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CFD simulations of large-scale reorganizations in PWR rod bundle flows

F. Muller,
A. Burbeau, B.J. Gréa, P. Sagaut

5^{th} International Conference on Turbulence and Interactions

June 28^{th}, 2018

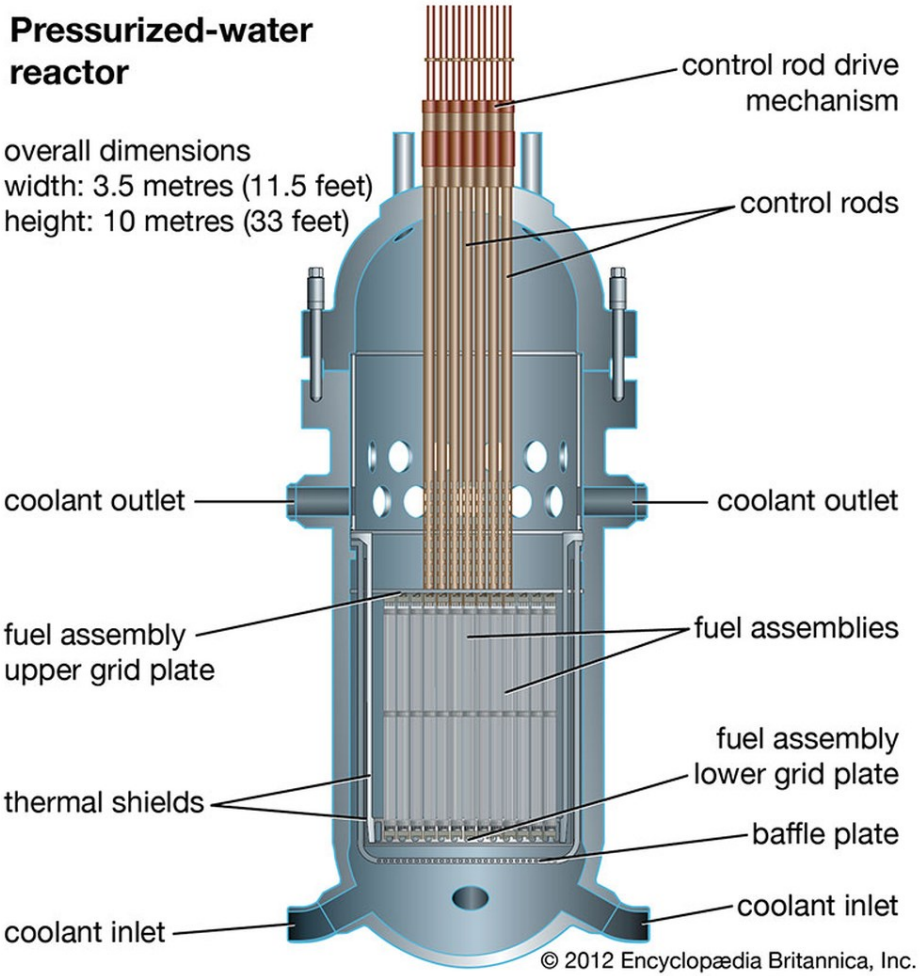
Summary

1. PWR core thermohydraulics
2. Cross-flow reorganizations in experiments and simulations
3. 2D Free decay simulations

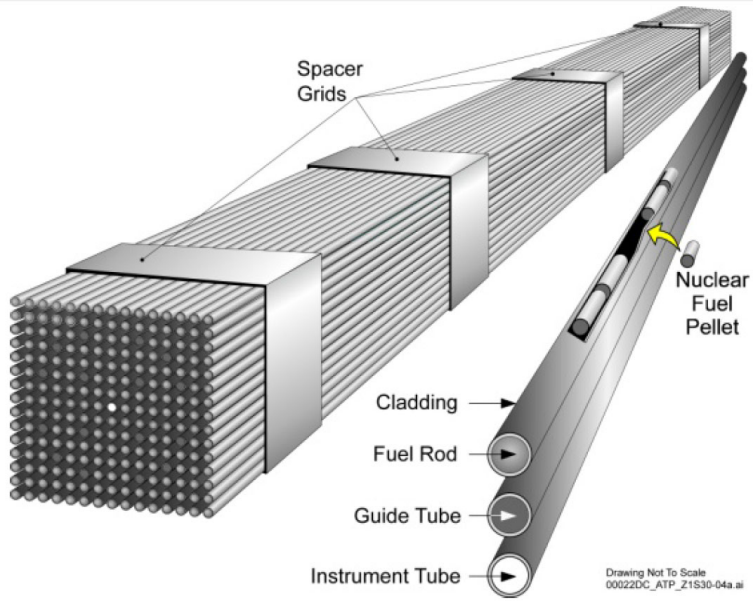
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PWR rod bundles

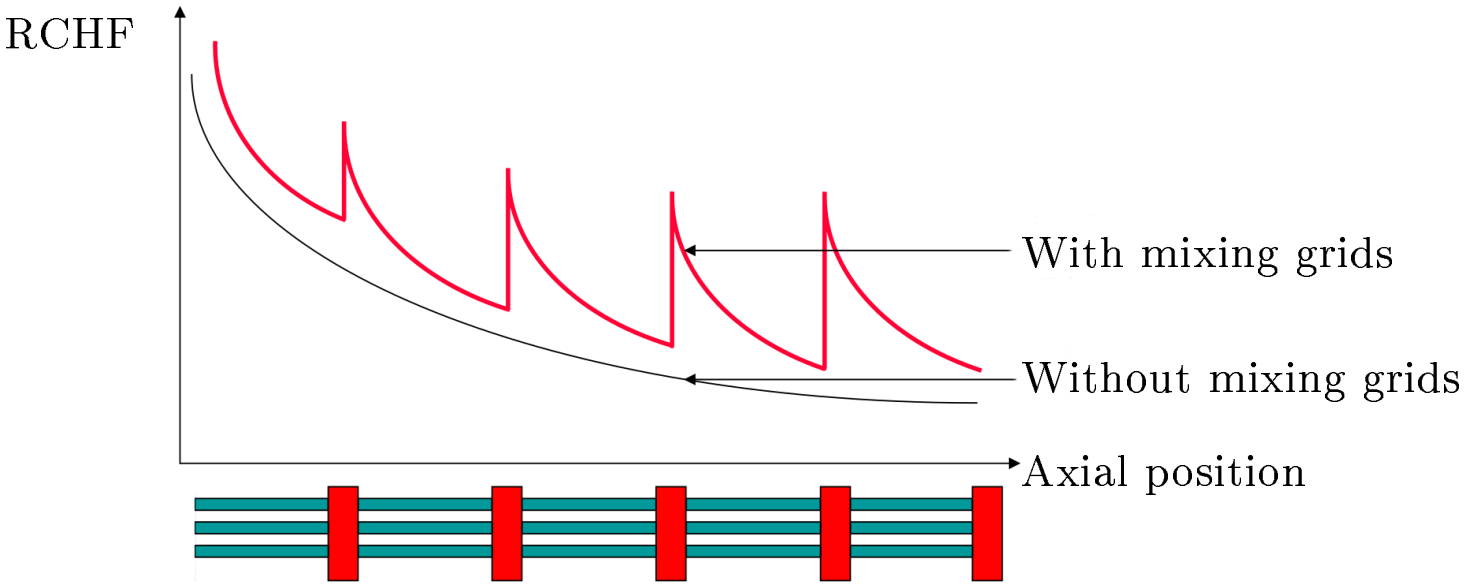


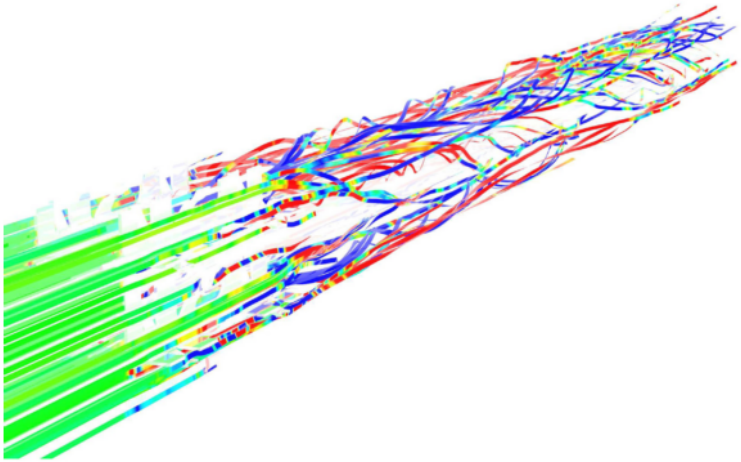
Sketch of a typical PWR pressure vessel.



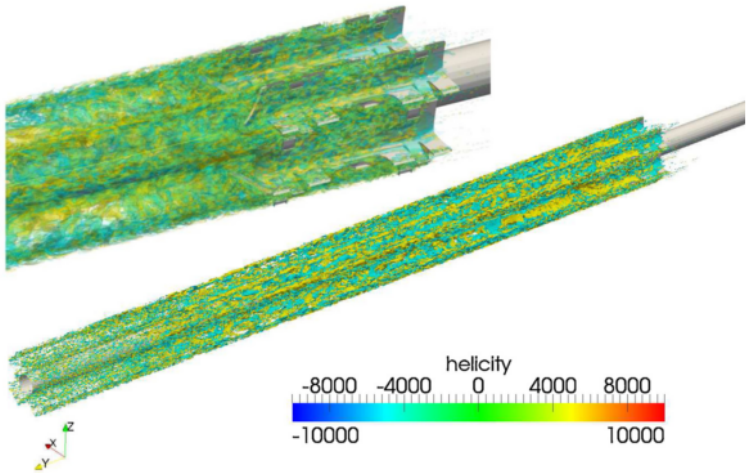
Sketch of a rod bundle with regularly spaced mixing grids.

Impact of the mixing grids on the RCHF





Velocity streamlines in the wake of a mixing grid.

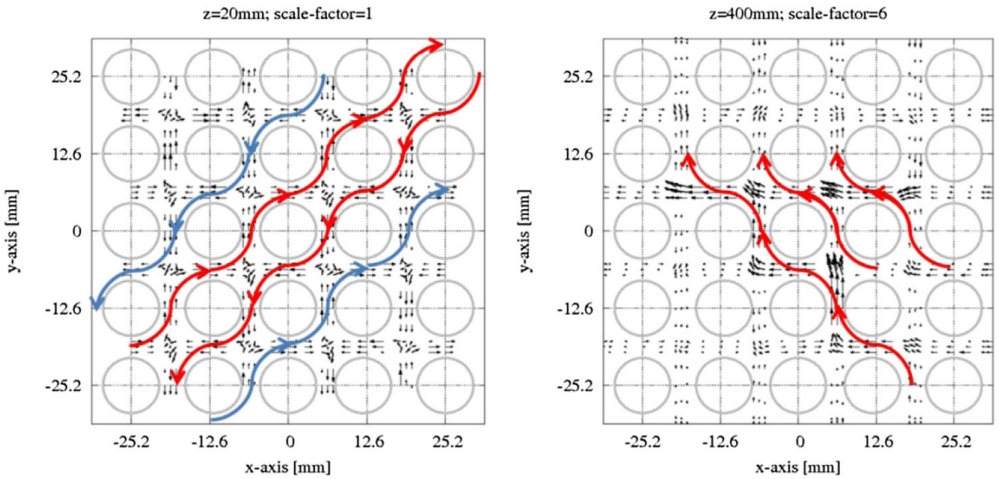


Helicity in the wake of a mixing grid.

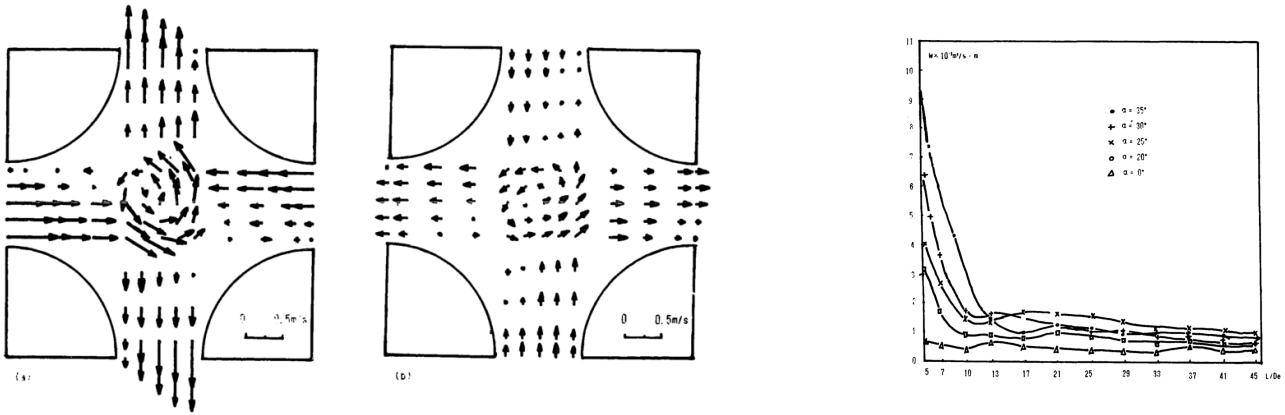
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Cross-flow reorganization phenomenon



Transverse flow structures observed in the AGATE experiment.



"Velocity inversion" of the cross-flow (left) and evolution of the mixing rate (right) as described by Shen et al. (An investigation of crossflow mixing effect caused by grid spacer with mixing blades in a rod bundle. Nucl. Eng. Des. 1991)

Cross-flow reorganization phenomenon

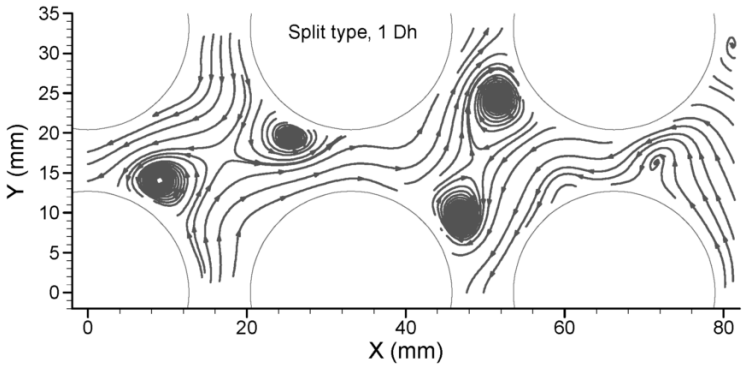
- Cross-flow reorganizations observed regularly in experiments but no satisfatory physical explanation (AGATE[a], MATHiS-H[b], NESTOR[c]).
- Very detrimental to PWR rod bundle thermal mixing efficiency.
- Consensus currently emerging on the necessity to understand and reproduce this phenomenon.

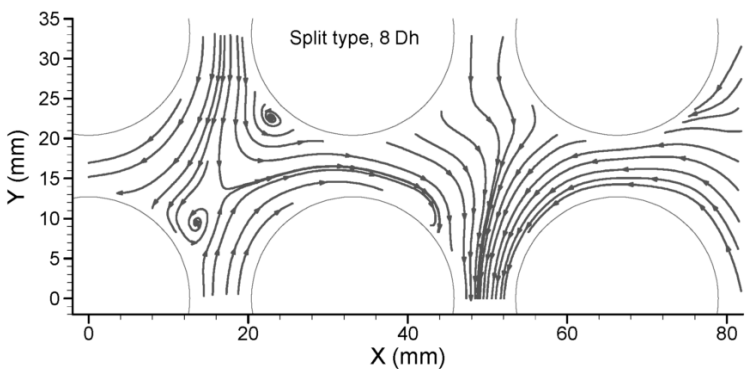
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[a] Bieder, Falk, and Fauchet, "LES analysis of the flow in a simplified PWR assembly with mixing grid".

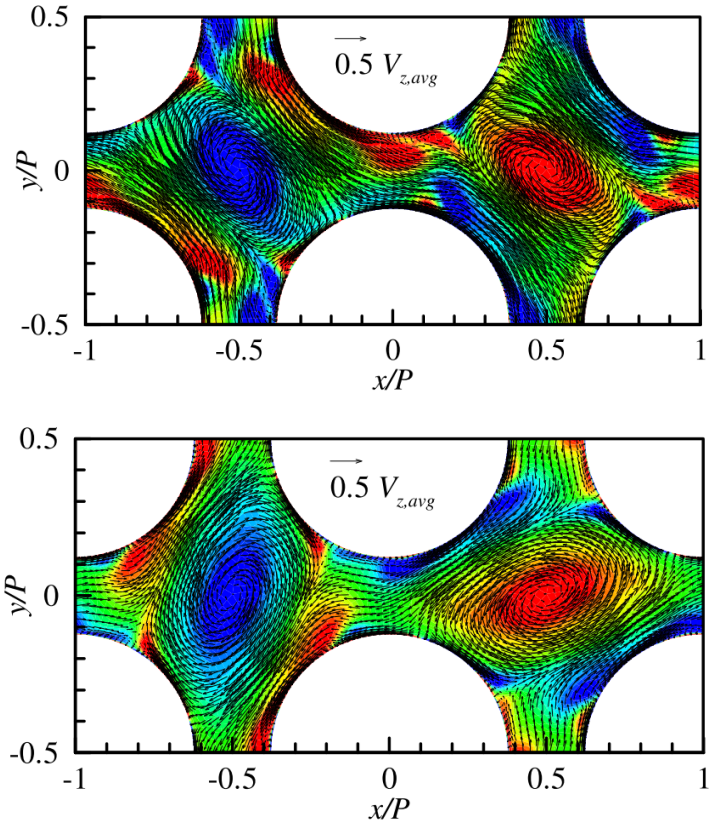
[b] Chang et al., "Phenomenological investigations on the turbulent flow structures in a rod bundle array with mixing devices".

[c] Kang and Hassan, "Computational fluid dynamics (CFD) round robin benchmark for a pressurized water reactor (PWR) rod bundle".

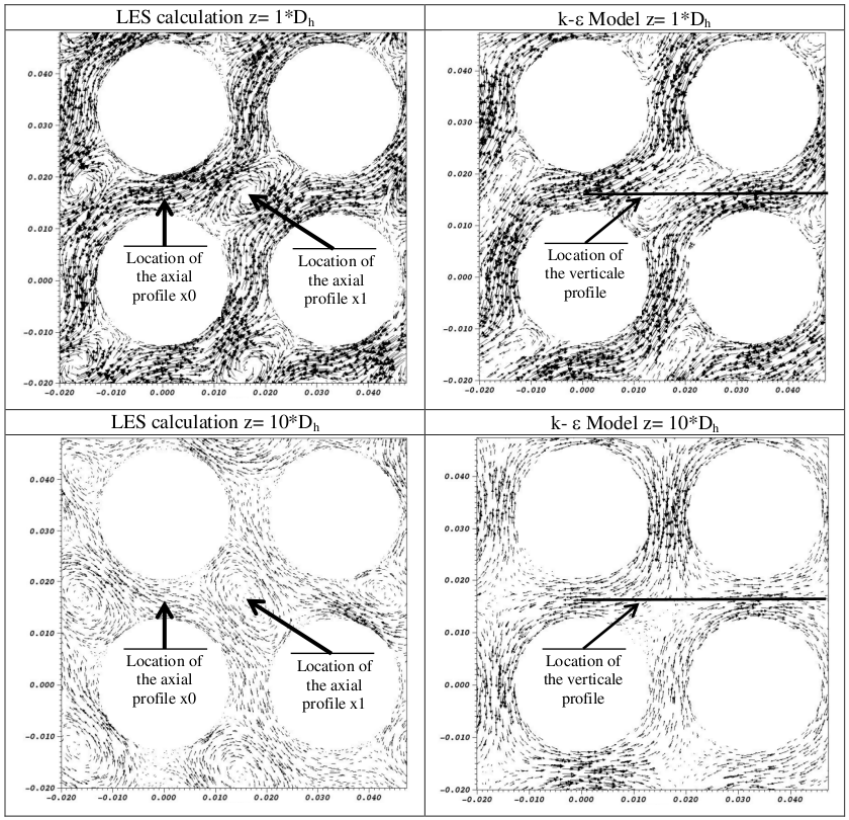




Reorganization phenomena in CFD simulations



Velocity inversion in SST $k-\omega$ simulations by Holloway et al.[a]

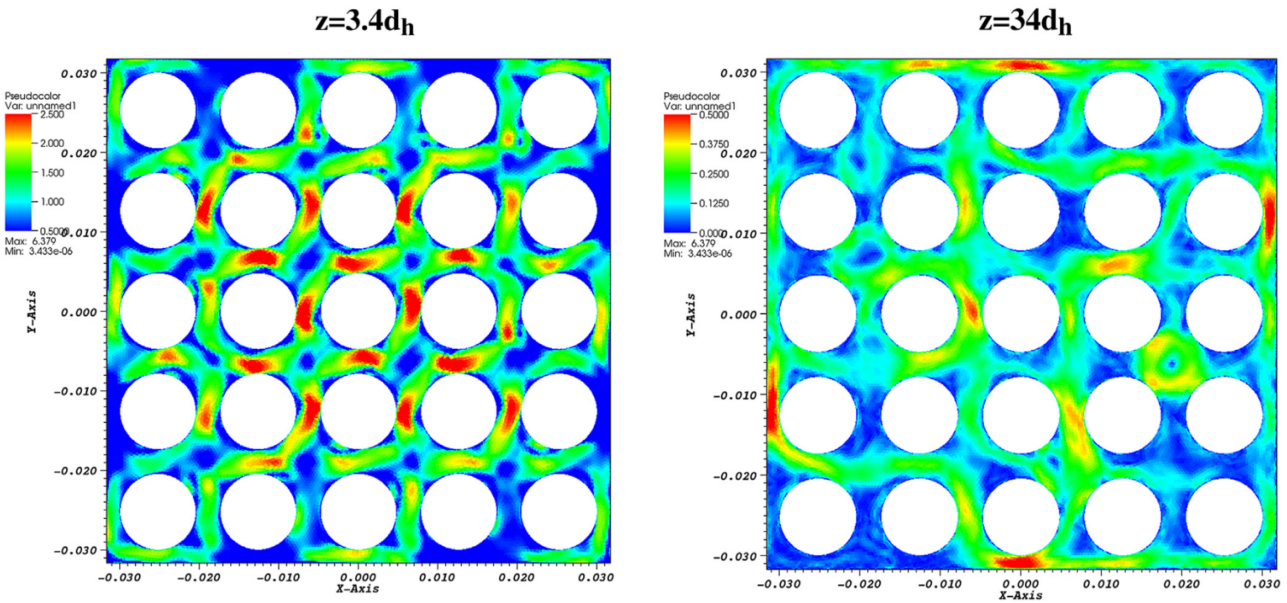


Cross-flow reorganization in LES simulations by Bieder et al.[a]

[a] Holloway, Beasley, and Conner, "Investigation of swirling flow in rod bundle subchannels using computational fluid dynamics".

[a] Bieder, "Analysis of the flow down-and upwind of split type mixing vanes".

Reorganization phenomena in CFD simulations



A phenomenon difficult to reproduce numerically

- Phenomenon very dependant on turbulent fluctuations
  $\Longrightarrow$ RANS-based models inadequate.
- Turbulence model needs to include anisotropic Reynolds stresses.
- Phenomenon can occur at any axial location downstream the grid
  $\Longrightarrow$ Large computing costs due to the meshing requirements.

Summary

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2D Frozen turbulence approach

Quasi-2D flow

- Axial velocity one order of magnitude $>$ cross-flow components.
- Very little variations of the axial component along the transverse plane.
- Long-lived coherent 2D structures (vortices) with a tendancy to merge $\Longrightarrow$ behaviour comparable to quasi-2D flows: atmospheric/oceanic layers, soap film experiments.

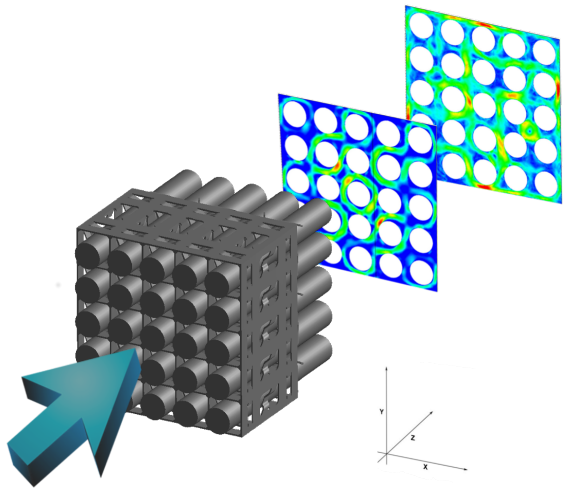
Goal of our research

- Possible to provide a physical explanation to rod bundle cross-flow reorganizations using 2D fluid mechanics?
- What are the critical physical parameters?
- How could a turbulence model be more finely tuned for rod bundle flow simulations?

Link with 2D statistical fluid mechanics

Hypotheses

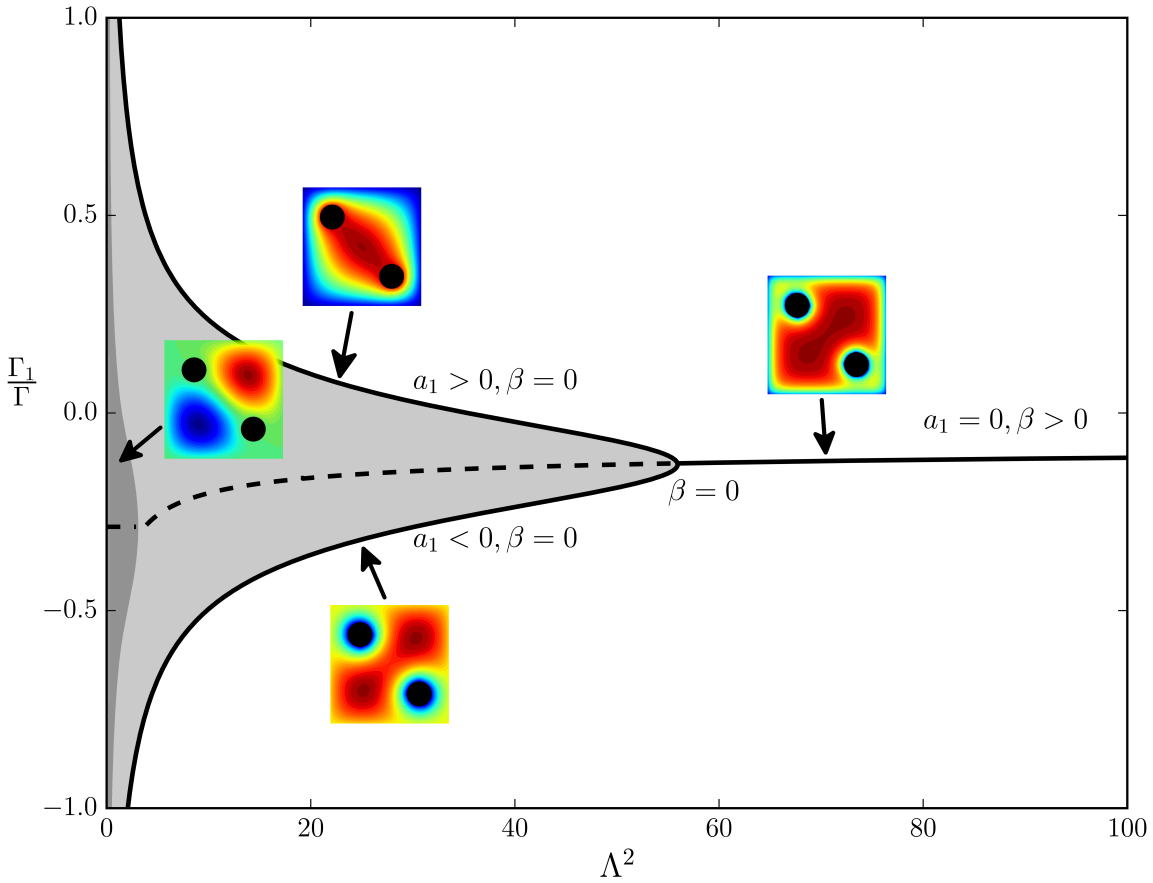
- Separation of the 3D velocity field into:
  $\mathbf{u} = \overline{u_z}\mathbf{z} + \overline{\mathbf{u_{x,y}}}(x,y,z) + \mathbf{u'}(x,y,z,t)$
  $\rightarrow$ mean axial velocity $\overline{u_z}$ almost uniform in the fluid bulk.
  $\rightarrow$ 2D flow field $\overline{\mathbf{u_{x,y}}}(x,y,z)$ convected through the Taylor "frozen turbulence" hypothesis as $\overline{\mathbf{u_{x,y}}}(x,y,\overline{u_z}t)$.
  $\rightarrow$ 3D turbulent fluctuations $\mathbf{u'}(x,y,z,t)$.
- Limited dissipation outside of boundary layers ($R_e = 1e^5$).



2D statistical fluid mechanics study

- Identification of stable 2D flows in domains with obstacles based on geometry and energy, circulation.
- Multi-constrained optimization problem.

Bifurcation diagram from statistical fluid mechanics



Bifurcation diagram showing the stable flows in a square with 2 obstacles, depending on the energy, circulation and circulation around the obstacles.

2D freely decaying simulations

Validation of the statistical theory through 2D CFD simulations

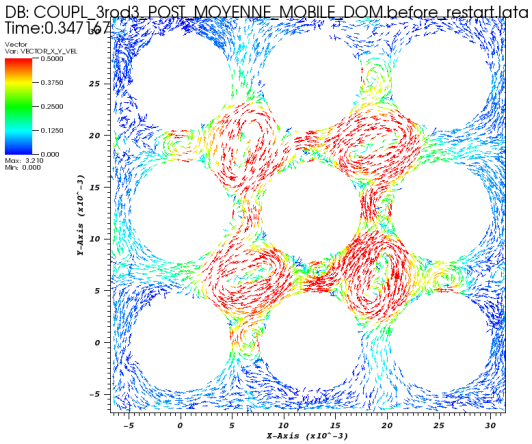
- Previous work[a] established that 2D simulations could recover as a final state the stable flow predicted by the statistical theory.
- Initial flows designed to induce a mixing phase but with precise integral quantities (energy, circulation).
- Cases of the square, disk, and square with 2 obstacles treated.

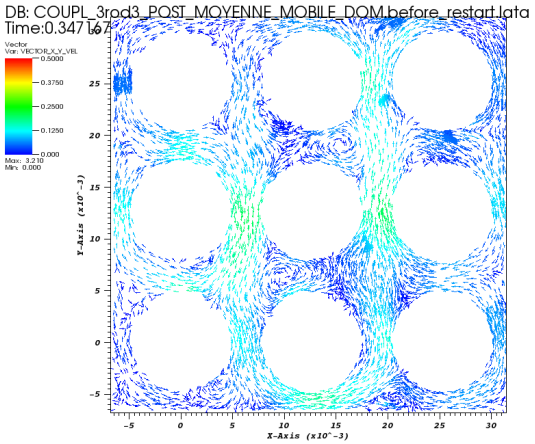
[a] Clercx, Maassen, and Van Heijst, "Spontaneous spin-up during the decay of 2D turbulence in a square container with rigid boundaries".

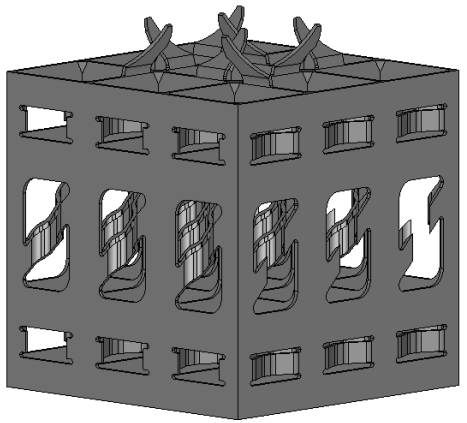
Excerpt shown here

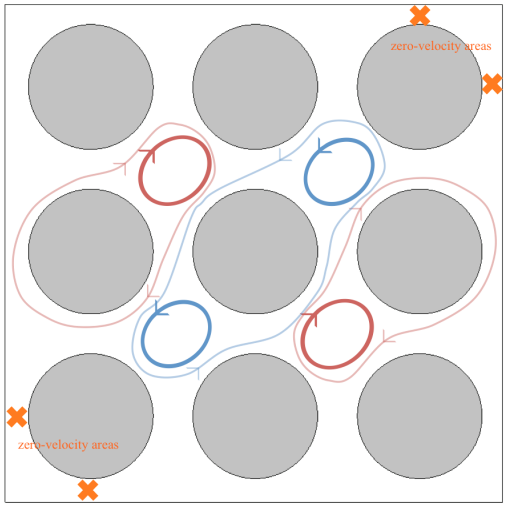
- 3D LES simulations were performed in a 3x3 rod bundle.
- In parallel, 2D simulation performed with geometry = cross-section of the 3D domain, initial condition = 2D cross-flow in the wake of the grid .
- Comparison of the time evolution of the 2D simulation and axial evolution of the 3D simulation.

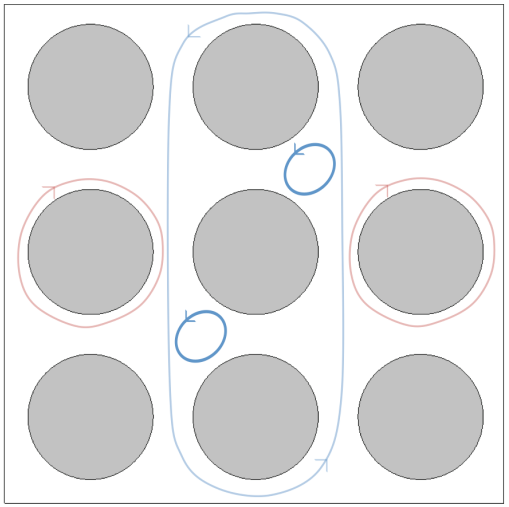
LES simulations in a 3x3 rod bundle







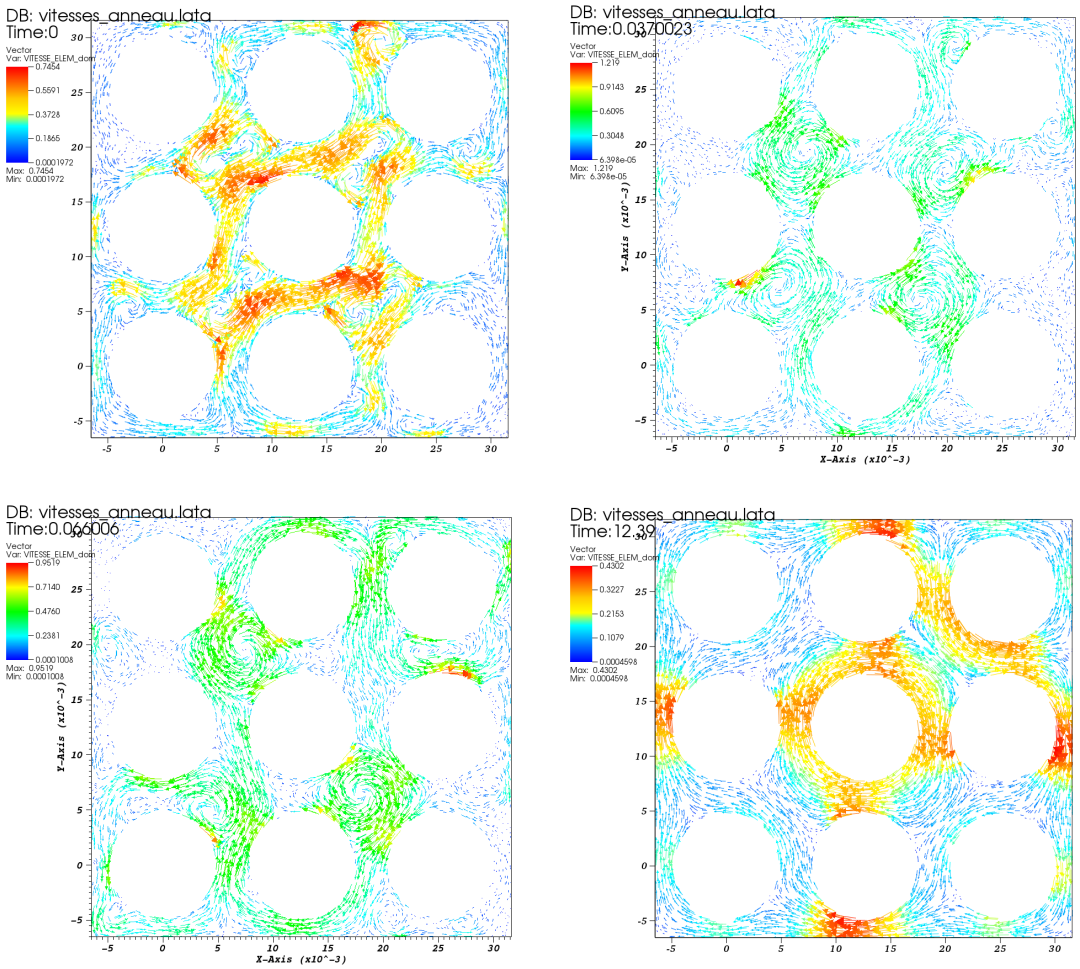




Cross-flow velocity fields at $8D_h$ (left) and $32D_h$ (right).

- Mesh: 65M tetraedric elements.
- WALE turbulence model (TrioCFD code).
- Mixing grid with internal vanes only.
- Cross-flow reorganization into a vertical vortex.

2D DNS simulations in a 3x3 rod bundle



2D velocity field at $t = 0$s, $t = 0.037$s, $t = 0.066$s (equivalent to the total 3D axial span) and $t = 12$s.

- Mesh: 135k triangular elements.
- No turbulence model (TrioCFD code).
- Initial condition = cross-section flow right after the mixing grid in the 3D simulations.
- Merging of same-sign vortices.
- Temporary reorganization into a vertical vortex.
- Long-term state restores symmetry.

Conclusion

Conclusions et résultats obtenus

- Highlighting of rod bundle cross-flow reorganizations in experiments and CFD simulations.
- 2D simulations performed based on a Taylor "Frozen turbulence" hypothesis.
- 2D & 3D evolutions are qualitatively comparable.
- 3D axial span only corresponds to first phase of 2D reorganization. $\Longrightarrow$ may not have time to reach stable state from statistical theory.

Perspectives

- Highlighting of typical 2D turbulence in the 3D simulations (-3 direct enstrophy cascade, coherent structures).
- Identification of requirements for a turbulence model tailored for rod bundle flow simulations.

Thank you for your attention