
- For spray painting process, dominant droplet size < 50 µm

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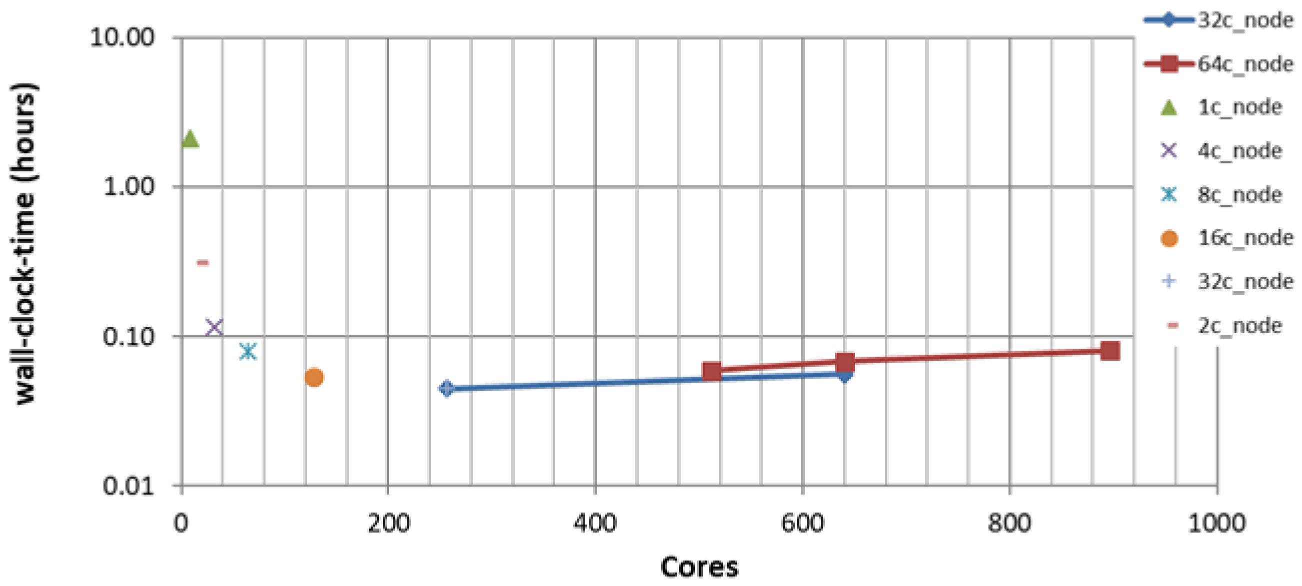
Computational performance

The numerical flow simulations were performed using the commercial flow solver ANSYSFluent v19.5 on the HPE APOLLO (HAWK) of the High Performance Computing Center (HLRS) in Stuttgart. The maximal128 cores/node is suggested to use.

- More memory per core is required because of the dynamic mesh adaption with overset-method
- The calculation with 32 cores/node and 256 cores used in total shows a better performance.



- A simulation case with 130 million cells was calculated up to 0.1 - 0.5ms of physical time with time step size < 1e-7s. Using 8 nodes and 256 cores, it consumed about 150 - 760 hours. The latter corresponds to the case with a large droplet.

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A detailed numerical study of the flake orientation by the viscous droplet impact on dry/wet solid surfaces has been carried out.

- A dynamic contact angle model that is suitable to the spray painting process was proposed and validated by the experimental observations
- Implementing a rigid body motion solver for calculating flake movement in ANSYS-Fluent
- A first parameter study was performed
  - Higher liquid viscosity is unfavorable to the flake movement and orientation
  - For real paint liquid, Non-Newtonian behaviors should be taken into account. The proposed characteristic shear rate and the resulting characteristic viscosity can be used to determine the suitable impact velocity
  - For a given low viscosity, small droplets ($D = 50\mu m$) with low impact velocity will benefit the final flake orientation without a strong film surface waviness

Outlook

- Further parameter study for $D < 50\ \mu m$ and $50 < D < 100\mu m$ …
- Flake orientation by baking processes….

Thank you very much
For your attention

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