Nuclear Engineering and Design 265 (2013) 814–825

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

On numerical simulation of fuel assembly bow in pressurized water reactors

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HIGHLIGHTS

- Simulation of fuel assembly bow by coupled CFD and finite element method.
- Comparison of calculated and experimentally measured bow shapes.
- Investigation of boundary condition effect on bow pattern of a fuel assembly row.
- Highlighting importance of consideration of fluid–structure interaction.
- Assessment of flow redistribution within the fuel assembly row model.

ARTICLE INFO

Article history:
Received 14 September 2012
Received in revised form
15 September 2013
Accepted 18 September 2013

ABSTRACT

Fuel assembly bow in pressurized water reactor cores is largely triggered by lateral hydraulic forces together with creep processes generated by neutron flux. A detailed understanding of the flow induced bow behaviour is, therefore, an important issue. The experimental feedbacks and laboratory tests on fuel assembly bow show that it is characterized to a high degree by fluid–structure interaction (FSI) effects, therefore, consideration of FSI is essential and indispensable in full comprehension of the bow mechanism.

In the present study, coupled computational fluid dynamics (CFD) and finite element simulations are introduced, calculating fuel assembly deformation under different conditions as a quasi-stationary phenomenon. The aim has been, on the one hand, to develop such a simplified fuel assembly CFD model, which allows set up of fuel assembly rows without loosing its main hydraulic characteristic; on the other hand, to investigate the bow pattern of a given fuel assembly row under different boundary conditions. The former one has been achieved by comparing bow shapes obtained with different fuel assembly (spacer grid) modelling approaches and mesh resolutions with experimental data.

In the second part of the paper a row model containing 7.5 fuel assemblies is introduced, investigating the effect of flow distribution at inlet and outlet boundary regions on fuel assembly bow behaviour. The post processing has been focused on the bow pattern, lateral hydraulic forces, and horizontal flow distribution. The results have revealed importance of consideration of FSI, and that an inhomogeneous inlet/outlet flow condition causes significant ‘C’ shaped deformation of fuel assemblies towards the core shroud. The important effect of the core shroud has been also shown.

1. Introduction

Operational deformation of pressurized water reactor (PWR) fuel assemblies is tolerated within a certain limit, however, excessive fuel assembly (FA) bow had caused many times incomplete rod cluster control assembly inserts during shutdown or drop time tests at the mid of the ‘90s (Jacobson and Francillon, 1996; Jadot et al., 1999). At the time investigations highlighted excessive deformation of fuel assemblies as the main reason for Incomplete Rod Cluster Assembly Insert (IRI), since the friction increased between the control rods and their guide thimbles. Moreover, it was also noticed that the whole core was dominated by assembly bow. The

Abbreviations: CFD, computational fluid dynamics; FA, fuel assembly; FR, fuel rod; FSI, fluid structure interaction; GT, guide tube (thimble); IRI, incomplete rod cluster assembly insert; MARS, monotone advection and reconstruction scheme; SG, spacer grid; UD, upwind discretization scheme.

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http://dx.doi.org/10.1016/j.nucengdes.2013.09.031

Nomenclature

a, b, c	constants for parabolic flow profile definition
D	fuel rod diameter
$\underline{F}_{fl}$	hydraulic forces (x-direction)
k	turbulent kinetic energy
$\underline{\underline{K}}_{st}$	structural stiffness matrix
P	fuel rod pitch
S_{v_w}	additive velocity source term for the momentum equation in axial (z) direction
$\lvert \underline{v} \rvert$	modulus of velocity
$\bar{w}$, $\bar{w}_{In}$, $\bar{w}_{Out}$	mean axial (z) velocity component; mean axial velocity component at inlet/outlet boundary regions
$\underline{u}_x$	displacement vector (all nodes, x-direction)
u_i	displacement of the ith node (x-direction)

Greek letters

α	inertial resistance factor
β	viscous resistance factor
γ	under-relaxation factor
ΔF_{max}	maximum difference of hydraulic forces between successive time steps, concerning all regions
ΔF_{tol}	predefined tolerance value for ΔF_{max}
$\Delta u_{x,max}$	maximum difference of displacement between successive mesh movements, concerning all nodes
$\Delta u_{x,tol}$	predefined tolerance value for $\Delta u_{x,max}$
ε	dissipation rate of turbulent kinetic energy
μ	molecular viscosity
ρ	density

sticking fuel assemblies had an 'S' shape bow showing significant amplitudes (up to 20 mm). Usually core deformations consisted of 'C' shape and 'S' shape deformations (Andersson et al., 2004).

It is already known that several phenomena and parameters have an impact on the deformation of the fuel assemblies, which, furthermore, superimpose each other:

- Irradiation induced creep deformation (length growth/creep behaviour of fuel assembly);
- Hold-down force on the fuel assembly;
- Fuel assembly design (lateral mechanical stiffness);
- Neutron physical aspects (e.g. fuel management);
- Core and fuel assembly hydraulics;
- Lateral hydraulic forces, interaction with neighbouring fuel assemblies/core shroud.

At the beginning researches were focused on structural aspects modelling in-core assembly bow (Stabel and Hübsch, 1995, 1999; Salaün et al., 1997), and consequently improved fuel assemblies were introduced (Gottuso et al., 2006). The experimental feedbacks on fuel assembly deformation measured at each grid level – either for all or only for selected number of fuel assemblies of a core – underline that fuel assembly bow is characterized to a high degree by fluid–structure interaction (FSI) effects (Stabel et al., 2011). Therefore, consideration of FSI effects is essential and indispensable in full comprehension of the bow mechanism.

Stabel et al. (2011) introduced an advanced methodology, which accounts for FSI effects. It consists of experimental tests, and validated analytical and numerical approaches. Its numerical approach is a coupled computational fluid dynamics (CFD) and finite element method which allows assessment of bow behaviour of different fuel assembly (spacer grid) types without any adjusted parameters. Furthermore, it provides useful information (hydraulic parameters) to

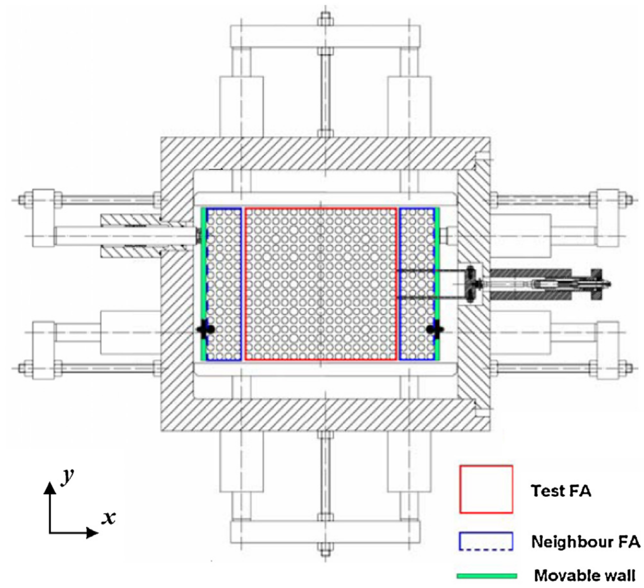

Fig. 1. Cross section of PETER loop for GLASSTRAN experiments.

the analytical approach, called network model, which can evaluate fuel assembly bow pattern of a total core over several cycles within reasonable time, therefore, investigation of bow affecting parameters/strategies (e.g. core inlet- and outlet flow profile/shuffling of fuel assemblies) has become possible.

The aim of the present study has been, on the one hand, to develop such a simplified fuel assembly model, which allows construction of fuel assembly rows without loosing its main hydraulic characteristic; on the other hand, to investigate the bow pattern of a given row under certain boundary conditions. The former one is represented in Section 2, the latter one in Section 3. Finally, Section 4 summarizes the results of the study.

2. Recalculation of experiment

The purpose of this section has been to develop and validate such a simplified fuel assembly model which is suitable to qualitatively reproduce fuel assembly bows under experimental conditions. After a short review of the experimental tests, the CFD and finite element model, as well as the FSI method are introduced shortly.

2.1. Tests to determine fuel assembly hydraulic bow characteristics

The so called GLASSTRAN experiments (Stabel et al., 2011) have been performed in the PETER loop at Erlangen, Germany. They have been setup in a way to simulate the in-reactor situation: one central full scale (17 × 17) fuel assembly, surrounded by two quarter neighbouring fuel bundles (4 × 17). The cross section of the loop is shown in Fig. 1.

The quarter fuel assemblies at the periphery are so mounted that typical bow shapes can be rigidly imposed on them by a fixed connection with the moveable outer flow channel walls (in x-direction). A typical selection of such bow shape configurations is shown in Fig. 2 (exaggerated sketches; configuration name alludes to shape of peripheral fuel assemblies). The elastic bow response of the central (test) fuel assembly has been measured by optical laser triangulation sensors at the levels of spacer grids (SG). The working fluid has been water at 40 °C and 1.5 bar.