RECENT RESULTS OF RESEARCH ON SUPERCRITICAL WATER-COOLED RECATORS IN EUROPE

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Abstract

In Europe, the research on Supercritical Water-Cooled Reactors is integrated in a project called "High Performance Light Water Reactor Phase 2" (HPLWR Phase 2), co-funded by the European Commission. Ten partners and three active supporters are working on critical scientific issues to determine the potential of this reactor concept in the electricity market. The recent design of the HPLWR including flow paths is described in this paper. Exemplarily, design analyses are presented addressing neutronics, thermal-hydraulics, thermo-mechanics, materials investigations and heat transfer.

1. Introduction

The High Performance Light Water Reactor (HPLWR) is a Light Water Reactor (LWR) with supercritical water at 25MPa as coolant and moderator. Co-funded by the European Commission, a consortium of 10 partners from 8 European countries and three so-called active supporters are working on critical scientific issues within the project "High Performance Light Water Reactor Phase 2" which last from 2006 until 2010. The objective of this project is to assess the feasibility of this reactor concept to determine the potential in the electricity market as described in more detail by Starflinger et al. [1]. This European project is part of the Generation IV International Forum research activities on Supercritical Water-Cooled Reactors (SCWR) carried out in Japan, Canada, South Korea, and Europe. There are also activities in China and Russia in this field.

Inside the reactor core of a HPLWR, water at a pressure of 25MPa is heated up from 280°C to 500°C, thus gaining an enthalpy rise of 1936 kJ/kg according to the IAPWS steam table [2]. In comparison to a modern PWR, like European Pressurized Water Reactor (EPR) with about 190 kJ/kg (15.5 MPa, 296°C to 328°C), the heat input in the core is 10 times larger. Consequently in order to reach the same energy (in kJ), a 10 times lower mass flow rate is required for the HPLWR concept. Due to the high steam parameters, a net cycle efficiency of about 44% and, due to much lower mass flow rate, a reduction of component sizes are envisaged, which strongly contribute to reduce the electricity generation costs and capital costs of this nuclear power plant, as described by Bittermann et al. [3]. Hence, the HPLWR has the potential to serve as a further step in the 1000MWe class of Light Water Reactors.

2. High Performance Light Water Reactor Phase 2

The European project "High Performance Light Water Reactor Phase 2" started in September 2006 with a 12 month "Initial Design Phase", after which a 1st design review was carried out, followed by a 12 month "Design Analysis Phase" (see Figure 1). The mid-term assessment of the project took place in September 2008, at which the 2nd review took place. From September 2008 to February 2009, a 6 month "Refinement of Design" is foreseen, followed by "Analysis of Refined Design". The concept of HPLWR shall be available after three years, where a final technical review shall be carried out. The last 6 months of the project are reserved for an assessment of the HPLWR concept.

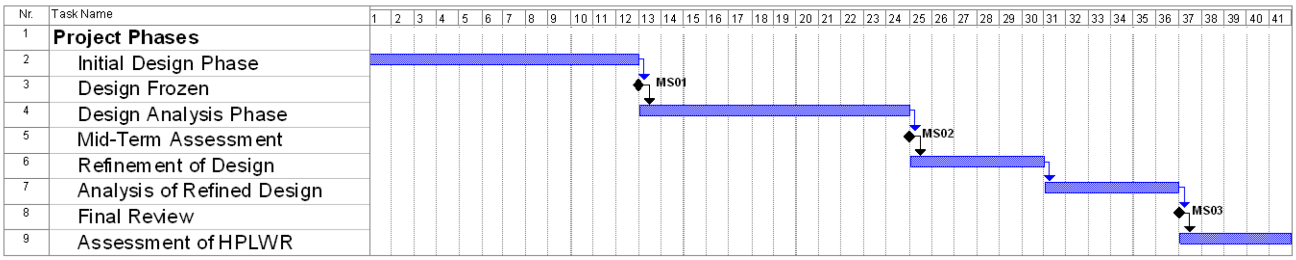

Figure 1 Phases of HPLWR Phase 2

3. General Design and Flow Path

The European HPLWR design is based on a pressure vessel type light water reactor as reported by Fischer et al. [4] and has been developed further with respect to the moderator flow path and sealing concept. The most recent design is described in detail by Koehly et al. [5]. It was necessary to change the flow direction of the water in the gaps between the assemblies from downwards to upwards to avoid possible flow reversal as predicted by calculations from Kunik et al. [6]. The new flow path is described in Chapter 3.1.

Figure 2 shows the improved reactor pressure vessel (RPV) and its closure head, inlets and outlets, core barrel, upper and lower mixing plenum, control rod guide tubes and exemplarily three fuel assembly clusters indicating the three heat-up steps of the core: evaporator, superheater 1 and superheater 2. The elaboration of this "three-pass core" is described in detail in Schulenberg et al. [7]. The total height of the HPLWR is 14.3 m with an inner diameter of the RPV of 4.5 m. Figure 2 shows also the flow scheme of coolant and moderator water. The blue arrows indicate feedwater and moderator water flows. The light brown arrows indicate the coolant flow inside fuel assemblies.

3.1 New Flow Path

Water at supercritical pressure of 25MPa and a temperature of 280°C is entering the reactor pressure vessel through four inlet flanges, each of them equipped with a backflow limiter. The feedwater flow is split into two parts of 50% (blue arrows in Figure 2). One stream flows downward through the downcomer towards the lower plenum of the reactor pressure vessel. The other part flows upwards to the RPV head, from there heading downwards through and along the control rod guide tubes, and through the moderator tubes of the fuel assemblies. At the lower end of a fuel assembly in the cluster foot piece, the moderator water is guided outward to the volume between the fuel assemblies (the so-called gaps). Inside these gaps, the moderator water flows upward and leaves the core region through the reflector and is guided to its lower end for reflector cooling. The moderator leaving the reflector is mixed with downcomer water in the lower mixing chamber and enters as coolant the evaporator region. The coolant flow path is indicated with light brown arrows in Figure 2. Heated-up to about 390°C, the coolant leaves the evaporator region, is mixed in the upper mixing chamber and enters the superheater 1 core region flowing downwards. At the lower end of the core, there is another mixing chamber homogenizing the coolant temperature to about 433°C. Leaving this mixing chamber flowing upwards, the supercritical water is heated up to 500°C in the superheater 2 and leaves the reactor pressure vessel through co-axial pipes directly to the turbine.

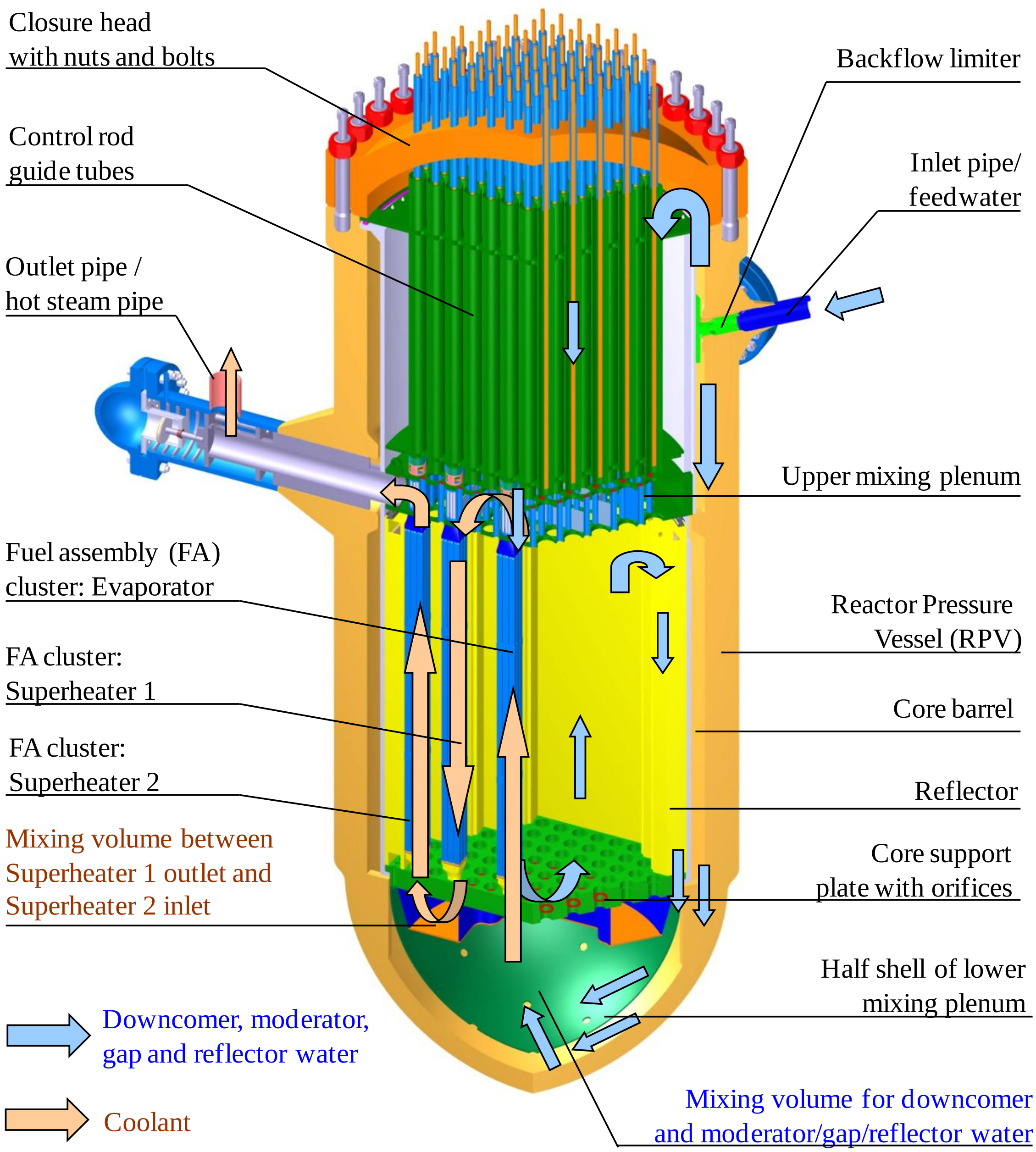

Figure 2 Reactor Pressure Vessel (RPV) design with internals and flow path (Koehly et al. [5])

3.2 Fuel Assembly Cluster

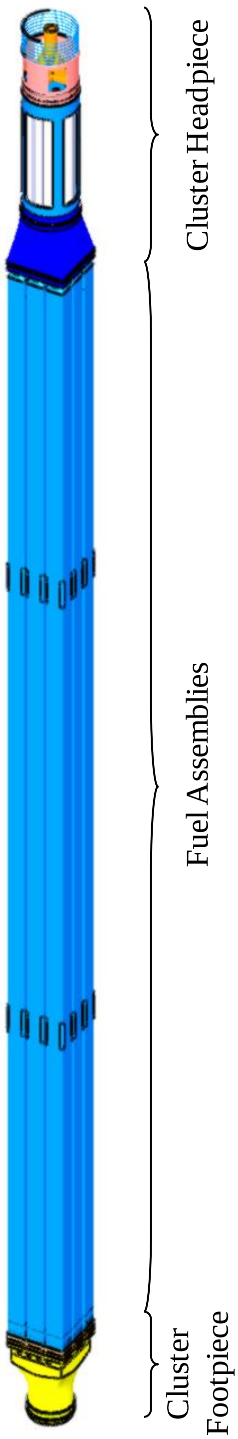

Figure 3
Fuel Assembly
Cluster

Figure 3 shows a fuel assembly cluster, which consists of nine fuel assemblies, which are connected at the top and the bottom with a common head- and foot piece (see Figure 4). Between them are gaps of 9 mm. To minimize bending of the assembly boxes during operational conditions, e.g. due to power gradients, two spacer pads are attached on each edge of the assembly boxes.

At the top, each cluster is equipped with a head piece (see Figure 4, left) containing five control rods lumped together in one technical device in form of a “spider”: One control rod is located in the center and four other on each side of it. The corner assemblies are not equipped with control rods, because the moderator tubes in the corner assemblies are intentionally bent in the headpiece. The fuel assembly head piece integrates nine assemblies into one device, which consists of a transition piece, a window element and a bushing. The window element can freely expand in the upper mixing plenum and is sealed with C-rings at the upper and lower end of the window. Fischer et al. [8] showed the leak-tightness between the fuel assembly head piece and the upper mixing plenum with a thermo-mechanical stress and deformation analysis under normal operating conditions. With the present sealing concept, a leakage flow of cold moderator water into the hot supercritical steam can be avoided. The head piece can be lifted grapping the bushing. A spring is attached at the top of the bushing to avoid floating of the assembly cluster during reactor operation.

At the bottom of a fuel assembly cluster, the nine assembly boxes are welded and screwed to the common foot piece (Figure 4, right) as described by Fischer et al. [4]. Also shown are the outlet openings in the foot piece, through which moderator water is released from the moderator boxes inside the assemblies into the gaps between them. The cluster is standing on the core support plate and is sealed with two piston rings to avoid leakage flow of moderator water into the hot core coolant. The foot piece can be disassembled to remove fuel rods for inspection or repair.

Moderator and Assembly Boxes

The moderator and assembly boxes consist of composite walls (see Figure 5), as described by Herbell et al. [9]. The tasks of these walls are to separate the hot coolant from the cold moderator inside the gaps and inside the moderator boxes, to guide the control rod inside the moderator box, simultaneously withstanding the stresses in the walls without using too much neutron absorbing material. It should be mentioned here that Zircalloy oxidizes fast at very high temperatures in supercritical water and cannot be used. Instead, stainless steel is proposed for the walls. In turn, stainless steel contains Nickel, which absorbs neutrons and decreases the criticality. Having this in mind and taking airplane construction principles into account, the box walls shall consist of a honeycomb-structure, which is filled with zirconia and covered with two thin stainless steel walls.

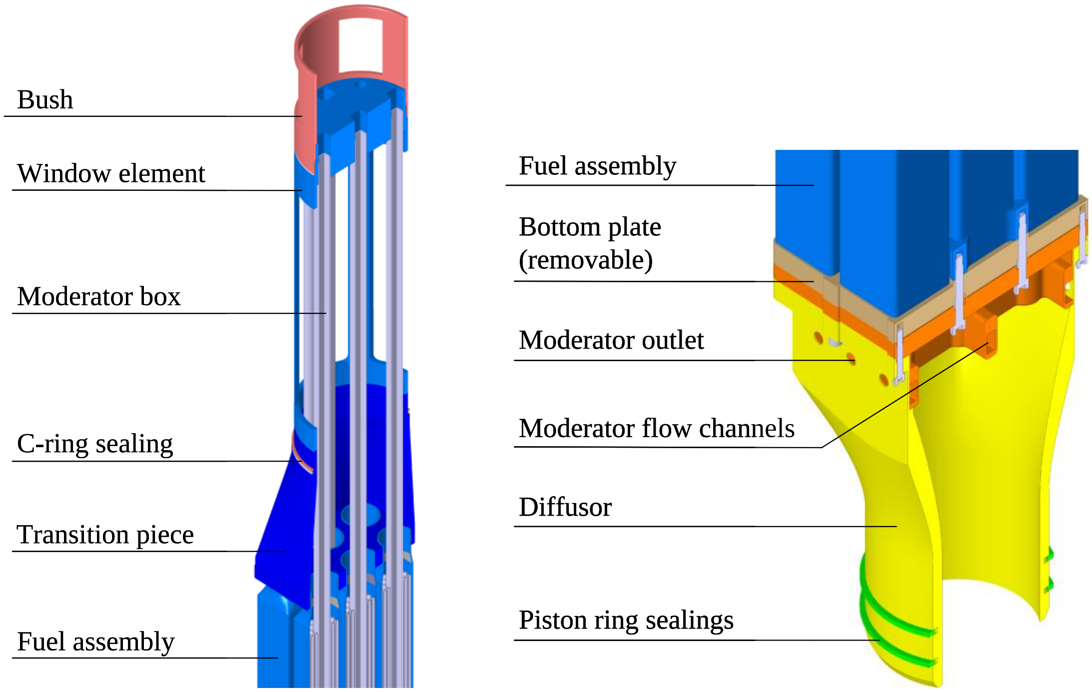

Figure 4 Cut through Head and Foot Piece of a HPLWR fuel assembly cluster

Such a honeycomb composite wall provides a good compromise between use of stainless steel and mechanical properties required to withstand pressure differences across the walls and other forces. The holes in the walls facing to the moderator and gap water avoid the deformation of the wall into the honeycombs once the reactor is at 25 MPa pressure. Wire wraps are used as spacers for good mixing of the coolant flowing through the fuel assembly (see Figure 5). It should be noted that such an innovative design has never been used in the nuclear environment and must be tested, e.g. mechanically investigating possible vibrations, etc.

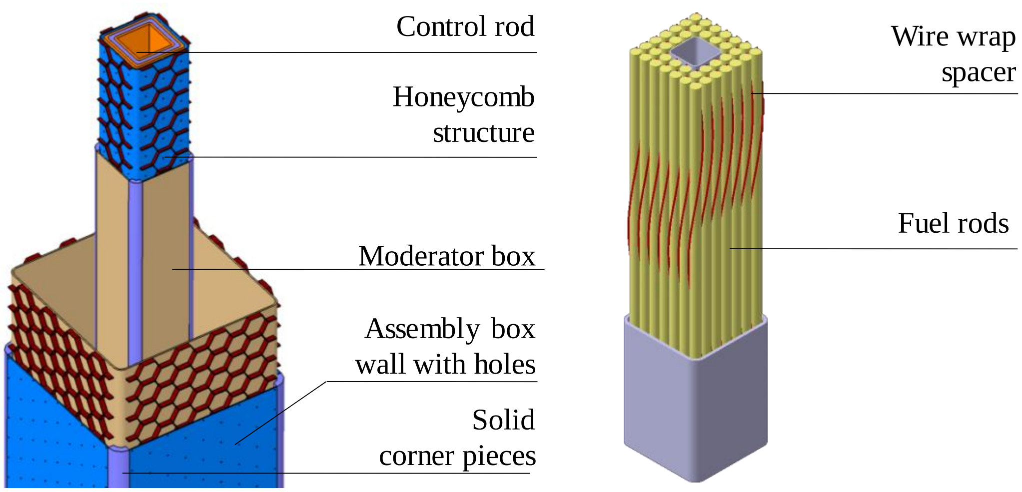

Figure 5 Honeycomb box walls and wire wrapped spacers

4. Analyses

During the design phase of the HPLWR project, the design work was supported mainly by simple approaches and “hand calculations”. After the first review, this design was frozen to be analysed with modern neutronics, thermal-hydraulics and structural mechanics codes. Brief examples of the results are described below. More detailed information about the analyses being carried out can be found in Starflinger et al. [10].

4.1 Coupled Neutronics / Thermal Hydraulics

The three pass core was analysed at AEKI-KFKI, Hungary by means of the coupled code system KARATE-SPROD. KARATE is a multi-group neutronics code developed by AEKI-KFKI, SPROD a sub-channel analysis code developed by the University of Tokyo. Both codes have been improved to deal with supercritical water and specific HPLWR boundary conditions like downward flow [11].

Having the flexibility of shuffling fuel assemblies after one year burn-up, AEKI-KFKI started to optimize the radial power profile further to obtain a uniform power profile in each region with a power ratio of regions [12]. While the power distribution in the evaporator turned out to be rather uniform in this coupled KARATE-SPROD analyses, the second superheater showed a pronounced radial power gradient, causing hot assemblies close to the first superheater and colder ones close to the reflector. A neutronic analysis with different reflector designs showed that the reflector should rather be build with a water layer of approximately 100mm thickness, in average, close to the second superheater assemblies, instead of the initial steel reflector. This would flatten the radial power profile in the superheater, but would increase the neutron fluence of the reactor pressure vessel, which is expected to be tolerable though. As depicted in Figure 6, the radial power peaking factor in SH2 can be reduced from 1.53 (red colour in Figure 6, left) to 1.39 (orange colour in Figure 6, right)). The recent design [5] has already been changed accounting for the inclusion of this 100mm water layer in the reflector. The neutronic core optimization is ongoing.

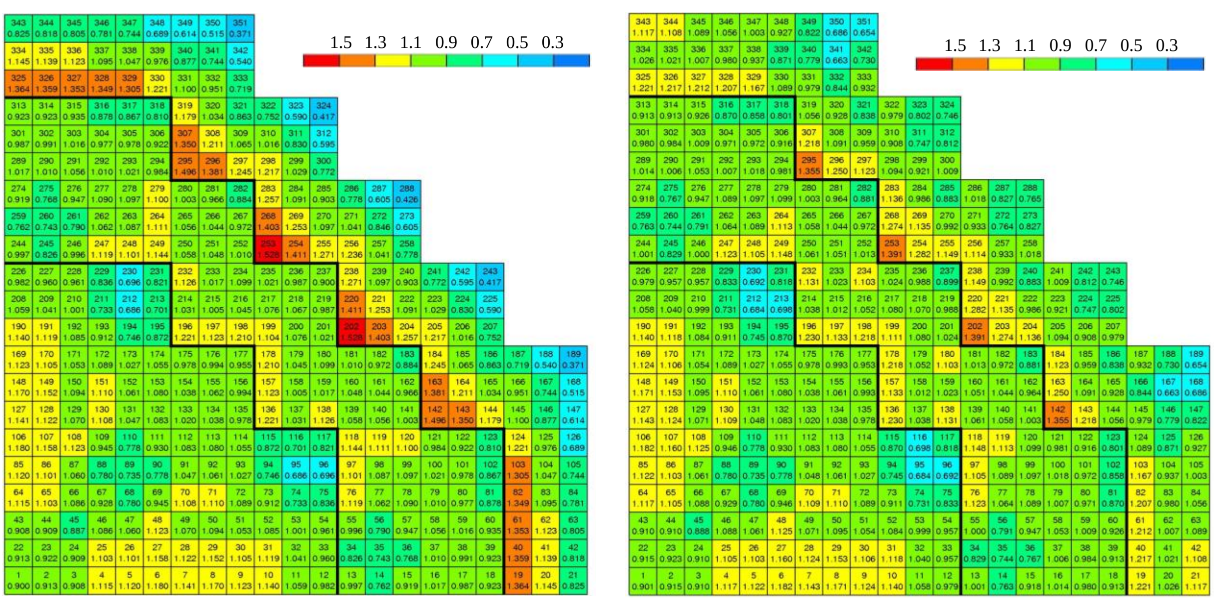

Figure 6 Local power peaking factors for each core region with steel reflector only (left) with 10cm water layer (right)

4.2 Thermo-Mechanical

Thermo-mechanical analyses have been performed for several parts of the reactor to verify the mechanical stability. Fischer et al. [8] examined the RPV and upper mixing plenum. Recent results of finite element analyses of the lower mixing plenum can be seen in Figure 7.

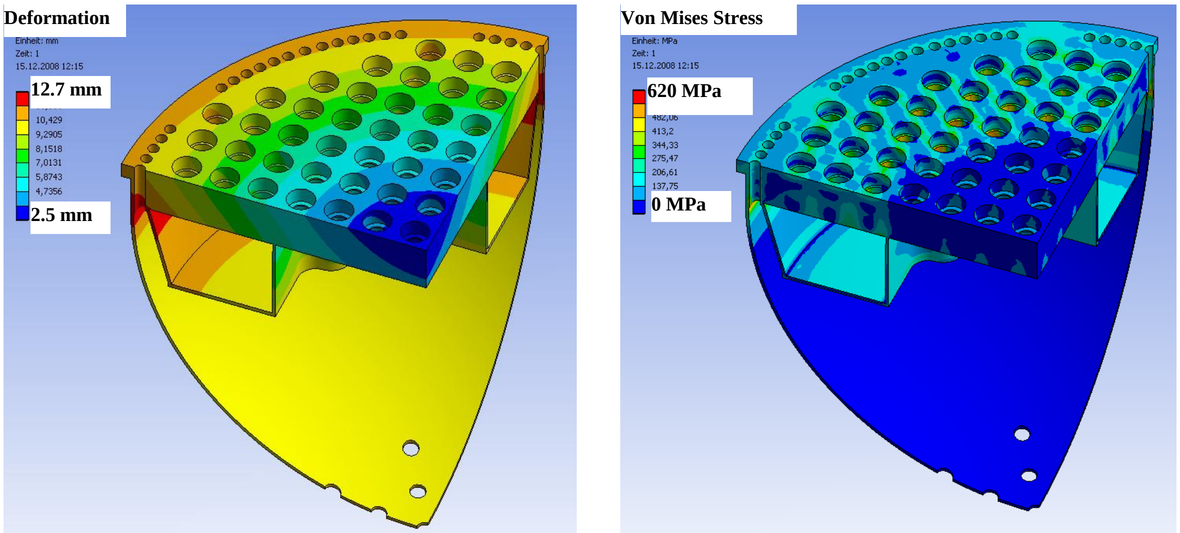

Figure 7: Deformation (left) and stress distribution (right) of a thermo-mechanical finite element analysis of the lower mixing plenum

For these calculations, gravity forces and the load of the clusters have been applied combined with local convective boundary conditions. Maximum stresses found in the structure were assessed applying the safety standards of the Nuclear Safety Standards Commission (KTA), in particular the KTA standard 3201.2 (1996) [13] dealing with the design rules of primary light water reactors components. The maximum deformation of 12.5 mm during steady state conditions occurs at the outer rim of the lower mixing plenum. This deformation is mainly caused by thermal expansion of the whole component, especially due to the larger heat-up of the outer mixing chamber 2. The maximum peak stress of 620 MPa complies with the low cycle fatigue strength of stainless steel 1.4970.

4.3 Materials

Materials are to be selected for all components of the HPLWR. The most important material is the fuel rod cladding material, because of the highest temperatures, small wall thicknesses and high radiation. Additionally, materials need to be found for other in-vessel components, like the steam pipe, which must sustain lower temperatures and lower radiation compared to the cladding, but for a much longer life time. Hence, the materials investigated within this project are not limited to a specific one, rather considering a variety of candidate materials of ferritic/martensitic steels, stainless steels, ODS (oxide dispersed strength) steels and Nickel base alloys.

A total of 16 materials have been tested against corrosion resistance in autoclaves at VTT and JRC-IE, Petten. In the autoclaves, materials samples have been exposed to a predefined temperature and oxygen content at supercritical pressure up to 1500 hours. The oxidized samples were later analysed by means of Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive Spectroscopy (EDS). For selected materials, Contact Electric Impedance (CEI) and Contact Electric Resistance (CER) measurements have been performed.

CEI and CER analysis have showed that most of the commercial materials behave like semiconductors under SCW conditions. These methods have also revealed that the effect of bulk Cr concentration is not as dominating at SCW condition as is under subcritical conditions. This means that austenitic stainless steels behave like ferritic/martensitic steels under SCW conditions, i.e. prevailing oxide is iron-like.

Recent results on oxidation of candidate materials are summarized by Penttilä et al. [14]. The effect of bulk metal surface condition was studied by performing different levels of polishing for the specimens [15]. Weight gains of the austenitic stainless steels 316NG and 1.4970 with different surface finishes (#600 or #1200 emery paper surface finish and "as received" condition, i.e. after machining) after 1000h exposure to SCW at 650°C are shown in Figure 8. The weight gains in all austenitic stainless steel 1.4970 samples were smaller than in 316NG sample with #600 emery paper surface treatments. Presumably, the surface finish with #600 emery paper produces higher degree of cold work on the sample surface compared to #1200 emery paper. Thus, samples with surface finish performed using #600 emery paper should have more lattice imperfections and thus higher density of diffusion paths in the near-surface. In that case, weight gain should be lower for the sample with #600 emery paper surface finish and for the sample with machined surface condition.

Further studies have showed that the effect of bulk metal surface condition on oxide thickness is evident. This was confirmed by additional test where austenitic stainless steel 316L tube sample with machined surface showed extremely good oxidation resistance [16]. The test resulted in an oxide thickness of 2 µm after 1000 hours exposure under SCW conditions at 650°C. Thus, the effect of surface condition on oxidation resistance deserves more extensive studies in the near future.

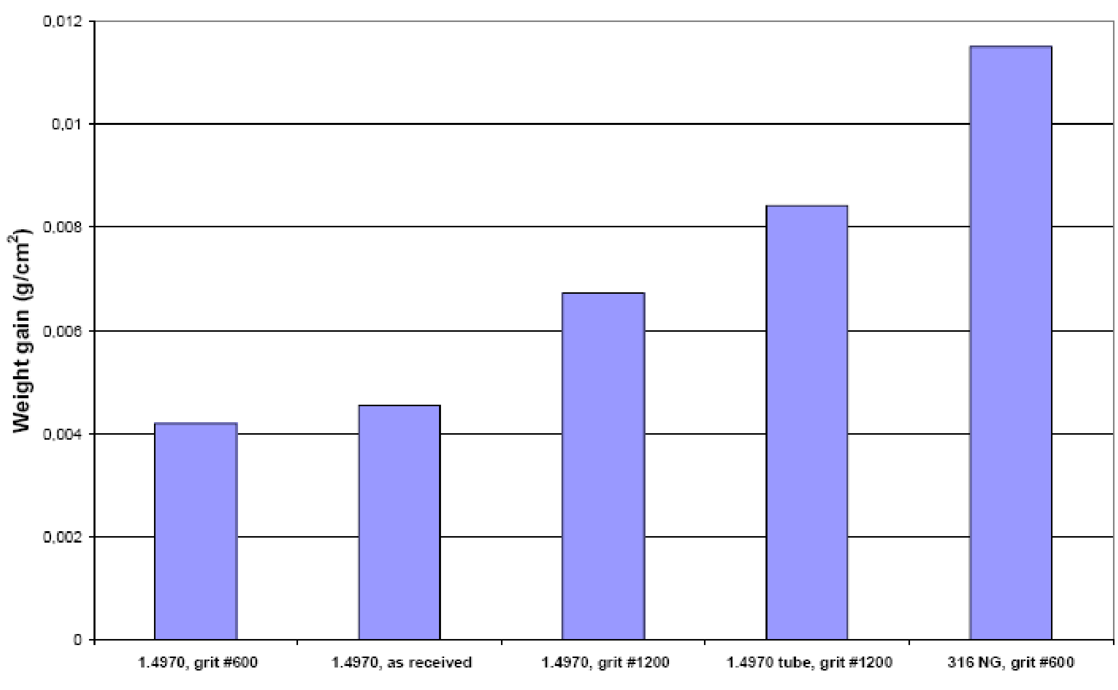

Figure 8 Weight gain of 1.4970 and 316NG stainless steels after 1000 hours at 650°C [14].

4.4 Heat Transfer

Heat transfer under supercritical conditions is strongly influenced by the non-linearity of fluid properties. Several heat transfer regimes have already been identified under supercritical conditions, e.g. enhanced, normal and deteriorated heat transfer. During heat transfer deterioration (HTD), the heat removal from the wall is limited which results in wall overheat.

The fuel rods in the HPLWR fuel assembly are wrapped with a wire (Figure 5), mainly serving as a spacer device, but additionally causing a swirl inside the assembly. Heat transfer at supercritical conditions has been studied recently by NRG [17], University of Stockholm [18], Budapest University of Technology and Economics [19], and University of Stuttgart [20].

The flow around a wire wrap has been simulated by NRG using the FLUENT code (Figure 9 left) [21]. The diagram in Figure 9 (right) shows the results: The red dashed line shows wall overheat and HTD. By introducing a helical wire the heat transfer deterioration does not occur. Instead, local wall temperature peaks are visible, which indicate a stagnation point right in front to the wire. The local wall temperature peaks are smaller than the wall temperatures during HTD. These numerical results will have to be confirmed by experiments and shall just give a first impression of the influence of wire wraps on flow of supercritical water. A heat transfer correlation taking wire effects into account is under development.

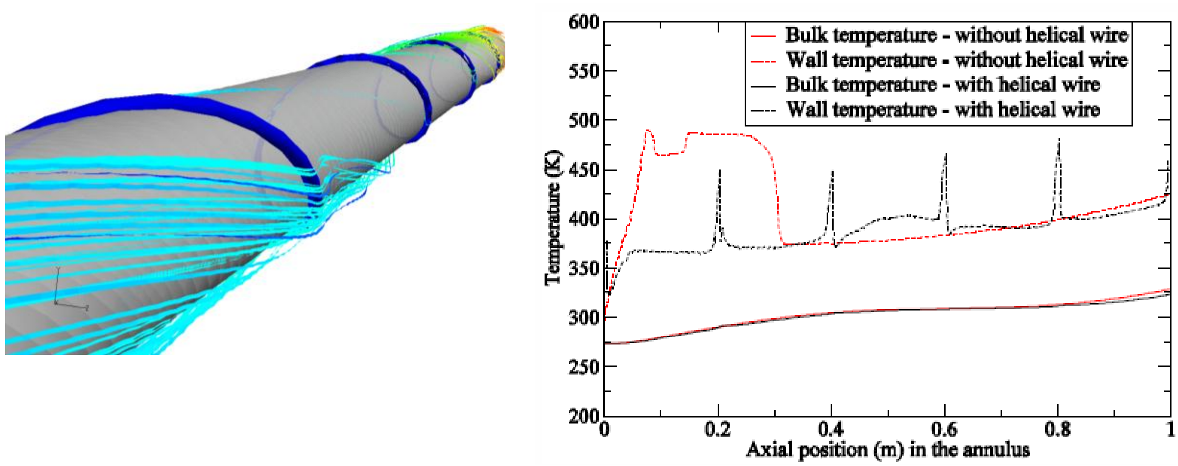

Figure 9 Effect of a wire wrapped spacer on heat transfer deterioration [21]

5. Summary and Conclusion

The design of the HPLWR is based on a pressure vessel type light water reactor, being assessed in the project “HPLWR Phase 2”, which is co-funded by the European Commission. Ten partners from eight European countries supported by three active supporters are working on scientific issues to determine the feasibility and the future potential of this reactor concept. Both coolant and moderator are flowing meander-wisely through the core. The coolant is heated up in three stages with intermediate mixing. The moderator is flowing downwards through special moderator boxes and upwards in the gaps between the assemblies, after leaving the fuel assembly cluster at the bottom. From there it flows upwards in the gaps between the assemblies and is guided through the reflector to be finally mixed with downcomer water.

As a result of the neutronics/thermalhydraulics analyses of the core, it was shown that the power peaks in superheater 2 can be flattened by adding a 100mm water layer in the reflector. The current design of the reflector has already been changed accordingly. The thermo-mechanical analysis of the core support plate and the lower mixing chambers shows that stresses and deformations are within materials limits. The materials investigation is an on-going task throughout the entire project. Special attention is drawn to heat transfer investigations. Recent analyses showed that the wires foreseen as spacers of fuel rods may help to suppress heat transfer deterioration. Summarizing, promising results are already available. However, there are still many open points to be addressed in this and future projects.

6. Acknowledgement

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