ARTICLE IN PRESS

Nuclear Engineering and Technology xxx (2017) 1–9

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Dynamics and control of molten-salt breeder reactor

Vikram Singh*, Matthew R. Lish, Ondřej Chvála, Belle R. Upadhyaya

Department of Nuclear Engineering, 315 Pasqua Engineering Building, University of Tennessee, Knoxville, TN 37996, USA

ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form
19 June 2017
Accepted 19 June 2017
Available online xxx

Keywords:
MSBR
molten-salt
two-fluid
dynamic analysis
control
load-following
thorium

ABSTRACT

Preliminary results of the dynamic analysis of a two-fluid molten-salt breeder reactor (MSBR) system are presented. Based on an earlier work on the preliminary dynamic model of the concept, the model presented here is nonlinear and has been revised to accurately reflect the design exemplified in ORNL-4528. A brief overview of the model followed by results from simulations performed to validate the model is presented. Simulations illustrate stable behavior of the reactor dynamics and temperature feedback effects to reactivity excursions. Stable and smooth changes at various nodal temperatures are also observed. Control strategies for molten-salt reactor operation are discussed, followed by an illustration of the open-loop load-following capability of the molten-salt breeder reactor system. It is observed that the molten-salt breeder reactor system exhibits “self-regulating” behavior, minimizing the need for external controller action for load-following maneuvers.

1. Introduction

The Molten-Salt Reactor Program (MSRP) operated from 1958 to 1976 at Oak Ridge National Laboratory (ORNL; 1 Bethel Valley Rd, Oak Ridge, TN 37830, USA) with the objective of developing fluid-fueled nuclear reactors that used solutions of fissile or fertile material in suitable carrier salts [1]. MSRP was preceded by the Aircraft Nuclear Propulsion (ANP) program during which the first molten-salt reactor (MSR), the Aircraft Reactor Experiment, was operated at ORNL in 1954. The experiment demonstrated desirable load-following features of the system, specifically the ability to drive the reactor power by heat demand alone [2].

A major achievement of the MSRP was the design, construction, and operation of the Molten-Salt Reactor Experiment (MSRE) between 1965 and 1969 [3]. Experiments carried out at the MSRE showed the practicality of handling molten salts in an operating reactor. The reactor's dynamic behavior correlated well with predictions. Many instruments were installed for reactor characterization, and control was mainly accomplished using more than 1,000 type-K thermocouples that measured temperature in various flow regions of the reactor system [4]. The MSRE is the only well-characterized operated MSR; therefore, its results serve as benchmarks for current MSR studies. Prior to the program's conclusion, efforts were devoted to technology development needed for full-scale MSR demonstrations. Results from these studies are documented in hundreds of reports and peer-reviewed publications. A world-wide web repository of many of these documents can be found in Ref. [5].

The focus of this paper is to develop dynamic models and control strategies for a molten-salt breeder reactor (MSBR). This research and development is inspired by the work done by MSRP on a conceptual two-fluid breeder reactor [6]. A schematic is shown in Fig. 1. The modular design consists of four reactor modules with an electrical output of 250 MW/module. The two-fluid reactor has a graphite-moderated core with FLiBe salt circulated through the core and blanket containing UF_4 and ThF_4, respectively. Thorium in the blanket salt cannot directly undergo fission, but is converted into uranium-233 in a breeding process in which thorium absorbs a neutron and subsequently undergoes two beta decays, becoming U-233, which is fissile. Thorium is called a fertile species for its property of being converted to a fissile species after absorption of a neutron. The U-233 isotope is then separated from the blanket salt and introduced to the fuel salt to undergo fission in the reactor core. These reactors are also called liquid fluoride thorium reactors or LFTR, to emphasize their thorium/uranium fuel cycle as distinct from other MSR concepts.

The developed nonlinear nodal model accurately reflects the reactor design presented in the study by Robertson et al. [6] and simulates the dynamic behavior of neutron kinetics, heat transfer,

---

* Corresponding author.
E-mail address: vsingh10@vols.utk.edu (V. Singh).

http://dx.doi.org/10.1016/j.net.2017.06.003

Please cite this article in press as: V. Singh, et al., Dynamics and control of molten-salt breeder reactor, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.06.003

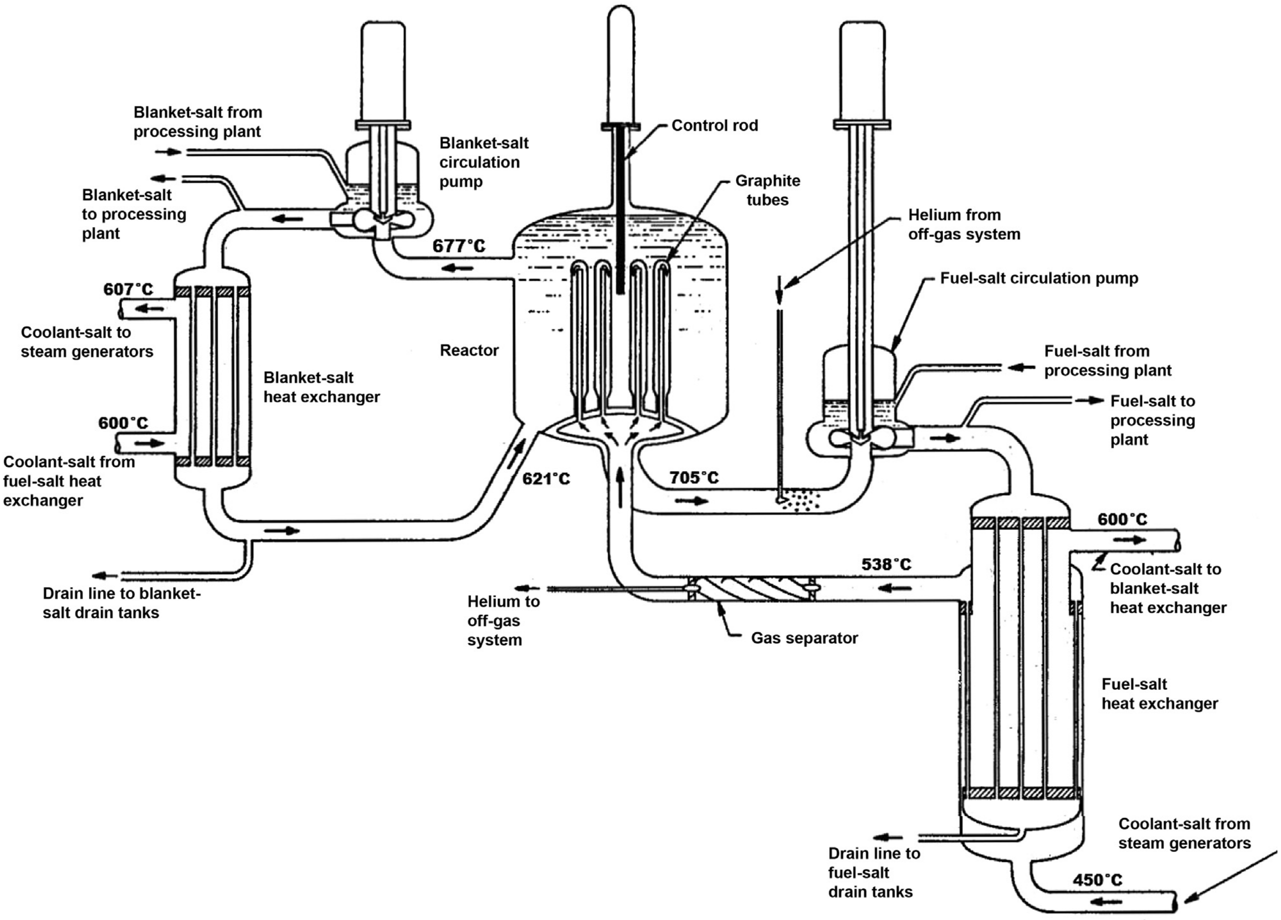

Fig. 1. Simplified schematic of the molten-salt breeder reactor system.
(Source: ORNL-4528, Oak Ridge National Laboratory, 1970.)

and fluid transport in the MSBR. A detailed discussion of the model and its dynamics are presented in a companion paper. As noted earlier, MSRE results are the only benchmark for such models. Hence, a model extending the approach has been developed for the MSRE, and the results and comparisons are the topics of a companion paper under preparation.

This paper focuses on the basic dynamics of the uncontrolled MSBR and explores strategies for controlling the reactor system to improve upon uncontrolled performance. A major objective here is to study the controllability of the MSBR system based on model predictions and examine the need for control action. The open-loop load-following capability of the MSBR system is also demonstrated and its implications are discussed.

2. Description of the two-fluid reactor

The two-fluid MSBR was conceived at ORNL following the successful operation of the MSRE [6]. The design particularly seeks to utilize the thermal-spectrum Th–U233 breeding cycle while producing high-potential heat.

The two-fluid MSBR is a 1,000-MWe plant with four power-producing reactor modules of 556 MWth each. Each core module has a hexagonal lattice of graphite assemblies for neutron moderation. The graphite assembly design consists of a cylindrical sleeve surrounding a bore drilled in the center. This creates a hollow space for fuel salt to flow through the graphite matrix, while also separating the fissile and fertile material. UF_4 dissolved in $^7LiF\text{-}BeF_2$ (>99% enriched) is used as a fuel salt with the same molar and isotopic composition as given in the study by Robertson et al. [6].

The fuel salt circulated through the core enters at ~537°C through a lower plenum and flows up the graphite channels through the hollow cylindrical sleeves. It then flows down through the bores. Meanwhile, fissions occur in the salt during transit, and it leaves the core at the bottom of the reactor vessel at ~705°C. The fuel salt then enters a countercurrent heat exchanger where heat energy is transferred to a secondary coolant salt.

The second of the two fluids, the fertile blanket salt, enters the reactor vessel at the bottom. The salt flows up both through interstitial spaces in the graphite channel matrix and in the blanket-only cells surrounding the core. This exposes the fertile material to higher neutron flux and encourages breeding. As a result, its temperature rises by ~50°C. The blanket salt then flows through its own heat exchanger. The coolant salt leaving the fuel salt heat exchanger is pumped through the blanket salt heat exchanger in series. The coolant salt at ~607°C then flows into a conventional steam generator system and produces superheated steam.

Helium is used as the cover gas over the salt in the pump bowl and as the medium for stripping gaseous fission products from the salt. In the latter case, small bubbles of helium are injected into the salt in the suction line to the pump. The small quantities of xenon and other gases form nucleate with the helium bubbles. The helium is then removed with its burden of krypton and xenon in a centrifugal separator in the line from the outlet of the heat

Please cite this article in press as: V. Singh, et al., Dynamics and control of molten-salt breeder reactor, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.06.003