Thermal-fluid-structure coupling analysis for plate-type fuel assembly under irradiation. Part-I numerical methodology

Yuanming Li, Pan Yuan, Quan-yao Ren, Guanghui Su, Hongxing Yu, Haoyu Wang, Meiyin Zheng, Yingwei Wu, Shurong Ding

1. Introduction

The plate-type fuel assembly has been widely applied in the nuclear research reactor for the compact structure, large heat transfer area and low temperature in fuel foil, which suffered from high neutron flux, non-uniform irradiation effect, non-uniform temperature field and hydraulic load induced by high coolant velocity etc. The complex deformation behaviors would appear for the plate-type fuel assembly under the coupling effect of thermal-hydraulic loads and mechanical loads, such as expansion, swelling, and bending etc. The deformations would change the flow resistance, heat transfer coefficient [1], flow rate redistribution, critical heat flux (CHF) and departure from nucleate boiling ratio (DNBR) in the plate-type fuel assembly, which are of great significance for the safety of nuclear reactor. Therefore, it is necessary to conduct thermal-fluid-structure coupling analysis and make it clear the complex performance for plate-type fuel assembly under irradiation. However, it is very expensive and time-consuming to conduct irradiation experiments for plate-type fuel assembly, which is also difficult to carry out real-time observation and measurements to acquire valuable experimental data. Recently, some coupling numerical methods have been developed based on irradiation-induced thermo-mechanical coupling simulation method [2], thermal-hydraulic numerical simulation [4] and fluid-structure interaction simulation method [5–7], which served as an important tool to study the mechanical deformation and thermal-hydraulic behaviors for plate-type fuel assembly under non-uniform irradiation and temperature field. The related numerical researches would be introduced in detail as follows.
1.1. Irradiation-induced thermo-mechanical coupling simulation for fuel plate

Some researchers studied thermo-mechanical behaviors of fuel plates under irradiation by considering the irradiation effect of the related materials. Kim et al. [2] applied ABAQUS finite element analysis simulation to study the fission induced creep behaviors of U–Mo alloy fuel plate, which adopted a model for fission product induced swelling and creep. And ABAQUS simulation would produce the best fitting swelling data with experimental results with the creep rate constant of $500 \times 10^{-23}$ cm$^2$/MPa for U–10Mo alloy fuel. Zhao et al. [8] developed the three-dimensional large deformation increment constitutive relations and stress update algorithms in the co-rotational coordinate framework, which were implemented in ABAQUS via the user-defined subroutines UMAT and UMATHTH to analyze the irradiation-induced thermo-mechanical behaviors of monolithic U–Mo/Zr fuel plates with the three-dimensional geometrical model. Yan et al. [9] also simulated the in-pile thermo-mechanical behaviors of monolithic fuel plates with three-dimensional finite element method by adopting different creep coefficients for U–Mo fuel foils, which proved that the creep coefficient for U–Mo foils was intensively related to the service life of U–Mo/Al fuel plates. However, most of irradiation-induced thermo-mechanical simulating researches focused on the deformation of fuel plate, which did not show the total deformation of fuel assembly and consider the coupling effect between the irradiation deformation and the coolant thermal-hydraulic characteristics.

Moreover, some thermo-mechanical coupling analysis codes were developed by different researchers, including 1.5-dimensional or 2-dimensional fuel plate behavior codes (FRAPCON [10], FEMAX [11] and ROBA [12]) and 3-dimensional FEM codes (BISON [13,14], BEEs [15], CAMPUS [16]). However, the fluid was simplified as one-dimensional flow in the above-mentioned codes, which might ignore the effect of non-uniform irradiation, non-uniform temperature and non-uniform flow velocity field.

1.2. Thermal-hydraulic numerical simulation for fuel assembly

Many researches focused on the thermal-hydraulic behaviors for plate-type fuel assembly with the assumed non-uniform power distribution, local blisters or flow blockage. Gong et al. [1] utilized FLUENT to calculate the thermal-hydraulic characteristics of standard and control fuel assemblies, which adopted standard $k-\varepsilon$ model to simulate flow turbulence and user-defined function to define the energy source term. Li et al. [4] adopted RNG $k-\varepsilon$ model to analyze the flow and heat transfer characteristics in plate-type fuel channels with assumed different distributing blisters on fuel plate, which showed that blisters could disturb local coolant flow and increase the heat transfer resistance. Ma et al. [17] performed the three-dimensional CFD simulation for the flow blockage accidents in a single fuel assembly with six coolant channels, which was validated with RELAP5 calculation results. Three-dimensional transient CFD simulation on 90% inlet flow blockage accidents in rectangular fuel assembly was conducted with the dynamic mesh technique by Fan et al. [3], which was also compared with one-dimensional steady calculation result using RELAP5 code. The transient CFD simulation showed that the development of flow blockage transients was so fast that the rapid redistribution of mass flow rates would occur in 0.015 s after the blockage formation. In the study on the thermal-hydraulic characteristics, CFD method was usually adopted for different plate-type assemblies under different conditions with specific power distribution and inlet velocity, which always ignored the influence of deformation and the change of material thermal properties under irradiation.

1.3. Fluid-structure interaction (FSI) numerical simulation for fuel assembly

The thin fuel plates suffered from high coolant flow velocity, which might result in the hydraulic instability and flow induced deformation. On purpose of simulating the fluid-structure interactions, some researches were performed by coupling CFD method and finite element analysis (FEA) method. Javier et al. [6] established a two-way fluid-structure interaction methodology for predicting the onset of hydroelastic instability of plate-type fuel assemblies [6] and stability of fuel plates with inlet support comb [5] by coupling ANSYS CFX and ANSYS Mechanical, which transferred force from fluid to solid and displacements from solid to fluid. Kennedy et al. [7,18] developed the bidirectional coupling method between STAR CCM+ and ABAQUS to calculate FSI behaviors of parallel fuel plates for plate-type fuel assembly of Missouri Research Reactor, which showed the stability of two-way coupling numerical simulation could be reached at the expense of efficiency. The FLUENT-MPCCI-ABAQUS coupling technique was applied to calculate the fluid-structure interaction behaviors of flexible and bimetal plate [19], which demonstrated that the coupling methodology based on Mesh-based Parallel Code Coupling Interface (MPCCI) could predict the large bending of plate well and would be adopted in present study. Different commercial CFD and FEA softwares were coupled based on ANSYS platform, self-programming code or MPCCI to calculate the behaviors of plate-type fuel assembly based on bidirecitonal fluid-structure coupling method. However, the aforementioned FSI numerical simulation did not take the irradiation and temperature effect on material properties into consideration, which might underestimate the deformation of fuel plate. And it was of great significance to predict the deformation accurately for the safety analysis of nuclear reactor.

As discussed above, most researches focused on irradiation-induced mechanical deformation, thermal-hydraulic characteristics and fluid-structure interaction by ignoring some effects in the plate-type fuel assembly. Few researches devoted to the coupling methodology considering the effects of all factors, including non-uniform irradiation, non-uniform temperature field, stress distribution and hydraulic load etc. In this paper, the thermal-fluid-structure coupling methodology have been established for the plate-type fuel assembly under non-uniform irradiation by considering the thermal and irradiated material properties of fuel foil and cladding via subroutines of ABAQUS, which could simulate the complex behaviors of plate-type fuel assembly under the irradiation-thermal-fluid-structure coupling effect. Based on the developed numerical methodology, the effects of non-uniform irradiation and fluid on fuel plates would be analyzed, which could give advices for the modeling simplification for different research purposes and provide technical support for the optimization of the plate-type fuel assembly.

2. Thermal-fluid-structure coupling methodology for plate-type fuel assembly under irradiation

In order to realize the three-dimensional thermal-fluid-structure coupling simulation method for plate-type fuel assembly under the considered irradiation effects, it is necessary to combine the radiation-induced thermo-mechanical coupling simulation method with thermal-fluid-structure coupling simulation method by exchanging data. In the irradiation-induced thermo-mechanical coupling behavior simulation, the material properties related to irradiation (referred to Appendix 1 and 2) were adopted in establishing the three-dimensional large-deformation constitutive relations and stress update algorithms in the co-rotational coordinate framework, which were referred to Zhao et al. [8]. And the non-uniform irradiation conditions were introduced to calculate the
heat generation rate and the fission density at different locations of fuel assembly. The fluid domain would affect the temperature field and apply hydraulic load on the solid domain of fuel plates. In turn, the deformation of fuel plate would change the flow characteristics. Therefore, the bidirectional fluid-structure coupling method was adopted to solve the stationary coupling problem with the consideration of the flexibility and accuracy. In this method, the solid domain and the fluid domain were calculated independently as shown in Fig. 1.

The interaction between the solid domain and the fluid domain was achieved by exchanging data of coupling quantities (thermal-hydraulic parameters and displacement) across fluid-structure interfaces during each iteration step. Since the deformation of the fuel plates and the flow characteristics in fluid domain could be considered as quasi-steady for the slow deformation rate under non-uniform irradiation, the explicit coupling scheme was chosen in the present study. Moreover, the coupling scheme was set as steady computation, which was different from that of FSI numerical simulation \[5,6\]. If one code finished a step of the iteration, it sent its data on the interface to the other code, which used it as the boundary condition in its own iteration. Both iterations continued until converged, yielding a state which fulfilled the equation of both physical domains \[19\]. The size of coupling time step for the coupling scheme was set as 2 in MpcCI, which was also the increment step in ABAQUS. And the total coupling iteration steps were 60 in this study which represented 120 irradiation days.

As material properties were related to fission density or fission rate, it needed to be updated during the solid domain solution with the irradiation time in each iteration step. The flow chart of thermal-fluid-structure coupling methodology under irradiation is illustrated in Fig. 1. The detailed calculating process would be introduced in the following sections, including CFD model, CSD model and data exchanging method via MPCCI.

### 2.1. CFD model

The thermal-hydraulic behavior analysis for the fluid domain was achieved by FLUENT. Energy transfer model was employed to consider the heat transfer between coolant channel and cladding surface. Reynolds Averaged Navier-Stokes (RANS) turbulence models were widely adopted in the analysis of flow characteristics for its accuracy and computational efficiency. As a popular RANS model, the standard $k$-$\varepsilon$ turbulence model was adopted in the simulation of fluid domain in this study, whose accuracy were verified extensively in the narrow rectangular channels \[1,4\]. When the deformation appeared on the wall, the wall $y+$ value would change with the distorted meshes. Moreover, Scalable Wall Function was applicable for the larger range of $y+$ value than Standard Wall Treatment \[20\]. Thus, Scalable Wall Function would be selected. Since the wall $y+$ was proportional to the dimensionless normal distance from the wall, the appropriate mesh height of the first layer should be chosen to satisfy the requirement of Scalable Wall Function. With the plate wall deforming gradually under irradiation, it was necessary to adopt the dynamic mesh method to accommodate the boundary motion on the interface, which was accomplished with the mesh smoothing and remeshing. And the

---

**Table 1**

<table>
<thead>
<tr>
<th>Residual</th>
<th>Convergence criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>x-velocity</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>y-velocity</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>z-velocity</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Energy</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$k$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Epsilon</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** Flow chart of the thermal-fluid-structure coupling methodology for plate-type fuel assembly under irradiation.
Table 2
Mesh sensitivity analysis for fluid domain.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Element numbers</th>
<th>Pressure drop, $\Delta P$, Pa</th>
<th>Relative deviation of $\Delta P$</th>
<th>Averaged heat transfer coefficient, $h_{ave}$, W m$^{-2}$ K$^{-1}$</th>
<th>Relative deviation of $h_{ave}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.52e5</td>
<td>77129.2</td>
<td>1.74%</td>
<td>38193.7</td>
<td>0.48%</td>
</tr>
<tr>
<td>2</td>
<td>7.14e5</td>
<td>77357.8</td>
<td>1.44%</td>
<td>38405.2</td>
<td>-0.07%</td>
</tr>
<tr>
<td>3</td>
<td>1.42e6</td>
<td>77927.1</td>
<td>0.72%</td>
<td>38378.7</td>
<td>0.00%</td>
</tr>
<tr>
<td>4</td>
<td>2.05e6</td>
<td>78491.6</td>
<td>-</td>
<td>38379.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3
Convergence criterion in solid domain.

<table>
<thead>
<tr>
<th>Residual</th>
<th>Convergence criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{f}$: criterion for residual force/heat flux</td>
<td>0.005</td>
</tr>
<tr>
<td>$C_{f}$: criterion for displacement/temperature correction</td>
<td>0.01</td>
</tr>
<tr>
<td>$I_{0}$: first equilibrium iteration for consecutive divergence check</td>
<td>4</td>
</tr>
<tr>
<td>$I_{R}$: equilibrium iteration at which logarithm convergence rate check begins</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4
Mesh sensitivity analysis for solid domain.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Element numbers</th>
<th>Maximum temperature, $T_{m}$, k</th>
<th>error of $T_{m}$</th>
<th>Maximum displacement, mm</th>
<th>error of Maximum displacement</th>
<th>Maximum Mises stress, MPa</th>
<th>Relative deviation of Maximum Mises stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.97e5</td>
<td>436.9</td>
<td>7.18%</td>
<td>0.1262</td>
<td>61.36%</td>
<td>278.7</td>
<td>-0.30%</td>
</tr>
<tr>
<td>2</td>
<td>3.86e5</td>
<td>467.0</td>
<td>0.79%</td>
<td>0.2813</td>
<td>13.87%</td>
<td>297.6</td>
<td>0.55%</td>
</tr>
<tr>
<td>3</td>
<td>5.26e5</td>
<td>470.3</td>
<td>0.08%</td>
<td>0.3284</td>
<td>-0.55%</td>
<td>295.2</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>6.75e5</td>
<td>470.7</td>
<td>-</td>
<td>0.3266</td>
<td>-</td>
<td>296.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Convergence criteria in the fluid domain were listed in Table 1.

With the given inlet velocity of 5 m/s and inlet temperature of 308 K, four cases with different mesh elements were tested in FLUENT. The element number, pressure drop and heat transfer coefficient of the four cases were listed in Table 2. Due to the small errors, Mesh 3 was selected for the following calculated cases, which consisted of 9 mesh layers. And $Y_{+}$ value ranged from 30 to 100, which satisfied the requirement of Scalable wall function.

2.2. CSD model

For the irradiation-induced thermo-mechanical coupling model of the plate-type fuel assembly, the user-defined subroutines programmed in FORTRAN were introduced to define the thermomechanical constitutive relations of materials in commercial software ABAQUS, which was used as the computational structural dynamics (CSD) code. The subroutines UMATHT and UMAT were respectively used to program the thermal and mechanical constitutive relations of the related materials.

For the purpose of obtaining the in-pile thermo-mechanical behavior in monolithic fuel plates, the whole calculation process should be divided into enough time increments. Moreover, in order to obtain the convergent results for each increment, a sufficient number of equilibrium iterations were required. Meanwhile, the three-dimensional stress update algorithms and consistent stiffness moduli need to be provided to calculate equilibrium iteration and update the user subroutines, which were referred to Gong et al. [21].

In this study, the contributions of thermal expansion, swelling strains, creep strains and elastic strains were considered for the fuel foil as shown in Appendix I, while the thermal expansion and elasto-plastic strain were assumed for the cladding with the correlations shown in Appendix II. The flow chart and stress updating process are shown in Fig. 1. At first, the elastic strain, thermal strain and swelling strain were calculated for fuel foil while the elastic strain and thermal strain were calculated for cladding, which were based on the non-uniform irradiation and specific boundary conditions. Secondly, the creep strain increment was obtained for fuel foil according to the creep constitutive theory and the proof stress was obtained for cladding in every iteration step. Then, the plastic strain for cladding was calculated based on the flow rule when the local stress was larger than the yield strength. Finally, the Cauchy stress, strain and consistent stiffness modulus could be updated. Meanwhile, the thermal constitutive relation describing the relation between the thermal flux and temperature gradient was updated according to the fission rate distribution and temperature boundary in every time increment. Based on the above process, the thermal and mechanical constitutive relations were calculated respectively. And the convergence criteria in the solid domain were

Table 5
Structure parameters of fuel plate.

<table>
<thead>
<tr>
<th>Element</th>
<th>Height/mm</th>
<th>Width/mm</th>
<th>Thickness/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding</td>
<td>101.473</td>
<td>25.4</td>
<td>1.397</td>
</tr>
<tr>
<td>Fuel foil</td>
<td>82.55</td>
<td>19.05</td>
<td>0.254</td>
</tr>
</tbody>
</table>
listed in Table 3.

With the given heat transfer coefficient of 0.035 W/(mm²·K) and wall temperature of 323K, four cases with different mesh elements were tested in ABAQUS, whose results were listed in Table 4. According to the maximum temperature, displacement and Mises stress, Mesh 3 was selected for the following calculated cases, which consisted of 4 mesh layers in fuel foil and 2 mesh layers in each cladding side.

Fig. 3. Schematic of boundary condition.

Fig. 4. Deformation of L1P04A fuel plate in thickness direction on the 98th day (Unit: mm; deformation scale factor of 5).

Fig. 5. Comparison of the relative increment of fuel foil thickness between numerical result and experimental data.

Fig. 6. Illustration of the computational domain (unit: mm)(not scaled).
2.3. Data exchanging method via MPCCI

The physical parameters across the fluid-structure interfaces were exchanged via the MPCCI server. As shown in Fig. 2, the serial coupling algorithms were utilized. In every coupling step, the physical parameters exchanged across the fluid-structure interfaces included the relative pressure \( P \), film temperature \( T_f \) and heat transfer coefficient \( h \) in fluid domain, and the nodal position \( d \) and wall temperature \( T_w \) in solid domain.

In the first step, the coolant behavior was calculated in FLUENT based on the assumed initial temperature on the fluid-structure coupling interface. After convergence in fluid domain, the heat transfer coefficient, film temperature and relative pressure data on the coupling interface were sent to the CSD code as the boundary conditions in solid domain via the MPCCI server. On the basis of these data, the CSD code executed the thermo-mechanical coupling computation in the solid domain according to the non-uniform irradiation conditions, and updated the fission density in fuel foil, nodal position and wall temperature of the coupling interface after the convergence. Then, the nodal positions and wall temperature of the coupling interface were sent back to the fluid domain as the new thermal boundary conditions via the MPCCI server. Based on the updated boundary conditions, the CFD code continued to execute the subsequent computations. During the whole calculation process, the above steps were repeated and recycled constantly until the thermo-mechanical and thermal-hydraulic parameters were converged.

Based on the above methods, the multi-physics field simulation methodology was established to study the in-pile thermo-mechanical behavior and thermal-hydraulic behavior under the coupling effect, which could realize the coupling analysis on the mechanical and thermal-hydraulic behaviors for the plate-type fuel assembly under a time-dependent and location-dependent irradiation condition.

3. Validation and verification of coupling methodology

The best way to validate the developed coupling methodology is to compare the numerical results with the experimental data under the same boundary conditions. However, experiments focusing on the thermal-fluid-structure coupling behaviors of plate-type fuel assembly under irradiation were extremely scarce, which were mainly attributed to the huge expense, the lack of effective measuring devices and limited irradiation resource. Therefore, on purpose of validating the developed coupling numerical methodology, the experimental data of fuel plates considering some coupling factors were under the authors’ consideration, such as the thermal-mechanical behaviors under irradiation and fluid-structure interaction behaviors under different flow rate. In this section, the deformation behaviors of L1P04A fuel plates in RERTR-9 irradiation experiments conducted by Idaho National Laboratory [22] were adopted to validate the mechanical response for the developed coupling numerical methodology; the experimental deformation data of plate fuel plates under different fluid loads acquired by Kennedy et al. [18] was utilized to validate the fluid-structure interactions for the developed coupling numerical methodology; and the conjugate heat transfer result acquired in FLUENT were compared with the developed FLUENT-MPCCI-ABAQUS coupling method.

3.1. Validation of mechanical response prediction

Aiming at validating the thermal-fluid-structure coupling methodology under irradiation, L1P04A fuel plate model was established based on RERTR-9 irradiation summary report [22] by Idaho National Laboratory. And the main structure parameters are shown in Table 5. L1P04A monolithic fuel plates consisted of U–Mo fuel foil and Al alloy cladding. The material properties of U–Mo fuel foil are shown in Appendix I, while the properties of cladding (Al6061) are summarized in Appendix II.

The computational solid and fluid domain and boundary conditions are shown in Fig. 3. The thickness of the parallel coolant channels was 1.5 mm, whose inlet and outlet domain heights were both 50 mm. And the standard k-ε model and scalable wall function were adopted to calculate the thermal-hydraulic characteristics. The inlet velocity and temperature were set as 10 m/s and 325.15 K respectively, while the outlet and system pressure were 0 MPa and 2.5 MPa respectively, which was referred to the experimental condition of the L1P04A monolithic fuel plates in the RERTR-9 irradiation experiment [22,22].

The deformation of L1P04A fuel plate in thickness direction on

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( \rho_{\text{fl}} )</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio, ( v )</td>
<td>0.33</td>
</tr>
<tr>
<td>Young’s modulus, ( E )</td>
<td>68.9 GPa</td>
</tr>
<tr>
<td>Yield strength, ( \sigma_y )</td>
<td>276 MPa</td>
</tr>
</tbody>
</table>

Table 6.

Aluminum alloy 6061-T6 properties.

Fig. 7. Deformation contour of the plate. (Unit: mm; deformation scale factor of 100).

the 98th day is shown in Fig. 4, which shows obvious irradiation swelling along the edge of fuel foil at high fission rate. As shown in Fig. 5, the thickness increment calculated by FEA was compared with the experimental results [2], whose maximum relative error was less than 5%. This demonstrated the FEA result was in good agreement with the experiments and the developed thermal-fluid-structure coupling methodology for the mechanical deformation of fuel plates under irradiation is credible.

3.2. Validation of FSI response prediction

In order to validate the FSI model for the simulation of plate-type fuel assemblies, a finite element model consisting of a flat plate used by Kennedy [18] was modeled. Both Kennedy [18] and Javier GM [6] studied the flow-induced deformation for a flat plate located between two coolant channels with the coupling method between different softwares, and validated their simulation results with the experiments conducted by Kennedy [18]. The same geometry parameters and materials properties were considered in present FSI calculations with FLUENT-MPCCI-ABAQUS coupling method, which is shown in Fig. 6 and Table 6.

Fig. 7 shows the contours of deformation of the plate, which is the main concern. As can be seen, the maximum deformation of the plate occurs in the plate central area. The deformation profiles along the centerline from the trailing edge to the leading edge on the surface of the plate with the inlet flow rate of 2.3 kg/s and 2.6 kg/s were extracted and plotted in Fig. 8, in which the error bars represented 95% confidence interval of the experimental results. As can be seen, the deformation profiles on the leading and trailing edge calculated in this study showed good agreement with that observed in the experimental results [18]. However, three points at inner locations showed some differences with experimental results, which resulted from that the developed methodology did not simulate the imperfections on the experimental plate surface [5,18]. The absolute error was about 0.122 mm for all experimental data, and the absolute error would be about 0.048 mm if the three
deviated points were not considered. Furthermore, compared with other numerical results calculated by Kennedy et al. [18] and Javier GM [6], the established coupling numerical methodology also did an excellent job in predicting plate deformation with enough accuracy and reliability. Therefore, it could be concluded that the developed coupling methodology was credible in predicting fluid-solid-interaction behaviors.

3.3. Verification of thermal response prediction

The best way to verify the thermal response prediction was to compare the experimental results and calculated temperatures. However, no experimental data for the fuel temperature was available. Thus, the thermal response verification were performed in an indirect way: a comparison between the conjugate heat transfer method in FLUENT and the developed FLUENT-MPCCI-ABAQUS coupling method.

The calculation geometrical model for verification is the same as that in Section 3.1, and the solid domain ignoring the deformation was modeled in ABAQUS. And a typical axial cosine power peaking profile was adopted for the fuel foil. The temperature fields on the middle cross-section calculated by FLUENT and FLUENT-MPCCI-ABAQUS are shown in Fig. 9(a), which demonstrated that their temperature fields were in good agreement. Moreover, the temperature profiles along the dark line in Fig. 9(a) were compared between FLUENT and FLUENT-MPCCI-ABAQUS as shown in Fig. 9(b), whose maximum difference was about 0.5 K. Based on the above verification process, it was confirmed that the current numerical results for the thermal analysis was sufficiently accurate.

4. Application of the developed numerical methodology

There was no doubt that the mechanical behaviors and thermal-hydraulic characteristics for plate-type fuel assembly under irradiation based on the developed numerical methodology were distinct from those only considering the thermo-mechanical coupling effect [9] or fluid-structure interaction for fuel assemblies [6]. In this section, the comparison would be conducted on the basis of computational domain consisting of two fuel plates and three coolant channels for U–Mo/Al monolithic fuel plates, which had good prospects of application in the research nuclear reactor.

4.1. Computational domain

The geometrical model is shown in Fig. 10 while the physical boundary conditions are shown in Fig. 11. For the solid domain, the front and back red surfaces were fixed in x, y and z direction while the blue surfaces were the fluid-structure coupling interface. The trailing and leading edge of each plate were free. For the fluid domain, the uniform inlet velocity boundary condition was adopted.

![Temperature contour](image)

![Temperature profile](image)

Fig. 9. Comparison of the temperature characteristics obtained from FLUENT and FLUENT-MPCCI-ABAQUS.
with the velocity of 5.0 m/s and temperature of 308 K while the outlet boundary condition was set as pressure outlet with 0 MPa. The surface of the coolant domain in contact with the fuel assembly was set as coupling interface, which was also the boundary condition employed at the initial condition with the temperature of 320 K. The remaining boundaries were set as the adiabatic wall. Moreover, the system pressure was set as 1.5 MPa (see Fig. 11). In the nuclear reactor cores, the power distribution had typical non-uniform characteristics. Therefore, the corresponding irradiation condition was defined as Appendix III. For the convenience of analyzing the numerical results, some paths and channels are defined as shown in Fig. 12.

4.2. Effect of non-uniform irradiation

In this section, the effects of non-uniform irradiation would be discussed based on two cases: one considered the non-uniform fission rate and all material properties listed in Appendix I and II, while the other ignored the porosity of nuclear fuels, irradiation swelling and irradiation creep. And it should be noted that both cases adopted the same non-uniform fission rate (shown in Appendix III) and boundary conditions in fluid and solid domain (shown in Section 4.1).

4.2.1. Mechanical deformation

As shown in Fig. 13(a), the mechanical deformation without non-uniform irradiation decreased with the downward flow development, whose maximum value was located at the leading edge of the fuel plate. Moreover, the inward deformation appeared near the outlet. And these phenomena without irradiation were in accordance with Javier GM [5,6], which mainly resulted from the differential pressure across the fuel plate due to the entrance and outlet effect. However, as shown in Fig. 13(b), the maximum mechanical deformation with irradiation occurred at lower half of the fuel plates, whose value was dozens of times larger than that without irradiation. It could be deduced that the irradiation creep and swelling might play an important role in the change of mechanical deformation due to the irradiation.

As shown in Fig. 14, it was interesting to observe that the mechanical deformation increased with the irradiation time and the location of the maximum mechanical deformation moved from the leading edge of the fuel plate to $Y = -145$ mm when irradiation time increased up to 120 days. Aiming to clarify the phenomenon, the profiles of differential pressure across Plate 1 with different irradiation time along $Y$ direction were plotted in Fig. 14. Remarkably, there was a significant coupling correlation between differential pressure and mechanical deformation. As can be seen from Fig. 14, the evolution of differential pressure resulted from the variation of flow channel due to the deformation of fuel plates. To be detailed, the maximum differential pressure was always located at the downstream of the maximum deformation of fuel plates, which was the presentative and direct reason for the evolution of deformation of fuel plates under irradiation effect. In essential, the irradiation creep behaviors of fuel foil played a significant role in the evolution of deformation when compared with the static deformation of fuel plates without irradiation. It should be noted...
Fig. 12. Definition of paths and channels.

Fig. 13. Mechanical deformation with/without irradiation on 120th irradiation day.
Fig. 14. The effect of irradiation time on the mechanical deformation along Path1 (top) and differential pressure between the both sides of fuel plate 1 (bottom).

Fig. 15. Velocity contour on the cross-section at $Y = -136.5$ mm.
that the strain of material would increase with time at the same stress under the irradiation creep effect.

4.2.2. Flow redistribution

The flow velocity contour on the plane at $Y = -136.5$ mm (the axial location of maximum deformation shown in Fig. 14) is shown in Fig. 15. The flow velocity in Channel 1 and 3 under irradiation was larger than that without irradiation, which resulted from the smaller channel thickness of Channel 1 and 3 (induced by the mechanical deformations shown in Fig. 13). Moreover, the flow velocity profiles at the central lines of different channels with/without irradiation are plotted in Fig. 16. As regard to flow velocity without irradiation, it almost stayed at stable except for the entrance and outlet region, which mainly resulted from the large changes for streamlines and flow field at the inlet and outlet region. However, the flow velocities in different channels with irradiation fluctuated with the flow development along $Y$ direction, and the fluctuating trend of Channel 2 was opposite to that of Channel 1 and 3, which indicated that the flow velocity was inversely proportional to the channel thickness influenced by mechanical deformation shown in Fig. 14.

In order to evaluate the flow redistribution, normalized flow rate was defined as $f_i = \frac{Q_i}{\bar{Q}}$, where $Q_i$ was the flow rate in the $i$th channel and $\bar{Q}$ was the averaged flow rate for all channels. The normalized flow rates in different channels with different irradiation time were shown in Fig. 17. The flow rate in Channel 2 increased with irradiation time within 80 days, while decreased when irradiation time exceeded 80 days. And the flow rates in adjacent channels (Channel 1 and Channel 3) showed the opposite trend, which were associated with the mechanical deformation. Within 80 days, the mechanical deformation showed the similar trend and increased with the irradiation time as shown in Fig. 14. However, when the irradiation time was larger than 80 days, the negative value arose for deformation of Path 1 in $X$ direction for $Y > 0$, which gave rise to the decrement of flow rate in Channel 2.

4.2.3. Temperature profile

As shown in Fig. 18, the temperature profiles of fuel foil along Path 2 had small differences, and the maximum temperature of fuel foil increased about 2.5 K when the irradiation time was up to 120 days. And the maximum thermal conductivity coefficient in fuel foil region decreased from about 17.4 W/(m·K) to 16.2 W/(m·K) as shown in Fig. 19. Therefore, it could be deduced that the increasing temperature was mainly attributed to the swelling and decreasing thermal conductivity under irradiation effect. However, the maximum temperature at 120th day was only about 2.5K larger than that without irradiation, which might be neglected on the whole.

4.3. The fluid effect on mechanical deformation

In order to analyze the fluid effect on mechanical deformation of fuel plates, three cases have been established:

Case A, without fluid interaction: no physical parameters were exchanged between solid and fluid domain, and the film temperature $T_0$ and heat transfer coefficient $h$ for solid domain were the area-averaged value calculated in Case C, only the solid domain was calculated, whose other boundary conditions were the same as those in Section 4.1.

Case B, without fluid pressure interaction: the exchanging data
from the solid domain to the fluid domain was the same as that shown in Fig. 2, while only film temperature $T_0$ and heat transfer coefficient $h$ were transferred from fluid domain to solid domain; the boundary conditions for solid and fluid domain were the same as those in Section 4.1.

Case C, with fluid interaction: the exchanging data between solid and fluid domain was the same as that shown in Fig. 2; the boundary conditions for solid and fluid domain were the same as those in Section 4.1.

4.3.1. Mechanical deformation

The mechanical deformation of fuel plates on 120th day is shown in Fig. 20 while that of Plate1 along Path1 is shown in Fig. 21 for the three cases. It should be noted that the mechanical deformation in X direction represented the displacement from the original location for each nodes. As can be seen, Case A had the similar deformation shape with Case B, which mainly resulted from the similar thermal expansion for the similar convective thermal boundary and fuel foil temperature as shown in Fig. 22. However, Case C had the distinct deformation shape, whose deformation was much larger than Case A and B. The results highlighted that the hydraulic load on fuel plates due to differential pressure played a dominant role in mechanical deformation of fuel plates.

4.3.2. Thickness increment

The thickness increment of Plate 1 along Path1 on 120th day is shown in Fig. 23 for different cases. It should be noted that the thickness increment was the dimension change of fuel plate thickness and represented the swelling of fuel plate. The thickness increment of Case B almost had the same value as that of Case C, which is larger than that of Case A. The thermal boundary condition might be responsible for the differences of thickness increment.
which could be attributed to the differences of thermal expansion at different temperature with the same irradiation condition. It should be noted that the difference of thickness increment was so small that it might be ignored in some conditions.

5. Conclusions

The thermal-fluid-structure coupling methodology has been developed based on finite element model (FEM) and computational
fluid dynamic (CFD) for plate-type fuel assembly under non-uniform irradiation effects, which has been validated or verified in mechanical deformation, FSI and thermal response with experimental or other numerical results. The numerical coupling methodology was based on the two-way physical parameter exchanging method via MPCCI, in which the pressure, film temperature and heat transfer coefficient in fluid domain calculated by CFD were transferred to the solid domain as boundary condition while the nodal position after deformation and wall temperature in solid domain calculated by FEM were sent back to fluid domain to conduct CFD analysis. Meanwhile, the three-dimensional large deformation incremental constitutive relations and stress update algorithms were introduced to FEM by user-defined subroutines program for the fuel assembly under non-uniform irradiation effects, and the deformation of fluid domain was accomplished with dynamic mesh method in CFD. Based on the established methodology, the effects of non-uniform irradiation and fluid on two fuel plates were discussed. And the following conclusions could be researched:

(1) The maximum mechanical deformation with irradiation occurred at lower half location of the fuel plate, whose value was dozens of times larger than that without irradiation. And with the irradiation time increasing, the mechanical deformation increases and the location of the maximum mechanical deformation moves downward from the leading edge of the fuel plate.

(2) The flow rates in different channels were affected by irradiation time, which might reach the maximum/minimum value at a certain time under the effect of mechanical deformation.
(3) The temperature of fuel foil increased with irradiation time but at a small amplitude, which might be neglected as some conditions.

(4) The hydraulic load resulting from the differential pressure across fuel plates played a dominant role in mechanical deformation.

(5) The thickness increment of fuel plates considering fluid thermal boundary was slightly smaller than that without fluid interaction for the thermal expansion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful for the support of the Natural Science Foundation of China (Grant No: U1867219, 11675161).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.10.016.

References


