The feasibility research of thorium breeding using fluoride salt as a fast reactor coolant

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ABSTRACT

Breeder reactors are considered as a unique tool for fully exploiting natural resources. Fast breeder reactors based on thorium fuel can enhance inherent safety. Fluoride salt has good performance as a coolant in high-temperature nuclear systems. However, there is some doubt about the fuel breeding ability using fluoride salt coolant for fast spectrum due to its moderating ability. The aim of this study was to choose a proper fluoride salt mixture for Liquid-salt-cooled Solid-fuel Fast Reactor (LSFR) based on thorium-uranium fuel and give parametric studies to provide a design window for flexible self-sustaining core design. Infinite assembly model was used to analyze the salt selection from five candidate fluorides for fast spectrum as coolant. Combining neutron balance analysis with linear least squares fitting method based on 0D model, parametric studies at the neutron balance equation unique solution with burn-up for several parameters such as fuel volume fraction, removing fissile gases process, total neutron losses and power density were presented in this paper. It was found that BeF2-NaF was a promising coolant in the five candidate fluoride salt mixture. This study proved that the design of a self-sustaining core for fluoride-salt-cooled fast breeder based on thorium fuel is achievable. A design window was found in the definition of a self-sustaining core for various fuel volume fractions and neutron loss fractions. Core design and fuel management strategy will be given in future.

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1. Introduction

In 2002, GFR, LFR, SFR, MSR, SCWR and VHER were selected as Generation IV systems, all of which have the advantage of sustainability, economics, safety, reliability and proliferation-resistance (US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002). In particular, four are fast neutron reactors. Energy sustainably and long-term availability of nuclear fuel are important researching content in Generation IV systems (Locatelli et al., 2013). The fast spectrum system has the ability to breed fuel, allowing nuclear fission reactors to provide a very long-term energy supply. For complete utilization of the fertile isotopes, it is necessary to develop breeder reactors which can transmute the fertile isotopes into the fissile isotopes at a rate faster than the rate of consumption of fissile material for power production. With these unique features, the utilization of uranium resource increases significantly compared to LWRs (Fast spectrum reactors, 2012).

Thorium is 3–4 times more abundant than uranium, widely distributed in nature as an easily exploitable resource in many countries. Thorium fuel cycle is an attractive way to generate long term nuclear energy with low TRU waste (Lung and Gremm, 1998). Application of thorium–uranium fuels have been widely researched in thermal reactors such as PWRs, HWRs, SCWRs, HTGRs and MSRs (Lung and Gremm, 1998; Anantharaman et al., 2008; Jeong et al., 2008). Research has shown that only the high discharge burn-up of thorium–uranium fuel had economy advantage for commercial applications in conventional PWRs and HWRs, but the existing materials couldn’t bear the radiation damage of the high accumulated burn-up (Long, 2002; Wang, 2003; Yildiz et al., 2011). SCWRs, HTGRs, and MSRs belong to generation IV reactors and are in a state of research and development. MSRs is the best candidate reactor for thorium-uranium breeding, but research has shown that a self-breeder MSRs (Nagy et al., 2008) requires a fast removal FP and MA online and the extraction of Pa and the re-introduction of the
formed U. Limited studies have been carried out concerning the use of thorium in fast reactors (FRs), historically conceived as breeder reactors, due to the superiority of the uranium/plutonium cycle from this standpoint. The thorium fuel cycle is known to offer a better neutron economy than the uranium fuel cycle at epithermal energies and does not have a large positive reactivity feedback upon spectrum hardening at high neutron energies because (1) $\eta^{(233)\text{U}}$ does not vary as steeply with neutron energy as $\eta^{(239)\text{Pu}}$ does, (2) the fissile cross-section of $^{232}\text{Th}$ has a higher threshold energy and smaller magnitude than that of $^{239}\text{U}$ (Fast spectrum reactors, 2012; Lung and Gremm, 1998). In addition, the relatively low mass number of $^{232}\text{Th}$ leads to a characteristically low TRU inventory when $^{232}\text{Th}$ closed cycle is established, with potentially beneficial impacts on the actinide radio-toxicity and decay heat. It is necessary to develop FRs for enhanced inherent safety with thorium-based fuel. Moreover, breeding $^{232}\text{Th}$ leads to a diversification of energy resource bases and allows greater flexibility in the choice of breeder reactor concept and fuel cycle (Fiorina et al., 2013).

Breeder reactors are regarded as a unique tool for fully exploiting natural nuclear resources. Coolant selection for FRs plays an important role in breeding performance and safety considerations. The fuel must be selected for most of existing fast breeder reactors was sodium, which is still considered the best candidate for these reactors (Lafuente and Piera, 2010). However, Na reacts chemically with air and water very easily and requires a sealed coolant system which leads to frequent accidents. Furthermore, Na-cooled FBRs have a positive void reactivity coefficient and this coefficient increases with the reactor size (Ichimiya et al., 2007). Another choice for FBRs coolant is Helium. Because the GFR requires a dense fuel element that can withstand very high temperature transients for lacking of thermal inertia of the system, its fuel element is still under design. Moreover, safety is a major concern for GFR (Anzieu et al., 2009), such as decay heat removal (DHR) without external power in depressurized conditions. As for lead- and lead-bismuth-cooled cores (Generation IV International Forum, 2014), several drawbacks must be overcome, including the need for coolant chemical (oxygen) control for prevention of lead erosion-corrosion effects on structure steels at high temperatures and flow rates, and seismic/structural issues due to the weight of the coolant. Therefore, it seems reasonable to explore new options for FBRs coolant.

In recent years, there has been a rapid growth in research and development on high-temperature molten salts in nuclear systems (LeBlanc, 2010; Serp et al., 2014). Fluoride salt as a coolant has been developed on high-temperature molten salts in nuclear systems as a reference (Perkko et al., 2015), the design of LSFR in this study use fluoride ceramic fuel and numerous favorable properties SiCf/SiC as cladding material and liner material with a cylindrical arrangement of hexagonal fuel assemblies. Actually the fuel element of GFR has good high temperature nuclear radiation performance and SiC/SiC is compatible with fluoride salt (He et al., 2014).

In this study, the research content mainly includes: (1) choose a proper fluoride salt mixture for LSFR based on thorium fuel; (2) investigates the effect on the thorium breeding capacity and the average batch discharge burn-up that an equilibrium cycle of a fast reactor can be operated at of several parameters such as fuel volume fraction, removing fissile gases, the effect of neutron loss and power density. In the fast neutron spectrum, because $^{232}\text{Th}$ is less fissile than $^{235}\text{U}$ and has a higher fission threshold energy, this study requires design of thorium-based fuel self-sustaining core with BR slightly $>1.0$ for multiple recycling of recovered thorium and uranium without actinides. This paper is divided into five sections. Section 1 is the introduction. Section 2 presents the methodology, first introduces the calculation tools and then describes the calculation procedure of the fluoride salt mixtures selection with infinite assembly model, finally focusing on the calculation procedure of parametric studies for long term with burn-up analysis based on a simplified 0D cores. Section 3 presents the results, firstly, investigated the BR, fluoride salts nuclide absorption share...
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