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Stability analysis of the Generation-IV nuclear reactors by means of the root locus criterion

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ABSTRACT

The development of next-generation nuclear reactors requires a careful investigation of their stability characteristics and of their overall dynamical behavior. In the current work, a stability analysis is carried out from the perspective of linear systems for all the Gen-IV reactor concepts. Linear, zero-dimensional models of the reactors are developed in MATLAB® and the root locus criterion is applied to investigate the stability of the systems over their entire power range. The analysis is carried out for the stand-alone cores, assuming the inlet coolant temperature as a fixed parameter, and also considering the primary coolant circuit of each reactor, in order to evaluate the effect of out-of-core energy dynamics on the systems stability. All the reactors proved to be stable with a large margin over their nominal power. In the last part of the work, a comparison of the dynamic behavior of the Gen-IV reactors is presented, in order to point out the influence of the different geometrical features and of the different materials employed as coolant.

1. Introduction

The Generation IV International Forum (GIF) is an international endeavor aiming at the research and development of next-generation nuclear energy systems. The main goals defined by GIF are an increased sustainability, economic competitiveness, improved safety and reliability characteristics, proliferation resistance and physical protection of the systems. These goals provided the basis for the identification of six nuclear reactor concepts for further development: the VHTR (Very High Temperature Reactor, Fig. 1), the MSR (Molten Salt Reactor, Fig. 2), the SFR (Sodium Fast Reactor, Fig. 3), the SCWR (Supercritical Water Reactor, Fig. 4), the GFR (Gas Fast Reactor, Fig. 5) and the LFR (Lead Fast Reactor, Fig. 6). The advanced reactor concepts under development offer a great potential for plant simplification and higher plant efficiencies compared to current Light Water Reactors, but also introduce new safety concerns and design challenges that must be addressed. For this reason, a stability analysis of the Gen-IV nuclear systems is needed, in order to verify the stability of the reactors following a reactivity change and to identify potential regions of instability.

In this perspective, the root locus criterion is a simple and straightforward approach to study the stability of a nuclear reactor over its entire operating power range. Bortot et al. (2013) calculated the root loci of the LFR at beginning and end of cycle, based on the ALFRED design (Alemberti et al., 2013). Cammi et al. (2011) studied the neutronics of the Molten Salt Reactor Experiment while Ball and Kerlin presented a stability analysis of coupled neutronics and thermal-hydraulics of the MSRE in 1965. In addition, Cervi and Cammi (2016) studied the SCWR stability by means of the root locus criterion, adopting a one-dimensional approach. However, few information is currently available on the stability characteristics of the SFR, of the GFR and of the VHTR. The aim of the current research is to study the stability behavior of all the Gen-IV reactors, in order to complete the dynamic characterization of all the main next generation nuclear systems. The root loci of the SFR, of the GFR, of the VHTR, of the LFR and of the MSR are calculated adopting a lumped-parameter approach for both the neutronics and thermal-hydraulics of the systems. The analysis will be presented for the stand-alone cores and also considering the primary coolant circuits, adapting the models to the specific features of each reactor concept.

The results of this work could constitute an important feedback for the designers, since the systems under investigation are still in an early conceptual phase in which all the specification are subject to frequent modifications.

2. Reference reactors description

The main features of the reference reactors under investigation in the current work are presented in the following subsections.

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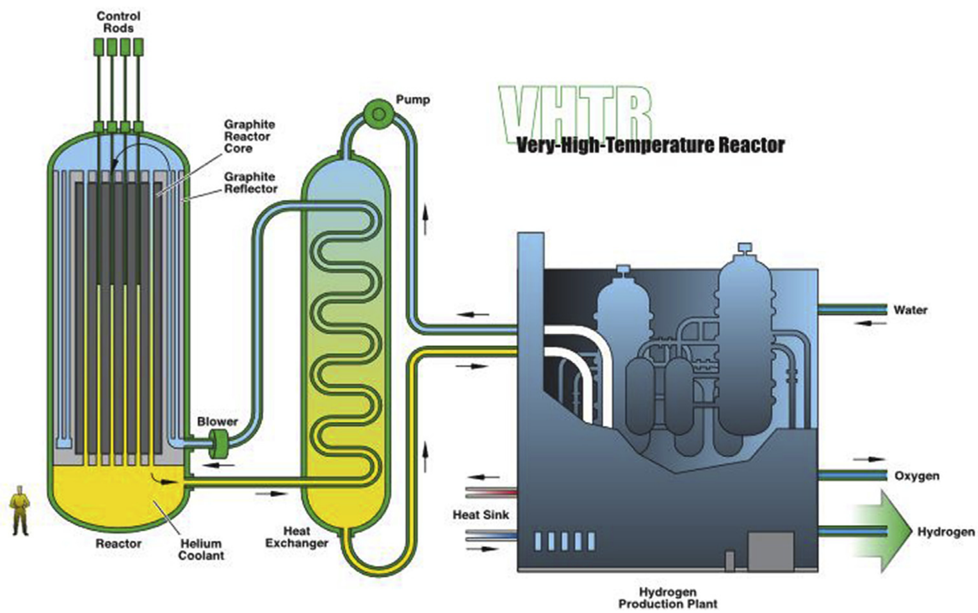

Fig. 1. Schematic layout of the VHTR power plant (https://www.gen-4.org/).

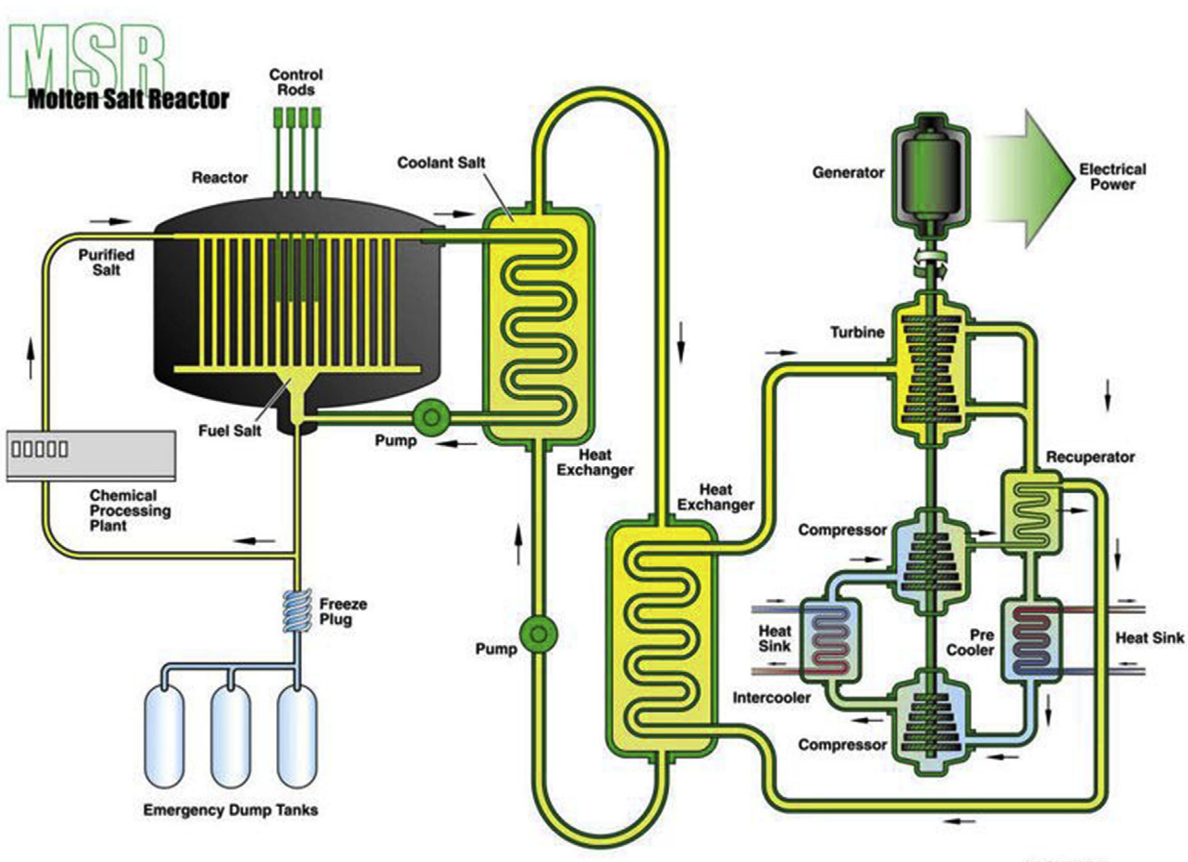

Fig. 2. Schematic layout of the MSR power plant (https://www.gen-4.org/).

2.1. Reference SFR description

The SFR is a fast neutron nuclear reactor, which uses sodium as primary coolant. The reference design adopted in this work for the SFR is based on the Japanese Sodium Fast Reactor (Ichimiya et al., 2007), which has a nominal power of 3570 MW_{th} and it is composed by 562 hexagonal fuel assemblies, each containing 255 fuel pins arranged in a triangular lattice.

The primary circuit and the power conversion system are separated by an intermediate sodium loop, in order to prevent mixing between the primary coolant and water. The hot primary sodium coming from the core is cooled by the secondary sodium in an intermediate heat exchanger (IHX). The secondary sodium, in turn, is cooled by a water flow in the steam generator, producing vapor that is sent to the turbine. The