Nuclear Engineering and Design 305 (2016) 179–190

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

A preliminary stability analysis of MYRRHA Primary Heat Exchanger two-phase tube bundle

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HIGHLIGHTS

- MYRRHA is a pool-type LBE-cooled ADS, operable also as a critical reactor.
- MYRRHA is a high priority infrastructure for nuclear research in Europe.
- PHX (primary side: LBE, secondary side: two-phase water), is a MYRRHA key component.
- The original MYRRHA PHX design does not offer a fully satisfying response to DWO.
- The adoption of an orifice allows extending considerably the stability of MYRRHA PHX.

ARTICLE INFO

Article history:
Received 17 February 2016
Received in revised form 6 May 2016
Accepted 17 May 2016

JEL classification:
K. Thermal Hydraulics

ABSTRACT

The MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) project, started at SCK·CEN since 1999, aims at the construction of a pool-type sub-critical Accelerator-Driven System (ADS) which could also operate as a critical reactor. The primary system, enclosed in the primary vessel, is filled with Lead Bismuth Eutectic (LBE) which acts as primary coolant. The power is then delivered through four heat exchangers to four secondary loops. The secondary cooling fluid is two-phase water operating at relatively low pressure (16 bar). Four aero-condensers act as heat sinks, since MYRRHA design does not foresee any electricity generation.

The MYRRHA Primary Heat eXchangers (PHXs) cover a role of fundamental importance in normal operation and accidental conditions, being part of the primary and secondary cooling system and of the Decay Heat Removal (DHR) system. It is thus highly relevant to understand the PHXs behavior under all the potential working conditions.

In particular, the stability of the PHXs must be guaranteed under all operating conditions.

System code models play an important role in understanding and predicting the behavior of the reactor in all conditions, from steady state to operational and accidental transients, and simulating all the postulated scenarios.

A solid PHX design requires a complete assessment of two-phase flow instabilities in the secondary system water tube bundle and the potential implementation of a suitable stabilizing device (orifice) to reduce the impact of the perturbations along the channel. The stability assessment should take in consideration all the possible reactor operational power levels in order to prove the stable behavior under all operational conditions.

The tube bundle stability assessment has been carried out by following a similar procedure used for BWR fuel channels, through a specific RELAP5-3D model representing the PHX and able to evaluate the propagation of a density wave in the tube length.

Abbreviations: ADS, Accelerator-Driven System; DHR, Decay Heat Removal; DWO, Density Wave Oscillations; EoL, End of Life; ETPP, European Technology Pilot Plant; HLM, Heavy Liquid Metals; HTC, Heat Transfer Coefficient; HX, Heat eXchanger; IPS, In-Pile Section; IVST, In Vessel Storage Tank; LBE, Lead–Bismuth Eutectic; LFR, Lead Fast Reactor; MYRRHA, Multi-purpose hYbrid Research Reactor for High-tech Applications; PHX, Primary Heat eXchanger; PP, Primary Pump; RVACS, Reactor Vessel Auxiliary Cooling System; SCS, Shutdown Cooling System.

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http://dx.doi.org/10.1016/j.nucengdes.2016.05.019
0029-5493/

A series of suitable boundary conditions, on both primary and secondary side, and perturbation triggers have been foreseen into the model, so to discover all kind of unstable behavior and to dimension the needed orifice to guarantee the flow stability in all operating conditions.

The PHX stability analysis is initially performed on the original tube bundle without the adoption of any stabilizing devices, in order to check the natural behavior of the system. The possible adoption and design of an orifice is then conducted on the basis of this preliminary study. The system response against the various types of instabilities, before the introduction of an orifice, is not completely satisfactory: a stable flow is found within certain specific system parameters ranges. After the introduction of a suitable orifice, the system behavior becomes stable under all operating conditions against all types of two-phase flow instabilities.

1. Introduction

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a pool-type Accelerator Driven System (ADS) with the ability to operate also as a critical reactor.

MYRRHA main targets can be summarized as:

- Flexible fast-spectrum irradiation facility (Abderrahim, 2011).
- Minor Actinides (MAs) transmutation demonstrator (Cerullo and Lomonaco, 2012).
- ADS demonstrator (Lomonaco et al., 2014).
- GEN-IV European Technology Pilot Plant (ETPP) in the roadmap for Lead Fast Reactor (LFR) (SNETP, 2013).

The MYRRHA project has been recognized as a high priority infrastructure for nuclear research in Europe. Several European FP6 and FP7 projects had, as main target, to finalize a preliminary design of the MYRRHA reactor:

- FP6 IP-EUROTRANS (De Bruyn et al., 2010), leading to the finalization of MYRRHA/XT-ADS version of MYRRHA in June 2008.
- FP7 Central Design Team (CDT) (Sarotto et al., 2013), defining the MYRRHA/FASTEF version in March 2012.
- FP7 MAXSIMA (Castelliti et al., 2015) (started in November 2012, ongoing), more focused on the MYRRHA safety analyses and component qualification.

The outcome of these European FP projects has been partly used to define the latest version of the MYRRHA design, which has been finalized in June 2014 (De Bruyn et al., 2016) and is currently in the verification phase. Though representing the current status, such version is not definitive: the MYRRHA design is still evolving taking into account results from the parallel R&D program.

SCK·CEN has actively participated in these FP6 and FP7 projects focusing on the safety analysis through use of system codes by performing code-to-code comparison of steady-state and transient calculations on the MYRRHA reactor operating in sub-critical and critical mode.

2. MYRRHA plant general description

A general overview of the MYRRHA primary system and its main components is provided in Fig. 1:[1]

MYRRHA plant primary system is cooled by liquid Lead–Bismuth Eutectic (LBE, 45% Pb, 55% Bi) (Nuclear Science Committee, 2015). This choice shows several advantages with respect to other typical liquid metals used in nuclear applications (mainly Na and pure Pb):

- More operation flexibility (and limited problems towards primary coolant freezing) thanks to the low melting temperature of the eutectic (~125 °C), which allows to operate a fast-spectrum irradiation facility with a relatively high core temperature difference without incurring in corrosion problems.
- Low chemical interaction with water and air excluding the possibility for fire or explosions.

A drawback connected with use of LBE as primary coolant is the accumulation of radioactive isotopes (mainly Po^{210}), which could pose difficulties during primary system maintenance or in case of accidental conditions in terms of radiological releases.

Further details on LBE properties are available in Nuclear Science Committee, (2015) and Tuček et al. (2006).

The primary system is completely enclosed in the primary vessel (pool-type system). The primary LBE coolant flows from the lower plenum into the core (T ~ 270 °C) to remove the core power (100 MW in critical mode) and, from there, into the upper plenum where it mixes with the cold by-pass flow. The average upper plenum temperature is 325 °C. Four Primary Heat eXchanger (PHXs) units receive the LBE from the upper plenum, which then flows into two Primary Pumps (PPs) (each PP serving two PHXs). From the PPs the LBE is reinserted into the lower plenum.

The cold lower plenum is separated from the hot upper plenum by the Diaphragm, an inner vessel structure supporting the core barrel and the penetrations for the PHXs and the PPs. Above the LBE free surface level an inert gas layer (nitrogen) separates the primary coolant from the reactor cover.

The primary system is linked to four independent secondary systems through the four PHX units. Each secondary system is operated in a forced-flow regime with a two-phase water mixture at 16 bar (~200 °C): the water enters the PHX in almost saturated conditions and exits with a quality ~0.3. The moisture is then separated in a steam drum, from where the steam is directed towards an air condenser (one per secondary loop) and the water is recirculated to the PHX. In normal operation the secondary water temperature is kept constant by the control system, letting the primary LBE conditions to change in function of the core loading.

The steam dissipates the heat to the external environment through the tertiary system air condenser and is then recirculated into the steam drum. Each tertiary system contains an air fan operated in forced circulation and logically connected to the steam drum pressure for power removal balance (Fig. 2).

All three systems are designed to operate in forced circulation (active mode) during normal operation. Nevertheless, the plant must also be able to remove the decay heat in accidental

[1] Some of the MYRRHA plant components are still under development; more generally, many studies on the development of components for HLM nuclear systems are still ongoing (e.g. Mangialardo et al., 2014; Ferrini et al., 2016).