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Hydrogen production potential of APEX fusion transmuter fueled minor actinide fluoride

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ABSTRACT

Main aim of this study is to investigate hydrogen production potential of **A**dvanced **P**ower **EX**traction (APEX) fusion reactor cooled with the molten-salt mixtures, as well as its neutronic performance to transmute minor actinides (MAs). In the original APEX reactor concept, fusion power (P_f) is quite high (4000 MW), and the FLiBe molten-salt flows as molten-salt wall. The FLiBe molten-salt is mixed with molten minor actinide tetra fluoride salt (MAF_4) to transmute minor actinides, and at the same time, to increase the energy multiplication. In addition to this mixture of FLiBe and MAF_4, FLiNaBe, LiF and Eutectic Lithium instead of FLiBe are mixed individually with MAF_4, and are used as the molten-salt coolant. Furthermore, two different compositions of MA nuclides are considered as follows: (i) The MA nuclides discharged from the pressured water reactor (PWR)-MOX spent fuel and (ii) The MA nuclides discharged from the PWR-UO_2 spent fuel. The neutronic analyses have been performed for these eight different molten-salt mixture cases and for both one and three-dimensional geometry models by using the XSDRNPM/SCALE4.4a neutron transport code and the MCNP4B code, respectively.

In order to produce hydrogen in large-scale, Steam-Methane Reforming (SMR) combined with the Mineral CO_2 Sequestration (MCS) is selected. Furthermore, the sulfur–iodine (S–I) thermochemical water splitting and high-temperature electrolysis (HTE) cycles, which are the most promising water-splitting cycles, are analyzed. The results of calculations bring out that the considered fusion reactor has a good neutronic performance, and it can produce in a considerable amount of the hydrogen production (up to 426 kg/s), as well as the minor actinide transmutation (up to 4.849 t/yr).

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1. Introduction

Nuclear wastes generated by commercial nuclear power plants appear to be the most important environmental safety issue, and they include mainly long-lived fission products and minor actinides (MAs). Fusion reactors can provide an attractive and complete solution for these waste problems. Several fusion transmuters have been developed as conceptual. A program called "**A**dvanced **P**ower **EX**traction (APEX)" has been initiated within the scope of the magnetic fusion energy program in the US Department of Energy [1]. Liquid wall (LW) concept is the main focus of this program. The liquid wall approach has a lot of attractive features (reductions of radiation effects and thermal stresses, and more attractive and competitive fusion power, and, etc.). The APEX fusion reactor has high neutron wall load (>10 MW/m^2) and associated surface heat flux (>2 MW/m^2)

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Nomenclature

A	atomic mass, gr/atom-gr
A_0	Avogadro's number (6.023×10^{23} atoms/atom-gr)
C_P	specific heat, MJ/kg K
E_f	energy per fission, 200 MeV
f	fission
h	enthalpy, MJ/kg K
$\dot{m}$	mass flow rate, kg/s or kg/yr
M	energy multiplication ratio
M	molar mass, kg/kmol
P	power, MW
q	energy per kilogram, MJ/kg
Q	fusion energy gain factor
Q	energy or heat
R	reaction number per fusion neutron, reactions/n
T	temperature, °C
T_6	tritium breeding per fusion neutron from ^{6}Li
T_7	tritium breeding per fusion neutron from ^{7}Li

Greek symbols

α	alpha particle
γ	capture reaction
ε	proportion coefficient
η	efficiency
μ, ξ, ν	ratio of molar mass
χ	power fraction
ψ	electrical power fraction
Φ	fusion neutron number per second

Subscripts

aux	auxiliary system
cir	circulation
dep	depleted
ds	driving system
e	electricity
eh	electricity for hydrogen production
f	fission or fusion power output
ge	gross electricity
gt	gas turbine
h	hydrogen
hp	hydrogen production
hpf	hydrogen production facility
i	input
ihx	intermediate heat exchanger
isf	isotope separation facility
j	nuclide or species index
mcs	mineral CO_2 sequestration
n	neutron particle
overall	overall
smr	steam-methane reforming
th	thermal
tot	total
wgs	water gas shift

Abbreviations

APEX	**A**dvanced **P**ower **Ex**traction
D–T	deuterium–tritium
FW	first wall
HHV	higher heating value
HTE	high-temperature electrolysis
I/B	inboard
LW	liquid wall
MA	minor actinide
MCS	mineral CO_2 sequestration
MOX	mixed OXide
MSFB	molten-salt fusion breeder
MSFT	molten-salt fusion transmuter
MSR	molten-salt reactor
O/B	outboard
PF	plant factor
PWR	pressured water reactor
S–I	sulfur–iodine
SMR	steam-methane reforming
TBR	tritium breeding ratio
TWS	thermochemical water splitting
WGS	water gas shift

capabilities [1–3]. Therefore, the APEX reactor would serve as a nuclear waste transmuter, as well as energy production.

Molten-salt reactors (MSRs) can be used for transmutation of actinides, production of fissile fuels and production of hydrogen, as well as electric production. In an MSR, the nuclear fuel (minor actinides and/or uranium and/or thorium fertile fuels) is dissolved in a molten fluoride salt coolant. For very high-temperature reactors such as fusion reactors, molten fluoride salts can be used as coolant because of high thermodynamic efficiency. Molten-salt fusion breeder (MSFB) and molten-salt fusion transmuter (MSFT) are a type of fusion reactor in which both the primary coolant and the nuclear fuel are in the form of molten-salt fluorides. In MSFBs and MSFTs, molten-salt Flibe (Li_2BeF_4), FLiNaBe, LiF, and eutectic lithium can be considered as the candidate liquid breeders. In recent years, a lot of studies on the fissile breeding performance of various MSFBs fueled with different molten-salt mixtures have been performed [4–14]. These investigations bring out that the use of mixture of molten-salt coolant and molten-salt uranium and/or thorium enhances significantly the neutronic performance and fissile breeding capability of the reactor, as well as energy production.

Hydrogen is one of the clean energy sources, and it has a great potential as an environmentally friendly secondary energy source. However, pure hydrogen does not exist naturally on the earth. It, therefore, cannot be called as "a primary energy source". Hydrogen only can be produced from its form of chemical compounds, such as water or hydrocarbons by using primary energy sources. Hydrogen is currently primarily produced from fossil resources. Nowadays, the energy transition from fossil-based energy to a new and renewable energy sources is one of the main important problems of developed and developing countries. The importance of carbon-free fuels and carbon-free technologies has been emphasized by Muradov and Veziroglu in their study [15]. In addition, the properties of hydrogen as a fuel tomorrow in sustainable energy system for a cleaner planet have been given by Momirlan and Veziroglu in ref. [16].

The candidates for a large-scale production of hydrogen are Steam-Methane Reforming (SMR), Thermochemical Water

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