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Fuel Assembly Design With Dual Rows And A Mixed Core For Supercritical-Water Cooled Power Reactor

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Abstract

One of the principal advantages of the supercritical-water cooled power reactor (SCPR) is high thermal efficiency, which is due to the use of supercritical pressure water as a coolant. On the other hand, fuel cladding surface temperature increases locally due to a synergy effect from the increase of coolant temperature and decrease of heat transfer coefficient, if the coolant flow distribution is non-uniform in the fuel assembly. Therefore the SCWR fuel assembly was designed using sub-channel analysis to evaluate detailed thermal hydraulic characteristics. In this paper, a new reactor core design is study on the basis of square assembly with dual rows of fuel rods and of a mixed core concept consisting of a thermal zone and a fast zone. The geometric structure of the fuel assembly of the thermal zone is similar to that of a conventional thermal supercritical water-cooled reactor (SCWR) core with two fuel pin rows between the moderator channels. In spite of the counter-current flow mode, the co-current flow mode is used to simplify the design of the reactor core and the fuel assembly. The water temperature at the exit of the thermal zone is much lower than the water temperature at the outlet of the pressure vessel. This lower temperature reduces the maximum cladding temperature of the thermal zone. Furthermore, due to the high velocity of the fast zone, a wider lattice can be used in the fuel assembly and the non uniformity of the local heat transfer can be minimized. The assembly design concept can be used as a general key component for any advanced core design of this reactor.

Key Words*: Supercritical Water Cooled Reactor, Square assembly with dual rows, Mixed Core, Fuel Assembly.*

1.Introduction

The supercritical light water reactor (SCWR) is one of the six concepts chosen by the Generation IV International Forum (GIF)and is the one most closely related to the light water reactors of the third generation, which are currently being built in various countries. This reactor is planned to be operated with a high system pressure of about 25MPa, a high heat-up of the coolant within the core by more than 200 ◦C, and high outlet temperatures of the coolant of more than 500 ◦C in order to achieve a higher turbine power and a better thermal efficiency compared with existing light-water reactors (Squarer et al., 2003). Due to the supercritical conditions of water, a sudden phase change ora boiling crisis cannot occur within the core, making the design safer. On the other hand, challenges for the fuel assembly design are a higher cladding temperature up to 620 ◦C and a higher density variation of the coolant by more than a factor of seven.

Several conceptual designs of SCWRs have been proposed: (a) super critical water-cooled thermal neutron reactor; (b) super critical water-cooled fast neutron reactor; (c) super critical water cooled mixed neutron spectrum reactor; (d) super critical water cooled pebble bed reactor; and (e) super critical heavy water cooled reactor. Table 1 shows the detailed design parameters of present typical SCWRs around the world. Although no boiling crisis occurs for the super critical coolant in the core, heat transfer deterioration occurring in the SCWR may lead to severe consequence. Therefore, the study of flow and heat transfer characteristics in the rod bundle channels in the supercritical water-cooled reactor is of significant importance for its de-sign and development.

Oka and Koshizuka (1993) investigated two different types of additional moderator: either a solid moderator made of Zirconium hydride, or water as moderator within tubes or rods which were integrated in the fuel assembly design. Dobashi et al. (1998) compared two different flow directions (upward and downward flow) of the moderator within the water rods of a hexagonal fuel assembly. As a conclusion, they preferred a downward flow of moderator water to flatten the high density variation in the core. A more uniform power distribution could be achieved by Oka et al. (2003a,b) using a square fuel assembly design, in which the moderator water is flowing downwards through 36 water rods per assembly and through the gap between the assembly boxes.

Reactors with a thermal spectrum have several advantages that are important for dynamic behavior in transient scenarios; for example, they use a lower enrichment fuel and have a high inventory of water in the reactor core. However, a fast spectrum reactor enables higher fuel utilization and a higher power density; it also creates the possibility of nuclear waste transmutation.

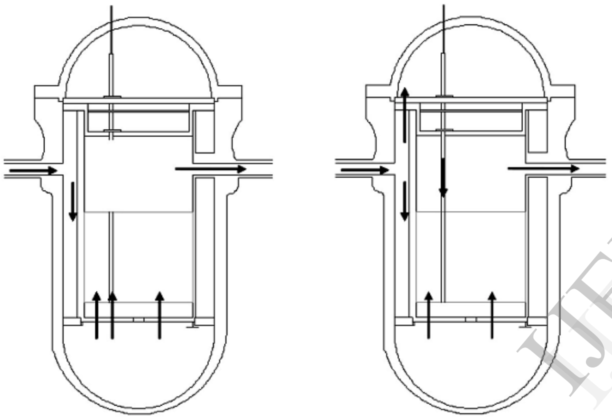


Fig.1. Two Different Flow Modes of a Thermal Spectrum of an SCWR Core (Left side: co-current flow mode & Right side: counter-current flow mode)

As indicated in the previous section, an SCWR with a thermal spectrum requires additional moderator channels. Note also, as shown in figure 1, that there could be two possible flow modes for the water flowing inside the reactor core. One mode is the co-current flow mode. Cold water comes to the lower plenum; it then enters both the cooling channels and the moderator channels before exiting the reactor core at the upper plenum. In this case, the average coolant temperature at the exit of the cooling channels is as high as 680^{o}C. This temperature ensures that if 30% of the water flows through the moderator channels the water temperature at the exit of the pressure vessel averages500^{o}C. This high coolant temperature leads to a cladding temperature that far exceeds the design limit. In the other words, to ensure that the average coolant temperature at the cooling channel exit is not higher than 500^{o}C, we must keep the average water temperature at the pressure vessel exit as low as 400 C. However, such a low temperature eliminates the main advantage of an SCWR: that is, high thermal efficiency. The other possible flow mode is the counter-current flow mode. In this case, water entering the pressure vessel is divided into two paths. One part flows in the down comer to the lower plenum. The other part goes upwards to the upper dome of the pressure vessel; from there it enters the moderator channels and exits the moderator channels in the lower plenum, where it mixes with the first part of the water. All the water then flows through the cooling channels and cools down the fuel pins. With this option the water temperature at the pressure vessel exit is the same as the average temperature at the exit of the cooling channels.

Although many researchers have proposed fuel assemblies with a counter-current flow mode, this method poses a huge challenge in terms of the design and mechanical realization of the fuel assembly, particularly at the juncture where the reactor core divides the water into separate channels with an ascending or descending flow. In contrast, the fuel assembly of the co-current flow mode over comes this difficulty. Nevertheless, the low exit temperature limits the thermal efficiency and subsequently destroys the main advantage of the SCWR. Thus, to avoid severe problems in the mechanical design and to simultaneously achieve a high temperature at the reactor exit, a mixed core design is proposed in this paper.

2. Design of a fuel assembly with dual rows.

The European concept of the High Performance Light Water Reactor (HPLWR) differs from current light water reactors in a higher system pressure beyond the critical point of water, as well as a higher heat-up of the coolant within the core and thus higher core outlet temperatures, leading to a significant increase in turbine power and thermal efficiency of the power plant.

The general layout of the reactor considered here is sketched in Fig. 2. Like in a PWR, the core is arranged in the lower half of the reactor pressure vessel. Control rods shall be inserted from the top of the reactor. Feed water entering the reactor pressure vessel is supplied not only through the down comer to the lower plenum, but also to the upper plenum of the reactor pressure vessel, from where it can be used as moderator water flowing downwards into the core. This counter current flow of moderator water and rising coolant requires a closed steam plenum on top of the core which collects the steam to be supplied to the steam turbines and, on the other hand, allows a moderator water supply to the top of the core. Moderator water and feed water through the down comer need to be mixed homogeneously at the core bottom, which requires a mixing plenum underneath the core.

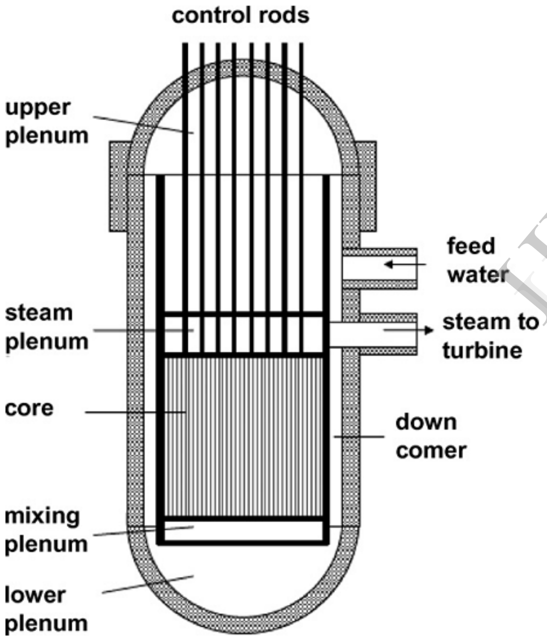


Fig.2. General Layout of the HPLWR.

A new design with small square assemblies of 40 fuel rods is presented, housed within assembly boxes with downward flowing moderator water in the gaps between them, and with a single moderator box in each assembly with downward flow inside, whereas the coolant around the fuel rods rises upwards. Combining nine of these small assemblies to an assembly cluster allows a reduction of the number of individual control rod drives to become similar in dimensions to a pressurized water reactor (PWR). This enables the use of state-of-the art PWR control rod drive technology.

i. Fuel assembly design systematic

Most concepts studied so far can be generalized in the following systematic. Either square (sq) or hexagonal (hex) arrangements of fuel rods shall be arranged in an assembly box containing n×n moderator boxes and m rows of fuel rods between the moderator and the assembly box. The considered fuel assemblies shall be denoted as "sq*m.n*" or "hex*m.n*" assemblies in the described systematic.

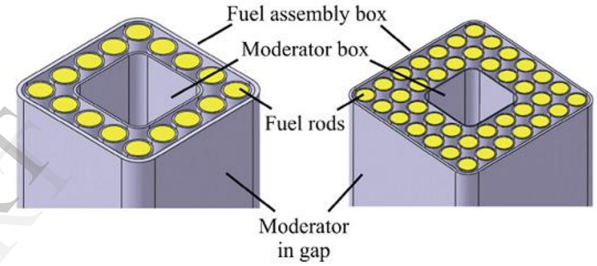


Fig.3. Square fuel assemblies "sq1.1" and "sq2.1".

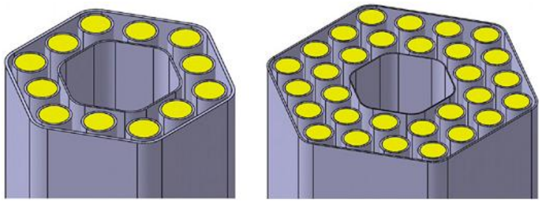


Fig.4. Hexagonal fuel assemblies "hex1.1" and "hex2.1".

For illustration, the 3D-models of two square ("sq1.1" and"sq2.1") and two hexagonal fuel assemblies ("hex1.1" and"hex2.1") are shown in Figs. 3 and 4. Based on preliminary sub-channel analyses, Cheng et al.(2003) proposed fuel rods of 8mm outer diameter, a pitch to diameter ratio of 1.15 for square arrangements and of 1.3 for hexagonal ones. The gap between a fuel rod and a box wall has been optimized to 1mm for each fuel assembly design.

Table.1. Dimensions of square and hexagonal fuel assemblies:

Assembly type	**sq1.1**	**sq2.1**	**hex1.1**	**hex2.1**
Number of moderator boxes per assembly (–)	1	1	1	6
Diameter fuel pellets (mm)	6.9	6.9	6.9	6.9
Inner cladding diameter (mm)	7	7	7	7
Outer cladding diameter (mm)	8	8	8	8
Pitch of fuel rods (mm)	9.2	9.2	10.4	10.4
Gap fuel rod/wall (mm)	1	1	1	1
Gap between fuel rods (mm)	1.2	1.2	2.4	2.4
Number of fuel rods (–)	16	40	12	30
Pressure difference (kPa)	50	50	50	50
E modulus (SS316L) (MPa)	162,000	162,000	162,000	162,000
Box deflection (mm)	0.2	0.2	0.2	0.2
Fuel assembly box				
Inner side length (mm)	46.8	65.2	26.7	37
Wall thickness (mm)	0.6	1	0.3	0.4
Outer side length (mm)	48	67.2	26.9	37.5
Moderator box				
Outer side length (mm)	26.8	26.8	15.1	15.1
Wall thickness (mm)	0.3	0.3	0.1	0.1
Inner side length (mm)	26.2	26.2	15	15

The wall thicknesses of square assembly boxes vary between 0.6mm for “sq1.1” and 5.2mmfor “sq1.6”.Thewall thicknesses of the hexagonal fuel assembly boxes vary between 0.3mm for“hex1.1” and 0.4mmfor “hex2.1”. This means that with increasing number of fuel rods and thus increasing inner side length, the wall thickness is increasing by a factor of $l^{7/6}$.

ii. Comparison of different fuel assembly designs

Structural material comprises the fuel assembly box, the moderator boxes and the fuel rod cladding. In each case, the structural material is considered to be stainless steel (density = 8000 kg/m3) and the fuel shall be UO2 (density = 11,000 kg/m3).

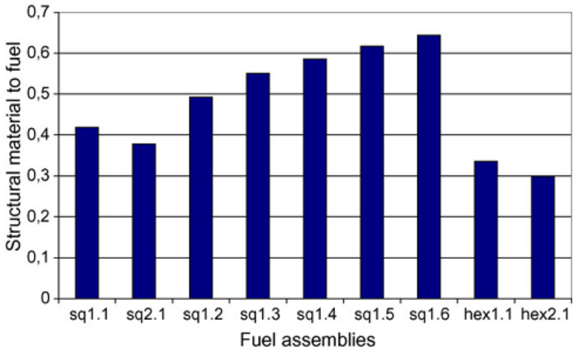


Fig.5. Mass ratio of structural material to fuel of different assemblies.

Fig. 5 depicts the calculated mass ratios. The lowest ratio has been obtained for the hexagonal assemblies (0.34 and 0.3 for“hex1.1” and “hex2.1”) because of the smaller wall thickness of the assembly boxes. For the square assemblies, the ratio of structural material to fuel increases from0.42 to almost 0.64 (for“sq1.1” to “sq1.6”) with increasing size, caused by the increasing wall thicknesses. It also shows the advantage of two rows of fuel rods within a fuel assembly, compared with those having a single row only. Adding a second row of fuel rods to “sq1.1”, the mass ratio of structural material to fuel decreases from0.42 to 0.38, reaching almost the ratio of hexagonal arrangements.

To predict the total moderator mass, first estimates of the density profiles of moderator and coolant in the core are needed. The density profile of coolant varies strongly with temperature along the height of the active core. Three cross sections has been considered: bottom (0m), middle (2.1m), top (4.2m).For comparison, the moderator to fuel ratio of a typical PWR is given in Fig. 6 as well, which is in the order of 0.1. Fig. 5 shows clearly that this ratio can only be met by the assembly types “sq2.1” and “hex2.1” at mid height. All other fuel assemblies (“sq1.1” to “sq1.6” and “hex1.1”) show higher ratios. The highest ratio has been predicted for “hex1.1”.

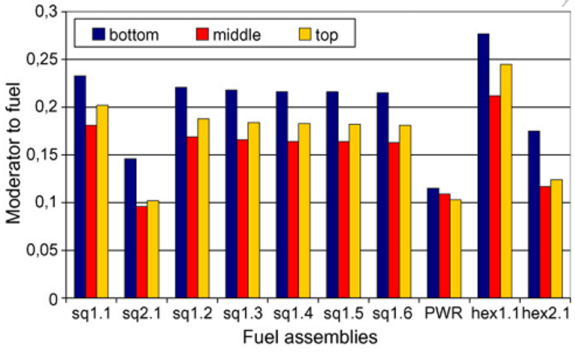


Fig.6. Mass ratio of moderator to fuel of different assemblies.

As a conclusion, a core consisting of hexagonal fuel assemblies or of fuel assemblies with dual rows of fuel rods provides the smallest structural material ratio within the core, so that a minimum of neutron absorption can be expected and also shows that only fuel assemblies with two rows of fuel rods could meet the mass ratio of moderator to fuel of a PWR. All other assemblies under consideration turn out to have much higher ratios, which cannot be reduced to the PWR ratio even if the gap size should be reduced to zero. Therefore, a square assembly with dual rows of fuel rods turned out to be optimum.

iii. Sub-channel analysis of a square assembly sq2.1

The fuel assembly “sq2.1” consists of 40 fuel rods, a fuel assembly box with an outer side length of 67.2mm (wall thickness: 1mm) and a single moderator box with an outer side length of 26.8mm (Fig. 3). To minimize the risk of oxidation on the surface of the steel SS316L, the wall thickness of the moderator box has been increased from 0.3mm to 0.4mm.

a. Fuel assembly cluster

The width of the outer box of the selected fuel assemblysq2.1” is only 67.2mm which is about one third of the typical fuel assembly size of a PWR. Taking these dimensions into account, the handling of a core consisting of these small fuel assemblies would be complex during a refueling process. To overcome this problem, a fuel assembly cluster is proposed instead, comprising nine fuel assemblies in a 3×3 arrangement. Fig. 7 shows such a 3×3 arrangement of the assembly “sq2.1”.Its extended moderator boxes penetrate the steam plenum.

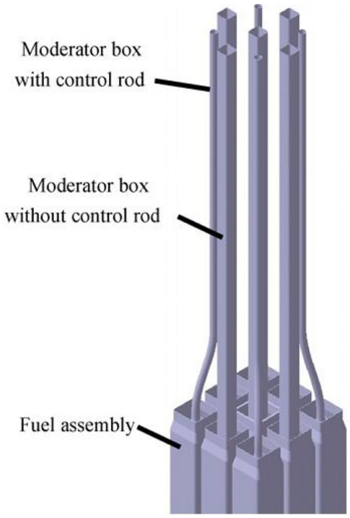


Fig.7.Fuel assembly cluster sq2.1

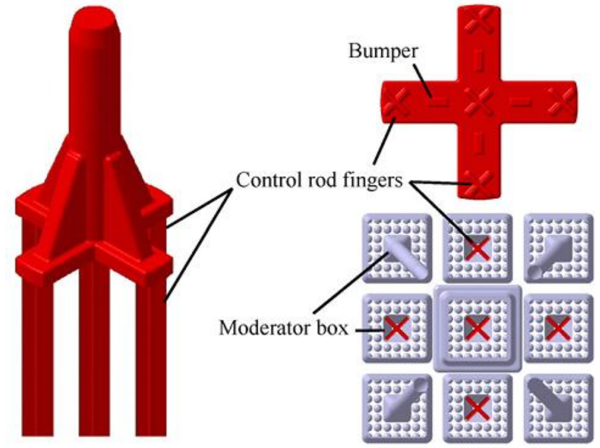


Fig.8. Control element (left), bottom view (top side), and cruciform control rod fingers instead in square moderator boxes (bottom right)

With a cluster side length of nearly 230mm, which is close to a PWR size, the conventional control rod drive of a current PWR could be adopted. Fig. 8 shows a proposal for a control element design. It is similar to the concept with control rod fingers of a PWR. The five cruciform control rod fingers shall be inserted from the top into each moderator box having a straight square extension. The corner moderator boxes of the cluster cannot be reached by control rod fingers, as the head piece needs to be smaller in diameter than the cluster to allow a residual stiffness of the steam plenum. The extension of these corner moderator boxes is round and bent to fit them into the same head piece.

b. Head piece of the fuel assembly cluster

The head piece of the fuel assembly cluster is composed by four elements: a head piece plate, a transition nozzle, a window element and a bushing (see Fig. 9). First, the nine assembly boxes shall be welded into the head piece plate. Then, the transition nozzle and the window element shall be welded onto the head piece plate. Finally, the moderator boxes shall be welded into the top of the window element. The superheated coolant will be accelerated through the transition nozzle into the window element and released horizontally into the steam plenum, Fig. 10

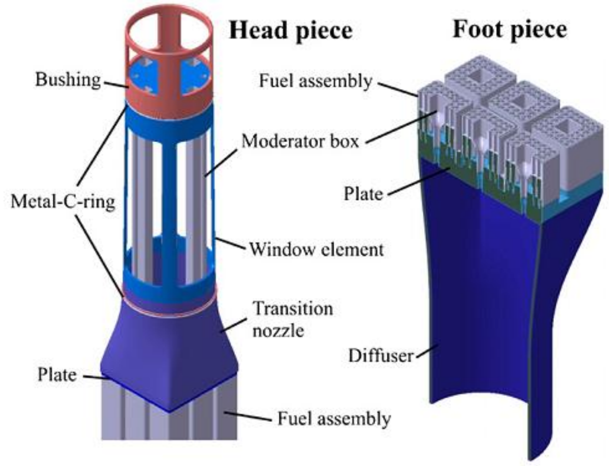


Fig.9. Fuel assembly cluster head piece and foot piece.

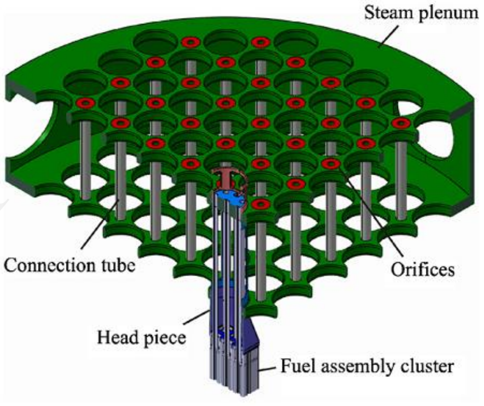


Fig.10. Steam plenum with fuel assembly cluster and head piece.

c. Foot piece of the fuel assembly cluster

The foot piece comprises a bottom plate and a diffuser (see Fig. 9). The fuel rods of the nine assemblies are supported by the bottom plate of the cluster foot piece. Only the central fuelassembly box of the cluster is connected with the foot piece by nuts and bolts. The other eight assembly boxes are hanging freely from the head piece, where they are welded in, to minimize thermal deflection of the cluster. A sealing element between these assembly boxes and the bottom plate is required to minimize leakage there. If the cluster will be turned upside down during an inspection, the foot piece can be removed and single fuel rods can be pulled out, e.g. for inspection and maintenance. The moderator boxes are equipped with outlet nozzles at the lower end, serving as orifices to avoid variation of the moderator mass flow rate with different control rod positions. The moderator water is injected through these nozzles into the diffuser. As this moderator water is hotter than the coolant, the diffuser needs to provide a homogeneous mixture of the moderator water with coolant supplied from below. After mixing in the diffuser, the coolant flows upwards through multiple holes in the bottom plate.

d. Steam plenum

The steam plenum, shown in Fig. 10, is a cylindrical leak tight box which is mounted over all head pieces of the core. Fig. 14 shows exemplarily one of the fuel assemblies held by the steam plenum. The main task of the steam plenum is to collect and mix the hot supercritical water being delivered to the high pressure turbine. Top and bottom of the steam plenum are connected with tubes to supply the moderator water to the gaps between the assemblies and to provide further stiffness of the steam plenum. Orifices in the connecting tubes adjust the mass flow of gap water. The height of the steam plenum has been minimized, maximizing the volume above the steam plenum which can serve as an in-vessel accumulator in case of abnormal operation conditions. The unavoidable gap between the head piece and the steam plenum is sealed with two metal-C-rings (see Fig. 11), which need to be resistant against irradiation, applicable to the hot environment and strengthening themselves, to minimize the remaining leakage.

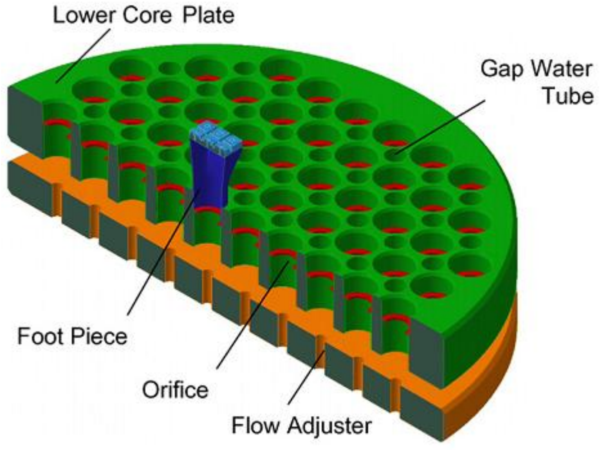


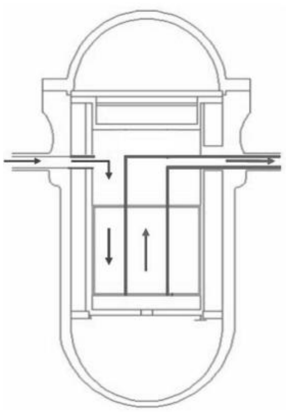
Fig.11. Lower core plate and flow adjuster.

e. Lower mixing plenum

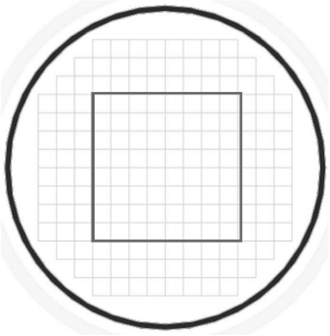
The lower mixing plenum underneath the core consists of a lower core plate with orifices and a flow adjuster (see Fig. 16). The lower core plate carries the foot pieces which support the fuel assembly clusters. The orifices mounted in the openings of the lower core plate are adjustable to reach uniform coolant exit temperatures of all fuel assembly clusters. They shall remain in the lower core plate during assembly repositioning, regardless the individual cluster position (Hofmeister et al.,2005b).The gap water flows downwards through the gap water tubes in the lower core plate into the mixing plenum between the lower core plate and the flow adjuster. There it mixes with the down comer water coming from below through orifices of the flow adjuster. A high momentum of these coolant jets from below is envisaged to stir well and to thus avoid hot streaks of the coolant. The main purpose of the design in this region is to provide a homogeneous mixture of moderator water and coolant which is essential to avoid hot streaks of the coolant entering the fuel assembly.

3. Mixed Reactor Core

Figure 12 schematically illustrates the geometrical arrangement of the proposed mixed core. The basic idea is to divide the reactor core into two zones with a different neutron spectrum. In one zone (for example the outer zone in Figure 12 or even the inner zone) the neutron energy spectrum is similar to that of a thermal reactor. In this zone the fuel assembly has a PWR-type structure but a co-current flow mode. The cold water entering the pressure vessel goes upward to the upper dome and into both the moderator channels and the cooling channels of the thermal zone. It then exits the thermal zone in the lower plenum, from where it enters the fast zone of the reactor core (for example the inner zone in Figure 12). Table 2 summarizes the main parameters of the proposed mixed core. The water temperature is 280^{o}C at the inlet of the pressure vessel and 510^{o}C at the exit of the pressure vessel. We assumed that the water is heated to 400^{o}C through the thermal zone. The average linear power rate is 190 W/cm for both the thermal zone and the fast zone. The active height is 4.0 m for the thermal zone and 2 m for the fast zone. There is a one meter blanket (or breeding material) in both the lower part and the upper part of the fuel rods in the fast zone. In the thermal zone, 30% of the total mass flow rate goes through the moderator channels.



a) Flow path in the core



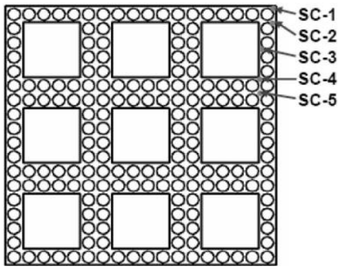
b) Fuel assembly arrangement in the core

Fig.12. Scheme of the Mixed SCWR Core

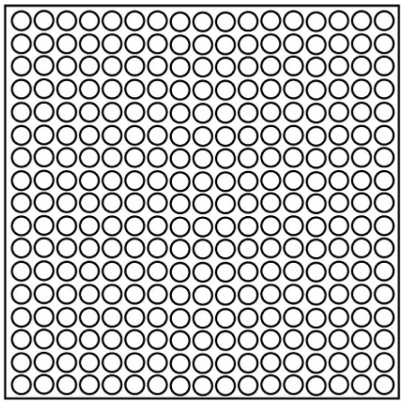
To make both zones geometrically compatible, we arranged the fuel assemblies of both the thermal zone and the fast zone in a square lattice. The size of the fuel assembly box is the same for both zones. However, the fuel pin size or the pitch-to-diameter ratio can be different in each zone. In the thermal zone, the PWR-type fuel assemblies are applied as indicated in Figure 13a. We arranged two rows of fuel pins between the moderator channels and each moderator channel takes the position of 4 x 4 fuel pins. Inside each fuel assembly we placed a set of 3 x 3 moderator channels, giving us a total of 180 fuel pins. Each fuel pin has a diameter of 8.0 mm and a pitch-to-diameter ratio of 1.20.The distance between each fuel pin and the moderator channel, as well as between the fuel pins and the fuel assembly box, is 1.0 mm. This distance gives a span distance of the fuel assembly box of 193.2 mm. The square fuel assembly of the fast zone has the same box size. Furthermore, the fuel assembly of the fast zone has the same structure as that of a conventional PWR. The diameter of the fuel pin is the same as that in the thermal zone (8.0 mm), and the pitch-to-diameter ratio has a larger value of 1.27. In each fuel assembly, as shown in figure 13b, we arranged a set of 17 x 17 fuels pins. Uranium oxide of low enrichment is used in the thermal zone, but MOX fuel with an enrichment of about 20% is used in the fast zone. The plutonium composition of the MOX fuel is similar to that of the depleted fuel from a PWR.

Table 2. Parameters of the Mixed Core

	Thermal zone	Fast zone	Entire core
Thermal power, MW	2460	1100	3560
Inlet temperature, C	280	400	280
Outlet temperature, ^{o}C	400	510	510
Active height, m	4.0	2.0	…
FA box size, mm	1732	1732	…
No. of fuel assemblies	180	100	280
Number of fuel pins	180	289	…
Fuel pin diameter, mm	8.0	8.0	…
Pitch-to-diameter ratio	1.20	1.27	…
Ave. linear power , W/cm	190	190	…
Power density, MW/m3	114	92	102
Relative moderation capacity, -	1.53	0.15	…
Equivalent outer diameter, m	3.302.0	2.0	3.30
Mass flux, kg/m2s	922	1145	…
Maximum fluid velocity, m/s	5.5	13.1	…
Pressure drop, kPa	25.0	98.0	123.0
Maximum coolant temperature, oC	550.5	526.9	550.5
Maximum cladding temperature, oC	610.4	616.7	616.7
Fuel	UO2 or MOX	MOX	
Enrichment	5-6%	~20%	



a) FA in the thermal zone.



c) FA in the thermal zone.

Fig.13. Fuel Assembly Structures of the Thermal Zone and the Fast Zone

4. Conclusions

The fuel assembly design for a HPLWR has been optimized taking into account the mechanical deflection of the assembly and moderator boxes by pressure differences. The new design presented here with small, square assemblies of 40 fuel rods and a single moderator box each, combines the following advantages:

- A small ratio of structural material to fuel to minimize neutron absorption.
- A moderator to fuel ratio being much closer to a PWR design than previous designs.
- A uniform power distribution in a cross section of the assembly at least as long as radial neutron leakage is negligible.

Combining nine of these small assemblies into a common assembly cluster allows reducing the number of individual control rod drives to similar numbers as in a PWR, which enables to apply common control rod drive technologies. A proposal for a control rod design has been presented here for such an assembly cluster.

Study on mixed core with two zones for SCWRs, Water entering the pressure vessel initially flows through the thermal zone and then cools the fast zone. The co-current flow mode is selected for the thermal zone; that is, the water flows downwards through both the coolant sub-channels and the moderator channels. Due to the low exit temperature of the thermal zone, the maximum cladding temperature of the thermal zone can be kept below the upper limit.

Further investigations on the Square assembly with dual rows mixed core design are still ongoing. A detailed analysis needs to be carried out with the coupled neutron-physics/thermal-hydraulics approach, particularly with emphasis on the safety behavior and the possibility of improved fuel utilization.

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