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Assessment of the neutronic performance of some alternative fluids in a fusion–fission hybrid reactor by using Monte Carlo method

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ABSTRACT

In this study, a fusion–fission hybrid reactor system was designed by using 9Cr2WVTa Ferritic steel structural material and the molten salt-heavy metal mixtures 99–95% $Li_{20}Sn_{80}$-1–5% SFG-Pu, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuF_4, or 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuO_2, as fluids. The fluids were used in the liquid first wall, blanket and shield zones of a fusion–fission hybrid reactor system. Beryllium (Be) zone with the width of 3 cm was used for neutron multiplication between the liquid first wall and blanket.

This study analyzes the nuclear parameters such as neutron flux, tritium breeding ratio (*TBR*), energy multiplication factor (*M*), heat deposition rate, fissile fuel breeding in liquid first wall, blanket and shield zones and investigates effects of spent fuel grade Pu content in the designed system on these nuclear parameters. Three-dimensional analyses were performed by using the Monte Carlo code MCNPX-2.7.0 and nuclear data library ENDF/B-VII.0.

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1. Introduction

Waste management, which occurs as a result of fuel combustion in obtaining energy, is one of the important problems in conventional nuclear reactors, today. Transformation of wastes into stable and short-lived isotopes through nuclear reactions is a radical solution. Moreover, while light water reactors (LWR) using enriched nuclear fuel use very small amounts of natural uranium, they leave the rest as radioactive waste, consequently it is estimated that nuclear fuel supply would become difficult in the future. Therefore; hybrid reactor system operating nucleus fusion and fission events together was developed in order to be a solution for problems of high energy output, radioactive waste management, and alternative fuel supply. An important advantage of hybrid reactor system is that it has a subcritical reactor system, where the reactor can operate securely.

The fuels used in hybrid reactor system are generally D–T or D–D fuels. When D–T fuel enters into fusion reaction, 14.1 MeV fusion neutrons and 3.5 MeV alpha particles are released. In order to use high energy fusion neutrons effectively and to behave compliantly to the purpose of the hybrid reactors, the plasma is surrounded by a wall made of fertile material, which cannot perform fusion reaction with thermal neutrons, however it can perform conversion with high energy neutrons such as 14.1 MeV. Thus, the high energy fusion neutrons perform conversion to fertile materials in order to obtain fissile fuel, fission neutrons and energy production. Hybrid reactor produces 30 times more nuclear fuel per nuclear energy amount compared with fast reactors (Nygren et al., 2004; Şahin and Übeyli, 2005; Şahin, 2007; Şarer et al., 2007; Günay et al., 2011, 2013).

The first wall surrounding the plasma is exposed to high energy fusion neutrons, gamma ray and charged particle flux. Application of high energy neutrons to a structural (solid) material causes the atoms in the structural material to change their place in the lattice structure of the material and called as radiation damage. If the first wall is made of the structural material, the greatest damage occurs in that section, it causes the structural material to be spoiled and reactor life to shorten. In order to reduce these negativities, the idea that first wall surrounding the plasma should be liquid instead of solid was initially suggested by Christofilos (Christofilos, 1989; Moir, 1997). The liquid wall concept proposed by Christofilos was used in APEX (Advanced Power Extraction) developed in the USA in early 1998 to investigate fusion energy technology (Abdou and The APEX Team, 1999; Abdou et al., 1999, 2001, 2005; Abdou, 2004; Şarer et al., 2007). Thus in APEX the traditional solid first wall that surrounds the plasma is replaced by a flowing liquid layer. The flowing liquid wall is used in APEX as two walls; a liquid first wall and as a liquid second wall. The liquid first wall is located beyond the plasma and the liquid second wall is located beyond the liquid first wall. Both liquid walls confine charged particles, thus significantly reducing radiation damage in structural materials, and confine the energy of the neutrons, converting it into heat (Abdou and The APEX Team, 1999; Abdou et al., 1999, 2001, 2005; Abdou, 2001, 2004; Ying et al., 1999; Youssef and Abdou, 2000; Youssef et al., 2002).

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This study presents a hybrid reactor system design by using of APEX fusion technology. In designed hybrid reactor system would be possible to obtain secure energy in high amount with D–T fuel usage and subcritical study. Furthermore, it would be possible to obtain qualified nuclear fuel (fissile material) such as ^{239}Pu through the reaction of fertile material with high-energy neutrons and enable production the self-sufficiency fuel of reactor through the reaction of neutron released by plasma. Substantial amount of spent fuel grade (SFG) plutonium (Pu) from the current nuclear reactors has been stored to be used in the future. The isotopic distribution of SFG-Pu is composition 2.4% of ^{238}Pu, 58.5% of ^{239}Pu, 24% of ^{240}Pu, 11.2% of ^{241}Pu, 3.9% of ^{242}Pu. SFG-Pu is quite valuable for obtaining fissile material and very dangerous in the case of a misuse. Therefore someone must be extremely careful in SFG-Pu method. The radiation from this material to the environment should be avoided, carefully. In study with this purpose, radioactive materials with plutonium additive were used in the hybrid reactor system designed to reduce the amount of spent fuel grade plutonium from the current nuclear reactors. This is very valuable for fissile fuel production and it is very dangerous in case of unintentional misuse. Therefore, it is considered to provide important contribution to environment and economy with convert into high quality nuclear fuel and short half life by using durable of dangerous plutonium present in spent fuel grade in designed hybrid reactor system.

In this study, a hybrid reactor system was designed by using 9Cr2WVTa Ferritic steel structural material, ENDF/B-VII.0 nuclear data library and 99–95% $Li_{20}Sn_{80}$-1–5% SFG-Pu, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuF_4, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuO_2 the fluids in the liquid first wall, blanket and shield zones.

Three-dimensional neutronic measurements such as average neutron flux, tritium breeding ratio (*TBR*), energy multiplication factor (*M*), heat deposition rate, fissile fuel production was done with conducted for the created design. MCNPX-2.7.0 Monte Carlo code was used for three-dimensional neutronic measurements.

2. Method

2.1. Geometry description

The radial structure of the designed hybrid reactor system in this study is shown in Table 1. Hybrid reactor system used in the study is in the shape of a torus. The radius of the torus is 552 cm. The fast-flowing liquid first wall is 2 cm thick and the slow-flowing layer (blanket) is 50 cm thick. The beryllium (Be) is a neutron multiplier that increases the neutronic measurements by (n,2n) reactions such as the rate of tritium breeding, energy multiplication, heat deposition. In this study, Be zone with a thickness of 3 cm that contributes to neutron multiplication effect by (n,2n) reactions was used between liquid first wall and blanket. A backing solid wall of 4 cm thickness, made of 9Cr2WVTa ferritic steel that has a low activation as structural material, follows the blanket zone. A shielding zone of 50 cm thickness (outboard) and 49 cm thickness (inboard) is located behind the backing solid wall for the outboard and inboard builds, respectively, and is assumed to have a structure-to-breeder (coolant) volume ratio of 60:40. The vacuum vessel wall is 2 cm thick and made of SS316LN stainless steel, and the interior is 16 cm thick (inboard) and 26 cm thick (outboard) with SS316LN stainless steel cooled with water by a structure-to-water ratio of 80:20 (Ying et al., 1999).

Table 1
The radial build of the hybrid reactor system design.

Inboard side		Outboard side	
Zone	*r* (cm)	Zone	*r* (cm)
SS316LN	276	Plasma	667
Vacuum vessel[a]	278	SOL	695
SS316LN	294	Liquid first wall[d]	697
GAP	296	Be[e]	700
Shield[b]	301	Blanket[d]	750
Ferritic steel[c]	350	Ferritic steel[c]	754
Blanket[d]	354	Shield[b]	804
Be[e]	404	GAP	838
Liquid first wall[d]	407	SS316LN	840
SOL	409	Vacuum vessel[a]	866
Plasma	437	SS316LN	868

[a] 80% SS316LN, 20% H_2O.
[b] 60% 9Cr2WVTa, 40% (99–95% $Li_{20}Sn_{80}$-1–5% SFG-Pu, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuF_4, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuO_2).
[c] 100% 9Cr2WVTa.
[d] 99–95% $Li_{20}Sn_{80}$-1–5% SFG-Pu, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuF_4, 99–95% $Li_{20}Sn_{80}$-1–5% SFG-PuO_2.
[e] 100% Be.

2.2. Numerical calculations

Calculation of all parameters of fission and fusion reactors, accelerator-driven systems and other areas of nuclear technology depend on cross section data. Experimental data are few for neutron-produced reactions in some energy intervals. Certain cross sections such as fission reactions are insufficient. There are significant differences between cross section and nuclear data libraries in all energy intervals from thermal to high energies. These differences will affect all parameter calculations used in areas of nuclear technology.

Nuclear reaction cross sections can be obtained in three different ways; experimental measurement, theoretical calculation and Evaluated Nuclear Data Files (ENDFs). For wide ranges of energy, measuring cross sections for all isotopes in the periodic table is unfeasible both physically and economically. Therefore, model calculations play an important role in the evaluation of nuclear data (Şarer et al., 2009; Günay, 2013).

The evaluated nuclear data file ENDF/B (Evaluated Nuclear Data File) was first developed in the USA in 1968. New versions were published periodically following large-scale investigations and additional research. ENDF/B-VII include data from 10^{-11} MeV to 20 MeV for all isotopes and up to 150 MeV for some isotopes (Chadwick et al., 2006; Pelowitz, 2011).

Three dimensional nucleonic calculations were performed using MCNPX-2.7.0 Monte Carlo code and ENDF/B-VII.0 nuclear data library. Analysis was performed for neutron wall loading 10 MW/m^2 and fusion power 4000 MW.

In this study, the fluids were composed of molten salt $Li_{20}Sn_{80}$ as the main constituent with increased mole fractions of heavy metals, 1–5% SFG-Pu, SFG-PuF_4, SFG-PuO_2. The fluids used in order to decrease amount of spent fuel grade Pu were used in the liquid first wall, blanket and shield zones of hybrid reactor system. Three-dimensional neutronic measurements such as average neutron flux, tritium breeding ratio (*TBR*), energy multiplication factor (*M*), heat deposition rate, fissile fuel production was done with the created design.

3. Numerical results

3.1. Neutron flux

Performance of a hybrid reactor system depends mainly on neutron flux level. In the investigations heavy metals contents were calculated and found to depend on average neutron fluxes. Fig. 1 shows variation of the average neutron fluxes versus the mixture components of 99–95% $Li_{20}Sn_{80}$, 1–5% SFG-Pu, SFG-PuF_4, SFG-PuO_2 in the liquid first wall, blanket and shield zones. In Fig. 1 it