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DE LA RECHERCHE À L'INDUSTRIE



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

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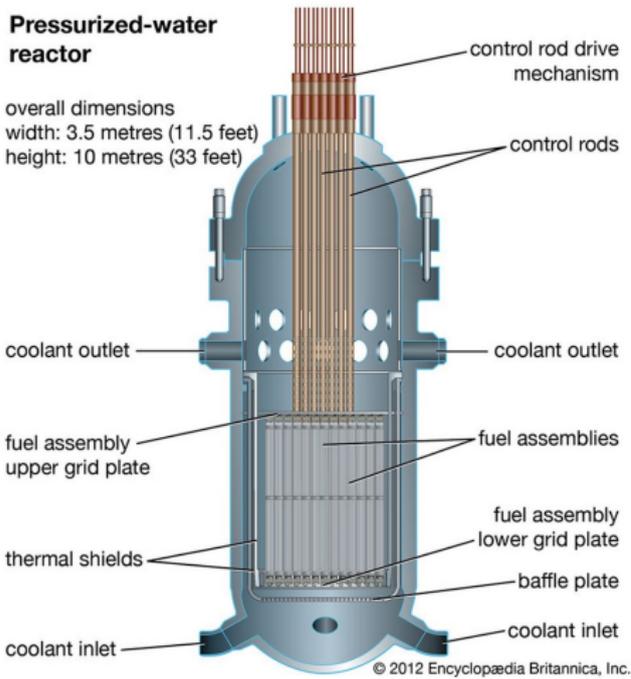
- 1 PWR core thermohydraulics
- 2 Cross-flow reorganizations in experiments and simulations
- 3 2D Free decay simulations

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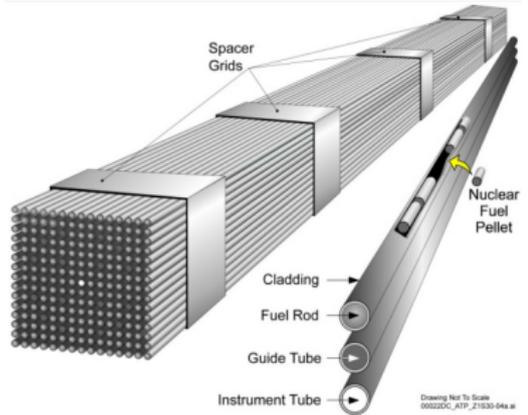
PWR rod bundles

Pressurized-water reactor

overall dimensions
width: 3.5 metres (11.5 feet)
height: 10 metres (33 feet)

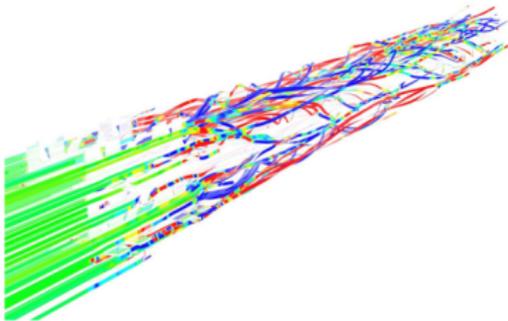
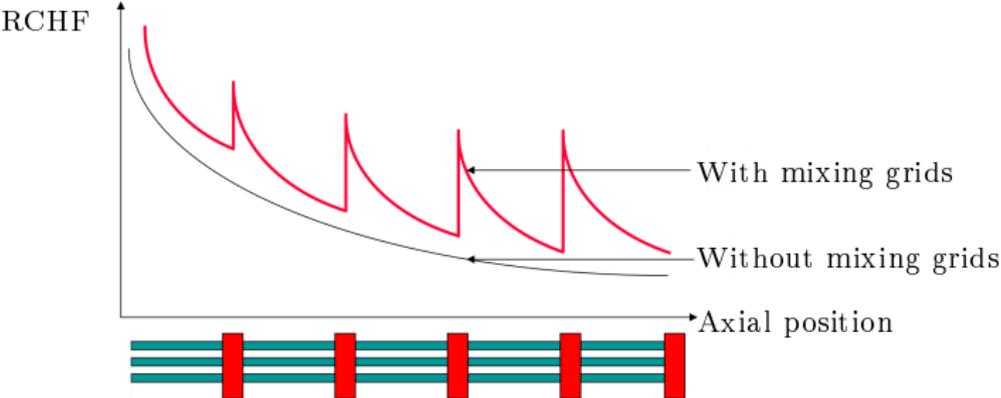


Sketch of a typical PWR pressure vessel.

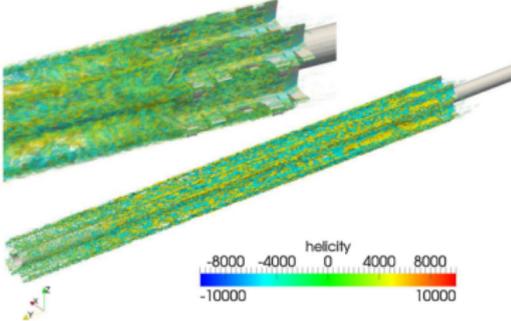


Sketch of a rod bundle with regularly spaced mixing grids.

Impact of the mixing grids on the RCHF



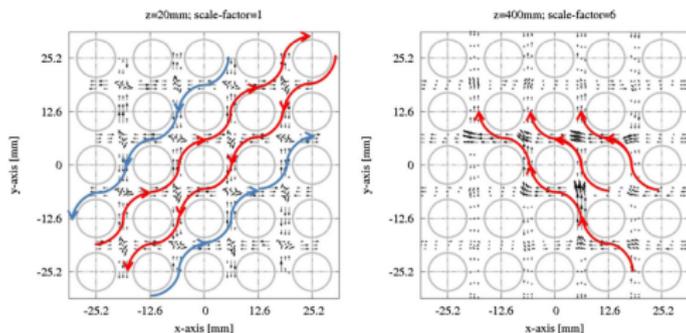
Velocity streamlines in the wake of a mixing grid.



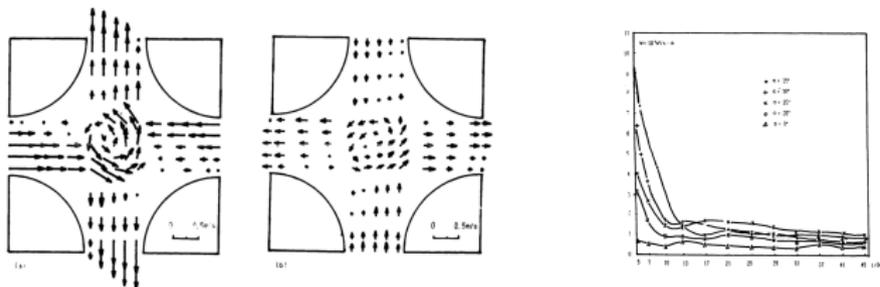
Helicity in the wake of a mixing grid.

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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)

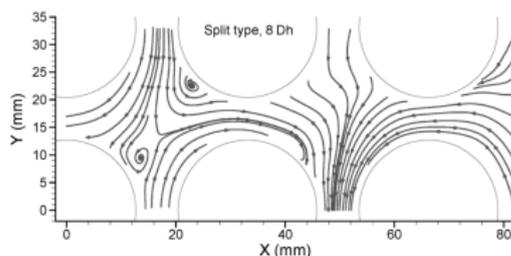
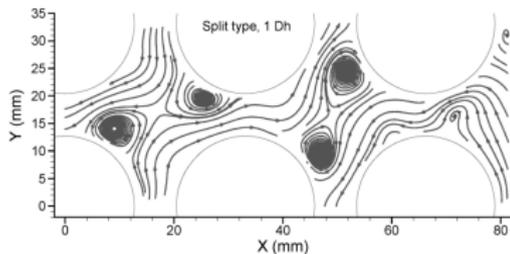
Cross-flow reorganization phenomenon

- Cross-flow reorganizations observed regularly in experiments but no satisfactory 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.

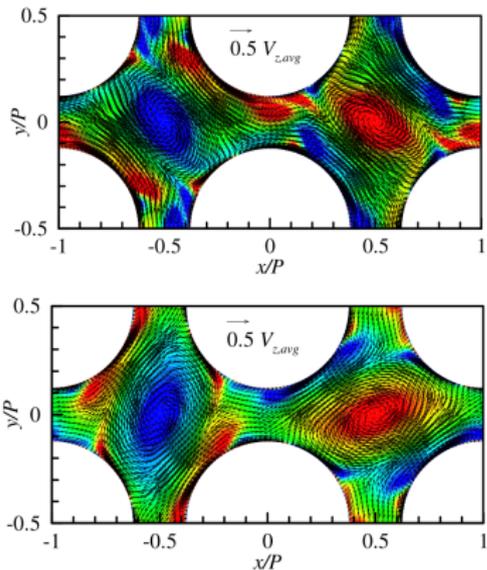
^aBieder, Falk, and Fauchet, “LES analysis of the flow in a simplified PWR assembly with mixing grid”.

^bChang et al., “Phenomenological investigations on the turbulent flow structures in a rod bundle array with mixing devices”.

^cKang and Hassan, “Computational fluid dynamics (CFD) round robin benchmark for a pressurized water reactor (PWR) rod bundle”.

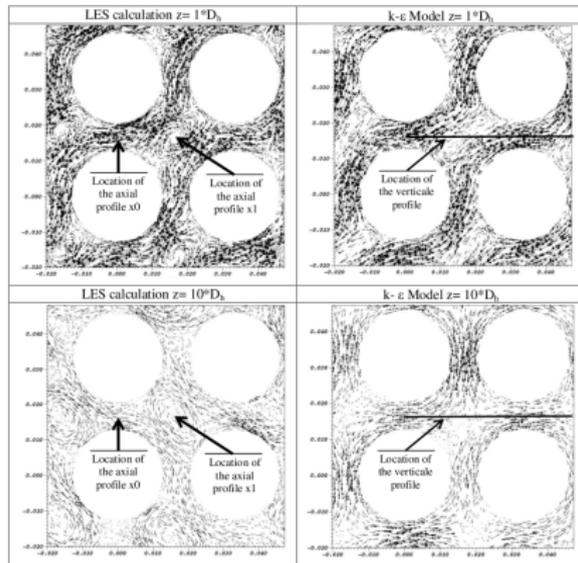


Reorganization phenomena in CFD simulations



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

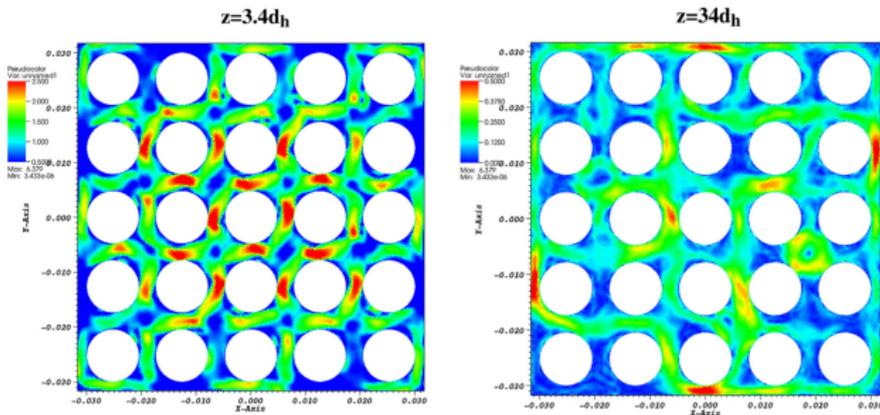
^aHolloway, Beasley, and Conner, "Investigation of swirling flow in rod bundle subchannels using computational fluid dynamics".



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

^aBieder, "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
⇒ RANS-based models inadequate.
- Turbulence model needs to include anisotropic Reynolds stresses.
- Phenomenon can occur at any axial location downstream the grid
⇒ Large computing costs due to the meshing requirements.

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Quasi-2D flow

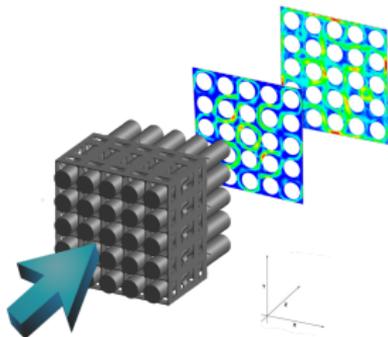
- Axial velocity one order of magnitude $>$ cross-flow components.
- Very little variations of the axial component along the transverse plane.
- Long-lived coherent 2D structures (vortices) with a tendency to merge \implies behaviour comparable to quasi-2D flows: atmospheric/oceanic layers, soap film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

Hypotheses

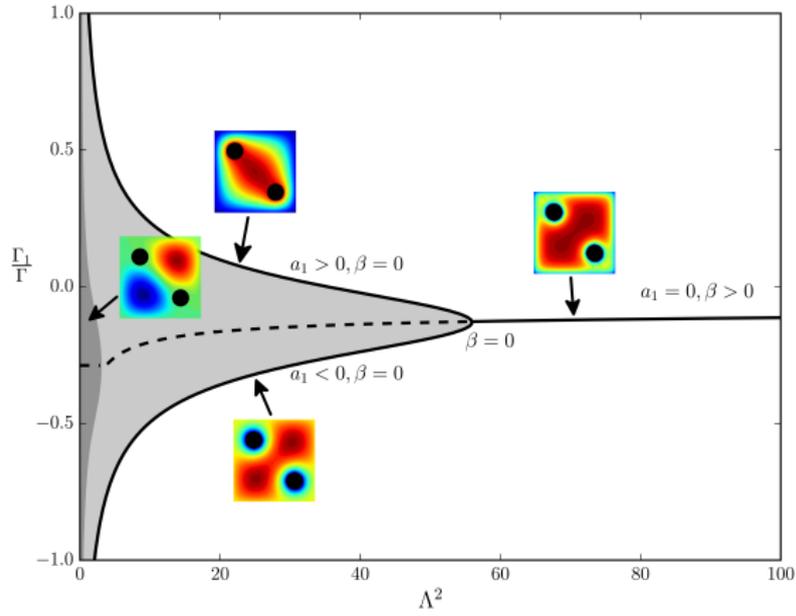
- Separation of the 3D velocity field into:
 $\mathbf{u} = \overline{u_z} \mathbf{z} + \overline{\mathbf{u}_{x,y}}(x, y, z) + \mathbf{u}'(x, y, z, t)$
→ mean axial velocity $\overline{u_z}$ almost uniform in the fluid bulk.
→ 2D flow field $\overline{\mathbf{u}_{x,y}}(x, y, z)$ convected through the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



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

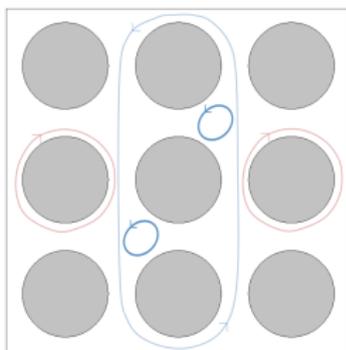
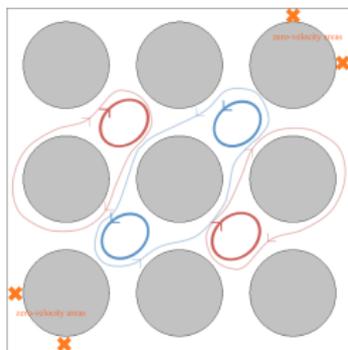
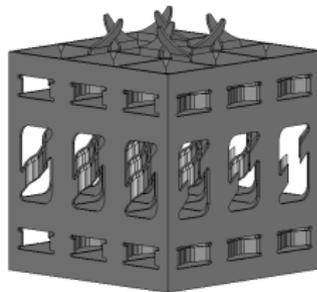
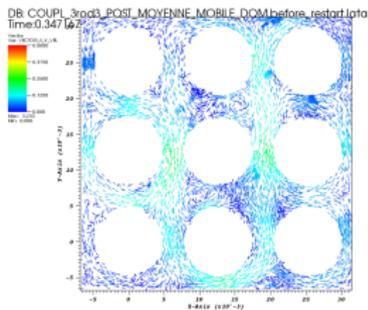
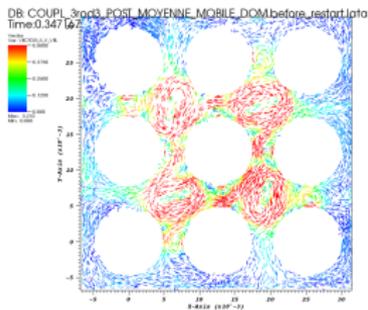
- Previous work^a established that 2D simulations could recover as a final state the stable flow predicted by the statistical theory.
- Initial flows designed to induce a mixing phase but with precise integral quantities (energy, circulation).
- Cases of the square, disk, and square with 2 obstacles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

^aClercx, 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.

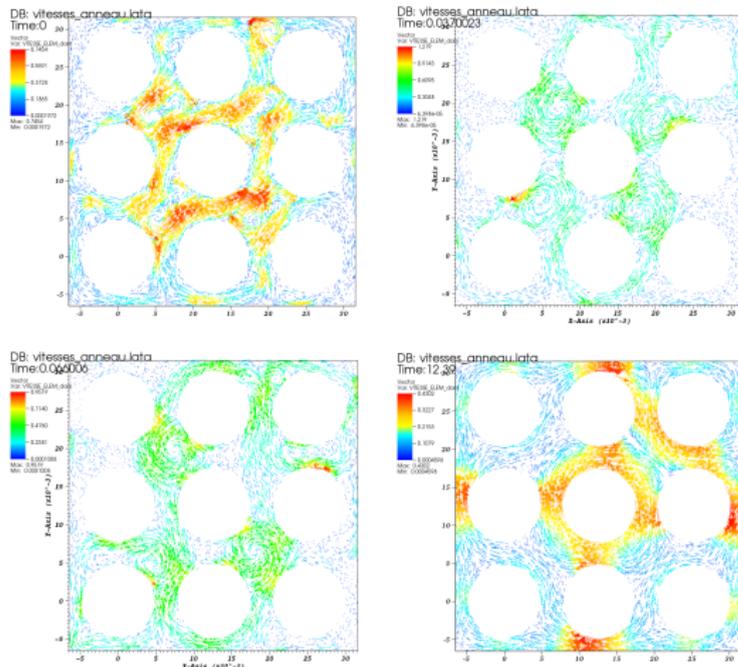
LES simulations in a 3x3 rod bundle



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

- 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.

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.
 \implies 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