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Core design of a high breeding fast reactor cooled by supercritical pressure light water

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HIGHLIGHTS

- Core design concept of supercritical light water cooled fast breeding reactor is developed.
- Compound system doubling time (CSDT) is applied for considering an appropriate target of breeding performance.
- Breeding performance is improved by reducing fuel rod diameter of the seed assembly.
- Core pressure loss is reduced by enlarging the coolant channel area of the seed assembly.

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ABSTRACT

A high breeding fast reactor core concept, cooled by supercritical pressure light water has been developed with fully-coupled neutronics and thermal-hydraulics core calculations, which takes into account the influence of core pressure loss to the core neutronics characteristics. Design target of the breeding performance has been determined to be compound system doubling time (CSDT) of less than 50 years, by referring to the relationship of energy consumption and economic growth rate of advanced countries such as the G7 member countries. Based on the past design study of supercritical water cooled fast breeder reactor (Super FBR) with the concept of tightly packed fuel assembly (TPFA), further improvement of breeding performance and reduction of core pressure loss are investigated by considering different fuel rod diameters and coolant channel geometries. The sensitivities of CSDT and the core pressure loss with respect to major core design parameters have been clarified. The developed Super FBR design concept achieves fissile plutonium surviving ratio (FPSR) of 1.028, compound system doubling time (CSDT) of 38 years and pressure loss of 1.02 MPa with positive density reactivity (negative void reactivity). The short CSDT indicates high breeding performance, which may enable installation of the reactors at a rate comparable to energy growth rate of developed countries such as G7 member countries.

1. Introduction

For countries with advanced nuclear technologies, such as some of the G7 countries, establishing fast breeder reactor (FBR) fuel cycles may be an attractive option to secure sustainable source of energy, because FBRs can breed fissile ^{239}Pu from naturally abundant ^{238}U and can save consumption of the limited ^{235}U resources.

One of the indices of breeding performance is the compound system doubling time (CSDT), which indicates required time to double energy output (i.e., total capacity) of the installed reactors by utilizing excess fissile materials gained from breeding (Waltar and Reynolds, 1981). It is evaluated by considering the following scenario. At first, some FBRs are operated, and excess fissile material (e.g., ^{239}Pu) is produced by breeding. The excess fissile materials are accumulated until the amount reaches the inventory required to startup another FBR reactor. At this point, the excess fissile materials are loaded into another FBR for operation.

One way to consider an appropriate target of breeding performance of FBRs may be to consider CSDT with respect to growth rate of energy demand. The linear relationship between energy demand of a country and its Gross Domestic Product (GDP) is generally well acknowledged and is also supported by evidences (Soytas and Sari, 2003; Richmond et al., 2013). In the meanwhile, according to the economy outlook by Organization for Economic Co-operation and Development (OECD), average GDP growth rate of the G7 countries has been almost constant at around 1.4% per year for the past 30

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Nomenclature

D	fuel rod diameter
D_e	equivalent hydraulic diameter
E	Young's modulus
f	friction pressure loss coefficient
g	gravitational acceleration
G	mass flux
K	form friction coefficient
L	length of channel
ΔP_{fric}	friction pressure loss
ΔP_{form}	form pressure loss
ΔP_{grav}	gravity pressure loss
ΔP_{acce}	acceleration pressure loss
P_{collapse}	buckling pressure
Re	Reynolds number
t	cladding thickness
u	axial coolant velocity
Δz	axial node width
ν	kinematic viscosity coefficient
ρ	coolant density

years (Gurria and Padoan, 2012). These relationship and data indicate that average energy demand of the G7 countries has been growing at about 1.4% per year and may continue to grow at the same rate and double in the next 50 years (i.e., $1.014^{50} = 2.0$). The role of nuclear power in such countries may be greatly enhanced if FBRs can be installed at similar rate to cope with the growing energy demand. In this study, CSDT of less than 50 years is considered to be a design target of FBRs.

Among different types of FBR systems, large amount of effort have been devoted to development of sodium cooled FBRs, because of its high efficiency in breeding (USAEC Division of Technical Information, 1970; Srinivasan et al., 2006). However, there remain issues with handling of sodium and the high capital cost. On the other hand, light water reactors (LWRs) have been commercially used in many countries for decades with generally excellent reliabilities and high economic competitiveness against other technologies. However, current commercial LWRs are thermal reactors fueled with enriched uranium and sustainability of the fuel cycle is limited. Concepts of FBRs cooled by light water have been studied for many years, but most concepts are high conversion type reactors (Edlund, 1975; Oldekop et al., 1982). Few of the concepts show breeding ability, but generally, high breeding is difficult with LWRs, because light water acts as good moderator and softens the neutron spectrum, which disfavors breeding. For example, BWR type RMWR concept of JAEA is a breeder reactor. It adopts tight fuel rod lattice of triangular arrangement to reduce coolant (moderator) to fuel volume fraction (V_m/V_f) to 0.17 and minimize neutron moderation (Iwamura et al., 2006). However, its CSDT is 245 years, which is far from achieving the above mentioned target of 50 years.

In order to achieve short CSDT (high breeding performance) with light water cooling, the tightly packed fuel assembly (TPFA) concept with coolant to fuel volume ratio of less than 0.085 has been proposed and studied at Waseda University (Oka et al., 2013). The TPFA concept was then applied in core design of Super FBR, which is Waseda University concept of Supercritical Water Cooled Reactor (SCWR) for breeding ^{239}Pu with mixed oxide (MOX) fuel (Yoshida, 2014). In Super FBR, coolant temperature is not limited by the saturation temperature of water and its density can be reduced to around 0.36 g/cm^3. Moreover, fuel rods can be effectively cooled with narrow coolant channel by powerful pumps operating at supercritical pressure. Thus, coolant inventory in the core can be greatly reduced to favor breeding. As the result, the study showed that Super FBR with TPFA achieved CSDT of 47 years.

However, the core pressure loss of Super FBR was high (1.48 MPa) and its influence (feedback) to the core neutronics was not considered in the previous study (Yoshida, 2014). Also, there is need to investigate ways of further reducing CSDT with the current core arrangement, which is yet to consider control rod designs. There may be different ways of modifications to the current core arrangement to accommodate control rod insertions, but such modifications may reduce breeding performance of the core and achieving the target CSDT of 50 years may be difficult with the current core arrangement.

By considering the above all, this study aims to show Super FBR core design with TPFA concept by considering fully-coupled neutronics and thermal-hydraulics core calculations, which takes into account the influence of core pressure loss to the core neutronics characteristics. Moreover, further improvement of CSDT and reduction of core pressure loss of Super FBR is investigated by considering different fuel rod diameters and coolant channel geometries.

2. Design method

2.1. Design goals and criteria

Design goals and criteria are adopted from the studies of previous Super FBR and Super FR (Yoshida, 2014; Liu and Oka, 2013). They are summarized as following:

The design goals

(1) Fissile plutonium surviving ratio (FPSR) should be over 1.0.
(2) Compound system doubling time (CSDT) should be shorter than 50 years.

The design criteria

(1) Positive water density (negative void) reactivity is achieved through a cycle.
(2) Maximum linear heat generation rate (MLHGR) should be below 39 kW/m.
(3) Maximum cladding surface temperature (MCST) should be below 650 °C at normal condition.

FPSR is an index of breeding for a reactor whose fission reactions are mainly from those of fissile plutonium (Pu) isotopes (such as ^{239}Pu and ^{241}Pu). FPSR of over 1.0 indicates that breeding of fissile Pu is achieved. The CSDT criterion of below 50 years is also adopted as described in the previous section. Definitions of these indices are provided in the following section.

The design criterion of positive water density reactivity corresponds to the negative void reactivity of BWRs and is essential for assuring inherent safety of water cooled reactors. The design criteria of MLHGR and MCST are tentatively determined to ensure fuel integrities during abnormal transients for the purpose of conceptual development (Yamaji et al., 2003).

Core pressure loss is not a design criterion, but high core pressure loss may influence coolant density distribution in the core and consequently influence its breeding performance (FPSR and CSDT). Hence, in this study, core pressure loss is evaluated and its influence on CSDT is evaluated through coupled neutronics and thermal hydraulics calculations as described in the following section. Another concern of high core pressure loss is channel stability and high pumping power requirement (Hetrick, 1993). Low core pressure loss is desirable from the viewpoints of these potential issues. One effective way to reduce core pressure loss is to enlarge coolant channel flow area, but this may influence the core breeding