TANDEM

Research and Innovation Action (RIA)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or he European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

Start date : 2022-09-01 Duration : 36 Months

ATHLET SMR model description

Authors : Dr. Fabian WEYERMANN (GRS), Sebastian Buchholz (GRS), Artur Hashymov (ENERGORISK)

TANDEM - Contract Number: 101059479

Project officer: Angelgiorgio IORIZZO

Document title	ATHLET SMR model description
Author(s)	Dr. Fabian WEYERMANN, Sebastian Buchholz (GRS), Artur Hashymov (ENERGORISK)
Number of pages	19
Document type	Deliverable
Work Package	WP2
Document number	D2.7
Issued by	GRS
Date of completion	2024-11-04 11:07:15
Dissemination level	Public

Summary

ATHLET SMR model description. Developpment and test of an SMR detailed models with ATHLET code with the same functionality of the CATHARE one. Furthermore, the coupling of the ATHLET model with Modelica will be developed and evaluated.

Approval

Date	By
2024-11-07 15:54:26	Dr. Stefano LORENZI (POLIMI)
2024-11-07 20:07:44	Dr. Claire VAGLIO-GAUDARD (CEA)

TANDEM

D2.7 – ATHLET SMR model description

WP2 - Task 2.4

October 28th 2024 [M26]

Sebastian Buchholz, Fabian Weywermann (GRS)

Artur Hashymov (ENERGORISK)

Funded by
the European Union

History

Date	Version	Submitted by	Reviewed by	Comments
28/10/2024	1	Sebastian Buchholz Fabian Weyermann Artur Hashymov	Thorsten Hollands Stefano Lorenzi Claire Vagio-Gaudard	

Funded by the European Union

Table of Contents

Funded by the European Union

List of Figures

Funded by the European Union

Abbreviations and Acronyms

Acronym	Description
AOO	Anticipated Operational Occurrences
(S)CSG	(Safety) Compact Steam Generator
CSA	Cross Section Area
DBA	Design Basis Accident
DBC	Design Basis Condition
DEC	Design Extension Condition
DLL	Dynamic Link Library
I&C	Instrumentation and Control
LOCA	Loss Of Coolant Accident
PWR	Pressurised Water Reactor
WP	Work Package
SMR	Small Modular Reactor
SBO	Station BlackOut
RPV	Reactor Pressure Vessel
SJP	Single Junction Pipe
PID	Proportional-Integral-Derivative
GCSM	General Control Simulation Module within ATHLET
HECU	Heat conduction module within ATHLET
TDV	Time Dependent Volume

Funded by the European Union

Executive Summary

The European TANDEM project addresses SMR safety issues related to the SMR integration into a hybrid energy system. Within the frame of TANDEM, the SMR and its coupling to (a part of) the hybrid energy system will be simulated by a coupling of Modelica and a thermal hydraulic system code. As a base for the related SMR design, the E-SMR [1] was chosen as use-case in TANDEM. While the development of the coupling and the system code input deck for CATHARE is reported in D2.6 [2], this report focuses on the work performed for AC^2/ATHLET.

The input deck describing the E-SMR was further developed from an AC^2/ATHLET input deck created in the frame of the EURATOM ELSMOR project in cooperation of LEI and GRS for the simulation of LOCA and SBO transients. It was agreed that the input deck could be used in the frame of TANDEM to develop it further for the simulation of TANDEM specific AOOs and DBAs and to couple it with dedicated Modelica models simulating the balance of plant and I&C since this was out of scope in ELSMOR.

As a starting point, GRS developed a coupling between the system code ATHLET and Modelica models for I&C, based on a controller implemented in Python. It uses the pyAFFE development of GRS to control the simulation of AC^2/ATHLET by Python and the transfer of data to or from AC^2/ATHLET and the Python library FMPy to control an arbitrary number of FMUs. The coupling between the ATHLET input deck for the E-SMR nodalization and the Modelica model of the balance of plant developed by CIRTEN-POLIMI in the open source “TANDEM” library [3] is still an ongoing action. The coupling will be used in TANDEM/WP4 to simulate AOOs and DBAs.

The report describes the AC^2/ATHLET input deck developments in TANDEM in a first part. The coupling between AC^2/ATHLET and Modelica models for I&C as well as first verification tests are described in a second part.

Keywords

SMRs, Hybrid energy Systems, Safety Methodology, Flexibility, Cogeneration, Europe, AC^2/ATHLET

Funded by the European Union

1. Introduction

The European TANDEM project addresses SMR safety issues related to the SMR integration into a hybrid energy system. Within the frame of TANDEM feasibility studies of the hybrid system will be performed. The modelling requirements depend on the transient scenarios that need to be studied. The safety scenarios that are studied in TANDEM range from normal operation to Anticipated Operational Occurrences (AOOs) to Design Basis Accidents (DBAs). Normal operation and AOOs are especially impacted by the cogenerating setup of the power plant and/or by the interaction between the plant and the hybrid energy system. Therefore, the main modelling requirement for simulating such transient scenarios consists in extending the simulation domain not only to the nuclear island modelled with the safety code AC^2/ATHLET, but also to the Instrumentation and Control systems (I&C), the Balance of Plant (BoP) and the hybrid energy system (all modelled with Modelica) [4]. Since the BoP as well as the hybrid energy system interacts with the heat generation in the nuclear island both codes need to be coupled with each other.

To do the feasibility studies, the E-SMR was chosen to be integrated into the hybrid system. The design of the E-SMR was developed in ELSMOR in which frame DBAs were simulated but without the consideration of its impact on other systems like H_2 co-generation or a district heating network. Nevertheless, the AC^2/ATHLET input deck created in ELSMOR is the basis of the GRS work performed in TANDEM related to safety simulations.

This report describes the AC^2/ATHLET input deck further developments in TANDEM in a first part. The coupling between AC^2/ATHLET and Modelica models for I&C as well as first verification tests are described in a second part.

Funded by the European Union

2. AC^2/ATHLET model of the E-SMR

The E-SMR was modelled in the EU funded project ELSMOR with the thermal-hydraulic code ATHLET [5], which is part of the AC^2 toolset [6]. The work was done by LEI and GRS and is documented in [7].

The overall nodalization of the thermal-hydraulic model is presented in Figure 1. It comprises the RPV as the primary system, the secondary side of the compact steam generators (used in normal operation) and of the safety compact steam generators (used in accident conditions). These are connected to the intermediate loop and the condenser. The secondary side of the condenser is connected to the water wall. Finally, a coarse model of the containment was created. The differences between the current TANDEM ATHLET input deck and the one created in ELSMOR by LEI and GRS are described below.

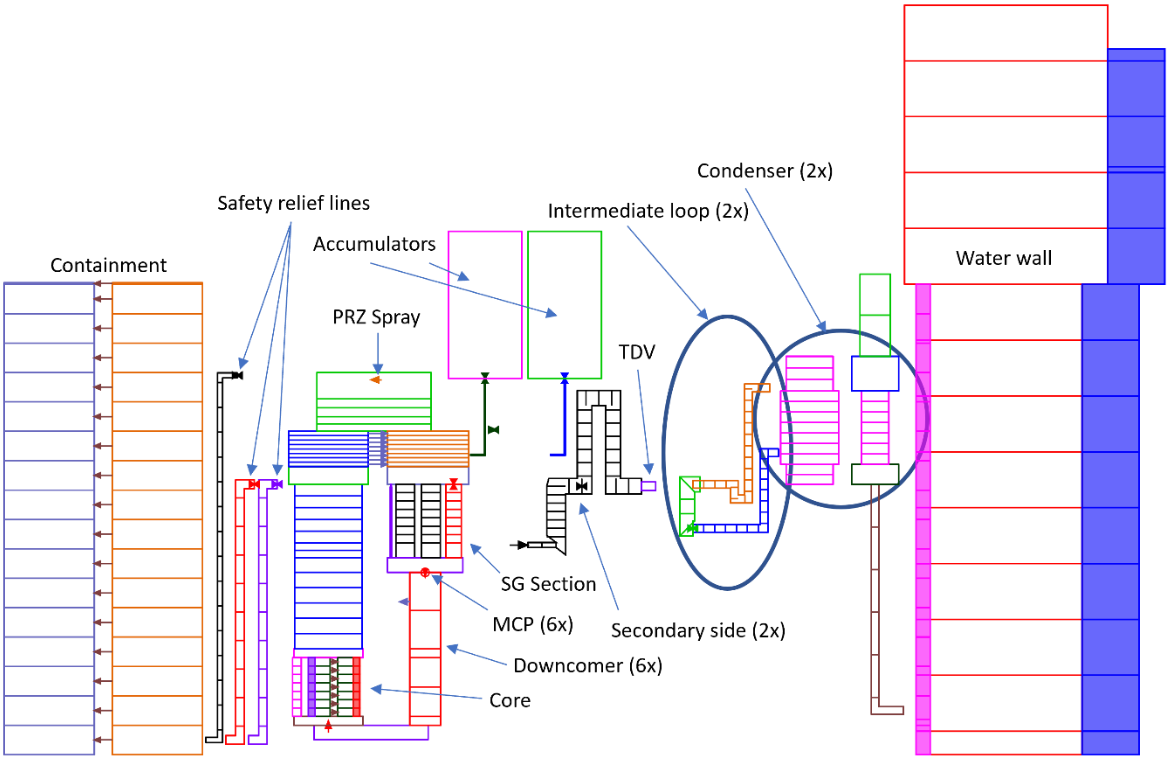

Figure 1: Overall model of the E-SMR in ATHLET

2.1 Primary system

The model and nodalization scheme of the primary system is presented in Figure 1. The basic description can be found in [7]. Due to the development of the coupling between ATHLET and Modelica, some changes in the nodalisation and model were required. First of all, a primary pressure control was added using spraying and heating of the pressuriser which is located on top of the upper plenum. It is modelled as a pipe instead of a branch now and incorporates a pressuriser heater modelled by a heat conduction object with a heat source and a Single Junction

Pipe (SJP) representing the pressuriser spray. The dedicated ATHLET spray model is activated here. The water mass is removed from the cold leg in the downcomer downstream of the pumps by a SJP. The needed enthalpy for the spray is taken from the control volume from which the mass is removed. Both the spray mass flow rate and the heater power are modelled by means of General Control Simulation Module (GCSM). The spray mass flow rate and the heater power can be controlled by a coupled Modelica model. Furthermore, both systems are deactivated by SCRAM signal.

2.2 Secondary system

The secondary side was extended in comparison with the ELSMOR input deck. First of all, the two types of steam generators are connected at their ending by a collector which continues via the main steam line towards a time-dependent volume. Feed water mass flow rate and enthalpy as well as turbine back pressure can be controlled externally, while steam mass flow rate and enthalpy can be used by the external controller. At the end of the main steam line is the turbine control valve, whose rated CSA and therefore opening can be also controlled by the external model .

2.3 Additional Logics

Further GCSM logics are implemented in the AC^2/ATHLET model to facilitate the Modelica coupling and the control by the external Modelica models. To do so, in the AC^2/ATHLET input deck, the respective GCSM signals must be of “EXTERNAL” type if AC^2/ATHLET needs to expect the respective value to be given by Modelica. This is the case for feed water mass flow rate and enthalpy, secondary back pressure and pressure control signals (pressuriser heater and spray mass flow rate). Furthermore, for power control, it is assumed that the external controller provides a control rod velocity. This is used by a GCSM integrator to determine the control rod position, which finally leads to estimate a rod worth using a table of control rod worth as a function of position. The core inlet and outlet temperatures are sent back to the Modelica model using it as input to determine the average core temperature and eventually the control rod velocity.

Figure 2 shows the locations in the AC^2/ATHLET model where thermal-hydraulic values like mass flow rate, temperature and pressure are exchanged with Modelica. The names of the different objects are given in Figure 1. Blue coloured marks represent values which are calculated by ATHLET and exchanged with Modelica (orange marks vice versa). The numbering is explained in Table 1.

Funded by the European Union

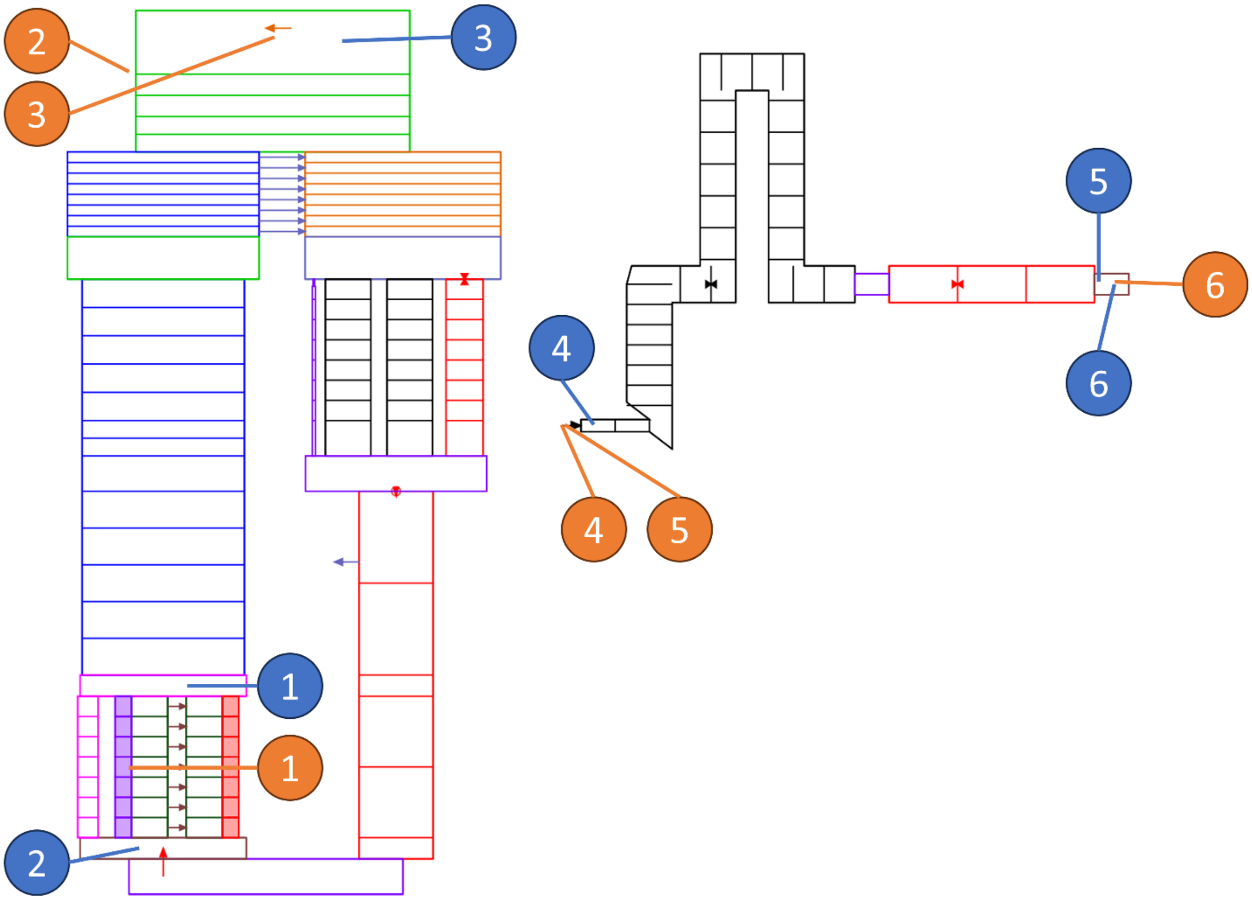

Figure 2: Exchanged data, blue: ATHLET → Modelica, orange: Modelica → ATHLET

ATHLET → Modelica (blue in Figure 2)		Modelica → ATHLET (orange in Figure 2)	
Number	Physical Value	Number	Physical Value
1	Core inlet temperature	1	Control rod velocity
2	Core outlet temperature	2	Rated pressuriser heater power
3	Pressuriser pressure	3	Spray mass flow rate
4	Feed water pressure	4	Feed water mass flow rate
5	Steam mass flow rate	5	Feed water enthalpy
6	Steam enthalpy	6	Main steam line pressure

Table 1: Exchanged physical values in the coupled model (see also Figure 2)

Funded by the European Union

3. Coupling with Modelica-Models

One goal of the TANDEM project is to perform coupled simulations of the interaction of a SMR and the rest of the hybrid energy system. For a detailed simulation of the SMR behaviour under different Anticipated Operational Occurrences (AOOs) or Design Basis Accidents (DBAs), the thermal-hydraulic system code ATHLET should be coupled to the Modelica model of the Balance of Plant (BoP) and I&C. For the coupling, the so-called Functional Mock-up Interface (FMI) is used to convert the Modelica models into Functional Mock-up Units (FMUs). Both will be presented in detail in the next chapter.

3.1 Functional Mock-up Interface

The Functional Mock-up Interface (FMI) is a free standard that defines a container and an interface to exchange dynamic simulation models [8]. It is supported by more than 200 software tools.

The Functional Mock-up Interface defines a ZIP archive containing an application programming interface (API) to exchange dynamic models using a combination of XML files, binaries and C code. This ZIP archive is called the Functional Mock-up Unit (FMU). The API is used by a simulation environment, the importer, to create one or more instances of an FMU and to simulate them, typically together with other models. The FMI defines three interface types:

- Co-Simulation (CS) where the FMU typically contains its own solver or scheduler,
- Model Exchange (ME) that requires the importer to perform numerical integration, and
- Scheduled Execution (SE) where the importer triggers the execution of the model partitions.

For the TANDEM purposes to perform coupled simulations between a thermal-hydraulic code and Modelica models, the co-simulation interface type is appropriate. The co-simulation interface is designed both for the coupling of simulation tools, and the coupling of subsystem models, exported by a modelling environment including its solvers as runnable code.

Funded by the European Union

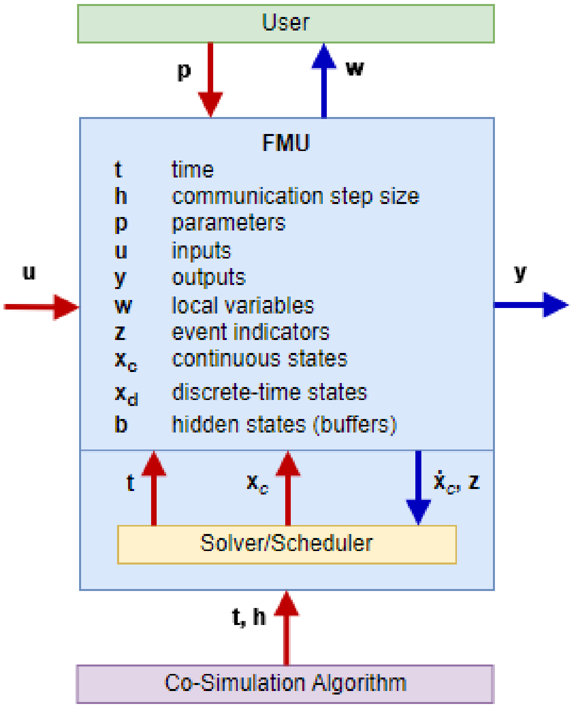

Figure 3: Schematic view of data flow between user, the scheduler of the importer and model partitions of the FMU for Scheduled Execution (taken from [10]).

3.2 The AC² FMU Controller

A dedicated simulation environment for the coupled simulation of ATHLET and the FMUs was developed. The so-called AC²/ATHLET-FMU controller for coupled simulations (see Figure 43) is based on Python. It uses the ATHLET-Python interface pyAFFE [10], which is part of the AC² package. By using pyAFFE, it is possible to control the simulation process of ATHLET via python and to transfer data from or to the ATHLET process. In order to handle FMUs, the ATHLET-FMU controller uses the Python library FMPy [9]. FMPy is able to create several instances of FMUs and to simulate them. It supports the FMI standards 1.0, 2.0 and 3.0 for co-simulation and model exchange. It is an open-source software and is released under the 2-Clause BSD license. The source code is available under github.com [9].

Funded by the European Union

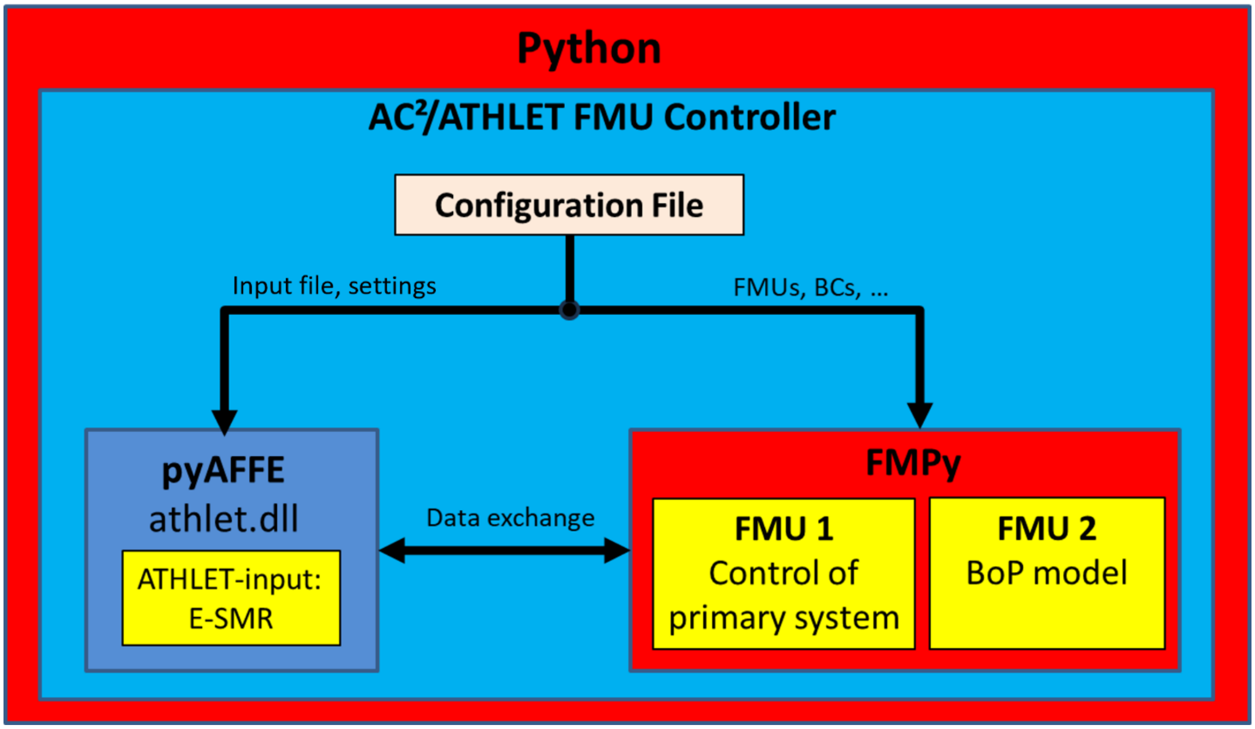

Figure 4: Overview on the AC²/ATHLET FMU Controller for the coupled simulation E-SMR ATHLET model – Modelica models.

The AC²/ATHLET-FMU controller can handle an arbitrary number of FMUs. The data to be transferred between ATHLET and the FMUs must be specified in a configuration file. Also, boundary conditions for the FMU models can be given in the configuration file and are set by the controller. The ATHLET input file is also specified in the configuration file.

After starting the ATHLET-FMU Controller, ATHLET is loaded as a Dynamic Link Library (DLL). It opens the given ATHLET input file and performs its initialization. After that, all needed FMUs are loaded, instances are generated and initialized.

In the transient simulation for every time step, ATHLET is called first and then the FMUs successively. Afterwards, all the coupling data are exchanged. The step size is determined by time integration module of AC²/ATHLET, while a maximum possible time step is set by the configuration. A direct transfer of highly fluctuating parameters with large gradients as pressures and velocities lead to small time step sizes. Therefore, it has been decided to filter these parameters by a low pass filter to dampen high frequency oscillations. This has resulted in a stable coupled simulation of the systems with sufficiently big step sizes. However, it needs to be checked whether this approach leads to a reduction in simulation accuracy. Test simulations of the E-SMR coupled to two FMUs (BoP model and control system for E-SMR) provides satisfactory results, as it can be seen next chapter.

Funded by the European Union

4. Test of the coupled model

It is planned to use the AC^2/ATHLET input deck developed in TANDEM to simulate a sudden increase or decrease of the energy (heat and/or electricity) demand from the end users. The demand of heat is therefore imposed by the dedicated Modelica model. From the AC^2/ATHLET point of view, only the turbine control valve of the main steam line is moved, resulting in feedback of the main steam mass flow rate, secondary pressure and temperature. The core power is externally controlled by Modelica. It must be checked that the AC^2/ATHLET model provides reliable and stable results when the valve of the main steam line is moved to a specific position.

In addition to GRS, ENERGORISK has also checked the ATHLET standalone input deck with respect to consistency, completeness for the selected cases plausibility. No inconsistencies were found.

Two verification tests of the coupled model are shown below, in which the turbine control valve is closed to 50 % of the fully opened valve and re-opened to 100 %. Two Modelica FMUs for I&C are coupled to the E-SMR AC^2/ATHLET model for these tests. The first one controls the primary system pressure and power. The second one controls the secondary side. The latter FMU was practically deactivated for the second simulation in order to improve the steady state conditions, which were not correctly met in the first simulation with respect to the reference data. Back pressure as well as feed water mass flow rate and enthalpy are kept constant in the second simulation so no Modelica data was used to determine the feed water parameters. However, in the frame of WP4 of TANDEM it is planned to use the FMUs for I&C and BoP (BoP model created by POLIMI) and to couple it with the AC^2/ATHLET input deck to control the secondary side pressure and feed water injection. Further improvements and adjustments of the AC^2/ATHLET input deck might be needed in the frame of WP4 to meet the reference steady state conditions when the Modelica BoP model will be coupled to the ATHLET input deck.

The behaviour of the power, pressure and temperatures of the primary circuit for both simulations are shown in Figure 5 and Figure 6. The line marked with “Reference” shows the expected steady state conditions of the plant at full power and therefore fully opened turbine valve given in [1]. From the transient start to the first movement of the turbine control valve, 250 s are required to establish steady state conditions in the primary side. It can be seen, that matching the reference core power, average core temperature and primary pressure satisfactorily was possible only if the feed water control is deactivated (ATHLET 2 run in the figures). Pressure and temperature given by the simulation differ from the reference data (Reference in the plots) by 0.6 bar and 0.1 K respectively in the steady state plateau for ATHLET 2 run and more in the ATHLET 1 run. The power during the first steady state until closing of the turbine valve at 250 s given by ATHLET 2 shows a good agreement with the reference data.

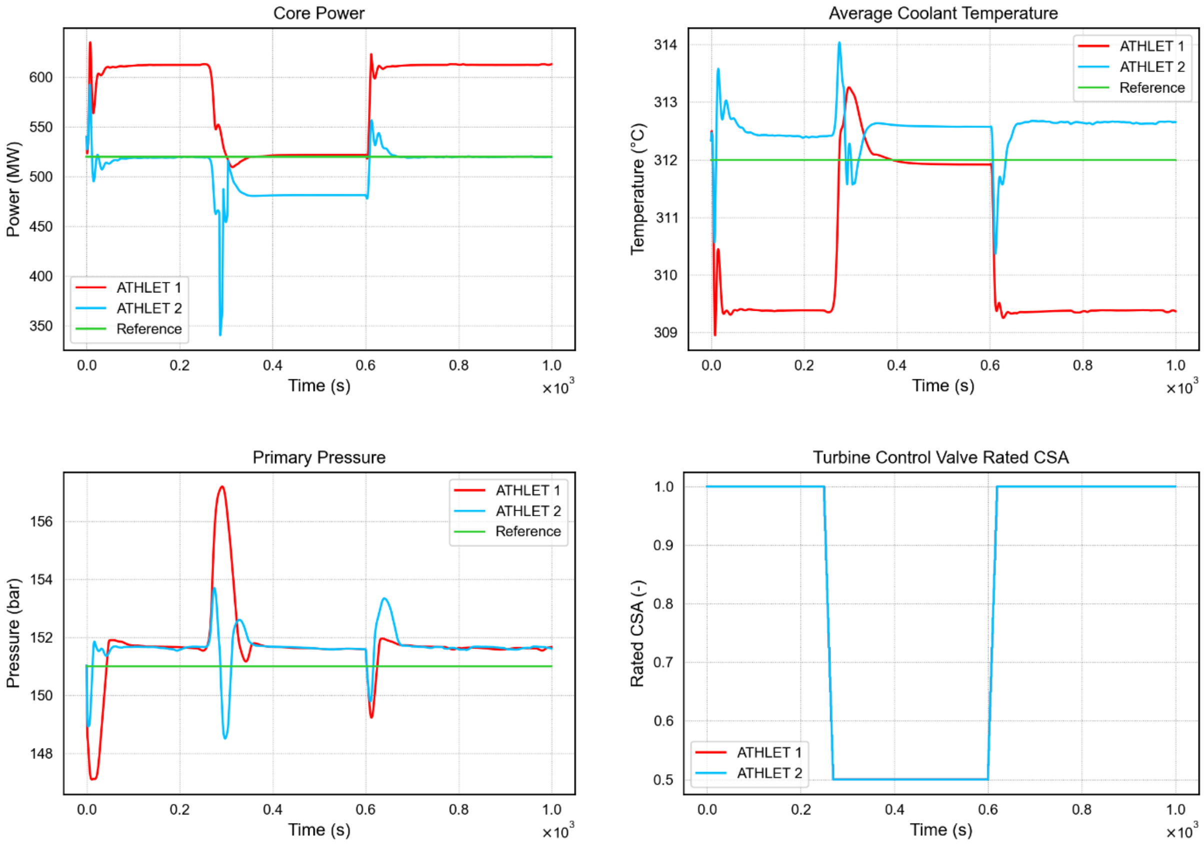

Figure 5: Core Power, Core Temperature, Primary Pressure and Rated CSA of Turbine Control Valve

At 250 s, the turbine control valve closes up to 50 % of the fully opened CSA. When doing so, secondary pressure rises (Figure 6 top left) reducing the temperature difference over the steam generator pipes, which results in a rise of the average core temperature (Figure 5). The external FMU controller starts inserting the control rods into the core which reduces the core power to approximately 520 MW in ATHLET 1 run and 480 MW in the ATHLET 2 run, and therefore the average core temperature. The primary pressure behaves in both cases quite similar and has also increased when the power was not balanced, resulting in spraying into the pressuriser. In this phase the heater is off. Then the pressure drops rapidly even below the nominal value, causing spraying to stop and the heater to switch on. After this short phase of fluctuation, the pressure is constant.

Feed water mass flow rate and enthalpy are shown in the centre of Figure 6. While in run 2 the values are fixed to the steady state values, in run 1 these values come from Modelica. It can be seen, that the determined feed water mass flow rate is higher than in run 1 than in run 2 leading to the abovementioned discrepancies in the steady state with respect to power and temperatures. However, it can be seen, that with closing the turbine valve and consequently lower steam mass flow rate also the feed water mass flow rate decreases in run 1.

Funded by
the European Union

At 600 s, the valve is fully opened again. The secondary pressure drops and the steam generator power increases, which reduces the average core temperature. This triggers the removal of control rods from the core. The core power reaches the same initial value as before closing the valve. However, the new steady states in both runs are at slightly different primary pressures and fluid temperatures (e.g. 151.66 bar old steady state vs. 151.60 bar new steady state and 312.40 °C old steady state vs. 312.65 °C new steady state respectively in the ATHLET 2 run). Also, the control rod position differs.

Funded by
the European Union

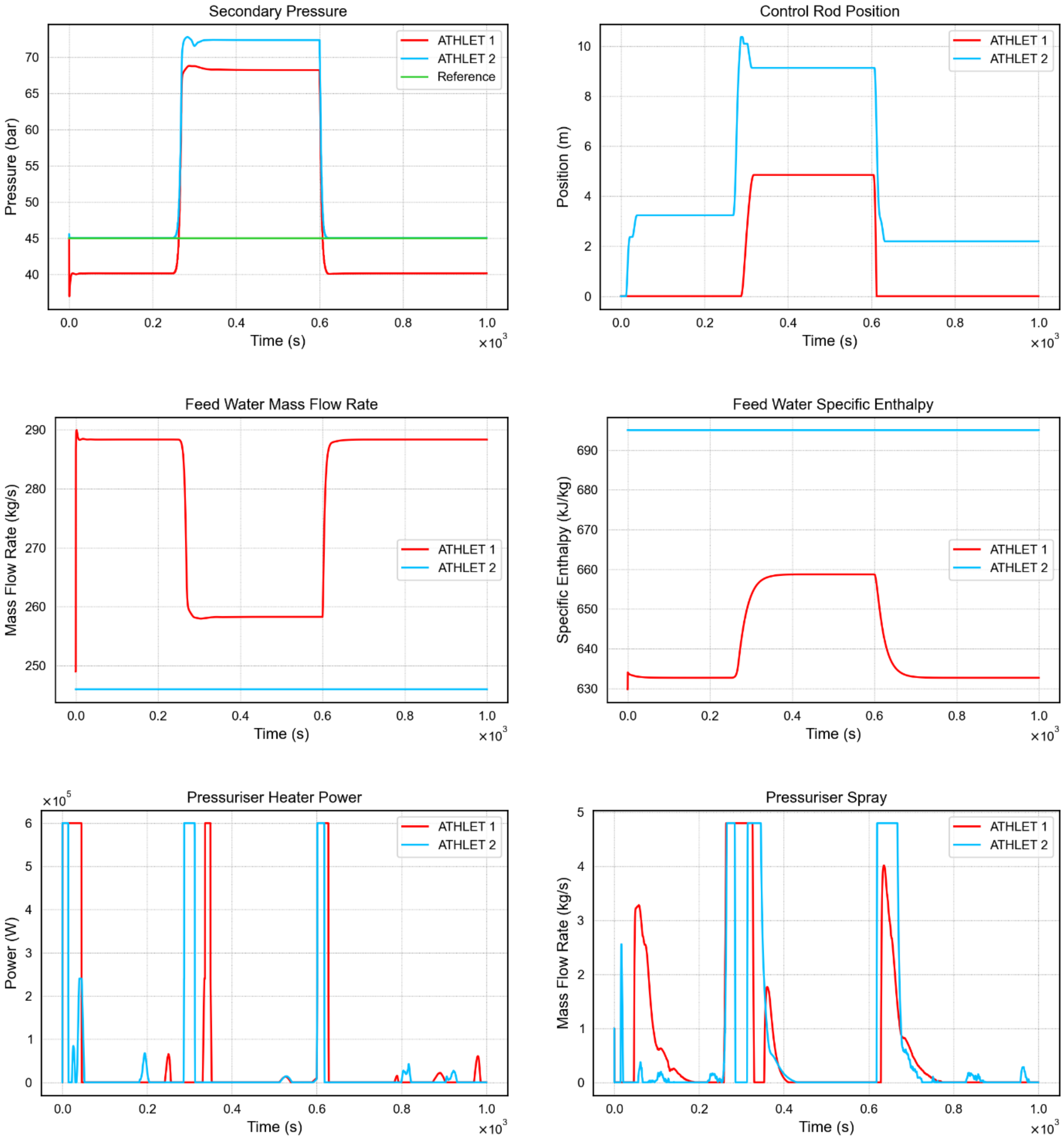

Figure 6: Secondary Pressure, Control Rod Position, Feed Water Properties and Pressure Control

Funded by the European Union

5. Conclusions

The existing AC^2/ATHLET input deck of the E-SMR was originally used in the ELSMOR Euratom project to simulate the behaviour of the E-SMR during LOCA and SBO initiated at full power. In TANDEM it was extended to simulate AOO with the development of the coupling between AC^2/ATHLET and Modelica FMUs. With the current status of the coupling, the Modelica models can control primary pressure and power of the ATHLET model. Pressure is controlled by determining pressuriser spray mass flow rate and heat input. Core power is controlled by using the average core temperature to determine the control rod velocity by the FMU which is considered in the ATHLET model to determine the control rod worth in the core. Furthermore, by coupling FMUs with AC^2/ATHLET secondary side steam in terms of mass and enthalpy can be transferred to the FMU and feed water can be injected into the AC^2/ATHLET model by the FMU. However, more work has to be done to reach correct steady state conditions with respect to the reference data with the coupling between the ATHLET input deck and the BoP Modelica model.

The development of ATHLET/Modelica coupling has well progressed today to think possible in the coming weeks the simulations of different AOOs such as the sudden increase or decrease of the energy demand from the end users.

Funded by the European Union

6. References

[1] E-SMR Dataset, ELSMOR Project, download from website: https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1, last visit: 29.08.2024

[2] Calogera Lombardo, Massimiliano Polidori, Marco Ricotti, Guido Masotti, Alessandro De Angelis, Andrea Pucciarelli, D2.6 – CATHARE SMR model description, Deliverable D2.6, TANDEM Project, 2024

[3] G. Simonini, Y. Hammadi, D2.3 – Modelica models description for the 'TANDEM' library, Deliverable D2.3, TANDEM Project, 2024

[4] Mr. Paolo OLITA, Walter Ambrosini, Oleksandr Sevbo, Calogera Lombardo, Thorsten Hollands, D2.2 – Modelling requirements with safety codes, Deliverable D2.2, TANDEM Project, 2023

[5] P. Schöffel, A. Di Nora, D. Eckert, M. Junk, D. von der Cron, F. Weyermann, A. Wielenberg, ATHLET 3.4.1 User's Manual, GRS gGmbH, GRS – P – 1 / Vol. 1 Rev 12, May 2024

[6] F. Weyermann, D. Eschricht, A. Wielenberg, T. Steinhoff, P. Schöffel, C. Spengler, L. Lovasz, AC^2 2023.2, AC^2 User Manual, GRS gGmbH, GRS – P – 15 / Vol. 1 Rev 2, May 2024

[7] F. Davelaar, N. Bakouta, A. Bersano, et. al., D5.2 E-SMR benchmark of code results for a SBO and a LOCA scenario, Deliverable D5.2, ELSMOR Project, 2023

[8] The leading standard to exchange dynamic simulation models. Functional Mock-up Interface. (n.d.). https://fmi-standard.org/

[9] FMPy Homepage on Github, https://github.com/CATIA-Systems/FMPy

[10] Functional Mock-up Interface Specification 3.0.1: https://fmi-standard.org/docs/3.0.1/

Funded by the European Union