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Multiphysics Simulation of Particle Clouds in Coating:

The long Journey from Modelling to validated Industrial Application

Keynote Address, 17th International Conference of Multiphysics

15th Dec 2022, G. Boiger, OSLOMET University, Oslo, Norway

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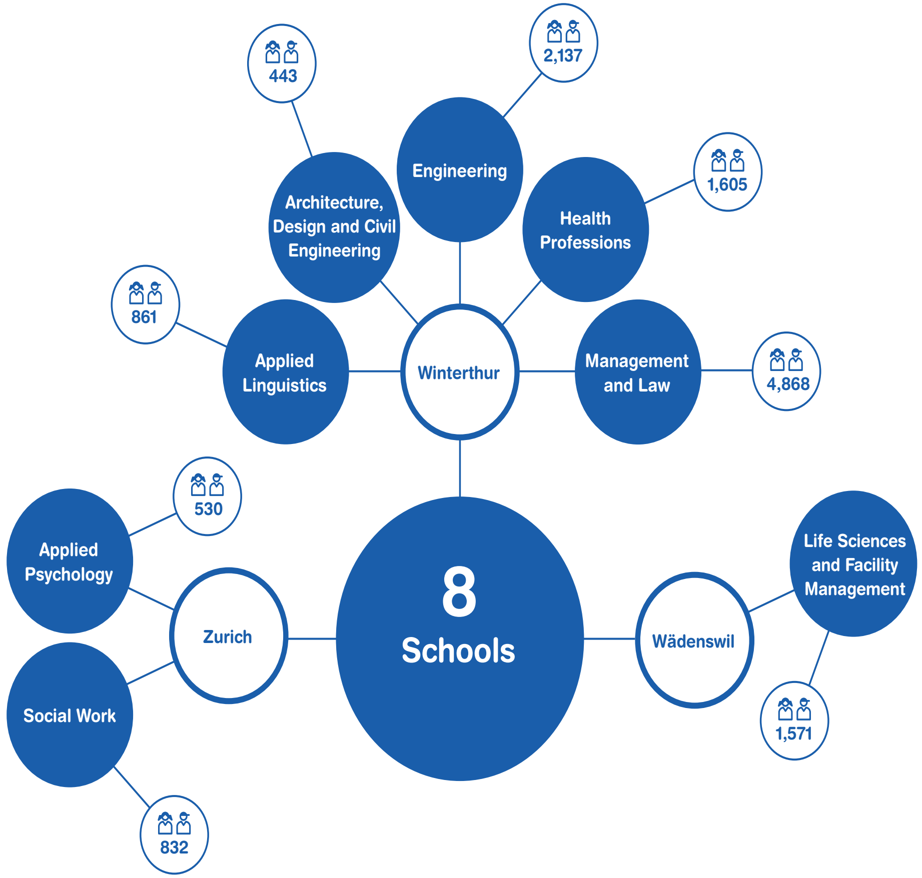
Europe
Switzerland
Canton of Zurich
Winterthur

Gernot Boiger

- Professor of Modelling Multiphysics Applications
- Head of Research Area Multiphysics Modelling and Imaging
- Vice President Europe Int. Soc. Multiphysics
- ZHAW Zurich University of Applied Sciences
- SoE School of Engineering
- ICP Institute of Computational Physics

Zurich University of Applied Sciences



Research Area
Multiphysics Modelling and Imaging

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Multiphysics Modeling


Gernot Boiger, Prof.


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Alain Schubiger, MSc.


Viktor Lienhard, MSc.


Vinzenz Muser, MSc.


Bercan Siyahhan, MSc.


Jhimy Rivero


Vincent Buff, MSc.


Marco Hostettler, MSc.


Sima Delbari, MSE Student


Darren Sharman, MSc.

Multiphysics Modeling and Imaging

Micro Structures & Imaging


Lorenz Holzer, PhD.


Lukas Keller. PhD.


Sebastian Spirig, MSc.


Philip Marmet, MSc.

FE Thermal- & Fluid- Eng.


Thomas Hocker, Prof.


Yasser Safa, PhD.


Guido Sartoris, PhD.


Sandro Ehrat, MSc.

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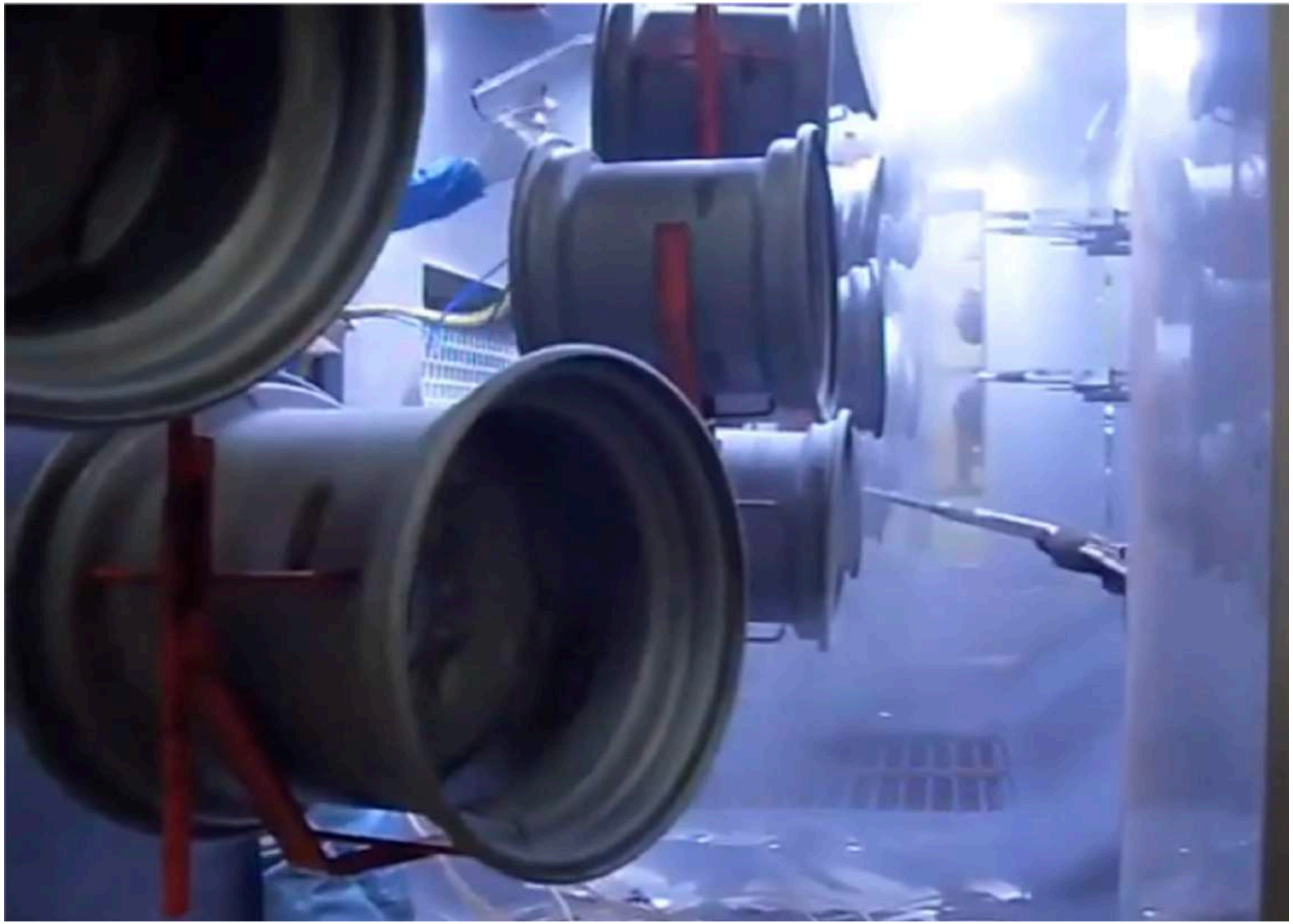
1. Overview & Introduction

Content

1. Overview & Introduction



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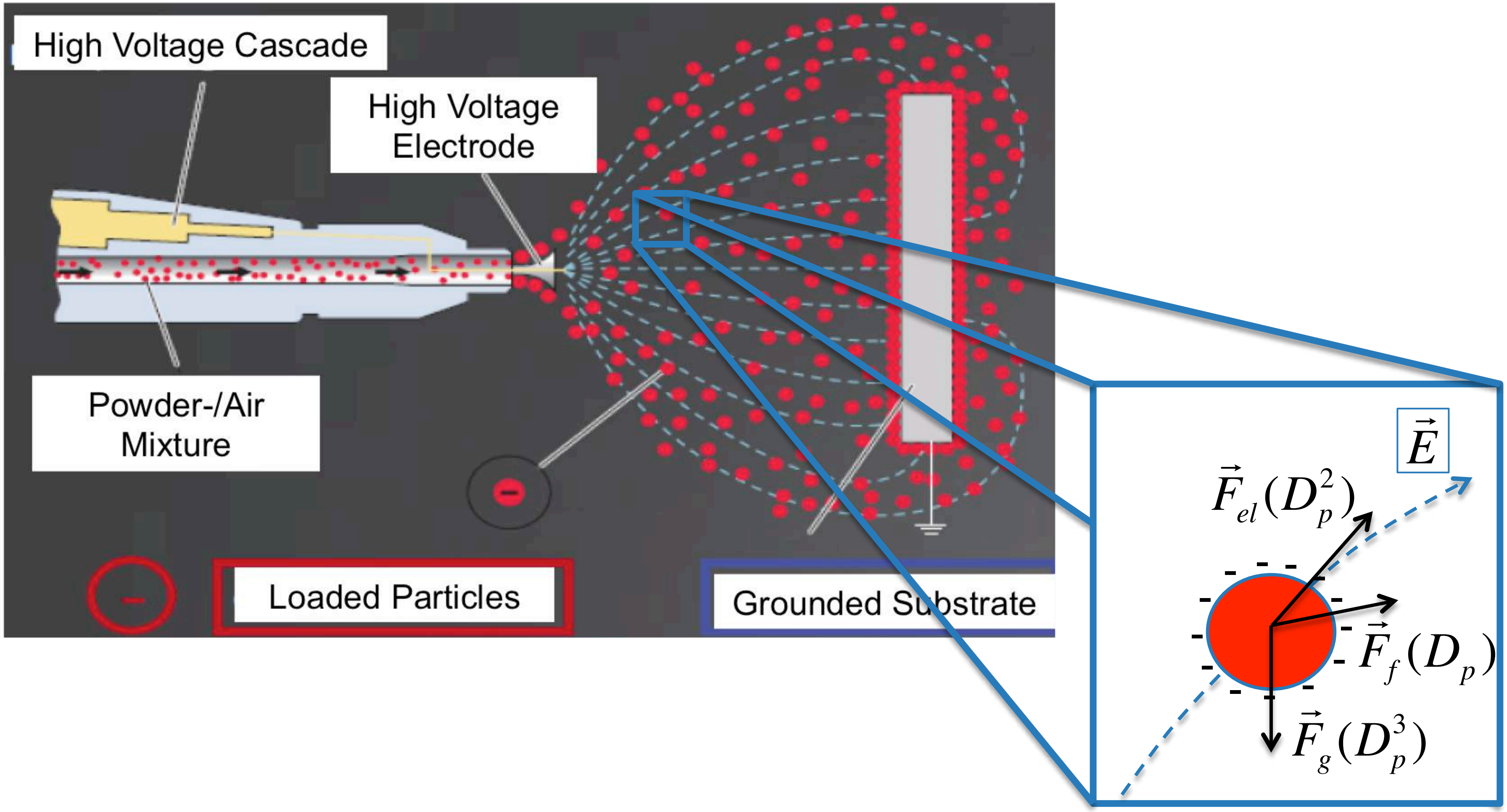
Powder Coating: Flow, Particle-Dynamics, E-Static



Acting Forces

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Main Task?

Content

1. Overview & Introduction

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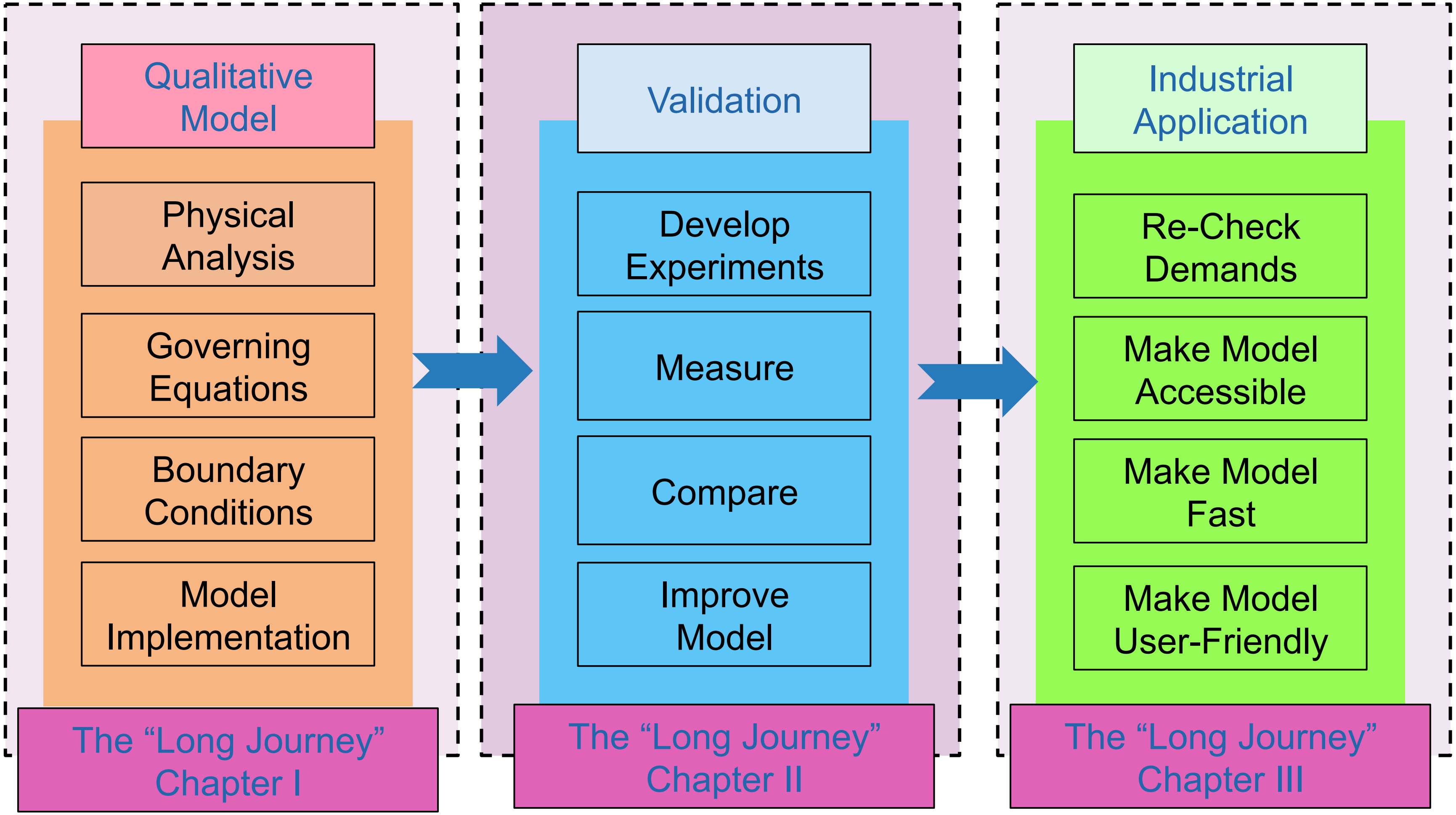

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2. Qualitative Modelling, Validation

Content

ICM 2007 - Manchester

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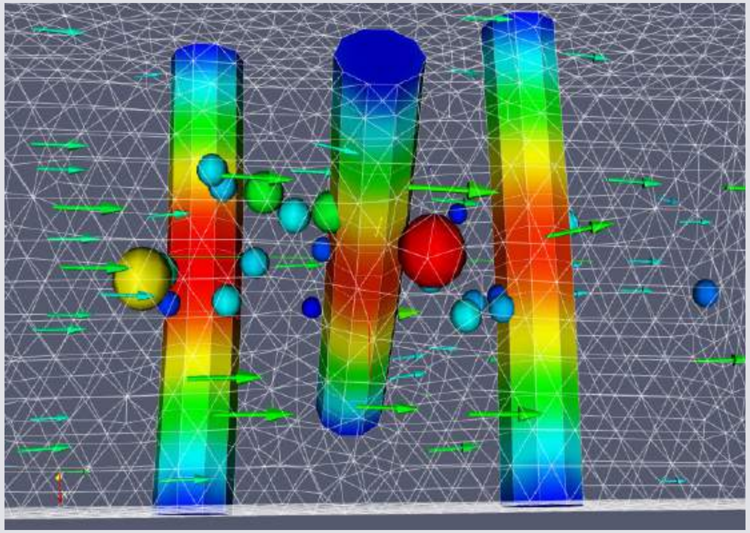
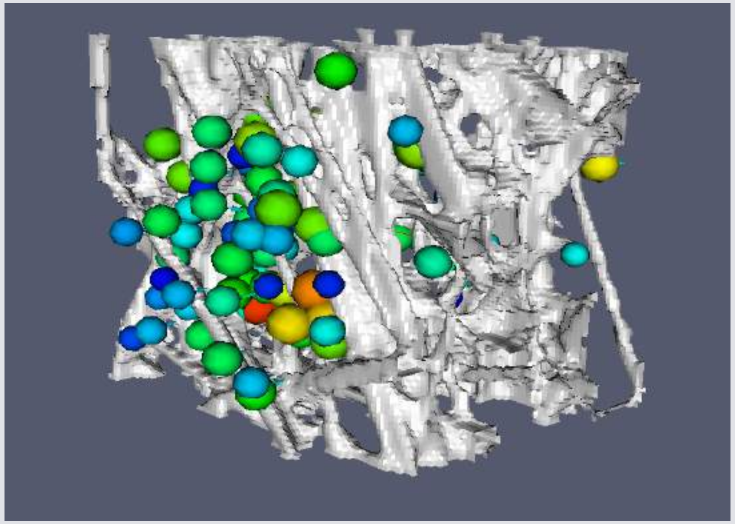
Source: https://www.multiphysics.org/past-conferences

Particle filtration processes in deformable media

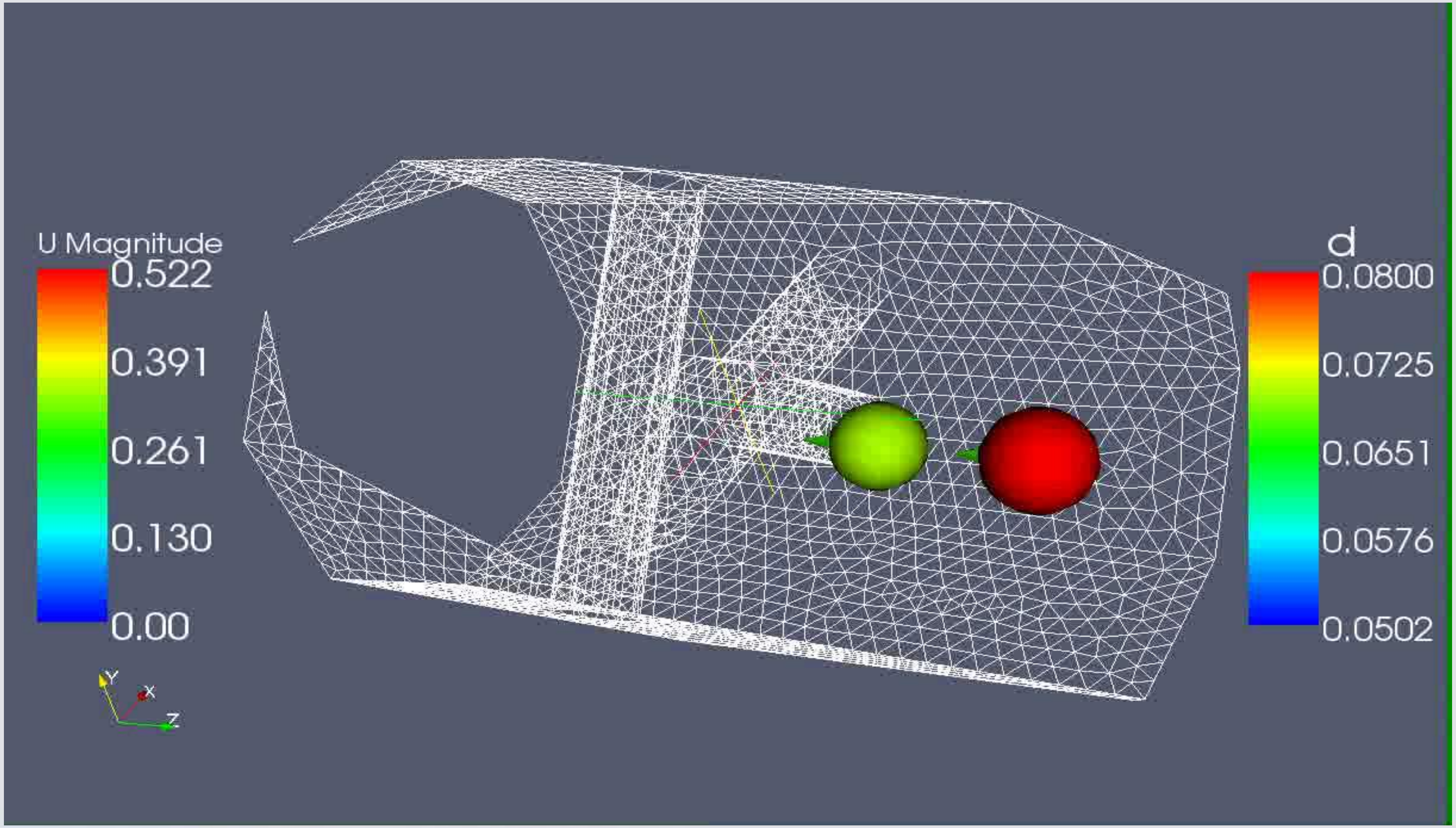




Multiphysics Conference, Manchester, 12.12.- 14.12. 2007

Gernot Boiger, Marianne Mataln

OpenFOAM: Euler - LaGrangian Solver – Blow Off Effect

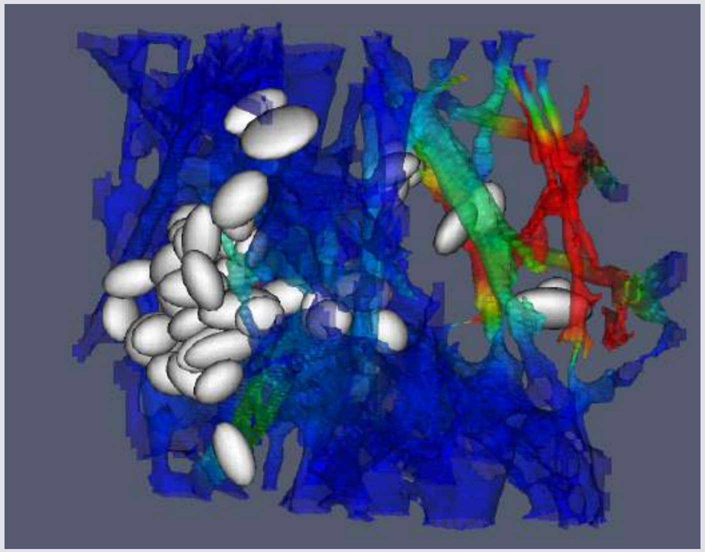


ICM 2008 - Narvik

Sources: multiphysics.org/past-conferences; agoda.com;

Simulation of Filtration Processes in Deformable media

Part 3: Non-Spherical dirt particle modelling



MultiPhysics, Narvik, 10.12.- 12.12. 2008

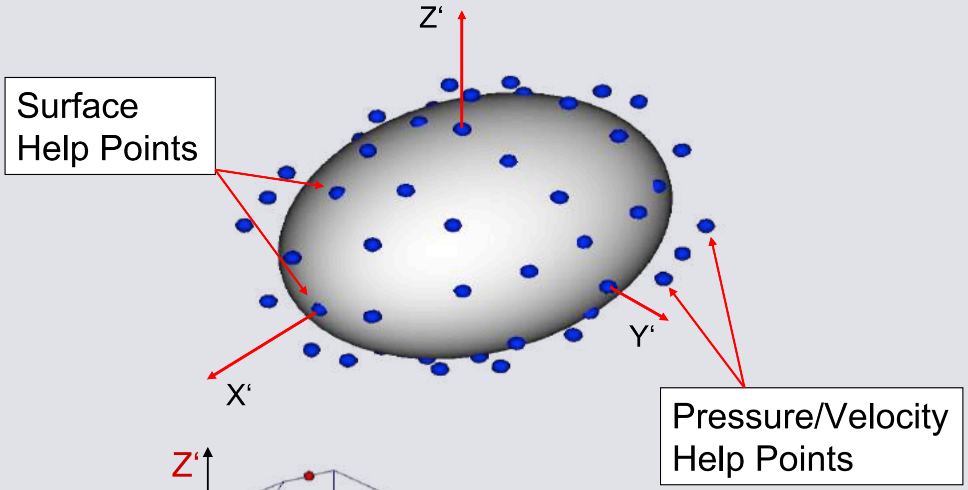
Gernot Boiger, Marianne Mataln

Auxiliary Concepts:

Pressure/Velocity Help Points:

66 Points for detection of:

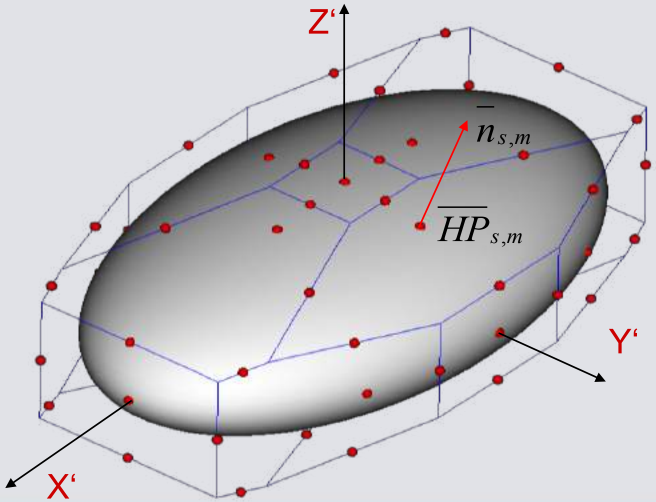
- relative fluid velocity
- acting pressure/shear force
- collisions



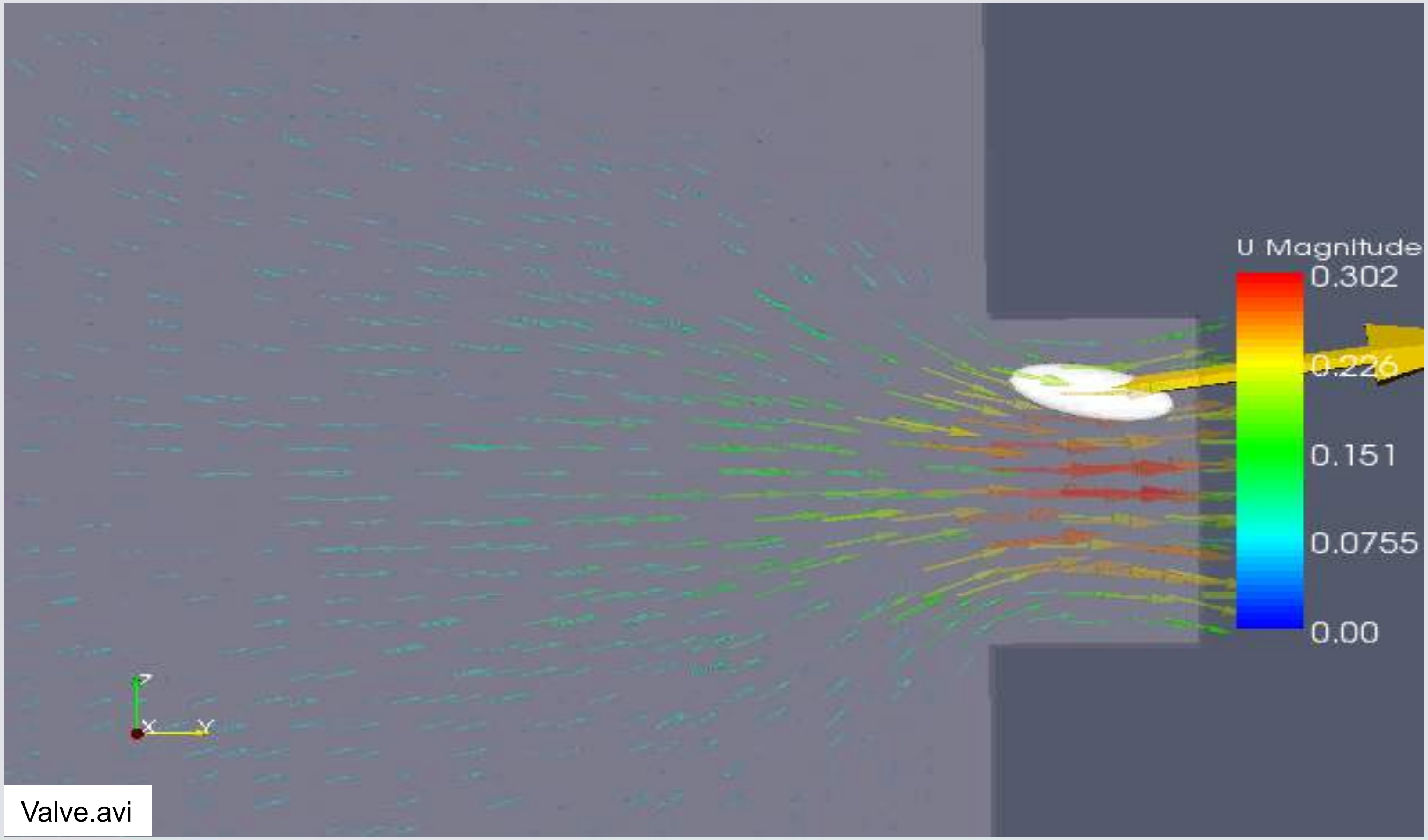
Panel methode:

18 Panels for calculation of:

- local drag force
- rotational effects

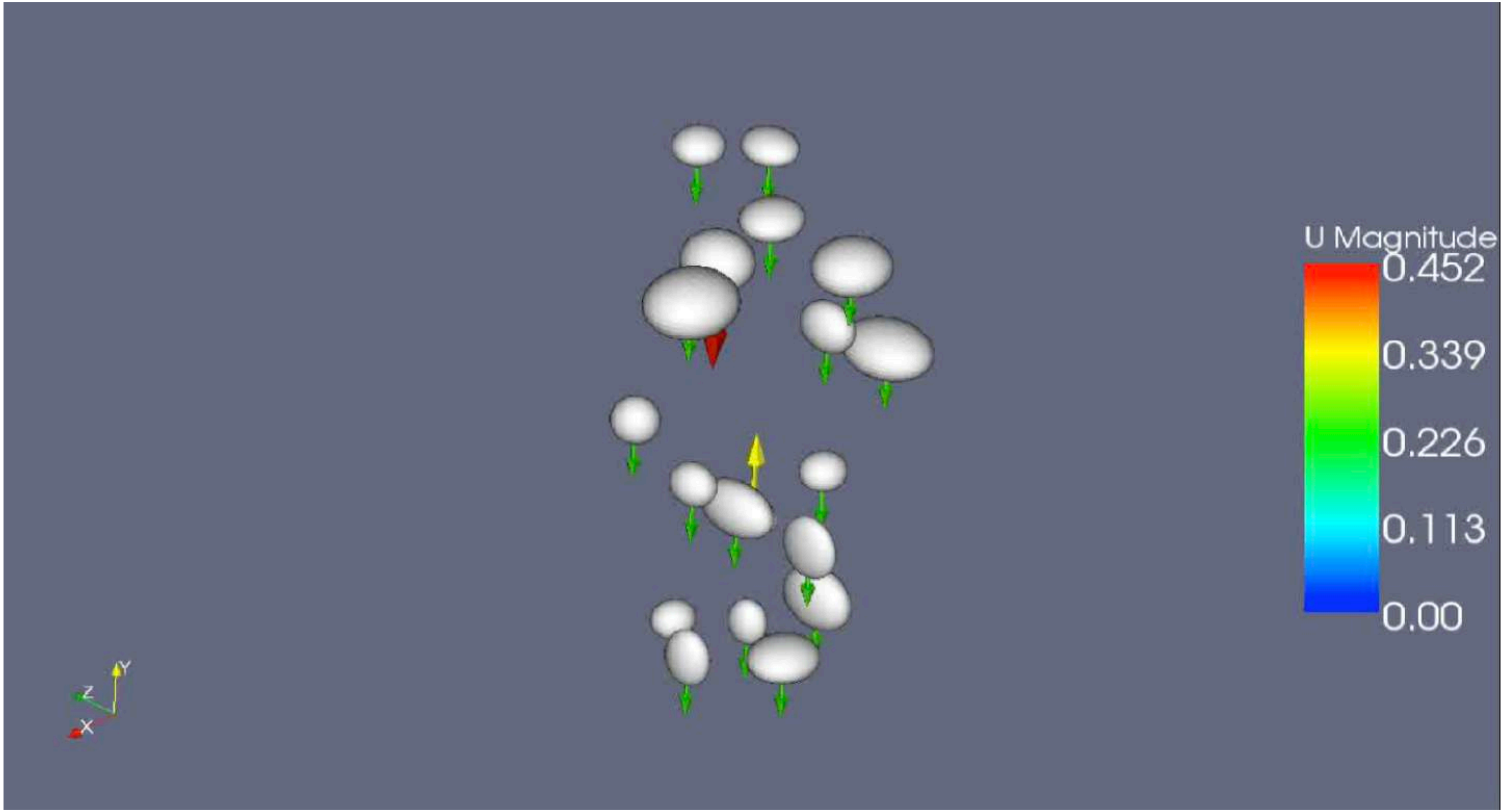


Benchmark – Valve Effect

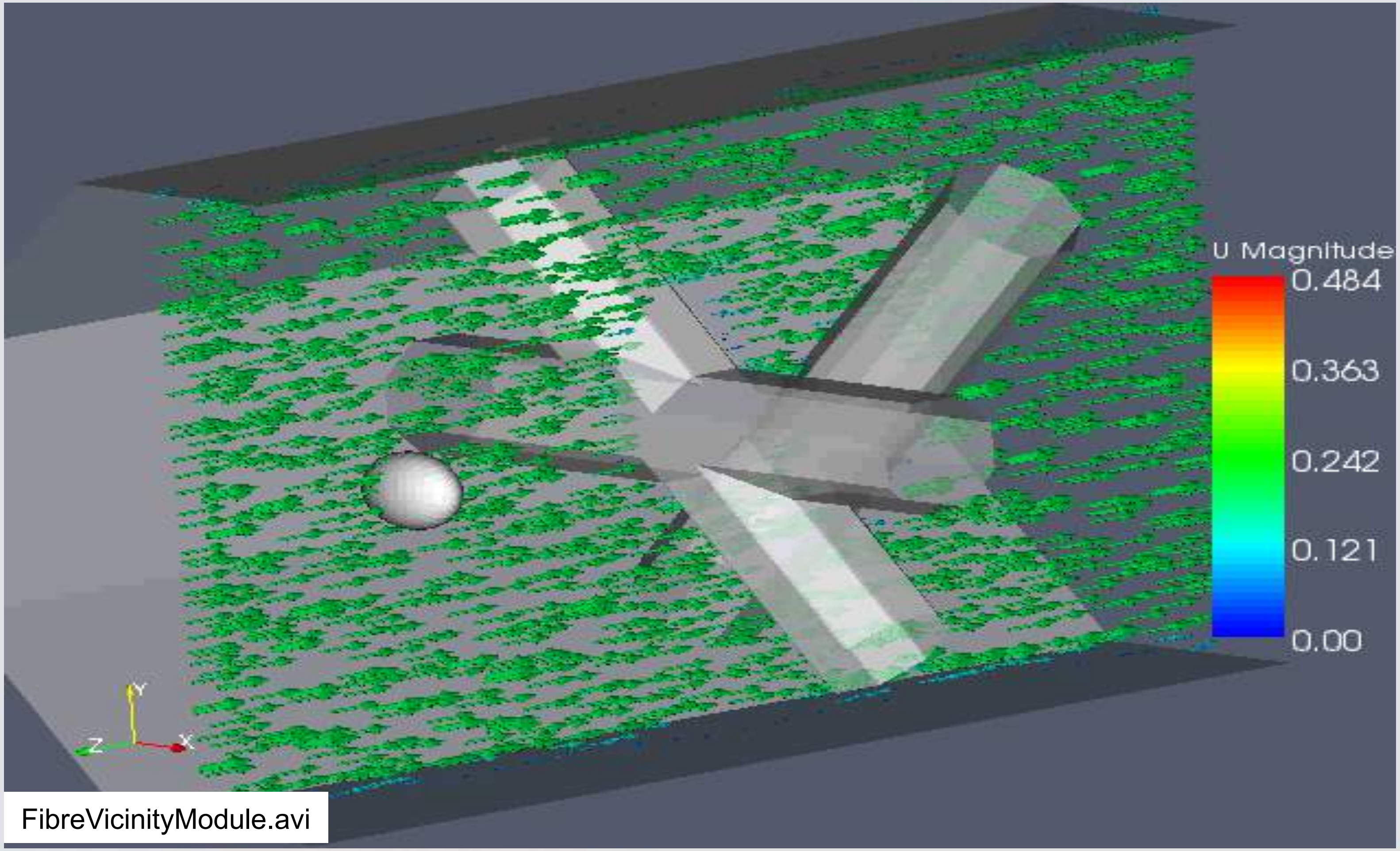


Valve.avi

ICM 2008 - Narvik

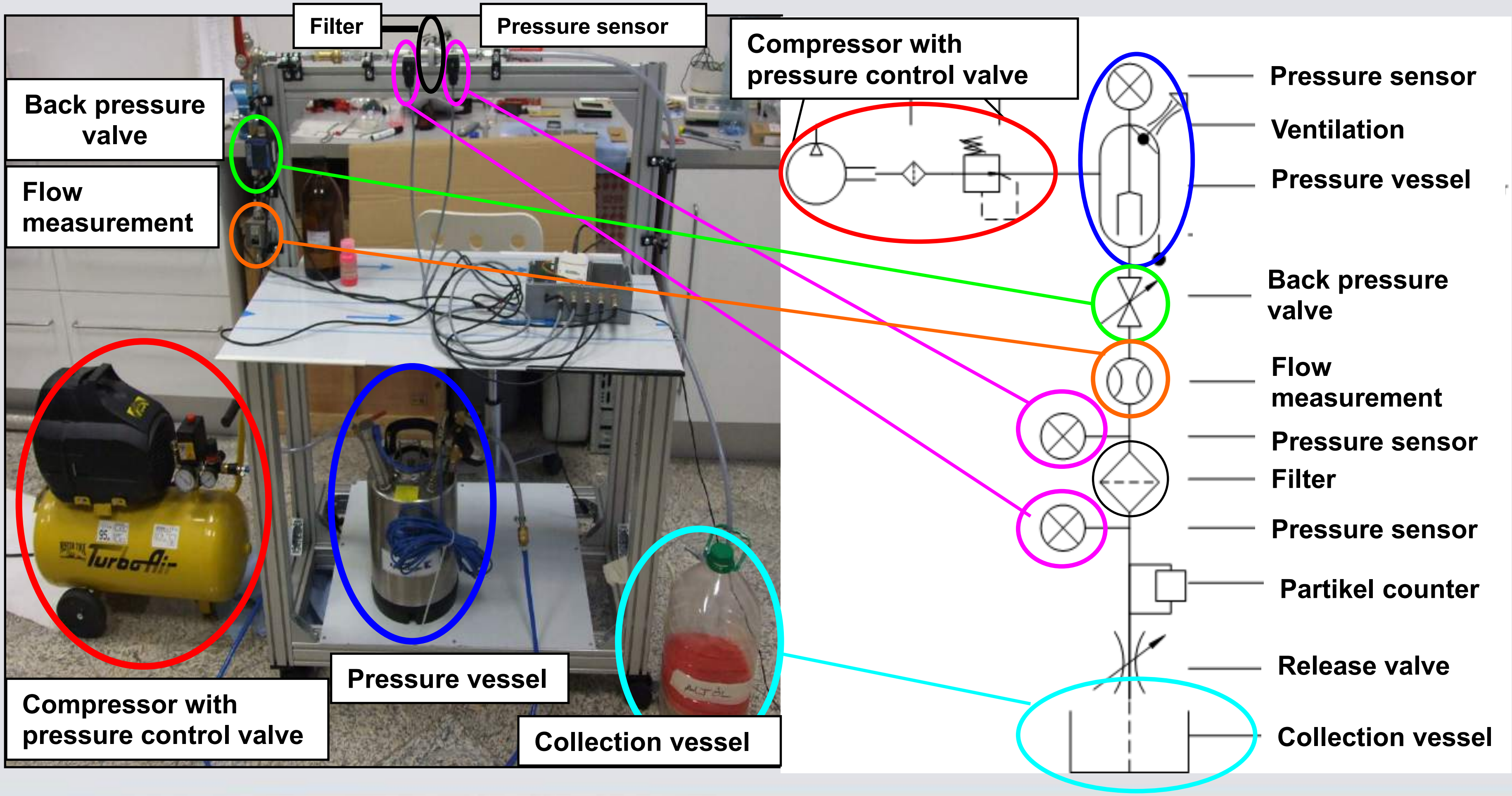


Benchmark – Fibre Vicinity Module



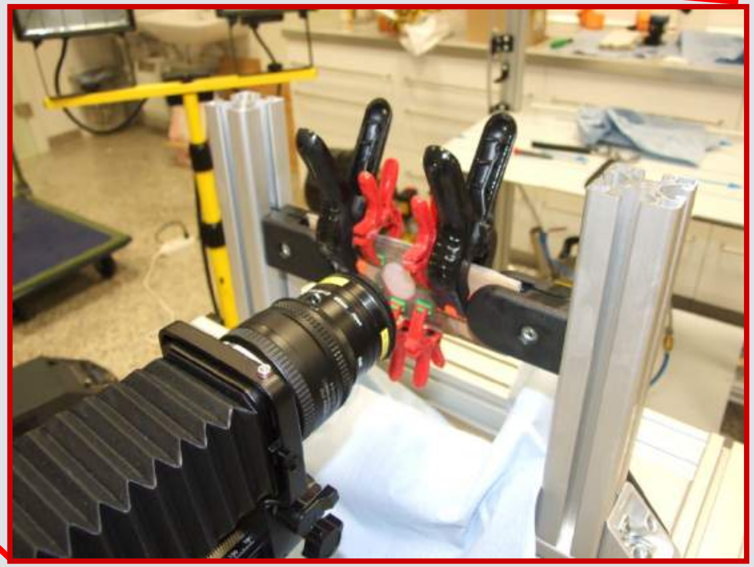
FibreVicinityModule.avi

Oil/Fibre Test according to ISO 4548 -12



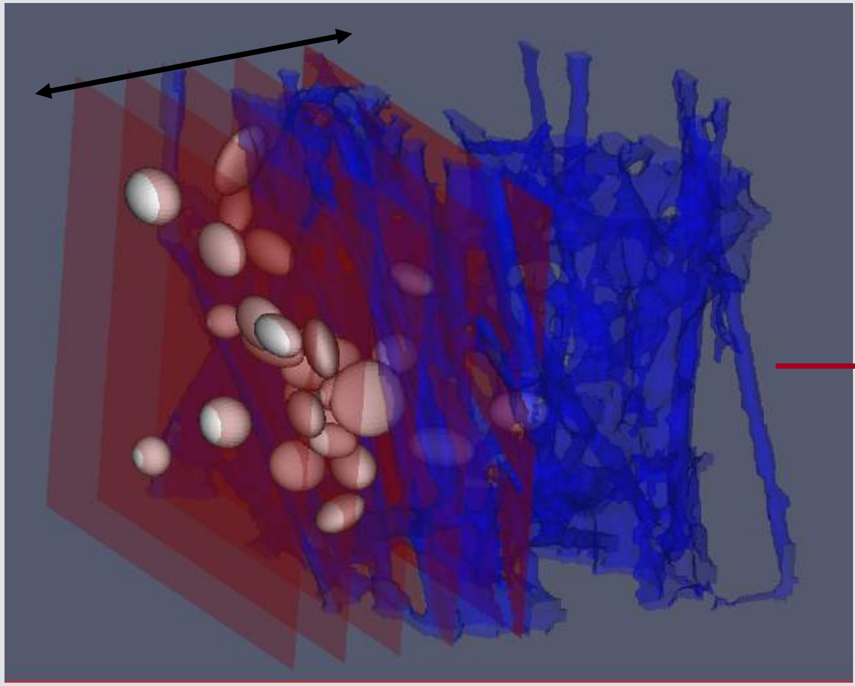
Evaluation Facility: Sample holding device

1. Sample holding device
2. PIV Cam
3. DriveSet
4. Laser

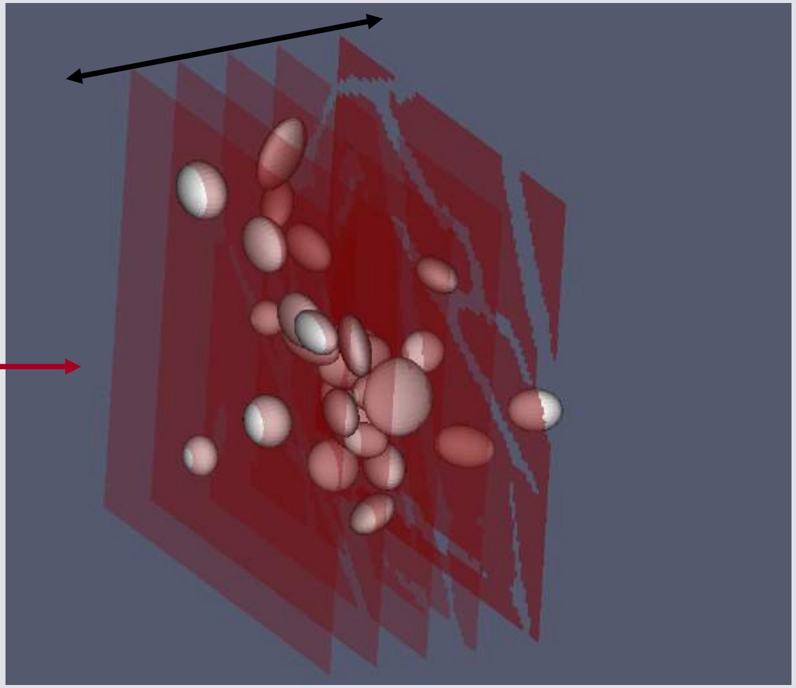


Principle of 3D Macroscopy

Focal Plane is moved through Fibre

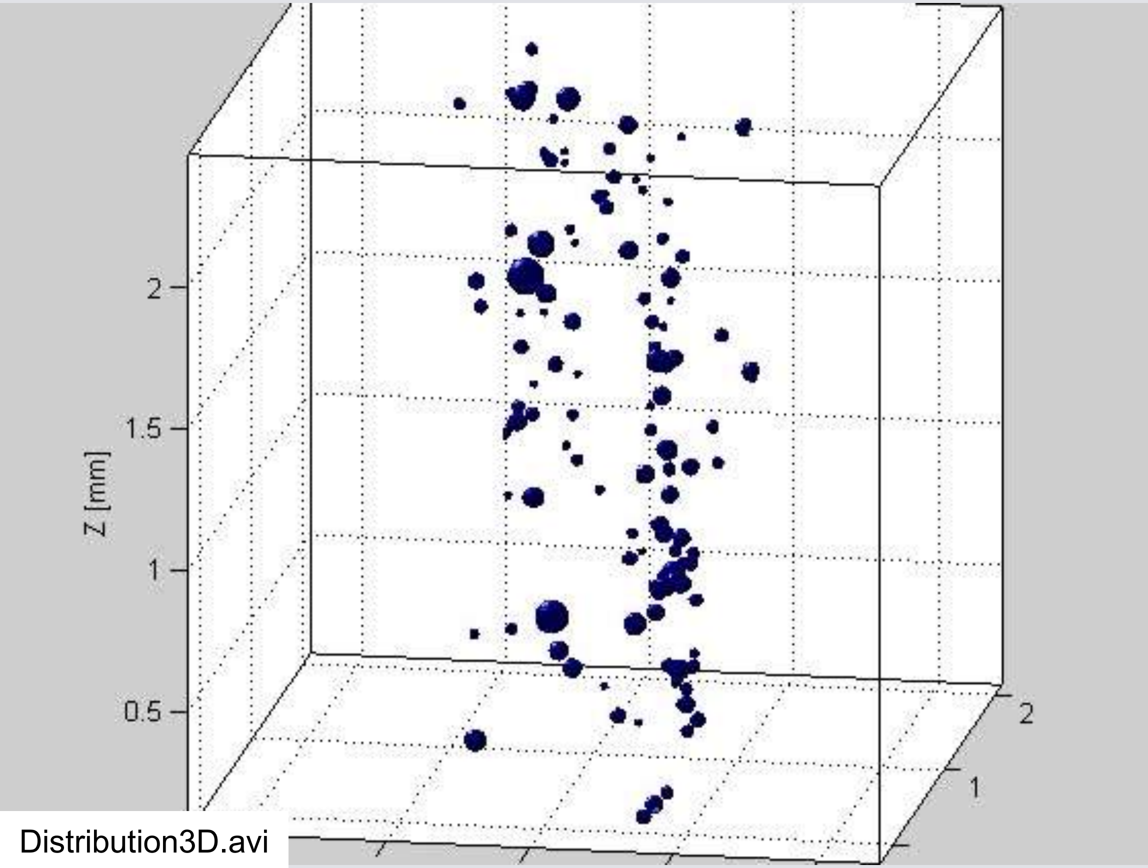


Particles entangled in Fibre structure



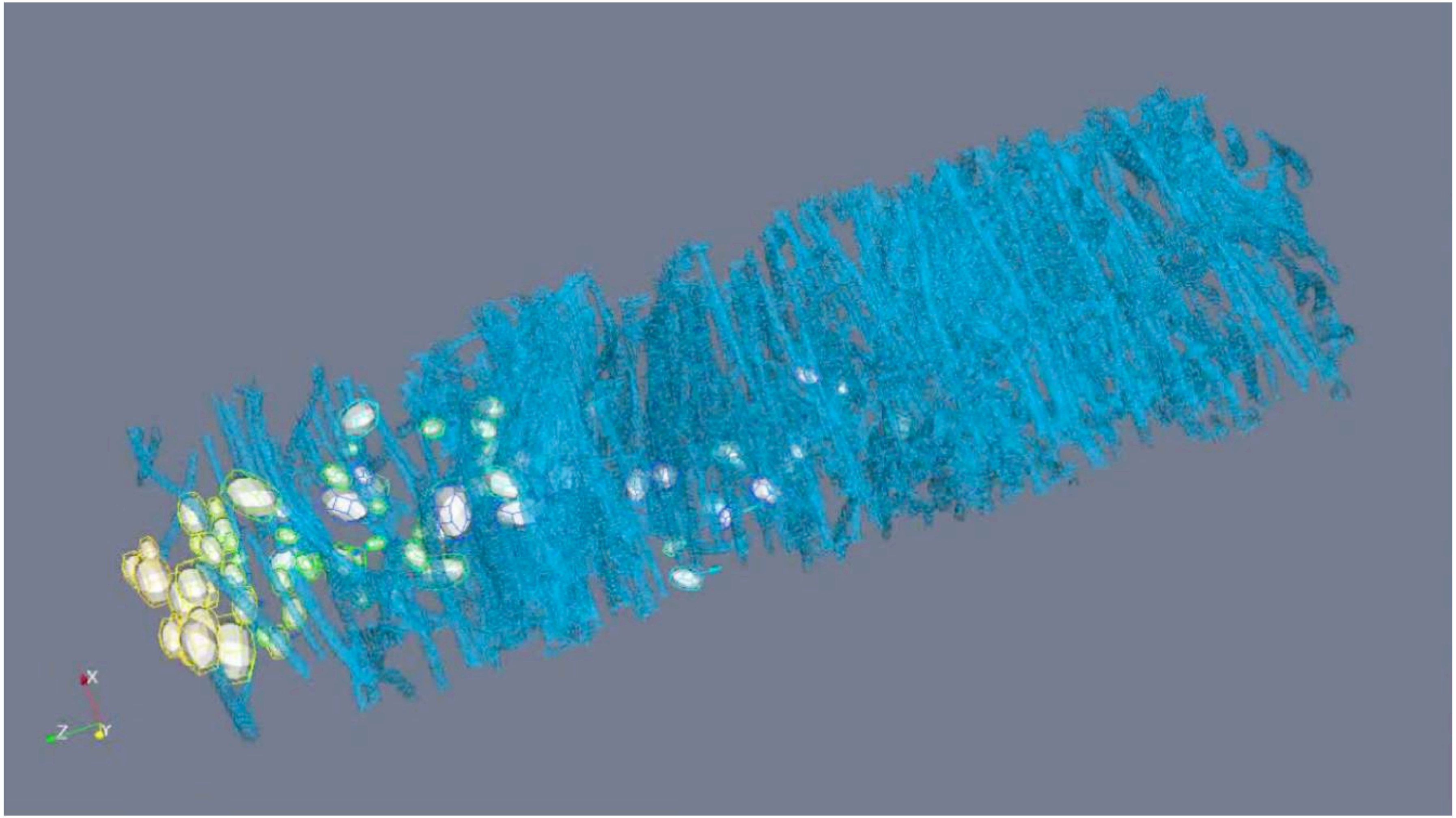
Reconstruction of Particle Distribution

Evaluation Results: Matlab Evaluation Algorithm



3D Reconstruction of Particle Distribution in Fibre Sample

Qualitative Model - 2010



Boiger,G.; Mataln,M.; Brandstätter,W., 2009. Simulation of Particle Filtration Processes in Deformable Media, Part 3.1: Basic concepts and particle-fluid force implementation of a non-spherical dirt particle solver, (2010), Int.Journal of Multiphysics. 3(4), pp. 407-232(26). DOI: 10.1260/1750-9548.3.4.407.

ICM 2013 - Amsterdam

Source: https://www.multiphysics.org/past-conferences

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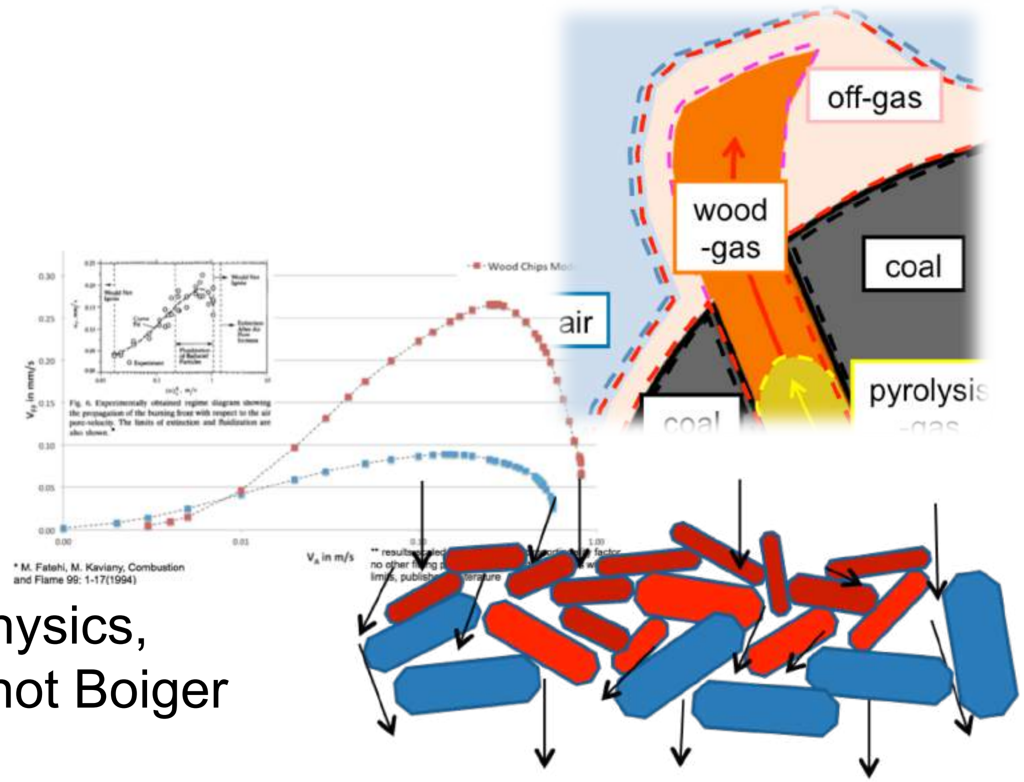
Thermo Fluid- Dynamic Model of Wood Particle Gasification and Combustion Processes

1st step:

Fully Featured 1D-Solver for Particle Gasification

2nd step:

Experimental Validation

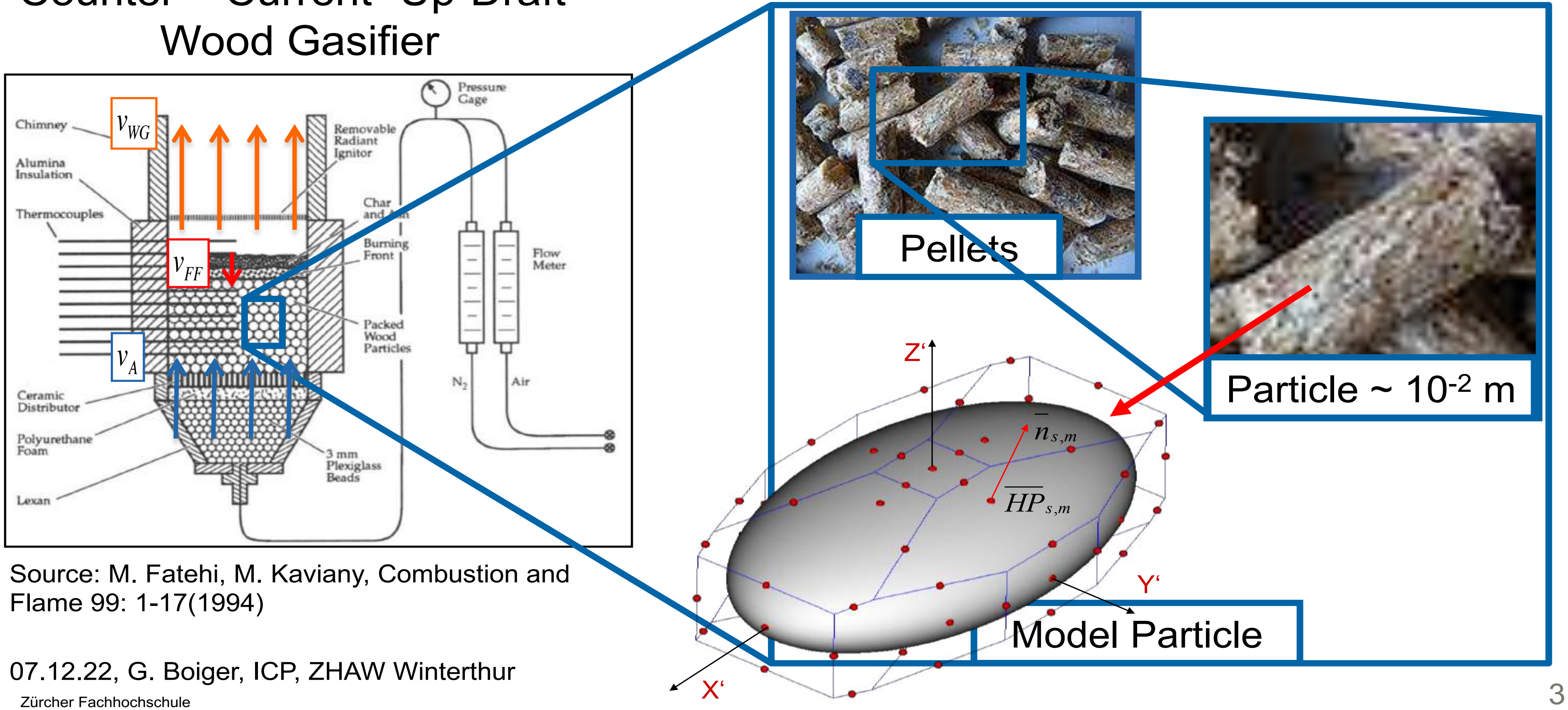


International Conference of Multiphysics,
Amsterdam, December 2013, Gernot Boiger

Model Scale: Packed Bed-/ Particle Level

Counter – Current "Up-Draft" Wood Gasifier

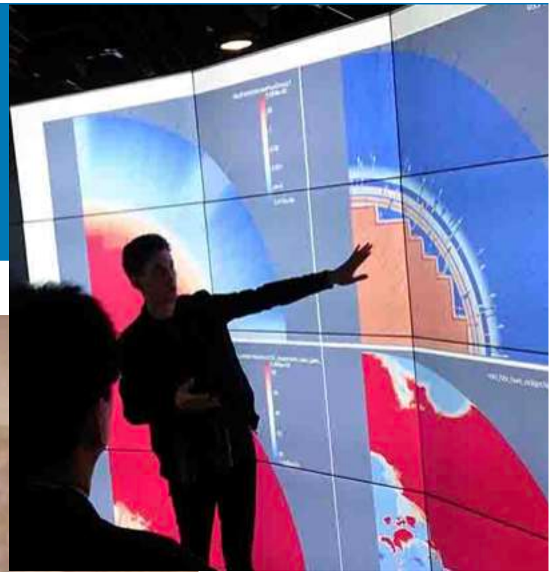
Hybrid Bulk- Particle Model



Source: M. Fatehi, M. Kaviany, Combustion and Flame 99: 1-17(1994)

Boiger,G., 2015. System Dynamic modelling approach for resolving the thermo- chemistry of wood gasification processes, (2015), Int.Journal of Multiphysics. 9(2), pp. 137-155(19). DOI: 10.21152/1750-9548.10.2.177.

ICM 2015 - London



Source: https://www.multiphysics.org/past-conferences

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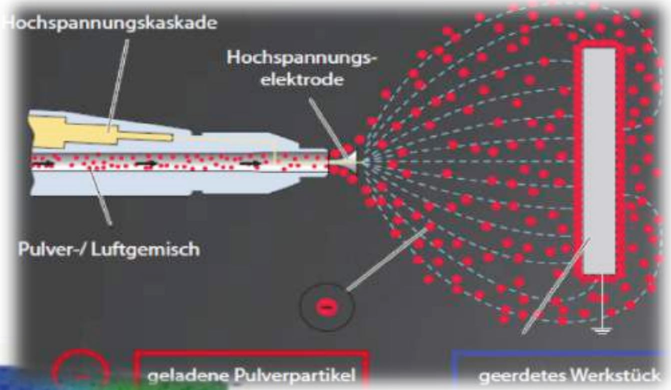
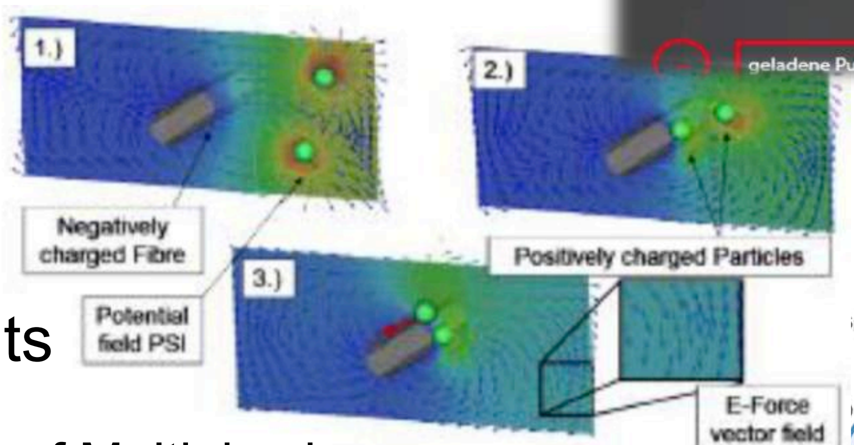
OpenFoam based Modelling of 3D LaGrangian Particle Motion and Deposition within E-Static Fields

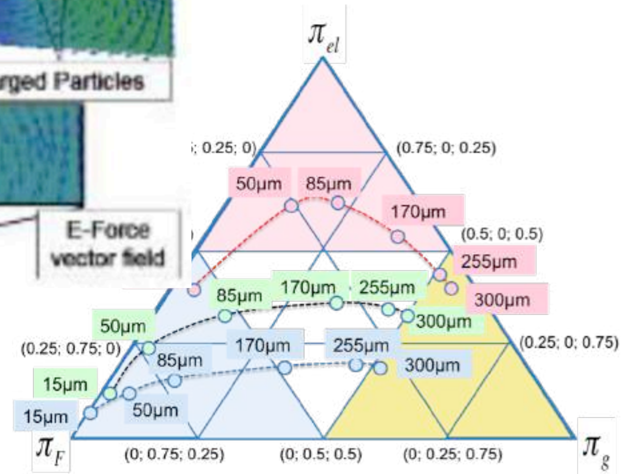


1st step:
Powder Coating

2nd step:
The 3D Model

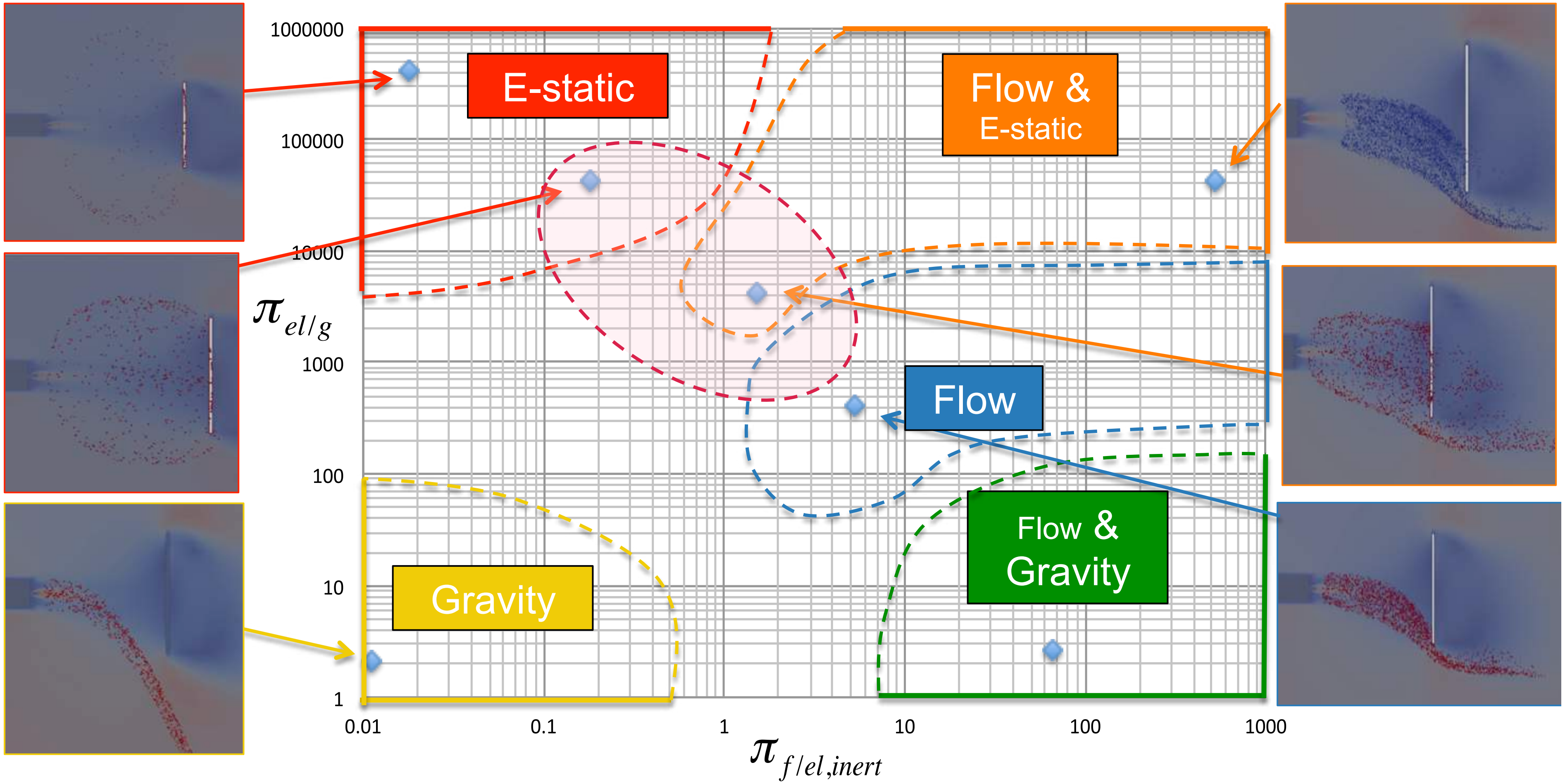


3rd step:
Validation and Results



International Conference of Multiphysics, London, December 2015, Gernot Boiger

ICM 2015 - London

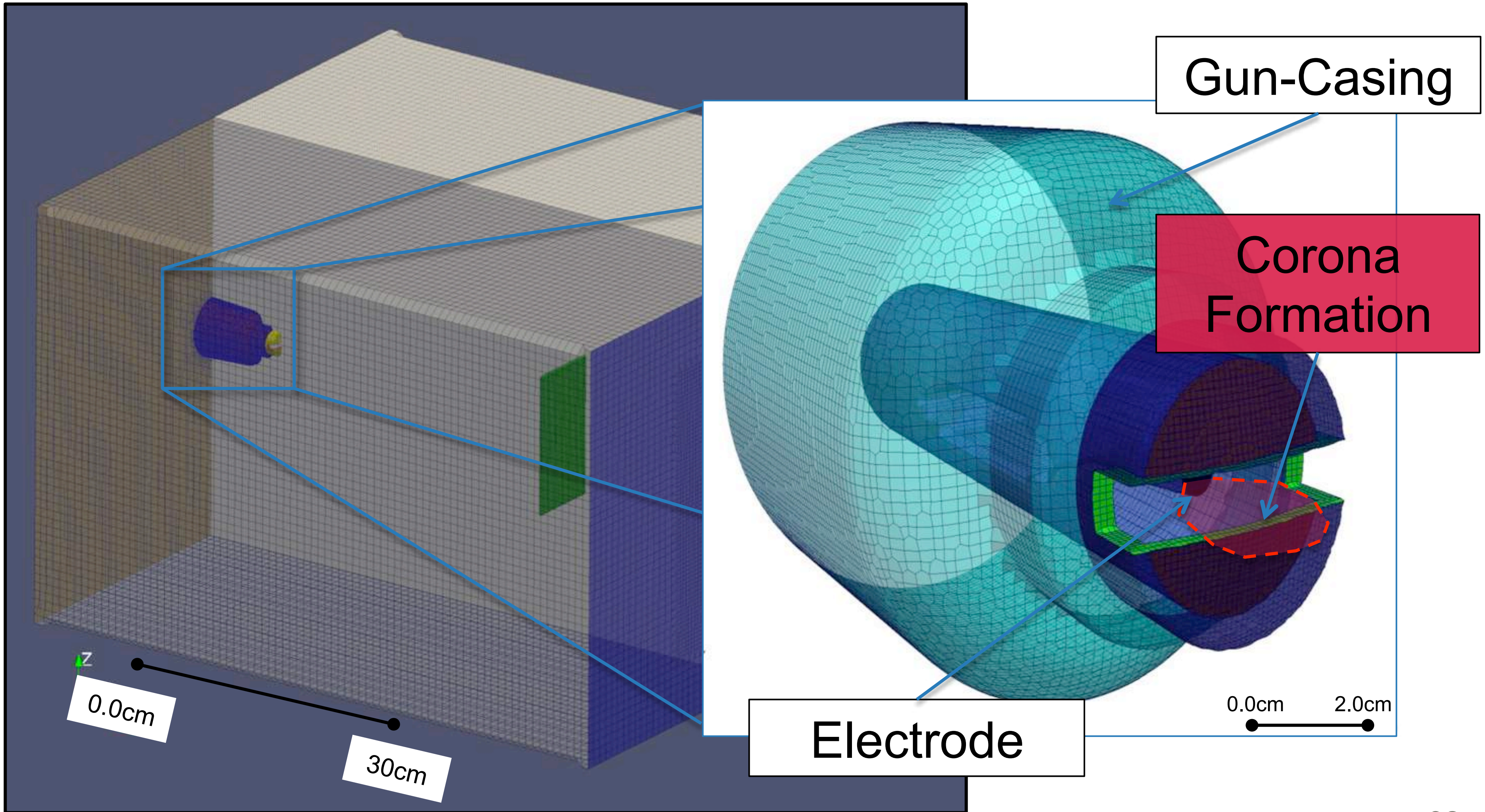


$\pi_{el,g}$: Ratio of E-Static to Gravit

$\pi_{f,el,inert}$: Ratio of Viscosity to E-Static * Inertia

Boiger,G., 2016. Eulerian-LaGrangian model of particle laden flows and deposition effects in electro-static fields based on OpenFoam (2016). Int.Journal of Multiphysics; 10(2), pp. 177–194(8); DOI: 10.21152/1750-9548.10.2.177

Modeling the Geometry & FV Meshing



Modeling Particle Dynamics: Particle Momentum Equation

$$\frac{\partial^2 \vec{x}_p}{\partial t^2} = \frac{\vec{U}_{FP}}{\tau_p} + \frac{\rho_p - \rho_F}{\rho_p} * \vec{g} + \frac{q_p D_p^2 \pi}{m_p} * \left(\vec{E} + \frac{D_p^2 \pi}{4\varepsilon} \nabla \rho_c \right)$$

Aerodynamic Coupling to Flow Field	Gravity Field	E-Static Field	Electric Particle-Particle Interaction

$\vec{U}_{FP}(m/s)$ … Particle - Flow Relative Velocity

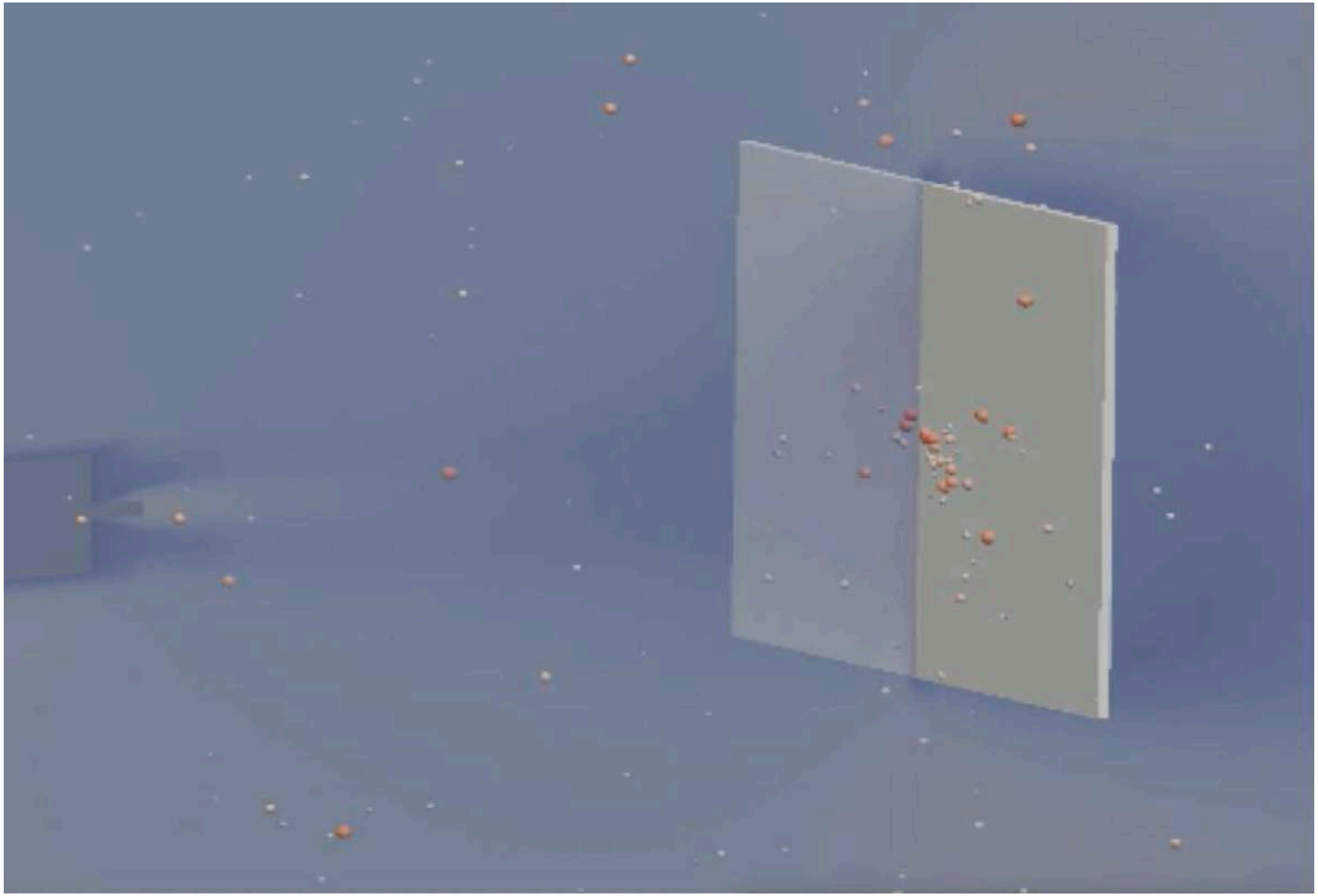
$q_p(C/m^2)$ … Particle Surface Charge

$\vec{E}(N/C)$ … Electric Field

$\tau_p(\mathrm{Re}_p)(s)$ … Particle Relaxation Time

Boiger,G., 2016. Eulerian-LaGrangian model of particle laden flows and deposition effects in electro-static fields based on OpenFoam (2016). Int.Journal of Multiphysics; 10(2), pp. 177–194(8); DOI: 10.21152/1750-9548.10.2.177

ICM 2015 - London



ICM 2016 – Winterthur/Zurich

Source: https://www.multiphysics.org/past-conferences

ICM 2016 - Winterthur

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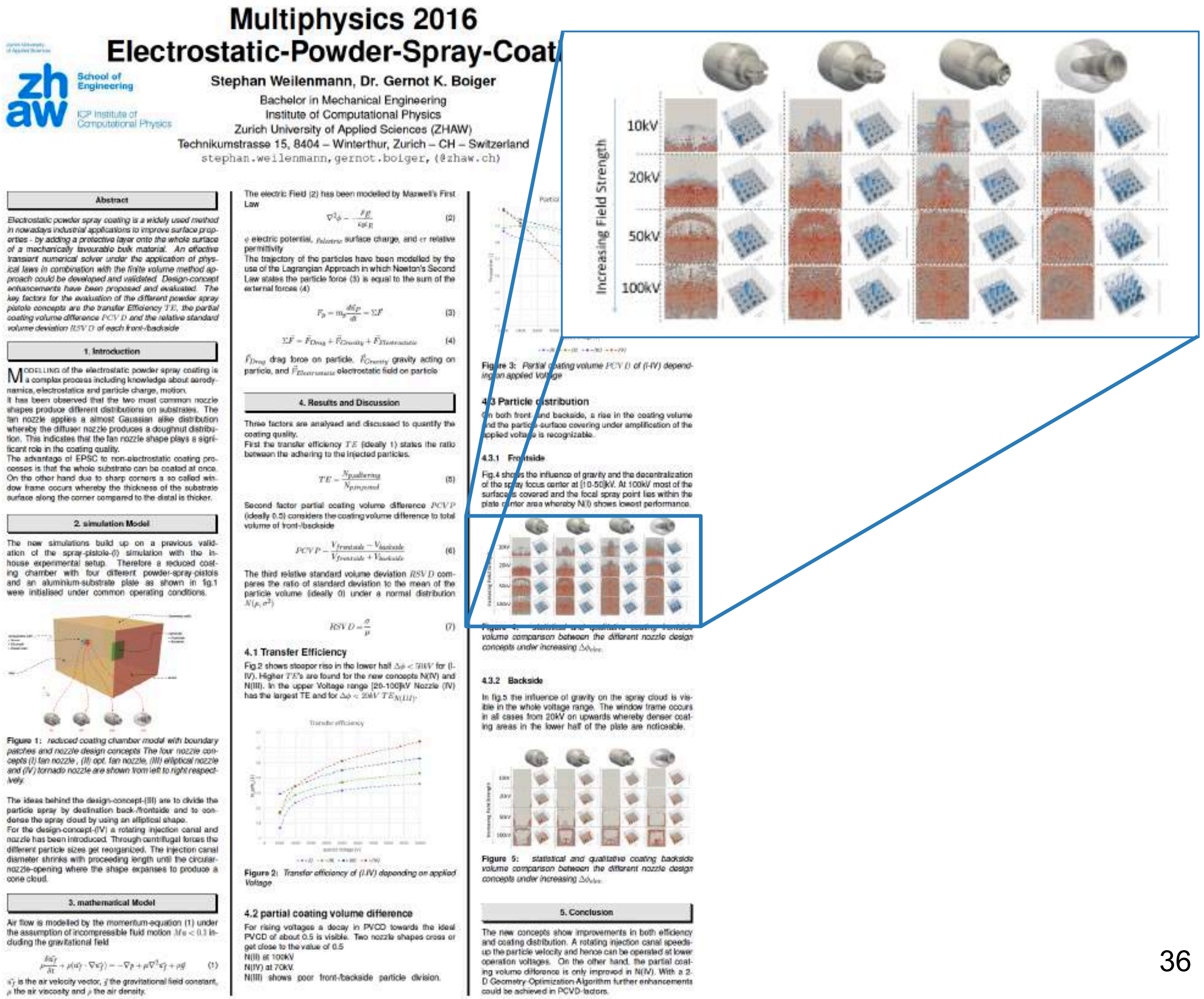

Multiphysics 2016
Electrostatic-Powder-Spray-Coat

Stephan Weilenmann, Dr. Gernot K. Boiger
Bachelor in Mechanical Engineering
Institute of Computational Physics
Zurich University of Applied Sciences (ZHAW)
Technikumstrasse 15, 8404 – Winterthur, Zurich – CH – Switzerland
stephan.weilenmann, gernot.boiger, (@zhaw.ch)

Abstract

Electrostatic powder spray coating is a widely used method in nowadays industrial applications to improve surface properties - by adding a protective layer onto the whole surface of a mechanically favourable bulk material. An effective transient numerical solver under the application of physical laws in combination with the finite volume method approach could be developed and validated. Design-concept enhancements have been proposed and evaluated. The key factors for the evaluation of the different powder spray pistole concepts are the transfer Efficiency TE, the partial coating volume difference $PCVD$ and the relative standard volume deviation $RSVD$ of each front-/backside

1. Introduction

MODELLING of the electrostatic powder spray coating is a complex process including knowledge about aerodynamics, electrostatics and particle charge, motion.
It has been observed that the two most common nozzle shapes produce different distributions on substrates. The fan nozzle applies a almost Gaussian alike distribution whereby the diffuser nozzle produces a doughnut distribution. This indicates that the fan nozzle shape plays a significant role in the coating quality.
The advantage of EPSC to non-electrostatic coating processes is that the whole substrate can be coated at once. On the other hand due to sharp corners a so called window frame occurs whereby the thickness of the substrate surface along the corner compared to the distal is thicker.

2. simulation Model

The new simulations build up on a previous validation of the spray-pistole-(I) simulation with the in-house experimental setup. Therefore a reduced coating chamber with four different powder-spray-pistols and an aluminium-substrate plate as shown in fig.1 were initialised under common operating conditions.

Figure 1: *reduced coating chamber model with boundary patches and nozzle design concepts The four nozzle concepts (I) fan nozzle , (II) opt. fan nozzle, (III) elliptical nozzle and (IV) tornado nozzle are shown from left to right respectively.*

The ideas behind the design-concept-(III) are to divide the particle spray by destination back-/frontside and to condense the spray cloud by using an elliptical shape.
For the design-concept-(IV) a rotating injection canal and nozzle has been introduced. Through centrifugal forces the different particle sizes get reorganized. The injection canal diameter shrinks with proceeding length until the circular-nozzle-opening where the shape expanses to produce a cone cloud.

3. mathematical Model

Air flow is modelled by the momentum-equation (1) under the assumption of incompressible fluid motion $Ma < 0.1$ including the gravitational field

$$\rho\frac{\delta\vec{u_f}}{\delta t} + \rho(\vec{u_f}\cdot\nabla\vec{u_f}) = -\nabla p + \mu\nabla^2\vec{u_f} + \rho\vec{g} \qquad (1)$$

$\vec{u_f}$ is the air velocity vector, $\vec{g}$ the gravitational field constant, μ the air viscosity and ρ the air density.

The electric Field (2) has been modelled by Maxwell's First Law

$$\nabla^2\phi = -\frac{\rho_E}{\epsilon_0\epsilon_R} \qquad (2)$$

ϕ electric potential, $\rho_{Electric}$ surface charge, and ϵ_r relative permittivity
The trajectory of the particles have been modelled by the use of the Lagrangian Approach in which Newton's Second Law states the particle force (3) is equal to the sum of the external forces (4)

$$F_p = m_p\frac{d\vec{u}_P}{dt} = \Sigma F \qquad (3)$$

$$\Sigma\vec{F} = \vec{F}_{Drag} + \vec{F}_{Gravity} + \vec{F}_{Electrostatic} \qquad (4)$$

$\vec{F}_{Drag}$ drag force on particle, $\vec{F}_{Gravity}$ gravity acting on particle, and $\vec{F}_{Electrostatic}$ electrostatic field on particle

4. Results and Discussion

Three factors are analysed and discussed to quantify the coating quality.
First the transfer efficiency TE (ideally 1) states the ratio between the adhering to the injected particles.

$$TE = \frac{N_{p,adhering}}{N_{p,injected}} \qquad (5)$$

Second factor partial coating volume difference $PCVP$ (ideally 0.5) considers the coating volume difference to total volume of front-/backside

$$PCVP = \frac{V_{frontside} - V_{backside}}{V_{frontside} + V_{backside}} \qquad (6)$$

The third relative standard volume deviation $RSVD$ compares the ratio of standard deviation to the mean of the particle volume (ideally 0) under a normal distribution $N(\mu, \sigma^2)$

$$RSVD = \frac{\sigma}{\mu} \qquad (7)$$

4.1 Transfer Efficiency

Fig.2 shows steeper rise in the lower half $\Delta\phi < 50kV$ for (I-IV). Higher TE's are found for the new concepts N(IV) and N(III). In the upper Voltage range [20-100]kV Nozzle (IV) has the largest TE and for $\Delta\phi < 20kV$ $TE_{N(III)}$.

Figure 2: *Transfer efficiency of (I-IV) depending on applied Voltage*

4.2 partial coating volume difference

For rising voltages a decay in PVCD towards the ideal PVCD of about 0.5 is visible. Two nozzle shapes cross or get close to the value of 0.5
N(II) at 100KV
N(IV) at 70KV.
N(III) shows poor front-/backside particle division.

Figure 3: *Partial coating volume $PCVD$ of (I-IV) depending on applied Voltage*

4.3 Particle distribution

On both front- and backside, a rise in the coating volume and the particle-surface covering under amplification of the applied voltage is recognizable.

4.3.1 Frontside

Fig.4 shows the influence of gravity and the decentralization of the spray focus center at [10-50]kV. At 100kV most of the surface is covered and the focal spray point lies within the plate center area whereby N(I) shows lowest performance.

Figure 4: *statistical and qualitative coating frontside volume comparison between the different nozzle design concepts under increasing $\Delta\phi_{elec}$.*

4.3.2 Backside

In fig.5 the influence of gravity on the spray cloud is visible in the whole voltage range. The window frame occurs in all cases from 20kV on upwards whereby denser coating areas in the lower half of the plate are noticeable.

Figure 5: *statistical and qualitative coating backside volume comparison between the different nozzle design concepts under increasing $\Delta\phi_{elec}$.*

5. Conclusion

The new concepts show improvements in both efficiency and coating distribution. A rotating injection canal speeds-up the particle velocity and hence can be operated at lower operation voltages. On the other hand, the partial coating volume difference is only improved in N(IV). With a 2-D Geometry-Optimization-Algorithm further enhancements could be achieved in PCVD-factors.

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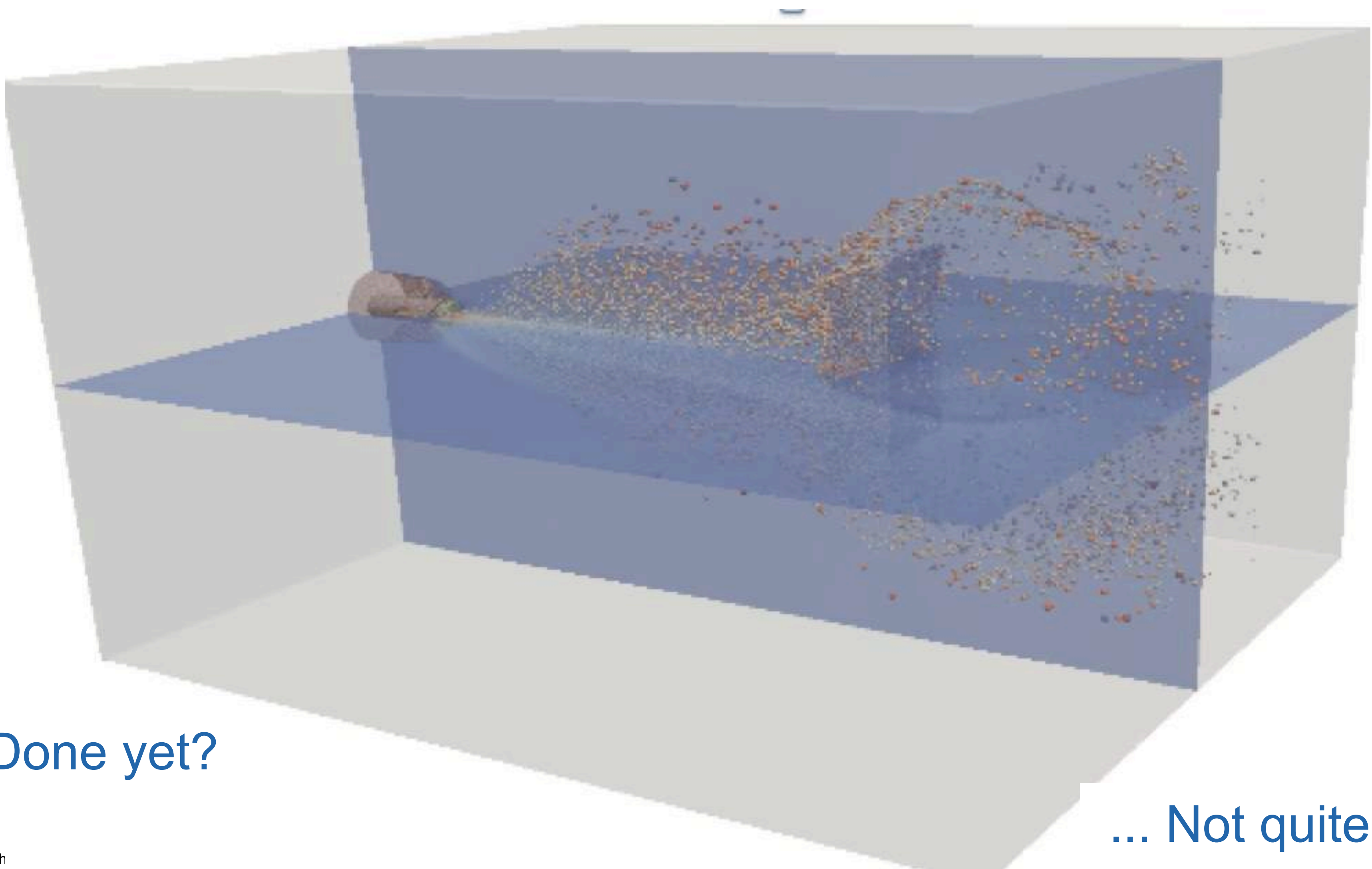

Done yet?

... Not quite!

Validation Experiments - 2016

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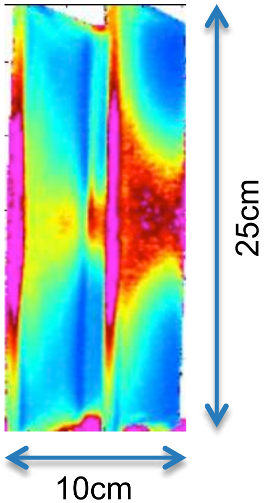
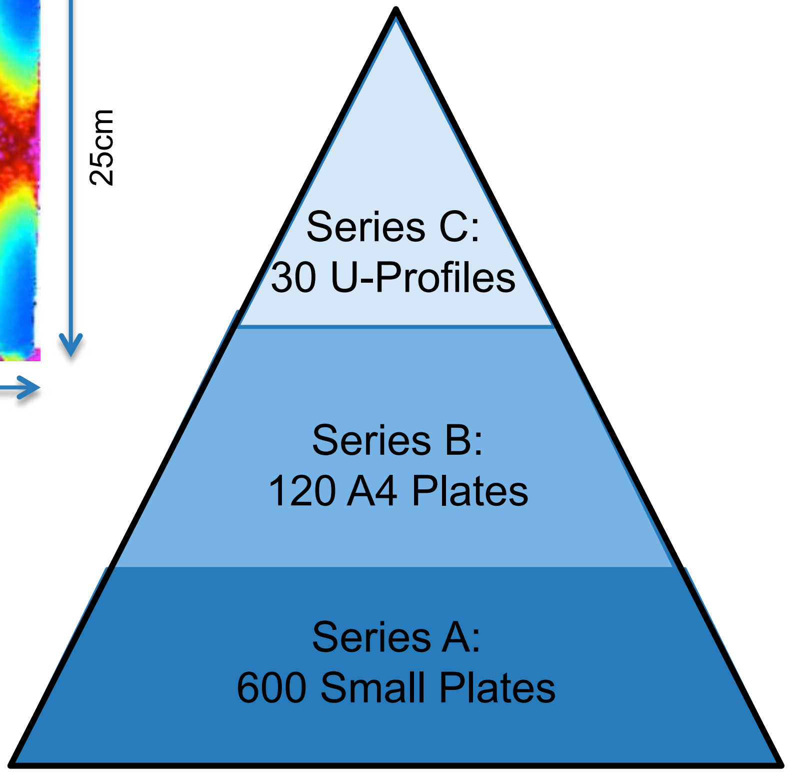
Coating Lab at ZHAW:

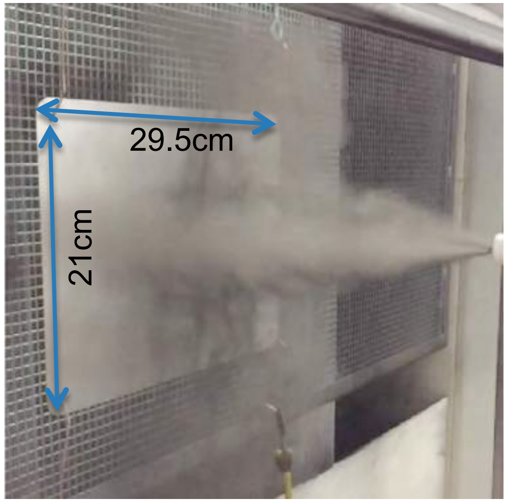
Coating Experiment
ZHAW Winterthur

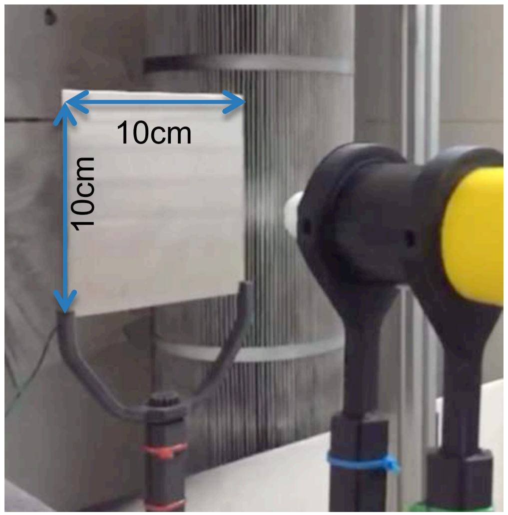
Validation Scheme - 2016

Experimental Solver Validation: Pyramid Model









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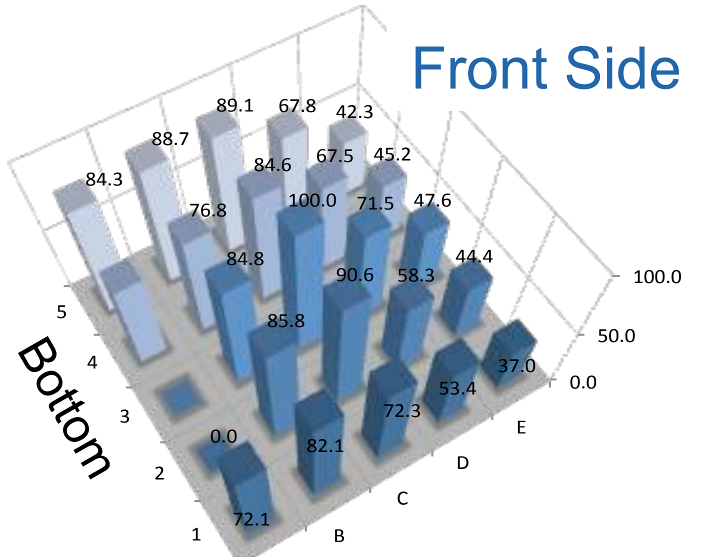
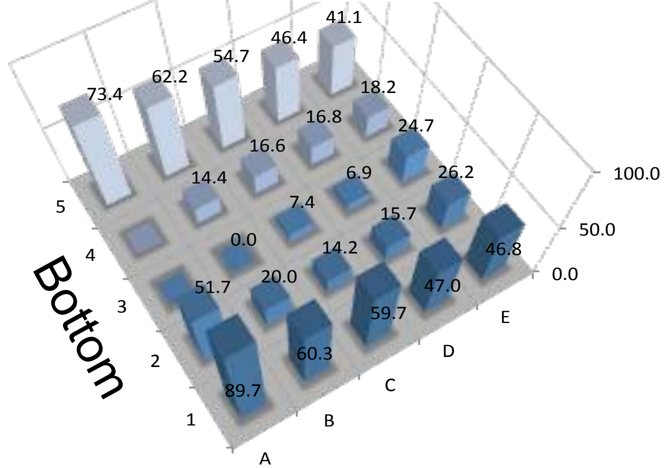
Measuring the Coating Thickness

Thermal Measurement of Thickness with Coatmaster





Evaluate Experiments - 2016

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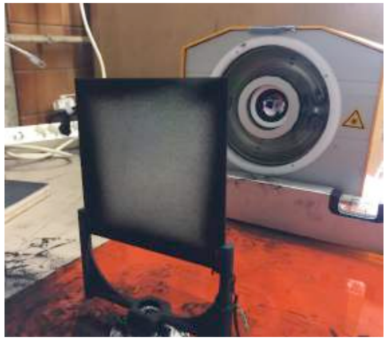
Development of Instant Evaluation Procedure:

Coating



Measurement

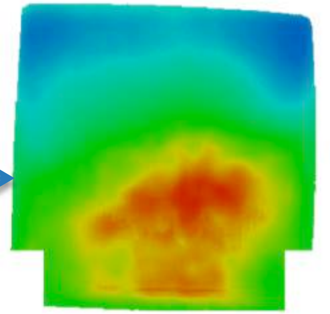
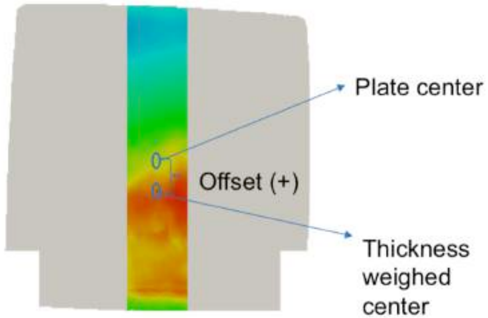
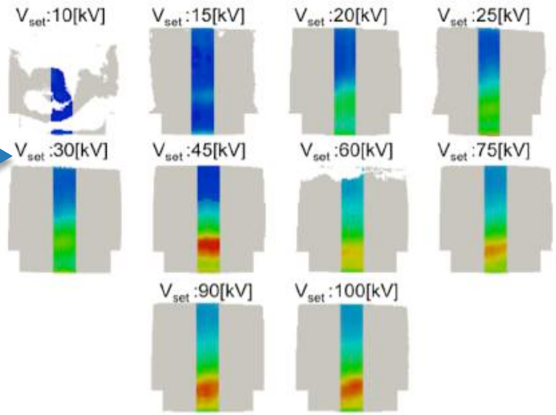


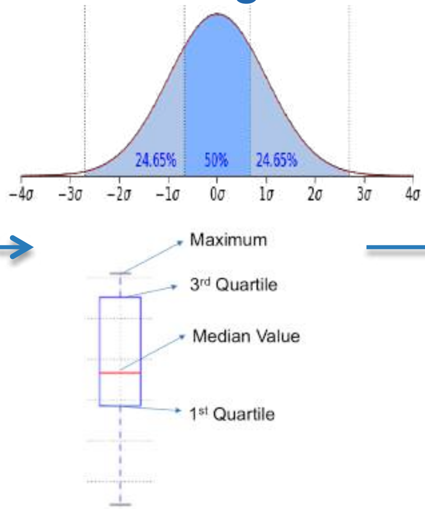
Image Processing



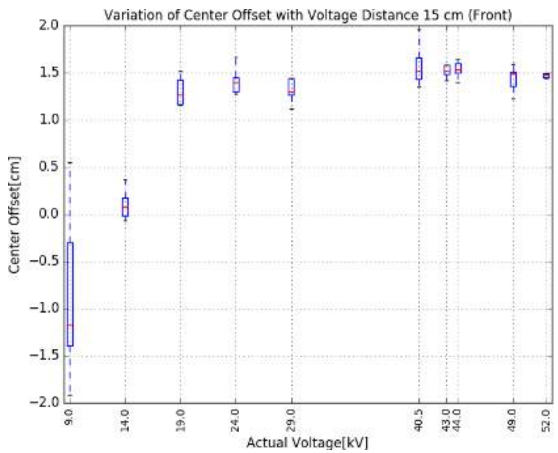
Data Processing



Ensemble Data



Statistical Data Analysis



Wrap-Up

Comparing - 2016

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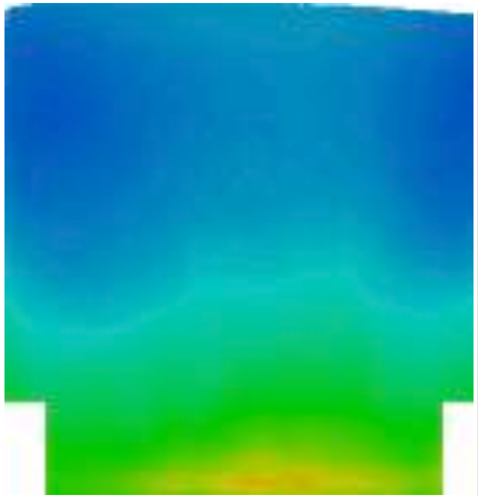
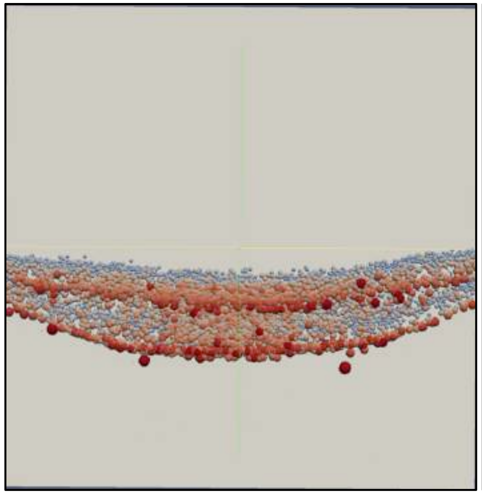
Problems with initial Matching: Coating Patterns

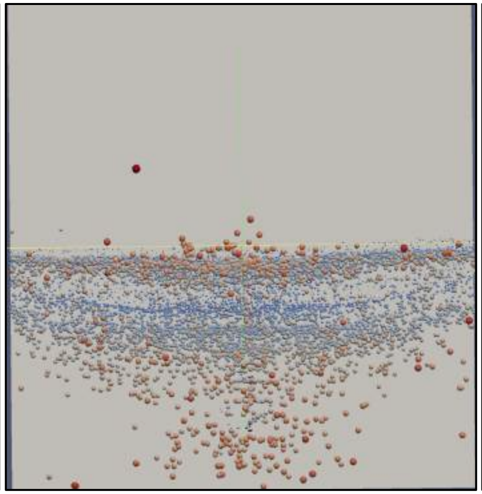
Experiment



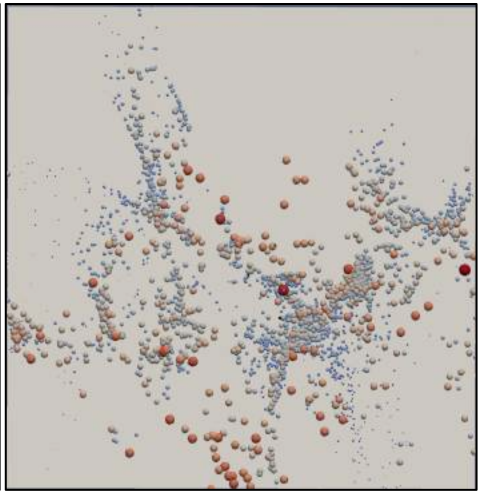
Attempt: A



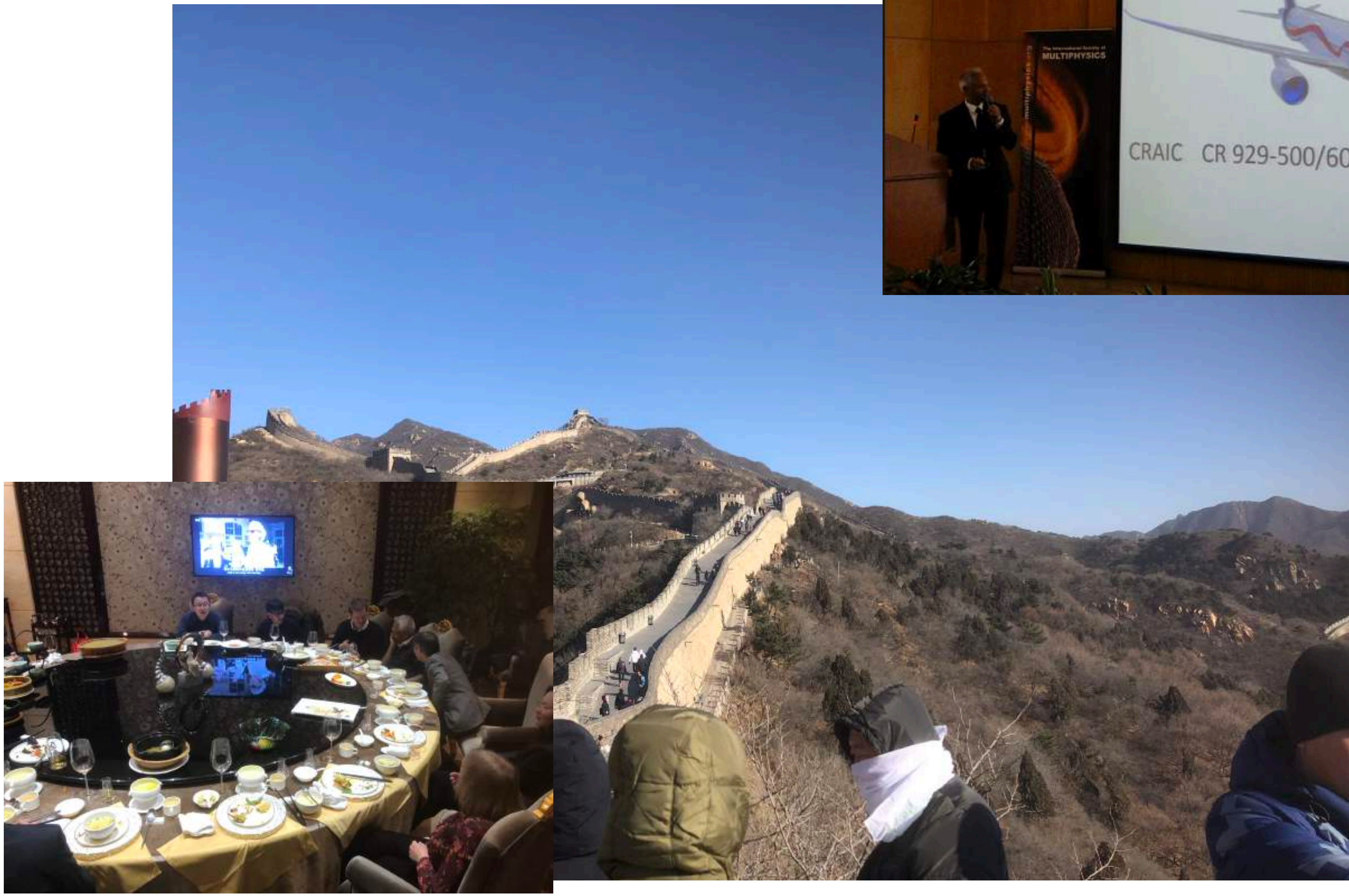
Attempt: B



Attempt: C

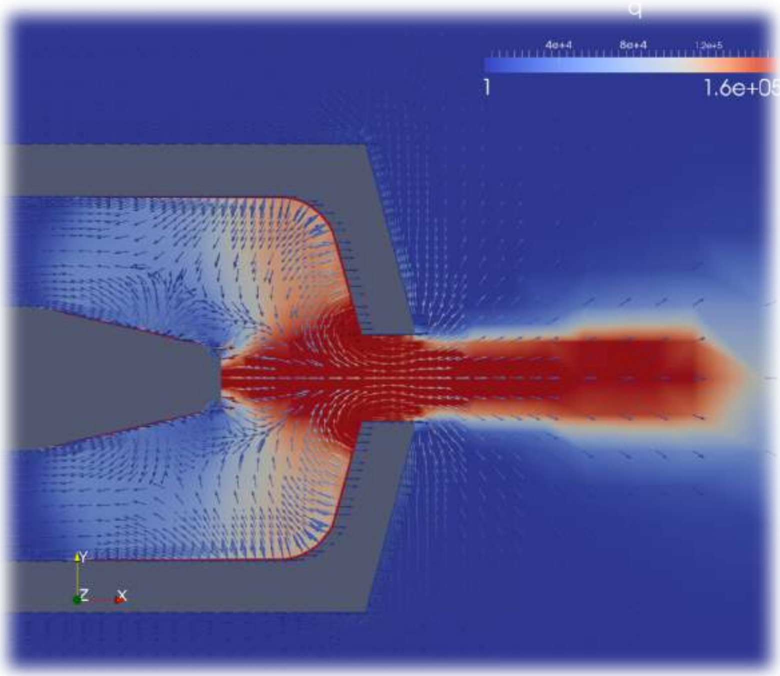


ICM 2017 - Beijing



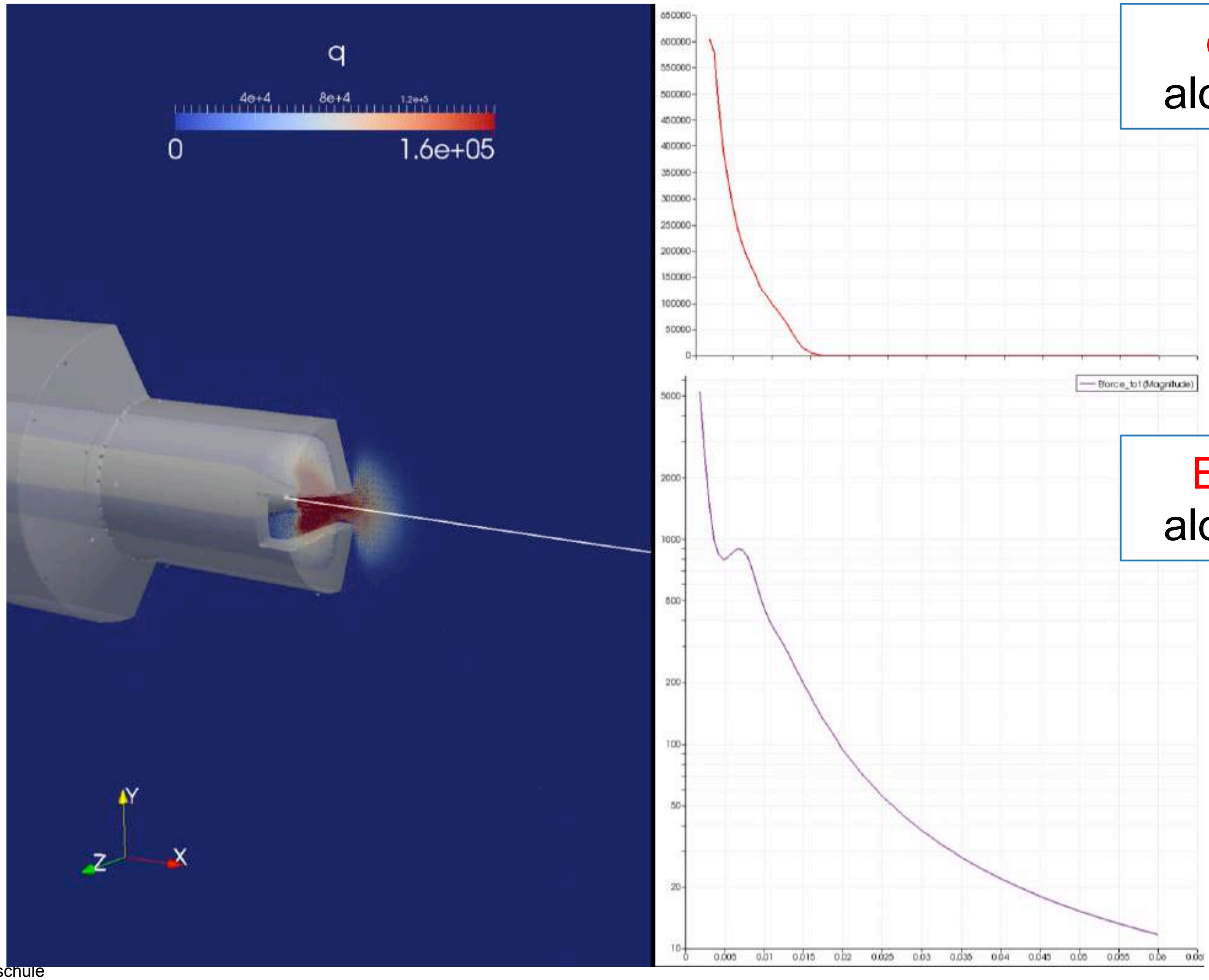
Source: https://www.multiphysics.org/past-conferences

Dynamic 3D Modelling of Ionized Oxygen Distribution within Powder Coating Applications



International Conference of Multiphysics, Peijing,
December 2017, G. Boiger, M. Boldrini, S. Weilenmann

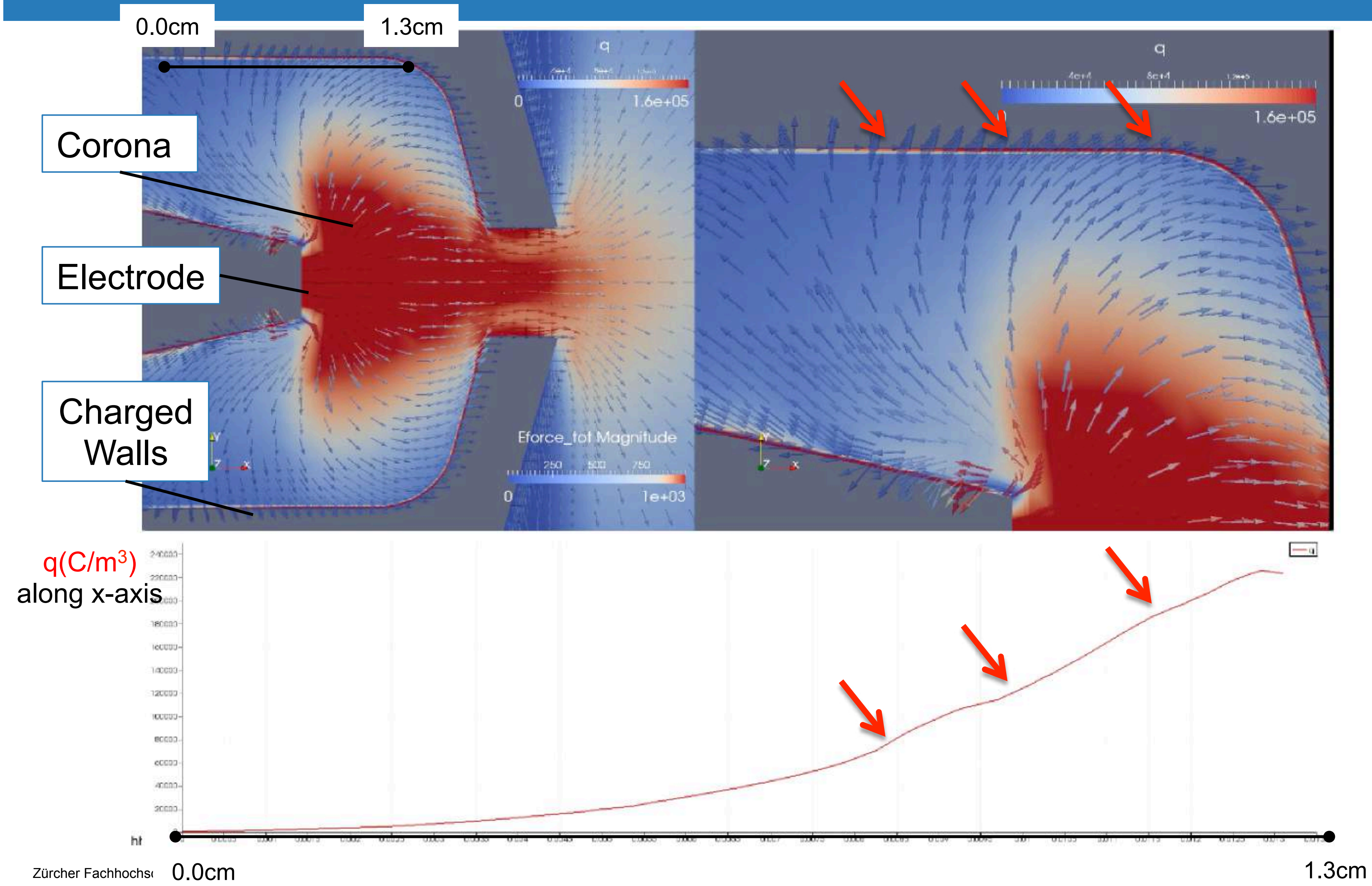
Evolution Step: Space Charge Model



q(C/m³) along x-axis

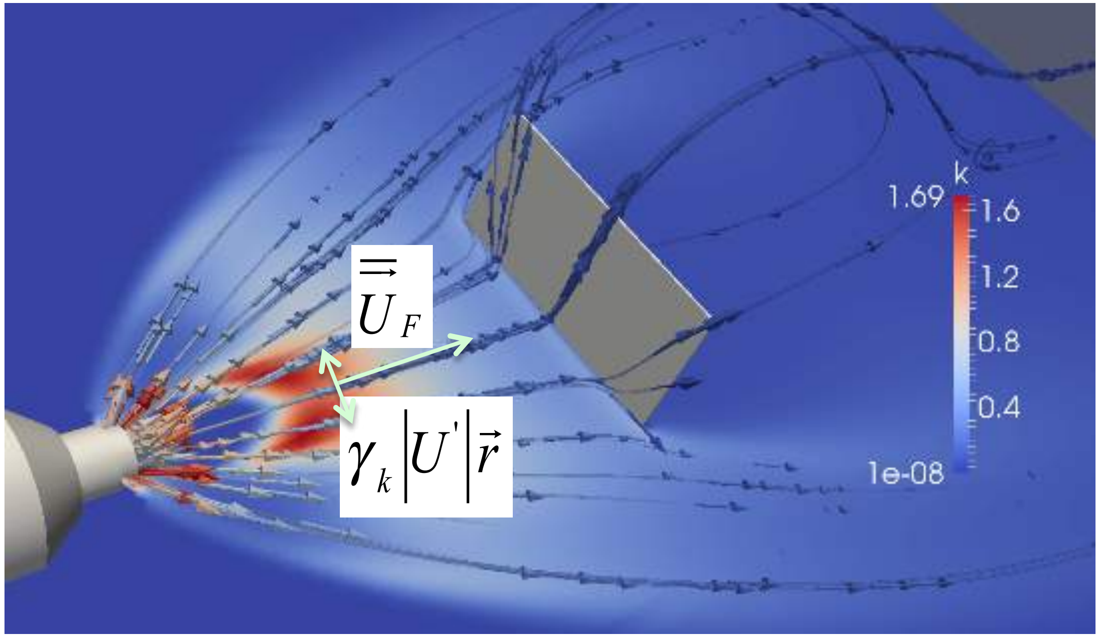
E_{tot} (N/C) along x-axis

ICM 2017 - Beijing



ICM 2017 - Beijing

Evolution Step: The k-Factor



k ... Turbulent Kinetic Energy (J/kg)

$\vec{r}$ ... Randomly oriented Vector Length 1 (-)

$\overline{\overline{U}}_F$ ... RAS averaged Flow Velocity (m/s)

U' ... Fluctuating Velocity Component (m/s)

Assumption of Isotropic Turbulence

$$k = \frac{3}{2}\left[\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}\right]$$

$$k = \frac{3}{2}\overline{(U')^2} \leftrightarrow |U'| = \sqrt{\frac{2}{3}k}$$

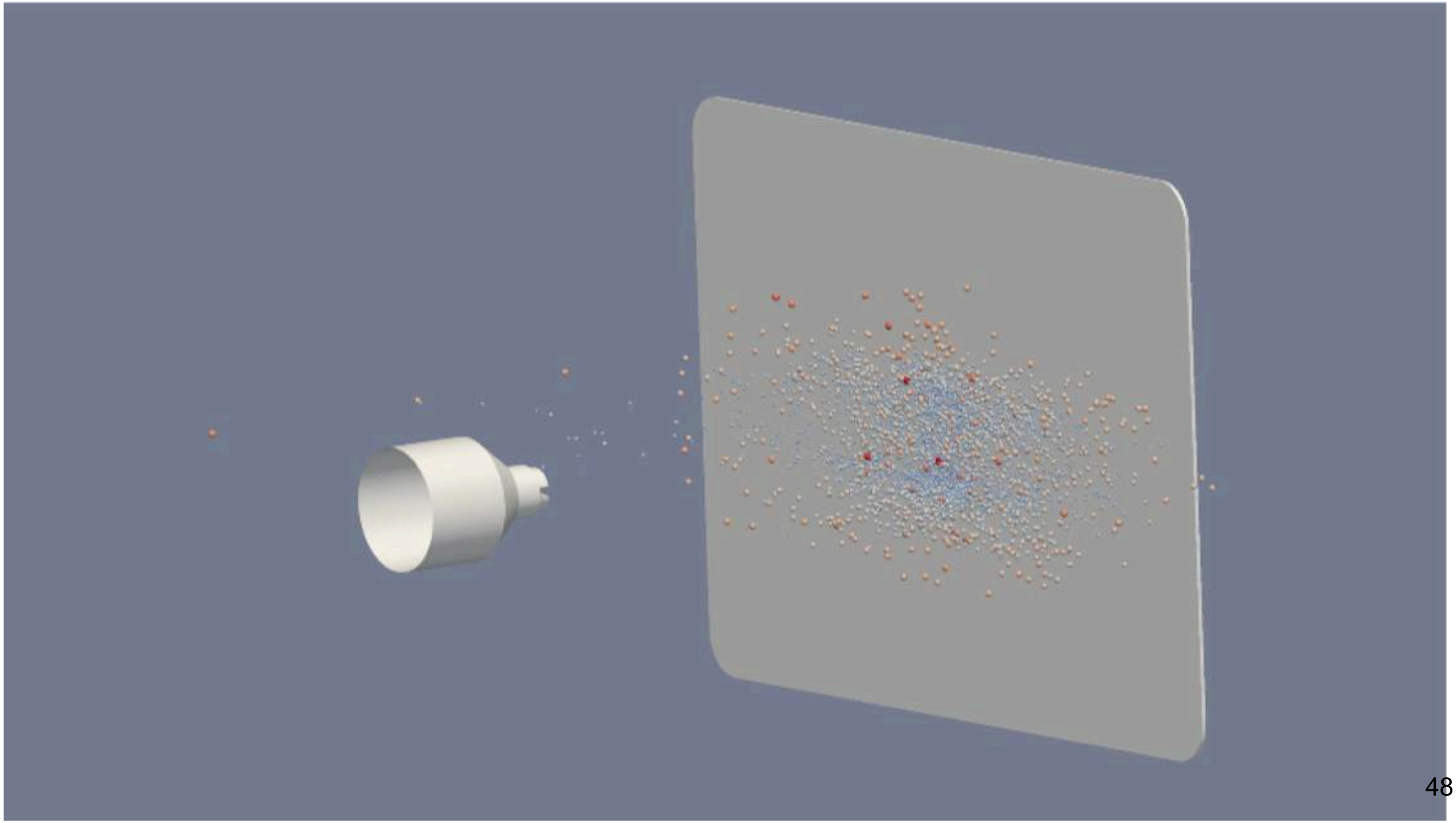
Modified Flow Velocity acting on Particles

$$\vec{U}_{F,\mathrm{mod}} = \overline{\overline{U}}_F + \gamma_k |U'| \vec{r}$$

Empirical „k-Factor"

ICM 2017 - Beijing

Evolution Step: Particle − Substrate Interaction



Next Stage Validation - 2017

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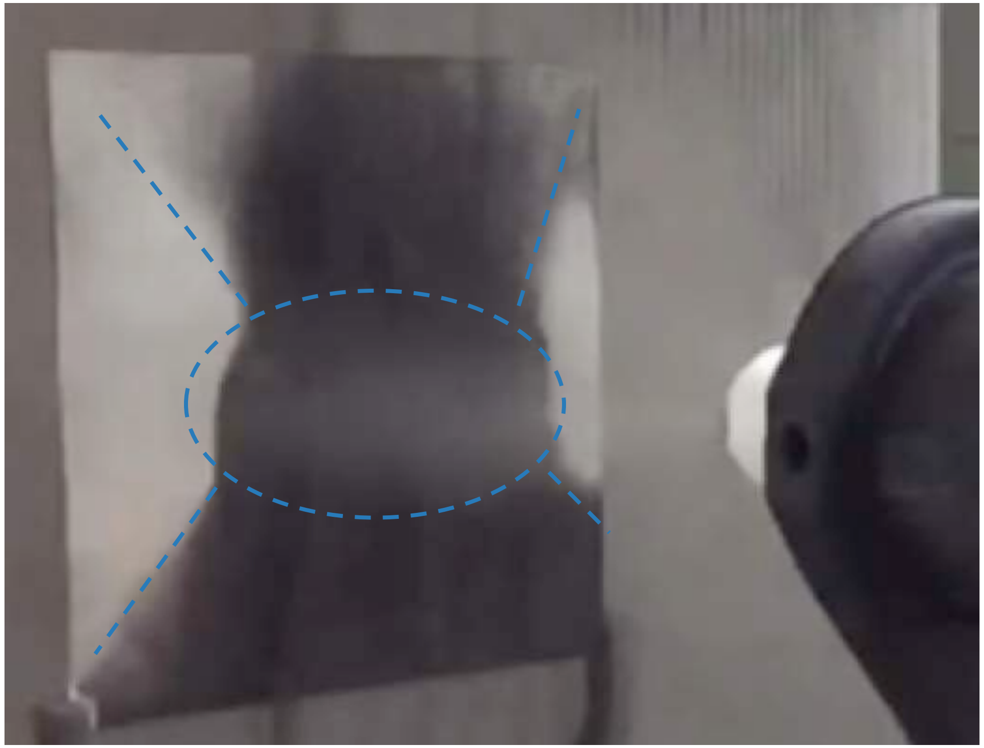
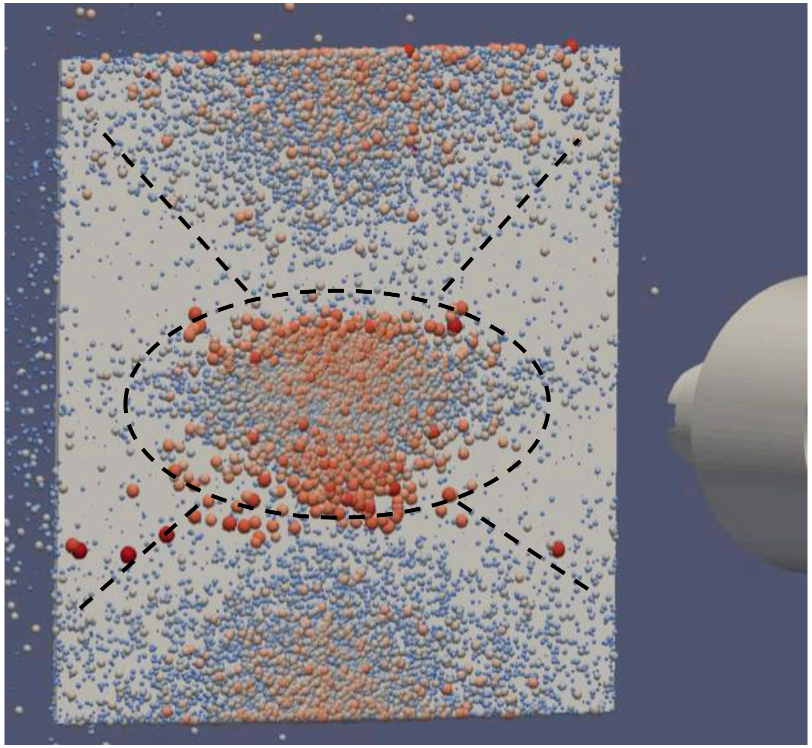
Qualitative Validation: Coating Process in Motion



Experiment



Simulation

Boiger, G.; Boldrini, M.; Lienhard, V.; Siyahhan, B.; Khawaja, H.; Moatamedi, M., 2019. Multiphysics Eulerian-Lagrangian Electrostatic Particle Spray- And Deposition Model for OpenFoam® and KaleidoSim® Cloud-Platform (2020). Int.Journal of Multiphysics. 14(1), pp. 1-15. DOI: 10.21152/1750-9548.14.1.1

Next Stage Validation - 2017

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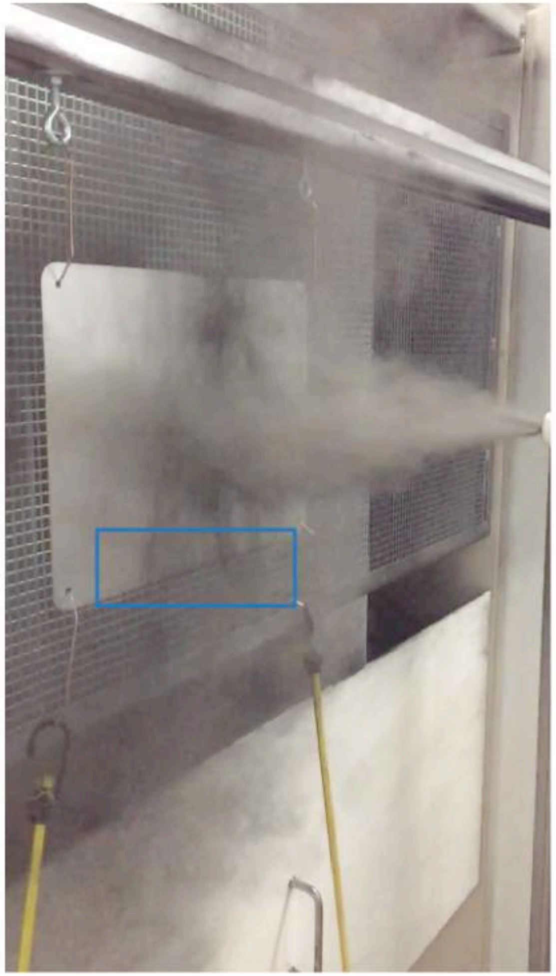
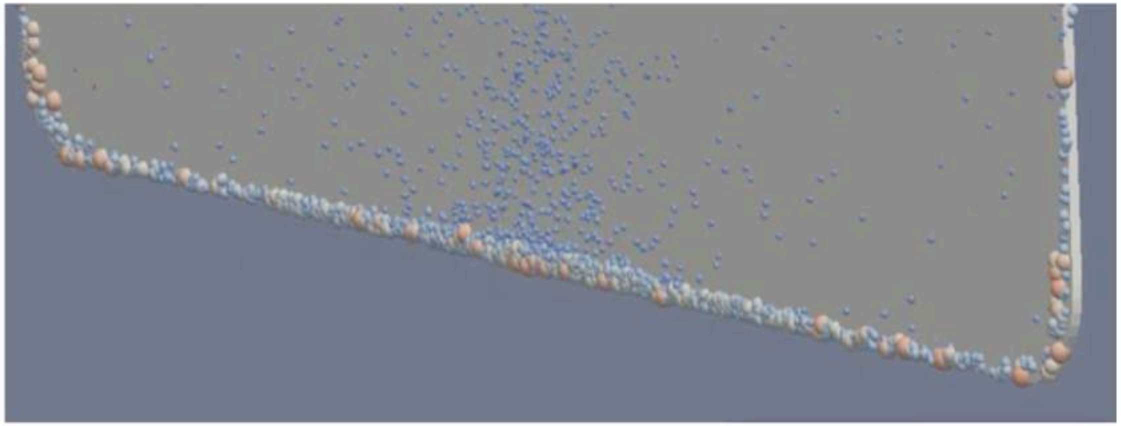
Qualitative Validation: Dynamic Development of Window Frame





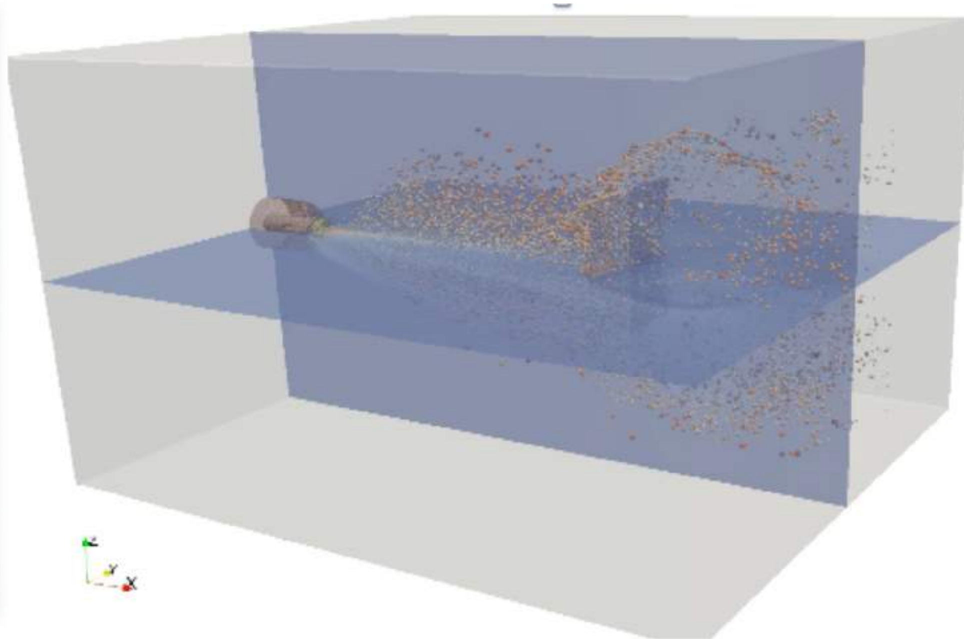
Simulation vs. Experiment

ICM 2018 - Krakow

Source: https://www.multiphysics.org/past-conferences

ICM 2018 - Krakow

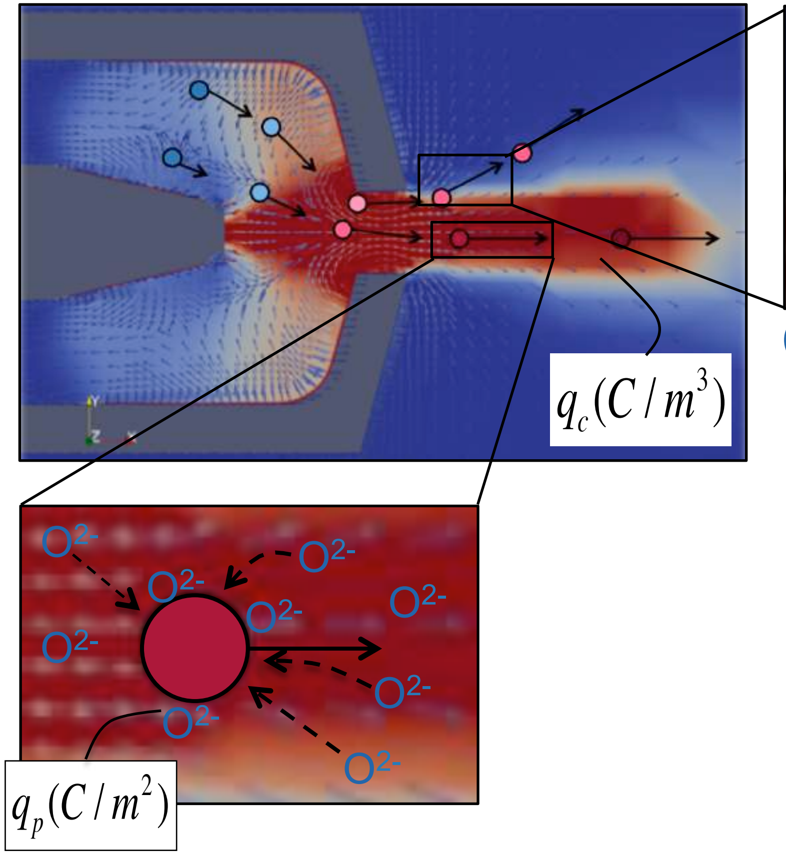
Enhancing the Understanding of Complex Phenomena in Powder-Coating by Applying Eulerian-LaGrangian Simulation Technology

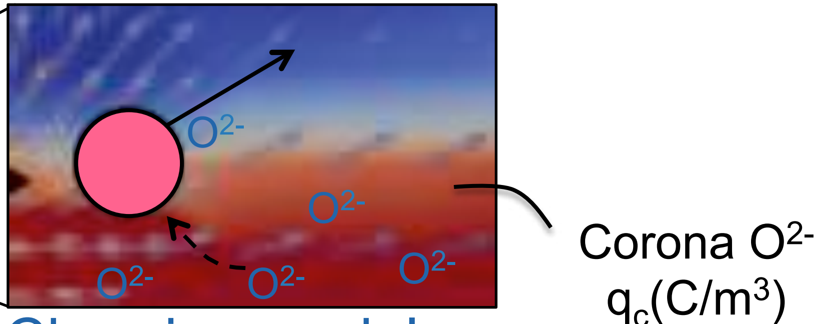


International Conference of Multiphysics 2018, Krakau, Poland

13-14th Dec 2018, G. Boiger, B. Siyahhan, M. Boldrini, V. Lienhard

Evolution Step: Dynamic Charging Model





Charging model:

$$\frac{dq_p}{dt} = \beta_{cp}\left(1-\frac{q_p(t)}{q_{p,\lim}}\right)\left[q_c\left(\vec{X},t\right)-\frac{6}{D_p}q_p\left(t\right)\right]$$

$$q_{p,\lim} = D_p^2\pi\varepsilon_0\left|\vec{E}\right|\cdot\left(1+2\cdot\frac{\varepsilon_{r,p}-1}{\varepsilon_{r,p}+1}\right)$$

$q_p(C/m^2)$ … Particle Surface Charge

$q_{p,lim}(C/m^2)$… Max. Particle Surface Charge

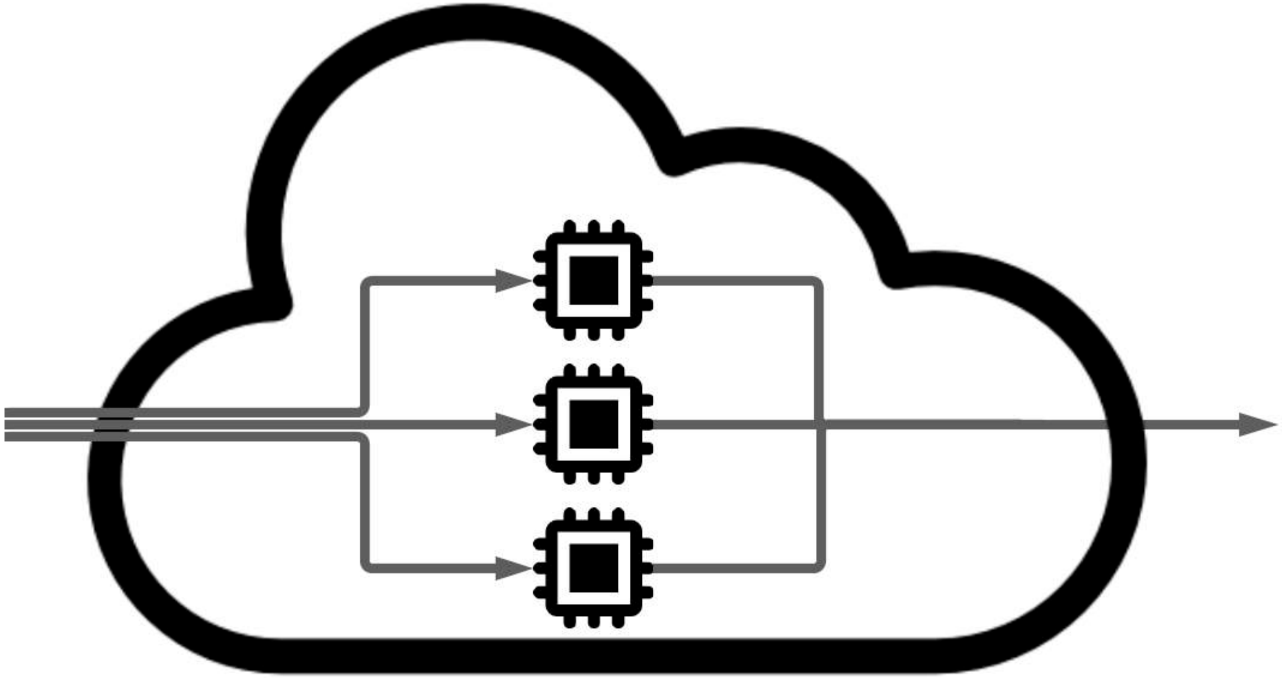
$q_c(C/m^3)$ … Corona O^{2-} Charge Density

$\beta_{cp}(m/s)$ ... Charge Transfer Coefficient

ICM 2020 - Online

Source: https://www.multiphysics.org/past-conferences

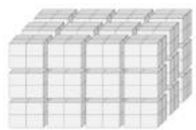
Introducing Massive Simultaneous Cloud Computing (MSCC) for Multiphysics-Simulation Applications



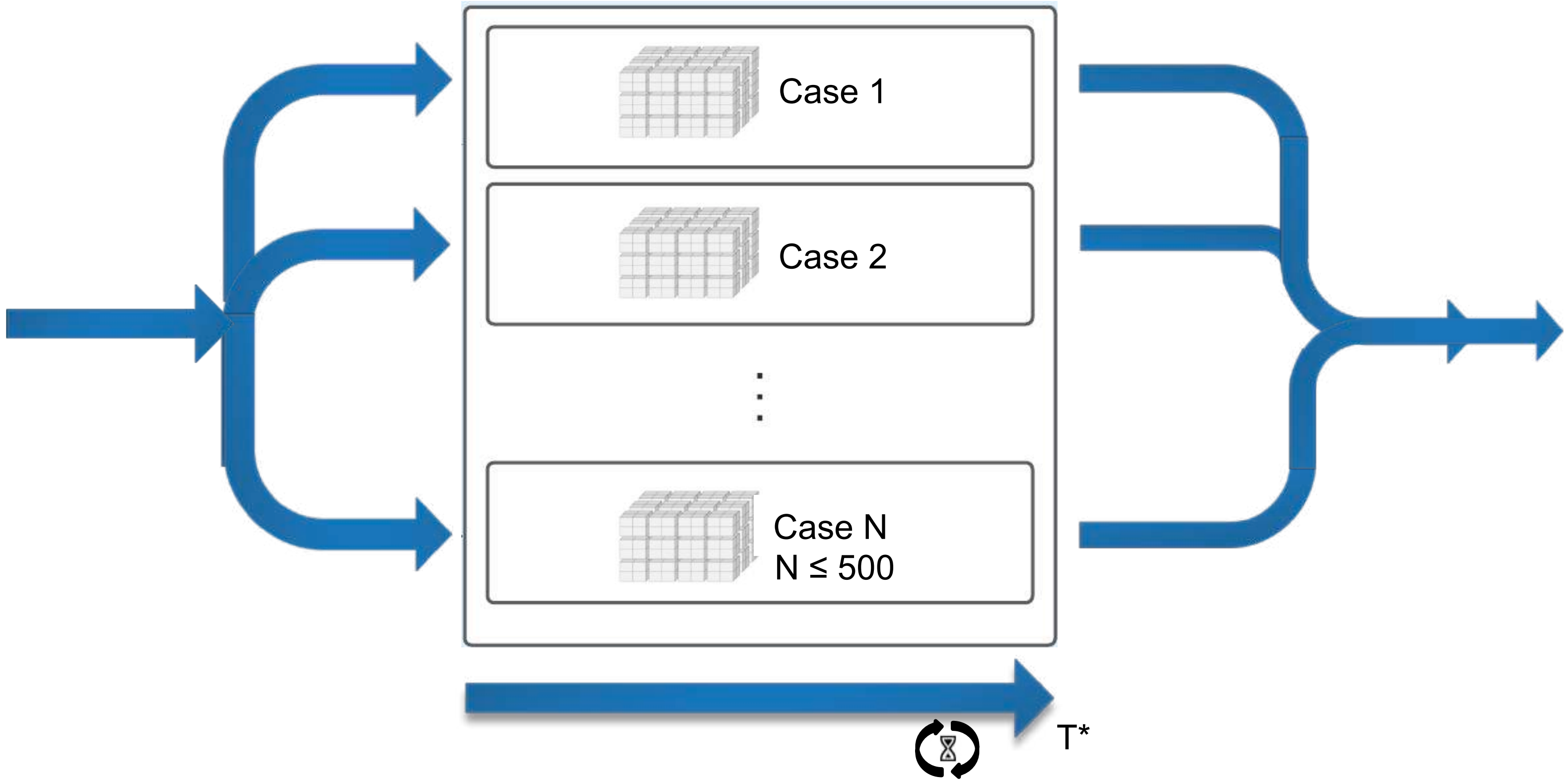
International Conference of Multiphysics 2020, Online

10-11th Dec 2020, G. Boiger, D. Sharman, M. Boldrini, M. Everitt

ICM 2020 - Online



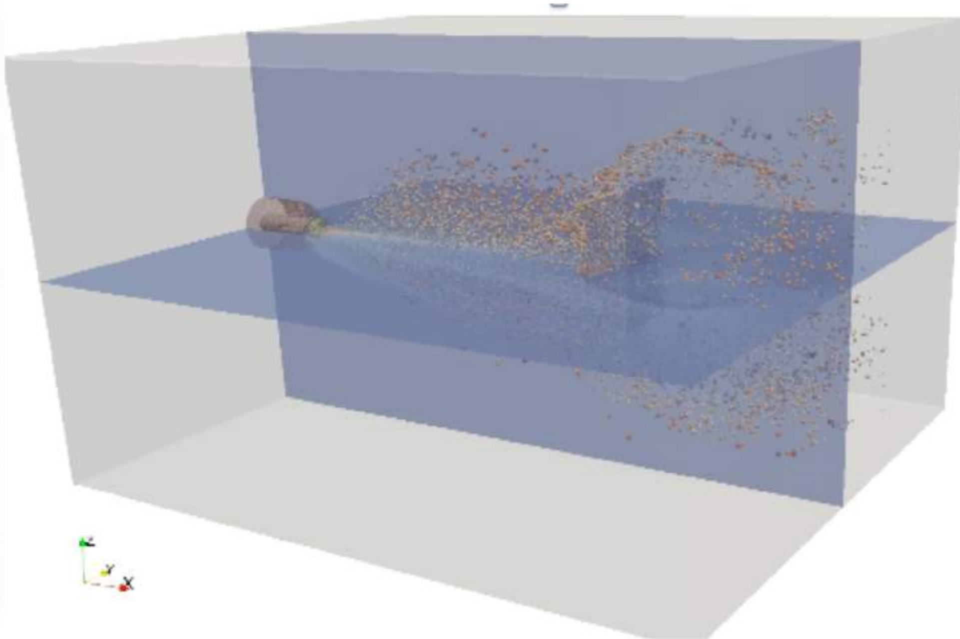
Up to 224 vCPUs per machine



T* .... Wall Clock Time to calculate one Single Case

ICM 2020 - Online

Advancing the Validation and Application of a Eulerian-Lagrangian Multiphysics Solver for Coating Processes in Terms of Massive Simultaneous Cloud Computing

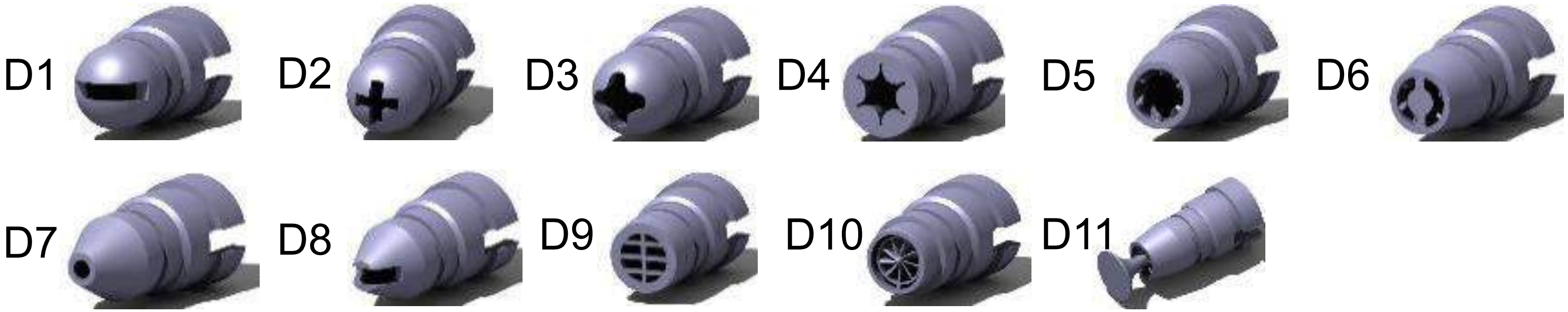


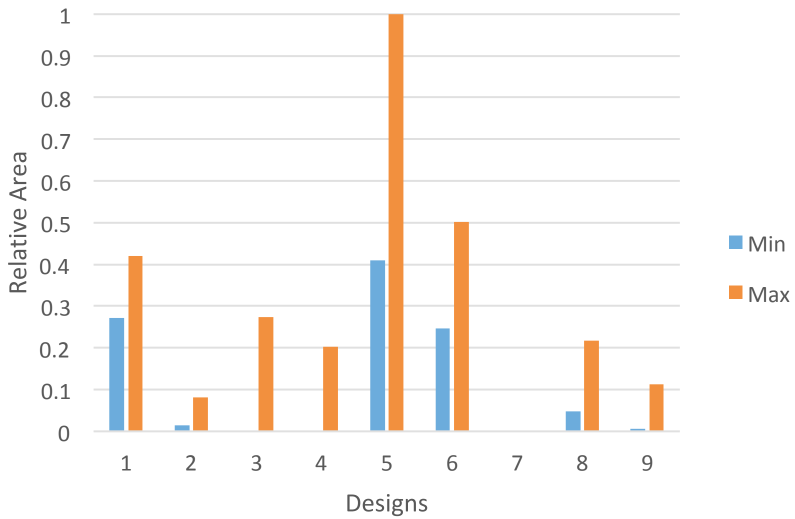
International Conference of Multiphysics 2020, Online

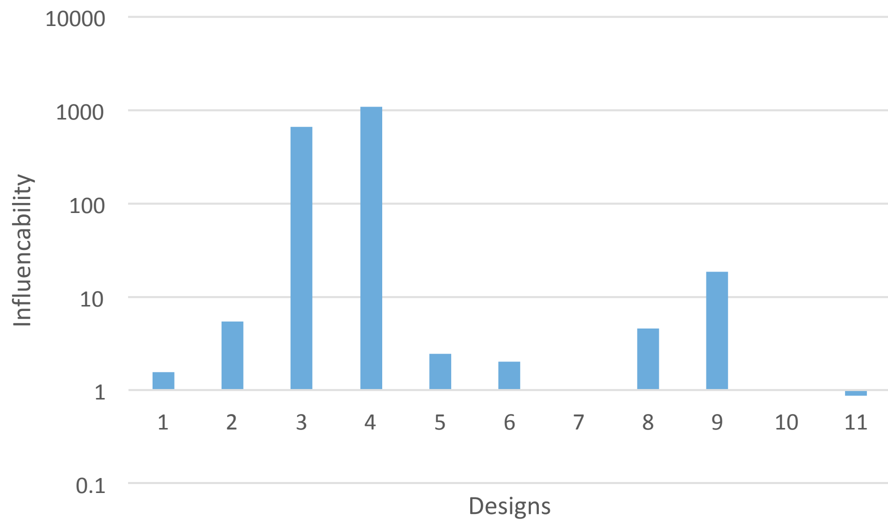
10-11th Dec 2020, G. Boiger, B. Siyahhan, M. Boldrini, V. Lienhard

ICM 2020 - Online

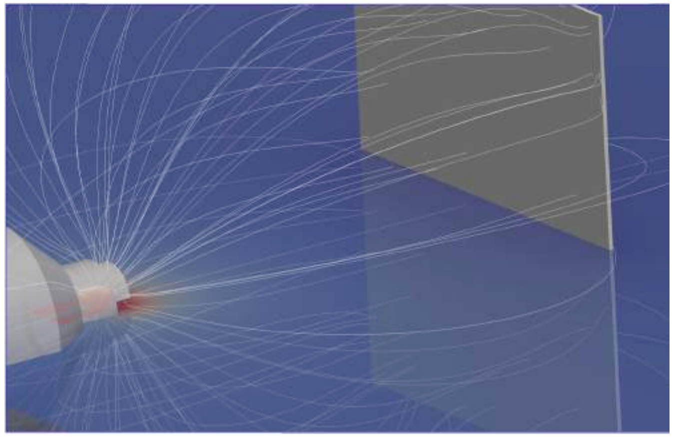
Cloud Simulation based Prototyping



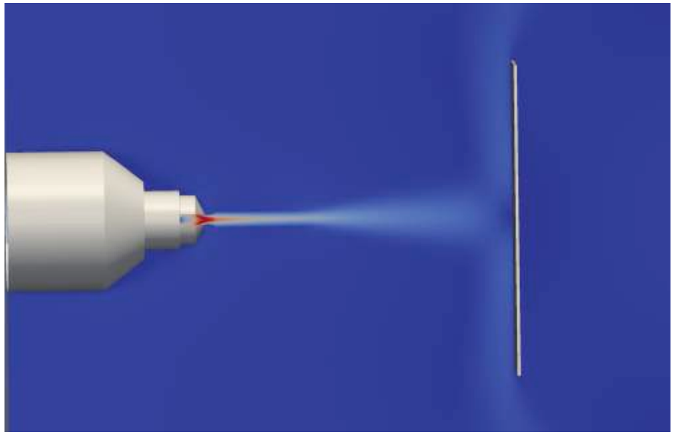




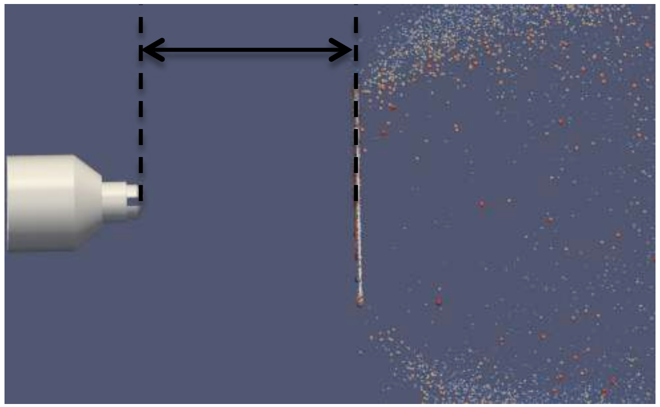
Experimental Solver Validation: Vary Process Parameters



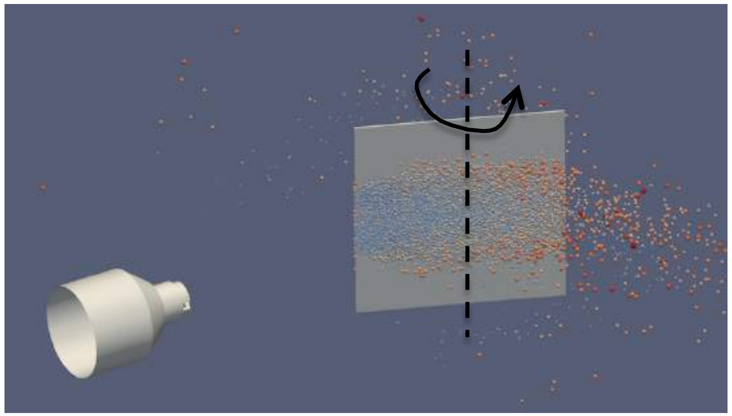
Voltage: 0kV-100kV



Flow-Rate: 2m³/min − 5m³/min



Distance: 10cm − 25cm



Angle: 0° - 90°

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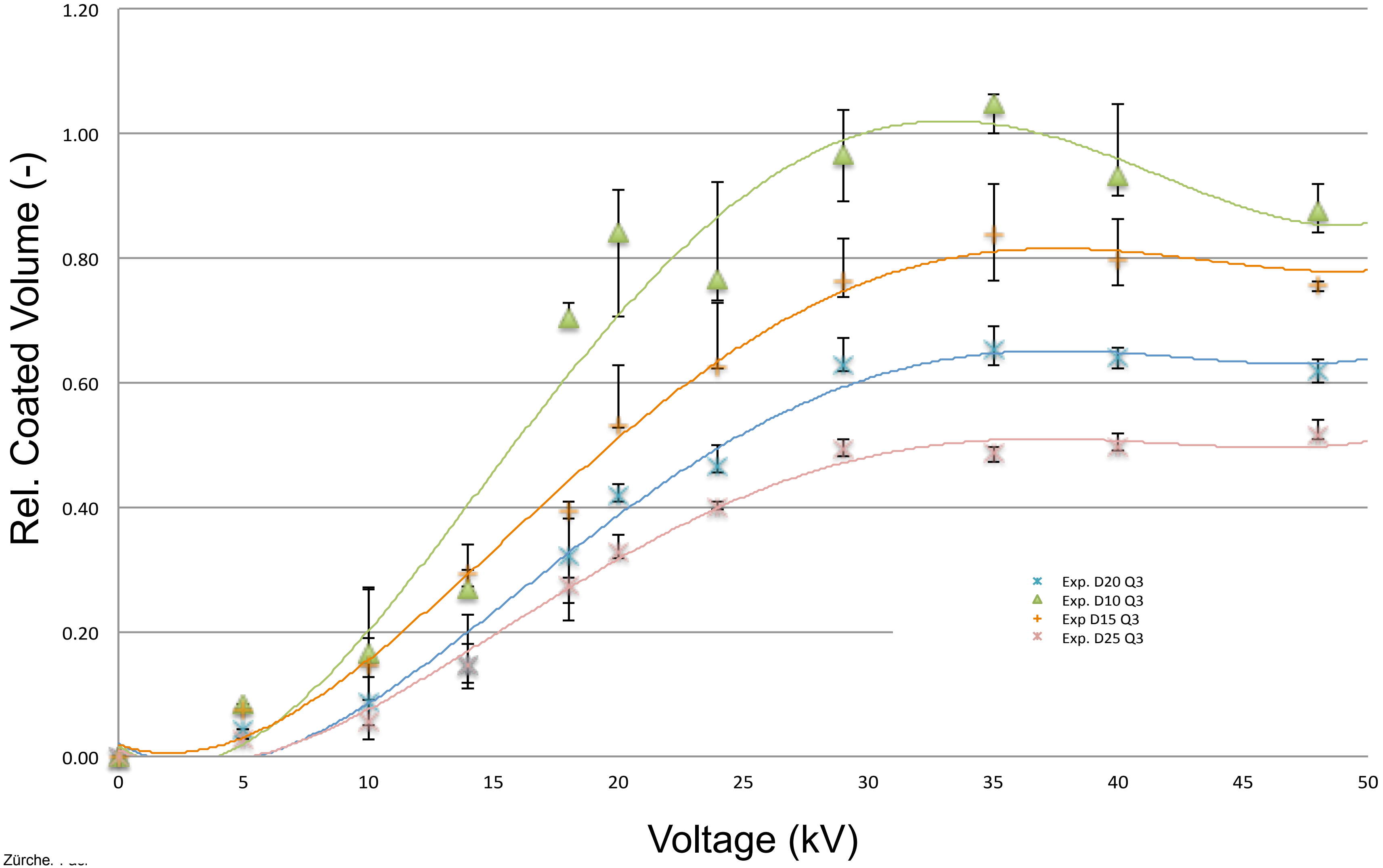
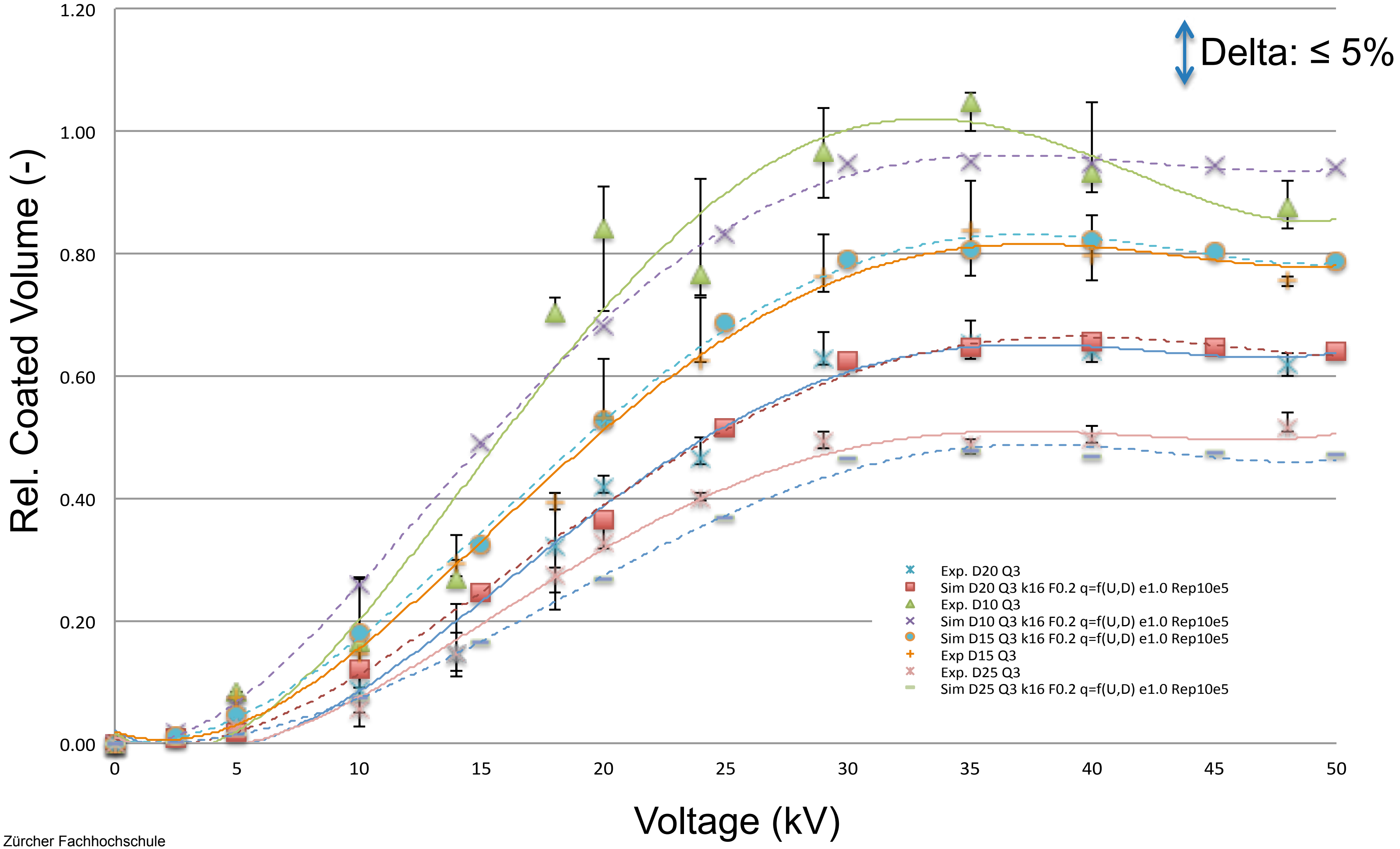
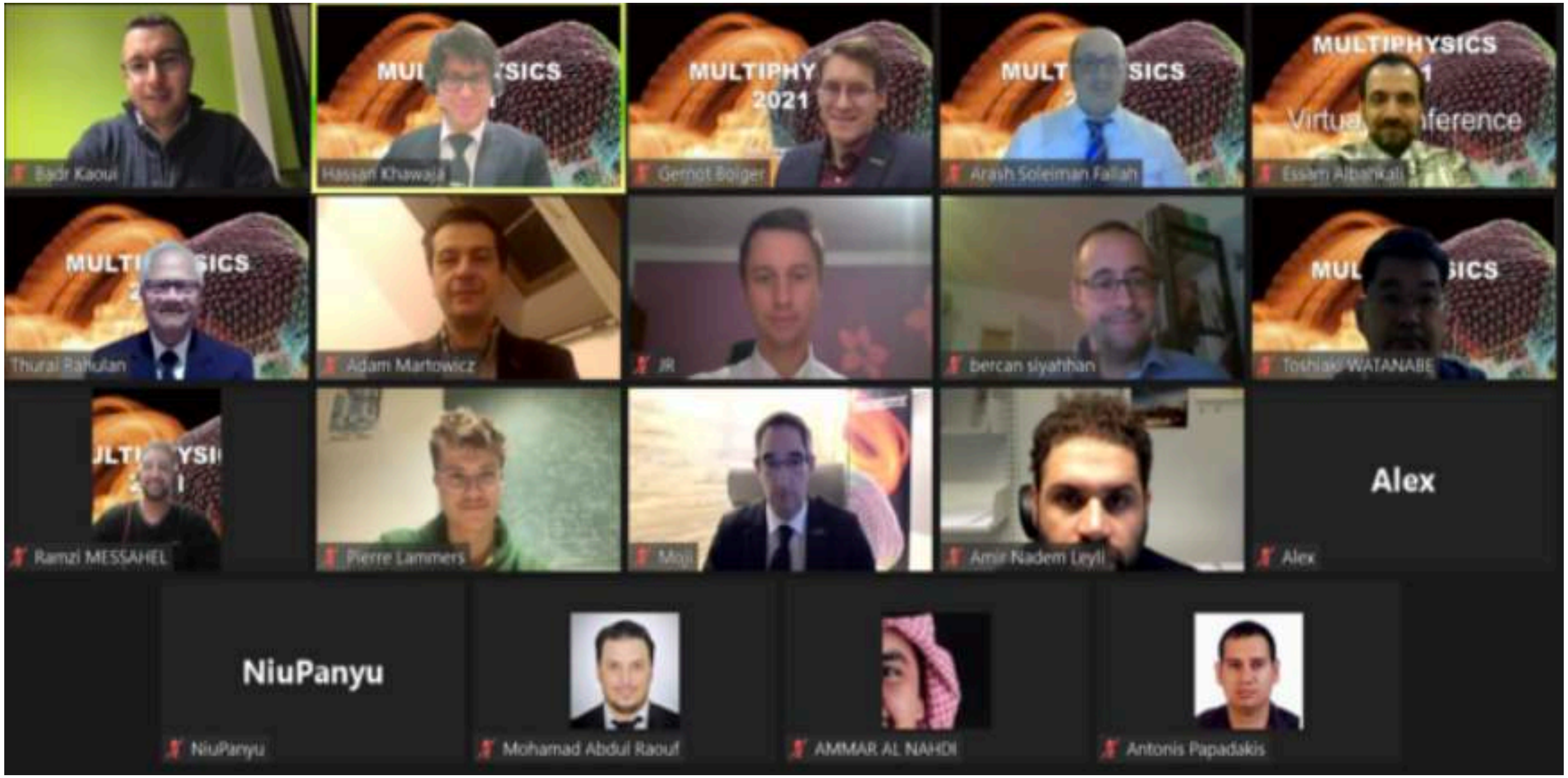
Quantitative Validation



Quantitative Validation



ICM 2021 - Online



Source: https://www.multiphysics.org/past-conferences

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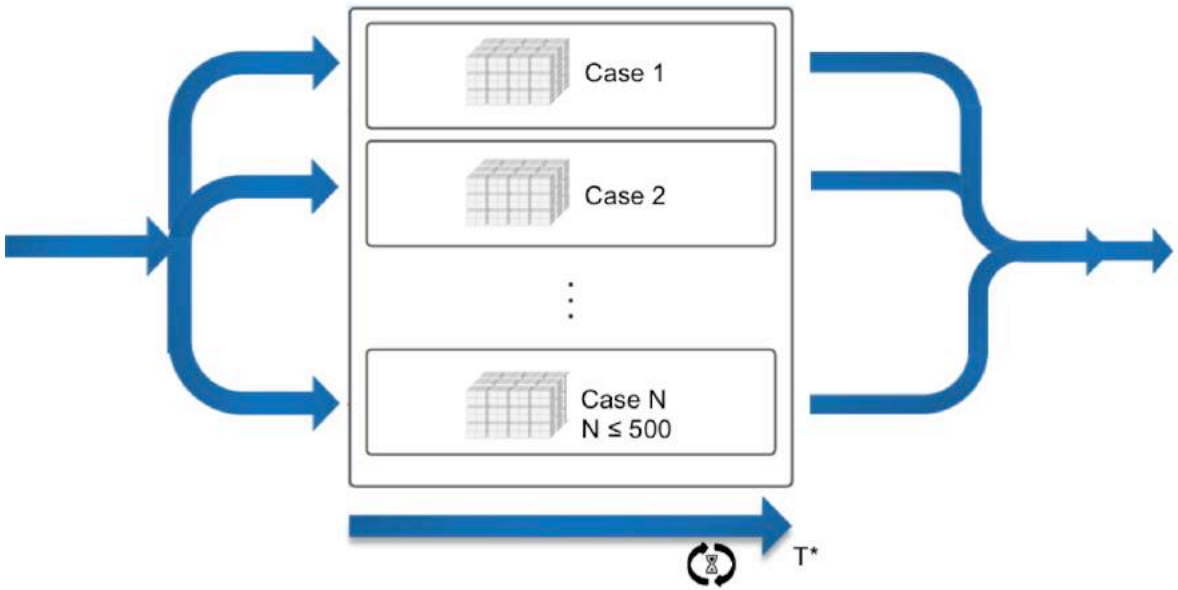
A Massive Simultaneous Cloud Computing Platform for Multiphysics Simulations

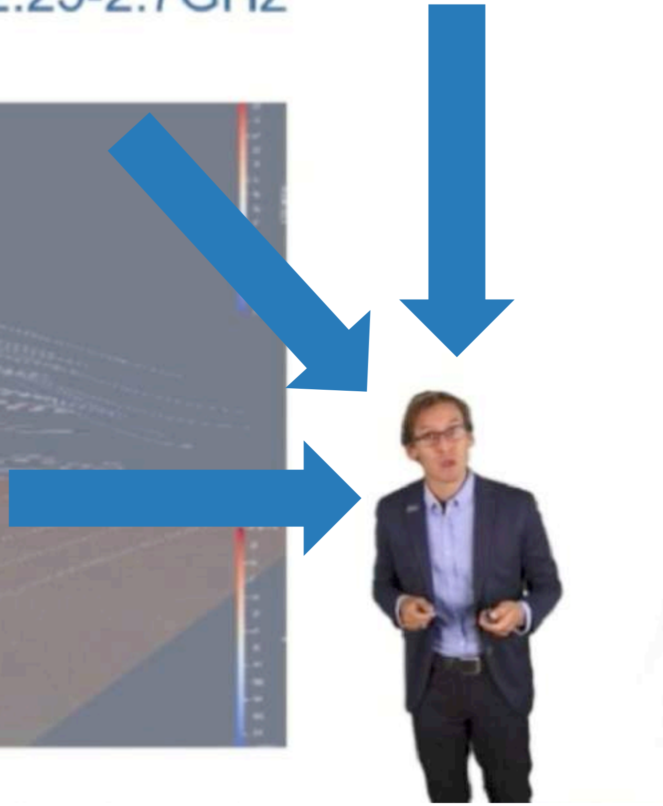


16th International Conference of Multiphysics 2021, Online

9th-10th Dec 2021, G. Boiger, D. Sharman, D. Drew, D. vanOerle, S. Delbari

Workflow: Motorbike

- Case: Motorbike
- Size of mesh: 300k cells
- Solver: simpleFoam
- Parameter Study: 160 cases
- MSCC on KaleidoSim: AMD Epyc Rome; 2.25-2.7GHz
- Each case parallelized on: 4 vCPU



3. Towards Industrial Application

Content

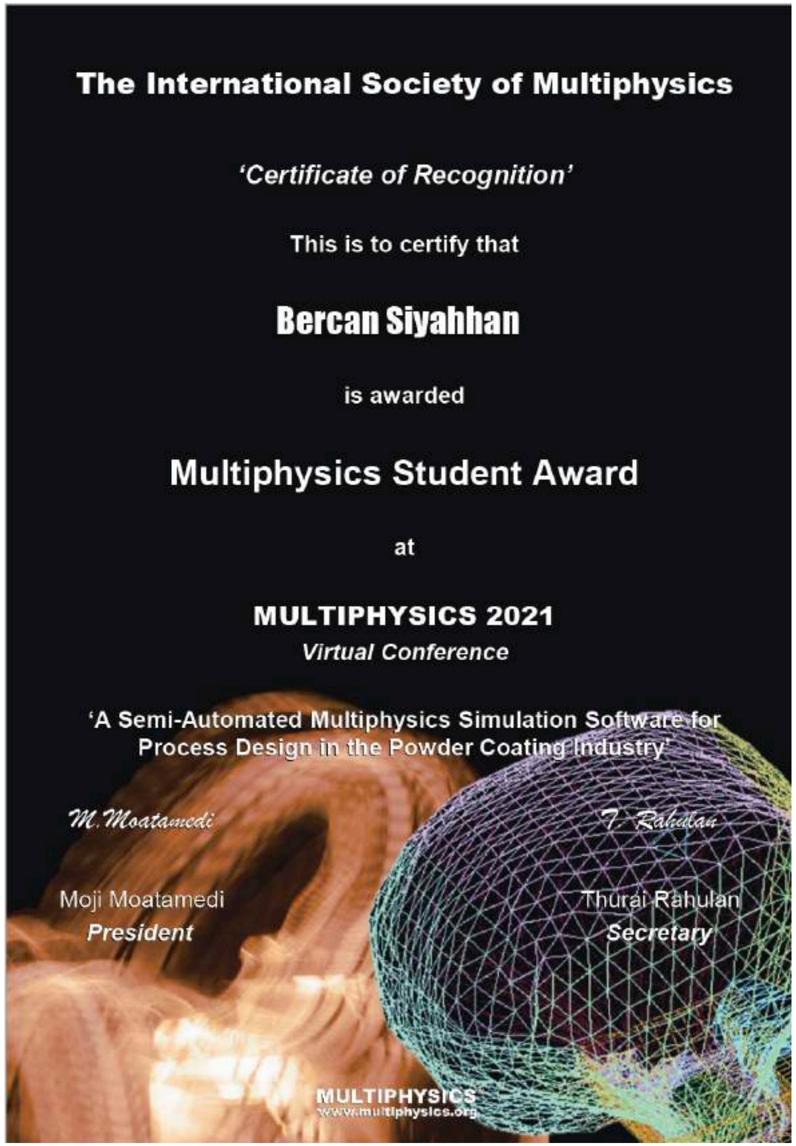
ICM 2021 - Online

A Semi-Automated Multiphysics Simulation Software for Process Design in the Powder Coating Industry

Bercan Siyahhan (siya@zhaw.ch)

Prof. Dr. Gernot Boiger (boig@zhaw.ch)

ICM 2021 - Online



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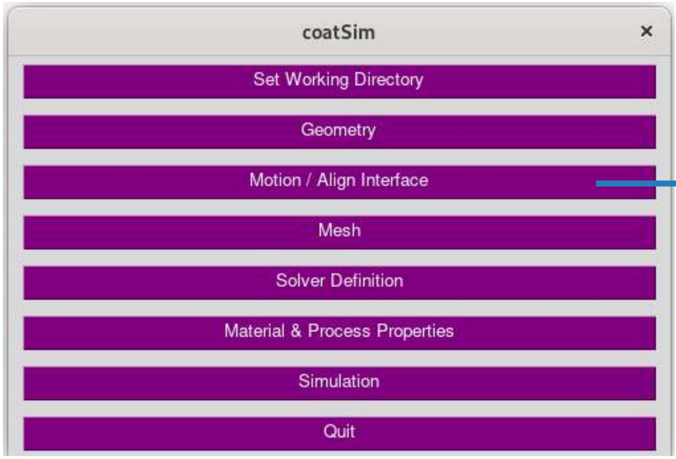
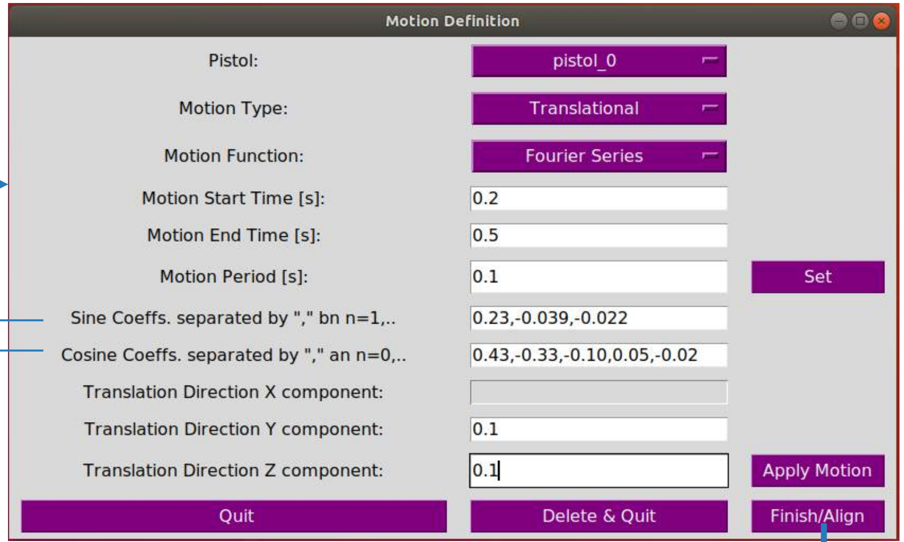
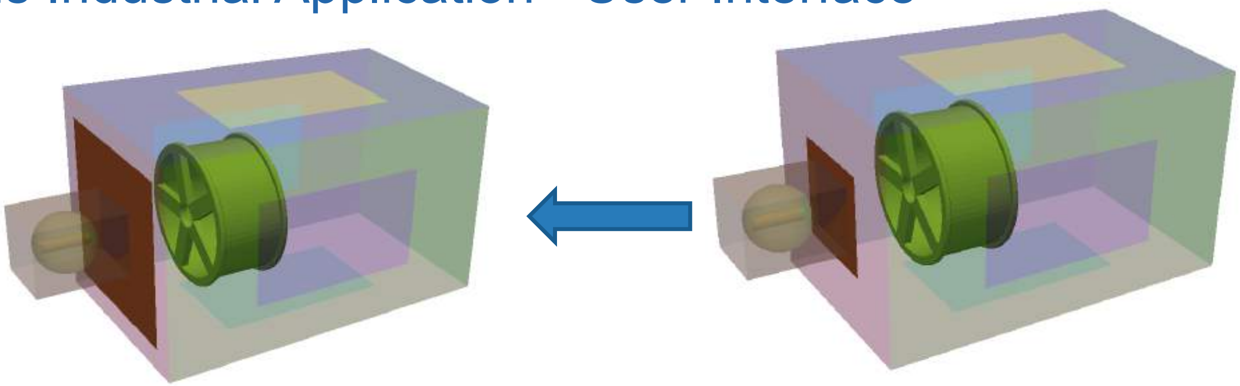




$$f(t) = \sum_{n=0}^{\infty} a_n \cos\frac{2\pi n t}{T} + \sum_{n=1}^{\infty} b_n \sin\frac{2\pi n t}{T}$$

Towards Industrial Application - User Interface



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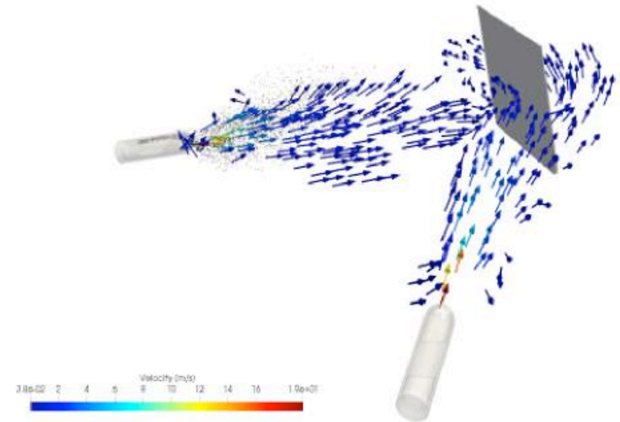

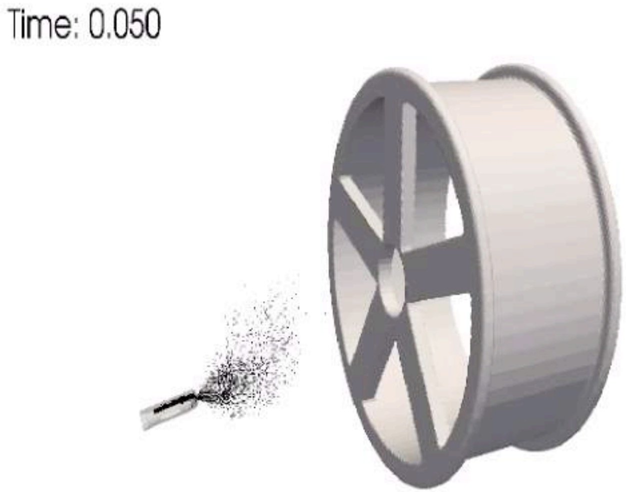

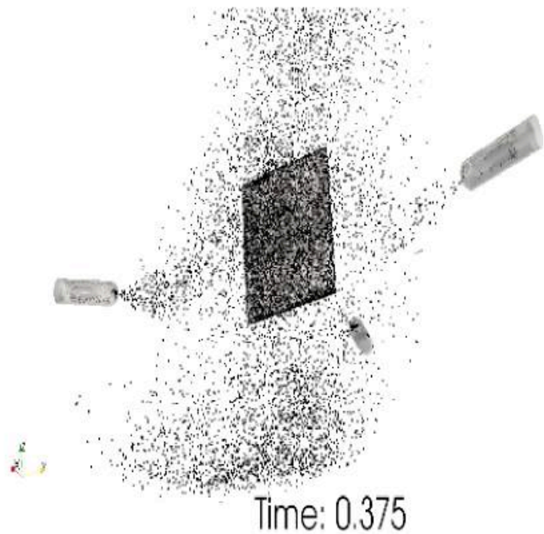

CoatSim in Action - 2022

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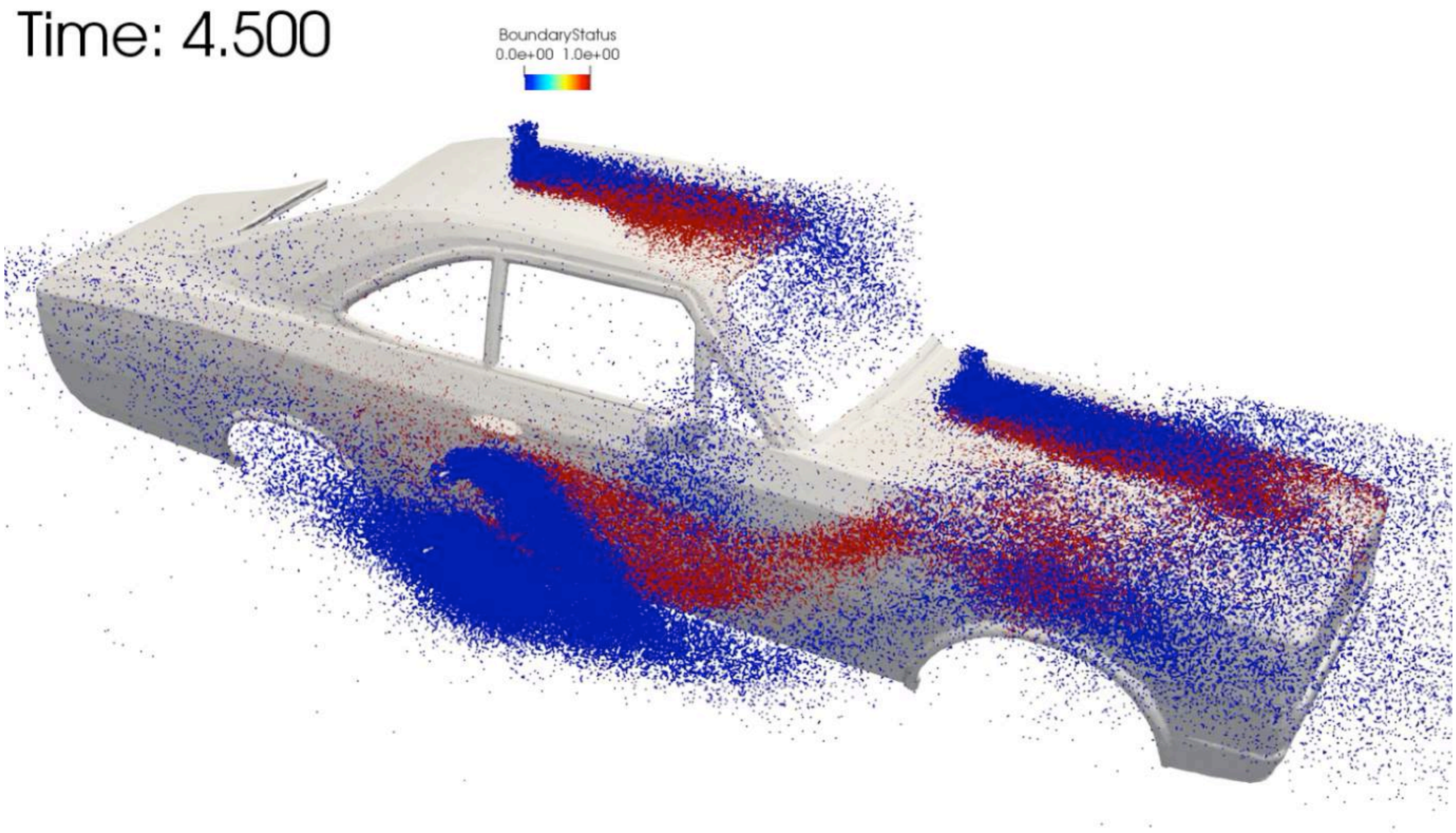

CoatSim in Action - 2022

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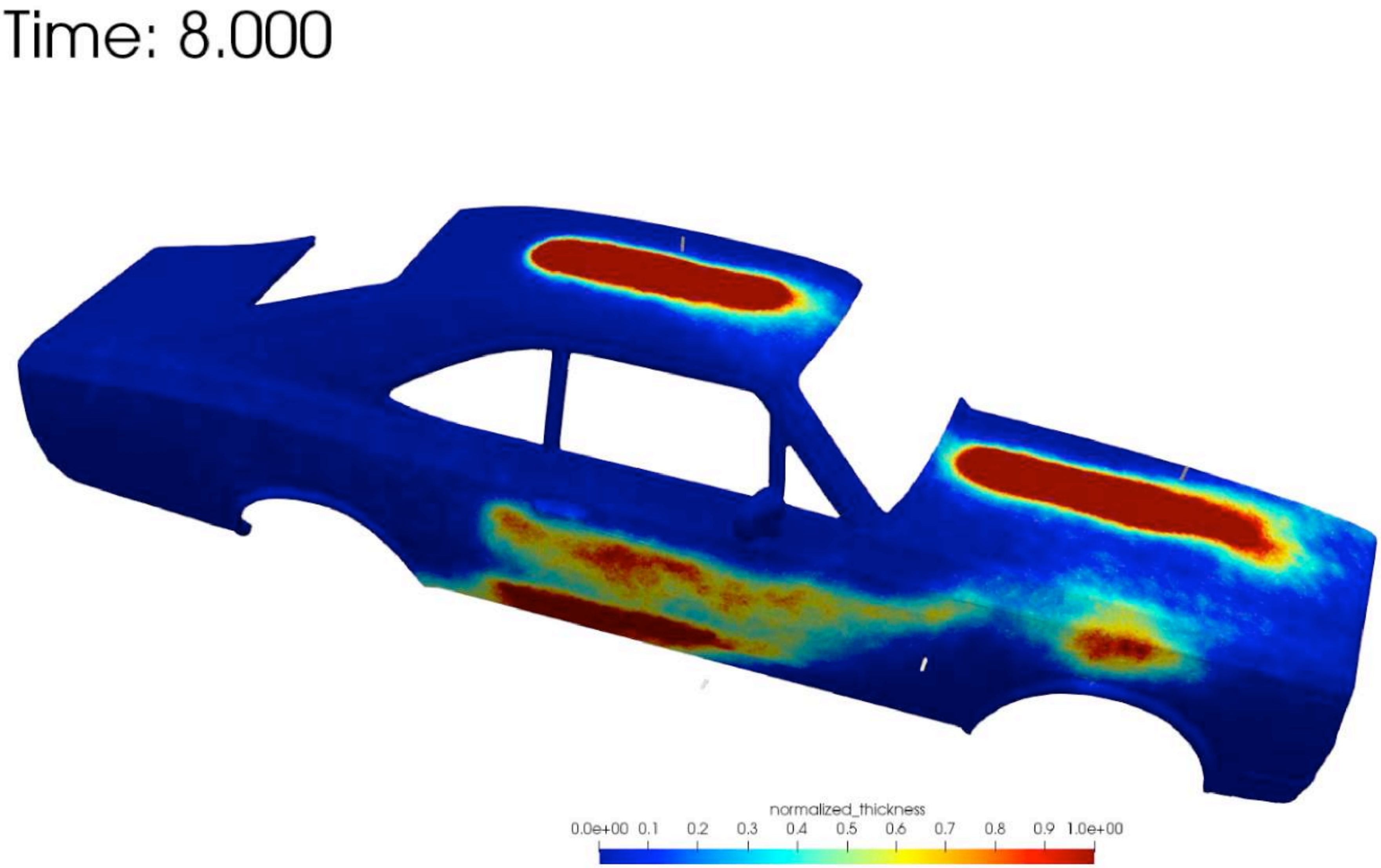
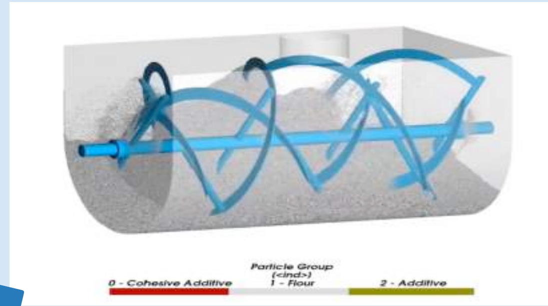


4. Outlook

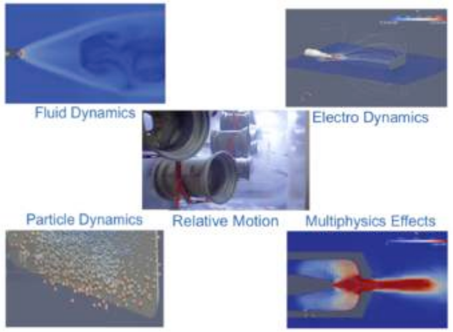
Content

Outlook

Production:
Galvanization

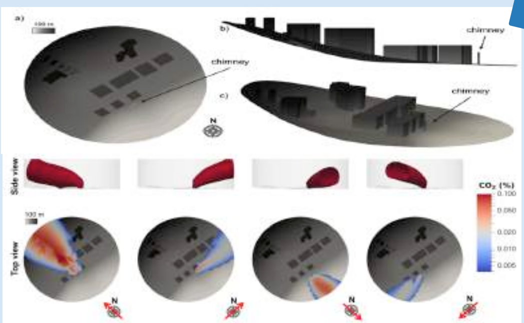


Pharma:
Mixing

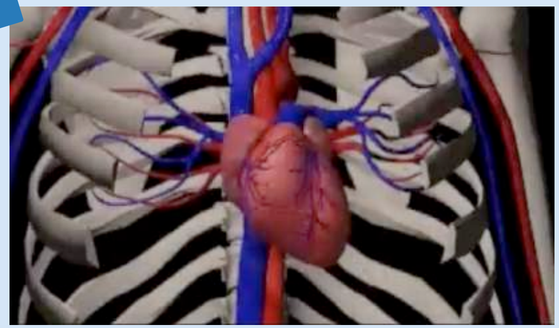


Modular
Physical Model

Environment:
Fine Dust Distribution



BioTech:
Blood Vessel Flow



So what is it all for?

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Thank you for your attention!

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