FLUID-STRUCTURE INTERACTION IN A WIRE-WRAPPED ROD BUNDLE COOLED WITH SUPERCRITICAL WATER

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ABSTRACT

The Supercritical Water Reactor (SCWR) is under consideration as one of the 4th generation nuclear reactors. In a SCWR the reactor core is cooled with supercritical water (SCW), which has distinctive advantages over water at subcritical conditions as used in current light water reactors (LWRs). Main advantages are, for instance, the expected higher thermal efficiency and simplified plant design.

For the design and operation of a SCWR, the characteristics of the heat transfer from the fuel rods to the SCW coolant needs to be well understood. These heat transfer characteristics are complex and cannot be captured by the correlations that are currently available in literature. First of all, the physical properties of SCW undergo strong changes near the pseudo-critical point which complicate the flow and heat transfer. Secondly, there is the complicated flow structure in the channels between the fuel rods separated by spacers. This is in particular true for the European design of the SCWR, which makes use of wire spacers that are wrapped around each fuel rod. In this respect, Computational Fluid Dynamics (CFD) analyses are essential.

The present paper focuses on the analyses of flow and heat transfer in a wire-wrapped 4-rod fuel assembly that are performed within the framework of the European SCWR-FQT project. Conjugate heat transfer analyses performed with the STAR-CCM+ CFD software. In order to determine the resulting thermal stresses and deformation of the fuel rods, structural analyses have to be performed based on the temperature distribution predicted by CFD. Due to the complex geometry and boundary conditions, the FSI problem was solved using STAR-CCM+ in combination with the structural code ANSYS.

KEYWORDS
Supercritical Water Reactor, heat transfer, FSI, rod bundle

1. INTRODUCTION

The SuperCritical Water-cooled Reactor (SCWR) is one of the six selected nuclear systems within the Generation IV International Forum [1]. The SCWR operates at high temperature and high pressure, using water above the thermodynamic critical point (374°C, 22.1 MPa) as coolant. It is expected that a SCWR will be more economical than conventional light water reactors with higher efficiency and better fuel utilization, producing less radioactive waste per kWh while still fulfilling the high safety standards. As fossil fired power plants already use supercritical water as coolant and the SCWR can be seen as evolutionary development from existing LWRs, certain components and technologies can be adopted from these proven systems. This minimizes the technical and financial risks.

In the development of the SCWR, significant progress has been achieved in recent years in developing basic technologies, such as materials for fuel cladding and heat transfer predictions for supercritical water (SCW) conditions. Core, reactor and plant design concepts have been worked out in substantial detail for the European High Performance Light Water Reactor (HPLWR), the European concept of the SCWR [2]. As a next step in the development of the HPLWR, it is planned to test materials and components for a small scale fuel assembly with 4 fuel pins under typical prototype conditions in the LVR-15 research reactor in Rez, Czech Republic. Design, analysis and licensing of this fuelled in-pile test section including the required loop with safety and auxiliary systems is subject of the SCWR-FQT (Fuel Qualification Test) project within the 7th Framework Programme of the European Commission [1]. This first nuclear facility cooled with supercritical water, being an in-pile loop in a research reactor is planned to be operational in 2015.

Within the SCWR-FQT project structural analyses, flow and heat transfer analyses and neutronic analyses will be performed to ensure the integrity of the in-pile test section including the fuel rods under normal steady-state operation, as well as during start-up and shut-down. In this paper, flow, heat transfer and structural analyses are presented for the wire-wrapped 4-rod FQT fuel assembly under normal steady-state operation. First, the non-uniform temperature distribution on the fuel rods is determined with CFD analyses. Next, structural analyses are performed to determine the thermal deformation and stresses in the fuel rods. These structural analyses are based on the fuel rod temperatures predicted with CFD.

2. SCWR FUELED LOOP

The Nuclear Research Institute in Rez offered the necessary infrastructure with their LVR-15 research reactor to test the small scale 4-pin fuel assembly in a critical arrangement and under reactor typical conditions. This comprises a realistic heat and mass flux, as well as realistic temperatures and pressures. The 4-pin fuel bundle shall be inserted into a pressure tube to be installed in the existing LVR–15 research reactor by replacing one of its fuel elements. The pressure tube containing the 4-pin fuel bundle will be connected with coolant pumps, safety and auxiliary systems to simulate a SCW environment at the fuel rods while the rest of the core is operated at ambient pressure.

The fuel rods are placed inside a square assembly box with rounded corners as shown in Fig. 1. The fuel rods have an inner/outer diameter of 7/8 mm and a length of 600 mm to match with the LVR-15 core height. The rod-to-rod pitch is 9.44 mm. A helical wire wrapped around each fuel rod acts as spacer and enhances mixing. These wires have a diameter of 1.44 mm and an axial pitch of 200 mm. The overall length of the selected computational domain is 721.2 mm. The SCWR loop is operated at a pressure of 25 MPa, with a corresponding pseudo-critical temperature of 385 °C. During normal operation the SCW coolant enters the heated section at about 366 °C and flows in upward direction through the fuel assembly with a flow rate of 0.25 kg/s. The nominal fissile power of the fuel rods is 63.6 kW (15.9 kW per fuel rod). Maximum allowable peak temperature of the fuel cladding is 550 °C.

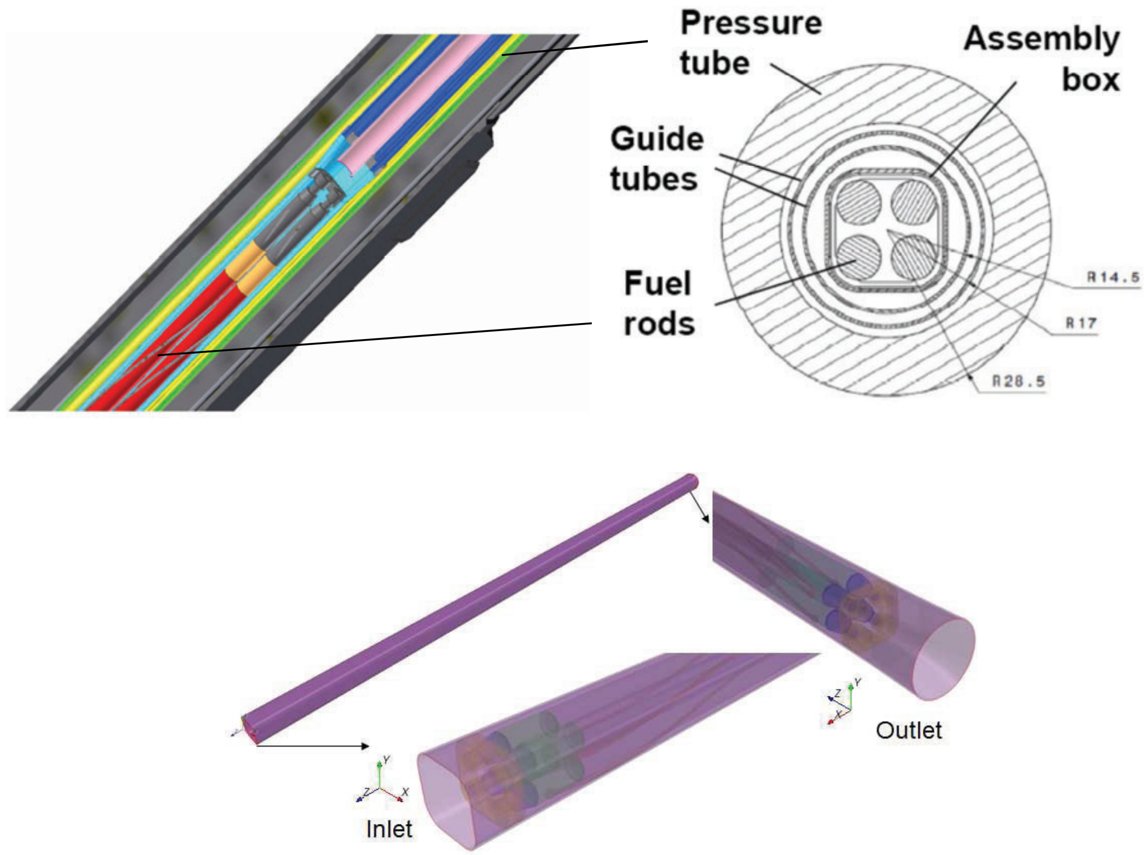

Figure 1. (Top) SCWR-FQT test section: On the left a view inside the test section with the fuel rods in red and on the right a cross-cut through the active channel (Bottom) Selection of the computational domain.

3. CFD ANALYSES

The CFD analyses presented here are performed with the commercial CFD code STAR-CCM+ 7.06 [3]. The main fluid dynamics model describes a single phase, steady state, isobaric, turbulent flow. Hence, incompressible steady state calculations are performed by using the Reynolds Averaged Navier-Stokes (RANS) modeling approach. A wide range of RANS models has been tested in [4-10] in order to assess their prediction capabilities for super-critical fluids. These studies showed that RANS models can successfully describe normal heat transfer of supercritical fluids. For the present study, the SST k-ω turbulence model with all y+ wall treatment is selected for the normal heat transfer analyses of the 4-rod fuel assembly.

The temperature dependent properties of SCW are implemented in the applied STAR-CCM+ code for viscosity, density, thermal conductivity and specific heat. These temperature dependent properties are adopted from the NIST database [11] and shown in Fig. 2. The fuel rod cladding and wire wrap spacer is made from stainless steel grade 316L (SS 316L). A constant density of 8030 kg/m3 and constant heat capacity of 502.5 J/kg.K is used in the CFD model for SS 316L [12]. The thermal conductivity of SS 316L increases linearly from 13W/m.K at 0 °C to 30 W/m.K at 1000 °C.

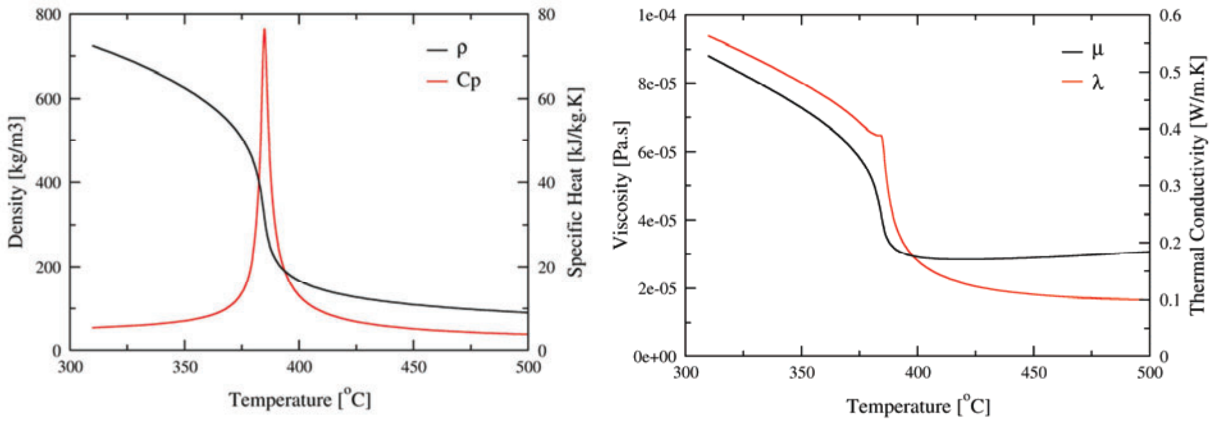

Figure 2. Temperature dependent properties of SCW at 25MPa [11].

Fig. 3 shows the modeled geometry and mesh. The full 4-rod fuel assembly is modeled with a rod-wire distance of -0.1mm over the full length of the wire, meaning that the rod and wire are in contact with each other. A minimum gap of 0.1 mm is assumed between wire and neighbouring rods and between wire and assembly box wall. It was found from an earlier study that the influence of the rod-wire contact area and/or the rod-wire gap on the cladding temperature is small [13]. The same study also showed that conduction through the cladding and wire plays an important role in the loss of heat from the fuel rods. Conduction through the cladding and wire is, therefore, included. A computational mesh of around 23 million cells is generated, 19 million fluid cells and 4 million solid cells. The cells are refined near the heated fuel rod walls to resolve the thermal and viscous boundary layer. The non-dimensional distance of the first cell to the heated fuel rod wall (y+ value) is around 10 on average. In all calculations, second order upwind schemes have been used for spatial discretization.

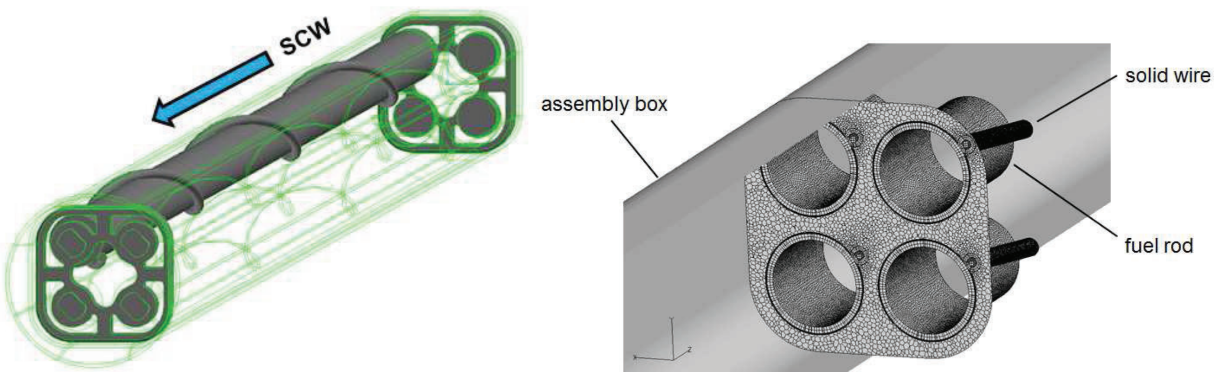

Figure 3. CFD geometry and mesh. The picture on the left shows the geometry of one of the four wire-wrapped rods as well as the rod support plates at bottom and top. On the right, a cross section through the FQT fuel assembly with mesh.

The predicted temperature distribution on the outer and inner surface of the fuel rods is shown in Fig. 4. For better visualization the square box with rounded corners around the fuel assembly is not shown and the whole assembly is scaled by a factor of $1/10^{th}$ in axial direction. The temperature on the inner surface is about 25 °C higher on average. The highest temperatures are found at $1/3^{rd}$ of the fuel rod height. Nevertheless, the calculated cladding temperatures stayed well below the acceptable peak cladding temperature of 550 °C.

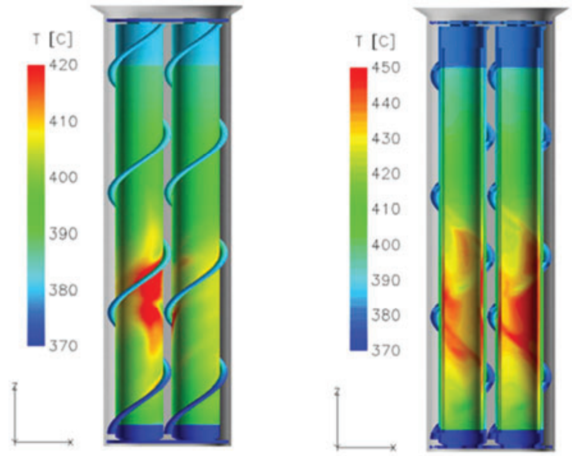

Figure 4. Temperature distribution on outer (left) and inner surface (right) of the fuel rods

4. STRUCTURAL ANALYSES

Structural analyses are performed with ANSYS 14, using the linear elastic model. All solid parts of the FQT test section are modeled, including the four rods with 0.5 mm thick walls and solid head/tail pieces, the solid helical wires wrapped around the rods, the rod support plates at top and bottom of assembly, and the 0.5 mm thick wall of the assembly box around the wire-wrapped rods. The geometry and mesh applied in the structural analysis is shown in Fig. 5. Close to one million (solid 186) elements are used to represent the solid parts of the FQT fuel assembly. The rods and assembly box are fixed at the lower end and are allowed to expand freely at upper end. The helical wires are fixed to the rods at the lower and upper end. A standard contact with friction coefficient of 0.1 between wire and rod and wire and assembly box is assumed.

Figure 5. Geometry and mesh for structural analysis.

The thermal expansion coefficient and Young's modulus of SS 316L are implemented as function of temperature. The instantaneous thermal expansion coefficient increases linearly from $1.63 \cdot 10^{-5}$ 1/m.K at 0 °C to $2.24 \cdot 10^{-5}$ 1/m.K at 800 °C. The Young's modulus decreases linearly from $200 \cdot 10^{3}$ MPa at 0 °C to $135 \cdot 10^{3}$ MPa at 800 °C. The reference temperature is set to 20 °C and pressure differences between inside and outside of the fuel rods are not considered in the structural analysis.

The thermal deformation and stress analyses is based on the temperature distribution calculated by CFD and presented in the previous section. Therefore, the temperatures obtained with CFD are first mapped onto the solid mesh constructed in ANSYS 14. Fig 6 compares the temperatures from CFD with the temperatures from ANSYS after mapping and demonstrates that the mapping procedure works well. The big grey areas is nothing but a visualization error occurs during this mapping procedure.

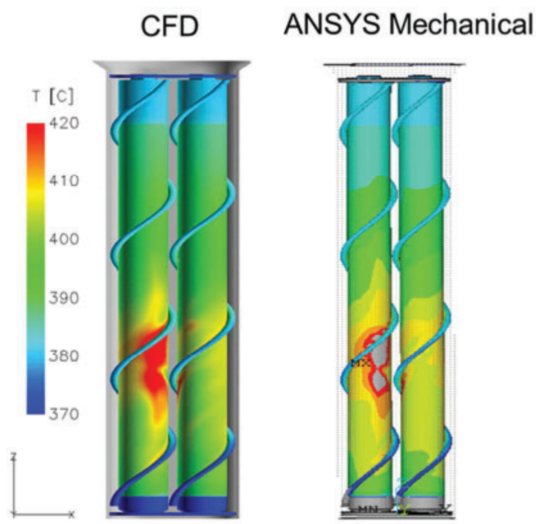

Figure 6. Comparison of the temperature distribution from CFD and the temperature distribution in ANSYS after mapping.

The structural analyses show that the fuel rods will bend slightly due to the non-uniform temperature distribution over the rods. A maximum horizontal displacement of the rods of up to 0.25 mm is observed. As shown in the scaled picture in Fig. 7, the rods bend in outward directions, away from each other and towards the assembly box wall. As a result, the wire spacer wrapped around each rods is pressed against the assembly box at some points, as shown in the second picture in Fig. 7. At these points, stresses just above the yield strength of SS 316L have been predicted. Since these peak stresses will relax directly after local plastic deformation, they are not a source of concern for safety.

5. CONCLUSIONS

The objective of the European SCWR-FQT project is to design and license a small scale supercritical water cooled fuel assembly with 4 fuel pins in the LVR-15 research reactor in Rez, Czech Republic. This paper presents CFD and structural analyses of the heated 4-pin fuel assembly under normal steady-state conditions. The CFD analysis of the heated 4-rod FQT fuel assembly shows that the peak cladding temperature stays well within the allowable limit of 550 °C. The structural analysis based on the temperature distribution calculated with CFD, shows that the fuel rods deform due to the non-uniform cooling. Due to the thermal deformation the rods bend towards the assembly box around the four fuel rods, pressing the wires against the assembly box wall at some points. High local stresses are predicted at these points. However, these peak stresses will relax directly after local plastic deformation and will not form a concern for safety. Nevertheless, this plastic deformation will have an influence on the thermal-hydraulic analysis, which is foreseen to be performed in the near future.

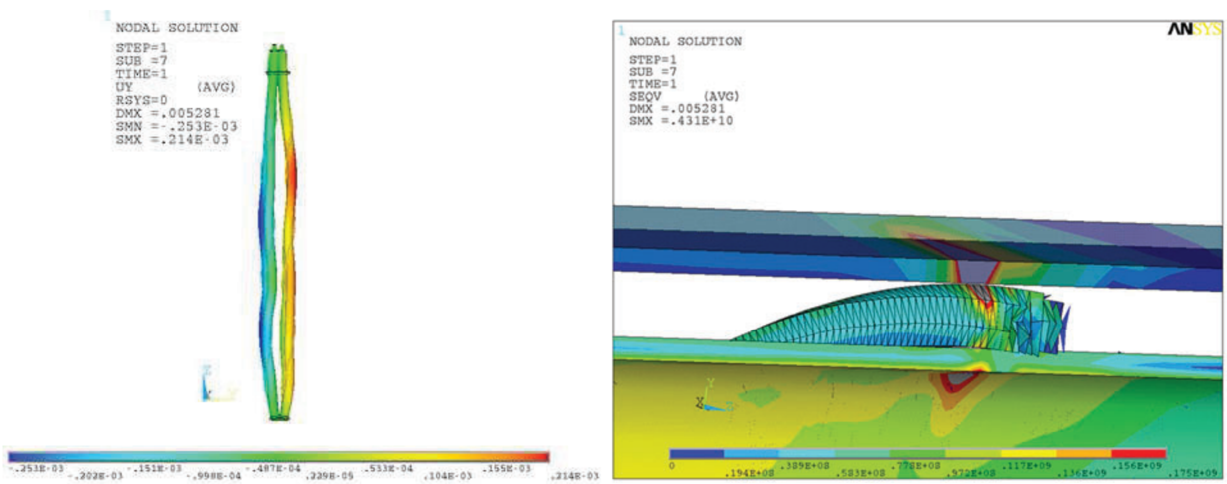

Figure 7. Left, the thermal deformation due to non-uniform cooling (scaled with factor 400 for better visualization). Right, the localized stresses as the result of bending of the rods towards the assembly box.

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