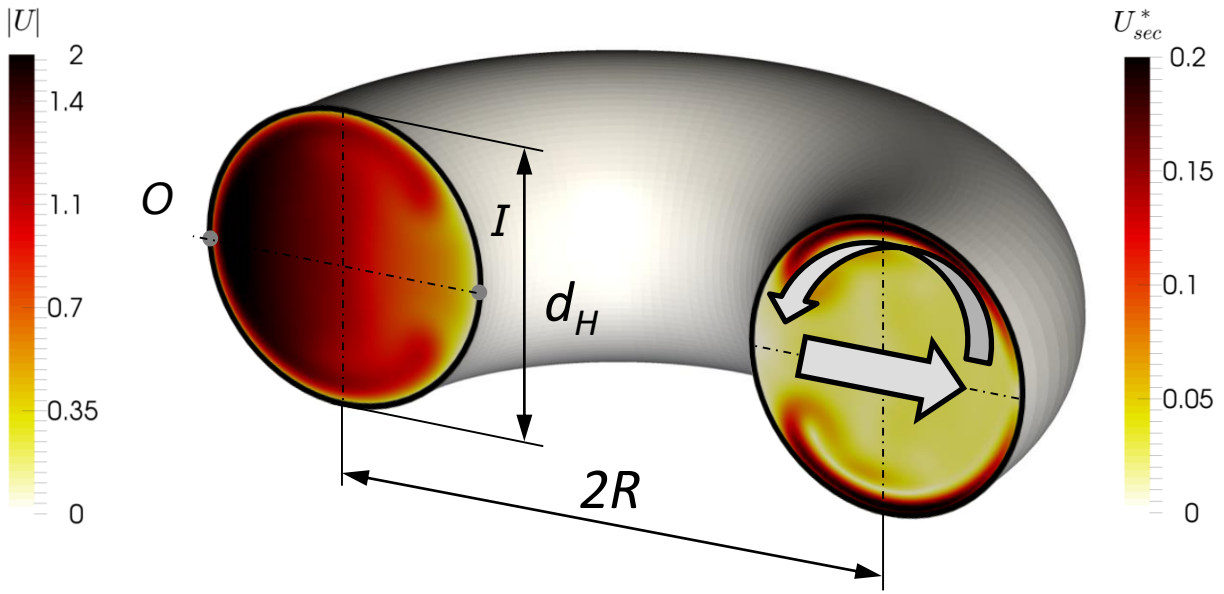
Separation by Design

Towards Simulation Guided Engineering of Coiled Channels for Precise Particle Separation

Jakob D. Redlinger-Pohn, Federico Municchi, and Stefan Radl

Institute of Process and Particle Engineering
Graz University of Technology

Coiled Channel Separation | Secondary Motion



$$\kappa = \frac{d_H}{2R}$$

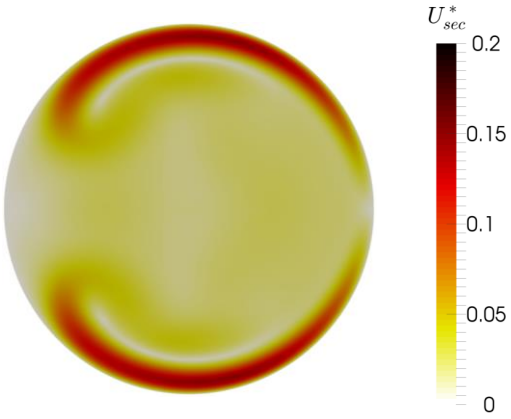
$$Da = \mathrm{Re}\sqrt{\kappa}$$

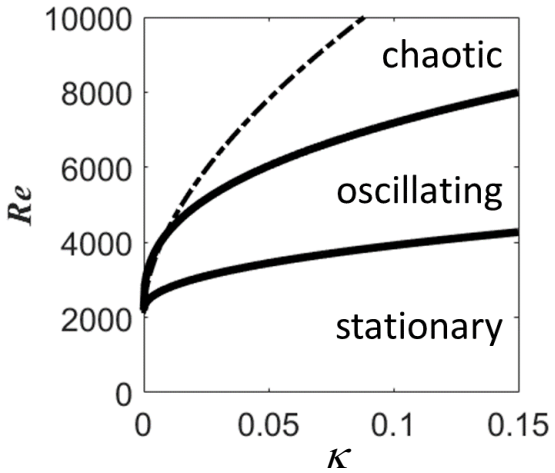
- Pipe, or channel of diameter d_H coiled around a centre of radius R
- Centrifugal forces acting on a flowing suspension [1,2]
  - cause deflection of the velocity maximum to the outer bend, and
  - lead to pressure differences resulting to a secondary motion = Dean flow

[1] Dean, Philos. Mag. J. Sci., 1927 | [2] Redlinger-Pohn et al., Int. J Multiphase Flow, 2016

Coiled Channel Separation | Secondary Motion

***Da* 688**





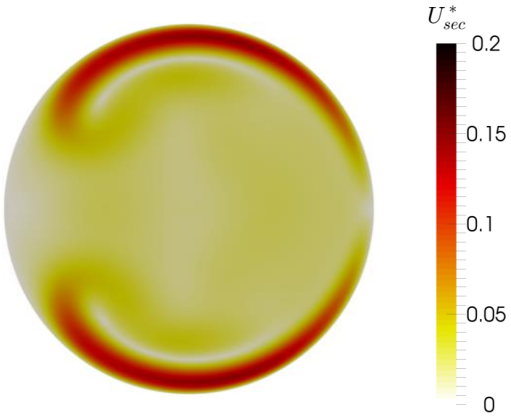
Features and Applications from Literature

- Critical Reynolds number Re_c, where fluid motion turns chaotic increases with κ [3]
- Particles suspended in coiled tube/pipe flow are picked up by the secondary motion
- Residence time distribution is narrower [4]
- Mixing time is reduced benefiting mass transfer and reactions [5]

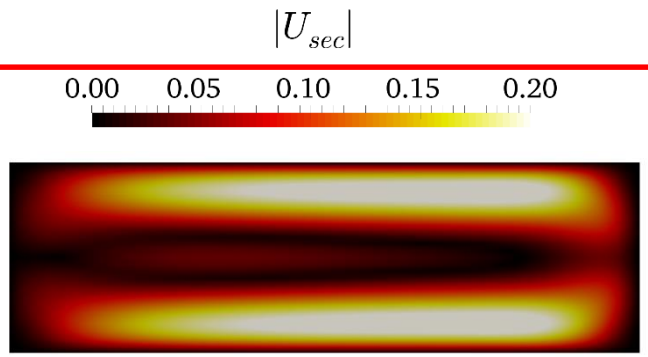
[3] I. DiPiazza, J. Fluid Mech., 2011
[4] J.A. Koutsky, Can. J. Chem. Eng. 1964
[5] S. Vashisth, et al., Ind. Eng. Chem. Res. 47, 2008

Coiled Channel Separation | Secondary Motion

***Da* 688**



***Da* 41**



Features and Applications from Literature

- Critical Reynolds number Re_c, where fluid motion turns chaotic increases with κ [3]
- Particles suspended in coiled tube/pipe flow are picked up by the secondary motion
- Residence time distribution is narrower [4]
- **Mixing** time is reduced benefiting mass transfer and reactions [5]

- **Separation** of particles in coiled channels with rectangular cross section: is it possible?

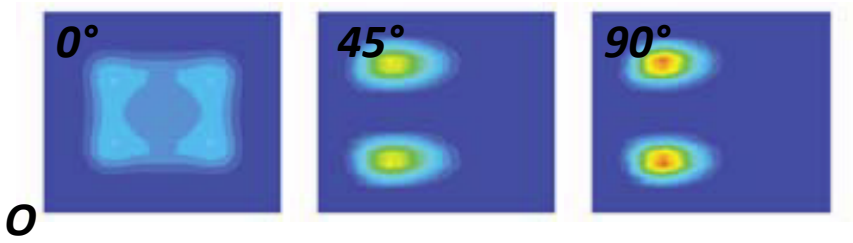
Agenda

- Motivation and Introduction
- Literature on Coiled Channels
  - Diverse effects for coiled channel suspension flow
- Simulations Studies on Coiled Suspension Flow
  - Flow, and Secondary Motion
  - Separation of Particles in Non-Circular Cross Section
- Conclusion and Outlook
  - Research Application and Future Focus

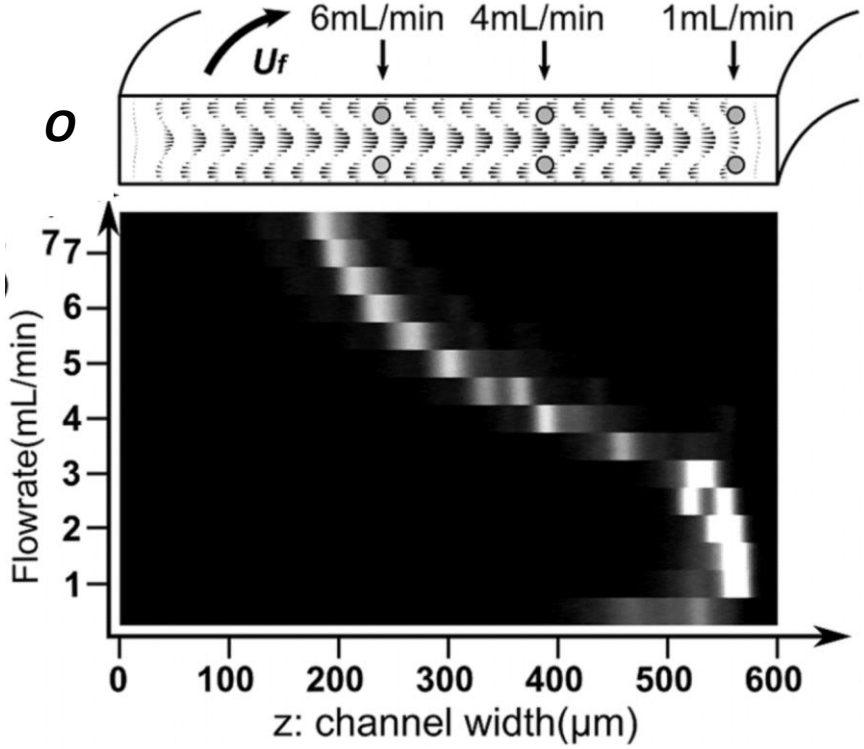
Coiled Channel Separation | Literature

- Literature hints to particle separation for non-circular cross section. **Why?**
- Larger particles are found to accumulate at
  - outer bend [7]
  - inner or outer bend [8]

Ookawara et al. [7], Euler-Euler Simulation
Concentration field | ***Re* 450 | κ 0.014**



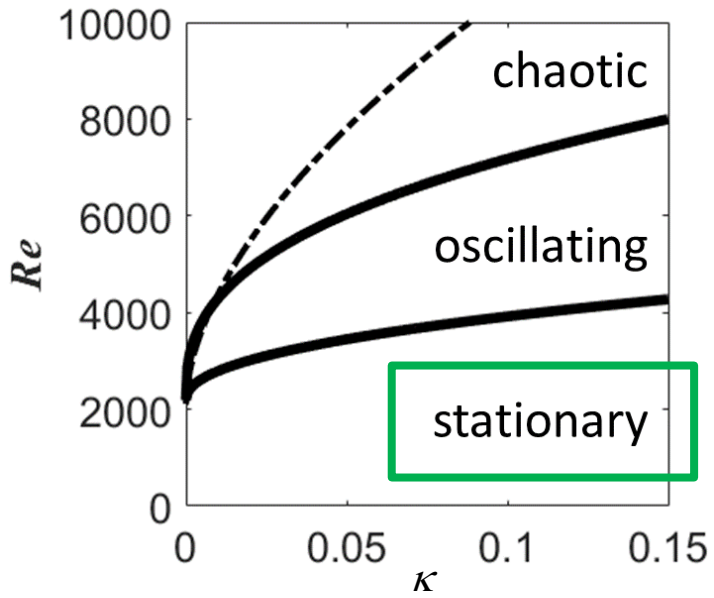
Guan et al. [8], Experiment
Particle Accumulation | ***Re*** $\leq$ **400** |
Archimedean Spiral κ **0.018 to 0.006**



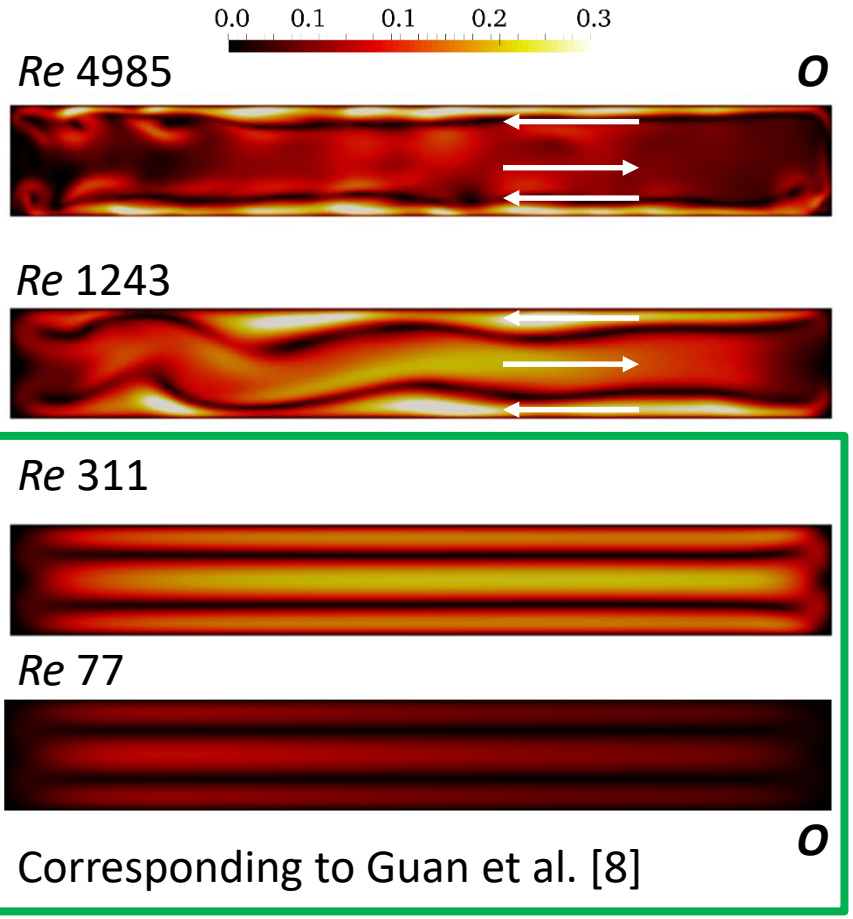
[7] Ookawara, et al., Chem. Eng. Sci., 2006 | [8] Guan, et al., Sci Rep, 2013

Coiled Channel Separation | Stationary Flow

- Flow field in dependence on
  - Reynolds number
  - Curvature
  - Cross Section Shape



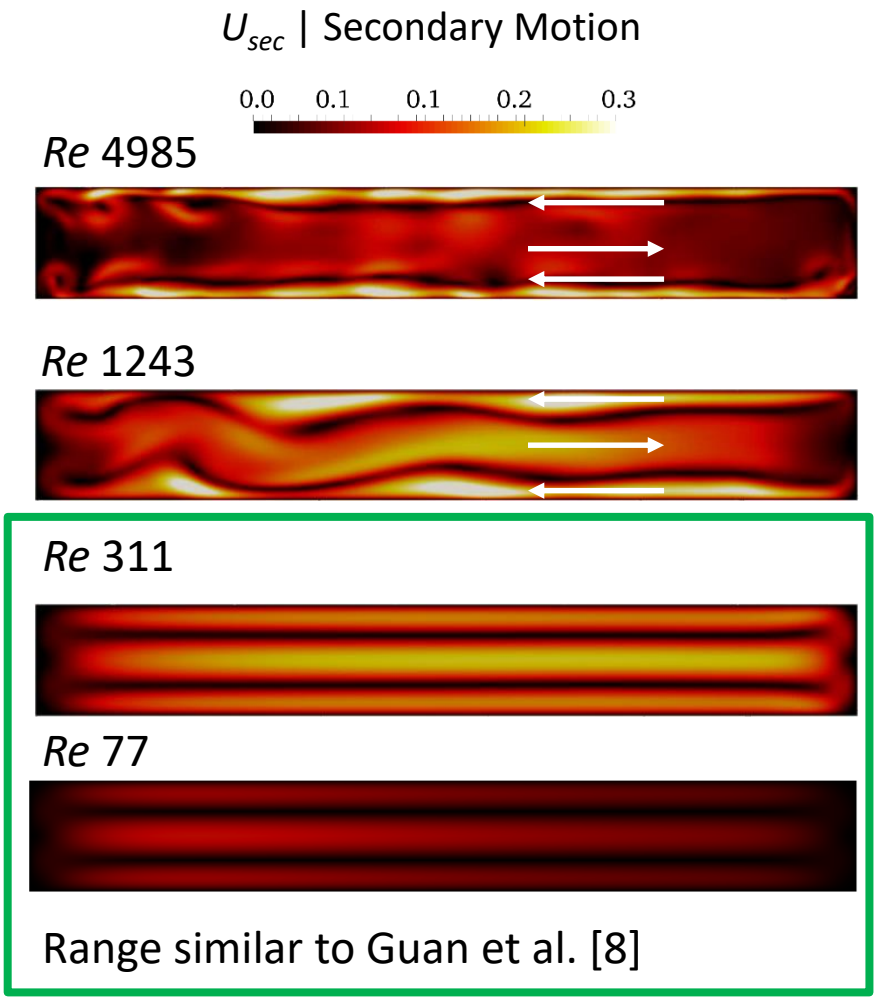
U_{sec} | Secondary Motion



[7] Ookawara, et al., Chem. Eng. Sci., 2006 | [8] Guan, et al., Sci Rep, 2013

Coiled Channel Separation | Stationary Flow

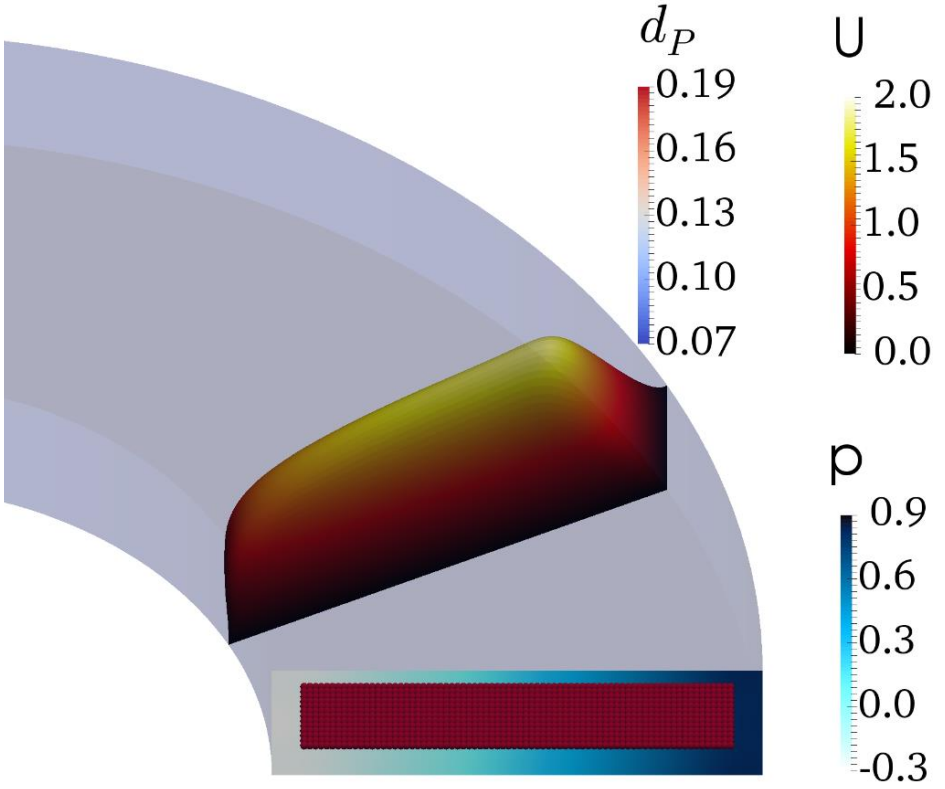
- Flow field in dependence on
  - Reynolds number
  - Curvature
  - Cross Section Shape
- Unresolved simulation approach [9], forces considered: **shear-induced lift**, Re-number dependend **drag,** spring-dashpot for wall **collisions**, **pressure gradient** (buoyancy)
- Answers from CFD-DEM Simulation
  - Particle size dependent accumulation
  - History of forces on particles



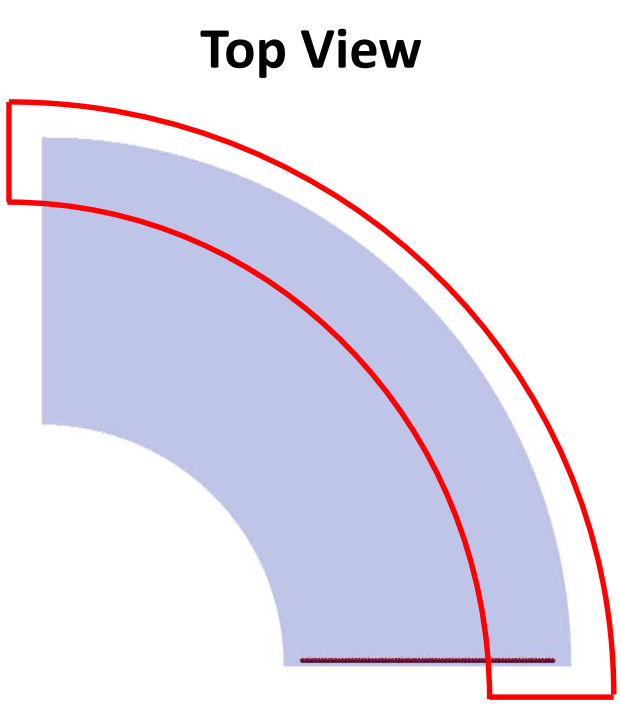
[9] Vigolo et al., PNAS, 111, 4770-4775, 2014

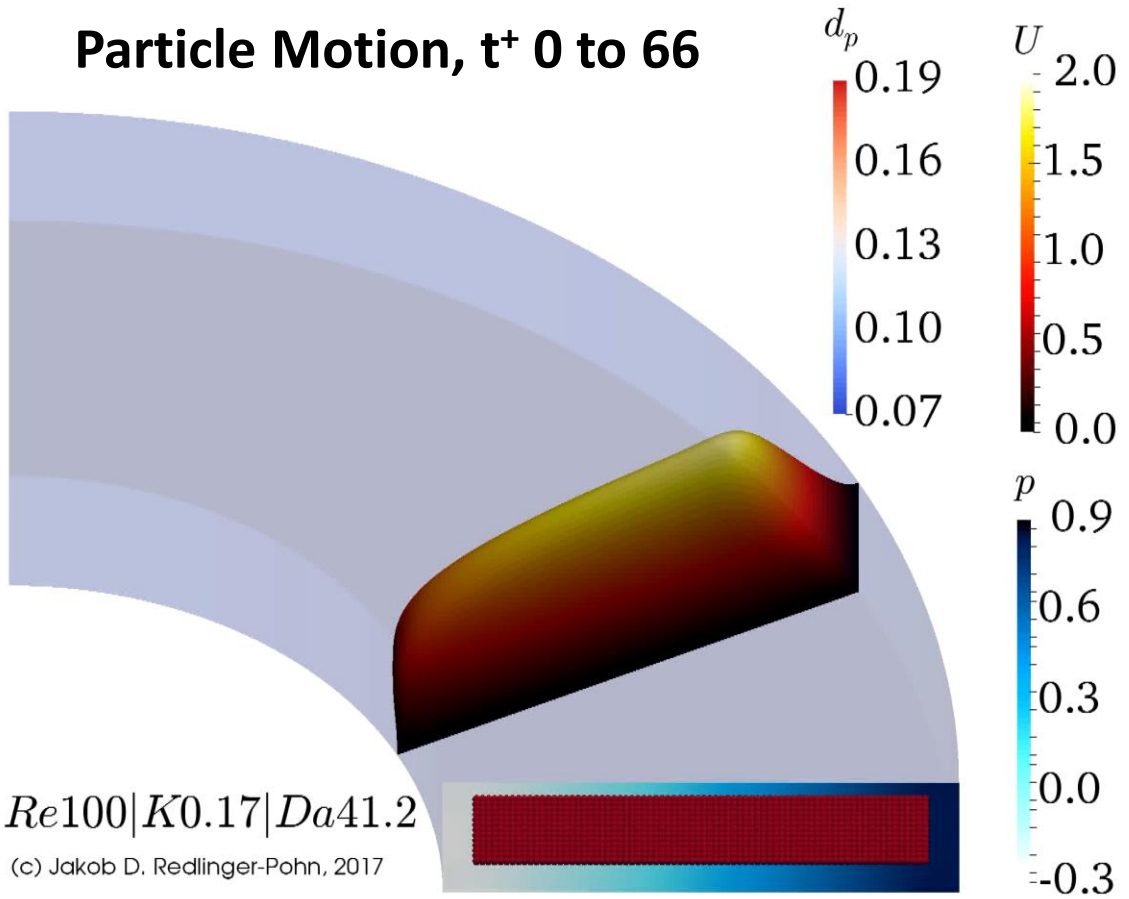
Coiled Channel Separation | Particle Motion

- CFD Simulation to provide fluid flow field (OpenFOAM®)
  - Channel aspect ratio 3.3
  - High curvature (computational limitations)
  - ***Re* 100 | κ0.17 |** *Da* 41.2
- CFD-DEM Simulation (software: CFDEM®coupling)
  - approx. 1000 particles per type
  - d_p / $H_{channel}$ 0.194 | 0.122 | 0.072
  - $\rho_{Particle}/\rho_{Fluid}$ 0.95
  - No particle-particle interactions



Coiled Channel Separation | Particle Motion



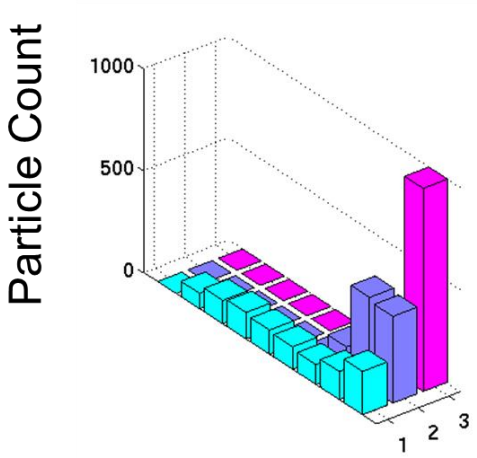


- Large particles accumulate at the outer bend

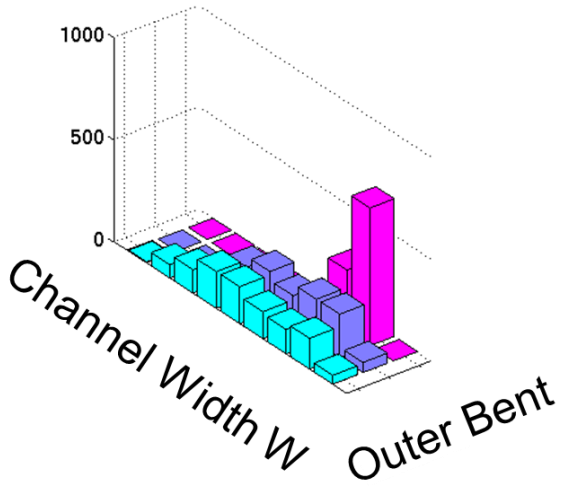
Coiled Channel Separation | Channel Shape

- Impact of the cross section shape on fractionation (at 360°, one full cicle)

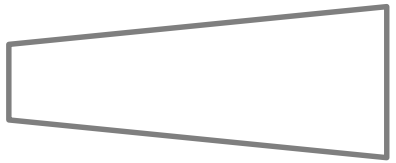
Aspect ratio 7.5

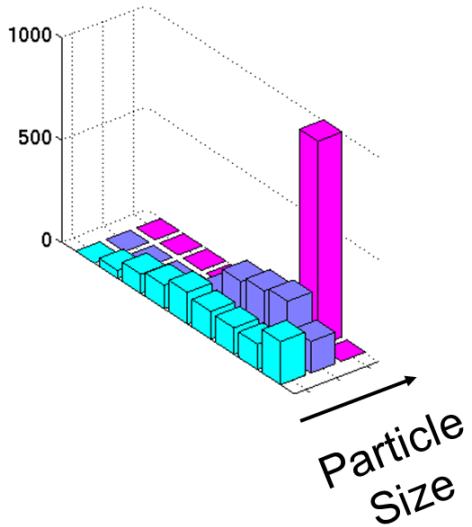


Aspect ratio 3.3



Trapezoidal

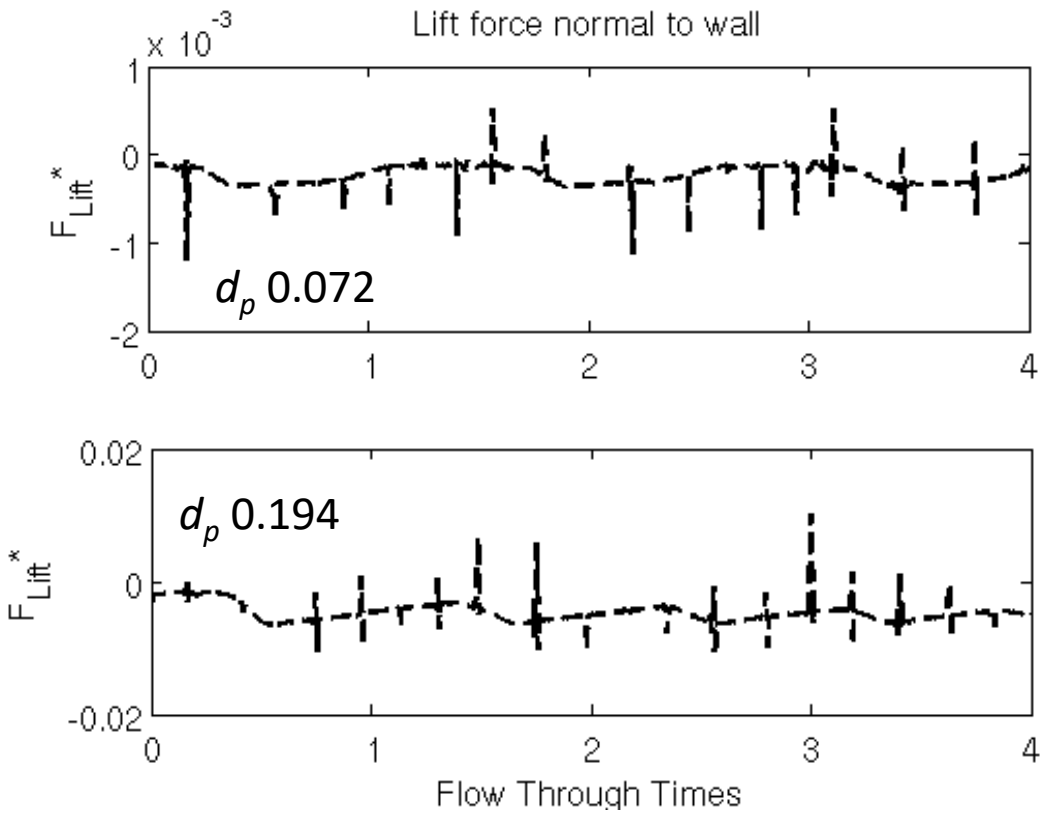




Coiled Channel Separation | Lift Force

- Lift force model: **shear-induced lift** as summarized by Loth and Dorgan [10]: **points away from wall**

- Strength of **normalized lift force** (relative to reference drag force) **increases with increasing d_p**.

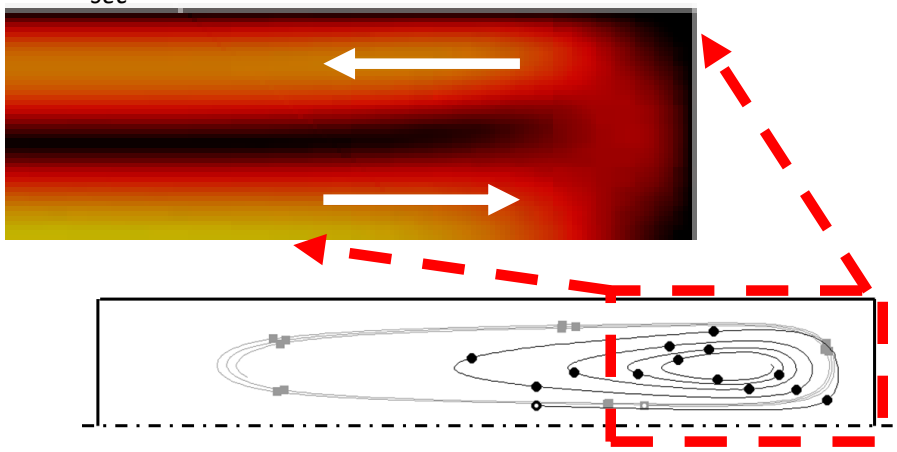


[10] E. Loth, A.J. Dorgan, Environ Fluid Mech, 2009

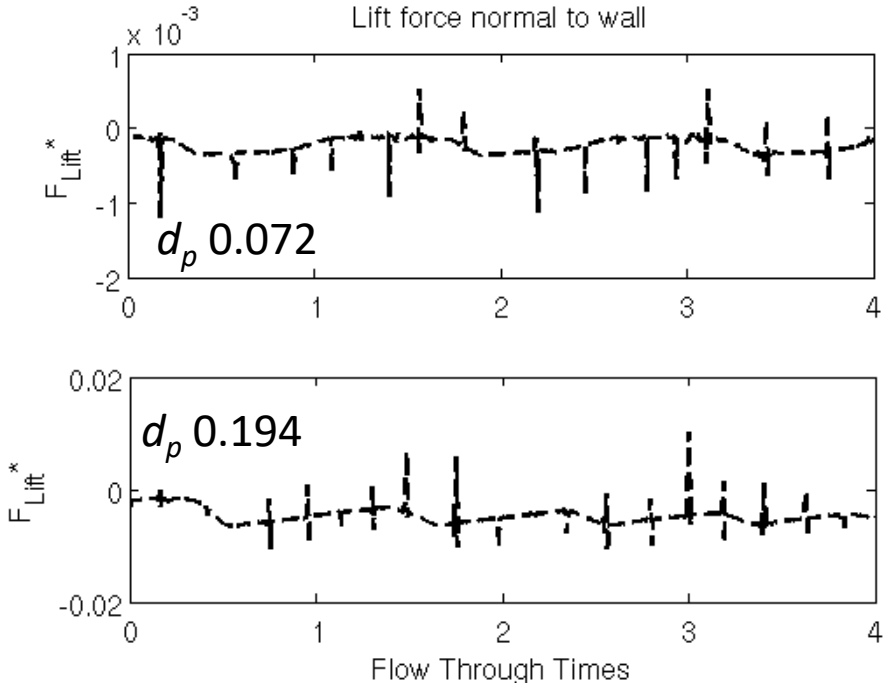
Coiled Channel Separation | Lift Force

- Particle motion in the channel cross section
  - d_p 0.072 : orbit with the secondary motion in the cross section
    Some depletion of particles near inner bend
  - d_p 0.194 : particles are **strongly deflected** from the walls
    Focusing near the outer bend

U_{sec} | Secondary Motion Close up

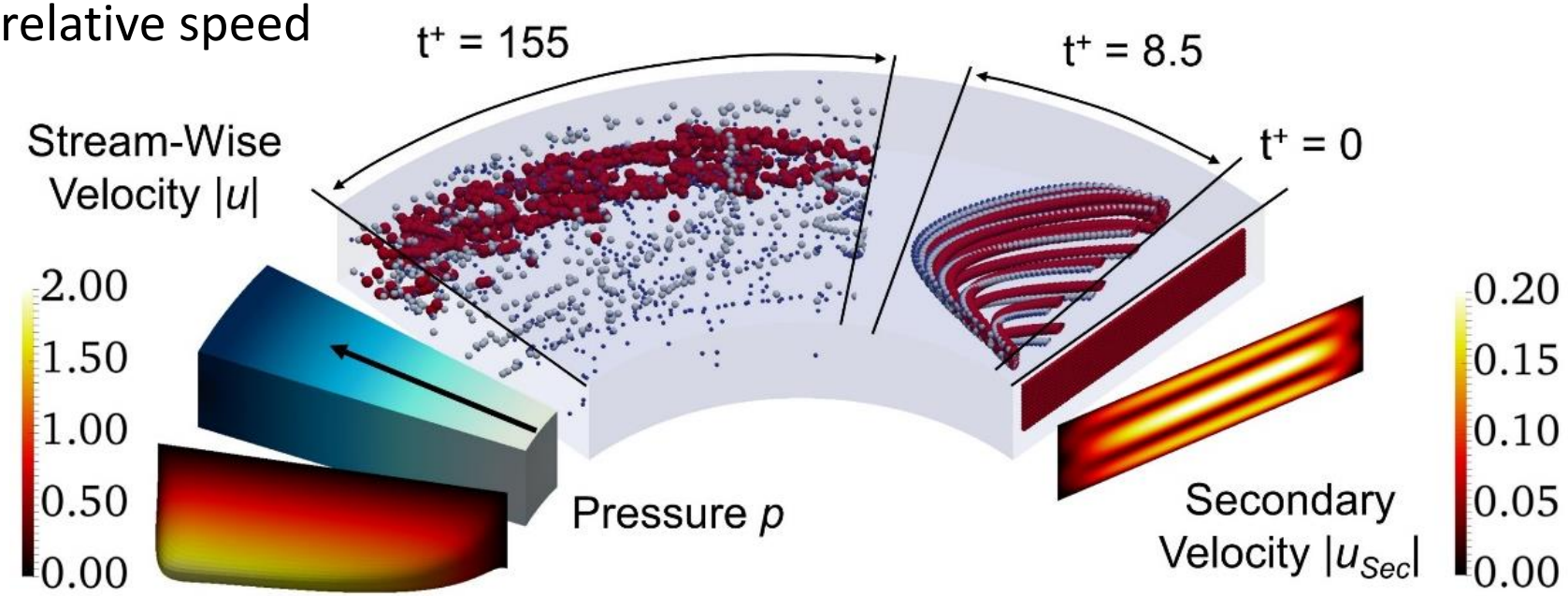


Grey, d_p 0.072 | Black, d_p 0.194



Coiled Channel Separation | Conclusion

- Separation of particles in non-circular coiled tubes is possible
- Lift force is found to cause **particle deflection from channel wall**
- Consequently, particles become trapped near the outer Dean vortex
- "**Trapping strength**" is controlled by lift force, and hence shear and relative speed



Particle Separation Phenomena in Coiled Channel