A New Design of a Vertical Pressure-Tube Type SCWR

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ABSTRACT

A conceptual super critical water reactor (SCWR) with vertical pressure tube (PT) is presented in this paper. The PT has re-entry flow path. The low temperature downward flow between the tube and fuel assemblies protects the tube from contacting high temperature heated fluid in fuel subchannels. A gas cylinder is established out of the PT to prevent heat loss from coolant at operation. This gas insulation can be removed out to cool PTs with heavy water moderator during severe accident. It can prevent any fuel pellets melting with the cooling from moderator.

KEYWORDS: SCWR, pressure tubes, concept design

1. INTRODUCTION

Super critical water reactor (SCWR) is thought to be a promising generation IV reactor not only because its technology is based on operation of PWR and BWR, but also on the success of fossil supper critical power stations. Both of them have run for several decades already. SCWR works over the supper critical point of water with very high exit temperature coolant. Its thermal efficiency is more than 45% compared to 36% of PWR or BWR. With the one-through circulation, the system is greatly simplified, and containment is small.

Many conceptual designs of SCWR were presented and developed in the past 20 years. Some of them are based on pressure vessel type, which reactor pressure vessel (RPV) is much like PWR. Fig.1 is a schematic of PV type SCWR[1]. In this design, when coolant is heated in subchannels its density becomes very small. Therefore water rods are needed to act moderation in fuel assemblies. Some other designs adopted pressure tubes as fuel and coolant channels, such as AECL SCWR and Russia design. Thus extra moderator fills the space out of pressure tubes.

AECL SCWR[2,3] (Fig. 2) adopted a lot of techniques of CANDU to reduce the technical risk, thus a lot of character of CANDU appear in it. The PT of AECL SCWR is horizontal in a DO_2 vessel. The passive heat removal system removes heat in DO_2 pool by natural circulation that is enhanced by flash vaporization. This system also works during accident when loss of coolant accident (LOCA) happens. Then the core melting is quite impossible.

Based on this priority, a new conceptual of PT type reactor is presented in this paper. It combines some characters of PV and PT types of SCWR.

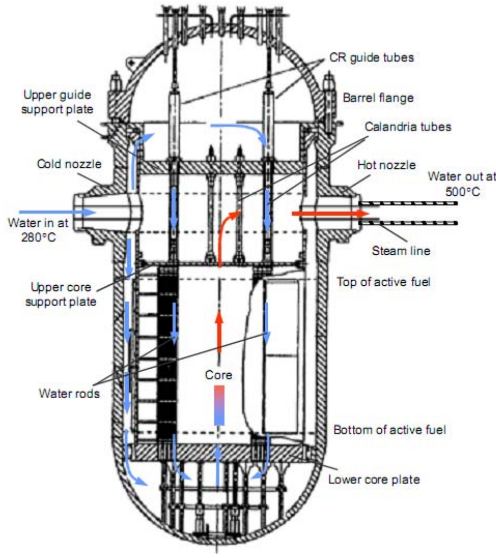

Fig. 1 The SCWR reactor pressure vessel and internals [1]

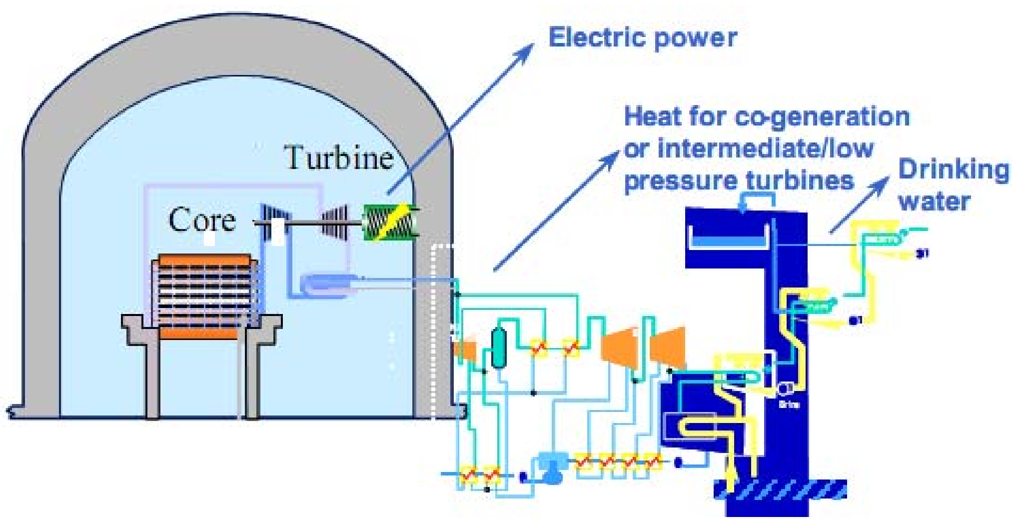

Fig. 2 Schematic of Candu SCWR

2. Reactor system introduction

The parameters of this reactor are listed in Table 1.

As Fig.3 shows, reactor has two systems, the high pressure system and low pressure system. The high pressure system includes the coolant inlet (cold leg), upper plenum, control rods, tube sheet, pressure tubes, fuel assemblies, and steam line (hot leg). The low pressure system is the moderate system. It performs two functions: one is provide moderation for the core, and the other is to bring heat in moderate out of reactor to some active or passive system, which transfers heat out of containment. This system includes a heavy water pool, control valves, and gas insulation.

In this design, pressure tubes are vertically located in a heavy water pool at the lower part of reactor. The upper end of pressure tubes is connected with a tube sheet. The configuration of upper part of reactor is same as the PV type SCWR. The reactor feed water from the feed pump goes into the upper plume and then flow to the core by two ways. One is to the core directly while the other goes upward and then pass through the paths in the control tubes to the core. After heated by fuel assemblies, the high temperature coolant exits from pressure tubes to the steam box, and then to turbines.

The pressure boundary of the design is isolated from the high temperature coolant. Therefore materials that used by PWR is still applicable for it. The control rod driving system is the same as the PWR's too. It is a good idea to apply the thermal sleeve to protect nozzles of the steam line from the high temperature coolant. By the design of the tube sheet, there is no need for tube folds as CANDU SCWR does. The refueling is the same as the PWR does.

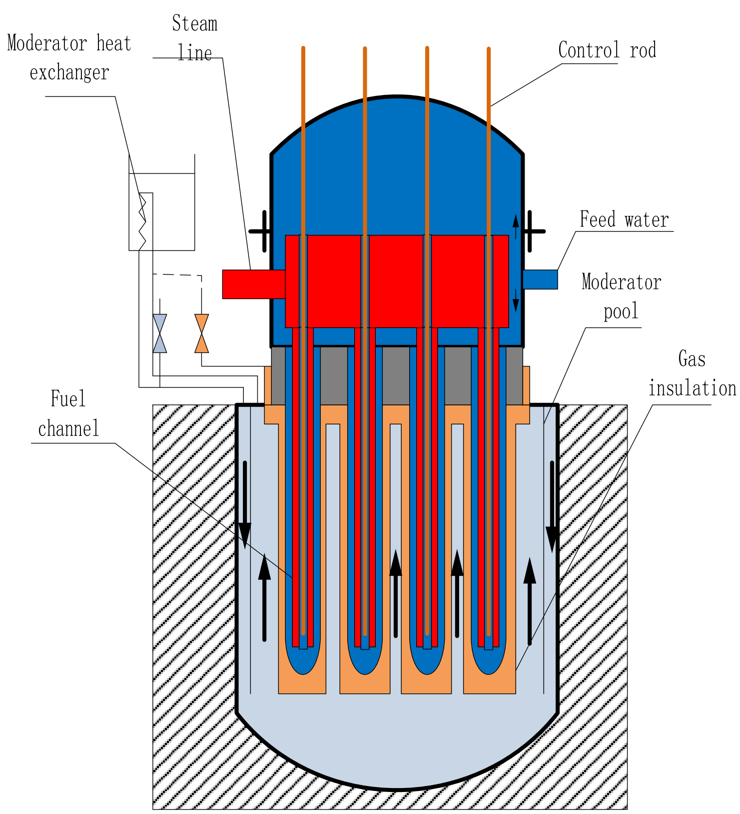

Fig.3 Schematic of vertical PT SCWR

Table 1 Parameters of SCWR

Parameters	Unit	
Reactor spectrum	-	Thermal
Power thermal	MW	2410
Electrical	MW	1040
Thermal efficiency	%	~43
Pressure	MPa	25
coolant	^{o}C	280
coolant	^{o}C	500

rate	kg/s	1245
Core height	m	~4
Core diameter	m	~4.3
fuel	-	UO2
Enrichment	% wt.	4
Cladding material	-	ODS
fuel assemblies	-	499
fuel rods in assemblies	-	54
Rod diameter	mm	10
Coolant	-	H2O
Moderator	-	D2O

The triangle arrangement of pressure tubes is adopted to get a compact core (Fig. 4). With small distance of fuel assemblies, it is expected that the light water moderator can be used in the future.

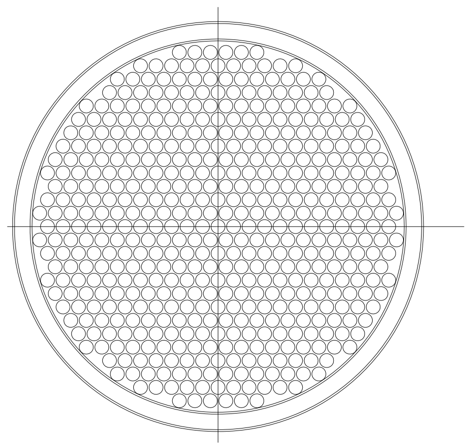

Fig.4 Pressure tubes arrangement in core

3. Pressure tube and fuel assemblies

Pressure tubes connect with the upper plenum by a large tube sheet. The lower end of pressure tubes is closed. There is a layer of He gas insulation to prevent pressure tubes from contacting directly with moderator, thus loss of heat from the coolant is reduced. A 2mm thin wall with honeycomb configuration is used as the outer enclosure of the fuel assembly. This configuration has two merits: one is stiff to support fuel rods in it, which has no grid spacer to fix them; another is heat insulation with Al_2O_3 in the interval of honey-comb. The re-entry flow path is used. There are two channels to allow coolant to flow downward, one is the channel between the pressure tube and the fuel assembly wall, the other is at the outside of the control rod. These two flows will mix in the lower head of pressure tubes and then go upward through fuel assemblies.

The fuel rods arrangement is triangle distribution (Fig. 5). There are 54 rods in each fuel assembly. The outer diameter of rods is 10mm. The pitch is 12mm. The control rod guide tube is in the center of the fuel assembly, which occupies 7 rods area. No doubt coolant in downward paths has moderation for fuel assemblies.

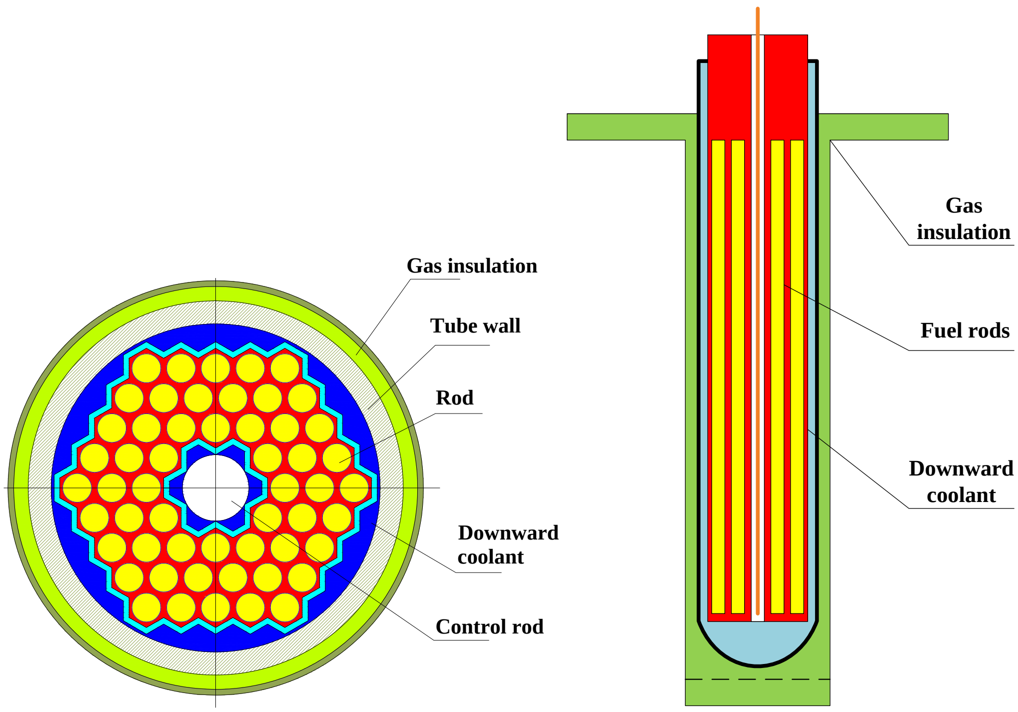

Fig.5 Fuel assemblies and gas thermal shield

4. Passive system

The passive safety is popular in recent years in nuclear reactor engineering field. In the PT type SCWR with the independent moderation system such as CANDU SCWR, the passive heat removal system was investigated by KHARTABIL et. al.[4]. Pressure tubes disperse in moderator. This means each fuel assembly has bigger heat transfer surface than the RPV reactor at the severer accident. Since power and wall thickness are small in each pressure tube, residual heat can be transferred from fuel to moderator through tube wall by conduction, radiation, and convection without fuel pellets melting or pressure tube deformation whenever there is water or not in the pressure tube.

In this design, to utilize this merit, a natural circulation should be established to remove heat in moderate at severe accident. During normal operation, a forced circulation is driven by pumps to remove heat out of moderator. H.F. Khartabil et. al. studied flashing phenomenon in riser. It can increase density difference and thus greatly increase natural circulation flow rate. It is better to set the passive system on the base of forced circulation system, because when accident happens, the inertial rotation of pumps can bring out more energy out of the core in the earlier stage of scenario, which is usually very short.

As AP1000 does, the final heat sink is ambient. Usually it is atmosphere. To release the core residual heat to atmosphere needs to realize two things: heat transfer without leakage of any fission products, and big heat surface in the air side. Air cooling has very low convective efficient, especially at the passive mode. In AP1000 design, a steel shell is used to realize heat transfer between atmosphere and the inner containment, and prevent fission materials transportation. With small containment of SCWR, this design is possible or not should be more studied. Furthermore, how to transfer heat from active heat exchanger to outside is a question. A water loop is a choice (Fig. 6).

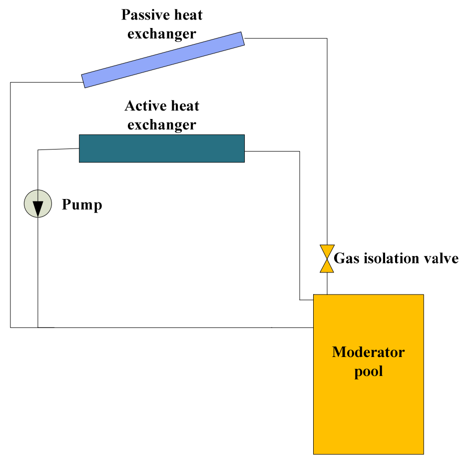

Fig. 6 Passive heat removal system

For high pressure coolant system, some PWR and BWR passive safety concepts still works, such as the accumulator, core makeup tank (CMT), passive heat exchanger, automatic depressurization system (ADS), pressure suppress pool and long term cooling system (LCS) with in-containment refueling water tank. Besides, the moderator passive safety system can be another heat channel during the design base accident (DBA).

Though the gas insulation out of pressure tubes prevents heat transfer at operation, at accident, it will be resistance to the residual heat transfer. A valve will open to discharge gas to the moderator retention tank, thus moderator can contact the pressure tube directly and natural circulation is established. A first analysis proved this design can keep the integrity of fuel pellets. The residual heat can be transferred to moderator by radiation from the high temperature surface of fuel cladding. The peak temperature is less than 1800^{o}C. It agrees with the study of VASIC et. al. [5]

5. Conclusions

A PT type SCWR with vertical pressure tubes is presented in this paper. The re-entry flow path is adopted to allow the low temperature coolant flows along tube wall at first, and then passes through fuel rods. Thus tube wall works under PWR temperature level. During operation, the gas insulation out of the tube reduces heat loss from tube, and during accident it is discharged to help heat transfer between moderator and tube wall. A passive safety system with natural circulation to transport moderator to heat exchanger, thus heat is removed out of moderator during accident. The core melting can be prevented.

6. REFERENCES

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