Annals of Nuclear Energy 87 (2016) 198–208

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A multi-physics reduced order model for the analysis of Lead Fast Reactor single channel

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ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 30 August 2015
Accepted 4 September 2015

Keywords:
Reduced Basis method
Proper Orthogonal Decomposition
Parametrized multi-physics
Single-channel analysis
Lead Fast Reactor

ABSTRACT

In this work, a Reduced Basis method, with basis functions sampled by a Proper Orthogonal Decomposition technique, has been employed to develop a reduced order model of a multi-physics parametrized Lead-cooled Fast Reactor single-channel. Being the first time that a reduced order model is developed in this context, the work focused on a methodological approach and the coupling between the neutronics and the heat transfer, where the thermal feedbacks on neutronics are explicitly taken into account, in time-invariant settings. In order to address the potential of such approach, two different kinds of varying parameters have been considered, namely one related to a geometric quantity (i.e., the inner radius of the fuel pellet) and one related to a physical quantity (i.e., the inlet lead velocity). The capabilities of the presented reduced order model (ROM) have been tested and compared with a high-fidelity finite element model (upon which the ROM has been constructed) on different aspects. In particular, the comparison focused on the system reactivity prediction (with and without thermal feedbacks on neutronics), the neutron flux and temperature field reconstruction, and on the computational time. The outcomes provided by the reduced order model are in good agreement with the high-fidelity finite element ones, and a computational speed-up of at least three orders of magnitude is achieved as well.

1. Introduction

The Lead Fast Reactor (LFR) has been selected as one of the innovative nuclear power plants able to meet the Generation IV International Forum (GIF-IV) goals (GIF, 2010): sustainability, economics, safety and reliability, proliferation-resistance and physical protection. This fission nuclear reactor has been the subject of several studies up to now, and numerous investigations have been carried out to assess its effective potentialities (Alemberti et al., 2011; Bandini et al., 2011; Tuček et al., 2006). At the same time, several issues still need to be fully addressed. In this context, the Multi-Physics (MP) modelling approach (Luzzi et al., 2011; CASL, 2012; Mahadevan et al., 2012; Mylonakis et al., 2014) is an emerging tool for analysing the "reactor system", both in normal and accidental conditions, thanks to the intrinsic coupling among neutronics, thermal–hydraulics, and thermal expansions phenomena.

Concerning the LFR study, the MP approach allows evaluating simultaneously a wide set of core parameters (e.g., temperature field, velocity field, neutron fluxes). This advantage may be valuable for core designing, when verifying the satisfaction of the operational constraints. In this context, a *parametrized* MP model with *real-time* simulation could be an even more powerful tool for design-oriented studies. The main novel contribution of this work is the development of a reduced order model (ROM) of a parametrized MP model for the LFR single-channel in order to demonstrate the potentialities of the reduced order modelling approach in this field. The goal of a computational reduction technique (Manzoni et al., 2012) is to capture the essential features of the input/output behaviour of a system in a rapid and reliable way, i.e. (i) by improving computational performance and (ii) by keeping the approximation error between the reduced-order solution and the full-order one under control. In particular, the reduced order modelling is aimed at approximating a parametrized partial differential equation (or a set of partial differential equations) solution with a handful of degrees of freedom instead of thousands or millions that would be needed for a full-order approximation. In this way, the full-order problem has to be solved only for a properly selected number of instances of the input parameter (through a demanding Offline computational step), in order to be able to perform many low-cost real-time simulations (inexpensive Online computational step) for new instances of the parameter. It is worth mentioning that simplification – or approximation – of an equation, or a system of equations, describing a phenomenon is indeed

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http://dx.doi.org/10.1016/j.anucene.2015.09.002
0306-4549/

Nomenclature

Latin symbols

C_p	specific heat [J kg^{-1} K^{-1}]
D	neutron diffusion coefficient [m]
E_f	average energy released per fission [J]
e_f	error in L^2 norm of the neutron flux [a.u.]
e_T	error in L^2 norm of the temperature [K^2 m^3]
K	thermal conductivity [W m^{-1} K^{-1}]
K_T	lead turbulent thermal conductivity [W m^{-1} K^{-1}]
$\mathbf{n}$	surface normal unit vector [–]
Q	volumetric heat source [W m^{-3}]
r	radial coordinate [m]
T	temperature [K]
T_0	reference temperature used in Eq. (5) [K]
u	generic trial function [–]
V	generic Hilbert space for the neutron fluxes [–]
$\mathbf{v}$	velocity vector [m s^{-1}]
v	generic test function [–]
w	generic trial function [–]
$\mathbf{x}$	generic vector of spatial coordinates [(m, m)]
W	generic Hilbert space for the temperature [–]
z	axial coordinate [m]

Greek symbols

α	coefficient used in Eq. (5) [–]
β	volumetric thermal expansion coefficient [K^{-1}]
γ_r	radial albedo coefficient used in Eq. (12) [–]
γ_z	axial albedo coefficient used in Eq. (11) [–]
Θ^q	generic coefficient of the qth term [–]
λ	eigenvalue associated to Eq. (3) [–]
μ	vector of parameters [m, m/s]
μ_1	varying parameter: inner fuel radius [m]
μ_2	varying parameter: inlet lead velocity [m/s]
ν	average number of neutrons emitted per fission [–]
ξ	generic basis function [–]
ρ	density [kg m^{-3}]
ρ_0	reference density used in Eqs. (5) and (6) [kg m^{-3}]
σ_q	generic coefficient of the qth term [–]
Σ	macroscopic cross-section [m^{-1}]
Σ_a	macroscopic absorption cross-section [m^{-1}]
Σ_f	macroscopic fission cross-section [m^{-1}]
$\Sigma_s^{g\to g'}$	macroscopic group transfer cross-section (from group g to g') [m^{-1}]
Σ_0	reference macroscopic cross-section used in Eqs. (5) and (6) [m^{-1}]
Φ	neutron flux [m^{-2} s^{-1}]
χ^g	fraction of prompt neutrons generated in the gth group [–]
ψ	generic test function [–]
Ω	generic spatial domain [m^2]

Subscripts/ superscripts

$'$	transpose
f	reference to neutron flux
g	gth neutron energy group
N	reference to the reduced order model
N_f	reference to the reduced order model of neutron flux
N_T	reference to the reduced order model of temperature
$\mathcal{N}$	reference to the full order model
T	reference to the temperature field

a reduced order technique and it can be phrased as: "Reduce-then-discretize". The herein proposed reduced order method is complementary and can be described as: "Discretize-then-reduce". The developed reduced order model is built upon a high-fidelity Finite Element (FE) (Quarteroni and Valli, 2008) model, which is assumed as "truth".

In the nuclear engineering field, ROMs are starting to gain momentum and several works has begun to appear in the literature (Wols, 2010; Buchan et al., 2013; Sartori et al., 2014; Reed and Roberts, 2015; Buchan et al., 2015). In this work, a Reduced Basis (RB) method (Rozza et al., 2008; Quarteroni et al., 2011; Rozza, 2014), based on a Proper Orthogonal Decomposition (POD) sampling (Sirovich, 1987; Holmes et al., 1996; Chatterjee, 2000; Du et al., 2012, 2013) technique, has been employed. In order to address the potential of such approach, both a geometric and a physical parameter have been considered. The development of a detailed and exhaustive simulation tool for fuel pin design is beyond the aim of the present contribution, which is focused on the methodological approach. Indeed, the proposed model has to be intended as a proof of concept to address the capabilities of reduced order techniques in a many-query context. Moreover, a particular strategy for handling the non-linear coupling between neutronics and temperature in order to achieve a competitive Offline/Online computational split is developed.

The paper is organised as follows. In Section 2, the parametrized MP model is briefly described. The RB methodology is presented in Section 3. In Section 4, the results obtained by the developed reduced order model are compared with respect to the high-fidelity FE model in terms of reactivity prediction, neutron flux and temperature fields reconstruction, as well as computational time requirements. Finally, the main conclusions, along with future developments, are presented in Section 5. Most of the symbols employed are defined within the body text, however, the reader may refer to the Nomenclature.

2. Parametrized multi-physics model

A parametrized LFR single channel model has been developed starting from the previous work of the authors (Aufiero et al., 2013), where reference is made to the European Lead-cooled System (ELSY) (Alemberti et al., 2011). Table 1 summarises the main physical quantities of the presented model. In particular, taking advantage of the rotational symmetry along the fuel channel, a $r-z$ model has been considered, which is depicted in Fig. 1, where the aspect ratio is not preserved for the sake of clarity. Indeed, the fuel channel length is much larger than the radius. The two varying parameters that have been taken into account are the following:

$$\mu_1 \in [0.1, 0.43] \quad (\text{cm}), \tag{1}$$

which is the inner radius of the fuel pellet, and the second parameter

$$\mu_2 \in [0.8, 1.6] \quad (\text{m/s}), \tag{2}$$

is the inlet lead velocity.[1] These two parameters have been employed in order to address the potential of reduced order techniques including both a geometric and a physical parameter.

[1] The range of the velocity taken into account allows simulating from one half to the nominal value of the mass flow rate. The lower bound is not zero in order not to have a transition from laminar to turbulent flow.