THE GEN-FOAM MULTI-PHYSICS SOLVER FOR REACTOR ANALYISIS: STATUS AND ONGOING DEVELOPMENTS

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The GeN-Foam (Generalized Nuclear Foam) [1] open-source software is an OpenFOAM [2] based solver for the steady-state and transient analysis of nuclear reactors, with a focus on core behavior.

Adoption of an open-source approach was stimulated both by the possibility to build upon previous effort towards OpenFOAM-based multi-physics nuclear solvers [3], [4], but also as a promising way towards a sustainable development strategy based on collaborative work with various institutions, and to provide the community with a transparent and easily accessible tool for research and education.

Objective of the solver is to complement nuclear legacy codes with additional flexibility for the modelling of non-traditional reactor designs, as well as complex phenomena in more traditional reactors. To achieve this, the development of GeN-Foam has been based on three main pillars: 1) the use of unstructured meshes to allow for a complete geometrical flexibility; 2) a massive parallel scalability to allow for large-scale simulations; and 3) the use of an intuitive finite volume formulation, combined with an object-oriented programming and a high-level API, to allow users to easily tailor the solver and its sub-solvers to their needs. In addition, specific choices have been made in terms of modelling to allow for different levels of modelling accuracy based on the user's specific needs. For example, user can adopt different sub-solvers for neutronics, and the thermal-hydraulic sub-solver has been designed to allow for different levels of modelling details (viz, CFD-like, sub-channel-like, or a combination of the two).

In terms of capabilities, GeN-Foam has been developed for the steady-state and transient analysis of reactors featuring pin-type, plate-type or liquid fuel (viz., MSRs). It includes:

- A set of sub-solvers for neutronics, including point kinetics, diffusion [5], SP3 [6], and SN [7]. The number of energy groups is user-selectable and a routine is provided to export nuclear data from the Monte Carlo code Serpent2 [8] to OpenFOAM-readable input files. The sub-solvers allow to employ assembly discontinuity factors and include moving-mesh features. In particular, the mesh can be deformed based on the displacement field provided by the thermo-mechanic sub-solver (see below) or by the user. The transport of delayed neutron precursors is accounted for in case of liquid fuel.
- Two thermal-hydraulic solvers [9], [10] for both single- and two-phase simulations. The single-phase solver allows for both fine- and coarse-mesh simulations. Fine-mesh simulations rely on a standard k-ε RANS model, while coarse-mesh simulations rely on a porous-medium approach, which can be turned into a subchannel approach by a proper selection of mesh and sub-scale models. The two-phase solver has mainly been conceived for coarse-mesh porous-medium (or subchannel) simulations, but it allows simulating each single phase using a standard k-ε RANS model. For both solvers, coarse- and fine-

mesh simulations can be simultaneously performed on different regions of a mesh, allowing for instance for an implicit coupling of CFD-like simulations of plena and sub-channel-like simulations of core and heat exchangers.

— A simple thermo-mechanical solver based on linear elasticity that can be used for instance to calculate thermal deformations in a fast reactor core.

The coupling between physics is obtained via fixed-point iterations and the time derivatives are solved based on a first-order implicit Euler scheme.

GeN-Foam has been developed since 2014 by making use of the git code versioning system, which combines with an object-oriented programming paradigm to allow seamlessly including contributions from various authors, as well as guaranteeing a means for quality assurance (QA). An additional step in QA has been introduced in 2018 by inclusion of a regression test. The latter consists in running, at every new git commit, a representative set of tutorials to verify that results are unchanged (or changed according to plans). Starting from 2019, coding has been improved and commented, while a documentation and several tutorials have been prepared in 2020. This allowed for an initial Beta release in 2020, while the first stable version of the solver has been publicly released on GitLab in July 2021 [11]. The repository includes the source code, several tutorials, some helper tools, and documentation. The latter is provided both in the form of pdf documents and presentations in the repository itself, and as a wiki associated to it.

In terms of verification and validation, the solver has undergone basic sanity checks against simple analytical cases (see for instance [10]), as well as preliminary validation and code-to-code benchmarks for: the neutronics sub-solvers (see for instance [5], [12]), including an ongoing extensive campaign based on measurements on the CROCUS reactor; the single and two-phase solvers (see for instance [9]); the coupling between the two (see for instance [13]).

Despite having reached a relatively advanced development status and a stable coding, GeN-Foam remains a complex solver. This is partly a consequence of its inherently multi-physics nature that require users to have a solid understanding of several different aspects associated to nuclear engineering. In addition, a layer of complexity is given by the adoption of a general finite-volume methodology. This requires some familiarity with concepts and best practices associated e.g. with mesh generation, mesh convergence, finite-volume discretization, solution of linear systems, etc. Typically, a background on CFD calculations has been observed to greatly reduce the initial barrier to a proficient use of GeN-Foam. Finally, familiarity with the Linux operating system is necessary.

On the other hand, GeN-Foam provides a large modelling flexibility and the open-source nature of the code combines well with a high-level object oriented programming to streamline code modification and allow for fast tailoring of the solver and its sub-solvers.

The complexity and flexibility of GeN-Foam tend to make it particularly suitable for PhD students and researchers that can take the time to familiarize with the solver and that wish to experiment on methods, address particularly complex problems, or investigate non-traditional reactors. However, an expanded documentation and set of tutorials have recently made it possible to use GeN-Foam in the frame of shorter projects such as Master Thesis (see for instance [14]).

To better illustrate the use and capabilities of the solver, Figs. 1 to 3 show a few examples of modelling performed with GeN-Foam. In particular:

— Fig. 1 shows a coupled neutronic, thermal-hydraulic and thermal-mechanic simulation of the core of the European Sodium Fast Reactor (ESFR). In this case, the moving-mesh capabilities of GeN-Foam were used to simulate the reactivity effects of core flowering and a hypothetical core compaction.
— Fig. 2 shows geometry and results related to the simulation of the loss of flow test 13 in the Fast Flux Test Facility (FFTF). In this case, the combined coarse-fine mesh capabilities of the GeN-Foam thermal-hydraulic sub-solver were employed for a multi-dimensional simulation of the primary and secondary circuits, and coupled with a point-kinetic solver for neutronics. The power shape was additionally obtained using the neutron diffusion sub-solver.
— Fig. 3 shows some of the results of a Master Thesis [14] where GeN-Foam was used to preliminary investigate the advantages and disadvantages of a point kinetics vs diffusion simulation for the Molten Salt Fast Reactor (MSFR).

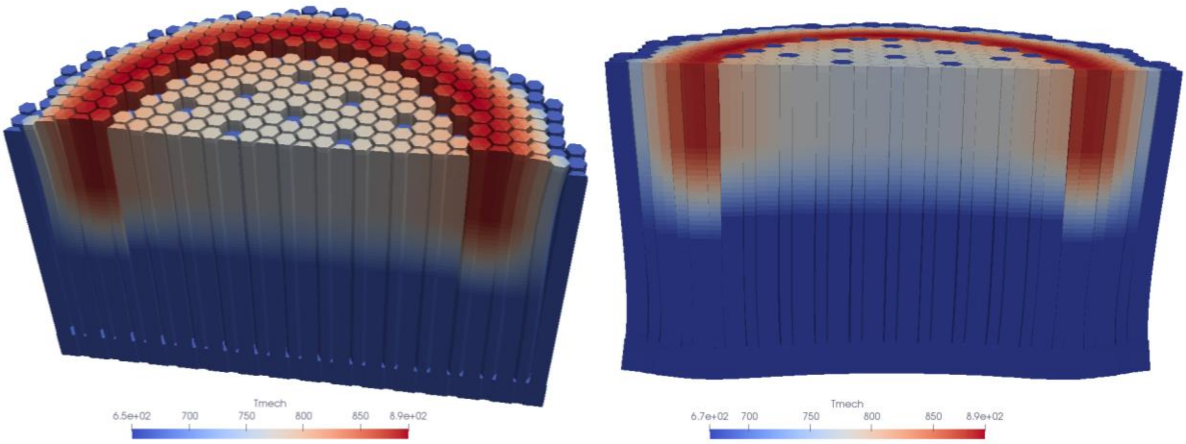

FIG. 1. 3-D multi-physics modelling of core flowering (left) and compaction (right) in the ESFR [7]

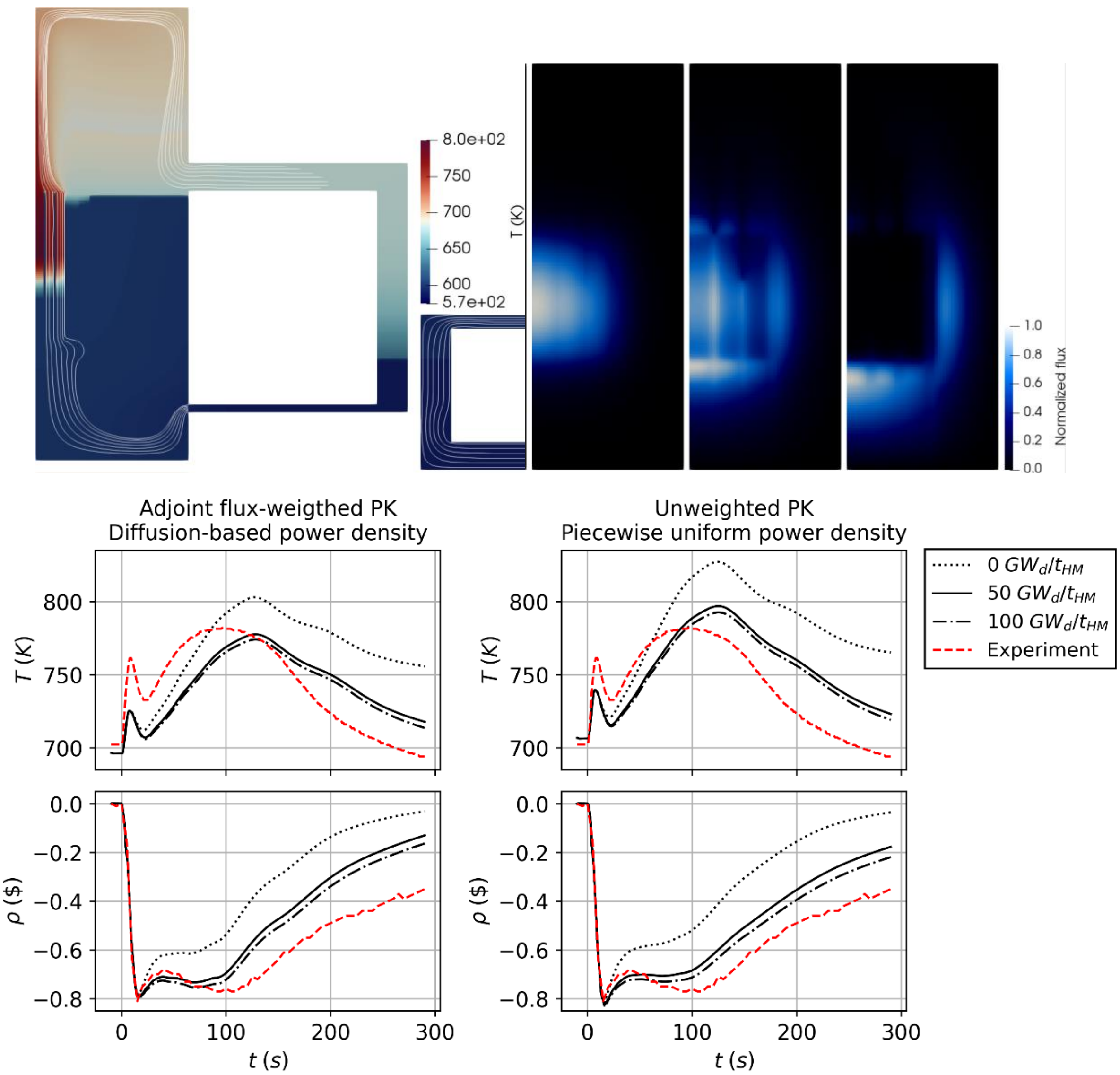

FIG. 2. 2-D multi-physics modelling and results for the FFTF loss of flow test 13 [15]

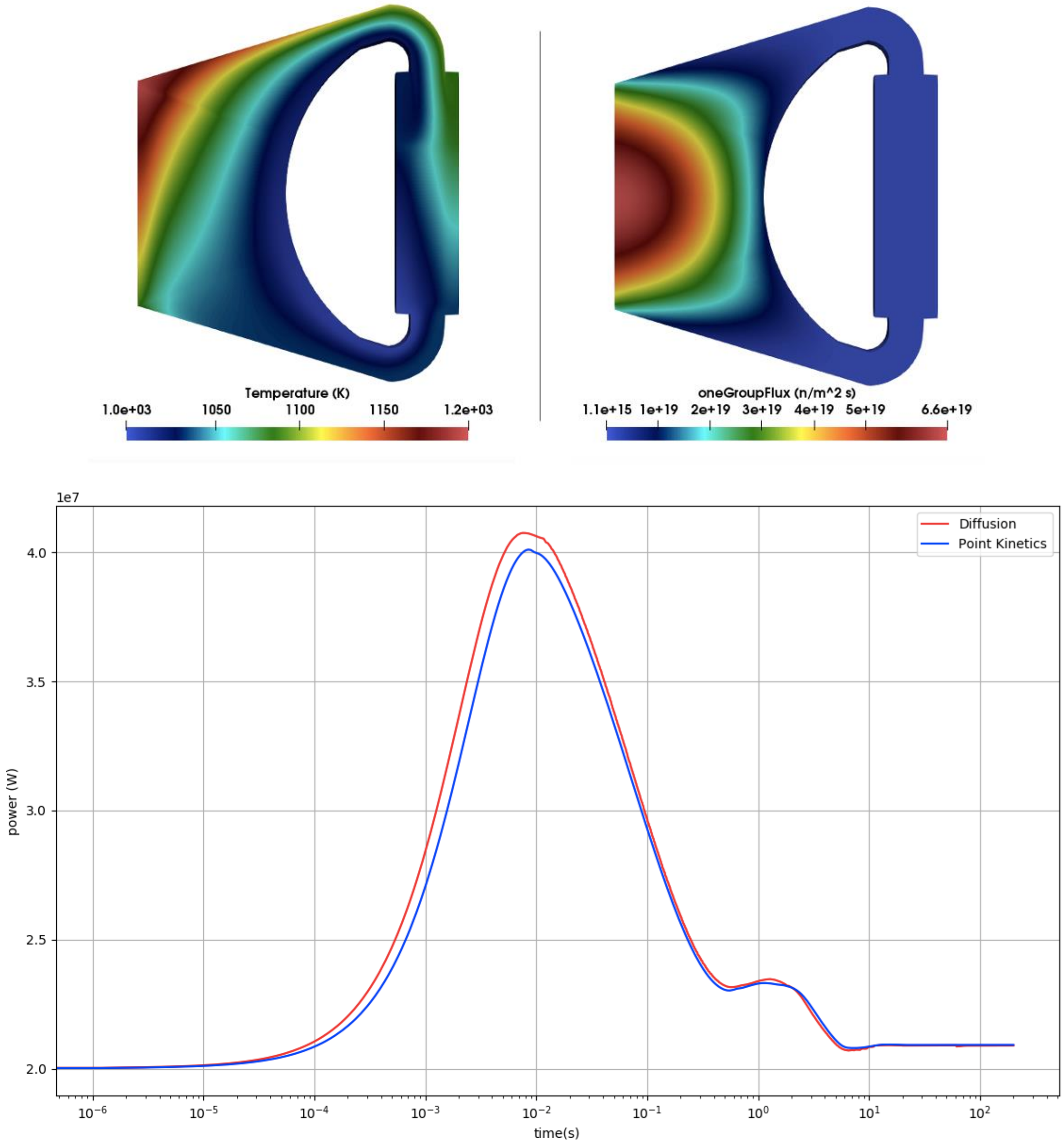

FIG. 3. 2-D multi-physics modelling and results for MSFR [14]

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