Adjoint sensitivity analysis of molten salt reactors multiphysics

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In the context of the energy transition, Molten Salt Reactors (MSRs) have re-emerged as a promising candidate for the next generation of nuclear reactors. The specificity of MSRs is that the nuclear fuel is dissolved in a molten liquid salt : the fuel itself circulates and transports the generated heat [2]. This entails a tight coupling between the different "physics" involved in the reactor operation, such as the neutronics and thermal-hydraulics. In reactor physics, numerical models are increasingly used to describe and monitor the state of the reactor core under normal, incidental, and accidental operating conditions. In particular, the simulation of MSRs requires the use of dedicated "multiphysics" tools, which couple the neutronics and thermal-hydraulics of the reactor.
The solutions (i.e. the *system state*) calculated by these tools are then often condensed into a few scalar quantities of interest (*responses*) : *sensitivity analysis* (SA) quantifies the first-order impact of a change in the system's input parameters on the considered response. Numerically, several SA methods are possible, each with its own advantages and drawbacks, notably in terms of computational cost. For a chosen response, the *direct* or *finite differences* (FD) SA methods explicitly calculate the sensitivity of the system's state to each input parameter, hence requiring as many calculations as there are input parameters to perturb [1]. On the other hand, the *adjoint* SA method directly calculates the sensitivity of the response considered to all input parameters, in a single calculation, by solving one additional (adjoint) problem. For nuclear reactor studies, where the number of input parameters is typically much larger than the number of output quantities of interest, the adjoint method is particularly well-suited. The goal of this work is to present an application of the adjoint SA method to the coupled neutronics – thermal-hydraulics of MSRs.
In the first place, the sensitivity analysis procedure is tested on the neutron diffusion equation in a 1D slab. Several responses are chosen, such as total reaction rates and the effective multiplication factor, for both the source and critical (eigenvalue) problems. The model is then extended to study a simplified, purely neutronic (uncoupled) 1D MSR loop, with transport of delayed neutron precursors, increasing the number of input parameters and quantities of interest. In both cases, the sensitivities are calculated using the FD and adjoint methods, and the results are compared in terms of accuracy and computational cost. The adjoint method is found to be consistently more efficient than the FD method, with minor discrepancies in the results. The neutronics will next be coupled to a thermal-hydraulics model, to validate the adjoint method in the multi-physics modelling of MSRs.

[1] C. Fiorini, M. A. Puscas, B. Després. *Sensitivity analysis for a thermohydrodynamic model : Uncertainty analysis and parameter estimation.* European Journal of Mechanics - B/Fluids, **105**, 25–33, 2024. doi :https://doi.org/10.1016/j.euromechflu.2023.12.010.

[2] J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J. L. Kloosterman, L. Luzzi, E. Merle-Lucotte, J. Uhlíř, R. Yoshioka, D. Zhimin. *The molten salt reactor (msr) in generation iv : Overview and perspectives.* Progress in Nuclear Energy, **77**, 308–319, 2014. doi :https://doi.org/10.1016/j.pnucene.2014.02.014.

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