



**HAL**  
open science

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

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

► **To cite this version:**

F. Muller, A. Burbeau, B.J. Gréa, P. Sagaut. CFD simulations of large-scale reorganizations in PWR rod bundle flows. TI2018 - 5th International conference on Turbulence and Interactions, Jun 2018, Les Trois Ilets, Martinique. cea-02338611

**HAL Id: cea-02338611**

**<https://cea.hal.science/cea-02338611>**

Submitted on 21 Feb 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DE LA RECHERCHE À L'INDUSTRIE



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

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

5<sup>th</sup> International Conference on Turbulence and Interactions

June 28<sup>th</sup>, 2018

[www.cea.fr](http://www.cea.fr)

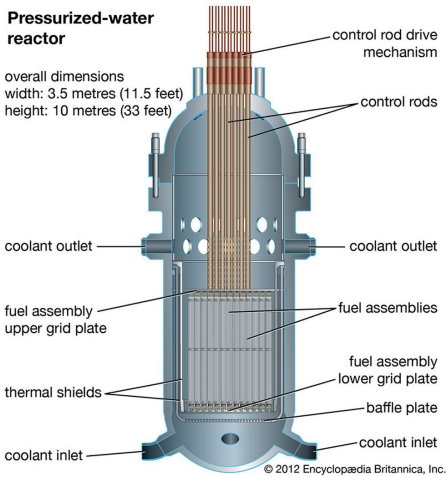
- 1 PWR core thermohydraulics
- 2 Cross-flow reorganizations in experiments and simulations
- 3 2D Free decay simulations

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

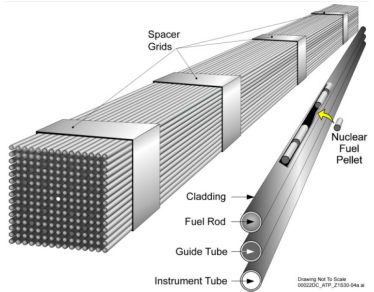
# PWR rod bundles

## Pressurized-water reactor

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

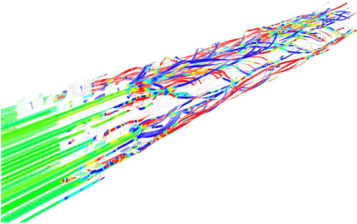
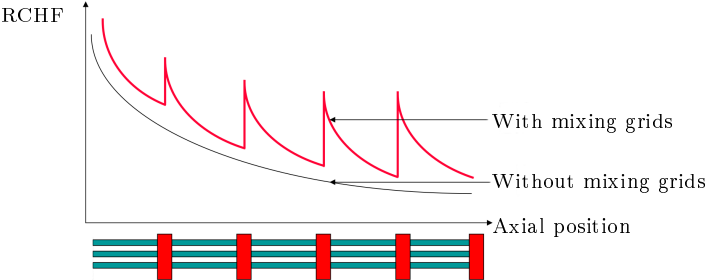


Sketch of a typical PWR pressure vessel.

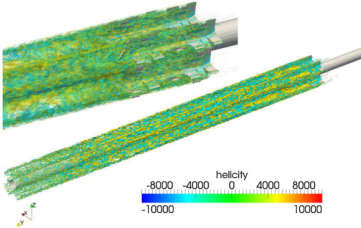


Sketch of a rod bundle with regularly spaced mixing grids.

# Impact of the mixing grids on the RCHF



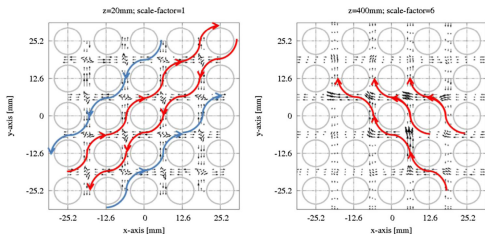
Velocity streamlines in the wake of a mixing grid.



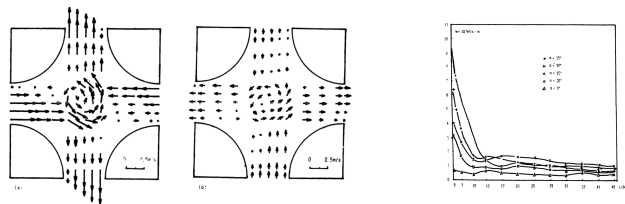
Helicity in the wake of a mixing grid.

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

# 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)



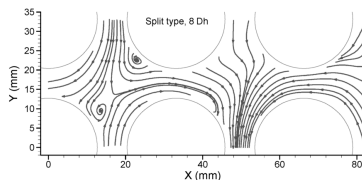
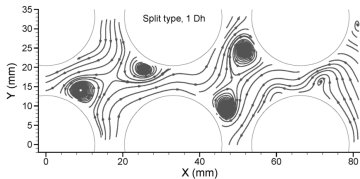
## Cross-flow reorganization phenomenon

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

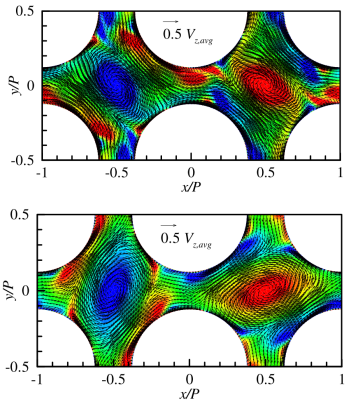
<sup>a</sup>Bieder, Falk, and Fauchet, “LES analysis of the flow in a simplified PWR assembly with mixing grid”.

<sup>b</sup>Chang et al., “Phenomenological investigations on the turbulent flow structures in a rod bundle array with mixing devices”.

<sup>c</sup>Kang and Hassan, “Computational fluid dynamics (CFD) round robin benchmark for a pressurized water reactor (PWR) rod bundle”.

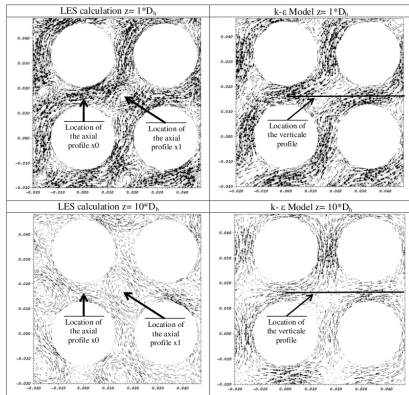


# Reorganization phenomena in CFD simulations



Velocity inversion in SST  $k - \omega$  simulations by Holloway et al.<sup>a</sup>

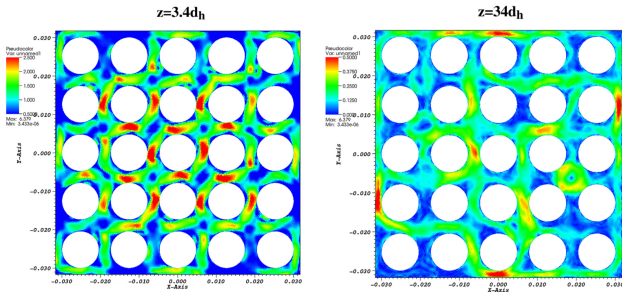
<sup>a</sup>Holloway, Beasley, and Conner, "Investigation of swirling flow in rod bundle subchannels using computational fluid dynamics".



Cross-flow reorganization in LES simulations by Bieder et al.<sup>a</sup>

<sup>a</sup>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  
 ⇒ 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.

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

## Quasi-2D flow

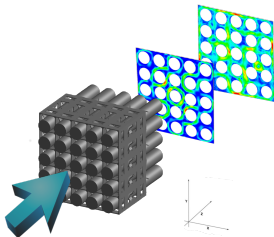
- Axial velocity one order of magnitude  $>$  cross-flow components.
- Very little variations of the axial component along the transverse plane.
- Long-lived coherent 2D structures (vortices) with a tendency to merge  $\implies$  behaviour comparable to quasi-2D flows: atmospheric/oceanic layers, soap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

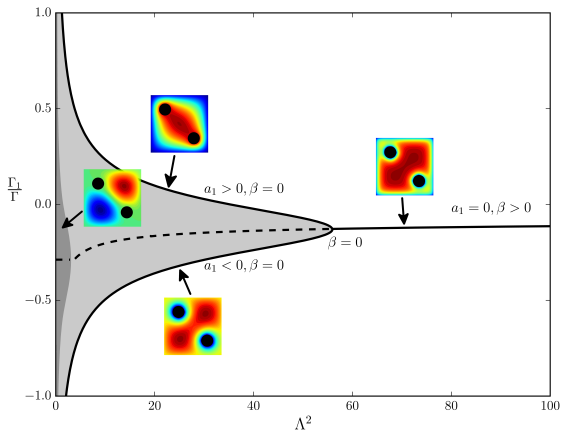
- Separation of the 3D velocity field into:  
 $\mathbf{u} = \overline{u_z} \mathbf{z} + \overline{\mathbf{u}_{x,y}}(x, y, z) + \mathbf{u}'(x, y, z, t)$   
→ mean axial velocity  $\overline{u_z}$  almost uniform in the fluid bulk.  
→ 2D flow field  $\overline{\mathbf{u}_{x,y}}(x, y, z)$  convected through 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<sup>a</sup> 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.

---

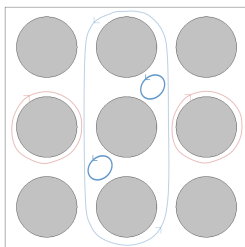
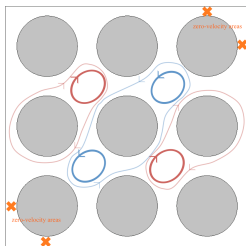
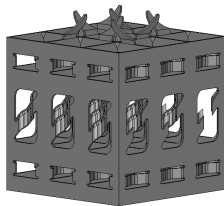
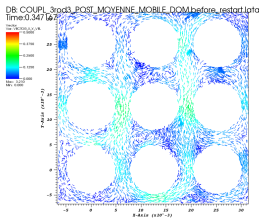
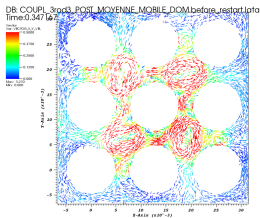
<sup>a</sup>Clercx, Maassen, and Van Heijst, “Spontaneous spin-up during the decay of 2D turbulence in a square container with rigid boundaries”.

### 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.



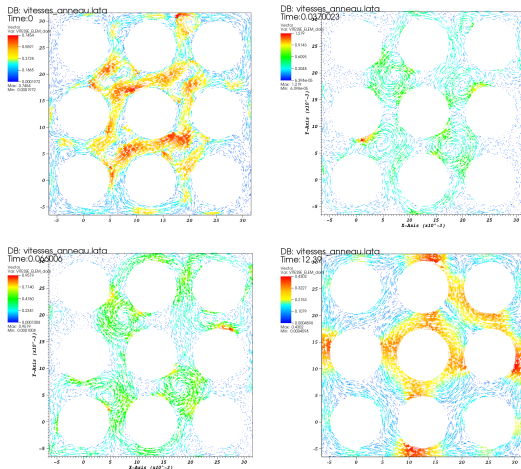
# LES simulations in a 3x3 rod bundle



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  $t = 0s$ ,  $t = 0.037s$ ,  $t = 0.066s$  (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.  
⇒ 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