Enhanced heat transfer in small diameter packed beds

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Introduction: packed beds

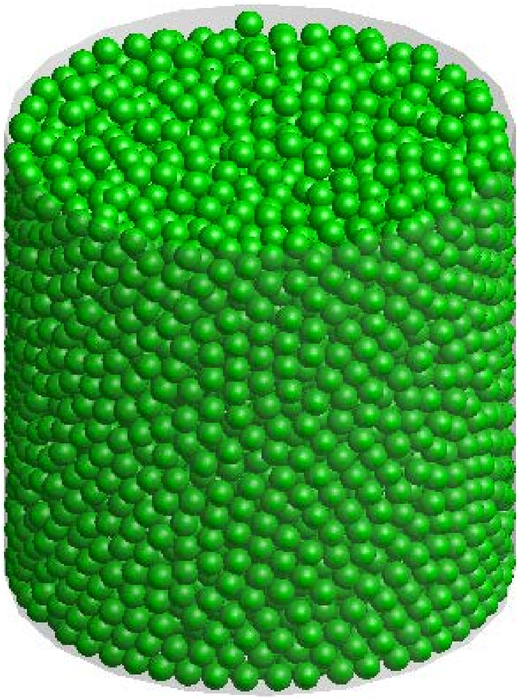
- Packed bed = “stacking of particles within a confinement”
- Stacking can be ordered (e.g. FCC, BCC) or random
- Different particle shape / size distribution possible

- Focus here: “small” random packed beds of spherical particles

- Applications:
  - Catalytic chemical (multi-tubular) reactors: e.g. Fischer-Tropsch process, the production of phthalic anhydride and terephthaldehyde and the epoxidation of ethylene oxide
  - Nuclear reactors: pebble bed reactor (VHTR)

Introduction: packed beds

- Advantages:
  - High specific surface area (+porous sphere)
  - Easy to construct and maintain
  - Option to refill 'online' (VHTR)
- Disadvantages:
  - Complex structure: heat/mass transfer?
  - Flow bypass near the wall: 'local ordening'
  - High pressure drop
  - Hot spots in the near wall zone

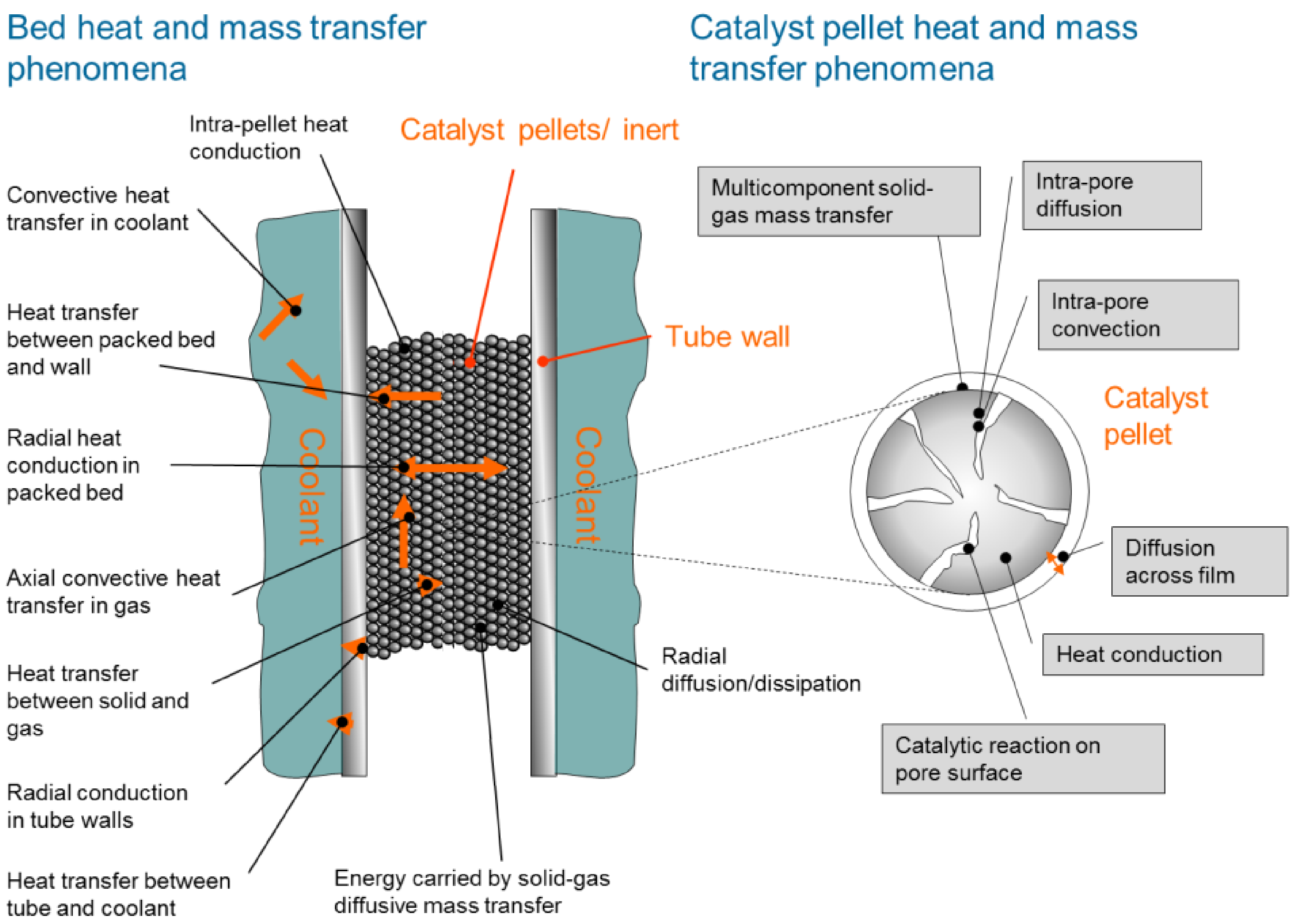


Packed bed thermo-hydraulics

- Complex interaction between different heat transfer modes:
  - Conduction: sphere-sphere, within the sphere
  - Convection: complex geometry, wakes, flow bypass, hot spots
  - Radiation: sphere to bed, bed to wall
  - Mass transfer: chemical reactions

- Different scales:
  - Inside the spheres
  - Inside the bed

Packed bed thermo-hydraulics



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- Different scales:
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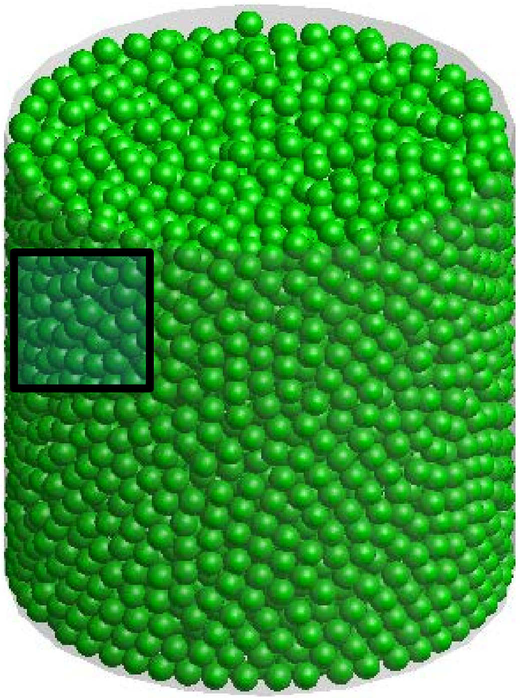
  - Inside the bed

- Difficult to model!
- Current approaches: porous media ↔ 3D CFD?

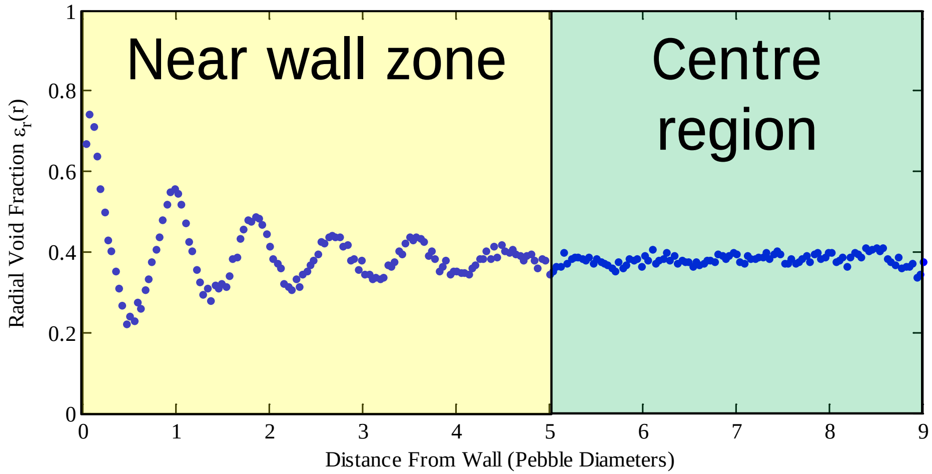
Porosity

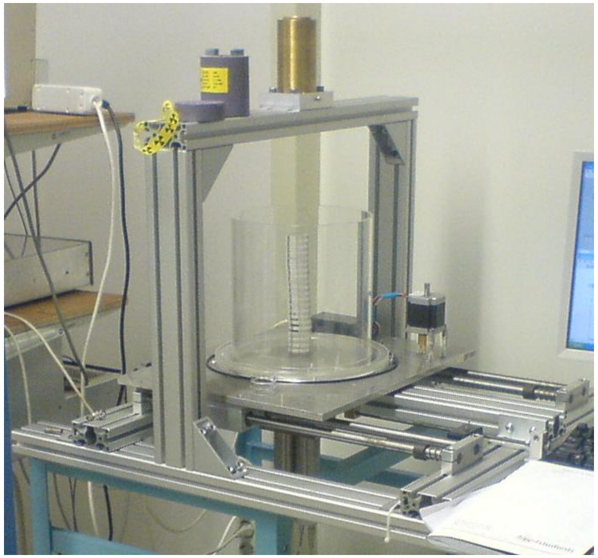
- Measure for the local amount of 'void'
- Near the wall: 'local ordening'
  - More open structure
  - Results in flow bypass, 'channeling'
- Strong impact on bed thermo-hydraulics
- Effect increases as bed becomes smaller
  - D_{bed} ~ 20-50 x D_{sphere}



Measuring porosity profiles?

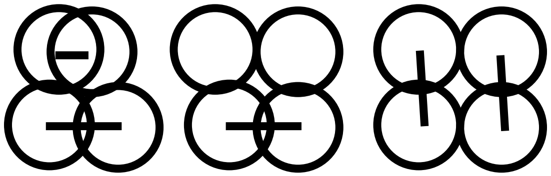
- Various techniques exist: gamma beam attenuation used @ DUT
- Provide radially averaged porosity data
- Can be modified to provide axial data



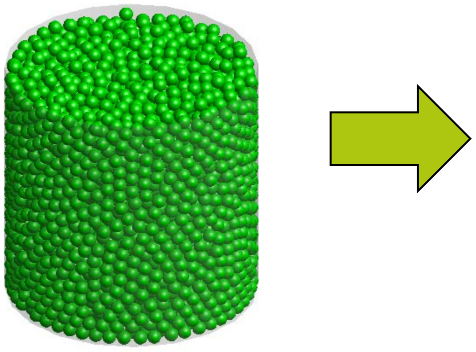


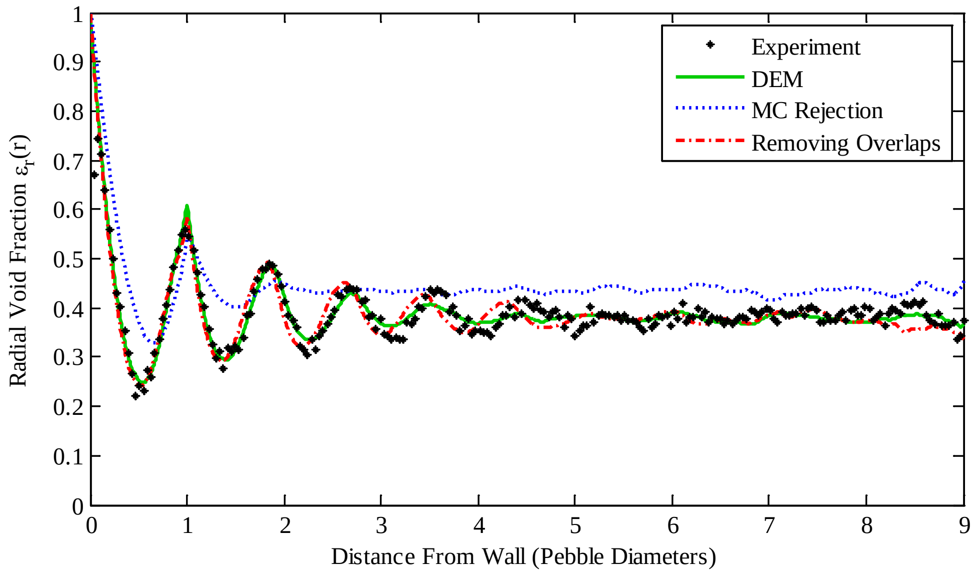
Simulating random beds?

- Generating a true random bed?
- Numerical models:
  - Monte Carlo rejection method
  - Discrete Element Method
  - Overlap removal method (in-house code, G. Auwerda)



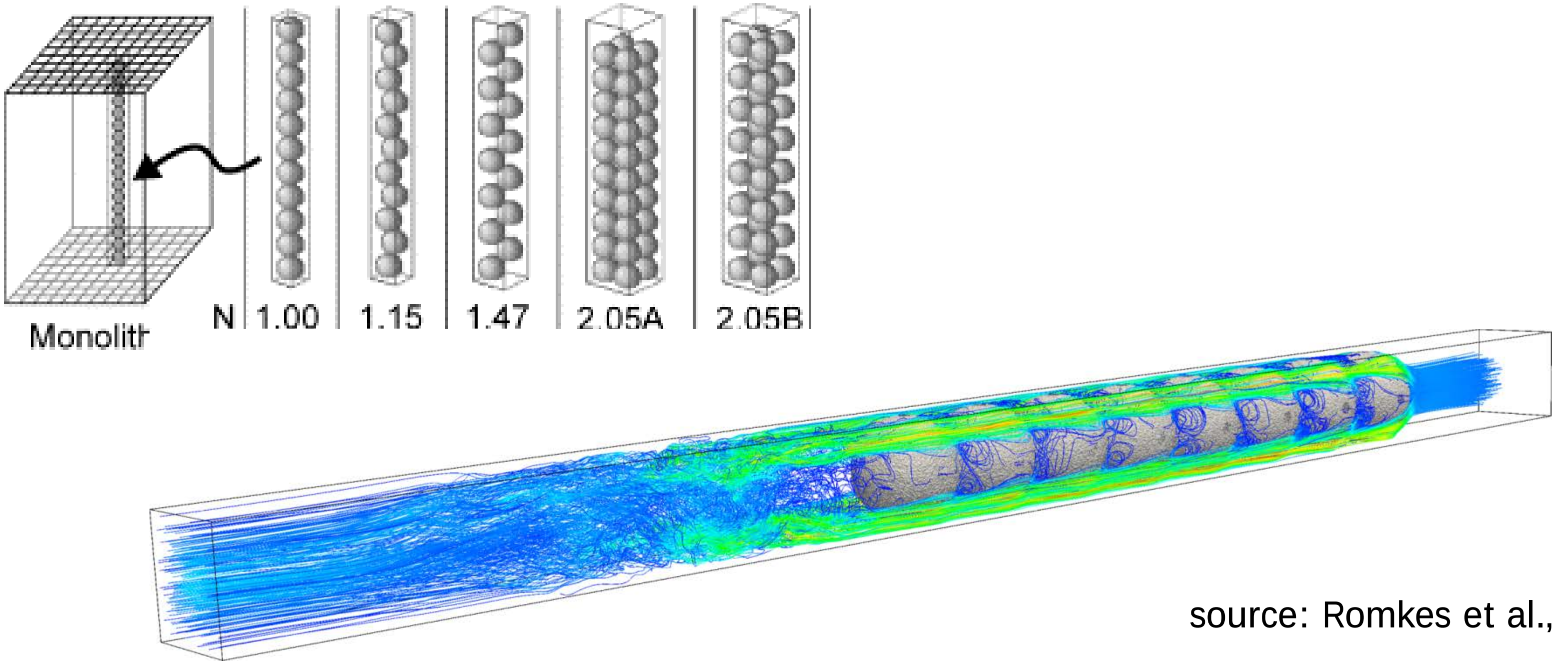
- Good agreement with data!





Simulating flow and heat transfer?

- Using both commercial and open-source CFD tools
- Fluidity (Imperial College London) and Openfoam
- Benchmark done for flow and heat transfer: CSP with N = 1



source: Romkes et al., 2003

Benchmarking the codes

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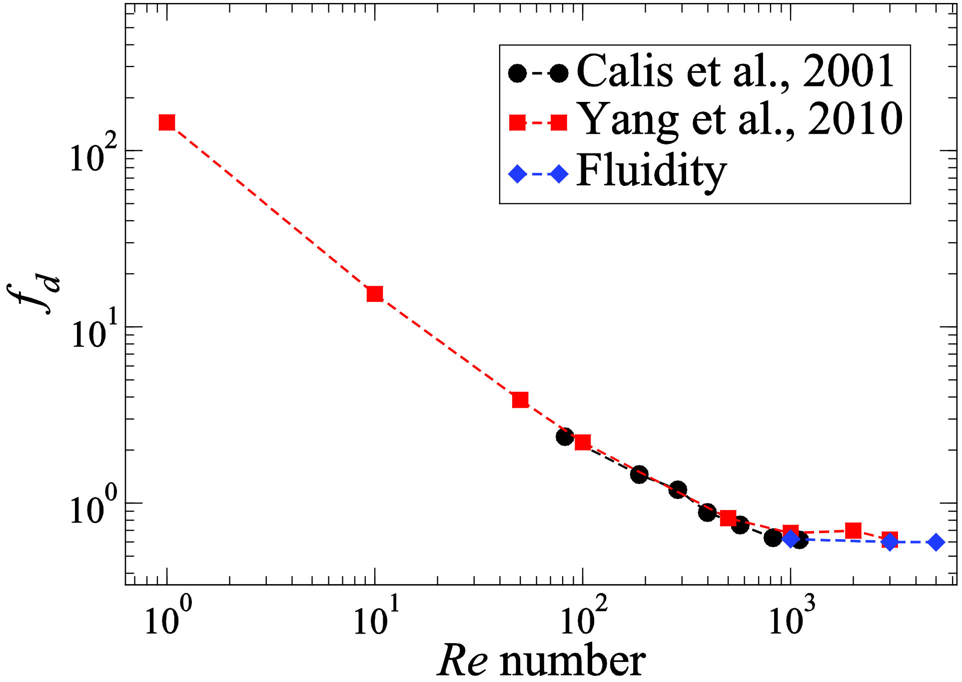
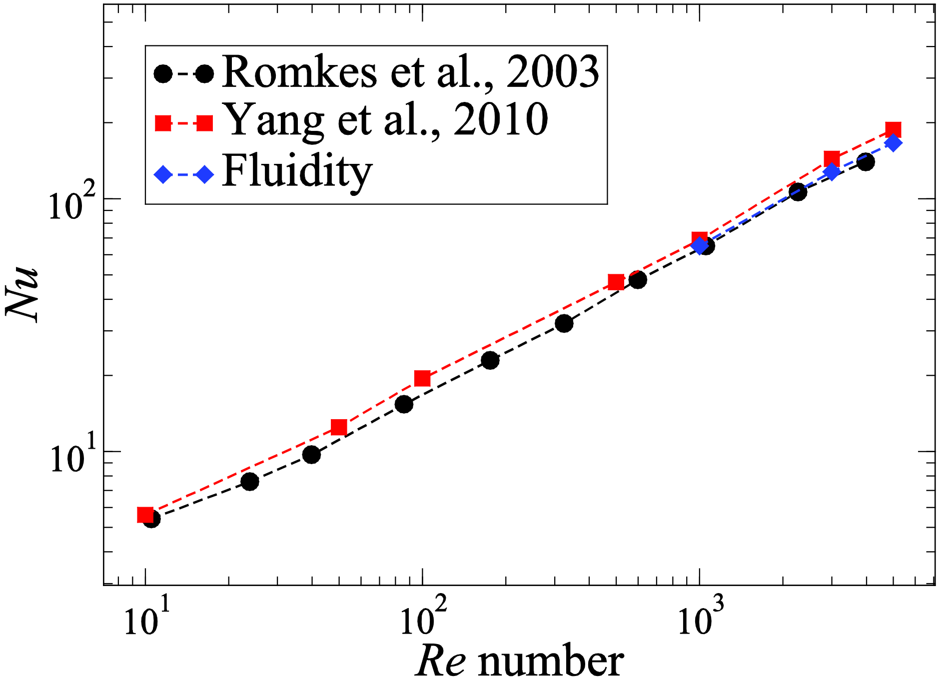
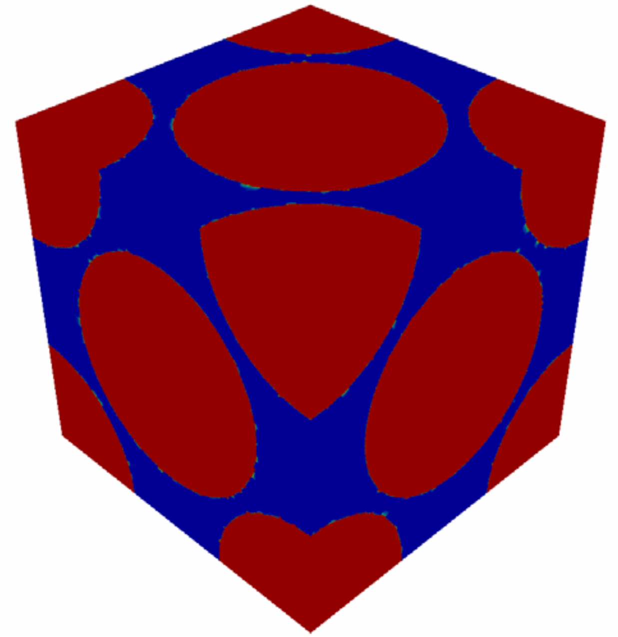
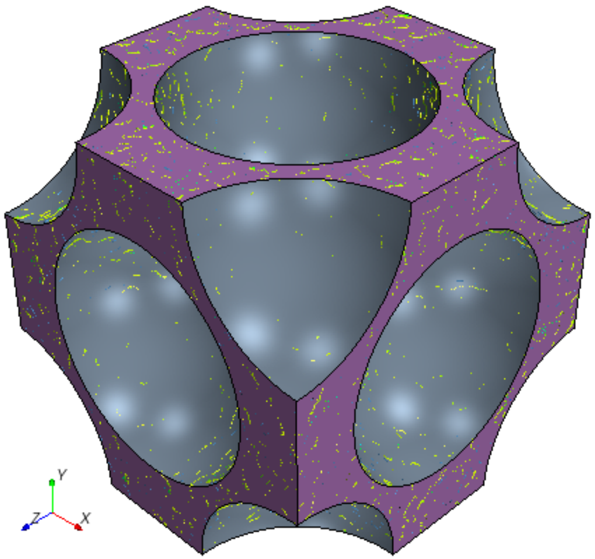




Benchmarking the codes

- Model inter-comparison (NRG:DNS, TUD:LES)
- Triple periodic domain with inter-pebble gaps
- Diagnostics: velocity field (domain mean and rms, plus probes)





Source: Shams et al. (NRG)

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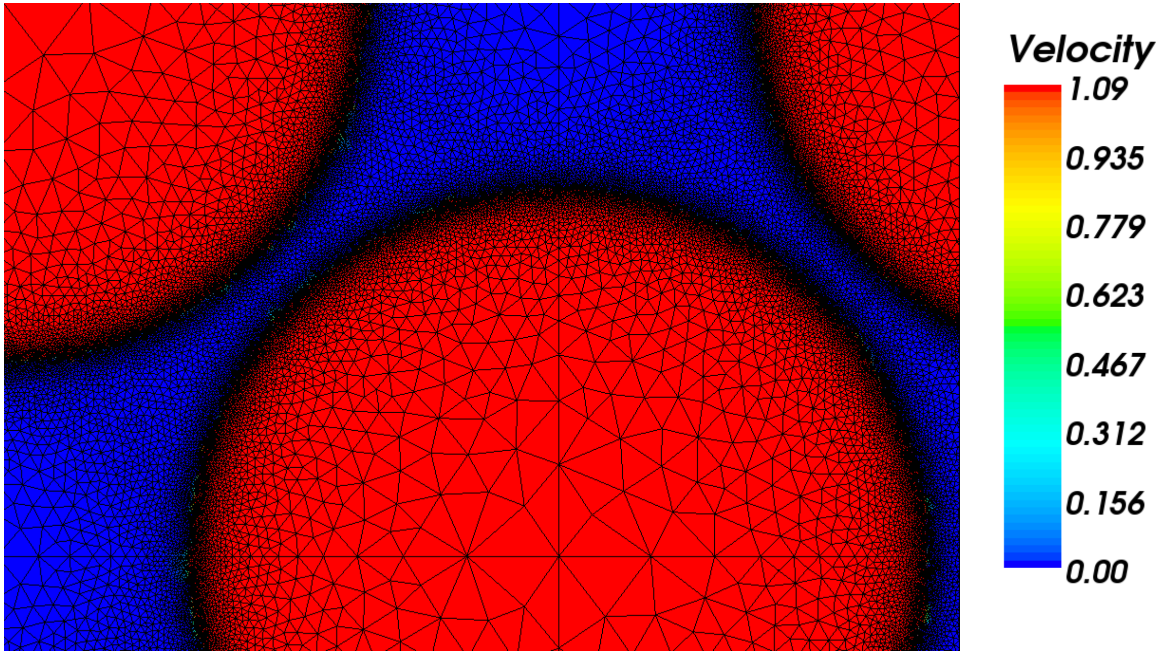
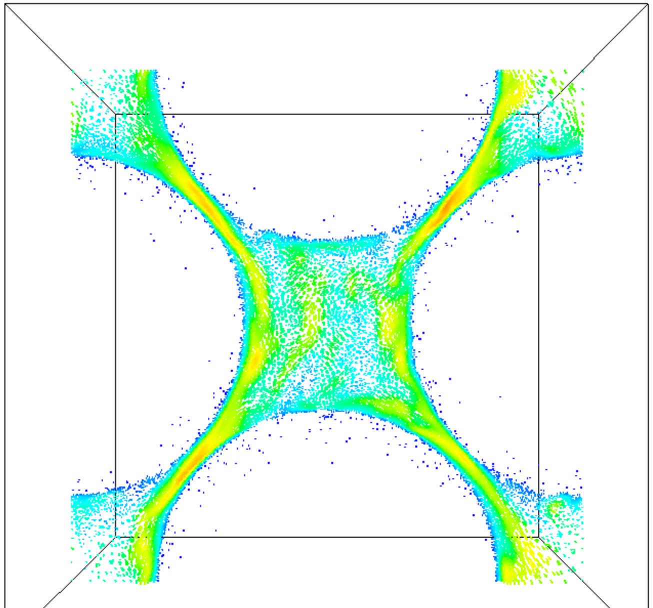
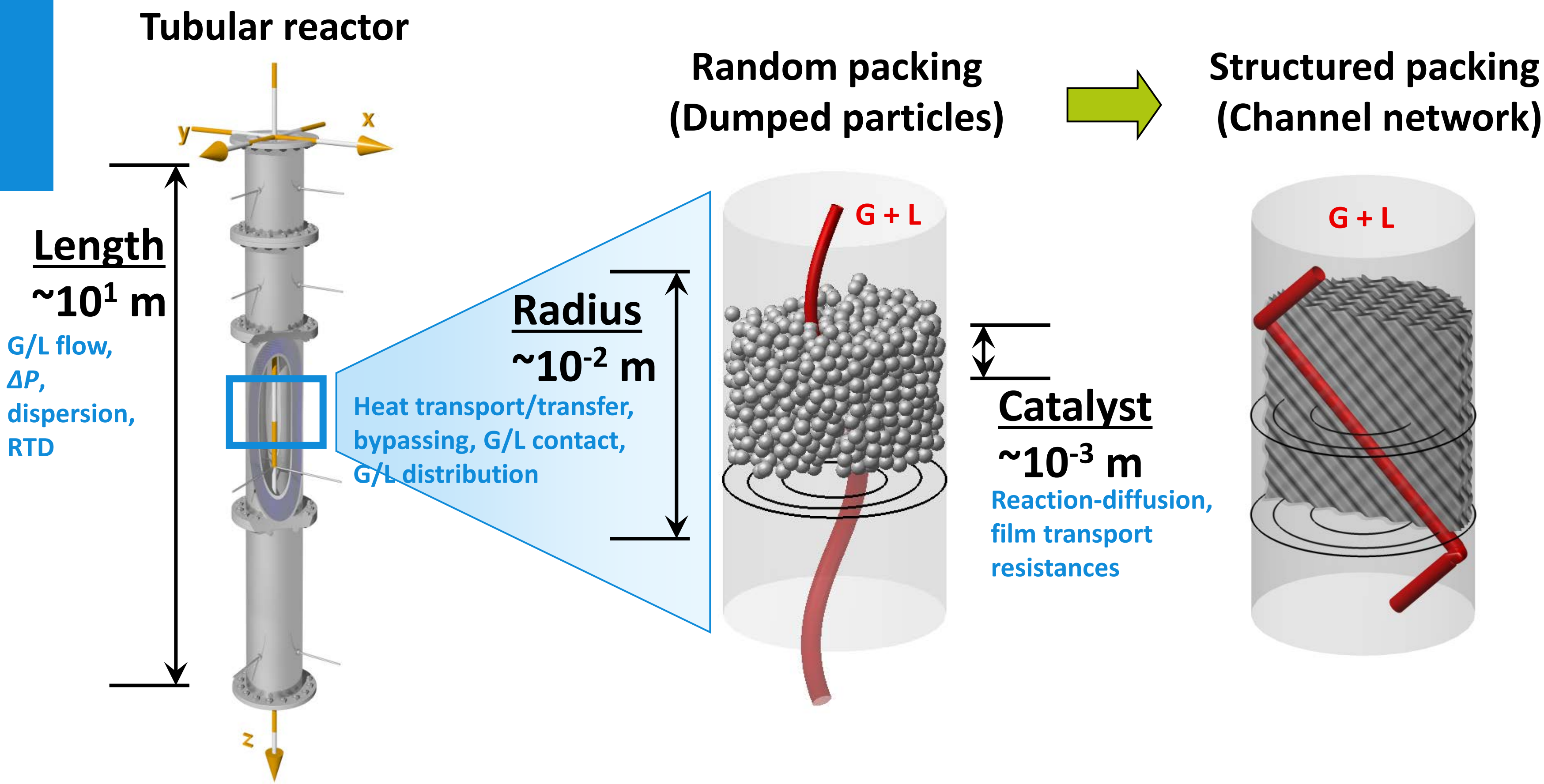




Source: Pavlidis et al. (DUT)

A Structured Tube for Gas-Liquid Reactions

D. Vervloet, F. Kapteijn, J. Nijenhuis, J.R. van Ommen

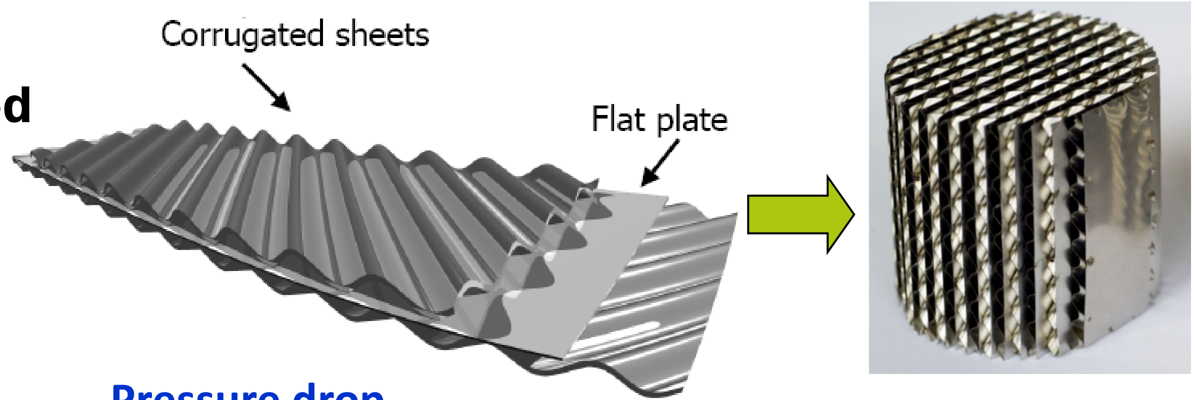


Different phenomena, at different length scales: complex interaction

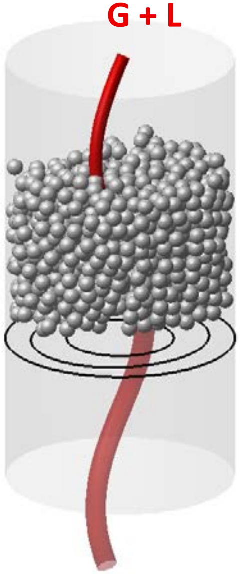
Objective: decouple phenomena → optimize performance

A Structured Tube for Gas-Liquid Reactions

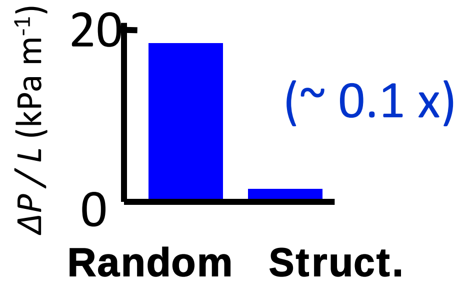
A randomly packed bed can be replaced by stacking corrugated and flat plates



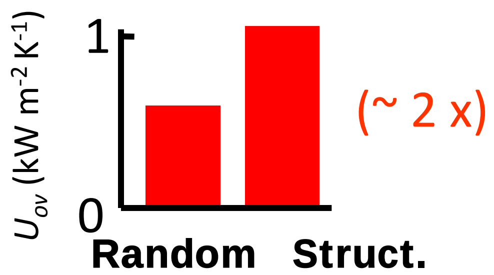
Random



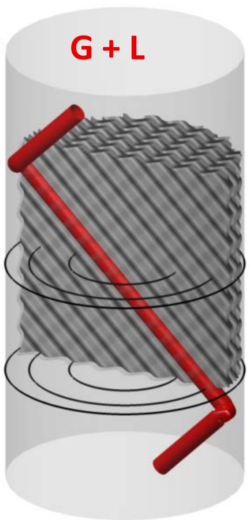
Pressure drop



Heat transfer → wall



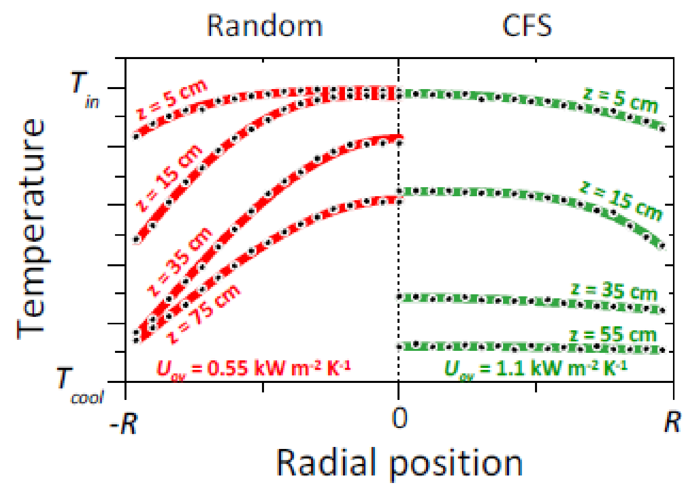
Structured



A Structured Tube for Gas-Liquid Reactions

Experimental results
(packed bed vs structured packing):

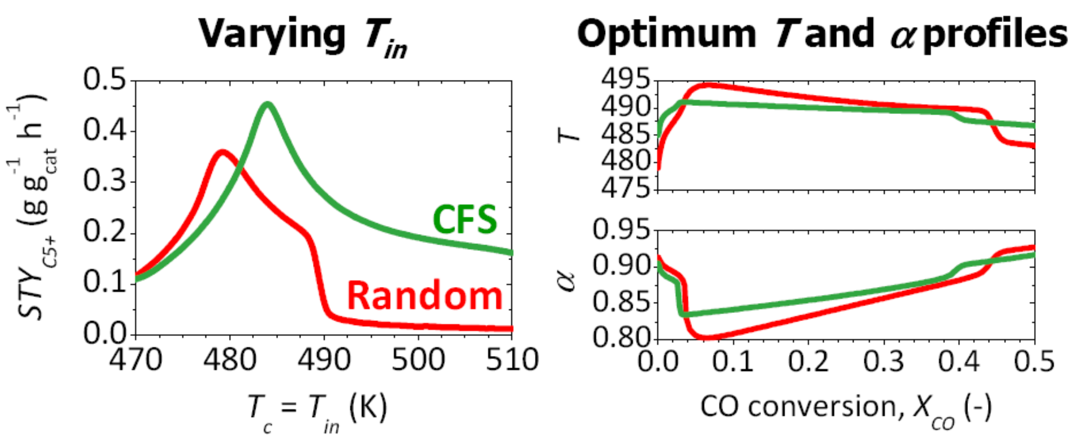
- Superior pressure drop
- Superior heat transfer
- Flatter temperature profiles
- Comparable mass transfer



Modelling of Fischer-Tropsch reactor (1-D) based on these parameters:

- Much higher selecitivity for C5+!

P_{syngas} = 30 bar, syngas ratio = 1.7, d_p = 1.5 mm, d_t = 5.0 cm



Outlook: further improvements?

- New proposal to STW-OTP: looking for partners (input)!
- Goal: further optimise small packed random beds with 'smarter' walls and particles for single phase fluids
- Smart walls: reduce porosity variation but with good heat transfer
  - →dimples, grooves, combinations?
- Smart particles: use varying particle sizes or non spherical shapes to dampen porosity oscillations
- Method: combined experimental and numerical (2 PhD): experiments will be used to validate 3D CFD (OpenFoam)

Proposed project outline

Experimental section

- Design experimental HT setup
- Validation experiments (tube flow)
- First heat transfer test cases (groove and a dimple case)
- Experimental parameter study: heat transfer and pressure drop, porosity profiles...

Numerical section

- Set up Openfoam code (RANS, LES)
- Code benchmarking
- Code validation: test case data (groove and dimple)
- Optimization (e.g. surrogate methods) using 'Design of Experiments'

Design guidelines for optimized systems

Project framework

- Project team: 2 sections of Delft University of Technology
  - ‘Product and Process Engineering’ (PPE): J. R. van Ommen
  - ‘Physics of Nuclear reactors’ (PNR): C. T’Joen, M. Rohde

- Large expertise available:
  - Large experimental facilities + computational cluster
  - Expertise in heat transfer and fluid flow experiments
  - Measurement setup for local porosity profiles
  - CFD + experimental benchmark data for packed beds (PNR, PPE)
  - VHTR projects on neutronics (PNR, EU project)
  - Structured tube project for Fischer Tropsch (PPE)

Conclusions

- Packed bed thermo-hydraulics are very complex due to the interaction of different heat/mass transfer mechanisms, on different scales and the complex random geometry.
- An overview was presented of current activities at DUT related to packed bed thermo-hydraulics (experimental and computational)
- A new STW research proposal is being drafted by PNR/PPE (DUT), goal: <u>to further optimise small packed random beds with 'smarter' walls and particles for single phase fluids, providing new design guidelines</u>

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