Nuclear Engineering and Design 305 (2016) 168–178

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Thermal-hydraulic analysis of an innovative decay heat removal system for lead-cooled fast reactors

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HIGHLIGHTS

- LOOP thermal-hydraulic transient analysis for lead-cooled fast reactors.
- Passive decay heat removal system concept to avoid lead freezing.
- Solution developed for the diversification of the decay heat removal functions.
- RELAP5 vs. RELAP5-3D comparison for lead applications.

ARTICLE INFO

Article history:
Received 14 November 2015
Received in revised form 17 April 2016
Accepted 5 May 2016

ABSTRACT

Improvement of safety requirements in GEN IV reactors needs more reliable safety systems, among which the decay heat removal system (DHR) is one of the most important. Complying with the diversification criteria and based on pure passive and very reliable components, an additional DHR for the ALFRED reactor (Advanced Lead Fast Reactor European Demonstrator) has been proposed and its thermal-hydraulic performances are analyzed. It consists in a coupling of two innovative subsystems: the radiative-based direct heat exchanger (DHX), and the pool heat exchanger (PHX). Preliminary thermal-hydraulic analyses, by using RELAP5 and RELAP5-3D© computer programs, have been carried out showing that the whole system can safely operate, in natural circulation, for a long term. Sensitivity analyses for: the emissivity of the DHX surfaces, the PHX water heat transfer coefficient (HTC) and the lead HTC have been carried out. In addition, the effects of the density variation uncertainty on the results has been analyzed and compared. It allowed to assess the feasibility of the system and to evaluate the acceptable range of the studied parameters. A comparison of the results obtained with RELAP5 and RELAP5-3D© has been carried out and the analysis of the differences of the two codes for lead is presented.

The features of the innovative DHR allow to match the decay heat removal performance with the trend of the reactor decay heat power after shutdown, minimizing at the same time the risk of lead freezing. This system, proposed for the diversification of the DHR in the LFRs, could be applicable in the other pool-type liquid metal fast reactors.

1. Introduction

Among the next generation of nuclear reactors, well-known as Generation IV, the lead cooled fast reactor (LFR) is one of the most promising advanced technologies able to comply the targets of sustainability, economics, safety and proliferation resistance. For these reasons, LFRs are actually deeply investigated and effort on R&D is being carried out. Complying with GEN IV requirements, an innovative pre-conceptual LFR design, ELSY (European Lead-cooled System), was proposed within the 6th European Framework Program (Alemberti et al., 2011). The ELSY project was an LFR reactor design aimed at electricity production, characterized by several innovations and by the closure of the fuel cycle. Subsequently, the LEADER (Lead-cooled European Advanced DEmonstration Reactor) project, aimed at reviewing and improving results of the ELSY design, was funded in the frame of EU-FP7. This project was aimed at contributing to the design of ALFRED (the Advanced Lead Fast Reactor European Demonstrator) (Alemberti, 2012a; Alemberti et al., 2013) toward the full-scale first-of-a-kind ETDR (European lead fast reactor Technology Demonstrator Reactor).

ALFRED is a 300 MWth lead cooled fast reactor, characterized by a pool configuration (Alemberti, 2012b). Eight steam generators (SG) transfer the thermal power from the primary system (lead) to

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http://dx.doi.org/10.1016/j.nucengdes.2016.05.005
0029-5493/

the secondary system (water); the primary coolant flow rate is assured by eight primary pumps (one for each SG). ALFRED normally relies on the secondary system to remove the decay heat power from the primary coolant, by-passing to the condenser.

Increasing standards of safety in GEN IV reactors require more reliable safety systems, among which the decay heat removal system is one of the most important. Over the years, several DHR systems have been analyzed taking into account the reactor type. The major trend of the last years, in order to enhance design safety features, is to design as passive as possible emergency systems (e.g. Eoh et al., 2007; Krepper and Beyer, 2010; Park et al., 2008). The main goals to be reached in a well-designed passive DHR system for a liquid metal reactor are:

1. being able to maintain primary fluid temperature in an optimal range, preventing the fluid to freeze and the primary system structure to suffer physical damage from creep or excessive thermal expansion of the fluid;
2. managing to guarantee an as long as possible autonomy of operation, preferably without requiring any active external support or intervention;
3. not recurring to any active component such as pumps, blowers or external motors.

Several analyses have been carried out about the reliability (Burgazzi et al., 2012; Arul et al., 2006; Mathews et al., 2008) and the performances (Hung et al., 2011; Parthasarathy et al., 2012) of such passive DHR systems.

The importance of the diversification of the safety systems is evidenced in Risk and Safety Working Group (RSWG), 2011 and, the adoption of a back-up solution is an improvement of the reliability of this fundamental safety function. The strict working temperature range for the primary coolant, to avoid lead freezing and to guarantee the integrity of the components, makes difficult the design of passive systems. For this, despite the thermal inertia given from the pool, the response time of the DHR system is fundamental in lead-cooled reactors. In the case of a loss of flow accident, the system must follow the trend of decay heat and reduce proportionally the thermal power removed over time.

The proposed DHR system is an additional and diversified option for the ALFRED reactor.

The main peculiarity of this system are:

1. radiation-based heat transfer mechanism, exploiting the void annulus between the primary and the secondary systems, enhanced by fins;
2. passive heat sink, able to automatically switch the heat transfer from water to air.

These two elements, which characterize the main components of the proposed DHR, are described in detail by Vitale Di Maio et al., 2012 and De Santis et al., 2012, while a focus on the decay heat exchanger component can be also found in De Santis et al., 2013.

2. Detailed decay heat removal (DHR) system description

A functional scheme of the DHR is presented in Fig. 1. The hot secondary coolant, exiting from the decay heat exchanger (DHX), flows toward a pool heat exchanger (PHX) submerged in cold water. In the first phase, after the activation of the DHR system, just a liquid-phase heating of the pool occurs; when saturation temperature is reached, water boiling starts in the pool, causing an increase in the heat transfer coefficient but also a decrease in the pool level. Before the complete evaporation of the water, some openings, located in the pool heat exchanger fins, allow air to flow and to give a partial contribution to the cooling, determining a transition heat transfer condition (boiling water and air). In the last phase all the water is vaporized and the heat removal function is accomplished only by the air flow, in natural circulation.

The proposed DHR system is a natural circulation loop, which is aimed at removing the decay heat from the core and transferring heat to the atmosphere. The DHR loop is based on 4″ schedule 80 piping, with about 15 m in height from the hot source to the heat sink for guaranteeing the natural circulation.

Despite the heat removal from the core is the basic function of a DHR system, in lead-cooled reactors it is also needed to maintain a temperature level above the freezing temperature of the coolant, (about 600 K for lead).

The combination of the features of the two heat exchangers in the proposed system allows to maintain the lead temperature within a preselected range, delaying by few days the possibility of coolant freezing, without any actions.

In addition, the backup DHR should be actuated by a check valve, located in the proximity of the DHX inlet, which guarantees the activation only in case of the malfunction of the main DHR system.

2.1. Direct heat exchanger – DHX

The main innovation of this component consists in replacing the more commonly used shell and tubes heat exchanger with a radiation-based bayonet tubes heat exchanger. Each bayonet tube is made of three coaxial tubes: the inner and the intermediate ones belong to the DHR secondary system with secondary fluid inside, while lead flows around the outer one. The secondary coolant enters the decay heat exchanger from the top of the inner tube, flowing downwards; then, inverting its direction, it flows upwards between the inner and the intermediate tubes, removing the power irradiated from the outer tube to the intermediate one. The void annulus is placed between the intermediate and the outer tube and fins are present to enhance heat exchange surface.

The DHX (De Santis et al., 2012) is made of several bayonet tubes (a schematic view is reported in Fig. 2) enclosed within a cylindrical structure which guarantees that the primary coolant (flowing downward) is in contact with the external surface of the submerged bayonet tubes. This structure also provides mechanical constraints for the bayonet tubes in case of earthquake (several grids are provided for this purpose).

A more accurate design of the DHX behavior under seismic condition, which is beyond the scope of the present work, could be required to optimize the mechanical constraints. The cylindrical structure of the top head is equipped with three tube plates, which allow (Fig. 2):

- the cold secondary fluid distribution within the inner tubes of each bayonet tube present in the DHX unit;
- the hot secondary fluid collection;
- the vacuum system pressure control, needed for the initial vacuum creation and successive monitoring.

2.2. Radiative-based bayonet tube

Each bayonet assembly is composed by three coaxial tubes (outer, intermediate and inner tubes), as shown in Fig. 3a. The intermediate (yellow) and outer (red)[1] tubes, are separated by a gap in which a rough vacuum condition (about 100–200 Pa) is

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.