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Power maximization method for land-transportable fully passive lead–bismuth cooled small modular reactor systems

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HIGHLIGHTS

- The power maximization method for LBE natural circulation cooled SMRs was developed.
- The two powers in view of neutronics and thermal-hydraulics were considered.
- The limitations for designing of LBE natural circulation cooled SMRs were summarized.
- The necessary conditions for safety shutdown in accidents were developed.
- The maximized power in the case study is 206 MW thermal.

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ABSTRACT

Although current pressurized water reactors (PWRs) have significantly contributed to global energy supply, PWR technology has not been considered a trustworthy energy solution owing to its problems of spent nuclear fuels (SNFs), nuclear safety, and nuclear economy. In order to overcome these problems, a lead–bismuth eutectic (LBE) fully passive cooling small modular reactor (SMR) system is suggested. This technology can not only provide the solution for the problems of SNFs through the transmutation feature of the LBE coolant, but also strengthen safety and economy through the concept of natural circulation cooling SMRs. It is necessary to maximize the advantages, namely safety and economy, of this type of nuclear power plants for broader applications in the future. Accordingly, the objective of this study is to maximize the reactor core power while satisfying the limitations of shipping size, materials endurance, and criticality of a long-burning core as well as safety under beyond design basis events. To achieve these objectives, the design limitations of natural circulating LBE-cooling SMRs are derived. Then, the power maximization method is developed based on obtaining the design limitations. The results of this study are expected to contribute to the effectiveness of the reactor design stage by providing insights to designers, as well as by formulating methods for the power maximization of other types of SMRs.

1. Introduction

Almost 30 years have passed since the Chernobyl nuclear accident (1986), which is called the worst nuclear accident to date. Because nuclear power plants worldwide played their respective role in ensuring safety in the energy spectrum during the period between Chernobyl and early 2011, it appeared that nuclear energy rebounded to experience a renaissance in the energy industry. Unfortunately, the Fukushima Daiichi Nuclear Power Plants (NPPs) accident that occurred in March 2011 in Japan putted many nuclear power plants around the world under heavy criticism.

On this account, nuclear energy should be developed as a new energy source for future energy needs. There are three weaknesses of the current pressurized water reactor (PWR) technology: (1) no countermeasure of spent nuclear fuel (SNF) disposal, (2) low public acceptance as a result of several accidents in the past (i.e., Chernobyl, TMI, and Fukushima), and (3) declining persuasive power on the economic benefits of nuclear energy owing to the large initial investment in NPPs, and the development of shale-gas energy.

To overcome these problems, we suggest the lead–bismuth eutectic (LBE) natural circulation cooling small modular reactors (SMRs) as the selected nuclear concepts. To maximize the economy of SMRs, the core power of SMR should be fully maximized while the limitations of shipping size, materials endurance, criticality of a long-burning core, and safety are satisfied. An economic assessment is conducted to show a logical justification for power

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Nomenclature

P	normalized power
F	normalized flow
A	power coefficient of reactivity (cent)
B	power/flow coefficient of reactivity (cent)
C	inlet temperature coefficient of reactivity (cent/K)
δT_{in}	coolant inlet temperature change
δT_{out}	coolant outlet temperature change
$\Delta\rho$	reactivity change
ΔT_C	coolant temperature rise
T_{CR}	cladding creep rupture limit temperature
T_{OUT}	coolant outlet temperature
ρ	coolant density
g	gravity coefficient
β	expansion coefficient
H	thermal height difference
ΔT	coolant temperature difference
V	coolant velocity
k	form loss coefficient
f	friction loss coefficient
A	coolant flow area
l	coolant flow length
d	hydraulic diameter
P_{core}	core power
m	mass flow rate
C_p	heat capacity

maximization. After that, the design limitations are derived and maximization process is developed through the case study. The purpose of this research is to develop a power maximization method for small modular reactors with LBE natural circulation, while at the same time satisfying the constraints of shipping size and materials endurance, as well as safety under beyond design basis events (DBEs).

2. Selected nuclear concepts

The weaknesses of current PWR technologies must be solved in order to supply enough energy with nuclear power. As a solution, the LBE fully passive cooling SMR is suggested in this study. LBE fully passive cooling SMR is developed based on an innovative nuclear reactor concept that consists of long burning technology and small modular reactors with natural circulation of the LBE coolant. Three concepts for future nuclear energy are introduced in the following subsections.

2.1. Long-burning technology

Long-burning technology uses a fast neutron spectrum that utilizes uranium more efficiently than thermal reactors. With these unique features, the energy potential of uranium increases significantly compared to light water reactors. Radioactive waste containing long-lived minor actinides has become practically insignificant. In addition, the economic benefits of the reactor are enhanced as well by lowering refueling costs with a long refueling cycle.

The requirement of a fast neutron spectrum implies the mandatory usage of coolants with low moderating power, such as LBE. The choice of lead–bismuth eutectic coolants is recommended based on its high boiling point (1670 °C), which helps avoid the risk of coolant boiling, and its low chemical activity with water and air, excluding the possibility of fire or explosions (Li, 2008). Drawbacks of using lead–bismuth eutectic are (1) accumulated radioactivity (mainly owing to the α emitter ^{210}Po, $T_{1/2}$ = 138 days), which could pose difficulties during fuel reloading or repair work on the primary circuit, and (2) the materials corrosion behavior between LBE and structure materials. However IPPE (Institute of Physics and Power Engineering) has developed methods to cope with the polonium during refueling and maintenance (Tucek et al., 2006; Zrodnikov et al., 2006), while KIT (Karlsruhe Institute of Technology), Tokyo tech. and MIT (Massachusetts Institute of Technology) have developed Al- and Si-coated materials to overcome the corrosive feature of LBE coolant (Muller et al., 2002; Rivai and Takahashi, 2008).

2.2. Small modular reactor

Larger nuclear power reactors typically have lower specific costs owing to the economy of scale, resulting in nuclear power plants with reactors of 1000–1600 MWe being the most commonly commercialized today. However, the development and commercialization of SMRs are a growing trend. The main advantages of SMRs are that they may be suitable for areas with small electrical grids and for remote locations, and that the financial risks associated with their deployment would be significantly lower than that of a large reactor owing to the smaller capital investment for a single SMR unit. This offers flexibility for incremental capacity increases, which could potentially raise the attractiveness of nuclear power to investors. In addition, a modular concept that reduces the amount of work on-site makes it simpler and faster to construct, while the design simplicity, including integral pool types, enhances the financial benefits. Smaller power opens door to passive safety features, such as more negative void coefficients of reactivity due to a harder neutron spectrum, while expanded potential sitting options, also act as advantages of SMRs (Vujic et al., 2012).

2.3. Natural circulation

Natural circulation is an important mechanism in several industrial systems. Thus, the knowledge of its behavior is of interest in nuclear reactor design, operation, and safety. In nuclear technology, this is especially true for new concepts that largely exploit the gravity forces for heat removal capability. Natural circulation in a PWR occurs owing to the presence of the heat source and heat sink constituted by the steam generator. In an environment with gravity, with the core located at a lower elevation than the steam generator, driving forces that generate a flow rate suitable for removing nuclear fission power develop.

The advantages of natural circulation of the reactor coolant are an improvement in safety through passive cooling characteristics, and simplicity in the design with miniaturization. In the nuclear industry, the TRIGA Mark II light water reactor having 250 kW was cooled by natural convection, and the silent operation of nuclear submarines has been cooled through only the natural convection of water. Particularly, the LBE coolant is suitable for natural circulation because its larger pitch to diameter (P/D) in the fuel bundle leads to a lower pressure drop in the core compared to the sodium coolant (Tucek et al., 2006; Ingersoll, 2009).

3. Economic assessment

In order to assess the economics of SMRs with selected nuclear concepts, the levelized unit electricity cost (LUEC) was calculated as a function of electricity generation. The LUEC is the cost to build and operate a power-generating asset over its lifetime divided by the