Development of a multi-physics calculation platform dedicated to irradiation devices in a material testing reactor

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Abstract

The physical phenomena involved in irradiation devices within material testing reactors are complex (neutron and photon interactions, nuclear heating, thermal hydraulics, ...). However, the simulation of these phenomena requires a high precision in order to control the condition of the experiment and the development of predictive models. Until now, physicists use different tools with several approximations at each interface. The aim of this work is to develop a calculation platform dedicated to numerical multi-physics simulations of irradiation devices in the future European Jules Horowitz Reactor [1]. This platform is based on a multi-physics data model which describes geometries, materials and state parameters associated with a sequence of thematic (neutronics, thermal hydraulics...) computations of these devices. Once the computation is carried out, the results can be returned to the data model (DM). The DM is encapsulated in a dedicated module of the SALOME platform [2] and exchanges data with SALOME native modules. This method allows a parametric description of a study, independent of the code used to perform the simulation. The application proposed in this paper concerns neutronic calculation of a fuel irradiation device with the new method of characteristics implemented in the APOLLO2 code [3]. The device is located at the periphery of the OSIRIS core. This choice is motivated by the possibility to compare the calculation with experimental results, which cannot be done for the Jules Horowitz Reactor, currently in design study phase.

KEYWORDS: Multi-physics data model, SALOME, neutronics, APOLLO2

1. Introduction

An efficient multidisciplinary simulation requires an efficient data-processing environment. We first present the data model developed to describe the data of the simulation. Then we use this data model to perform a neutronic simulation of an experimental device.

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2. Data Model

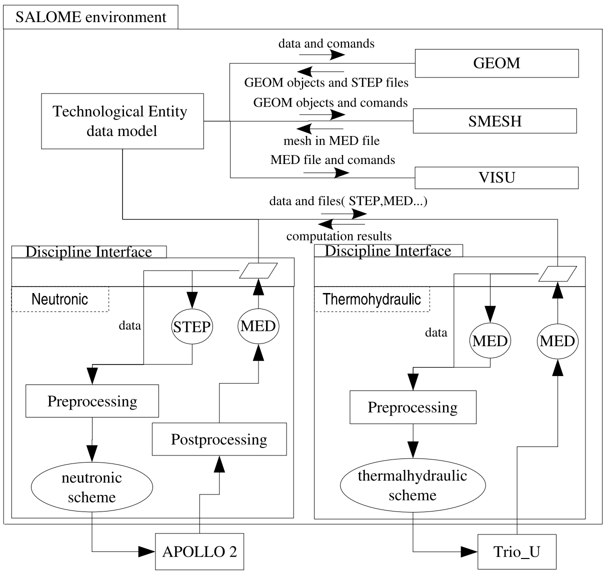
2.1 Overview

The Technological Entity data model we are developing, describes the irradiation devices in a tree-like structure. Technological Entity data model is encapsulated in a SALOME module called TECHENTITY. This can be run in the SALOME environment in graphic mode or in a PYTHON [4] batch mode. The Figure 1 presents an overview of the application.

SALOME platform is a free software dedicated to CAD and CAE[a] application. Today several numerical solvers are integrated in this platform. The SALOME architecture is flexible and expandable by means of plugin-like components. The SALOME platform provides various pre/post-processing and visualization tools, related to geometries, meshes and fields of results of numerical simulations. The SALOME platform is composed of several modules, such as :

- *GEOM*, which offers CAD functions to build geometric objects, perform geometric operations, and to export and import CAD models in several formats (STEP[b],IGES[c]) ;
- *SMESH*, which allows meshing of geometric objects with several algorithms. This geometric objects are GEOM module objects. Meshes are converted and saved in MED[d] format [5] ;
- *VISU* for the scientific visualization of meshes and field values.

Figure 1: Platform overview



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[a] CAD: Computer Aided Design, CAE: Computer Aided Engineering

[b] Application Protocole 214 (AUTOMOTIVE DESIGN)

[c] IGES : Initial Graphics Exchange Specification

[d] MED : Exchange Data Model

We consider that the input data of all thematic computations are known by the Technological Entity data model. These are principaly geometric data and associated materials characteristics. The integration of the TECHENTITY module in SALOME environment enables the use of other SALOME modules. The Technological Entity runs the GEOM module to build, delete and make geometric computations on geometric instances. In the same way, the SMESH module for meshing geometries and the VISU module for scientific visualizations can be called by our module. Thematics computations like neutronics or thermalhydraulics are encapsulated in discipline interfaces which provide result access methods, independent of the result format of the calculation code. It will improve the data exchange for calculation sequences.

An advantage of this architecture is to give a unified user environment from CAD to post-processing. It will also increase the prediction capabilities for fuel/material behavior when all the disciplines will be integrated in this platform. Anymore, it will help the user to perform parametric studies in a conception phase.

2.2 TECHENTITY Component

The TECHENTITY module provides tools to manage Technological Entities. The Technological Entity data model will be used during differents phases of an irradiation device life cycle.

2.2.1 Geometric Modeling of devices

The Technological Entity data model assures the CAD-CAE link, as proposed in [6]. Simulation tools need geometries which can be meshed (for example to finite elements calculations and method of characteristics calculations) or not (Monte Carlo calculations). So, the Technological Entity needs a true CAD geometry model with shape connectivity information (topology) for simulations. Technological Entity data model is a Feature oriented model [7]. The advantage of a Feature oriented model is to allow both CSG and B-REP[e] [8] geometric models. A CSG model is useful to describe device geometry and B-REP allows to keep connectivity information between shapes.

2.2.2 The Technological Entity

A technological Entity is the smallest element of the tree-like technological entity data model. It is composed of a local geometry, an associated material and a list of children and a mother dependant technological entity instances (if the technological entity is not the root instance). Figure 2 presents how to model the geometry of a device (Modelled object) with a Technological Entity tree.

During the design phase, only local geometry attributes are given with their associated materials. After that, children are defined for each Technological Entity (the mother link is automatically done). In a third time, a representation of this tree is computed (by the GEOM Component) and stays resident in memory. At this time, a simple new assignment to a local geometry attribute or to an entity in the children list, updates the computed geometry.

Furthermore, a version identification can be attached to the current tree construction. Each Technological Entity saves the modifications between versions and a mechanism allows the reloading of an older version with a simple assignment to the current version attribute.

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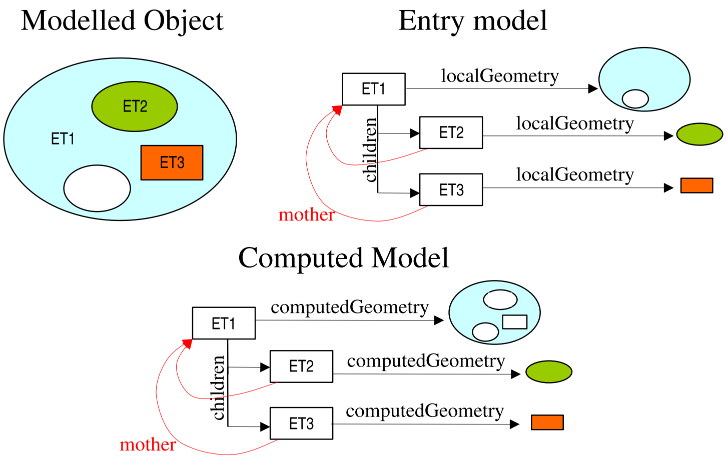
[e] CSG : Constructive Solid Geometry, B-REP : Boundary REPresentation

Figure 2: Technological Entity device modeling



2.3 Data exchanges

Conceptually, there are two directions of data exchanges : a data exchange from the Technological Entity data model towards the discipline interface (downward exchange direction), and a data exchange from results of code calculations towards the technological entity data model (upward exchange direction). In practice, during the downward data exchanges, the discipline interface gets geometry and material characteristics data and query thematic calculation results to the data model. The query of the results can be considered as the upward data exchanges, but it is done in the same time as the downward data exchanges.

Thematic calculations, encapsulated in the discipline interface, can get entry geometry (and material characteristics) data and build a geometry model itself, as decribed before, or query an exportation of GEOM computed geometry model in a specific format (STEP, IGES).

The result calculation are queried to thematic calculations to a space and time location integrated on a neigborhood and a specific field of results, identified by a unique name. As many code calculations produce results in MED format, a generic discipline interface with the query result method will be developed to simplify adaptation to TECHENTITY.

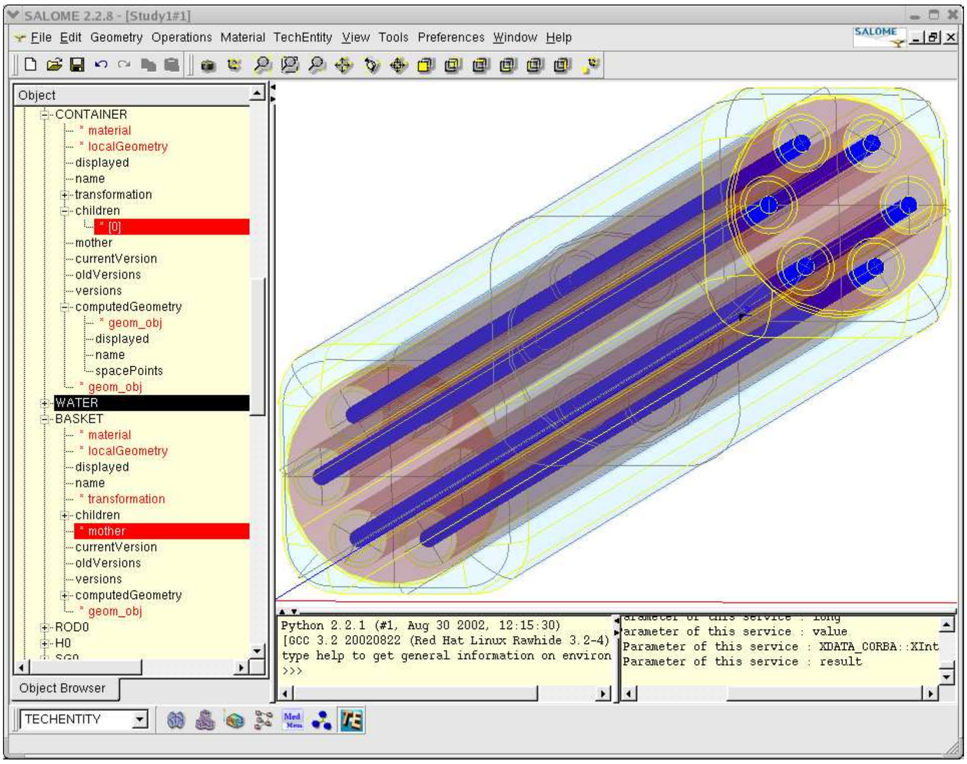
2.4 Example of application

This application presents the adaptation illustrating the APOLLO2 neutronic scheme calculation to the Technological Entity data model, especially data exchanges between the data model and the scheme calculation. The neutronic scheme will be detailed in the next section.

The device, located in the periphery of the OSIRIS reactor, is composed of six fuel rods. A Technological Entity data model has been produced. On the right of the Figure 3, we can see how the six fuel rods are located in the device. This latter is built with a fillet box called CONTAINER which contains a cylinder (BASKET). Between the CONTAINER and the BASKET, there is a space filled with water, called WATER. We can see in the Technological Entity tree representation (left of the Figure 3) that both children attribute of CONTAINER and mother attribute of BASKET refer to WATER (highlighted in the tree representation). A value change of an attribute of one entity will automatically update all the data model.

The APOLLO2 MOC calculation uses a 2D general geometry, meshed by the user-friendly SILENE code [9]. The mesh of the reactor geometry has been done previously. The neutronic interface scheme queries a 2D cut of the device geometry, based on the technological entity

Figure 3: Visualization of the Technological Entity data model of the device



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Python 2.2.1 (#1, Aug 30 2002, 12:15:30)
[GCC 3.2 20020822 (Red Hat Linux Rawhide 3.2-4)
type help to get general information on environ
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arameter of this service : long
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Parameter of this service : XDATA_CORBA::XInt
Parameter of this service : result
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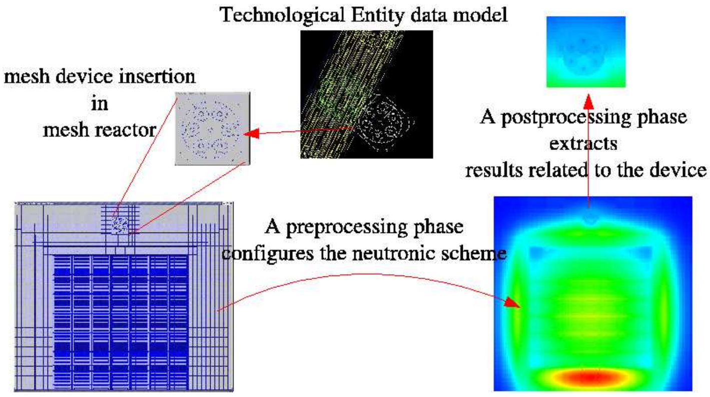
data model. This 2D cut is carried out by GEOM component and exchanged toward SILENE code in STEP format [10]. The device geometry is then meshed and inserted into the mesh of the reactor (Figure 4).

Figure 4: From data model toward neutronic calculation



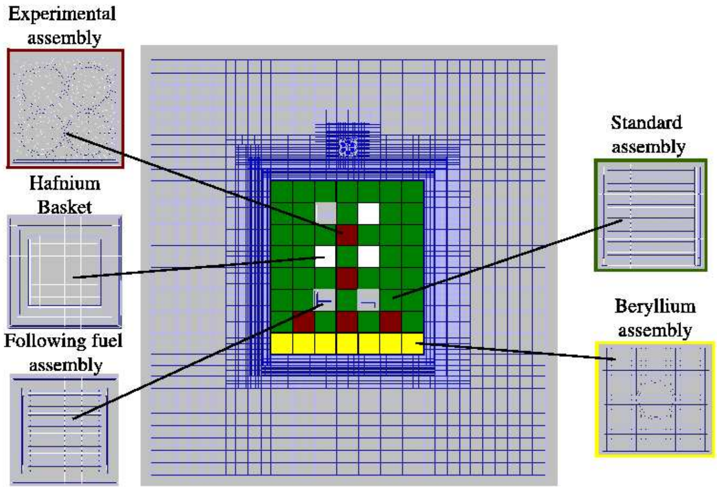
A preprocessor sets the options for the neutronic scheme calculation (mesh and material data) and the calculation is performed. Finally, a postprocessor converts the results from the APOLLO2 MOC specific format to MED format, in order to allow other thematic calculations to query neutronic results.

3. Neutronic calculation

3.1 Scheme description

As the SALOME module, GEOM works with 3D unstructured geometries, and we want to conserve the generality of the data model, we need a neutronic solver which can perform computations on this kind of geometries. This made possible by using the characteristics solver of the APOLLO2 code, which can carry out computations on 2D unstructured geometries composed of several tens of thousands of mesh cells. Therefore, the OSIRIS as well as the JHR [11] neutronic calculation scheme are based on characteristics method. The Figure 5 shows the mesh description of the computation (core assemblies are not homogenized). One APOLLO2-MOC calculation is carried out per cycle.

Figure 5: Mesh description for the neutronic calculation of a device located in OSIRIS reflector



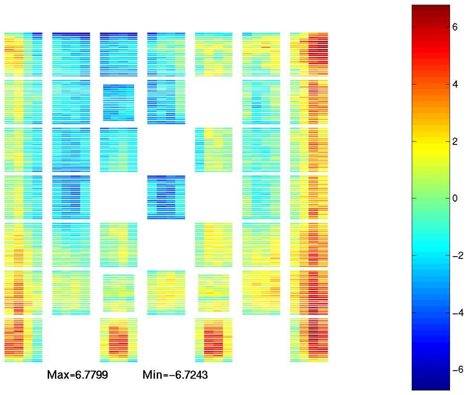
The capabilities of the neutronic scheme are the following :

- About 30 000 mesh-cells and 4 000 evolving materials (4 for each plate, 4 for each burnable poison) varying according to the loading pattern
- Transport calculation within 20 energy groups and P0* anisotropy order
- Output of fluxes and power distribution on each quarter of a plate
- Depletion calculation on each quarter of a plate
- Typical computation time for a fresh fuel core on a Linux Pentium 3Ghz : 30 minutes per burnup step
- Unloading of fuel assemblies at any desired burnup and reloading of fuel assemblies according to a specific loading pattern
- 172 energy groups re-selfshielding at any desired burnup
- In core material irradiation devices taken into account in a modular way

3.2 Validation of the neutronic calculation

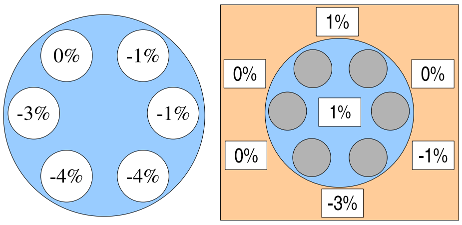
The calculation scheme has been validated in terms of reactivity and power distribution (as the fission rate) per plate for the fresh fuel core and for the fuel rods in the device by comparison to Monte Carlo simulations with the TRIPOLI4 [12] code. The statistical standard deviations are about $2.5\%(2\sigma)$ on the quarter plate power. The Monte Carlo discrepancy with 20 energy groups calculated reactivity on this core is smaller than $100pcm$. The discrepancy on the absorber efficiency is only -2%. The differences on $1/4$ plate power are below 7% and compatible with technical specifications.

Figure 6: $1/4$ Plate power comparison (in %) of MOC (20 energy groups, P0*) versus Monte Carlo



The caculated power in the six device fuel rods and on thermal fluxes in the seven SPND[f] is validated (Figure 7). The differences on fuel rod power are very satisfying : below 4% and 3% for thermal fluxes.

Figure 7: Device thermal fluxes and power comparison (in %) of MOC (20 energy groups, P0*) versus Monte Carlo



Power in fuel rods

Thermal fluxes in SPND

4. Conclusion

The Technological Entity data model, developed with the SALOME environment, provides a standard CAD models which can be used in other CAD systems. In a multi-physics study, it is a common model for all thematic computations, so it improves data exchanges, allows

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[f] SPND : Self Powered Neutron Detector

parametric studies and contributes to the coupling of codes. The APOLLO2 MOC calculation used is efficient compared to Monte Carlo calculations.

The numerical validation of the neutronic sheme is achieved, so we need to compare calculations to experimental results. Futhermore a thermal hydraulics calculation of the device is under investigation with the TRIO_U code. Neutronics and thermal hydraulics will be coupled through the technological entity data model. Finally, the architecture has to be adapted to JHR devices.

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