A MIXED CORE FOR SUPERCRITICAL WATER-COOLED REACTORS

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In this paper, a new reactor core design is proposed on the basis 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 nonuniformity of the local heat transfer can be minimized. This mixed core, which combines the merits of some existing thermal SCWR cores and fast SCWR cores, is proposed for further detailed analysis.

KEYWORDS : Supercritical Water Cooled Reactor, Mixed Core, Thermal Spectrum, Fast Spectrum, Co-Current Flow Mode

1. INTRODUCTION

As one of the most suitable clean energy sources, nuclear power will surely become more and more important and undergo a rapid development, especially in developing countries such as China [1]. Considering the present situation and future programs, water-cooled reactors are likely to be used as the main reactor concept for nuclear power plants in most countries. However, the current generation of water-cooled reactors has some shortcomings from a long-term development point of view. The continual safety improvements have lead to a more complex system and, in turn, the greater complexity poses a serious challenge to economic competitiveness. Water-cooled thermal reactors have very low fuel utilization (that is, less than 1%). Due to the shortage of natural uranium resources, especially in uranium-poor countries such as China, fuel utilization is of crucial importance for the long-term development of nuclear power.

Nuclear power plants with supercritical water-cooled reactors (SCWRs) have advantages in terms of economic competitiveness, sustainability, technological availability and continuity of experience. An SCWR is a direct cycle nuclear system that operates under supercritical pressure conditions (for example with an operating pressure of about 25 MPa). The coolant at the outlet of a reactor core has a temperature higher than 500°C and goes directly to the turbine. With a thermal efficiency as high as 45%, the SCWR has much higher thermal efficiency than existing water-cooled reactors [2]. In addition, nuclear power plants with an SCWR have no need of a steam generator, pressurizer or steam separator. Hence, the cooling system is significantly simplified.

In China, water-cooled reactors are and will be the main reactor concept for the generation of nuclear power. China's experience and the technology developed in the design, manufacture, construction, and operation of nuclear power plants are mainly concentrated on water-cooled reactors. Thus, the development of SCWRs is a smooth extension of the existing nuclear power generation park in China. From a technological point of view, an SCWR is a combination of the water-cooled reactor technology and the supercritical fossil-fired power generation technology. Hence, SCWRs ensure the technological availability.

In spite of the merits mentioned above, the SCWR also faces significant challenges. Extensive R&D activities, including conceptual design, feasibility studies and basic technological development, have been carried out since the 1990s [2]. Recently, however, the Chinese nuclear industry, as well as research institutes and universities, have expressed strong interest in the development of SCWRs. The Shanghai Jiao Tong University is currently engaged in various aspects of SCWR R&D, including the reactor

Table 1. Summary of Some Existing SCWR Core Designs

	Squarer et al. [3]	McDonald et al. [4]	Yamaji et al. [5]	Oka et al. [2]	Bae et al. [6]	Bushby et al. [7]
Spectrum	thermal	thermal	thermal	fast	thermal	thermal
Power, TH	2188	2575	2740	3897	3846	2540
Power, El	1000	1600	1217	1728	1700	1140
q', kW/m	24	19.2	18	--	19	---
Efficiency, %	44.0	44.8	44.4	44.4	44.0	45.0
Pressure, MPa	25	25	25	25	25	25
Tinlet, C	280	280	280	280	280	350
Texit, C	508	500	530	526	508	625
Flow rate, kg/s	1160	1843	1342	1694	1862	1320
Core H, m	4.2	4.3	4.2	3.2	3.6	oo
Core D, m	---	3.9	3.7	3.3	3.8	4.0
Cladding	SS	Ni	Ni	TBD	SS	Ni
No. of FA	121	145	121	419	157	300
No. of FR	216	300	300	---	284	43
FR D, mm	8.0	10.2	10.2	7.60	8.2	11.5
Pitch, mm	9.5	11.2	11.2	8.66	9.5	13.5

core design analysis. This paper reports on a mixed core concept consisting of a thermal spectrum zone and a fast spectrum zone. A preliminary assessment is made to show the performance of the mixed core.

2. BRIEF OVERVIEW OF EXISTING REACTOR CORE DESIGNS

A large number of preconceptual designs of SCWR cores have been proposed in the open literature. Some of them are summarized in table 1.

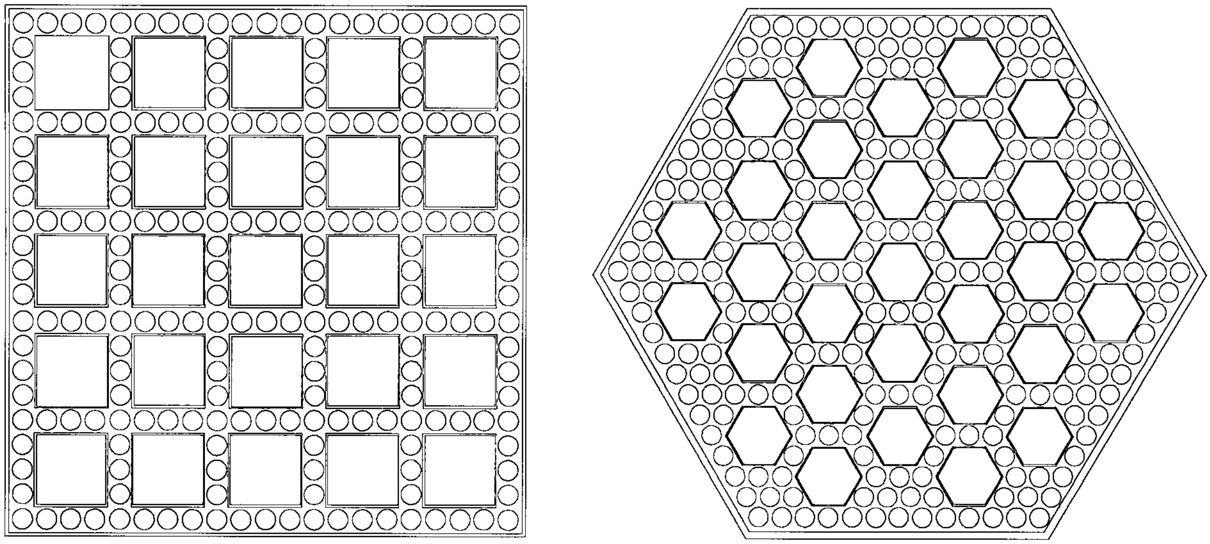
Most of the concepts in table 1 are based on a thermal spectrum. Researchers have also endeavored to design SCWR cores with a fast neutron spectrum. In a fast spectrum reactor core, the fuel pins are tightly arranged inside the fuel assemblies in a hexagonal lattice. The reactor core consists of seed fuel assemblies and blanket fuel assemblies, and they are arranged in several layers. Two options have been proposed for the flow path of the coolant. In one option, the coolant flows upwards through both the seed fuel assemblies and the blanket fuel assemblies; in the other option, the coolant flows upwards in the seed fuel assemblies and downwards in the blanket fuel assemblies, causing the coolant to have a high temperature at the core exit.

Compared to the fast core design, the fuel assembly structure of the thermal reactor core is much more complicated, mainly due to the introduction of additional moderator into the core or into the fuel assemblies. The additional moderator has inspired a large number of design options proposed in the open literature. These design options can be divided into two classes, i.e. PWR-type and the BWR-type.

The PWR-type fuel assembly is similar in size and nature to a PWR fuel assembly. As shown in figure 1, the fuel pins can be arranged in a square lattice or in a hexagonal lattice.

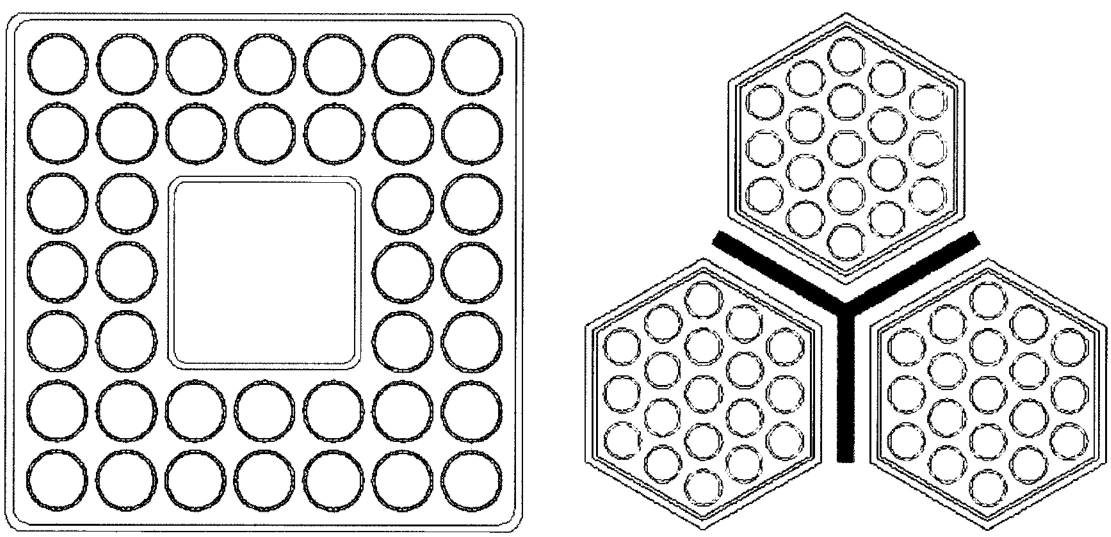
The flow channels inside the fuel assembly are divided into two groups: coolant channels and moderator channels. High density (low temperature) water flows inside the moderator channels. Usually, a counter-current flow mode is used. The water entering the pressure vessel is divided into two paths. One part goes through the down-comer to the lower plenum. The other part flows upwards to the upper dome of the pressure vessel, enters the moderator channels, and then flows downwards to the lower plenum, where it merges with the water from the down-comer and flows upwards through the cooling channels. Obviously, this core design is much more complicated than that of a conventional PWR.

The BWR-type fuel assembly is smaller than the PWR-type fuel assembly. As indicated in figure 2, the fuel pins in the BWR-type fuel assembly can be arranged in either a square lattice or a hexagonal lattice. Due to the insufficient moderation capability inside the BWR-type



(a) Square lattice (b) Hexagonal lattice

Fig. 1. Example of PWR-Type Fuel Assemblies [8]

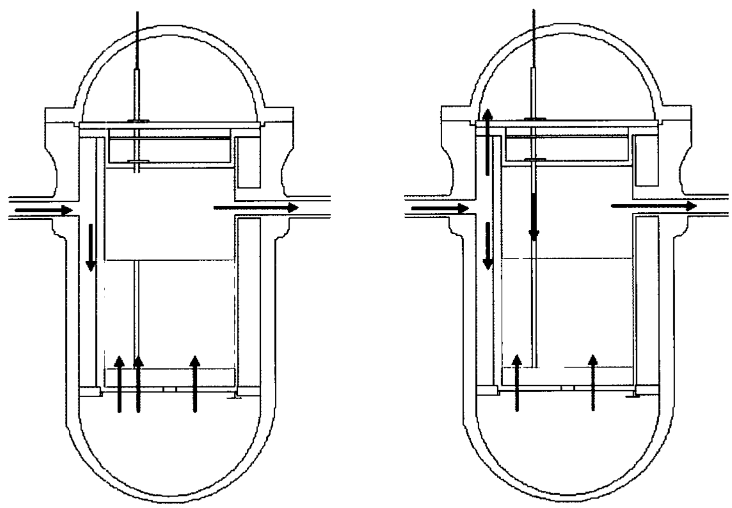


(a) Square lattice [9] (b) Hexagonal lattice [10]

Fig. 2. Examples of a BWR-Type Fuel Assembly

fuel assembly, additional water gaps are required between the fuel assemblies. In the fuel assembly design of Hofmeister et al. [9], three groups of flow channels are identified: namely, cooling sub-channels, moderator channels and assembly gaps. The water that flows through both the moderator channels and the assembly gaps should exit at the lower plenum of the vessel and then flow through the cooling sub-channels to ensure the coolant has a high exit temperature. This process would be an extremely challenging task in the mechanical design of the reactor core.

Reactors with a thermal spectrum have several advantages that are important for dynamic behavior in



(a) Co-current flow mode (b) Counter-current flow mode

Fig. 3. Two Different Flow Modes of a Thermal Spectrum of an SCWR Core

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.

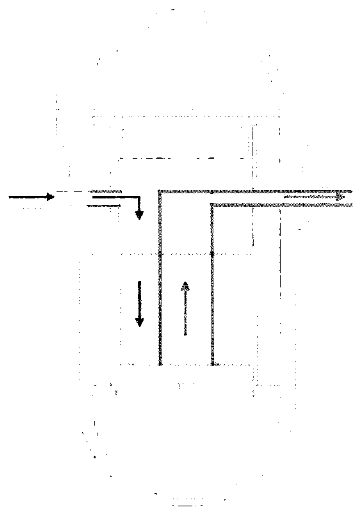
As indicated in the previous section, an SCWR with a thermal spectrum requires additional moderator channels. Note also, as shown in figure 3, that there could be two possible flow modes for the water flowing inside the reactor core. One mode is the co-current flow mode. Cold water comes to the lower 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°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 averages 500°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°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.

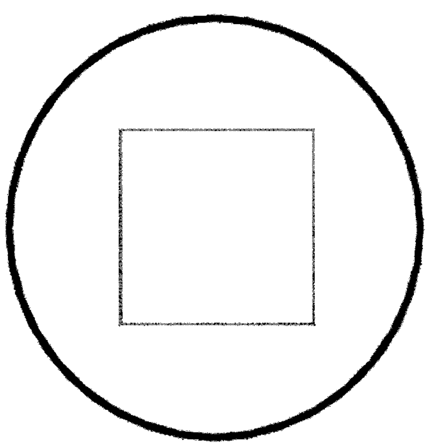
Although many researchers have proposed fuel assemblies with a counter-current flow mode, this method poses a huge challenge in terms of the design and mechanical realization of the fuel assembly, particularly at the juncture where the reactor core divides the water into separate channels with an ascending or descending flow. In contrast, the fuel assembly of the co-current flow mode overcomes 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.

3. MIXED REACTOR CORE

Figure 4 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 4 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 4). Table 2 summarizes the main parameters of the proposed mixed core.

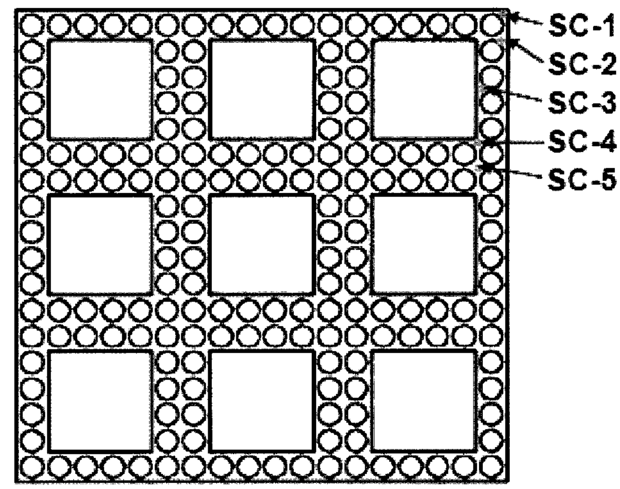


(a) Flow paths in the core

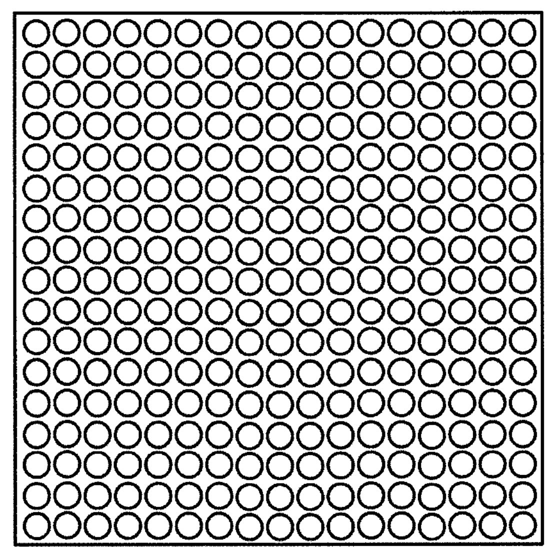


(b) Fuel assembly arrangement in the core

Fig. 4. Scheme of the Mixed SCWR Core



(a) FA in the thermal zone



(b) FA in the fast zone

Fig. 5. Fuel Assembly Structures of the Thermal Zone and the Fast Zone

The water temperature is 280°C at the inlet of the pressure vessel and 510°C at the exit of the pressure vessel. We assumed that the water is heated to 400°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. 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 5a. 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

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, °C	400	510	510
Active height, m	4.0	2.0	---
FA box size, mm	173.2	173.2	---
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/m^3	114	92	102
Relative moderation capacity, -	1.53	0.15	---
Equivalent outer diameter, m	3.30	2.0	3.30
Mass flux, kg/m^{2}s	922	1145	---
Maximum fluid velocity, m/s	5.5	13.1	---
Pressure drop, kPa	25.0	98.0	123.0
Maximum coolant temperature, °C	550.5	526.9	550.5
Maximum cladding temperature, °C	610.4	616.7	616.7
Fuel	UO_2 or MOX	MOX	
Enrichment	5-6%	≈20%	

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 5b, 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.

4. ASSESSMENT OF THE CORE PERFORMANCE

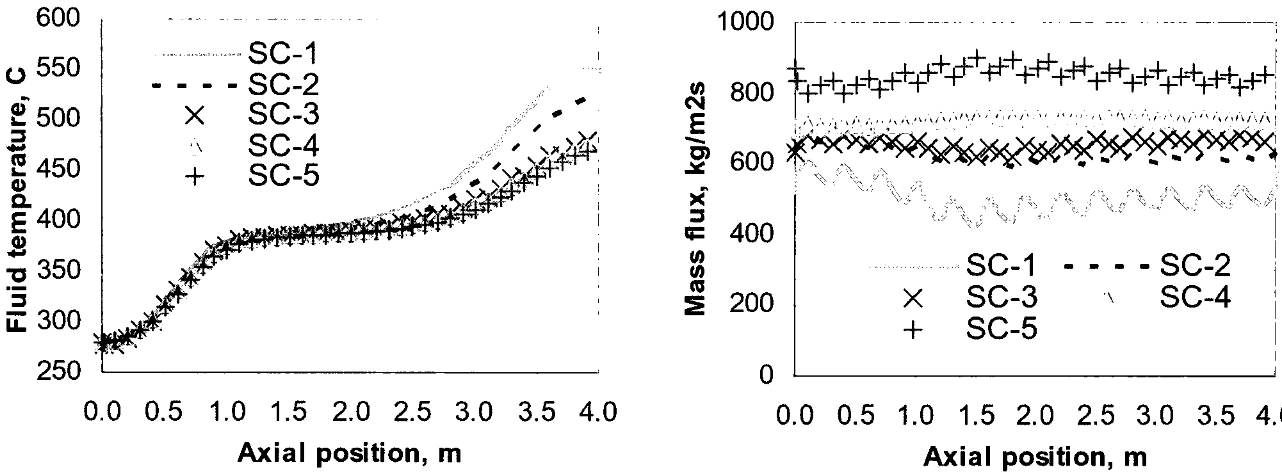
The performance of a reactor core can be assessed by considering various aspects including neutron physics, thermal-hydraulics and safety. We carried out a simplified assessment to gain insight into the basic performance of the proposed core design. For this purpose, we used the following four criteria:

(1) Moderation capacity. In the thermal zone, a sufficiently large moderation capacity must be ensured. For simplicity, we used the mass ratio of water to fuel to assess the moderation capacity. We also used the mass ratio of a conventional PWR as a reference value. In the fast zone, the mass ratio should be as low as possible. For the reference value in the fast zone, we assumed that the value of a high convention PWR was about 0.04 [11].

(2) Power density. For economic reasons, the reactor core needs a high level of thermal power. On the other hand, the size of the pressure vessel is limited due to the high operating pressure. Thus, the power density plays an important role in limiting the thermal power of the reactor and consequently affects economic competitiveness. For comparison, we used as a reference the power density of a conventional PWR, which is about 100 MW/m^3.

(3) Maximum cladding temperature. The maximum cladding temperature is one of the key design criteria. According to the experience available, the maximum cladding surface temperature should be kept below the limit of 650°C.

(4) Maximum fluid velocity. The density of supercritical water varies greatly as the temperature of the fluid varies. Up to a tenfold decrease in density occurs when the water temperature increases from about 280°C to a value higher than 500°C. In our mixed core proposal, the entire reactor core area is divided into two serially



(a) Coolant temperature (b) Mass flux

Fig. 6. Flow Parameters in the Sub-Channels of the Thermal Zone

connected parts. This division reduces the effective flow area and leads to higher mass fluxes, especially in the fast zone. A higher mass flux and a low density in the fast zone cause a high flow velocity and, subsequently, a high pressure drop. In addition, a high flow velocity causes erosion concerns for the structural materials in the fast zone. Thus, an upper limit should be considered for the flow velocity.

To assess the performance of the reactor core, we conducted a simplified sub-channel analysis by using the sub-channel analysis code STAFAS [8], which was developed especially for SCWR conditions. The STAFAS code solves the mass, momentum and energy conservation equations for each sub-channel by taking into account the energy exchange between the sub-channels and the moderator channels. The computation of the heat transfer between the solid wall and the liquid fluid is based on several heat transfer correlations incorporated into the STAFAS code. These correlations were reviewed and documented by Cheng and Schulenberg [12].

As indicated in figure 5a, the macro sub-channel approach was applied to the fuel assembly of the thermal zone, where five geometrically different types of sub-channels are identified. The distribution of different sub-channel types inside the fuel assembly of the thermal zone is rather heterogeneous. In contrast, the fuel pins and, subsequently, the sub-channels inside the fuel assembly of the fast zone are arranged homogeneously. Hence, for the fuel assembly in the fast zone, we applied a single-channel analysis method by assuming a hot channel factor of 1.10. The axial power distribution in the thermal zone was taken from Liu et al. [13], whereas a cosine profile was assumed for the axial power distribution in the fast zone. We also applied to both zones a uniform radial distribution of heat power inside each fuel assembly.

Some of the results are summarized in table 2. The effective core diameter of the proposed mixed core is 3.3 m, which gives an average power density of 102 MW/m^3. The power density of the fast zone is higher than that of the thermal zone. The inner fast zone has an effective diameter of 2.0 m, which makes up nearly 40% of the entire reactor core area. The relative moderation capacity in the thermal zone is very close to that of a conventional PWR, whereas the moderation capacity in the fast zone is about one-sixth of a PWR, still 40% lower than that of a high conversion PWR. In addition, due to a smaller flow area, the mass flux in the fast zone is about twice the mass flux in the thermal zone. Note also that the maximum velocity in the fast zone is as high as 13 m/s and that the high flow velocity causes a much higher pressure drop in the fast zone. The erosion of structural material at this high velocity also needs to be investigated, though we note that the coolant velocity can be reduced by reducing the active height of the fast zone. However, a reduction in the active height also yields a larger core diameter, a smaller power density, and a lower overall level of heat transfer. Another possible way of achieving an optimum parameter combination is to simultaneously vary the active height and the pitch-to-diameter ratio.

Figure 6 shows the axial profile of the fluid temperature and mass flux in various sub-channels in the thermal zone. Obviously, the hot sub-channel of the thermal zone is the corner sub-channel. The sub-channels adjacent to the moderator channels show a much lower enthalpy rise, and the outlet temperature of the corner-sub-channel is as high as 550°C. The high enthalpy rise in the corner sub-channel is mainly due to the small hydraulic diameter of the corner

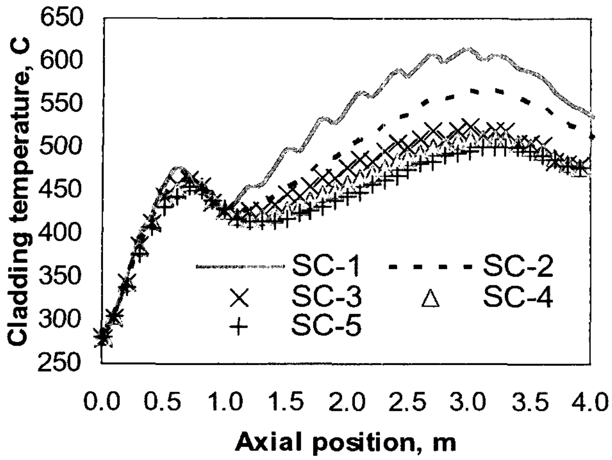


Fig. 7. Cladding Temperature in Various Sub-Channels

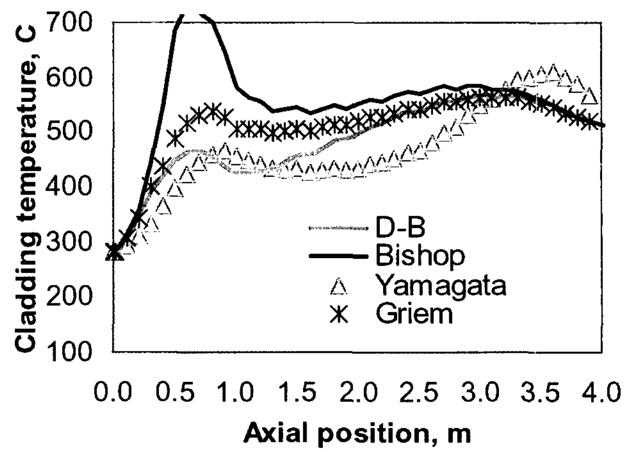


Fig. 8. Effect of Correlations on the Calculated Cladding Temperature in SC-2

sub-channel; that diameter is 3.5 mm and much smaller than the bundle average value of 4.8 mm. As a result, the mass flux in the corner sub-channel is much lower than the mass flux in the other sub-channels. The grid spacers located along the FA cause oscillation of the coolant mass flow in the sub-channels.

Figure 7 shows the cladding surface temperature in five sub-channels. Here the heat transfer coefficient was derived from the Dittus-Boelter equation. The maximum cladding temperature, which is as high as 610°C, can be clearly observed in the corner sub-channel. The cladding temperature in the other sub-channels is much lower. Note also that the temperature profiles show double peaks, though, with only one power peak in the lower part of the FA, there is a temperature peak at about 0.7 m from the bottom. However, because of the effective heat transfer in the lower part, the cladding temperature in the lower part is kept low in spite of the high power density released in the fuel. In the upper part, the heat transfer from the cladding surface becomes worse due to the low density and small specific heat of coolant. The location of the maximum temperature is close to the upper end of the active height. Moreover, the hot spot in the corner sub-channel can easily be overcome by structural modification; for example, by the introduction of dummy rods in the corners [8].

Using different heat transfer correlations, figure 8 presents the calculated cladding temperature profile in the wall sub-channel SC-2. The results indicate that the correlation of Bishop [14] gives a much higher maximum cladding temperature; that temperature is far greater than the upper limit value (650°C) and is located in the lower part of the active height. The behavior of this high peak is similar to the so-called heat transfer deterioration. The other three correlations yield a maximum cladding temperature of less than 600°C in the upper part of the active height. Thus, the correct selection of the heat transfer correlation is crucial for assessing the performance of the reactor core design.

Figure 9 shows the axial distribution of the hot channel cladding temperature of the fast zone in relation to different heat transfer correlations. The results agree well with various correlations for the case with the fluid temperature higher than 400°C. The maximum cladding temperature is lower than 650°C, except when we used the values given by the correlation of Bishop.

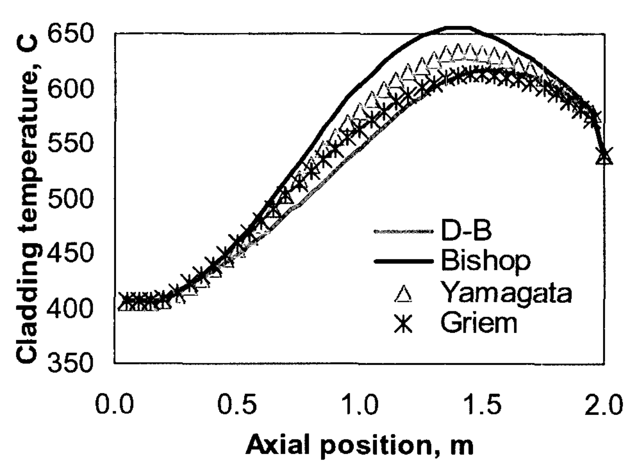
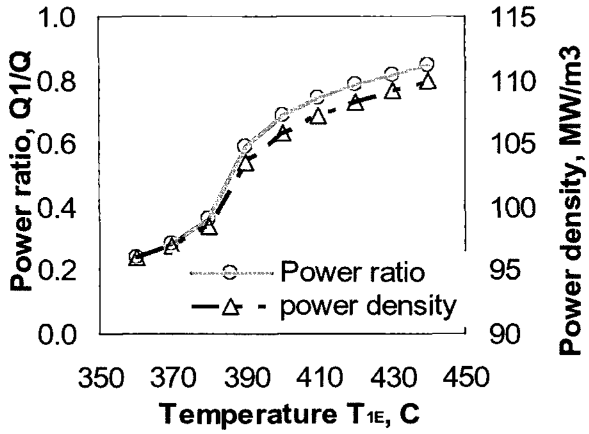


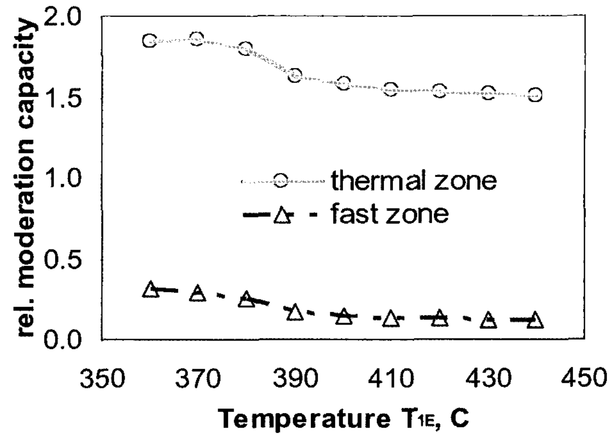
Fig. 9. Cladding Temperature in the Hot Channel of the Fast Zone

5. EFFECT OF THE EXIT TEMPERATURE OF THE THERMAL ZONE

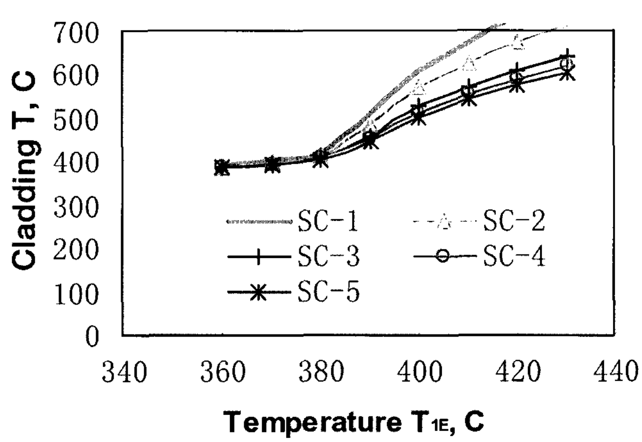
In the reference case, the thermal zone has an exit temperature (T_{IE}) of 400°C. Figure 10 shows the effect of T_{IE} on the operating conditions of both zones. As T_{IE} increases, the power released in the thermal zone



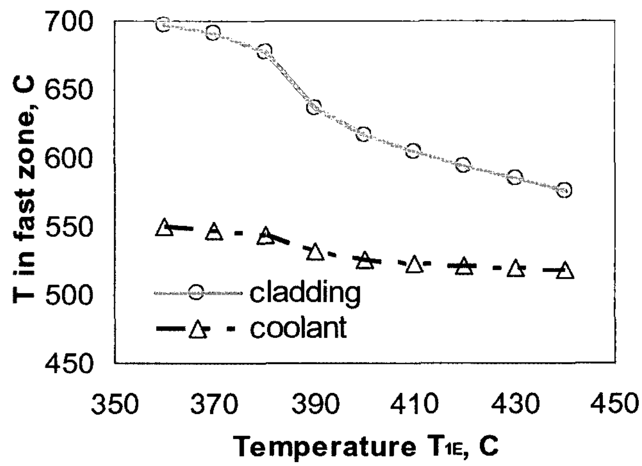
(a) Power ratio and power density



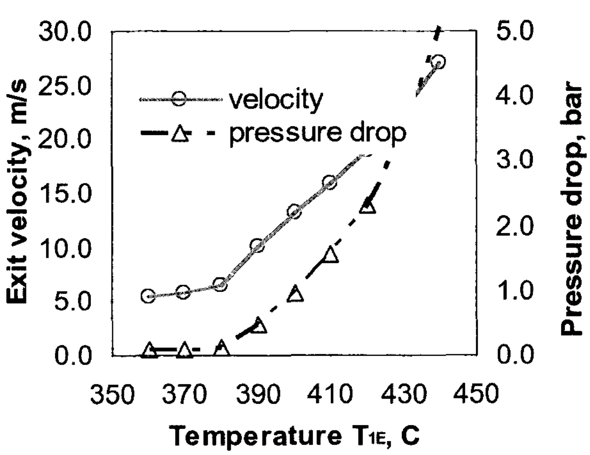
(b) Moderation capacity



(c) Cladding temperature in the thermal zone



(d) Maximum temperatures in the fast zone



(e) Maximum velocity and pressure drop in the fast zone

Fig. 10. Effect of the Exit Temperature (T_{1E}) in the Thermal Zone

increases. When T_{1E} reaches about 390°C, the power ratio of the thermal zone to the fast zone is close to 1.0. A further increase of T_{1E} reduces the size of the fast zone but slightly increases the size of the entire reactor core. This leads to a slight decrease in the power density. However, in terms of the entire temperature range, the average core power density is still comparable to that of a conventional PWR. The moderation capacity of both zones decreases as T_{1E} increases. To keep a sufficiently low moderation capacity of the fast zone, we need to ensure that T_{1E} is higher than the pseudo-critical value.

The maximum cladding temperature in the thermal zone rises sharply when T_{1E} exceeds the pseudo-critical value. Due to the limitation of the cladding temperature, the exit temperature of the thermal zone should not be much higher than 400°C. The exit coolant temperature of the hot channel in the fast zone decreases slightly as T_{1E} increases, whereas the maximum cladding temperature in the fast zone falls sharply when T_{1E} exceeds the pseudo-critical value. This outcome is another factor that determines the lower limit of the exit temperature in the thermal zone. The maximum velocity in the fast zone increases significantly when T_{1E} exceeds the pseudo-critical value. By considering all the aspects shown in figure 10, we can deduce that a reasonable range of values for T_{1E} is about 390°C to 400°C.

6. SUMMARY

We proposed a 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.

The preliminary assessment of the core performance was conducted in terms of the power density, the moderation capacity, the maximum cladding temperature and the maximum coolant velocity. The sub-channel analysis code STAFAS was applied to the thermal zone, whereas a single channel approach with a predefined hot channel factor was used for the fast zone. For the reference parameters, the effective core diameter of the mixed core is 3.30 m, which gives an average power density of 102 MW/m^3. The relative moderation capacity in the thermal zone is very close to that of a conventional PWR, whereas the moderation capacity in the fast zone is much less than that of a high conversion PWR. For the geometric arrangement assumed in this analysis and a uniform radial power distribution, the corner sub-channels and the wall sub-channels have the highest enthalpy rise in the thermal zone. A coupled neutron-physics/thermal-hydraulics analysis [13] shows that the fuel rods in the corner have a lower power density than the average value of the bundle. This lower power density reduces the hot-channel factor. Furthermore, the high enthalpy rise in the wall sub-channels can also be reduced by suitable selection of the geometric arrangement, such as the wall clearance.

The cladding temperature in the thermal zone depends strongly on the selection of heat transfer correlations, whereas the maximum cladding temperature in the fast zone shows negligible dependence on the selection of heat transfer correlations. The selection of the average exit temperature of the thermal zone is mainly determined by the maximum cladding temperature and the maximum flow velocity. A low exit temperature in the thermal zone enhances the moderation capacity of the fast zone and also leads to a high cladding temperature of the fast zone. An increase in the exit temperature of the thermal zone yields an increase in the cladding temperature of the thermal zone and an increase in the coolant velocity in the fast zone. The results achieved so far indicate that a reasonable core performance can be obtained when the thermal zone has an average exit temperature of about 400°C.

Further investigations on the proposed 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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