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## ► 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**

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Submitted on 21 Feb 2020

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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

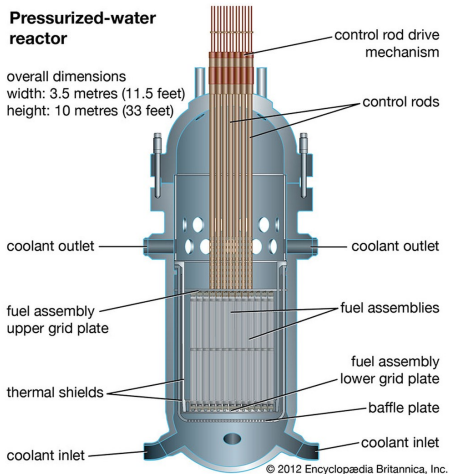
June 28<sup>th</sup>, 2018

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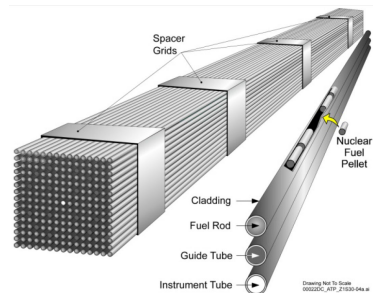
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- 2 Cross-flow reorganizations in experiments and simulations
- 3 2D Free decay simulations

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## PWR rod bundles

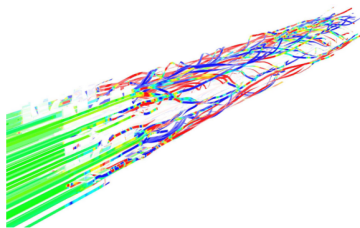
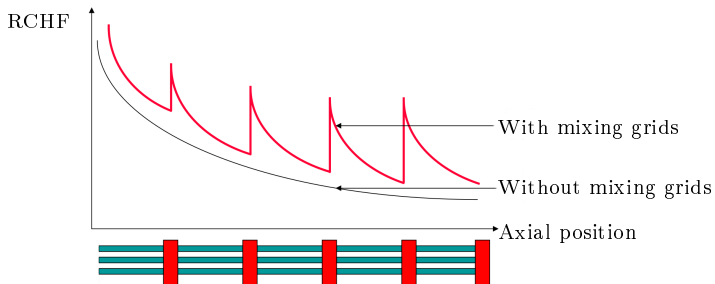


Sketch of a typical PWR pressure vessel.

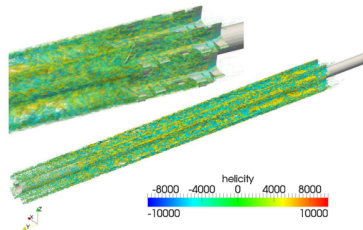


Sketch of a rod bundle with regularly spaced mixing grids.

## Impact of the mixing grids on the RCHF



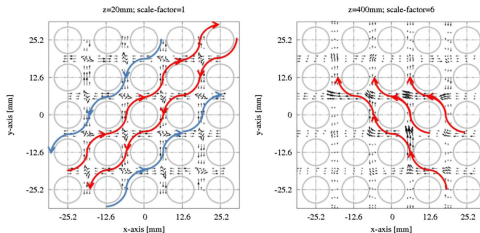
Velocity streamlines in the wake of a mixing grid.



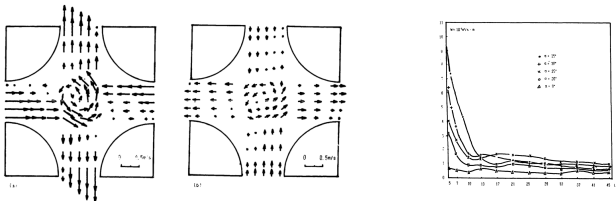
Helicity in the wake of a mixing grid.

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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)



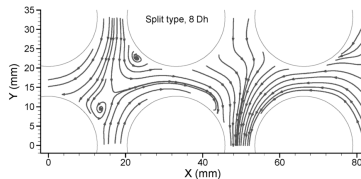
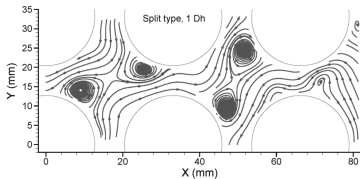
## Cross-flow reorganization phenomenon

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

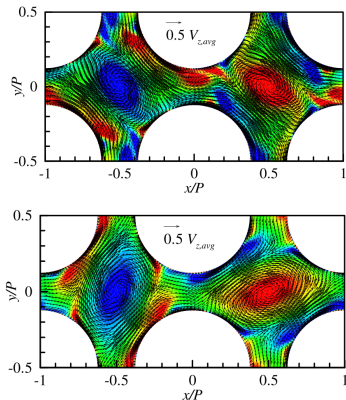
<sup>a</sup>Bieder, Falk, and Fauchet, “LES analysis of the flow in a simplified PWR assembly with mixing grid”.

<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”.

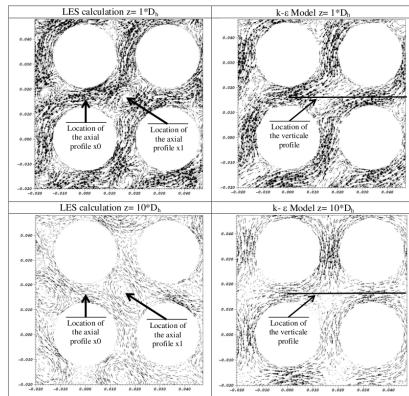


# Reorganization phenomena in CFD simulations



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

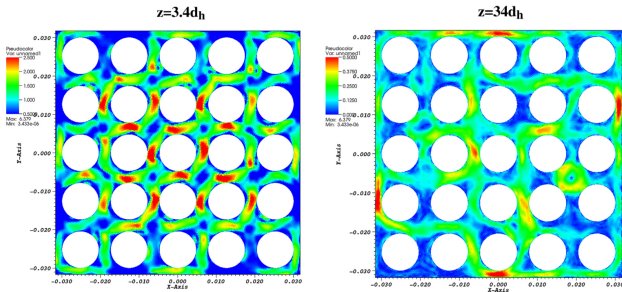
<sup>a</sup>Holloway, Beasley, and Conner, "Investigation of swirling flow in rod bundle subchannels using computational fluid dynamics".



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

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## 2D Frozen turbulence approach

### Quasi-2D flow

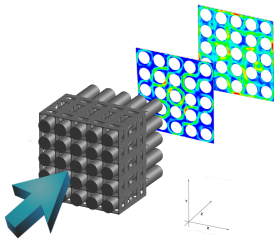
- Axial velocity one order of magnitude  $>$  cross-flow components.
- Very little variations of the axial component along the transverse plane.
- Long-lived coherent 2D structures (vortices) with a tendency to merge  
 $\Rightarrow$  behaviour comparable to quasi-2D flows: atmospheric/oceanic layers,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

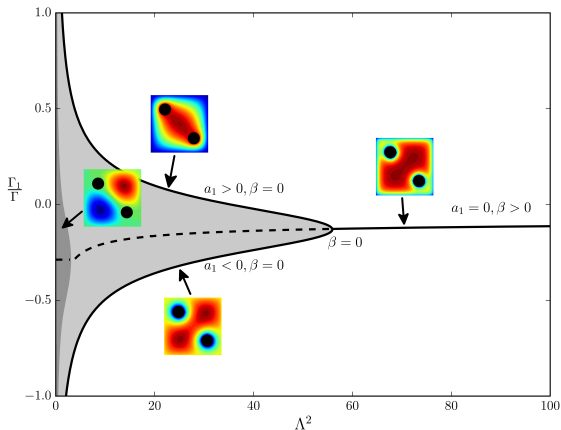
- Separation of the 3D velocity field into:  
 $\mathbf{u} = \overline{u_z} \mathbf{z} + \overline{\mathbf{u}_{x,y}}(x, y, z) + \mathbf{u}'(x, y, z, t)$   
→ mean axial velocity  $\overline{u_z}$  almost uniform in the fluid bulk.  
→ 2D flow field  $\overline{\mathbf{u}_{x,y}}(x, y, z)$  convected through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

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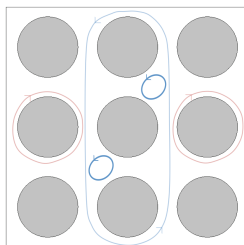
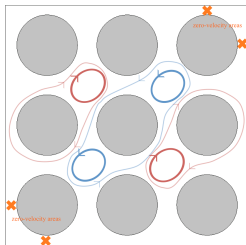
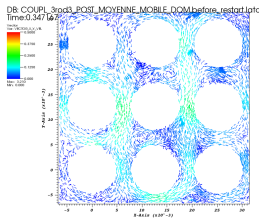
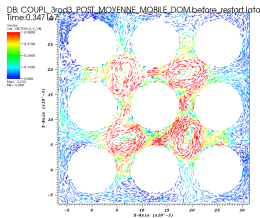
<sup>a</sup>Clercx, Maassen, and Van Heijst, “Spontaneous spin-up during the decay of 2D turbulence in a square container with rigid boundaries”.

### Excerpt shown here

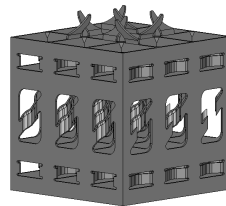
- 3D LES simulations were performed in a 3x3 rod bundle.
- In parallel, 2D simulation performed with geometry = cross-section of the 3D domain, initial condition = 2D cross-flow in the wake of the grid .
- Comparison of the time evolution of the 2D simulation and axial evolution of the 3D simulation.



# LES simulations in a 3x3 rod bundle

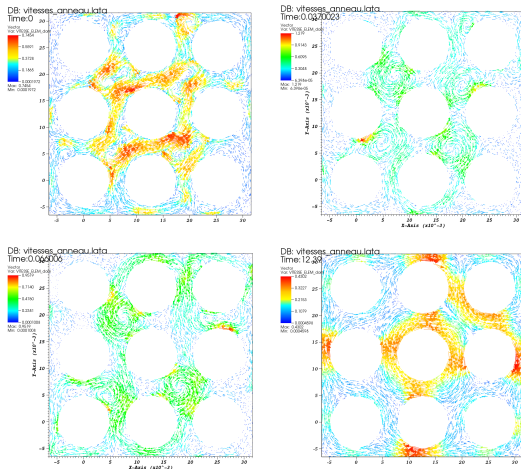


Cross-flow velocity fields at  $8D_h$  (left) and  $32D_h$  (right).



- 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.  
 $\implies$  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