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Simulation of unsteady fluid forces on a single rod downstream of mixing grid cell

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A B S T R A C T

The CALIFS study is part of a program that will combine hydraulic tests on 5 × 5 mock up of a fuel rod bundle and CFD simulations to evaluate the fluctuating fluid forces exerted at high Reynolds number in PWR fuel rod bundles. In this study, we consider a first intermediate geometry of the calibration bench, implementing one single rod and one grid equipped with mixing vanes.

This article provides an extensive analysis of the capabilities of CFD to estimate the fluctuating fluid forces exerted by the turbulent flow with high Reynolds inside a fuel rod bundle with mixing grids. It benefits from high accuracy experimental results obtained through an original device developed at CEA[2] and providing a direct measurement of the fluctuating pressure on the surface of the rods, allowing the characterization of the turbulence scales and effects close to the walls and therefore establishing a valuable data of reference for the analysis of turbulence in fuel assemblies. The validation of CFD simulations is very important in order to then assess the turbulent excitation forces, more particularly in areas of great turbulence not accessible to measurements, for example in the feet of the assemblies.

1. Introduction

In the fuel assemblies of PWR nuclear reactor cores pressurized water circulating at high velocity with a Reynolds number about 500 000 is used as a heat transfer fluid. The structure of the assembly consists mainly of rods and structural grids.

The mixing fins, implanted at the outlet of each grid cell, have a dual purpose, firstly to increase the level of turbulence in the subchannels to improve the heat transfer between the surface of the fuel rods and the coolant; secondly create radial flow redistributions between the hydraulic subchannels of the bundle rod to homogenize the temperature in the bundle to avoid hot spots, or even more seriously a boiling crisis.

Random vibration excitations induced by flow turbulence (Paidoussis, 1982, 2003) can produce severe vibration solicitations on a wide range of components in nuclear power plants, particularly fuel core assemblies. The improvement of the fuel combustion rate leads the assemblies to spend more time inside the heart and at the end of the life of the assemblies the relaxation of the springs and the dimples supporting the rods, makes them more sensitive to the induced vibrations. Those vibrations are the source of fretting, *i.e.* wears under small vibratory movements at the contact points of the rods with the springs and the dimples in the grid cells. In extreme cases, this may lead to the piercing cladding of the fuel rod, the first confinement barrier, with a consequential dispersion of fission products in the primary circuit and at the shutdown of the nuclear power plant.

The development of modeling tools for estimating wear and tear damage requires a multidisciplinary approach. This problem is very complex to study because it depends jointly on the mechanical properties of rods and grids (stiffness, damping and friction-coefficient) which can degrade over time and produce plays in cell's supports (Kim, 1999; Rubiolo and Young, 2009), as well as on the topology and characteristics of turbulent flows in the fuel assemblies.

First important progress has been made in the modeling of the dynamic behavior of rods with non-linear supports, subject to turbulent flow mainly axial (Choi et al., 2004; Kim and Kim, 2005; Rubiolo et al., 2004, 2006; Hassan et al., 2003; Antunes et al., 1990, 2008, 2009, 2011; Piteau et al., 2012; Elmahdi et al., 2011). Then to allow a realistic modeling of the dynamic response of the rods, subjected to turbulent flows, it is necessary to have precise values of speed fields in the assembly and to quantify the fluid forces acting on the whole height of the rods.

Several approaches have been explored to provide useful data to the mechanical modeling. Axisa et al. (1990) and then (Beaufils and Portier, 1991), have studied random excitation of axial or cross-flows in tube bundles. In another way Park et al. (2009) proposed an indirect experimental identification of these fluid forces by fitting the experimental vibration results with a finite element model response. Likewise

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Nomenclature

CFD	Computational Fluid Dynamics
GMRES	Generalized Minimal Residual Method
GTRF	Grid To Rod Fretting wears
Hd	Hydraulic diameter
LDV	Laser Doppler velocimetry
LV	Laser Vibrometer
Re	Reynolds number
PIV	Particle Image Velocimetry
PWR	Pressurized Water Reactor
PSD	Power Spectral Density
RANS	Reynolds Average Navier Stokes equations
URANS	Unsteady Reynolds Average Navier Stokes equations
LES	Large Eddy Simulation of turbulent flow
LDV	Lasser Doppler Velocimetry
VEF	Finite Element Volume discretization
VDF	Finite-Difference Volume discretization
r_e	External radius
r_i	Internal radius
r_m	Radius of maximum velocity
U_d	Flow rate
u^*	Friction velocity
U^+	Dimensionless velocity
y^*	Wall unit
y+	Dimensionless wall distance
κ	Von Karman constant
μ	Dynamic viscosity
ρ	Density
τ_p	Wall shear stress

Antunes et al. (2014) have presented an extensive approach for extracting the dynamical features of a flow excited multi-supported nuclear fuel rods. The identified items include the structure modal parameters, as well as the spectral and spatial characteristics of the distributed flow excitation. Mohany and Hassan (2013) have developed a numerical model to predict the vibration response and the associated fretting wear of a CANDU fuel bundle subjected to turbulent flow excitation.

To improve understanding and provide analytical data on turbulent flows in fuel assemblies, experimental investigations by Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) measurement methods (Ikeda and Hoshi, 2006; Dominguez-Ontiveros and Hassan, 2009; Caraghiaur et al., 2009), were used. They showed that the turbulent flow downstream the mixing grid and the field velocity are strongly dependent on the grid geometry. CFD modeling was first widely used to study critical fluxes in fuel assemblies of PWR cores (Kasuo et al., 2006; Conner et al., 2010, 2013; Bieder et al., 2014; Kang and Hassan, 2016), comparisons with available measurements have allowed significant results for predicting axial and transverse temperature distributions in the assemblies, but significant progress remains to be made in predicting the fine distribution of temperatures on the surface of the rods.

CFD modeling can provide valuable insights for the study and understanding of the GTRF problem. Abbasian et al. (2009) simulated turbulent flows in a 43-rod bundle of CANDU nuclear reactors. Comparisons of the results produced by different turbulence models, with fluctuating pressure measurements from miniature sensors, have shown that the Smagorinsky dynamic LES model gives the best results, the closest to the experimental data. On the same theme, the LES modelization of turbulent flow surrounding one and a half simulated 43-element CANDU fuel bundle by Zhang and Yu (2011), showed that the results, in good agreement with the authors' measurements, could be applied to a structural model for vibration prediction and pressure tube fretting analysis.

More recently Barkosi et al. (2012) carried out an implicit LES simulation of time-dependent single-phase turbulent flow in 3 × 3 or 5 × 5 rod bundles with single grid spacer. The main purpose of their studies is to determine the time history and statistics of the forces loading the fuel rod. The comparisons of simulation results with data from experiment at Texas A&M, demonstrated the relevance of this approach the calculate random excitation forces causing the wear and tear problem.

Carried out at the Laboratory of hydrodynamics of the core and systems of the CEA[2] at Cadarache, the research program involving the current contribution aims at determining the vibratory excitation forces at the origin of the GTRF problem and more generally at providing advanced validation data for CFD simulation software, with the application purpose of contributing to the improvement of the design of the fuel assemblies for existing and future PWRs.

This research and development program (internally called CALIFS) has two components; the experimental part concerns the study of the flow in mock-ups of 5 × 5 rod bundles with different grids. The classical measurements of turbulent flow characterization by PIV and LDV are completed with a new measurement system of the pressure fluctuations directly on the wall of the central rod of the bundle. These mock-ups were done at scale 2.8 to integrate the measurement system into the central rods of the assembly. This measurement system was developed and tested at the LHC by Moreno et al. (2016); it can be moved in the axial direction and in azimuth to explore a measurement zone between two grids extending over 40 Hd. It gives us access to the time history and statistics of the pressure induced by the vortices at the rod wall, at the origin for turbulent excitation forces.

The second part of the program is designed to use CFD simulation methods to predict the fluctuating forces exerted by fluids on nuclear fuel bundles at high Reynolds number. The validation of the CFD calculation methods shall enable the estimation of the amplitude and the spatial distribution of the excitation forces downstream of the mixing grids and in areas of high turbulence that are less accessible to measurements, for example at the bottom of the fuel bundle. Such precise determinations of the vibratory excitation spectra can then be used as input data for the computation of the vibratory behavior of the rods under turbulent flow using a non-linear vibratory mechanics code developed at CEA[2] by Antunes et al. (1990–2014).

The present article thus deals with a first exploratory modeling phase, designed to set the relevant paradigms for the flow simulations in the complex geometry of the test introduced above. To provide the flexibility and computational efficiency necessary for the generic evaluation of potential simulation frameworks, from Reynolds Averaged Navier-Stokes to Large Eddy Simulation with their own internal parameters to precisely discriminate, a simpler, yet representative, configuration is chosen, implementing one instrumented rod equipped with one grid cell with the supports and the vanes, centered in a transparent cylindrical Plexiglas tube. Even if the turbulent flow in an annular space is not totally representative of the anisotropic turbulence that develops in a tube bundle with a square pitch (object of the future studies), this step enables comprehensive parametric analyses, involving sensitivity to the mesh and to turbulence models, with datasets of reasonable size from 7 to 15 million cells.

The paper is organized as follows. The first section is dedicated to the description of the principal features of the experimental and numerical framework, giving first the characteristics of the reference experiment and second the numerical models and methods analyzed further in the article. The second section provides the extended analysis, following a procedure recalled at the beginning of the section, in terms of relevant data for comparison between simulation and experiments, computed from the raw calculation results. The third and fourth