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Design study on reactor structure of Pb–Bi-cooled direct contact boiling water fast reactor (PBWFR)

Minoru Takahashi [a,*], Shoji Uchida [b], Yoshiyuki Kasahara [b]

[a] *Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, N1-18, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550, Japan*
[b] *Advanced Reactor Technology Co., Ltd, 2-16-5 Kohnan, Minatoku, Tokyo 108-0075, Japan*

Abstract

Pb–Bi-cooled direct contact boiling water small fast reactor (PBWFR) can produce steam by direct contact of feedwater with primary Pb–Bi coolant above the core, and circulate Pb–Bi coolant by means of buoyancy of steam bubbles. The PBWFR is capable of eliminating components of the cooling system such as primary pumps and steam generators, and thereby making the reactor system simple and compact. The specifications of the PBWFR are as follows: the fuel is Pu–U nitride; the core height is 75 cm; the core diameter is 278 cm; the average burnup is 80 GWd/t; the refueling interval is 10 years; the rated electric power is 150 MWe; the rated thermal power is 450 MWt; the core outlet/inlet temperatures are 460 °C/310 °C, respectively; and the operating steam pressure is 7 MPa. The reactor structure design has been formulated, where reactor vessel sizes are 4200 mm (ID) × 19,750 mm (H), the guard vessel is a closed type, the upper structure is made of chimneys, and the core support structure is hung up. An ultrasonic flow meter is installed inside the vessel. The seismic evaluation, design of refueling procedure and cost evaluation have been performed.

Keywords: Fast reactor; Lead–bismuth; Direct contact boiling; Gas lift pump; Construction cost

1. Introduction

Small reactors are noticeable because of their simple, safe and flexible design features which are suitable for remote use and low investment. However, there have been no economically acceptable concepts of small reactors except for the pebble bed modular reactor (PBMR). Lead alloy-cooled fast reactor (LFR) is more economical than sodium-cooled fast reactor (SFR) because of no intermediate cooling systems including intermediate heat exchangers (IHXs).

A more compact and economical LFR than the conventional forced circulation type LFR, i.e. PBWR, has been proposed by Buongiorno et al. (1999, 2001). This concept is similar to the concept of direct contact steam generator (Grachev et al., 1993, 1999). In the PBWR, primary pumps and steam generators are eliminated. The present authors have formulated the design concepts of a small PBWR with a long-life core through research and development (Uchida et al., 2003, 2005; Takahashi et al., 2004, 2005a). The reactor has been designed based on the following requirements: (1) small reactor with the feature of portable, modular and low investment type; (2) long-life core with a breeding ratio higher than unity for high uranium utilization efficiency and as a result nuclear proliferation resistance because of lower risk of refueling; (3) negative void reactivity for safety enhancement; and (4) reasonable performance of the steam lift pump and direct contact steam generation. The reactor has been called the Pb–Bi-cooled direct contact boiling water small fast reactor (PBWFR).

In the present study, the structural and plant system concept of the PBWFR have been formulated in more detail in addition to an alternative safer core with respect to void reactivity, and the construction cost has been evaluated.

2. Reactor design

2.1. Specifications of PBWFR and core design

Fig. 1 shows the concept of the PBWFR and Fig. 2 shows a bird's eye view of the reactor. Sub-cooled water is directly

* Corresponding author. Tel./fax: +81 3 5734 2957.
E-mail address: mtakahas@nr.titech.ac.jp (M. Takahashi).

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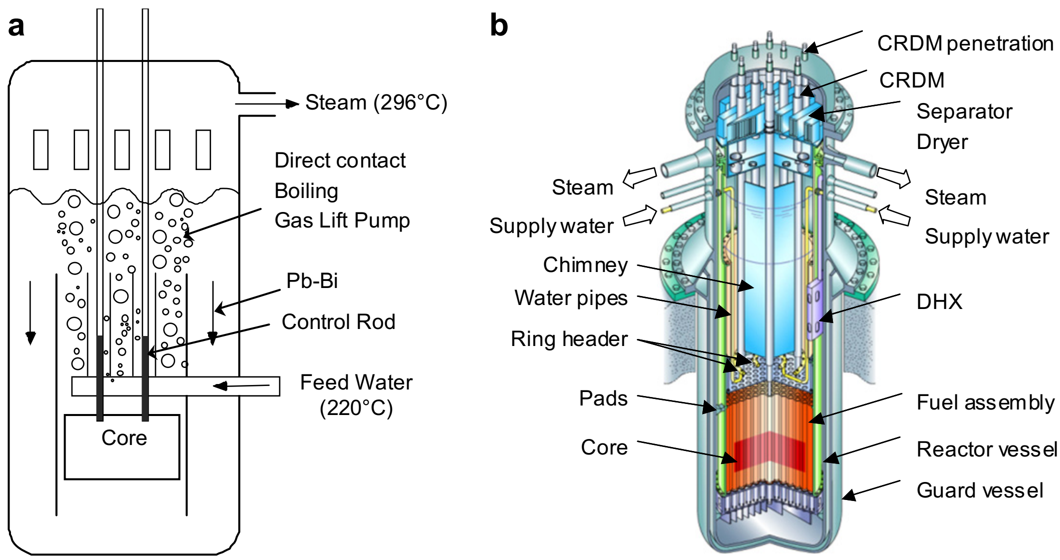

Fig. 1. Direct contact type LFR (PBWFR). (a) Concept of PBWFR and (b) Bird's eye view of PBWFR.

fed into high temperature Pb–Bi coolant in a plenum above the core. Steam is generated by direct contact boiling of the feedwater with primary Pb–Bi coolant in chimneys, and the buoyancy forces of steam bubbles drive the circulation of Pb–Bi coolant in a primary circuit, i.e. the steam lift pump. The generated steam is conveyed to the high pressure turbine.

The electric power is determined so that the reactor has cost competitiveness to large commercial reactors even if it is a small size reactor. Major specifications for the reactor design are presented in Table 1 and heat and mass balances are shown in Fig. 2. The steam conditions are nearly the same as those of the conventional boiling water reactors, although the steam is superheated by 10 °C to avoid the accumulation of condensate on Pb–Bi free surface.

Fig. 3 shows the horizontal cross-section of the reactor. The reactor consists of the inner and outer cores with lower blankets, the reflectors and the control rods. Specifications and characteristics of the core are presented in Tables 2 and 3, respectively. Plutonium–uranium mixed nitride fuel is used for the fuel material. Pb–Bi flow rate is distributed in two regions in inner core and three regions in outer core.

Fig. 4 shows a schematic of the fuel assembly. The maximum hot spot temperature of the cladding tube material is 619 °C. Fe–Al alloy-surface-coated high Cr steel may be suitable as the corrosion-resistant cladding tube material according to the result of corrosion test at 700 °C (Rivai and Takahashi, 2006). Grid spacers and supporters that work as flow obstacles should be made of erosion-resistant materials such as tungsten (W), molybdenum (Mo), or ceramics (SiC, Ti_3SiC_2) (Rivai and Takahashi, 2006).

2.2. Design of reactor structure

2.2.1. Reactor vessel and inner structure

The reactor vessel and inner structure are shown in Fig. 5. The inner diameter and height of the reactor vessel are 4200 mm and 19,750 mm, respectively.

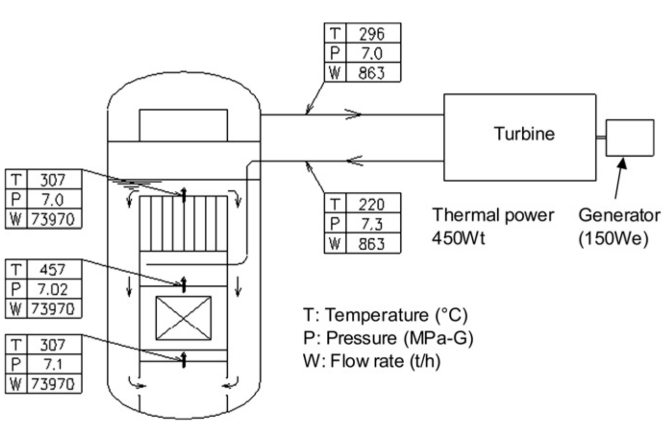

Fig. 2. Heat and mass balance.

Table 1
Major specifications of reactor

Power (thermal/electric) (MW)	450/150
Thermal efficiency (%)	33
Core inlet/outlet temperature (°C)	460/310
Core pressure drop (MPa)	0.04
Maximum cladding temperature (°C)	619
Pb–Bi flow rate (t/h)	73,970
Steam temperature (°C)	296
Steam flow rate (t/h)	863
Steam pressure (MPa)	7
Feedwater temperature (°C)	220
Refueling interval (years)	10
Refueling	One batch refueling
Candidates of cladding and structural material	Al–Fe alloy coated high Cr steels, high Cr steels with Al and Si addition, ceramics (SiC, etc.) and refractory metals