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Conceptual design of lead cooled reactor for hydrogen production

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ABSTRACT

Hydrogen is considered as the most potential energy carrier in the near future and can be produced from nuclear energy by several means. Lead-based reactor is one of the advance reactors in hydrogen production. In this paper, a novel feasible system of lead cooled reactor coupled with solid oxide electrolysis cells (SOEC) is presented, which is named China LEAd-based Reactor for Hydrogen production (CLEAR-H). By taking advantage of the chemically inert and high density of lead–bismuth eutectic (LBE), the concept of LBE-water direct-contact steam generator is proposed to supply high temperature (up to 600 °C) and low pressure (0.1–0.2 MPa) steam for SOEC stack without additional decompression devices. The results show that 47 tons hydrogen and 3000 tons oxygen-enriched air are obtained per day, and the thermal-to-hydrogen efficiency can reach about 39%.

Introduction

Over the last decades, massive carbon dioxide emissions into the atmosphere accelerate the global warming and the climate change by fossil fuels production and consumption. Beside improving the fossil fuels efficiency, research and develop renewable energy sources is a better way to resolve those issues, such as solar energy, geothermal energy, wind power and nuclear energy. Nuclear energy is one of the expanding energy in the world because of its clean, safe and efficient. According to the World Nuclear Association, there are over 430 commercial nuclear power reactors operable in 31 countries, with over 370,000 MWe of total capacity and around 11% of the world's electricity [1].

Lead-cooled Fast Reactor (LFR) is one of the Generation IV Nuclear Energy Systems because of its safety and efficiency. In China, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences has done a lot of research in lead-based (with lead or lead-based alloy coolant) reactors, including a serials of liquid lead lithium cooled fusion reactor design [2–8] and a serials of China LEAd-based Reactor (CLEAR) design [9,10], and several liquid heavy metal loops and materials technology test platform have been developed for verification and validation the design and key technology [11,12]. It does provided a good foundation for use of lead-based reactor in the future.

Except generate electricity, LFR are hopefully be applied in industrial process for heat supply, such as desalination, petroleum refining, steam reforming of natural gas, and

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hydrogen production cause of its high temperature [13–15]. Hydrogen is a clean energy resource with no production of greenhouse gases, and no other forms of air pollution. Hydrogen production from solid oxide electrolysis cells (SOEC) for splitting water has been attracted much attention in recent years due to its high electrical energy conversion efficiency and environment-friendly [16]. However, the SOEC need plenty of high temperature (up to 600 °C) and low pressure (0.1–0.2 MPa) steam to operate. The heat transfer efficiency is very low for steam, so how to design a heat exchanger to produce the steam by taking full advantage of the heat of the reactor is a critical issue.

In this paper, an innovation conception of China LEAd-based Reactor for Hydrogen production (CLEAR-H) has been developed, which integrated CLEAR and SOEC with a simple direct-contact steam generator. By taking advantage of the chemically inert and high density of LBE, the steam generator can produce low pressure steam up to 600 °C, without additional heating and decompression equipments. Both the electricity and heat of the SOEC needs are supplied by the reactor. This conception is introduced in this paper.

System design

Primary components of CLEAR-H include nuclear reactor, direct-contact steam generator, electricity generator and SOEC stack, which shows in Fig. 1. The reactor is an integral modular lead cooled fast reactor with a thermal output of 200 MW. There are two kinds of second circuit which transport the heat out of primary circuit, electricity production circuit (blue (in the web version)) and steam production circuit (red). Both the electricity and steam are provided to SOEC for hydrogen production. In order to take full advantage of the nuclear reactor energy, the heat power of these two second circuit is distributed in reasonable proportion which shown in Table 1. The input water is pumped through heat exchanger where it is heated to 220 °C by the downstream water from

Table 1 – Parameters of coolants.

Primary circuit (yellow)	Coolant	Lead
	Pressure (MPa)	0.1
	Inlet/Outlet temperature (°C)	600/650
Electricity production circuit (blue)	Coolant	Water
	Pressure (MPa)	7
	Inlet/Outlet temperature (°C)	290/310
	Power distribution (MWt)	180
Steam production circuit (red)	Coolant	LBE
	Pressure (MPa)	0.1
	Inlet/Outlet temperature (°C)	550/600
	Power distribution (MWt)	20

turbine. Then the water is injected to the direct-contact steam generation. The room temperature water is be heated to 600 °C by this two devices.

Reactor design

The CLEAR-H reactor is integral type, and effective layout of the primary components makes the reactor compact by installing most of the components inside the main vessel. The core is located in the lower part, the control rod driven machine in the upper part of the reactor. Heat exchangers (HXs) in the top half part, 2 HXs for electricity production circuit and 2 HXs for steam production circuit. The reactor vessel is a double layer design in order to improve the safety of the reactor. Major parameters of CLEAR-H are shown in Table 2.

Lead was selected as the primary coolant because of its attractive properties [13]:

- No exothermic reaction between lead and water or air.
- The high boiling point (~1750 °C) of lead eliminates the risk of core voiding.
- The high heat of vaporization and high thermal capacity of lead provide significant thermal inertia in case of loss-of-heat-sink.

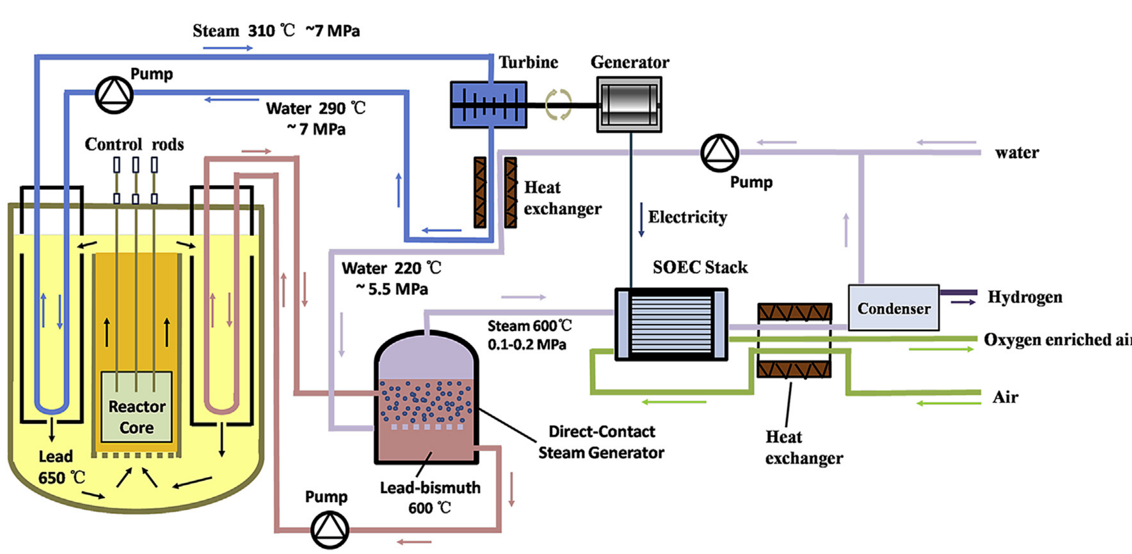

Fig. 1 – The Schematic of CLEAR-H.