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Analysis of lead-cooled fast reactor using a core simulator

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ABSTRACT

The Lead-cooled Fast Reactor (LFR) is a novel reactor concept, the core of which can be simulated by developing a dynamic model. The model consists of 3 sub-models; a block for reactor kinetics, thermal hydraulics and the reactivity feedback calculations. By implementation of the LFR core simulator, the response of the reactor has been shown for various test inputs. Certain events have been simulated in the LFR core (unprotected transient of overpower, loss of heat sink, loss of flow and a SCRAM shutdown). A sensitivity analysis has been performed and it is observed that the LFR core power is the most sensitive to changes in the average coolant temperature. A stability analysis has been performed to show that the LFR core has a stable configuration (for its normal operating conditions). Similarly, a noise analysis has revealed that the output parameters have the most adverse effect in case of a Gaussian noise being introduced in the reactivity of the core.

1. Introduction

In order to advance the research and development in the LFR (Generation IV lead-cooled fast reactor) (Smith et al., 2016), it is crucial to understand and develop a dynamics simulator. The core simulator is a very useful tool for determining the uncontrolled response of a particular nuclear reactor, by changing its input parameters (Xu et al., 2017). The use of HLMCs (Heavy Liquid Metal Coolants) aides in great simplification of a nuclear reactor concept by offering better thermal efficiencies as compared to Generation IV reactor concepts. As far as plant design safety is concerned, however, there are great challenges associated with HLMCs. This increases the demand of using an LFR core simulator to gauge the uncontrolled response of the core, in order to design reliable control and safety systems.

As with most of the Generation IV nuclear reactors, it is important to observe the response of a nuclear reactor with transient inputs applied at the control parameters. Based on its conceptual design, a nuclear reactor may become unstable during its normal operation e.g. the thermal hydraulic instability occurring in SCWR (Zhao, 2005) (Supercritical Water-cooled Reactor) core as the coolant transitions to supercritical state within the core. Hence in order to gauge the stability of an LFR core, a mathematical simulator is required, which could couple the reactor's kinetics with its thermal hydraulics, giving a comprehensive dynamic response. The LFR is implemented in an uncontrolled configuration, in order to observe its natural response.

The transfer model (which is used to lay the groundwork for the core simulator) (Colombo et al., 2010) is based on the use of first-principle balance equations. These are particularly useful choices for looking into the system dynamics of an LFR. Following are some of the requirements of the LFR simulator:

A By linearization of the constitutive equations about the normal operating conditions, the stability and robustness of the system should be evaluated.
B Typical transients should be introducible in the controllable parameters of the nuclear reactor.
C A basis should be formed for the development and implementation of a control strategy.
D A basis should be formed for designing the full LFR system.

In order to serve the aforementioned purposes, a non-linear, zero dimensional model has been presented. It is typical to consider an LFR core alongside its steam generator, coolant pump, collectors and the coolant cold pool. In this study, however, only the core has been considered, since it is the only component which produces the dominant response, whenever a transient is initiated upstream. The point-reactor kinetics model is used to describe the behavior of reactor kinetics. The thermal hydraulics is described by an average temperature heat transfer calculation. The reactivity feedback effect has also been incorporated in the simulator. All of these subsystems have been combined and

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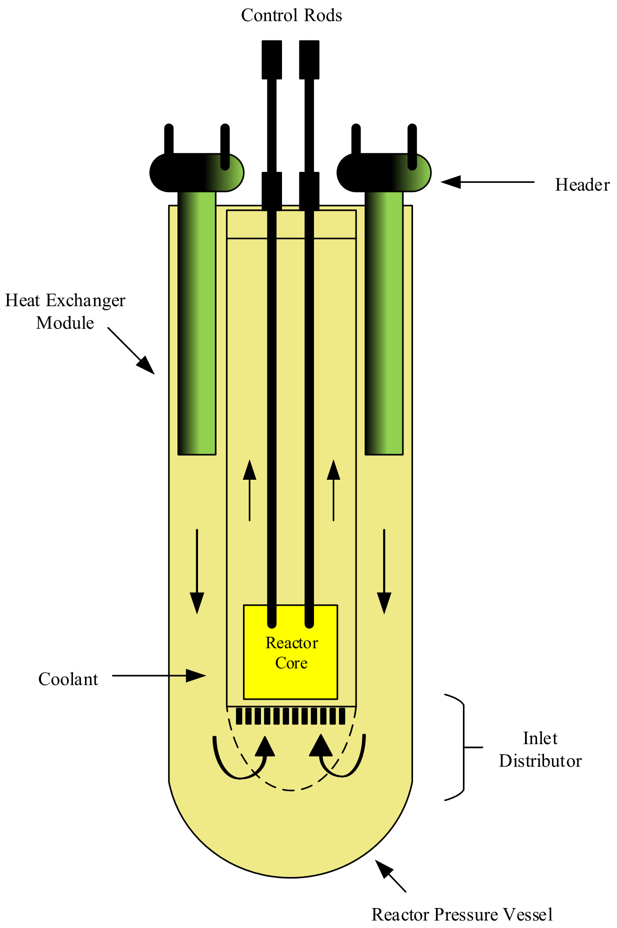

Fig. 1. Lead-cooled fast reactor.

Table 1
Parameters of LFR core (Bortot et al., 2012).

Parameter	MOX	Units
Average coolant outlet temperature	480	°C
Average coolant speed	3.00	m/s
Cladding outer diameter	6.0	mm
Cladding thickness	0.34	mm
Coolant inlet temperature	400	°C
Fuel column height	650	mm
Fuel inner diameter	1.71	mm
Fuel outer diameter	4.59	mm
Fuel rod pitch	8.53	mm
Number of pins/FA	744	–
Number of FAs (inner/outer)	10/14	–
Plenum height	650	mm
Pu fraction (inner/outer)	29.3/32.2	wt. %
Thermal Power	300	MW_{th}

implemented inside MATLAB/SIMULINK to simulate the behavior of an LFR core. The response of the LFR simulator has been observed by inserting various test inputs in the core parameters (reactivity, inlet temperature and mass flow rate of the coolant). A stability analysis has been performed with this model. At last, noise has been introduced in one of the input parameters of the LFR core, to show its variable effect on the output parameters of the simulator.

Nomenclature

C	Specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
c_i	ith precursor density (cm^{-3})
h_{cl}	Cladding-coolant overall heat transfer coefficient ($W\ K^{-1}$)
k	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_{fc}	Fuel-gap-clad overall heat transfer coefficient ($W\ K^{-1}$)
M	Mass (kg)
$\dot{m}$	Mass flow rate of the coolant ($kg\ s^{-1}$)
n	Neutron density (cm^{-3})
q	Reactor thermal power (MW)
T	Temperature (°C)
t	Time (s)
α_D	Doppler reactivity feedback coefficient ($pcm\ K^{-1}$)
α_H	Control rod reactivity feedback coefficient ($pcm\ cm^{-1}$)
α_R	Radial expansion reactivity feedback ($pcm\ K^{-1}$)
α_Z	Axial expansion reactivity feedback ($pcm\ K^{-1}$)
β	Delayed neutron fraction (pcm)
β_i	ith precursor group delayed neutron fraction (pcm)
Δh_{cr}	Control rod insertion length (cm)
Λ	Average neutron lifetime (s)
λ_D	Precursor decay constant (s^{-1})
ρ	Reactivity (pcm)

Subscripts

0	Steady-state value
c	Cladding
f	Fuel
in	Inlet
l	Lead coolant
out	Outlet

Abbreviations

FA	Fuel Assembly
LFR	Lead-cooled Fast Reactor
MATLAB	Matrix Laboratory
SISO	Single Input Single Output
ELSY	European Lead-cooled System

2. Description of LFR core reactor

The 300 MW_{th} LFR reactor concept is based on the European Lead-cooled System (ELSY) (Bortot et al., 2013). All of the primary parts are located inside a single cylindrical RPV (reactor pressure vessel), with a flat head and a hemispherical bottom head (Fig. 1). Several headers are located in the RPV having 8 exit ducts, leading towards their respective steam generator. A cylindrical vessel, located inside the RPV structure, is used to provide lateral restraint, which is connected to a core support plate. The lead coolant level is always kept below the upper head of RPV, so that there is a smaller thermal gradient between the upper head and sides (directly in contact with the coolant). The collector (flow distributor) is situated between the RPV and the inner vessel. The LFR core consists of ductless fuel assemblies (FAs) arranged in a square lattice structure. There are 10 and 18 FAs in the inner and outer enrichment zones, respectively. Table 1 specifies the major core parameters of the LFR reactor:

3. Development of the simulator

The development of the LFR core simulator is based on a modular approach, so that it is convenient to replace and modify the individual calculation blocks, without having to affect the whole core model. A zero-dimensional model is employed for modeling the reactor kinetics and thermal hydraulics of the core, which are coupled together, using the reactivity feedback effect of the temperature. A schematic is used to