<u>Contribution to the multiphysical analysis of fuel assembly bow</u>

Summary of the thesis research

1. General purpose

The subject of the PhD thesis, which is titled '**Contribution to the multiphysical analysis of fuel assembly bow**', focuses on **the deformation of fuel assemblies containing nuclear fuel pellets** within pressurised water reactors (PWR). This bow phenomenon (Figure 1) has been observed for the first time in the 90's, following incomplete rod cluster control assembly insertions (IRI) at the Ringhals Nuclear Power Plant in Sweden [1]. Throughout this time, it appeared that consequences turn out to be much broader. For instance, fuel assembly bow relates to the nuclear core operation (asymmetry of the nuclear power in each core quadrant called ***tilt***, local changes of the burnup, …), but also fuel assembly handling (complication with insertion and removal of fuel assemblies, damaging of nuclear **mixing grids**, …) or even in terms of core management (optimisation of fuel assemblies reloading and reshuffling) [2].

Figure 1 - Assembly bow (reference: Anna Franzén, Uppsala Universitet, 2017)

In France, the deformation of fuel assemblies is tracked by EDF, through measures of grid displacement with ultrasound (apparatus called DAMAC), outside the nuclear core [3]. Today, a sufficient knowledge of the mechanical behaviour of fuel assemblies enables engineers to correctly describe the structure including both mixing grids, guide tubes and fuel rods. However, the influence of **themalhydraulic in-core conditions** and the numerous associated **coolant redistributions** remain grey areas in the scope of the fuel assembly bow mechanism [4, 5]. Thus, a simulation of a full nuclear core, which requires an extended knowledge of **fluid-structure interactions** of the assembly, is still currently a subject of major concern for industrial companies.

Neutronic consequences, like quadrant power tilts, call for dedicated modeling whatever is the scientific software used (*i.e.* either a **Monte Carlo** or **deterministic** solver). The interest of studying neutronic consequences lies for instance in the anticipation of tilt effects impacting the nuclear core operation, in radiation protection (change of dose rate), or even in the boiling crisis in nuclear reactor safety [6]. Neutron flux maps set up in operation can also be seen as **indirect in-core measures** of fuel assembly bow (measures are, as mentioned above, only realised outside the nuclear core today) [7].

In these instances, the research undertaken during the thesis can be gathered in **two different sections**. The first one is the fluid-structure interaction of the assembly, which allows, through simulation, to depict the mechanical flow-induced deflection. The second one is the study of neutronic consequences of fuel assembly bow. The latter section thus consists in setting up a link between the geometry of the deformed fuel assembly (which, for instance, stems from a fluid-structure interaction calculation), and its consideration within a Monte Carlo or deterministic neutronic code.

2. Fluid-structure section of the thesis

Within the scope of fluid-structure interaction of the fuel assembly, the thesis took an interest in an important phenomenon, yet little studied, or even ignored in the literature: it is the **coolant redistribution in the vicinity of mixing grids** of the fuel assembly. The question arisen by this phenomenon is: which ratio of the **flow rate** goes into the grids, and which one goes into the **bypass** (area located between two adjacent fuel assemblies)? (Figure 2) This ratio plays a key role as the fuel assemblies are bowed, and the bypasses width is not equally distributed throughout the core. Consequently, the pressure is different on both sides of one grid, leading to a **hydraulic force**.

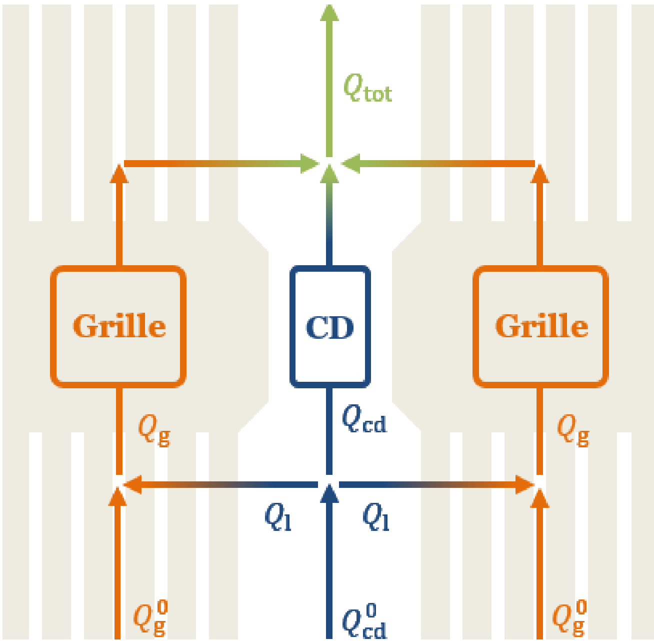

Figure 2 – Illustration of flow rates redistribution upstream from the mixing grids: whether the fluid soaks into the grid itself, or into the bypass (named CD here)

First of all, the work aimed at depicting this redistribution through a simple approach: grids and bypasses were modeled with 1D hydraulic pipes and appropriate **pressure loss** coefficients. When two of these branches (grid and bypass) are joined together, one can set up a **hydraulic network** (Figure 2), which is similar to a nonlinear electric circuit (thanks to the law $\Delta P = KQ^2$ instead of the classical Kirchhoff's law $U = Ri$). These network laws are modified in order to take into account several physical effects. For example, a stagnation point effect (in other words, a 'peak pressure' upstream from a grid), or lateral hydraulic resistances owing to the presence of fuel rods below the grids. These models were validated thanks to detailed simulations with the help of **CFD** softwares, but also **experimentally**, with the help of a dedicated mock-up specially designed for the thesis, made up of 3D printed grids [8].

Secondly, considering that the developments allowed to successfully reproduce the behaviours observed with CFD simulations and the experimental mock-up, the work was focused on modeling a whole fuel assembly with the same approach afterwards. In other words, one simulates the coolant flow up above the assembly's height taking into account both its internal and external parts (purpose of the precedent models). A numerical tool named **Phorcys** was developed then, written with the python language and dedicated to solving such networks. Hydraulic forces calculated through a network calculation are forwarded to a mechanical model of the fuel assembly structure, which in return can estimate the assembly's displacement and change the bypasses width in the hydraulic network calculation. These return trips between hydraulics (Phorcys) and mechanics (Cast3M) constitute the **hydromechanical coupling** of the whole fuel assembly. The latter was validated with success on the basis of tests run within the CEA's HERMES T hydraulic loop analysing the mechanical response of a fuel assembly in axial flow.

Thirdly, a **row of fifteen fuel assemblies** was simulated with the same coupling scheme (Figure 3), and the results were compared to the literature. The hydraulic network model is able to qualitatively reproduce (there are no experimental measures at such a scale) the main bowing patterns. Finally, a simple hydraulic core model has been set up to depict the flow redistributions within a **full 3D core**. This model is based on successive calculations of independent 2D rows oriented towards the X/Y axes to estimate 3D hydraulic forces. At this time, this 'row sweeping' (faster) model is advised for future 3D couplings as comparison with real 3D redistribution (*i.e.* made of dependent rows) tends to highlight little differences in terms of forces distribution in the core.

The main prospect of this section is to set up a full 3D core hydromechanical coupling, leaning on existing models proposed in this thesis research.

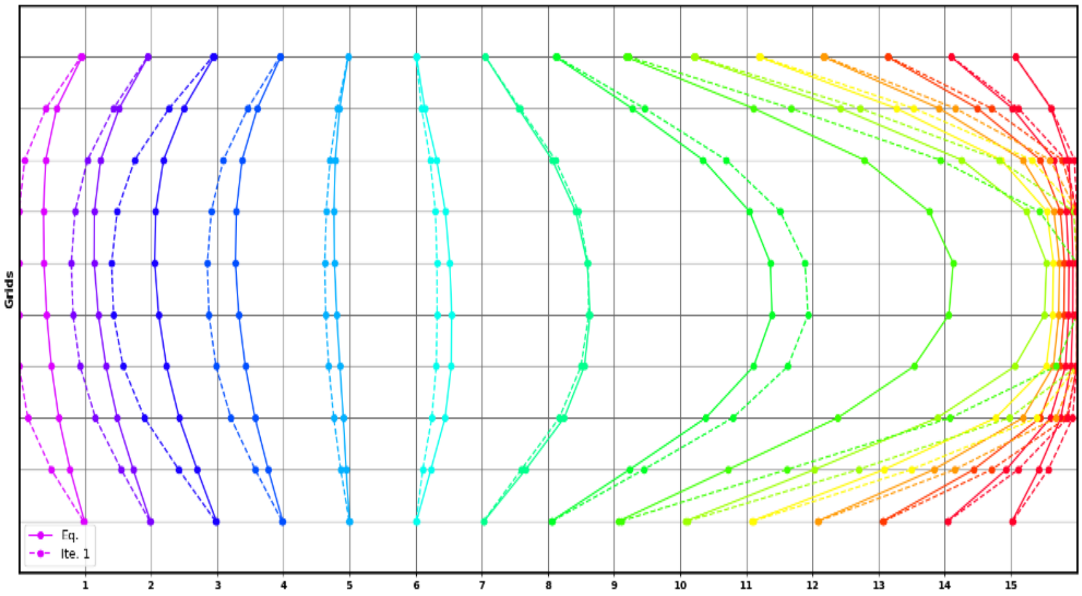

Figure 3 – Illustration of the deformation of a row of 15 fuel assemblies deformed with the hydromechanical coupling

3. <u>Mechanics-neutronics section of the thesis</u>

The link between deformation and its representation inside a neutronic code was also undertaken in several steps.

First, at the scale of a few fuel assemblies, the deformed fuel rods forming the whole structure are modeled through a series of small inclined cylinders (called **segments**). A python script generates every single element in the form of a geometry legible by a Monte Carlo code (in the thesis, the CEA's code **TRIPOLI-4®**) (Figure 4).

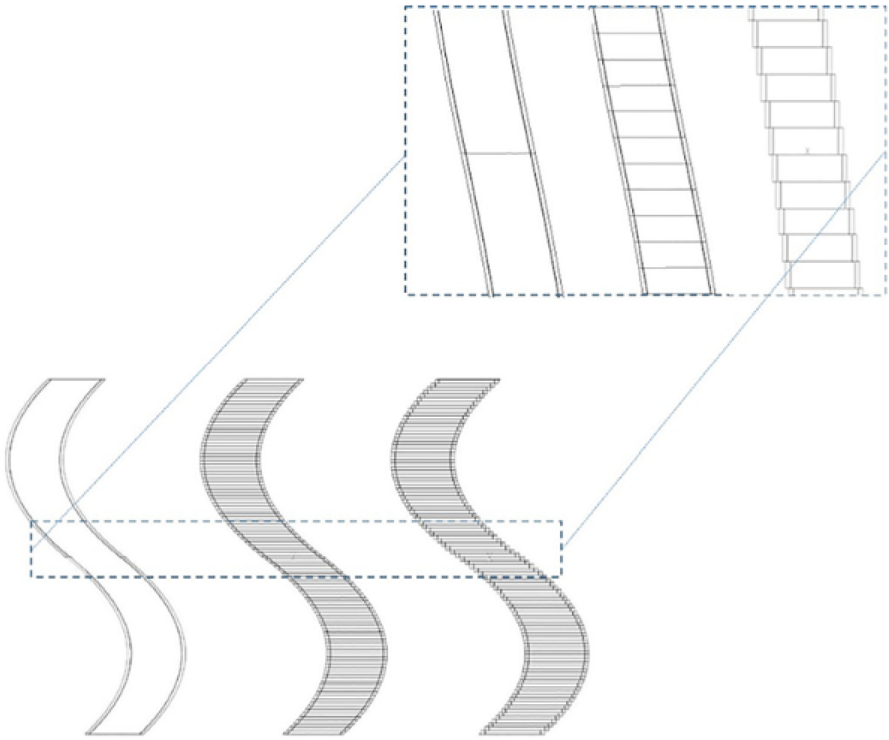

Figure 4 – Discretising a fuel rod with TRIPOLI-4®, the stacking modeling (right) is the one used in the literature, the segment modeling (centre) has been set up in the work

This discretisation of fuel rods was validated with success by comparison with a continuous fuel rod (made of tori). Several deflection magnitudes were used (from 10 to 20 mm) along with several kinds of deformations ('C' shape and 'S' shape) [9]. Although this discretised approach (based on a Monte Carlo simulation) allows a priori to depict any deformation, it is time consuming. As a consequence, 'segments' are in theory limited to studies with a few assemblies. For instance it can be useful to validate higher scale models with the help of a mini core.

Secondly, the core scale was modeled with the help of a deterministic code (which uses meshes for space and energy to solve the Boltzmann equation), in our case the CEA's code **APOLLO3®**. The first step of this neutronic scheme is the production of a **cross section library**, thanks to fine 2D calculations in a quarter of assembly and depending on the adjacent bypass width (also called water gap in neutronics). This step is named '**lattice calculation**'. The fine calculation precisely describes the geometry inside a fuel rod, and the resultant flux enables to **homogenise** the cross sections over a less detailed geometry (for instance, only one cell per fuel rod). Thus, the second step is the use of the latter generated library of homogenised cross sections, but in **wider and less**

detailed geometries (with one cell per fuel rod). This step is called '**core calculation**'. The regular comparison of a mini core made up of 5x5 fuel assemblies (Figure 5) through several cases of deformation, with a reference Monte Carlo code (TRIPOLI-4®), allowed to validate the present approach in 2D.

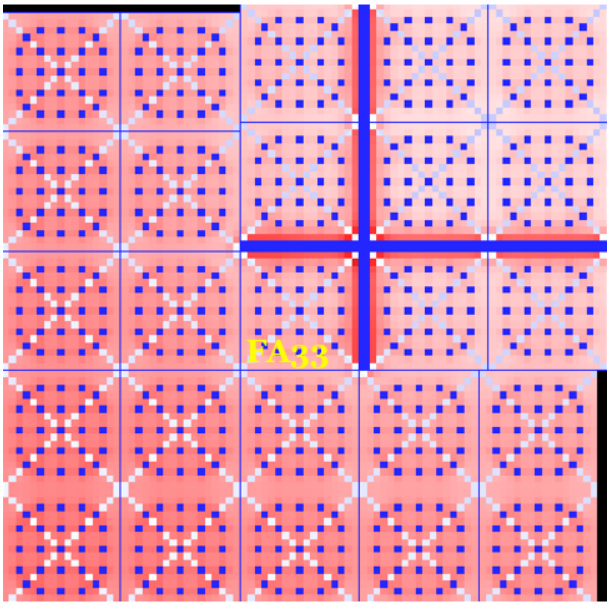

Figure 5 – Core calculation run with APOLLO3® (5x5 fuel assemblies) realised with homogenised cross sections. The fuel assemblies in the top right-hand corner were displaced to depict their bowing and a gap enlargement next to FA33

A prospect of this section would be to set up a 3D core with an adapted axial mesh of fuel assemblies and the use of the previous library, generated in 2D.

4. References

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