



Article

A High-Temperature Carnot Battery for Enhancing Nuclear Power Plant Flexibility: Steady-State Performance Assessment and Transient Discharge Characterization

Benoît Payebien ¹, Vincent Audoly ², Nicolas Tauveron ^{1,*}, Fabrice Bentivoglio ¹, Laura Matteo ², Nadia Caney ¹ and Gédéon Mauger ³

¹ CEA, Université Grenoble Alpes, LITEN/DTCH/LCST, 17 Av. des Martyrs, 38000 Grenoble, France

² CEA Cadarache, DES/IRESNE/DER, 13108 Saint-Paul-Lez-Durance, France

³ CEA Saclay, DES/ISAS/DM2S, 91190 Gif-sur-Yvette, France

* Correspondence: nicolas.tauveron@cea.fr

Abstract

Carnot batteries (CBs) offer an appealing alternative to saturated pumped-hydro facilities and electrochemical batteries dependent on critical raw materials. A concept recently highlighted in the literature is that of coupled CBs, in which the discharge cycle of a CB interacts directly with the power cycle of a thermal power plant. Such configurations show promising gains in performance, cost, and responsiveness. However, their dynamic behavior remains insufficiently characterised, restricting assessment of the grid services they could realistically deliver. This work examines an innovative architecture in which a nuclear Rankine cycle is coupled to a CB to enhance operational flexibility. Following the preliminary system sizing, a detailed numerical analysis is performed using the CATHARE-3 thermal-hydraulic code to characterize the overall steady-state performance and transient behavior during CB discharge. The results show that the high-pressure turbine acts as an effective filter, absorbing most disturbances introduced by the CB. A refined breakdown of inertial contributions within both the Rankine cycle and the CB enables the identification of the most sensitive components. Finally, under these preliminary sizing assumptions, the coupled system exhibits high performance and would be capable of meeting the primary frequency control requirements during discharge operation, suggesting that coupled CBs constitutes a promising solution for providing fast frequency-regulation services to the electrical grid.

Keywords: Carnot battery; nuclear energy; transient simulation; electricity storage; grid services



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1. Introduction

In the broader context of climate change, which stems largely from the carbon emissions of modern societies, the integration of renewable energy sources into our energy mixes is now widely recognized as a key pathway for decarbonization. The transition toward renewables has already begun, as evidenced by their annual penetration rate of 15.1% in global energy production for 2024 [1]. Despite being low-carbon, renewable energy sources often suffer from a major drawback: their non-dispatchable nature due to intermittency. This lack of controllability can lead to a mismatch between electricity production and consumption. These effects are particularly evident for wind energy, which is highly dependent on weather conditions, and for solar energy, whose peak production at

zenith is misaligned with the typical demand profile of our societies. In the case of solar energy, this phenomenon has been theoretically described in studies on the so-called “Duck Curve” effect [2]. Thus, integrating non-dispatchable renewable sources into an energy mix can induce congestion and imbalances across the power system. The growing stress on power distribution infrastructure systems originates not only from the increasing share of renewables, but also from the strong shift toward electrification and the intensification of electricity usage [3]. These strains manifest in various ways and are actively monitored by grid operators. For example, negative electricity prices are increasingly observed during the day, reflecting the challenges faced by grid operators in matching supply and demand, thereby encouraging consumers to reduce or shift their energy consumption. Moreover, the recent incident on the Spanish power grid further highlights the mounting pressure on energy infrastructure [4].

In order to increase the stability and resilience of energy distribution networks, it is necessary, on the one hand, to maintain a share of dispatchable energy production, and on the other hand, to enhance their flexibility, for example through the integration of energy storage systems. To maintain dispatchable power generation capacity, nuclear energy could provide part of the solution. Indeed, there is currently a strong political push to increase global installed nuclear capacity, particularly because it is a low-carbon source of energy [5]. In parallel, there is clear interest and substantial investment in the research and development of new nuclear technologies, such as the study of SMRs (Small Modular Reactors), which could offer significant flexibility to the grid [6].

On the other hand, increasing the flexibility of a network can be effectively achieved through the deployment of energy storage technologies. Integrating energy storage into the grid allows for the absorption of mismatches between electricity supply and demand, load following, congestion relief, avoidance of curtailment events, and participation in grid balancing [7].

The value of integrating energy storage into power systems was recognized early on, and historically, large-scale storage systems were commissioned as early as the 1900s [8]. The first systems implemented were Pumped Hydro Electrical Storage (PHES), in locations where geographical conditions made such installations feasible. To this day, PHES remains the most widely deployed storage technology worldwide in terms of installed capacity estimated by the International Hydropower Association at 9000 GWh in 2024 [9], well ahead of electrochemical batteries (190 GWh in 2023 [10]).

There is still growing interest in expanding PHES capacity, as illustrated by megaprojects in China and Australia [11]. However, in many countries, electrochemical batteries are now preferred, as the potential for PHES has often reached its geographical and economic limits [12]. Nevertheless, electrochemical batteries come with significant monetary and environmental costs due to their reliance on critical metals, which has not prevented their rapid deployment [13].

To address the growing need for additional energy storage capacity, new large-scale electricity storage technologies are currently under investigation, among which the promising concept of Carnot Batteries (CB) stands out. CBs are a highly modular technology [14,15], capable of storing energy in quantities ranging from a few kWh up to hundreds of GWh, over durations extending to several tens of hours [10].

When there is an excess of electricity on the grid, a CB converts this electricity into heat through a charging process, typically involving a Heat Pump (HP) or an Electrical Heater (EH). The resulting thermal energy is then stored in a thermal storage module. When electricity needs to be supplied back to the grid, the previously stored thermal energy is recovered and converted into electricity via a Power Cycle (PC) [16].

A conventional CB, involving two successive energy conversions, typically achieves a global round-trip efficiency of about 40–50% [10]. These modest efficiencies, compared to those of electrochemical batteries and PHES, combined with the high infrastructure costs [17], often limit the economic profitability of such systems, despite their superior environmental performance [18].

Numerous studies have sought to improve the overall efficiency of CBs by incorporating additional heat flows, originating from waste heat [19], geothermal energy [20], or solar Power Plants (PP) [21], for example. These integrated configurations, referred to as Integrated Carnot Batteries (ICB), demonstrate improved global efficiencies [22], suggesting a more favorable economic potential than that of conventional CBs.

CBs therefore represent a credible alternative to existing storage technologies, providing flexibility to the grid [23]. However, unlike electrochemical batteries, they suffer from limited responsiveness due to the time required for thermal ramp-up and the startup of the PC. To the best of the authors' knowledge, little literature is available on the dynamic behavior of CBs. Most existing studies focus on CBs based on a Brayton cycle, as this configuration inherently enables rotational speed and working fluid inventory control strategies, allowing modulation of the generated power. Yang et al. [24] investigated load-following transients for a reversible Brayton CB and reported ramp rates relative to nominal power of approximately $20\% \cdot \text{min}^{-1}$ during CB operation. Huang et al. [25] and Krüger [26] also examined load-following capabilities for Brayton-based CBs optimized for trigeneration of heat, cooling, and electricity, reporting ramp-up rates relative to nominal power of $15\% \cdot \text{min}^{-1}$ and $2\% \cdot \text{min}^{-1}$, respectively, during CB operation. Although the ramp rates achievable with these systems enable load-following operation, they generally do not allow participation in primary frequency regulation. Tassenoy et al. [27] reached similar conclusions for a CB based on a subcritical organic Rankine (RK) cycle, reporting load-following ramp rates relative to nominal power of $33\% \cdot \text{min}^{-1}$. They concluded that, in a European context, the CB could provide secondary and tertiary frequency regulation, but that the requirements for primary frequency response were not met. Finally, Lu et al. [28] modeled the complete startup of a CB based on a reversible Brayton cycle and reported several minutes (mean ramp rate relative to nominal power of $20\% \cdot \text{min}^{-1}$) before full and stabilized operation was achieved, thereby preventing participation in fast balancing services. Overall, the literature reports moderate responsiveness for conventional CBs, enabling participation in tertiary and potentially secondary frequency reserves, but generally under the restrictive assumption of part-load operation.

A new type of CB has recently emerged in the literature [29–32], with its conceptual diagram and corresponding temperature diagram shown in Figure 1. This system is no longer a standalone CB but is coupled to a PP, and is referred to as a Coupled Carnot Battery (CCB). When the charging process of the CCB relies on an EH, the charging phase is independent of the operation of the power plant [29]. However, when a HP is used, its cold source is advantageously drawn from the nominal thermal stream of the PP. This configuration allows the HP to operate over a reduced temperature difference, which enhances its performance and leads to a temporary reduction in the power output from the PC [31]. During discharge, the CCB injects the heat previously stored in its thermal storage module into the nominal thermal stream of the PP. This results in an electricity overproduction from the PC, enabling the CCB to discharge [29,32].

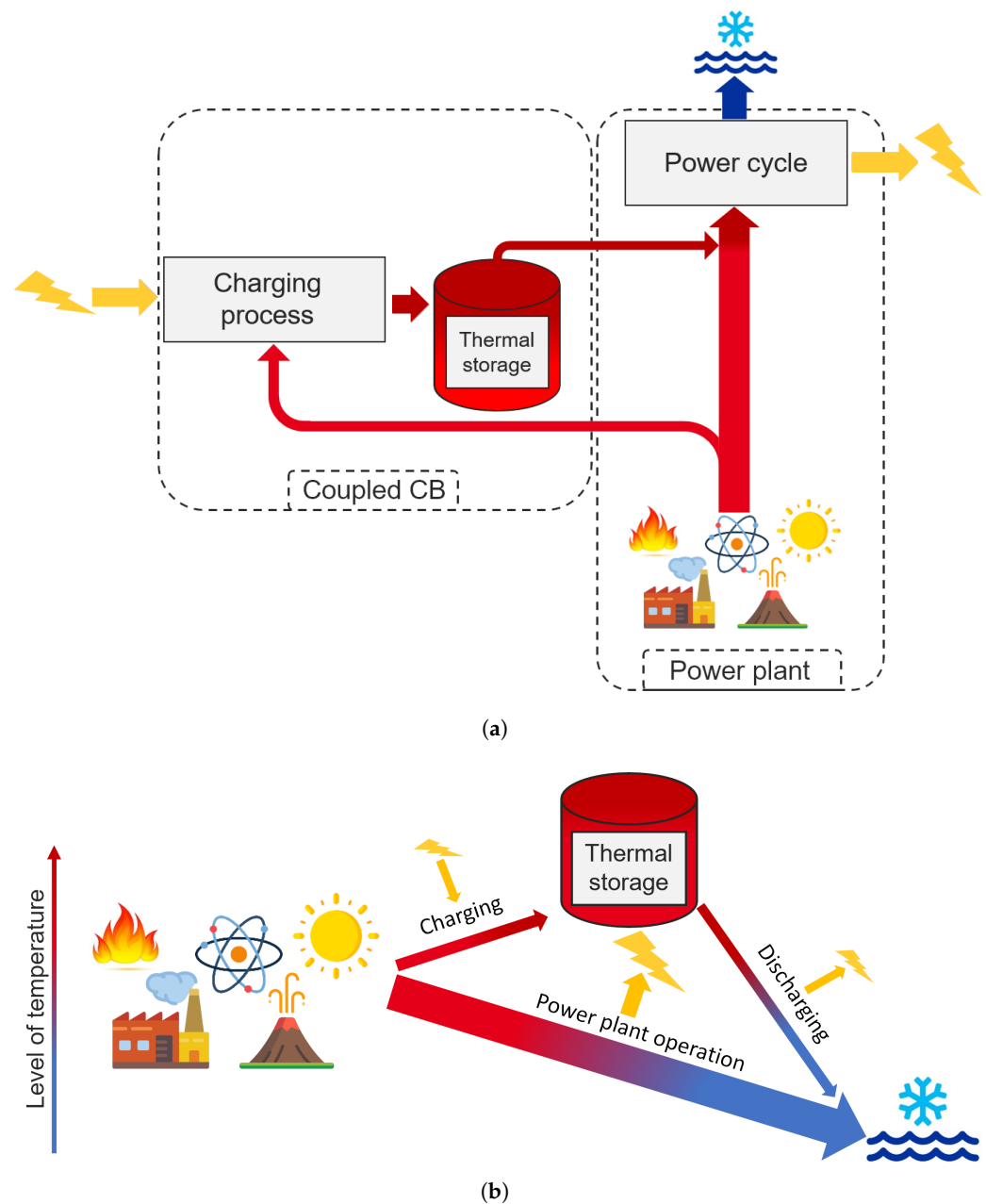


Figure 1. (a) Conceptual diagram of the CCB (b) Temperature diagram of the CCB.

There are several advantages to implementing such a CB. According to Borissova and Popov, global round-trip efficiencies can reach around 60%, even when using an EH for charging [29]. Furthermore, since the PC is shared between the PP and the CCB, infrastructure costs are expected to be lower, contributing to improved economic profitability. Additionally, because the PC operates continuously within the PP, the dynamic response of the CCB is expected to be significantly better than that of conventional CBs or ICBs. To date, the literature has not characterized the response time of CCBs. Thus, it remains an open question whether a CCB can provide new types of grid services, such as frequency regulation. Since such services are financially compensated [33], demonstrating that a CCB is sufficiently responsive could indicate even greater economic viability.

An interesting parallel can be drawn with systems conceptually close to direct thermal energy storage integrated into a thermal power plant. Direct electricity storage in a thermal power plant relies on a temporal decoupling between the instantaneous availability of heat and electricity production: a fraction of the thermal flow is temporarily diverted toward

a storage system (typically a steam accumulator [34], a molten salt tank [35,36], or an ice storage system [37]) and subsequently returned to the PC in order to modulate the electrical output without adjusting the plant heat source [38]. These systems are particularly well suited for load-following and potentially frequency regulation applications [34], since power modulation is mainly achieved through flow-rate control at a specific location within the PC, resulting in significantly lower inertia than direct modulation of the heat source. Similarly to CCB systems, the integration of direct storage into the PC can be implemented at different locations, for instance downstream of the Steam Generator (SG), downstream of the feedwater heater, or potentially at the inlet of the low-pressure turbine or at a steam extraction point, depending on the PC characteristics and the targeted temperature level [39]. These systems typically achieve efficiencies ranging from 60% to 85% on intra-day timescales [40–43]. Although these systems exhibit high responsiveness and good performance, they suffer from low energy density due to the direct storage of heat, i.e., without conversion into a higher-grade form of energy. CCB systems therefore offer the advantage of utilizing the plant's thermal energy while simultaneously upgrading it, thereby reducing the constraints associated with heat exchanger pinch points. Furthermore, a CCB also enables the integration of both thermal and electrical energy, thereby enhancing the flexibility provided to the power plant compared with direct storage systems.

In this article, we present a detailed numerical study of a CCB under transient conditions during discharge in order to characterize the dynamic behavior of such CBs. At this stage of the state of the art, it is essential to better understand and assess the dynamics of CCBs to determine whether this CB technology could extend the range of grid services traditionally provided by conventional CBs. To perform transient simulations, the CATHARE-3 thermal-hydraulic system code is used. This tool, widely employed in the nuclear industry for the analysis of thermohydraulic phenomena in Nuclear Power Plants (NPPs), is also suitable for simulating power conversion systems such as RK cycles, as shown in [44].

Thus, Section 2 details the design of the considered CCB and its implementation within the CATHARE-3 simulation tool. Then, Section 3 presents the modeling results, describing both the behavior of the CCB and its impact on the PC of the PP. A steady-state performance assessment of the CCB model is first carried out, followed by a transient characterization of the CCB discharge responsiveness, with particular emphasis on decoupling the different inertial contributions. Finally, a sensitivity analysis is conducted to consolidate the established conclusions and strengthen the modeling assumptions.

2. Methodology and System Design

The case study selected in this work involves a CCB coupled to a 620 MW_{el} Sodium-cooled Fast Reactor (SFR) based on the design of the Superphénix (SPX) reactor [45]. SFRs are considered as 4th generation reactors, offering the advantage of closing the fuel cycle and achieving higher thermodynamic efficiency due to their ability to operate at higher temperatures. The schematic diagram of the coupling between the NPP and the CCB is shown in Figure 2.

The CCB was intentionally connected to the RK cycle to avoid compromising the reliability of the primary and secondary sodium loops. Accordingly, the CB is coupled between the SG and the first stage of the high-pressure turbine. This configuration allows the CCB to either extract or inject thermal energy from/to the steam at the SG outlet, thereby modulating the degree of superheat at the inlet of the high-pressure turbine. The CCB thus provides increased flexibility to the NPP, which, from a system perspective, can either contribute to increasing the inherent flexibility level of the PP, or alternatively, the CCB can absorb the entire flexibility demand, allowing the NPP to operate without power

modulation over time. Furthermore, as certain NPPs are required by national regulations to operate at around 98% of their nominal power in order to preserve a modulation reserve [46], coupling with a CB would eliminate the need for this reserve capacity, thereby enabling more efficient fuel utilization and increasing the capacity factor of the NPP.

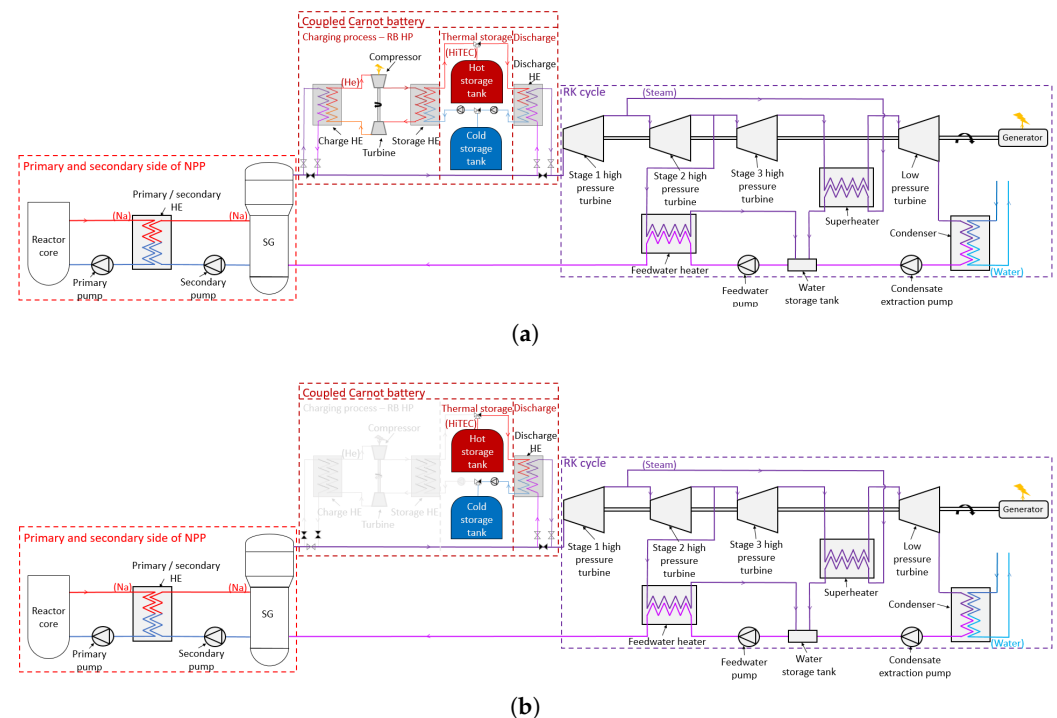


Figure 2. Diagram showing the implementation of the CCB on the NPP (a) The overall system (b) Operational components of the system during discharge.

The CCB consists of a charging process based on a helium-operated Reverse Brayton (RB) cycle. It includes a first heat exchanger extracting heat from the RK cycle, a second heat exchanger rejecting heat to the thermal storage, and a turbo-compressor assembly mounted on a single shaft. The HP was sized based on similarities with two other experimental machines [47], and its maximum operating temperature was constrained to 600 °C to ensure consistency with both numerical [48] and experimental [47] investigations reported in the literature. It also includes a two-tank thermal storage module using HiTEC (7%NaNO₃ 40%NaNO₂ 53%KNO₂), a molten salt selected for its operating range compatible with the CCB temperature and its low melting point [49], which helps prevent the risk of solidification in the discharge Heat Exchanger (HE). Finally, a discharge HE connects the thermal storage module to the RK cycle.

Table 1 summarizes the main data related to our case study. This concept and architecture are consistent with other architecturally similar concepts [50], such as that proposed by Marmier and Fütterer [48], which consists of a helium heat pump coupled to a nuclear reactor to upgrade the cycle temperature and supply a hydrogen cogeneration process. The sizing and performance of the system developed in this article are consistent with those reported for similar heat pump architectures applied to nuclear energy systems. In the following section, the CATHARE-3 code used for modeling the present case study is presented. A detailed description of both the RK cycle and the CCB architecture, along with their respective modeling approaches, is then provided.

Table 1. Main characteristics of the proposed system for one steam cycle.

Element Name	Value	Unit
Primary and secondary side of NPP		
Core thermal power	1500	[MW _{th}]
RK cycle		
Nominal inlet condition of high-pressure turbine	490	[°C]
	184	[bar]
Turbines total mechanical power	−609	[MW]
Condenser thermal power	−904	[MW _{th}]
Pumps total consumption	18	[MW]
Steam mass flow rate	681	[kg/s]
Net electrical power production	567	[MW _{el}]
Net cycle efficiency	37.8	[%]
Steam quality at the outlet of the high-pressure turbine	0.943	[-]
Steam quality at the outlet of the low-pressure turbine	0.870	[-]

2.1. Description of the CATHARE-3 Code

CATHARE-3 is the latest version of the French thermal-hydraulic code developed by CEA, EDF, FRAMATOME and ASNR for the safety analysis of nuclear reactors [51]. It is based on a two-fluid approach (six transport equations) to represent complex two-phase flows. It enables different scales of modeling using three types of modules which are 0D (VOLUME), 1D (AXIAL) and 3D (THREED). A complete system is modeled using an association of these elements. The equations are solved using an implicit scheme of the Newton–Raphson algorithm, allowing for variable time step. The CATHARE-3 code, developed by a French consortium since 1979, has been extensively validated against numerous transient nuclear experimental results, as discussed in reference [51].

2.2. Description of the RK Cycle Model

2.2.1. General Description

The SPX NPP featured two identical steam–water RK cycles, each with a gross nominal electrical output of 620 MW_{el} and a gross efficiency of 41.3%. The nuclear reactions take place in the sodium primary circuit and the heat is transferred to the RK cycle by intermediate sodium circuits. Thus, the RK cycle is in this case the tertiary circuit of the NPP. In order to study the coupling between the CCB and the NPP, a simplified model of the RK cycle is implemented in CATHARE-3. An overview of the RK cycle model, derived from the user graphical interface of the CATHARE-3 software, is given in Figure 3.

Only parts of the secondary and cooling circuit are modeled and simulated with boundary conditions. In total, 20 hydraulic modules and 510 meshes are defined in order to model the RK cycle and its components including: SG, high and low-pressure turbines, feedwater heater, dryer-superheater, condenser, and the feedwater tank. Only 0D and 1D hydraulic modules are used for this work. Indeed, by defining properly the cross sections, friction perimeters, hydraulic diameters and, if necessary, by using specific correlations for heat transfer or friction laws, various kinds of geometries and physical situations can be simulated. The complete set of model-specific parameters, geometric data, assumptions, and the expressions of the laws employed in the RK cycle modeling are provided in detail in [52]. The model is also described more precisely and tested in references [44,53] where dynamic studies are performed to assess its validity. Appendix A provides a detailed description of the system of equations on which a 1D CATHARE-3 module is based. The behavior of the 0D module is also presented, highlighting the additional assumption of negligible momentum conservation effects compared with the 1D formulation.

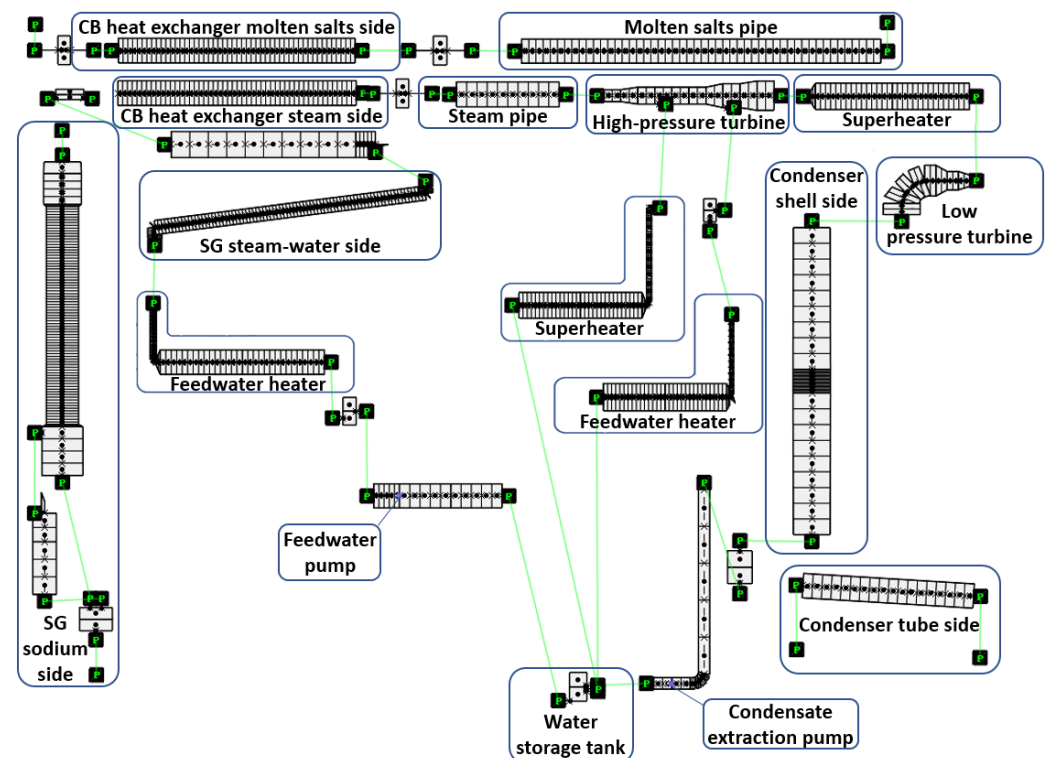


Figure 3. Nodalization diagram of the NPP coupled CB in CATHARE-3.

2.2.2. The Steam Generator

Each SG (once through type) transfers 750 MW of thermal power, in order to vaporize the water initially at 237 °C and 215 bar to obtain superheated steam at 490 °C and 184 bar. The water of the tertiary side circulates in helical coiled tubes around a central body. On the secondary side, the sodium flows inside the shell from the top to the bottom transferring the heat to the tubes. As for all the HEs of the circuit, the heat transfer is modeled with two 1D modules coupled with a thermal sub-module.

2.2.3. The Turbines

The turbo-alternator group is divided in several parts: three groups of stages for the high-pressure turbine and one for the low-pressure turbine. Each groups of stages is modeled with a 0D sub-module added at a vector point of a 1D element. Using Stodola's ellipse law [54] and the Ray model [55] for the efficiency at nominal and partial load conditions, the head and torque are calculated and the corresponding source terms are added in the momentum and energy balance equations of the 1D element.

2.2.4. The Condenser

The condenser is a shell and tubes exchanger modeled with one module representing the vapor flow in the shell through the horizontal tube bundle and another representing the cooling water circulating in the tubes. Since the vapor flow has a complex geometry, a methodology was developed in order to simulate the flow with a 1D module based on equivalent hydraulic parameters and specific correlations for pressure drop and heat exchange [53].

2.2.5. Other Components and Integration of CCB

The modeling of the other components (pumps, feedwater heater, feedwater tank, valves) of the cycle is not detailed here. Compared to the reference RK cycle described in [52], two new HE are added between the SG and the high-pressure turbine to enable the

coupling with the CCB, which is described in the following section. A visualization of the modeling is shown in Figure 4.

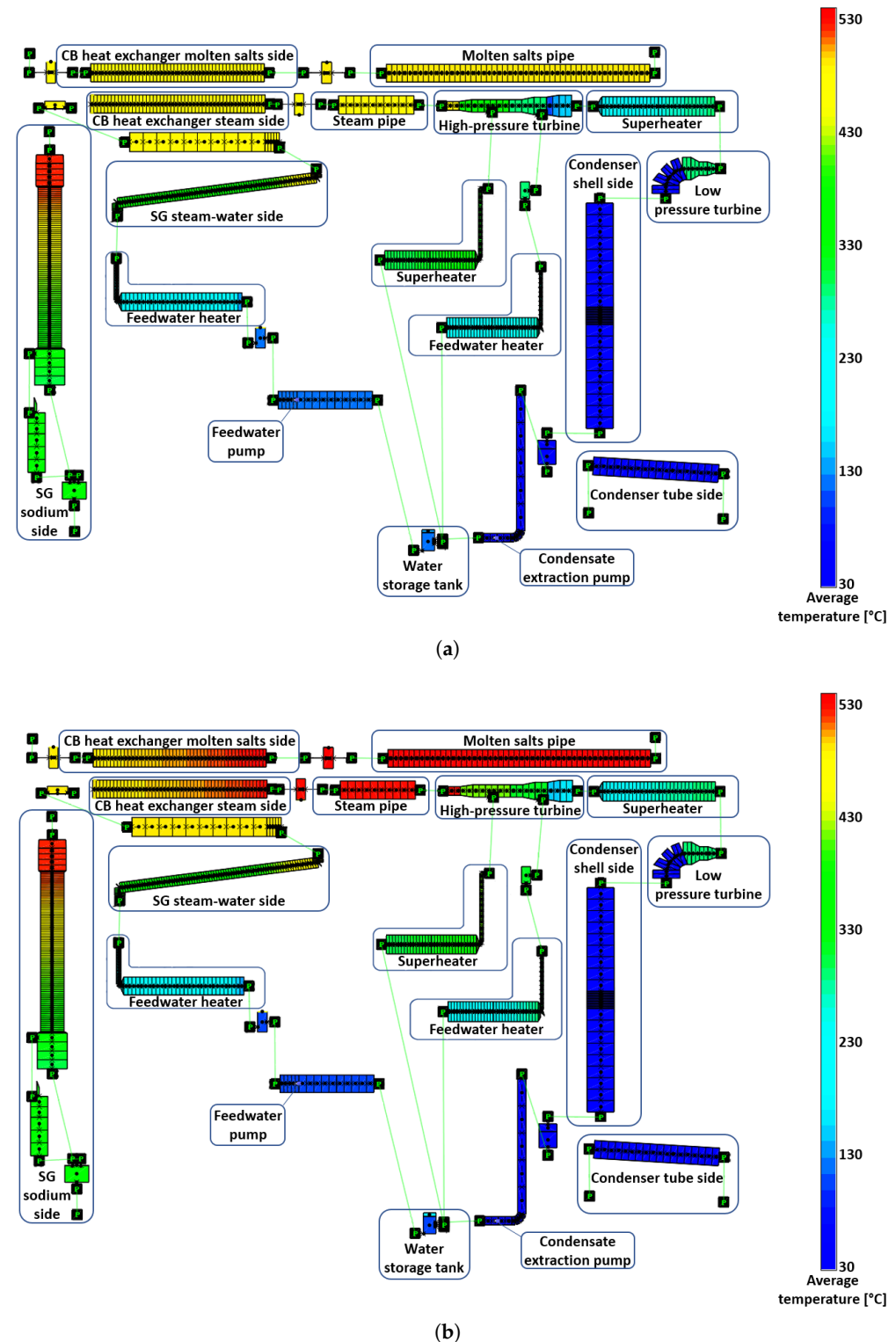


Figure 4. CATHARE-3 schematic with temperature fields of the nuclear reactor and the CCB (a) Nominal conditions (b) During discharge in steady state.

2.3. Description of the CCB Model

The modelling framework of this work focuses exclusively on transient discharge behaviour and steady-state operation during charging and discharging. The modelling

strategies related to CCB operation are detailed below, and Table 2 summarizes the results of the sizing procedure for the three CCB heat exchangers (HEs).

Table 2. Main design characteristics of the three heat exchangers.

Parameter	Steam/Helium	Helium/Hitec	Hitec/Steam
Nominal thermal power [MW]	50	100	100
Number of submodules [-]	4	4	4
Plate height [m]	0.6	1.1	1.5
Plate width [m]	1	1	1
Number of plates [-]	500	220	2200
Total heat transfer area [m ²]	295.2	235.5	3231.1
Total fluid volume [m ³]	0.384	0.253	4.003
Overall heat transfer coefficient U [W m ⁻² K ⁻¹]	3559	4402	4972

2.3.1. Thermal Storage

The thermal storage section of the CCB was designed using a two-tank configuration with operating temperatures of 495 °C and 540 °C. Each tank has a height of 13.5 m and a diameter of 24.2 m, resulting in a storage volume of approximately 6200 m³. Since the storage does not participate in the immediate dynamics during the CCB discharge, it was preferred not to model it within CATHARE-3 (the molten salts inventory into the two tanks), but rather to impose boundary conditions at its interfaces. These boundary conditions must accurately represent the circulation of molten salt from the hot storage to the cold storage during discharge. Thus, even though the molten salt pump was not included in the CATHARE-3 model, the boundary conditions were defined accordingly, modeling a pump start-up operating profile given in Equation (1) and taken from literature [56] (characteristic time $3\tau = 6.2$ s taking into account intrinsic inertia).

$$\dot{m}_{HiTEC}(t) = \dot{m}_{HiTEC,nominal} \cdot \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \quad (1)$$

A 40 m pipe was added upstream of the discharge HE to account for the fact that the storage units, due to their large size, may need to be located at some distance from the RK cycle. This pipe therefore represents both the upstream and downstream lengths separating the molten salt pump from the hot storage tank and from the discharge HE, respectively. The 40 m assumption, being conservative, not only accounts for the spacing between the storage unit and the discharge HE, but also includes the short distance between the storage and the molten salt pump, which is either directly attached to or embedded within the storage unit. This pipe, which contributes to the discharge dynamics of the CCB through thermal inertia effects and a molten salt transport velocity limit of $v_{lim,HiTEC} = 5 \text{ m}\cdot\text{s}^{-1}$, was implemented in the CATHARE-3 model as a one-dimensional component, to which a wall was associated in order to account for thermal accumulation in the materials.

2.3.2. Discharge Heat Exchanger

The discharge HE ensures the transfer of thermal energy from the CCB storage to the RK cycle. It has been sized to provide a nominal discharge power of 100 MW_{th}, thereby supplying approximately 40 °C of additional superheating to the outlet temperature of the SG.

The HEs were designed based on the principle of the plate-and-shell exchangers developed as part of the ASTRID reactor project [57,58]. These compact exchangers combine machined metal plates and diffusion welding, forming a fully welded bundle without any gaskets. As such, they are optimized to offer high thermal transfer density and strong

mechanical resistance, while remaining compact and leak-tight, withstanding pressures up to 200 bar. During their design, each exchanger was subdivided into four sub-modules to optimize both mechanical stresses and pressure drop constraints. In the CATHARE-3 modeling, heat transfer coefficients and pressure losses were estimated using correlations adapted to plate-type exchangers [59].

For design purposes, on the steam side, the allowable pressure drop limit was set to 5 bar, leading to an additional electrical consumption of the pump of approximately 2%.

The sizing procedure thus led to the definition of the HE geometry, consisting of 4 sub-modules, each measuring 2 m in height and 1.6 m in width, and equipped with 190 plates per sub-module, each with a thickness of 2 mm. The diameter of the connection flanges was set to 53 cm, identical to the other piping in the RK cycle, ensuring constrained pressure losses at the nozzle. Supplementary sizing results for the discharge HE are available in Table 2.

In the CATHARE-3 model, the HEs were represented by two 1D components coupled through a dedicated HE sub-module, in which the proper laws for pressure drop and thermal exchanges were implemented. At this interface a wall has been implemented, modeling the thermal accumulation inside the material of the exchanger.

2.3.3. Charging Process

The CCB charging process is performed by a HP operating in RB with helium. This is the component of the CCB that extracts heat at the SG outlet and raises it to a higher temperature in order to supply the thermal storage section. The HP was dimensioned by similarity with a HP known as HHV [47], an experimental closed-cycle helium facility built in Germany in the 1980s. It is a monoblock system comprising an 8-stage compressor and a 2-stage turbine mounted on a single shaft, with a total weight of approximately 66 tonnes.

The HP is based on four components. The first is a steam/helium HE with a nominal power of 50 MW_{th}, reducing the steam temperature by approximately 11 °C and raising the helium temperature to 483.9 °C, with a pinch of about 5 °C. The second component is the compressor, which heats the helium up to 590.2 °C and compresses it to a pressure level of 35.5 bar, with a compression ratio of $\pi_{HP} = 1.3$. Then, the second HE provides the interface between the HP and the molten salt section. It was designed to transfer a thermal power of 100 MW_{th}. Finally, mounted on the same shaft as the compressor, rotating at 3000 tr/min, is the turbine, which recovers the expansion energy of the helium, lowering its temperature from 504.5 °C to 440.5 °C. The resulting mechanical power on the HP shaft, delivered to the grid, is 50 MW_{el}, giving the HP a COP of 2.02. The two HE (Steam/Helium and Helium/Molten Salts) were designed and sized following the same technology and methodology as that used for the discharge HE and exhibit smaller overall dimensions. Sizing results for these two HEs are available in Table 2.

2.4. Coupling of the Two Models

To avoid adding excessive complexity to the RK cycle model dataset, the full CCB model was not directly coupled for the discharge and charge phases. Instead, the RK model was extended to include the two steam extraction lines from the SG to the discharge HE, the discharge HE itself, the molten salt piping connecting it to the thermal storage module, and, separately, the charge HE with its connections to the RK cycle. For the same reason related to initialization complexity, the HP model was not directly coupled with the other components. However, it was used to define the relevant boundary conditions necessary for sizing the other CCB components and for operating the two separate CCB models during charge and discharge phases.

In particular, the boundary conditions applied to the two developed CATHARE-3 models are as follows:

- SG primary side: inlet sodium temperature and mass flow rate, and outlet pressure (common to both the charging and discharging models)
- Condenser secondary side: inlet cooling water temperature and mass flow rate, and outlet pressure (common to both the charging and discharging models)
- Discharge HE primary side: inlet molten salt temperature and mass flow rate, and outlet pressure (discharging model)
- Charge HE primary side: inlet helium temperature and mass flow rate, and outlet pressure (charging model)

Prior to discharge, the initial state of the system was modeled as the nominal operating condition of the RK cycle, with the CCB in stand-by mode and a homogeneous temperature of all its components (except for the hot storage tank) at 495 °C. Regarding the state of the CCB during the standby phase preceding discharge, it is assumed that the discharge heat exchanger valves remain open and that RK cycle steam continuously flows through the exchanger in order to maintain its temperature and avoid any loss of responsiveness associated with valve opening. Indeed, it is assumed that the entire CCB is electrically trace-heated to prevent issues related to molten salt crystallization caused by thermal losses and to enhance the responsiveness of the CCB. This overall temperature maintenance strategy is consistent with the system design aimed at achieving high levels of responsiveness, and was bounded to a maximum consumption of 0.5 MW_{th} [60] during CCB stand-by phases. This temperature maintenance strategy, which is necessary for the operation of the storage system and beneficial to the dynamics of the CCB, nevertheless induces an efficiency penalty for the overall system. A first order of magnitude of this round-trip efficiency loss has been estimated at approximately 5% (including both temperature maintenance for dynamic purposes and crystallisation avoidance). Therefore, in order to prioritise the overall performance of the CCB, a trade-off can be made on the level of electrical tracing at the expense of the global responsiveness. In particular, alternative control strategies for the standby phases could be implemented. For instance, to reduce the pressure losses upstream of the high-pressure turbine, the working fluid could be prevented from continuously flowing through the discharge heat exchanger. Although this approach would improve the nominal performance of the Rankine cycle, it would significantly reduce the system's responsiveness, as the discharge heat exchanger would no longer be maintained at operating temperature (assuming only the thermal storage system is trace-heated), and additional time would be required to open its bypass valves.

Finally, this modelling approach, based on separating the charging and discharging models, provided a compromise in terms of computational resources. The simulated sequences, including an initialization phase, a stabilization phase, a discharge phase, and a relaxation phase, require 2.5 GB of RAM and 2 s of CPU time per second of simulated time for a non-parallelized calculation.

3. Results and Discussion

In this section, the results from the CATHARE-3 simulations of the coupled model between the RK cycle and the CCB are presented.

3.1. Stationary Characterisation

The first simulation that was run serves to characterize the free response of the RK cycle to the CCB discharge. Indeed, this initial simulation reflects the adaptability of the RK cycle to a temperature step induced by the discharge of the CCB, without any modification to the operation of its internal control systems. Figure 4 shows two synoptic diagrams from

CATHARE-3 illustrating the stabilized operating points in temperature under nominal conditions and during the CCB discharge.

It is therefore possible to observe in this figure the propagation within the RK cycle of the heat released by the CCB. In particular, it can be noted that during the CCB discharge, the molten salt piping homogenizes with the storage temperature, and the discharge HE partially increases in temperature, thereby allowing the transfer of heat from the molten salt to the steam. The resulting superheat propagates through the steam line at the outlet of the discharge exchanger and reaches the first stage of the high-pressure turbine. A first result is thus the fact that the heat released by the CCB primarily propagates up to the first stage of the high-pressure turbine, which acts as a filter for the rest of the RK cycle. The CCB therefore has a moderate impact on the RK cycle, with the superheat of approximately 40 °C being reduced to less than 10 °C after the first stage of the high-pressure turbine.

A major issue concerning the CCBs is the adaptability of the PC to the CCB discharge and to the allowable superheat range that a component can withstand during the discharge. This result is therefore of interest from the perspective of CCB sizing. Indeed, since the heat is mainly filtered by the high-pressure turbine, the focus should primarily be on investigating the constraints affecting this component. For CCBs that provide greater flexibility to the PC, thus causing higher superheat, it is clearly not necessary to oversize the entire PC, but only the first stages of the high-pressure turbine. Having established this observation, several scenarios are possible: for a CCB of modest size, it may not be necessary to retrofit the high-pressure turbine if the excursions generated by the CCB, being punctual events rather than continuous fatigue loading, remain within the tolerance range of the component. If the stresses imposed by the CCB charge and discharge phases exceed the tolerance of the high-pressure turbine, retrofitting a higher-power turbine may then be considered, or alternatively installing a second freely sized turbine in parallel. Operations of this magnitude on existing NPPs have already been implemented, as illustrated by the example of Sweden, which took advantage of extended technical outages in several NPPs to carry out a power upgrade by replacing various major components (including the steam turbine in the case of the Ringhals NPP) [61]. Thus, a CCB can be suitable for integration in existing PP as well as in new ones, making this technology relevant both for growing markets such as Asia and for already established markets such as Europe or the US.

Thus, although the turbine acts as a filter, residual heat is still propagated to the condenser. As a result, this induces a deviation of the condensation pressure from its nominal design point, both during the charging and discharging phases of the CCB. In the SPX RK cycle, the condenser is significantly oversized for safety reasons in the event of severe accidents [62]. Therefore, since the condenser, its cooling water circulation pump, and the cooling towers are all substantially oversized, it is possible to define a control strategy to maintain the condensation pressure at its nominal design point during CCB operation. Although not commonly implemented in the current nuclear fleet, high-power medium-voltage variable-frequency drives for the cooling water circulation pump are now a mature technology and are widely used in large industrial pumping applications. Future nuclear power plants may benefit from such systems to improve operational flexibility and reduce auxiliary power consumption. Tables 3 and 4 present the steady-state operating points of the RK cycle obtained with the CATHARE-3 models during charging and discharging, respectively, comparing the cases where the condenser control strategy is activated or not.

As observed during the charging phase relative to the nominal operating point of the PC under steady-state conditions (Table 1), the heat extraction induced by the operation of the HP effectively reduces the turbine inlet temperature, thereby decreasing the degree of superheating and consequently lowering the total mechanical power output of the turbines. It can also be noted that the thermal power extracted from the NPP core is reduced by

approximately 1%, leading to a loss of about 1.9% in gross efficiency. Regarding condenser control, the results indicate that it is not beneficial during the charging phase, as it leads to a slight decrease in gross efficiency and a reduction in turbine power output. During charging, heat is extracted, which results in a decrease in condensation pressure. The increase in condensation pressure induced by the control strategy therefore compensates this effect but ultimately reduces the heat transfer, leading to a global loss in power production. Consequently, preventing the deviation of the condensation pressure during the charging phase is not advantageous. It is important to note that, despite deactivating the control strategy, the data suggest that the HP is still able to collect the thermal power required for its operation, thereby validating the sizing of the components.

Table 3. Main characteristics of the CCB during charge evaluated using CATHARE-3.

Element Name	Value	Unit
RK cycle under CCB charge conditions (condenser regulation enabled)		
Inlet condition of high-pressure turbine	479.7	[°C]
	169.5	[bar]
Turbines total mechanical power	−572.9	[MW]
Condenser thermal power	−874.6	[MW _{th}]
Pumps total consumption	13.2	[MW]
SG thermal power	1485.0	[MW _{th}]
Steam mass flow rate	669.3	[kg/s]
Charge HE thermal power	−50.7	[MW _{th}]
Gross efficiency	37.7	[%]
Steam quality at the outlet of the high-pressure turbine	0.926	[-]
Steam quality at the outlet of the low-pressure turbine	0.871	[-]
RK cycle under CCB charge conditions (condenser regulation disabled)		
Inlet condition of high-pressure turbine	479.6	[°C]
	169.6	[bar]
Turbines total mechanical power	−574.4	[MW]
Condenser thermal power	−874.9	[MW _{th}]
Pumps total consumption	13.1	[MW]
Vapor Generator thermal power	1486.4	[MW _{th}]
Steam mass flow rate	669.7	[kg/s]
Charge HE thermal power	−50.2	[MW _{th}]
Gross efficiency	37.8	[%]
Steam quality at the outlet of the high-pressure turbine	0.926	[-]
Steam quality at the outlet of the low-pressure turbine	0.870	[-]

For the discharging phase, similar conclusions can be drawn: the CCB succeeds in increasing the turbine inlet superheating, which results in higher electrical power production as well as a gain of 3.4% in gross efficiency. In contrast to the charging phase, condenser control is beneficial during discharge, leading to an increase in both electrical output and gross efficiency. A reciprocal effect is also observed at the SG, with an increase in heat transfer of approximately 2% compared to nominal PC operation. It should be noted that these variations in thermal power extracted from the NPP core remain moderate and within the acceptable operating range. Finally, the thermal energy discharged by the CCB is slightly higher than that determined during the sizing phase, thereby enabling the CCB to achieve its targeted flexibility gain of 10%.

Table 4. Main characteristics of the CCB during discharge evaluated using CATHARE-3.

Element Name	Value	Unit
RK cycle under CCB discharge conditions (condenser regulation enabled)		
Inlet condition of high-pressure turbine	529.3	[°C]
	183.3	[bar]
Turbines total mechanical power	−671.3	[MW]
Condenser thermal power	−970.7	[MW _{th}]
Pumps total consumption	13.3	[MW]
SG thermal power	1527.8	[MW _{th}]
Steam mass flow rate	670.2	[kg/s]
Discharge HE thermal power	100.9	[MW _{th}]
Gross efficiency	43.1	[%]
Steam quality at the outlet of the high-pressure turbine	0.943	[-]
Steam quality at the outlet of the low-pressure turbine	0.871	[-]
RK cycle under CCB discharge conditions (condenser regulation disabled)		
Inlet condition of high-pressure turbine	529.5	[°C]
	183.2	[bar]
Turbines total mechanical power	−668.9	[MW]
Condenser thermal power	−969.9	[MW _{th}]
Pumps total consumption	13.3	[MW]
SG thermal power	1525.3	[MW _{th}]
Steam mass flow rate	669.8	[kg/s]
Discharge HE thermal power	100.2	[MW _{th}]
Gross efficiency	43.0	[%]
Steam quality at the outlet of the high-pressure turbine	0.943	[-]
Steam quality at the outlet of the low-pressure turbine	0.870	[-]

Based on the results presented in Tables 3 and 4, it is possible to characterize the effect of CCB operation on the steam quality at the outlet of the high and low-pressure turbines, which is a major safety and durability concern. Indeed, the successive increase and decrease in the degree of superheating are expected to affect these operating conditions. According to Table 3, the reduction in superheating at the high-pressure turbine inlet induced by CCB charging decreases the steam quality at the high-pressure turbine outlet by 0.02, while leaving the steam quality at the low-pressure turbine outlet unchanged. It is worth noting that, despite a substantial reduction in superheating exceeding 10 °C, only a 2% decrease in steam quality is observed, confirming that the high-pressure turbine effectively acts as a filter, thereby preventing any impact on the low-pressure turbine. During CCB discharge, only very small variations in steam quality can be observed in Table 4. Therefore, when designing such a CCB, particular attention should be paid to ensuring that its dimensionless size does not induce an excessive reduction in the steam quality at the high-pressure turbine outlet. This study suggests that, should steam quality become a limiting factor, only specific control strategies applied to the high-pressure turbine, or an appropriate sizing of this turbine, would need to be considered. Appendix B presents three process flow diagrams corresponding to the charging, reference, and discharging operating modes, respectively. Each diagram is annotated with the relevant thermohydraulic variables, providing a comprehensive representation of the steady-state results obtained from the CATHARE-3 simulations.

From the steady-state conditions of these initial simulations, it is possible to determine the steady-state performance of the CCB at the NPP using the following Equation (2):

$$\Pi_{res} = \frac{\int_{dis} (\dot{W}_{net,dis} - \dot{W}_{net,ref}) dt}{\int_{ch} (\dot{W}_{net,ref} - \dot{W}_{net,ch} + \dot{W}_{net,charging\ process}) dt + \int_{ch+ref+dis} (\dot{W}_{net,loss}) dt} = 73.5\% \quad (2)$$

This relation is constructed as follows: the electricity delivered by the CCB in the numerator corresponds to the difference between the electrical production during the discharge phase and the nominal electrical production of the RK cycle ($\dot{W}_{net,dis} - \dot{W}_{net,ref}$), weighted by the discharge duration. The denominator contains the electricity consumption terms. First, weighted by the charging duration, are the difference between the nominal electrical production of the RK cycle and the electrical production during the charging phase (the electrical production curtailment term during charging: $\dot{W}_{net,ref} - \dot{W}_{net,ch}$), as well as the direct electricity consumption of the CCB charging process ($\dot{W}_{net,charging\ process}$). Finally, the last electricity consumption term is the share attributable to thermal losses ($\dot{W}_{net,loss}$), occurring over the entire simulation duration and determined in Section 2.4. The performance assessment is provided for a 24 h simulation scenario, including 2 h of charging and 2 h of discharging, with activation of the condenser control strategy. The steady-state performance of the CCB was therefore evaluated at 73.5%, highlighting the interest of the concept compared with the performance levels reported in the scientific literature for conventional CB systems [10].

3.2. Transient Characterisation of the Discharge

In Figure 5, the response of the RK cycle's electrical output to a nominal CCB discharge is shown in red. It can first be observed that the CCB discharge results in an electrical overproduction of approximately 65 MW_{el}, bringing the flexibility contribution provided by the CCB to 10.5% compared to the nominal state of the RK cycle (with the CCB deactivated). This result thus validates the behavior and performance of the CCB, in line with the design specifications. It also confirms the positioning and architecture of the CCB, enabling it to effectively discharge its previously stored heat.

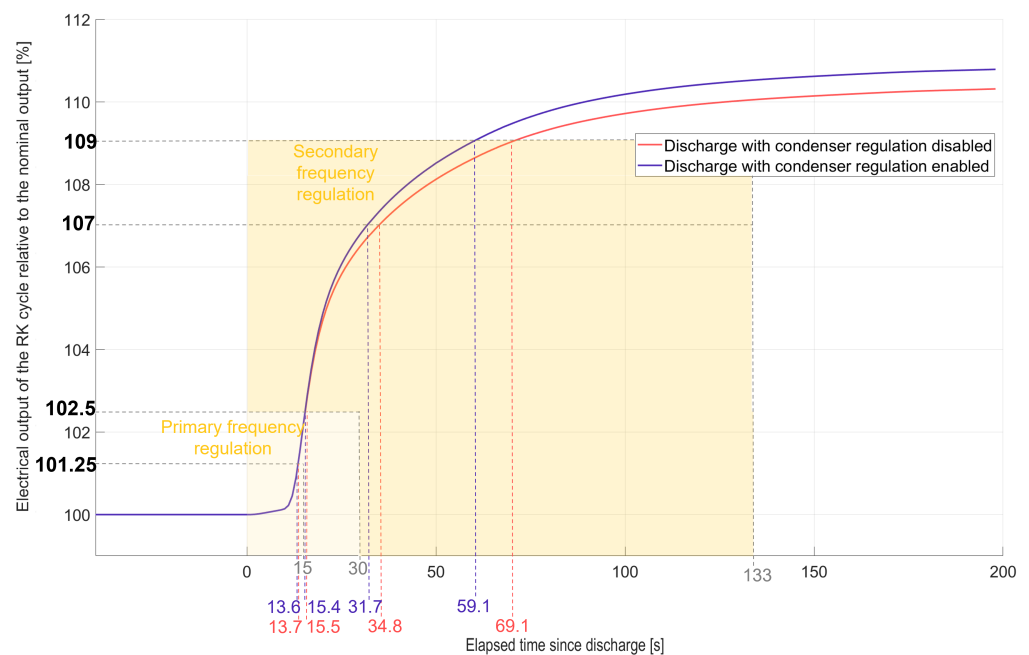


Figure 5. Evolution of the electrical power output of the power block after the onset of CCB discharge.

It was previously indicated that the heat released from the CCB is mainly filtered by the first stages of the high-pressure turbine; however, a residual portion of this superheat propagates to the condenser. This residual superheat results in an increase in the condensation pressure of the water within the condenser. This pressure rise of 5 mbar relative to the nominal condensation pressure of 58 mbar, as shown by the red curve in Figure 6 (the scale being expressed as a percentage variation relative to the nominal condensation pressure), is detrimental to the electrical output of the RK cycle. Thus, since in this type of NPP the condenser is oversized relative to nominal needs for safety reasons, the addition of a control loop on the NPP's cooling pumps was investigated. A basic Proportional Integral Derivative (PID) controller was implemented on the cooling pump speed, allowing the condensation pressure to be maintained at its design value as shown in Figure 6 as the blue curve. The PID controller was not optimized as part of this study, it was however tuned so that the variations in condenser pump rotational speed induced by the discharge of the CCB remained below the ramp rates admissible for this pump under accidental operating conditions. Therefore, optimization of the condenser pump control strategy remains a perspective of this work and could further refine and improve the RK cycle response.

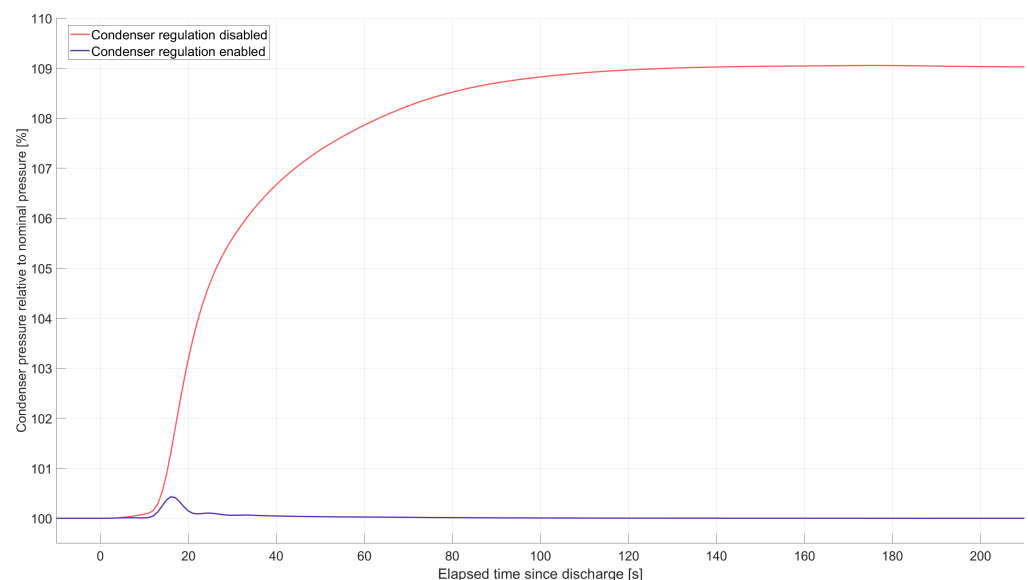


Figure 6. Condenser pressure evolution during CCB discharge.

The response of the RK cycle's electrical output with condenser regulation is shown in Figure 5 via the blue curve. As evidenced by the graph, condenser regulation is indeed beneficial for the electrical production of the RK cycle. Thus, from the same thermal power discharged by the CCB, the new electrical overproduction of the RK cycle reaches 67 MW_{el}, bringing the flexibility provided by the CCB to the RK cycle to over 11%.

On the question of the CCB's responsiveness, the curves in Figure 5 provide information on the phase shift between the start of the discharge and the response of the RK cycle. Indeed, it can be observed that the RK cycle reacts within about ten seconds to the discharge of additional heat, and that the RK cycle electrical output stabilizes after a few hundred seconds. It can also be noted that adding a regulation system to the PC condenser is beneficial for the CCB's responsiveness. To characterise the responsiveness of such a CCB, it was decided to compare its performance to a regulatory benchmark, namely the power system frequency regulation requests of the ASTRID NPP [63], as the strategic importance of such CBs was discussed in the introduction. This regulatory benchmark was selected as it is representative of the French regulatory framework. Figure 5 thus presents a comparison between the CCB's dynamics with and without condenser regulation (in

blue and red, respectively), compared to the French regulatory thresholds shown in grey. To respond to secondary frequency regulation calls from the power grid, a PP should be able to mobilize 107% and 109% of its nominal power within 133 s. These thresholds are largely met by the CCB. For primary frequency regulation, the required power thresholds are 101.25% and 102.5% of nominal power within 15 s and 30 s, respectively. The RK cycle response thus shows that the first and second primary frequency regulation threshold are also met, in respectively 13.7 s and 15.5 s. It should be noted that the addition of condenser regulation, as previously mentioned, is beneficial for the CCB's dynamic response, but acts mainly in the time domain relevant to secondary frequency regulation.

In comparison with the literature, the CCB exhibits a mean ramp-up rate relative to nominal power of $63\% \cdot \text{min}^{-1}$, which is typically higher than the ramp rates reported for conventional CB transients in the introduction. This high level of responsiveness is intrinsic to the CCB concept, which relies on a power cycle already in operation and at thermal steady state prior to discharge. Consequently, compared to a conventional CB, a CCB does not need to start the entire power cycle during discharge but only to modulate its load, thereby significantly reducing ramp-up requirements. Moreover, prior to the initiation of the discharge phase, the CCB operates in thermal stand-by mode and does not interfere with the RK cycle power output, thereby enhancing the modularity of the concept. The characteristic startup time of the CCB to reach 95% of its nominal power is estimated at 80 s, which should be compared with the 250 s required under similar conditions for the CB studied by Lu et al. in the most favorable case [28].

Several phenomena contribute to the dynamic behavior of the CCB, and they are decoupled in the chronological analysis that follows. For the two tests presented in this article, the RK cycle response with and without condenser regulation, a comparison between analytical calculations and the results of the CATHARE-3 model is provided. In Figure 5, several time domains are visible regarding the responsiveness of the CCB:

- The first begins a few seconds after the start of the discharge, where a slight inflection in the electrical production curve occurs.
- The second time domain occurs after the second inflection of the RK cycle's electrical output curve, near 10 s after discharge.
- Third time domain can be identified when the electrical output curve with condenser regulation (in blue) diverges from the red curve (without condenser regulation), approximately around 20 s after the start of the discharge.

During this first time domain, the responsiveness of the CCB is governed by the start-up inertia of the molten salt pump, as seen in Figure 7, and by the propagation of the thermal front through the molten salt pipe between the storage and the discharge HE, as shown in the same figure (L_x being the relative position along the molten salt pipe, with $L_x = 0$ at the inlet and $L_x = 1$ at the outlet).

The dynamics are also governed by thermal accumulation in the molten salt pipe and in the plates of the discharge HE, as shown respectively by the dark blue and orange curves in Figure 8. This figure also shows that thermal accumulation in these two CCB components begins as soon as the discharge starts, that is, as soon as molten salt circulation is established. Figure 9 provides information on the thermal power profile exchanged by the discharge heat exchanger.

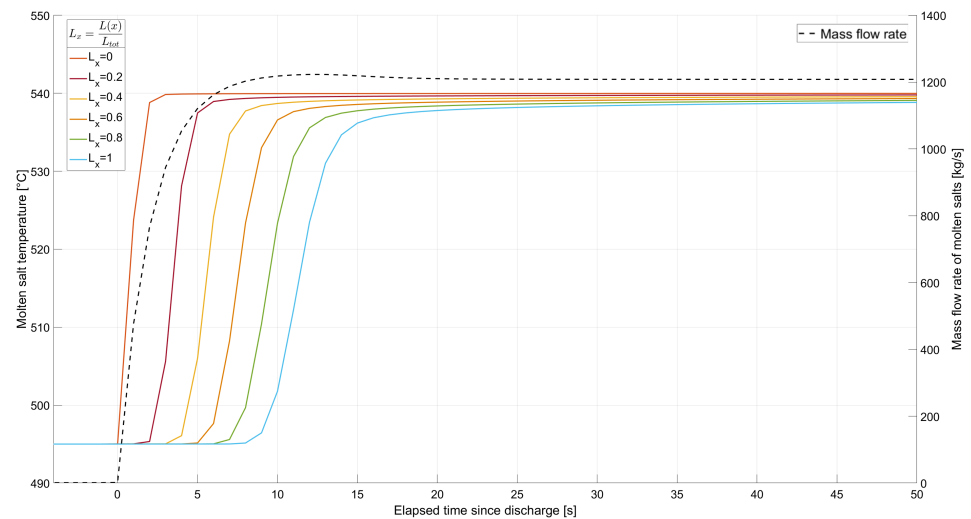


Figure 7. Evolution of inertial contributions induced by the start-up of the CCB.

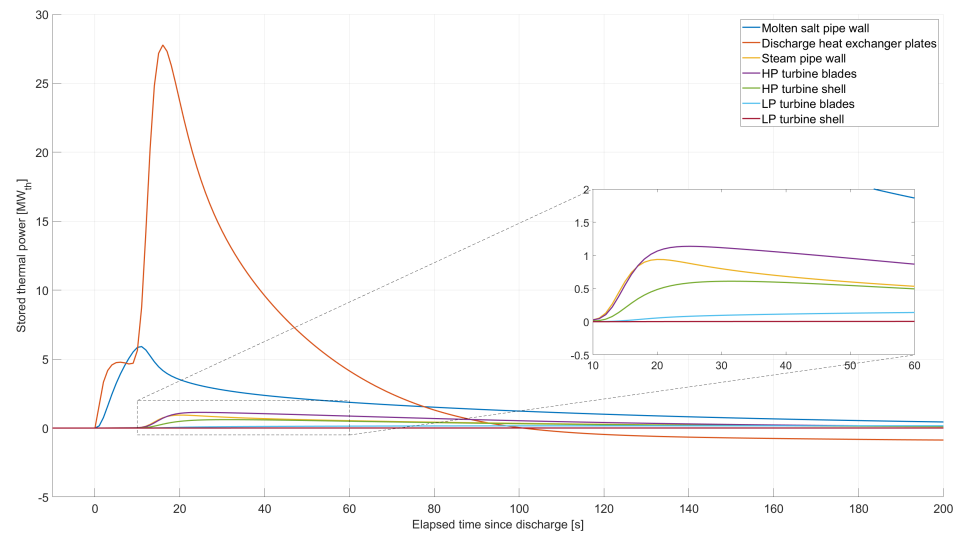


Figure 8. Evolution of stored thermal power after the onset of CCB discharge.

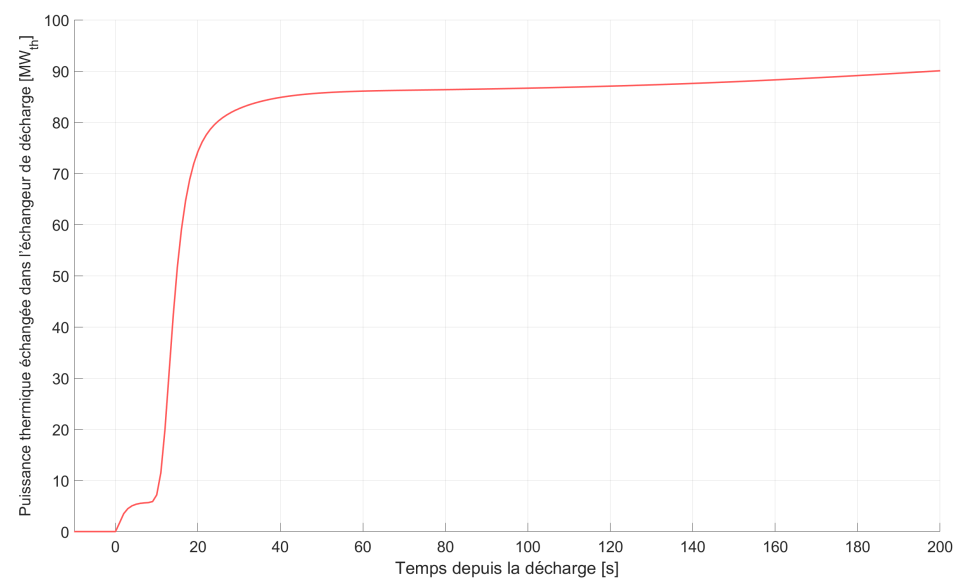


Figure 9. Evolution of thermal power in the discharge heat exchanger after the onset of CCB discharge with condenser regulation enabled.

The thermal power exchanged at the discharge HE at a time 12 s after the start of the discharge is 25% of its nominal power, corresponding to a power of 24 MW_{th}. This exchanged power should be compared to the order of magnitude of the total power accumulated during this first domain (i.e., before 10 s in Figure 8). During this first time domain, from the initial inflection of the electrical output curve to approximately 10 s after the discharge begins, molten salt circulation is established and the mobilized power is almost exclusively stored by thermal accumulation in the materials of the CCB.

During the second time domain, as shown in Figure 8, the thermal accumulation in the discharge HE reaches its peak around 18 s after the discharge begins, from 15 s onward the thermal power discharged to the HE is significantly higher than the thermal accumulation in the materials, thus explaining the sharp increase in the RK cycle's electrical output.

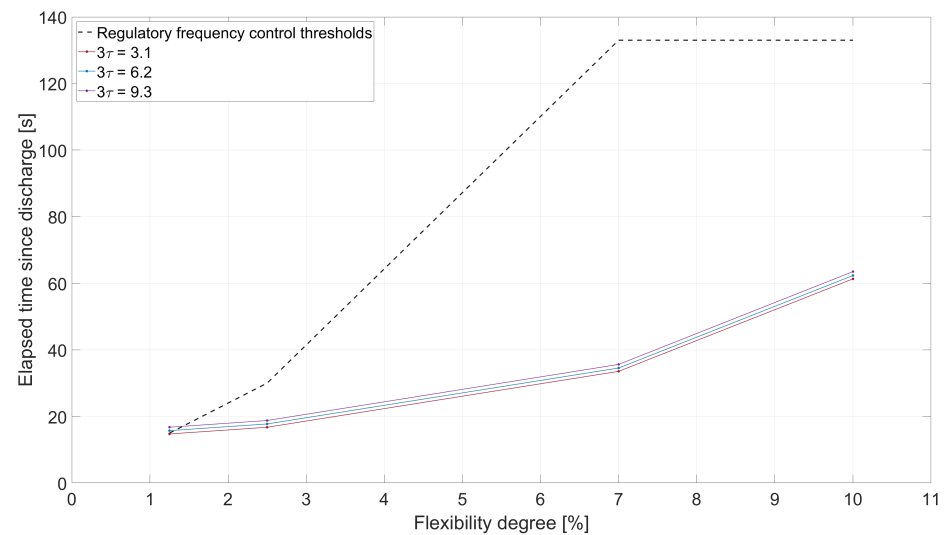
Finally, the last domain is the one in which condenser regulation begins to impact the PC's dynamics. Indeed, condenser regulation is beneficial in maintaining the condensation pressure at its setpoint, but it only becomes effective after about 20 s, the characteristic transport time of the heat from storage to the condenser. This is thus fully consistent with the fact that this regulation strategy only affects secondary frequency regulation.

Moreover, Figure 8 provides insight into the influence of each inertial component on the dynamics of the CCB. In particular, the dynamics of the molten salt pump and the length of the pipe are significant inertial elements, adding a direct delay during discharge. The thermal inertias of the molten salt pipe and the thickness of the plates are also important components, adding an indirect delay to the system's responsiveness. Finally, the thermal inertias of the steam line as well as the blades and shells of the high-pressure and low-pressure turbines appear to be second-order parameters due to their diffusive nature. An additional comment can be made regarding the discharge profile of the discharge heat exchanger in Figure 9. Although the discharge heat exchanger reaches 90% of its nominal thermal power in approximately 40s, its nominal power is only achieved after 1300 s from the start of the discharge, which is consistent with the thermal inertia profile shown in Figure 8, no longer predominant beyond 40 s but remaining diffuse long after the start of the discharge.

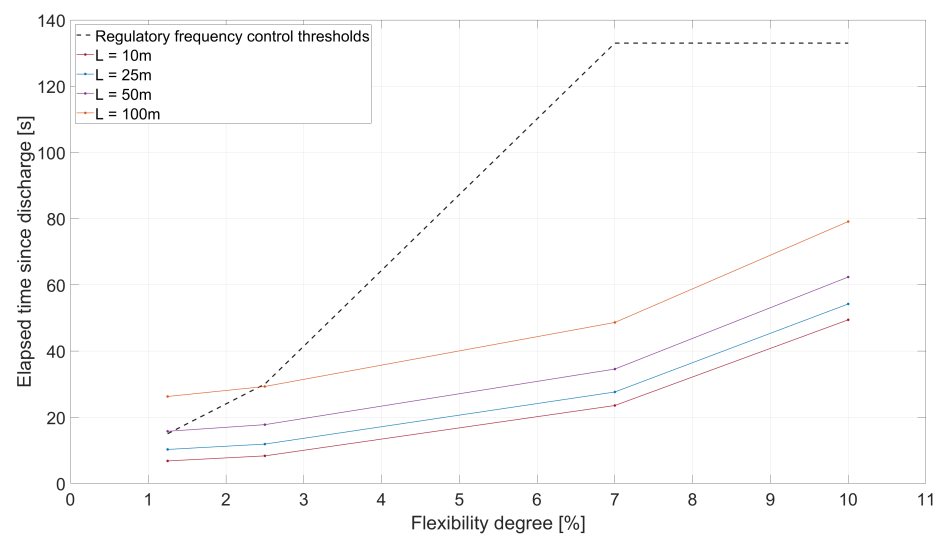
3.3. Sensitivity Analysis

A sensitivity analysis was carried out to identify the criticality of the different CCB design assumptions on the discharge responsiveness. Figure 10 presents these results in comparison with the different regulatory frequency control thresholds, represented by dashed lines.

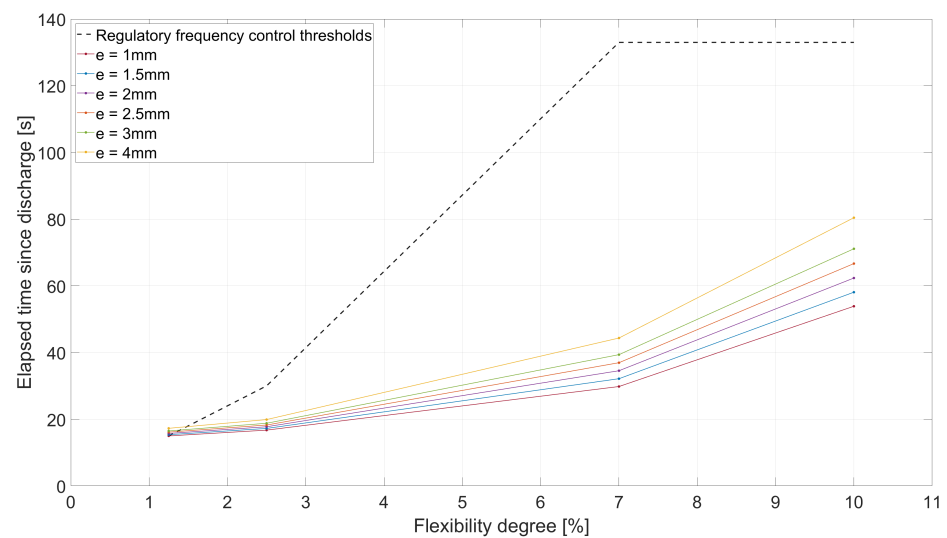
It can be observed that, for the molten salt pump start-up characteristic time, the molten salt pipe length, and the discharge heat exchanger plate thickness, more favorable assumptions can independently allow all primary and secondary frequency regulation thresholds to be satisfied. Regarding the steam pipe length, regardless of the assumption considered, all thresholds are met. It should therefore be noted that the most critical parameter is the molten salt pipe, for which a length greater than 48 m leads to exceeding the first primary frequency regulation threshold. Consequently, optimizing the distance between the thermal storage system and the discharge heat exchanger may provide a significant leverage effect on the responsiveness of the CCB, thereby relaxing the design constraints associated with both the molten salt pump and the discharge heat exchanger.



(a)



(b)



(c)

Figure 10. Cont.

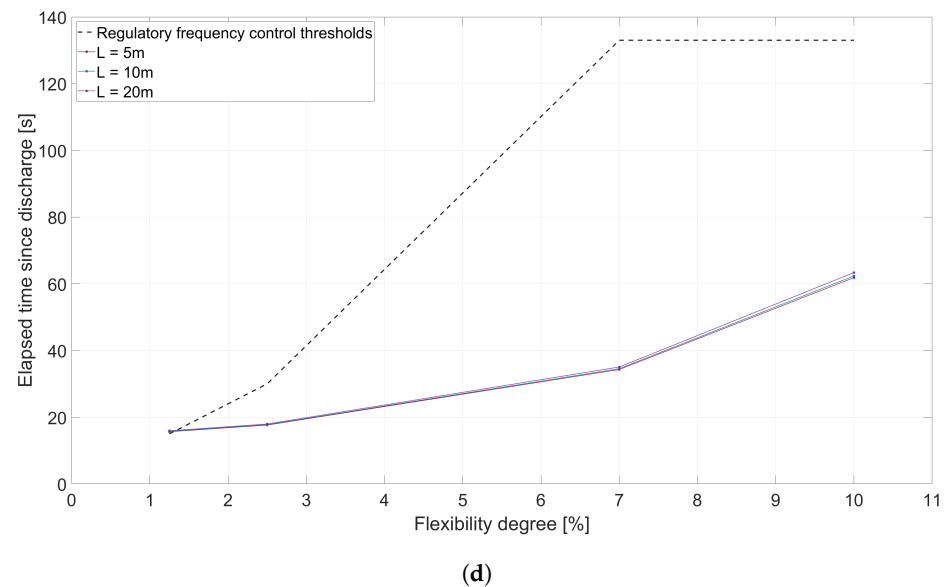


Figure 10. Sensitivity of the nominal parameters to the different primary and secondary frequency regulation thresholds for (a) molten salt pump start-up characteristic time (b) molten salt pipe length (c) discharge heat exchanger plate thickness (d) steam pipe length.

4. Conclusions and Prospects

In this article, preliminary results from a CATHARE-3-based modeling of a CCB coupled to a NPP have been presented and discussed. The main conclusions are as follows:

- The steady-state performance of the CCB, based on CATHARE-3 model of the system, was evaluated at 73.5%;
- The CCB discharge induces significant superheating at the outlet of the discharge HE, but this thermal energy is mainly filtered by the first stage of the high-pressure turbine;
- The various inertial components affecting the CCB dynamics during discharge were decoupled, and it was shown that the dynamics of the molten salt pump, the length of the molten salt pipe, as well as the thermal inertias of this pipe and of the discharge HE plates are first-order components. The sensitivity analysis further expanded these results, showing that the molten salt pipe length is the main parameter offering optimization potential;
- By comparison with French regulatory frequency regulation thresholds, it was shown that the CCB meets all thresholds during discharge. Thus this architecture of CCB could contribute during discharge to frequency regulation for grid balancing, at least under French or less demanding benchmarks.

In addition to the expected high performance and reduced infrastructure cost, this paper reinforces the potential for adoption of CCB technology, having demonstrated the good adaptability of the receiving PP, thereby enabling an easy coupling, at least for the small dimensionless sizes of CCBs. Furthermore, the high level of discharge responsiveness shown here confirms an interesting architecture compared to the responsiveness domain of conventional CBs reported in the literature. In light of this exploratory study, it is therefore relevant to broaden the potential responsiveness spectrum of CBs, opening the way to new grid services and further enhancing the potential for the deployment of this technology. It should nevertheless be emphasized that this study constitutes a first step toward the assessment of new fast grid services. In particular, the conclusions regarding the primary frequency regulation, although reinforced by the sensitivity analysis, remain dependent on the assumptions made, including the molten salt start-up ramp assumption, which would warrant a dedicated study of its own. A more comprehensive system-level description,

accounting for the NPP control strategies, whether existing or specifically optimized for integration with the CCB, would be highly relevant for future investigations. However, questions remain regarding the acceptable size of the CCB relative to an existing PP, and the extent of changes required in terms of safety and durability, which are directly linked to the economic viability of the operation. Assessing the thermo-mechanical stresses induced by the ramps associated with the CCB is therefore an important step in demonstrating the feasibility of the concept. Moreover, the assessment of the CCB charging dynamics also constitutes an important perspective for more broadly assessing the grid services that can be provided by this architecture.

In terms of outlook, this work will be complemented by an experimental study on the dynamics of CCBs that will be published soon.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Abbreviations

CB	Carnot Battery
CCB	Coupled Carnot Battery
COP	Coefficient Of Performance
EH	Electrical Heater
HE	Heat Exchanger
HP	Heat Pump
ICB	Integrated Carnot Battery
NPP	Nuclear Power Plant
PC	Power Cycle
PHES	Pumped Hydro Electrical Storage
PID	Proportional Integral Derivative
PP	Power Plant
RB	Reverse Brayton
RK	Rankine
SG	Steam Generator
SMR	Small Modular Reactor
SPX	Superphenix

Subscripts

ch	Charge
dis	Discharge
el	Electrical
HiTEC	Molten salt HiTEC
in	Relative to inlet
lim	Limit

net	Net
nominal	Relative to a nominal state
out	Relative to outlet
ref	Reference
res	Restitution
th	Thermal
tot	Total
x	Proportion [–]

Symbols

$\dot{m}$	Mass flow rate [kg · s ^{−1}]
$\dot{W}$	Work [W]
Π	Ratio [%]
τ	Specific time [s]
L	Length [m]
t	Time [s]

Appendix A. Description of CATHARE-3 Governing Equations

The thermo-hydraulic modelling implemented in the CATHARE-3 code relies on a two-fluid approach based on a system of six balance equations, three equations for each phase, as described in [64]. These equations are derived from the Navier–Stokes equations averaged over the flow cross-sectional area.

Appendix A.1. Mass Balance

$$\frac{\partial}{\partial t}(A\alpha_k\rho_k) + \frac{\partial}{\partial z}(A\alpha_k\rho_k V_k) = (-1)^k A\Gamma + S_k \quad (A1)$$

Appendix A.2. Momentum Balance

$$\begin{aligned} & A\alpha_k\rho_k\left(\frac{\partial V_k}{\partial t} + V_k\frac{\partial V_k}{\partial z}\right) && \text{Total derivative of momentum} \\ & + A\alpha_k\frac{\partial P}{\partial z} + AP_i\frac{\partial \alpha_k}{\partial z} && \text{Pressure work term} \\ & + (-1)^k A\beta\alpha_k(1 - \alpha_k)\rho_m\left(\frac{\partial V_G}{\partial t} - \frac{\partial V_L}{\partial t} + V_G\frac{\partial V_G}{\partial z} - V_L\frac{\partial V_L}{\partial z}\right) && \text{Added mass term} \\ & = (-1)^k A\Gamma(W_i - V_k) && \text{Phase change term} \\ & - (-1)^k A\tau_i && \text{Interfacial friction term} \\ & - \chi_f \frac{C_{k\rho_k}}{2} V_k |V_k| && \text{Regular pressure loss} \\ & - A \frac{K}{2\Delta Z} \alpha_k \rho_k V_k |V_k| && \text{Singular pressure loss} \\ & + A\alpha_k\rho_k g_z && \text{Gravitational term} \\ & + \frac{R(1-\alpha_k)}{4} + P_i \frac{\partial A}{\partial z} && \text{Stratification term} \\ & + SM_k && \text{Source term} \end{aligned}$$

Appendix A.3. Energy Balance

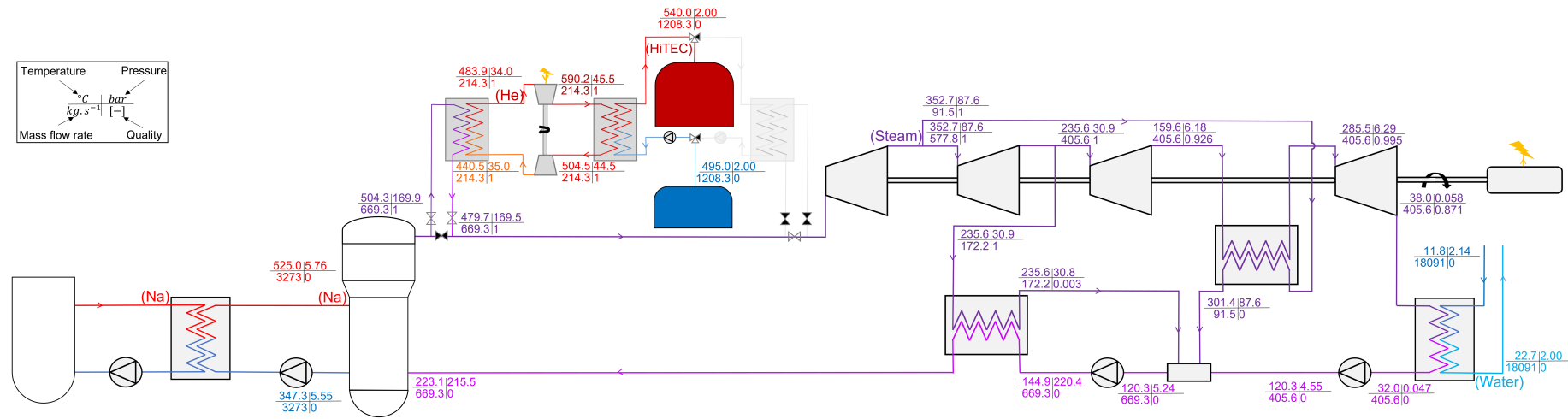
$$\begin{aligned} & A \frac{\partial}{\partial t} \left(\alpha_k \rho_k \left(H_k + \frac{V_k^2}{2} \right) \right) + \frac{\partial}{\partial z} \left(A \alpha_k \rho_k V_k \left(H_k + \frac{V_k^2}{2} \right) \right) && \text{Total derivative of energy per phase} \\ & - A \alpha_k \frac{\partial P}{\partial t} && \text{Pressure work term} \\ & = A q_{ke} && \text{External heat flux} \\ & + \chi_c q_{pk} && \text{Heat source term} \\ & (-1)^k A \Gamma \left(H_k + \frac{W_i^2}{2} \right) && \text{Phase change term} \\ & A \alpha_k \rho_k V_k g_z && \text{Gravitational term} \\ & SE_k && \text{Source term} \end{aligned}$$

Appendix A.4. Specific Nomenclature for Appendix A

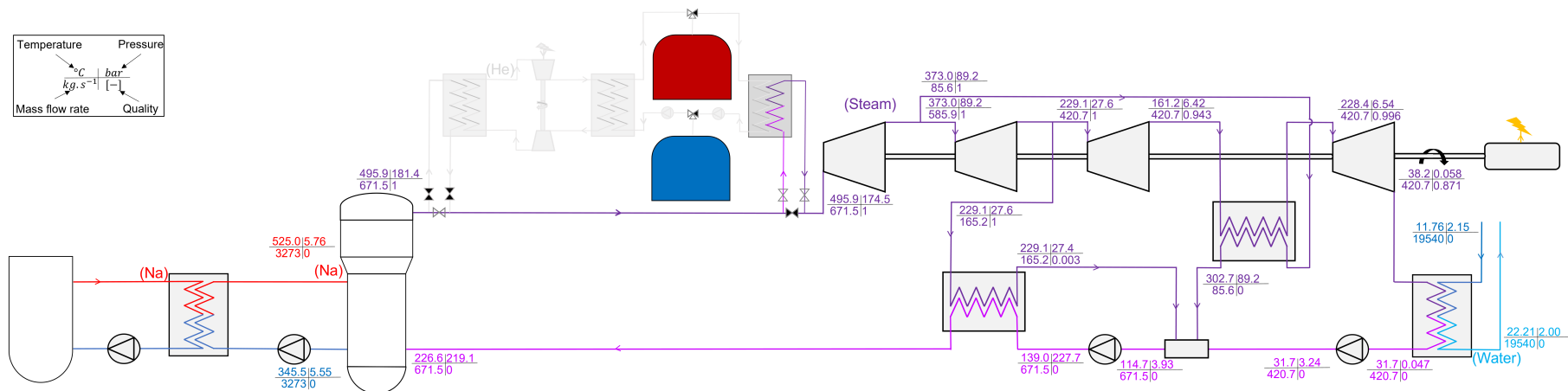
- k : phase index, 1 for liquid and 2 for gas
- A : cross-sectional area [m^2]
- α_k : phase volume fraction [-] (the gas-phase volume fraction corresponds to the void fraction), with $\alpha_G + \alpha_L = 1$.
- β : added mass coefficient [-]
- ρ_k : density of phase k [$\text{kg}\cdot\text{m}^{-3}$], and $\rho_m = \alpha_k\rho_G + (1 - \alpha_k)\rho_L$.
- Γ : interfacial mass transfer rate [$\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$]
- V_k : velocity of phase k [$\text{m}\cdot\text{s}^{-1}$]
- W_i : interfacial velocity [$\text{m}\cdot\text{s}^{-1}$]
- P_i : interfacial pressure [Pa]
- H_k : enthalpy of phase k [$\text{J}\cdot\text{kg}^{-1}$]
- τ_i : interfacial shear stress [$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$]
- C_k : regular friction coefficient [-]
- K : singular pressure loss coefficient [-]
- g_z : projection of gravity along the flow direction [$\text{m}\cdot\text{s}^{-2}$]
- R : stratification coefficient [-]
- χ_c : heated perimeter [m]
- q_{pk} : wall-to-phase k heat flux [$\text{W}\cdot\text{m}^{-2}$]
- q_{pi} : wall-to-interface heat flux [$\text{W}\cdot\text{m}^{-2}$] (involved in the calculation of Γ)
- q_{ke} : interface-to-phase k heat flux [$\text{W}\cdot\text{m}^{-2}$]
- SM_k : momentum source term for phase k [W]
- SM_E : energy source term for phase k [W]

Appendix B. Process Flow Diagram of the NPP CCB with CATHARE-3 Numerical Evaluation of the Operating Points

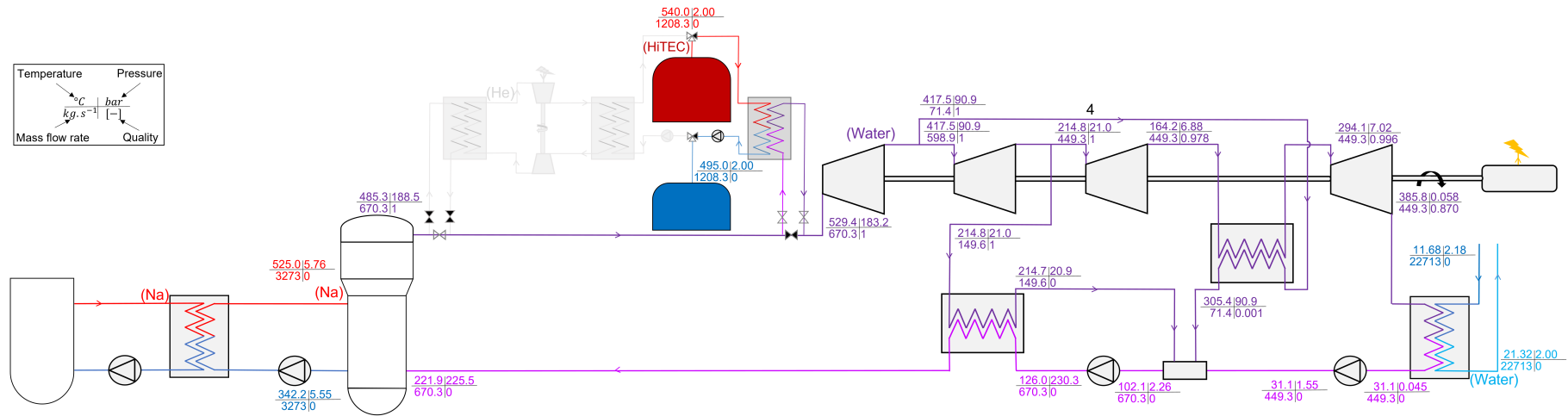
Appendix B.1. Charging Phase



Appendix B.2. Reference Phase



Appendix B.3. Discharging Phase



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