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Erosion prediction in a horizontal to vertical elbow by the Euler-Lagrange approach

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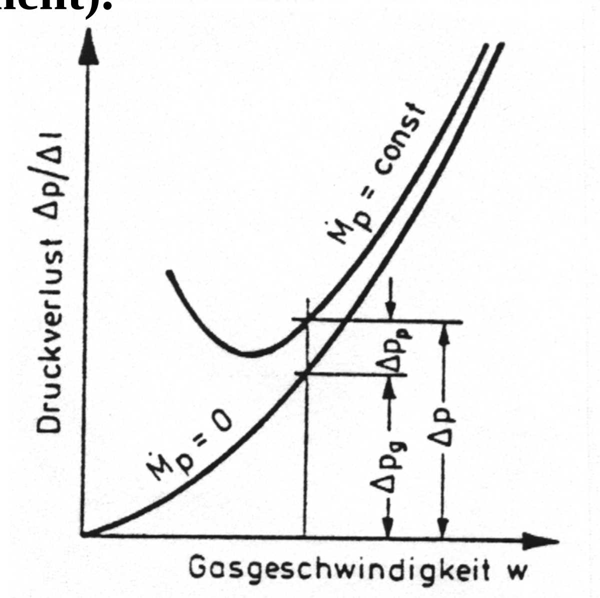
Introduction and motivation

- Design of a wide variety of engineering processes mostly relies on empirical correlations developed on the basis of numerous experiments
- Example: *Pneumatic Conveying*

In designing a conveying line the pressure drop is an essential parameter (determines blower capacity and energy requirement).

$$\Delta p_{tot} = \left(\lambda_{Single} + \eta\, \lambda_{Part}\right) \frac{L}{D} \frac{\rho}{2} U_{av}^2$$



✗ The main contribution for the particle phase comes from particle-wall collisions

✗ The "wall friction" is depending on numerous parameters: pipe inclination, pipe diameter, pipe material, particle size and shape, particle material

Moreover, as processes are running for long times, particle-wall collisions erode the duct walls, which is a severe problem in several systems as pneumatic conveying, particle separation in cyclones or fluidized beds

Introduction and motivation

- **Erosion by solid particles depends on numerous parameters such as:**
  - **Wall material and structure, particle material, shape and surface structure**
  - **Kinematic parameters: particle velocity and impact angle**
- **Two main mechanisms accepted for erosion:**
  - **Cutting erosion wear (shallow particle impact angles)**
  - **Deformation erosion wear (close to normal impact angles)**
- **In the past, due to the importance of the phenomenon, many erosion models have been developed based on experiments, but the majority are specific for the studied case.**
- **However, for predicting erosion, the flow and particle fields need to be known as particle kinematic variables are essential. Therefore, in this study Euler – Lagrange approach is chosen because it is the natural frame to describe essential micro processes happening at the particle scale**
- **This contribution highlights the influence of wall roughness and inter-particle collisions as well as particle mass loading on predicted erosion rates on an elbow flow configuration.**

Summary of Euler-Lagrange approach

The **fluid flow** is calculated by solving the Reynolds-averaged conservation equations (steady or unsteady) by accounting for the influence of the particles (source terms).

Two-way coupling

Turbulence models:

- ✓ k-ε turbulence model
- ✓ Reynolds-stress model

The **Lagrangian approach** relies on tracking a large number of representative particles (point-mass) through the flow field accounting for rotation and all relevant forces like:

- drag force
- gravity/buoyancy
- pressure and added mass
- **slip/shear lift**
- **slip/rotation lift**
- torque on the particle

Plus elementary processes:

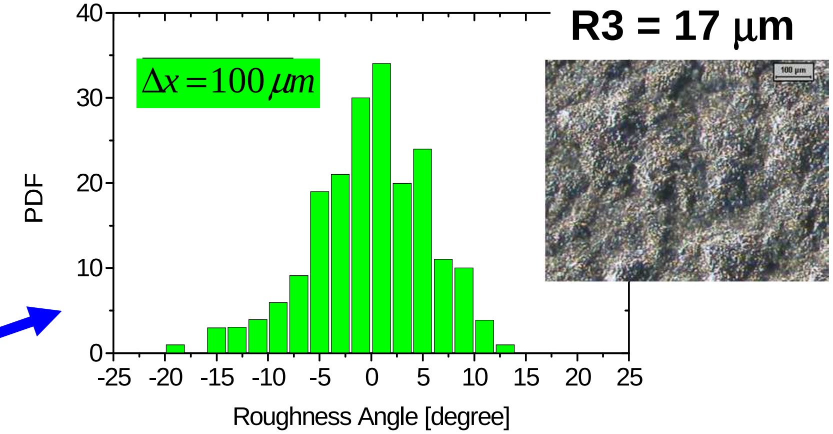
- particle-turbulence interaction
- particle-rough wall collision
- inter-particle collisions

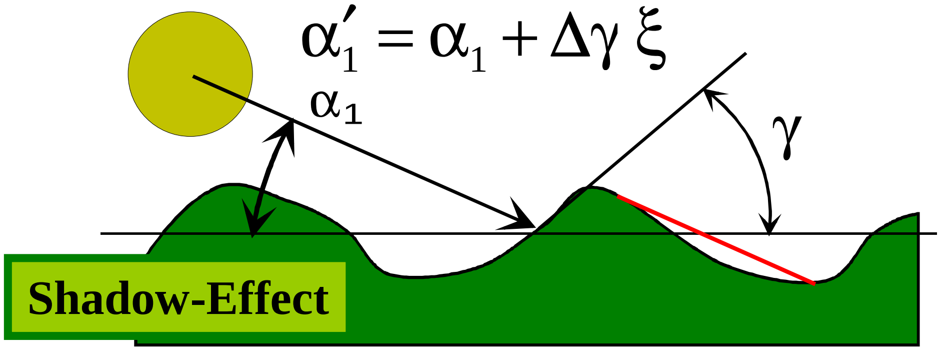
Particle properties and source terms result from ensemble averaging for each control volume

Modelling particle-wall collisions

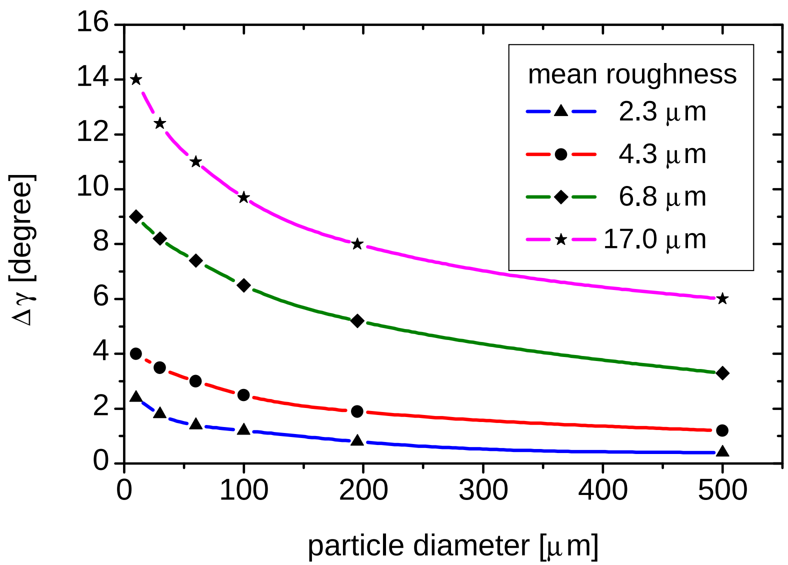
Particle-rough wall collision:
momentum equations + Coulomb´s law of friction
Sommerfeld & Huber (1999)

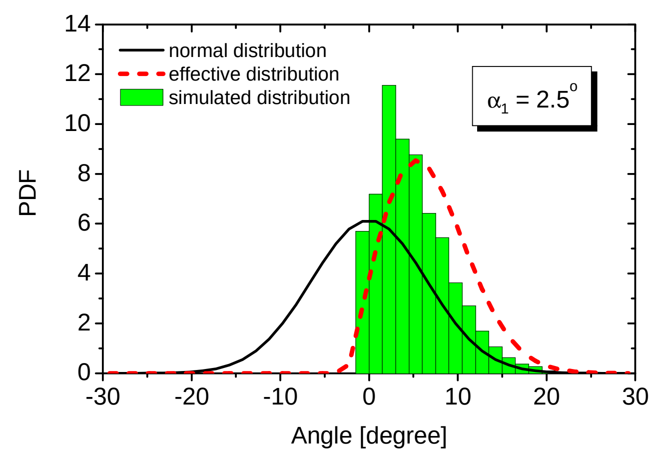
$$p(\gamma) = \frac{1}{\sqrt{2\,\pi\,\Delta\gamma^2}} \exp\left(\frac{\gamma^2}{2\,\Delta\gamma^2}\right)$$





Dependence of roughness angle Δγ on particle size (measurements)





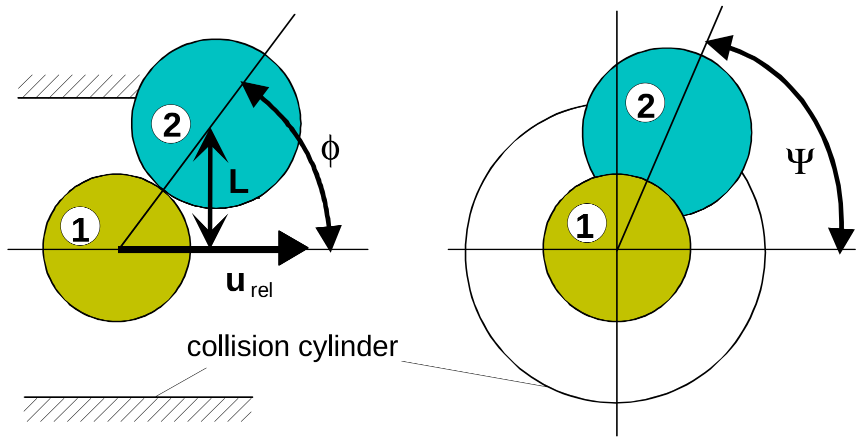
Modelling inter-particle collisions

- **Stochastic inter-particle collision model (Sommerfeld, 2001)**

Based on the fictitious collision partner concept, generated at each time step of particle trajectory computation

Properties of fictitious particle sampled from local distribution functions

⇒ Particle diameter
⇒ Particle velocities



- **solution of the impulse equations**
- **Coulomb`s law of friction**
- **oblique inelastic collision (Hard Sphere Model)**

Correlation of fluctuating velocities of colliding particles respected

$$R(St_K) = \exp\left(-\frac{\alpha\, St_K^2}{1+\gamma\, St_K^{\beta}}\right)$$

Laín et al. (2010)

$$\alpha = 0.019,\ \beta = 1.725,\ \gamma = 0.044 \qquad St_K = \frac{\tau_p}{\tau_K}$$

Erosion model Oka et al. (2005)

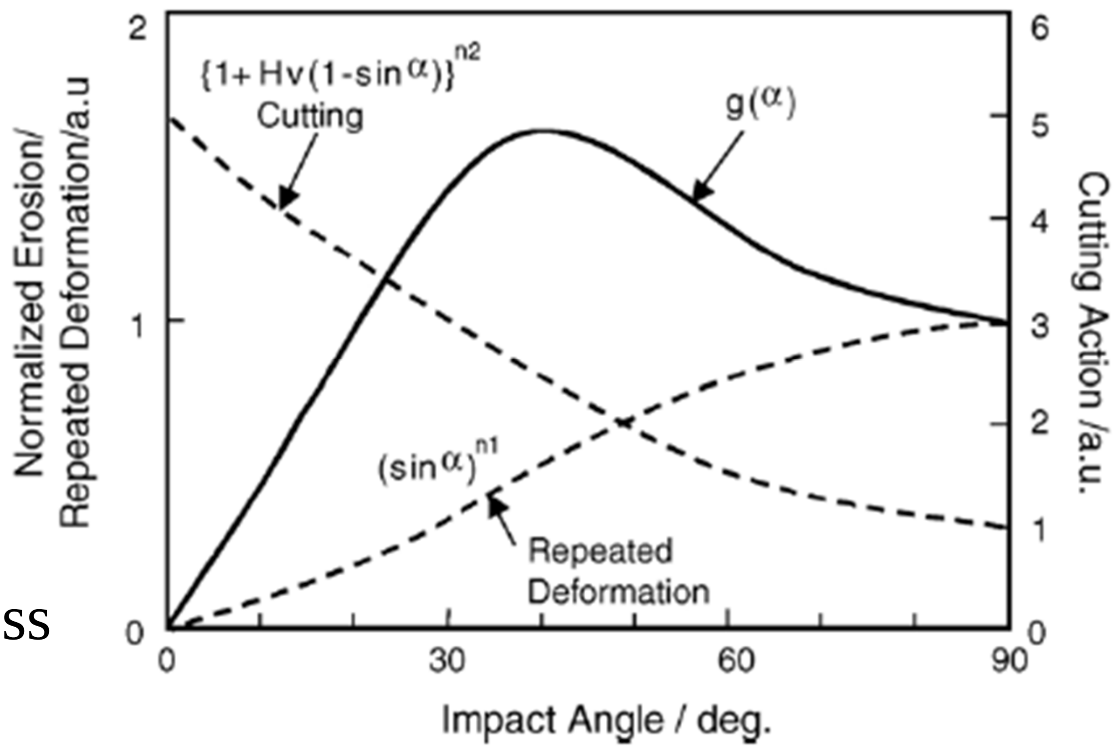
- **"... propose predictive equations for erosion damage caused by solid particle impact that can be applied to many types of metallic materials under various conditions involving impact angles, velocity, size and properties of the particles"**

$$E(\alpha) = g(\alpha)\, E_{90} \qquad g(\alpha) = (\sin\alpha)^{n_1}\left[1 + Hv\,(1 - \sin\alpha)\right]^{n_2}$$

$$n_1 = s_1 (Hv)^{q_1}$$

$$n_2 = s_2 (Hv)^{q_2}$$

Hv: Vickers Hardness



Erosion model Oka et al. (2005)

$$E(\alpha) = g(\alpha)\, E_{90} \qquad E_{90} = K\left(a\ Hv\right)^{k_1 b} \left(\frac{u_p}{u_{ref}}\right)^{k_2} \left(\frac{D_p}{D_{ref}}\right)^{k_3}$$

K, k_1 & k_3 : constants depending on particle properties

$k_2 = r\left(Hv\right)^{p}$: depends on wall material and particle properties

a, b : factors related to the behaviour of load-relaxation ratio of wall material

$E(\alpha)$ gives erosion damage in mm^3/kg which is converted to penetration ratio by:

$$PR_S = 10^{-9}\,\frac{E_S(\alpha)}{A_S}\,[\mathrm{m/kg}]$$

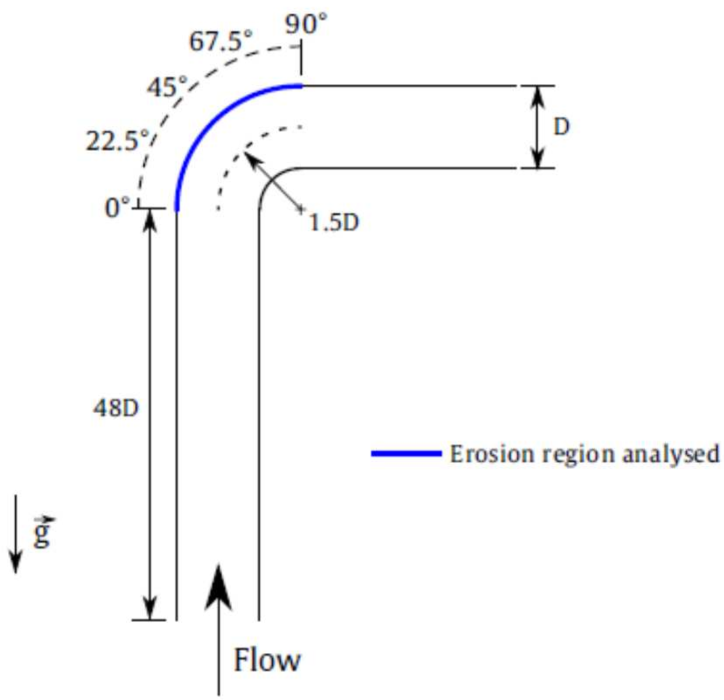
A_S : surface area

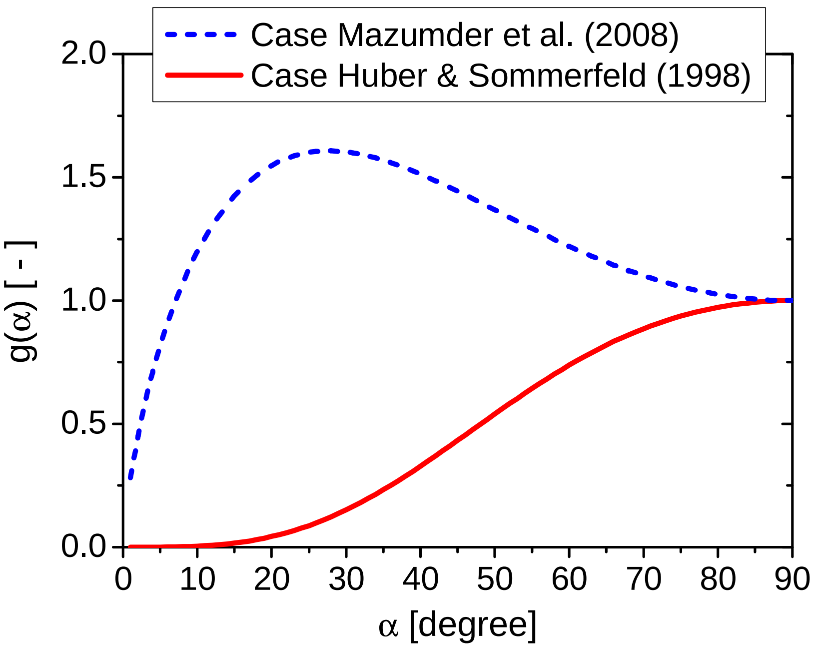
Validation erosion model

Mazumder et al. (2008) experiments (sand & aluminium)

Hv = 1.049 GPa; D_p = 182 μm

K	k_1	k_2	k_3	u_{ref} (m/s)	D_{ref} (μm)	n_1	n_2
65	-0.12	$2.3Hv^{0.038}$	0.19	104	326	$0.71Hv^{0.14}$	$2.4Hv^{-0.94}$





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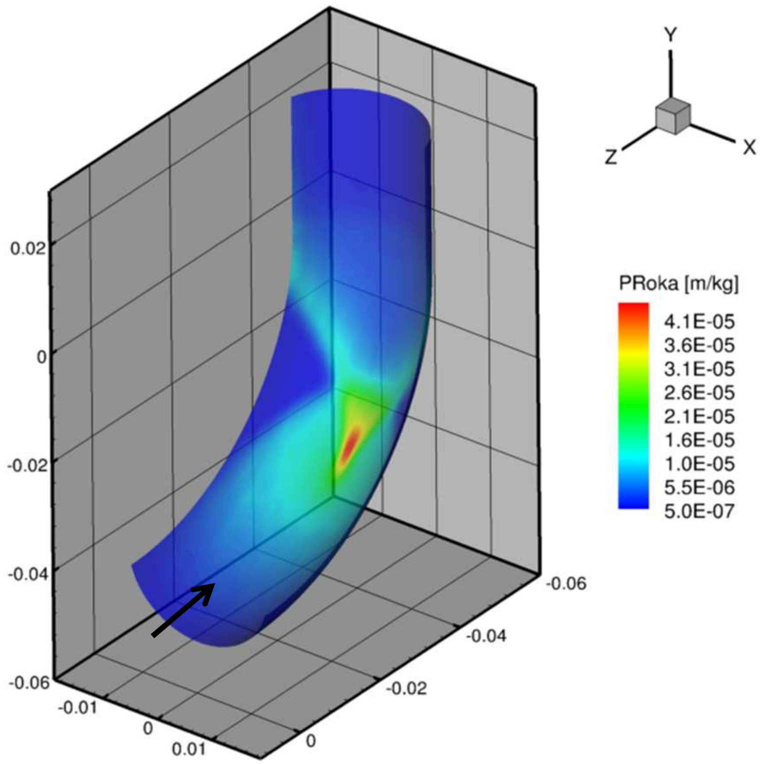
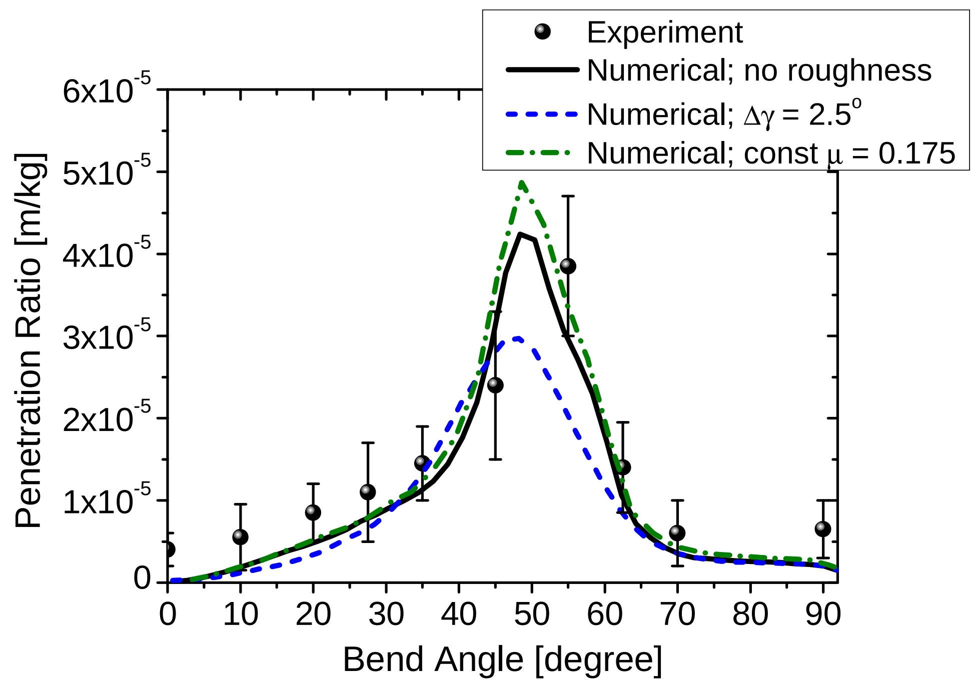


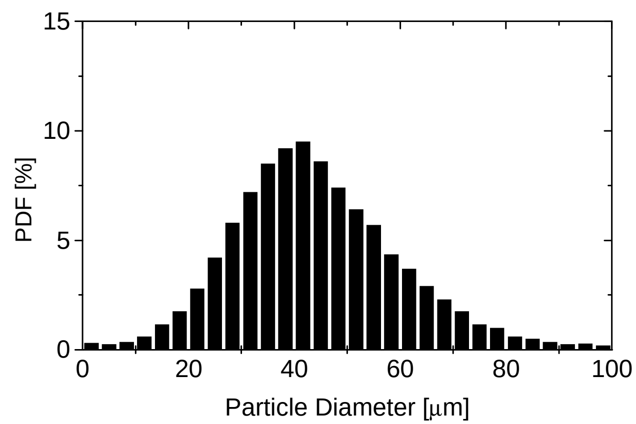


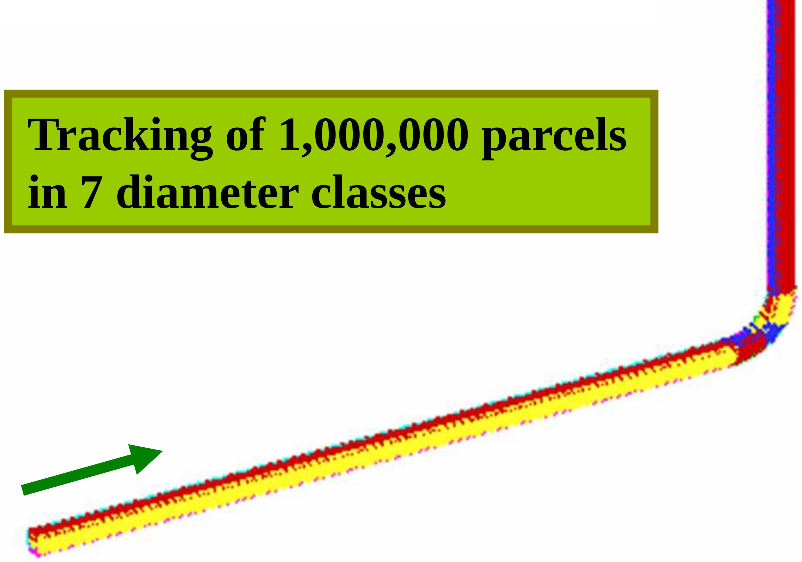
One-way coupling computations

Pipe bend flow Huber & Sommerfeld (1998)

Base case

Pipe diameter: 150 mm
Horizontal pipe length: 5 m
Bend radius: 2.54 x 150 mm
Vertical pipe length: 5 m
Conveying velocity: 27 m/s
Glass beads: 40 µm mean
Mass loading: 0.3



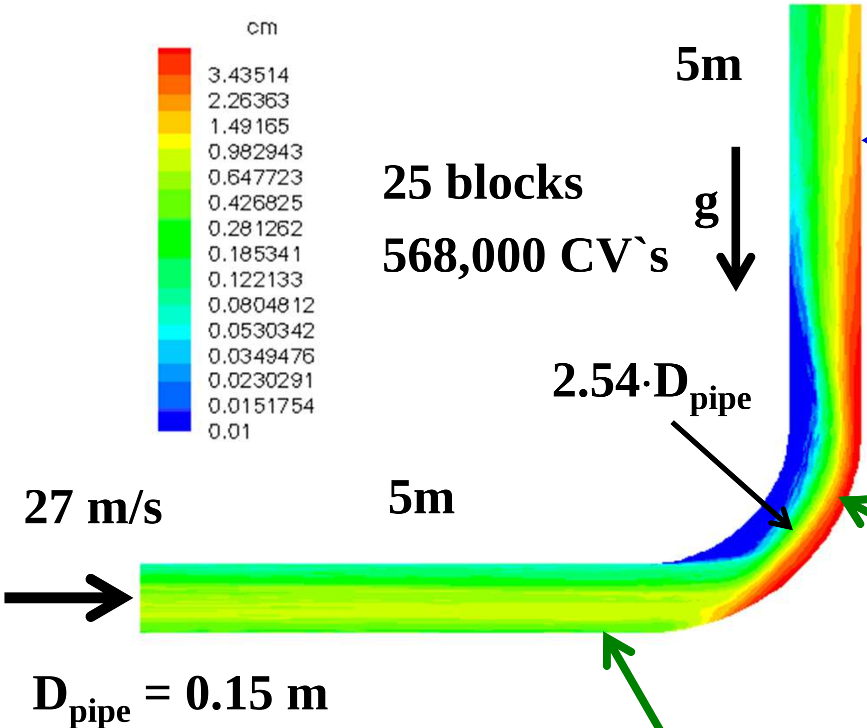


Tracking of 1,000,000 parcels in 7 diameter classes

- **Three-dimensional computations**
- **k-ε turbulence model**
- **Block-structured grid with 25 blocks**
- **568,000 hexahedral control volumes**
- **Full coupling Euler/Lagrange**
- **Inter-particle collisions**
- **Wall roughness**

Pipe bend flow Huber & Sommerfeld (1998)

- Pressure drop of the pipe system



- Particle rope disintegration
- Secondary flow effects

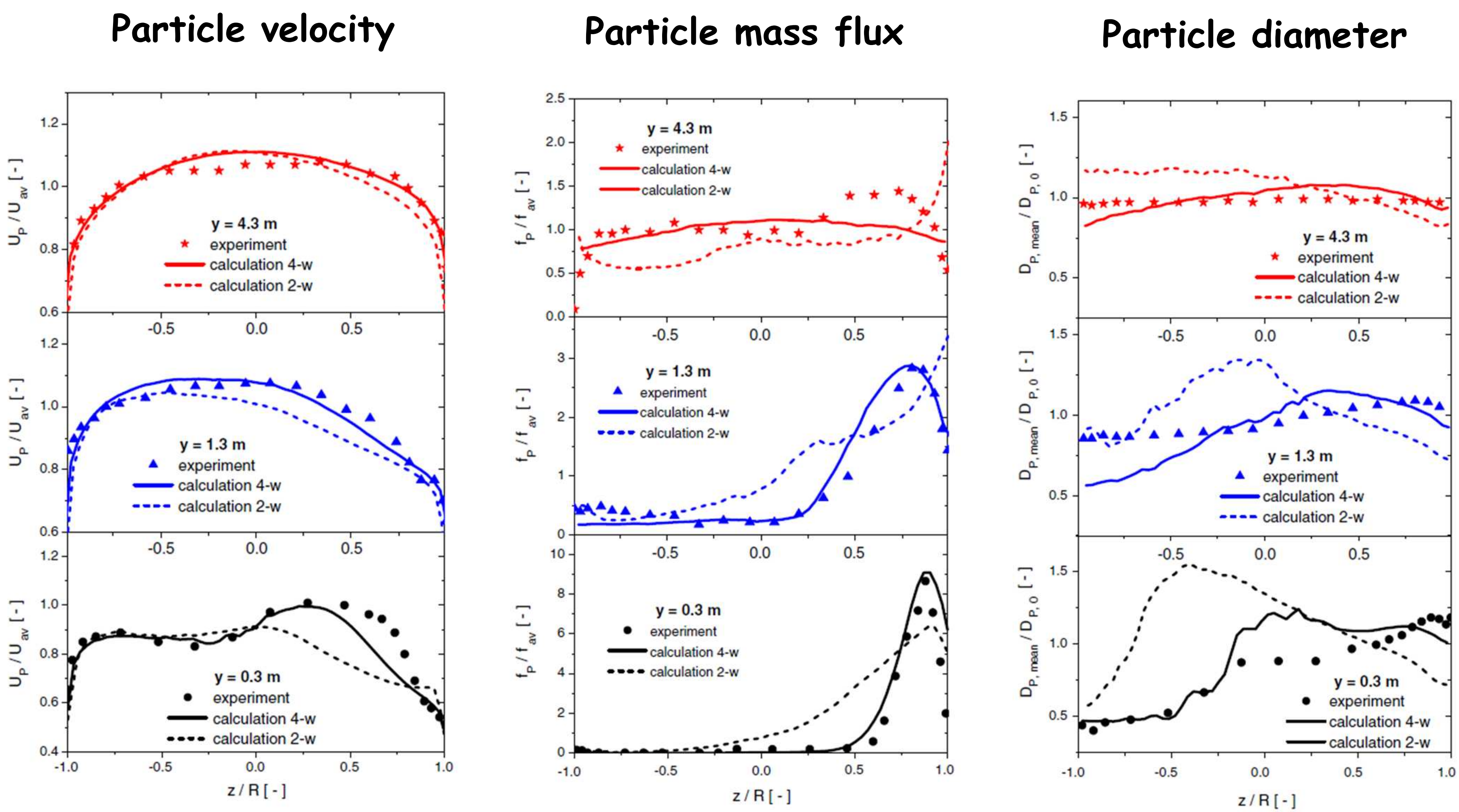
- Inertial particle separation
- Rope formation
- Secondary flow modification

- Gravitational settling
- Turbulent dispersion

Tracking of
1,000,000 parcels

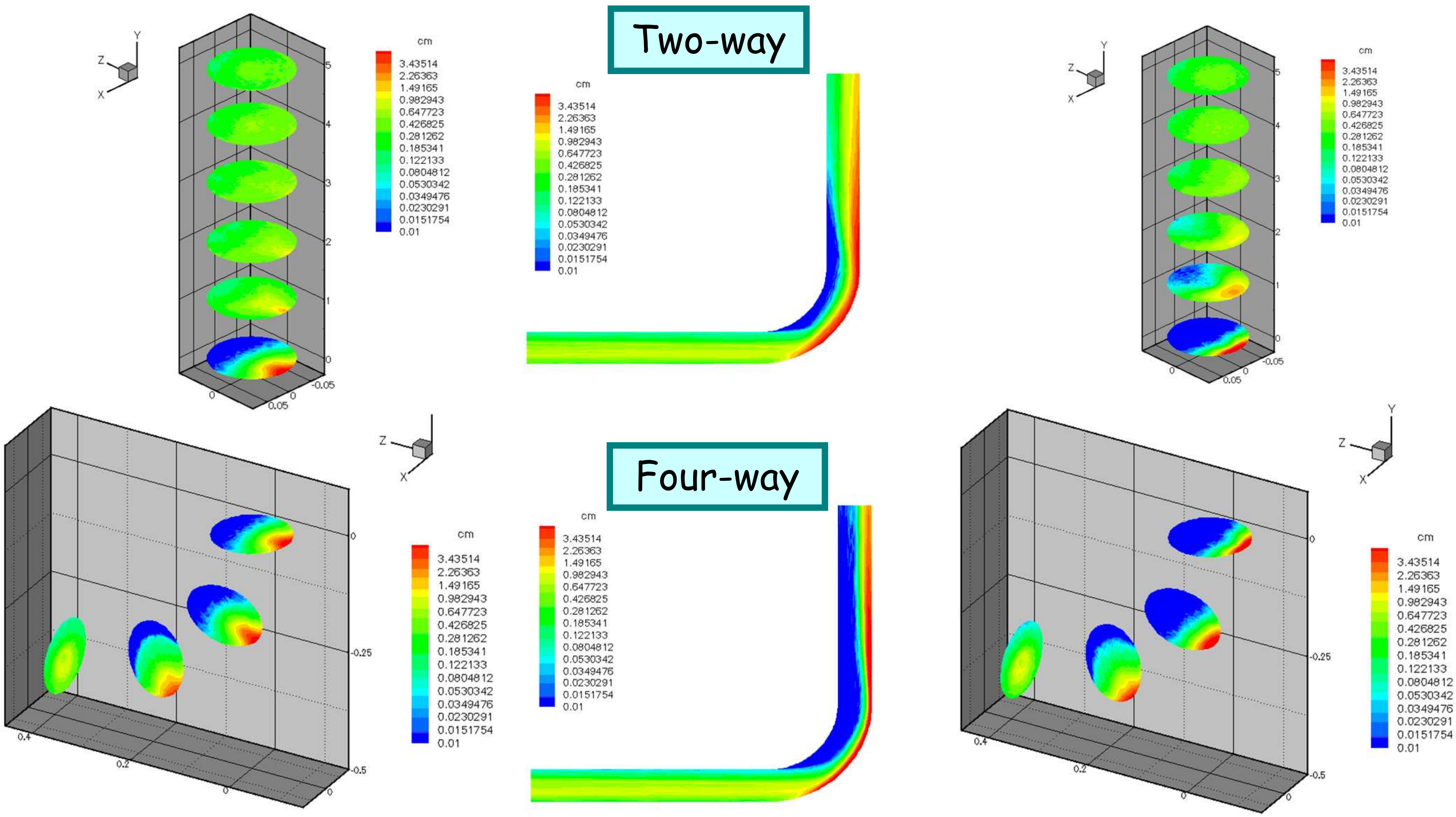
Pipe bend flow Huber & Sommerfeld (1998)

D = 0.15 m



Validation versus experimental measurements

Pipe bend flow Huber & Sommerfeld (1998)

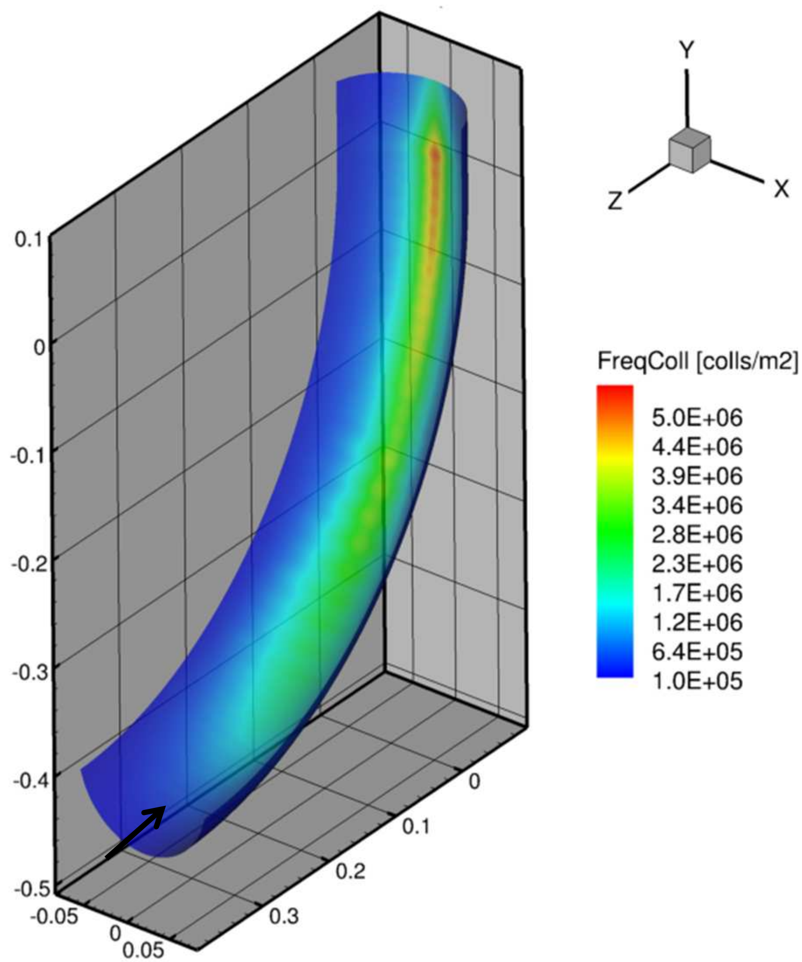


$Two-way$ **D = 0.15 m** $Four-way$

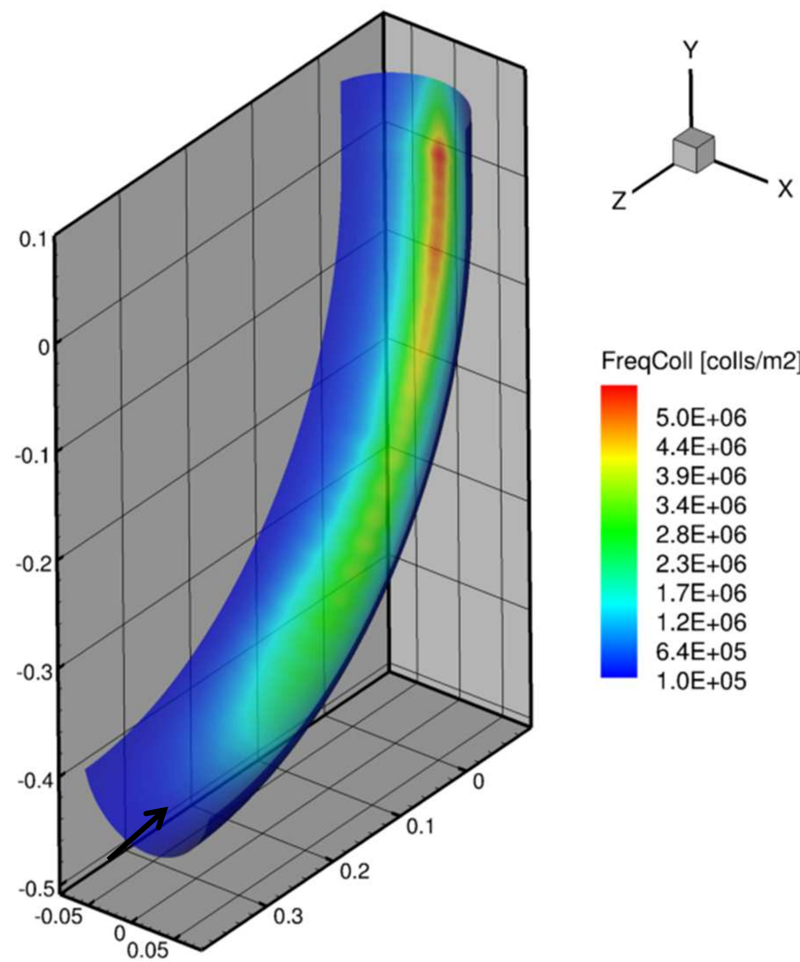
Pipe bend flow Huber & Sommerfeld (1998)

Particle-wall collision frequency

Two-way



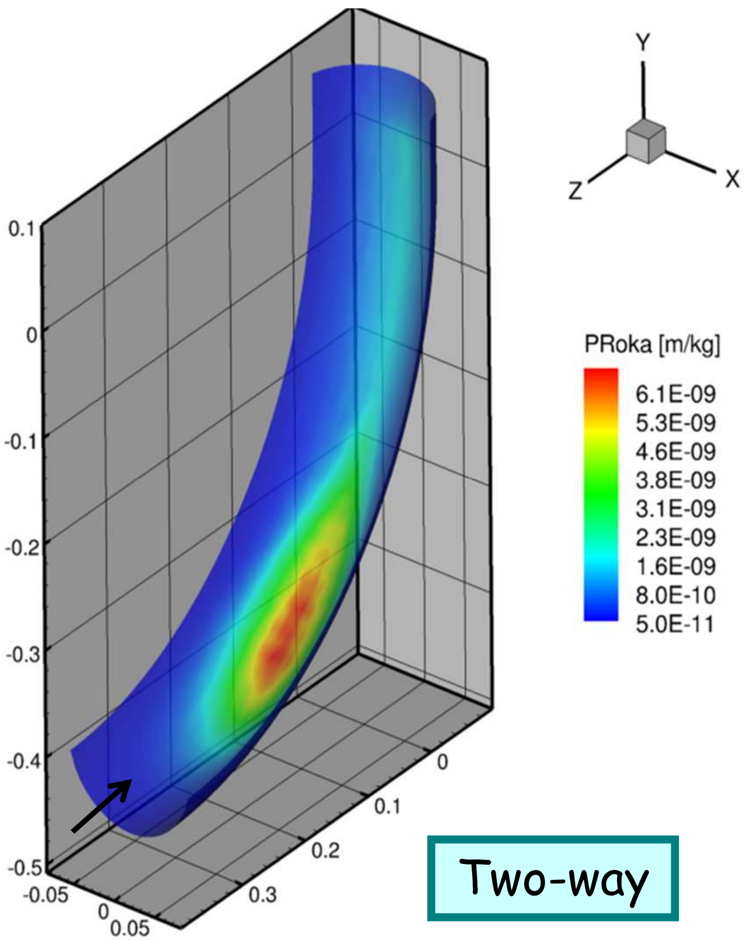
Four-way

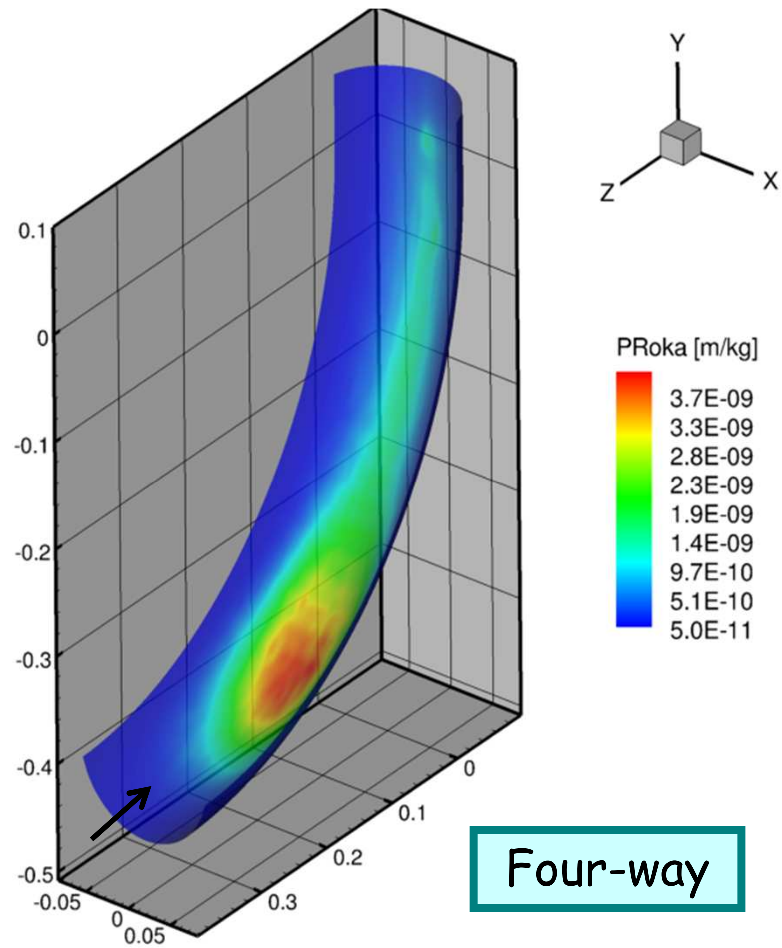


Pipe bend flow Huber & Sommerfeld (1998)

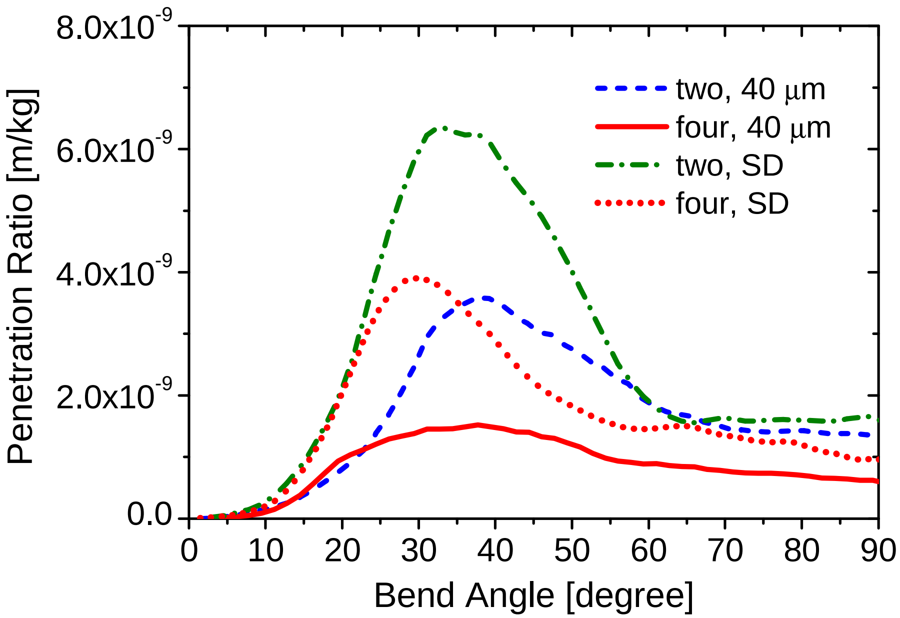
Erosion computation, Hv = 1.96 GPa

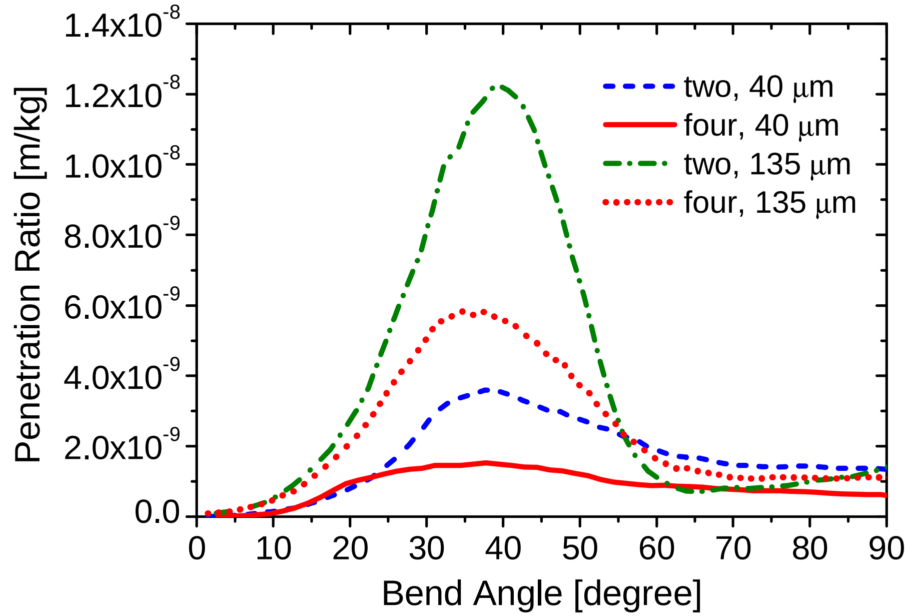
K	k_1	k_2	k_3	u_{ref} (m/s)	D_{ref} (μm)	n_1	n_2
27	-0.16	2.1	0.19	100	200	$2.8Hv^{0.41}$	$2.6Hv^{-1.46}$



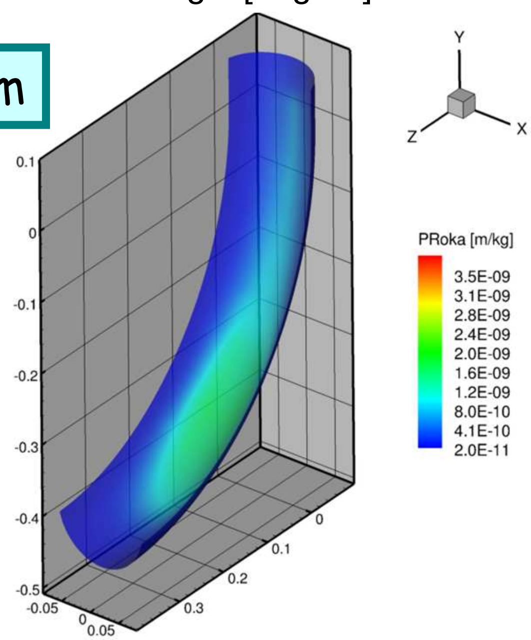


Pipe bend flow Huber & Sommerfeld (1998)

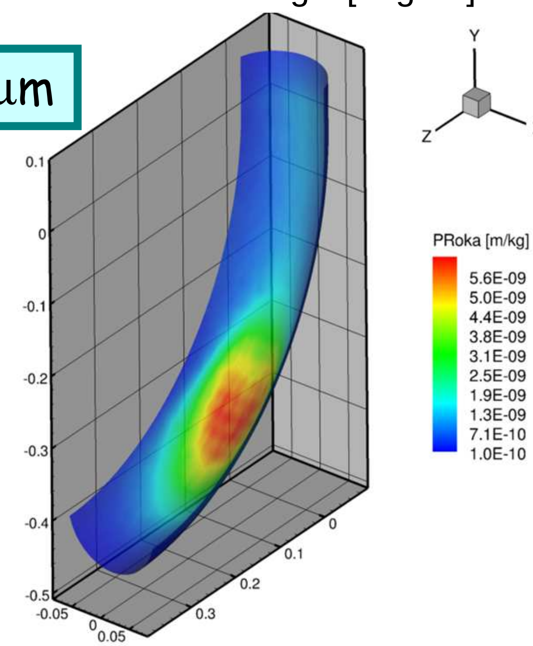




D_p = 40 μm

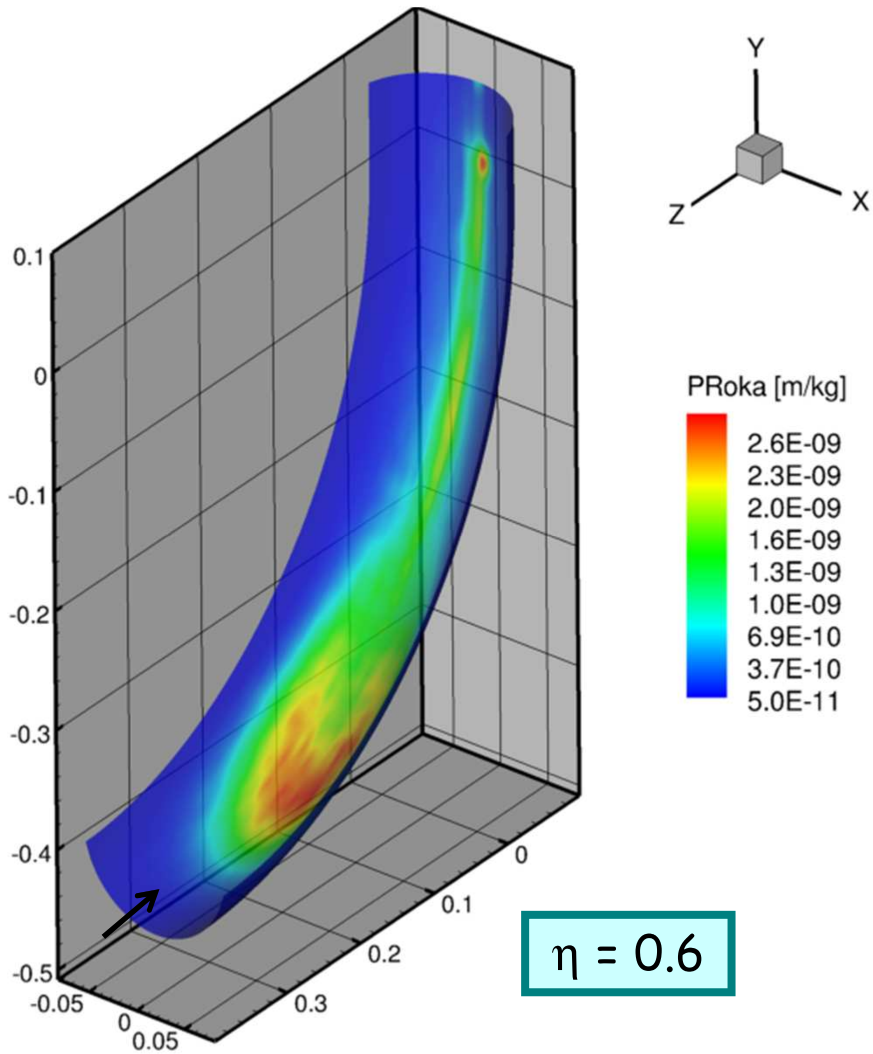


D_p = 135 μm

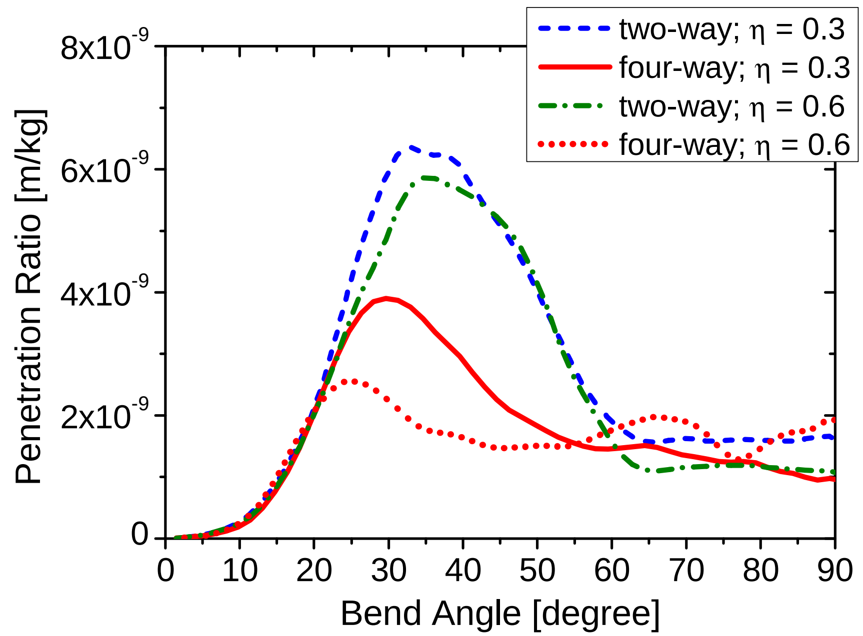


Pipe bend flow Huber & Sommerfeld (1998)

Comparison between mass loadings $\eta = 0.3, 0.6$



η = 0.6



Conclusions

- The Euler/Lagrange approach has been used for calculating dispersed confined particle-laden flows in connection with wear estimation
  - Realistic modelling of elementary processes
  - Consideration of particle size distribution
- Wall roughness decreases PR due to its effect on particle re-dispersion
- Also, friction decreases PR due to lower particle velocity at impact
- Size distribution increases PR regarding mono-disperse particles due to higher erosion damage produced by the highest diameters in the size distribution
- Inter-particle collisions reduce PR regarding two-way coupling even though particle-wall collision frequency increases. This effect is due to the combined effect of particle velocity and angle at impact.
- Higher particle mass loading yields also lower values of PR as a consequence of increasing inter-particle collisions. Particles near the wall “shield” it from direct impacts from incoming particles.