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Research paper

# Modeling and validation of the DYNASTY natural circulation loop with the RELAP5 code

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ABSTRACT

The DYNASTY (DYnamics of NAtural circulation for molten SalT internallY heated) facility, developed at the Energy Laboratories of Politecnico di Milano, offers a unique platform for investigating natural circulation dynamics under conditions of internal heat generation. Primarily focused on advancing the understanding of these critical processes, DYNASTY provides high-quality experimental data essential for validating numerical models. Beyond its primary scope, DYNASTY also delivers key insights for the study of passive safety systems based on natural circulation in light-water small modular reactors and Generation-IV reactors. This paper presents the development and validation of a novel RELAP5 model of the DYNASTY natural circulation loop. The RELAP5 code was selected for its established reliability in modeling thermal-hydraulic systems, providing efficient and accurate predictions. Model validation was conducted using experimental data from recent campaigns, which tested the facility's behavior under various conditions, including different cooling fan speeds and heating configurations. In addition to validating the model's predictive capabilities, a sensitivity analysis was conducted to assess its robustness under different numerical methods and nodalization schemes. The RELAP5 model demonstrates accurate reproduction of the DYNASTY experiments, with a maximum root mean square error of 7.25 °C, recorded in a case lasting more than 23000 seconds. This model provides a solid foundation for integrating additional physical and engineering aspects beyond thermal-hydraulics, expanding its application in the development of reliable passive safety technologies. Finally, in the context of advancing nuclear safety, this paper contributes valuable insights into the validation of passive safety systems models based on natural circulation, addressing critical challenges and paving the way for enhanced safety and efficiency in future deployments.

## 1. Introduction

### 1.1. Natural circulation in nuclear engineering

In the presence of temperature-induced density gradients, fluids can exhibit convective motions driven by buoyancy forces. Systems capable of harnessing these flows for heat transfer between a hot source and a cold sink are termed Natural Circulation (NC) loops. While forced convection may offer greater efficiency in cooling, natural convection presents an advantage in reliability as it operates without active components, making it suitable for high-reliability engineering applications. Notably, the stringent safety standards in the nuclear industry, amplified after the Fukushima accident, have spurred research into emergency systems taking advantage of natural convection. However, NC systems may be susceptible to dynamic oscillations, posing challenges in their implementation and operation [8,10].

The interest in NC has been growing steadily within the nuclear industry and research, for both normal and safe operation. Several Small Modular Reactors (SMRs) concepts, including NuScale [33], CAREM [23], and ABV-6M [34], have adopted NC to circulate the primary fluid, without the use of primary pumps. Not only used for normal operation, NC can also provide a passive way to extract the decay heat in accidental scenarios, as in Generation-III$^+$ nuclear reactors [31,29]. Moreover, several studies in the scientific literature propose NC for the safety systems of Generation IV nuclear reactors, notably the Molten Salt Fast Reactors (MSFR) and Lead-cooled Fast Reactors (LFR) [24,20].

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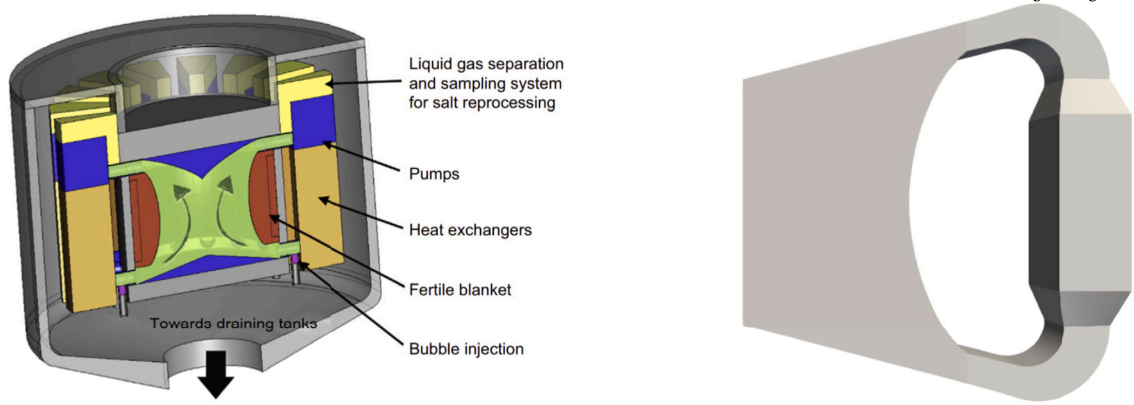



(a) (b)

**Fig. 1.** Overview of the MSFR core configuration, showing both the conceptual layout and the geometric model. (a) Schematic representation of the reference MSFR fuel circuit [30]. (b) CAD part representing 16th of the entire reactor core [11].

A crucial challenge in scientific research is the identification and validation of the conditions necessary for ensuring the safe operation of passive safety systems. Thus, experimental investigations of NC-based systems and the subsequent validation of thermal-hydraulic models are essential. Over the past few years, several thermal-hydraulic numerical codes have been used to perform the thermal-hydraulic analyses of NC systems, including ATHLET, GOTHIC, RELAP5, and TRACE [6,1,26,21,22]. Among those codes, RELAP5 is the most extensively utilized best-estimate code for the thermal-hydraulic analysis for light water reactors [32]. Developed by the Idaho National Laboratory for the Nuclear Regulatory Commission, it has been extensively utilized to support the rulemaking, licensing, audit calculation, evaluation of accident mitigation strategy, evaluation of operator guideline and experiment planning analysis [15].

### *1.2. The DYNASTY facility*

The MSFR (Fig. 1) presents a unique challenge in reactor design due to the presence of fuel in a homogeneous mixture with the thermal carrier, leading to an innovative phenomenon: NC with Internal Heat Generation (IHG) [18]. This configuration, where the fissile fuel remains in liquid form and is fully mixed with the thermal carrier, requires an in-depth analysis of IHG effects on thermophysical properties, mass flow, and pressure losses. IHG poses design and operational complexities distinct from external heating because the heat is generated directly within the fluid.

Setting up an experimental facility to replicate IHG is inherently difficult, as it would involve controlled chemical or nuclear reactions to generate heat internally. However, an axial section sufficiently long to allow radial effects to be negligible can serve as an effective first approximation for studying IHG behavior, making it possible to approximate IHG with an external heat source [27].

DYNASTY (DYnamics of NAtural circulation for molten SalT internallY heated) is a NC loop facility constructed in the Energy Laboratories at Politecnico di Milano. Although the DYNASTY facility is not designed to reproduce the exact dynamics of a MSFR, it serves as a simplified test platform to study the behavior of NC under approximated internal heat generation conditions, which are characteristic of MSFR designs during certain accidental scenarios. This work does not attempt to capture the inherently three-dimensional effects associated with NC in MSFRs. Instead, it focuses on the stability and global behavior of a NC loop through a one-dimensional modeling approach. DYNASTY has been playing a role in nuclear research over the past years, being the focus of extensive stability analyses aimed at investigating instabilities in NC loops. Besides, it has generated a wealth of experimental data, facilitating the validation of computational models under various heating conditions [4,7,27,9,2,5,25].

As shown in Fig. 2, the DYNASTY facility consists of a rectangular loop with sides of approximately 3 meters. It features a finned pipe cooler located at the top, which is subjected to airflow generated by a fan positioned beneath it. NC is driven by electric heating strips, made of copper and encased in fiberglass, that act as the heat source, while the cooling fan serves as the heat sink.

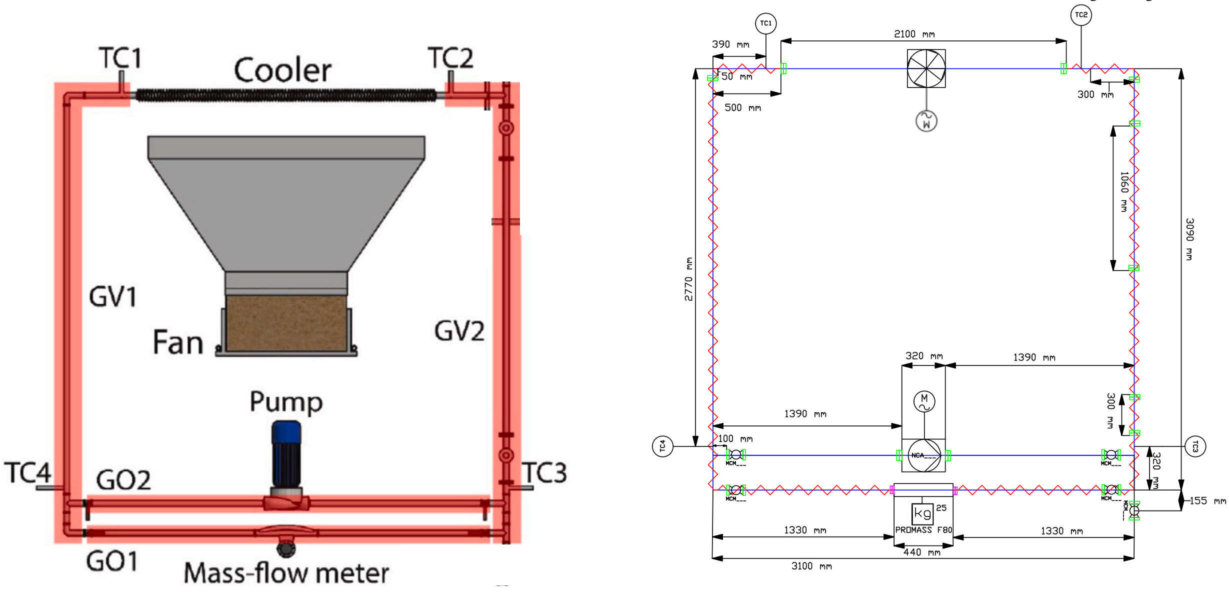
The DYNASTY facility can be utilized by exploiting different heating configurations, as depicted in Fig. 3. The legs composing the loop could be heated all at the same time when the loop is operated in the Distributed Heat (DH) configuration. Alternatively, a localized heat source can be activated in selected legs, with experimental configurations including Vertical-Heater-Horizontal-Cooler (VHHC), and Horizontal-Heater-Horizontal-Cooler (HHHC).

The DYNASTY loop piping is made of AISI316L stainless steel, which was chosen to withstand the high temperature when being operated with a circulation fluid such as molten salts. Other working fluids that can be circulated are glycol and water, as reported and detailed in Benzoni [3]. Single-phase water is used in this study as a working fluid to preliminarily assess the stability of a NC loop with internal heat generation. Ongoing experiments involve glycol, a fluid with thermal properties similar to those of molten salts. Future tests with molten salts will leverage the facility's full capabilities to replicate realistic reactor thermal-hydraulics more accurately.

As shown in Figs. 2a and 2b, the instrumentation installed in the DYNASTY facility consists of four ELSI® Type J class 1 thermo-couples [13], namely TC1, TC2, TC3, TC4; and one ENDRESS-HAUSER® Promass F80 DN25 Coriolis mass flow rate meter located in the GO1 leg [14]. The tolerance of the measuring system is 1.5 °C for the thermocouples and 1.5% of the read value for the mass flow rate meter.

The modeling of the DYNASTY facility has been previously pursued using both one-dimensional and three-dimensional approaches, employing tools such as DYMOLA and OpenFOAM [4,9,2]. However, existing models exhibit limitations, including incomplete representations of certain thermal-hydraulic phenomena and partial validation against experimental data. Notably, the computational fluid dynamics model developed in OpenFOAM has not yet been validated against data covering the full duration of the experimental transients.

A novel RELAP5/MOD3.3 model of the DYNASTY facility is developed to address current knowledge gaps in NC systems with internal heat generation. The DYNASTY loop is specifically designed to emulate volumetric heating using distributed electric heaters, enabling realistic experimental conditions. The RELAP5 model is validated for the first time against experimental data from three distinct heating configurations: VHHC, HHHC, and DH. This comprehensive validation across multiple operational regimes represents a contribution not previously available in




(a) (b)

**Fig. 2.** Overview of the DYNASTY facility. (a) Schematic representation [5]. (b) CAD representation.

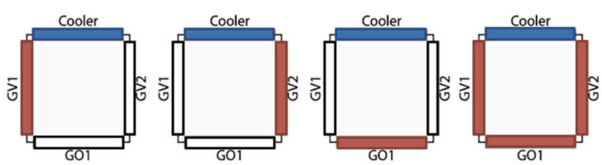



**Fig. 3.** The heating configurations of the DYNASTY facility, where the blue leg represents the NC heat sink (the cooler) and the red legs refer to the heat source. Benzoni et al. [5].

the literature. Furthermore, a benchmark comparison with the existing DYMOLA model demonstrates the superior accuracy and predictive capabilities of the RELAP5/MOD3.3 simulations.
However, some limitations must be acknowledged. RELAP5 is a one-dimensional code and cannot fully capture inherently three-dimensional phenomena, such as flow stratification or localized mixing. Moreover, the DYNASTY facility lacks pressure sensors, preventing validation of the model against pressure data. The loop is also uninsulated, and thermal losses to the environment are not yet characterized, introducing uncertainty in the energy balance. Additionally, the fan system is modeled using a simplified approach, assuming a constant Heat Transfer Coefficient (HTC). Despite these limitations, the model shows good agreement with temperature and mass flow data, with a maximum Root Mean Square Error (RMSE) of 7.25 °C in a case lasting over 23000 seconds, providing a solid basis for future analysis and improvements. The work reported here is structured as follows. Section 2 presents the novel RELAP5 model, along with descriptions of the selected experimental cases used for model validation. Additionally, the details of the sensitivity analysis are reported, covering both the numerical methods and nodalization schemes. Section 3 presents the key findings of the sensitivity analysis, the RELAP5 model validation, and the benchmark with the DYMOLA model. Section 4 summarizes the main findings of this study, offering insights for refining the model and identifying potential applications.

## 2. Methods

### *2.1. RELAP5 modeling*

The modeling of the DYNASTY loop is performed using the best-estimate code RELAP5/MOD3.3. The RELAP5 code is based on a non-homogeneous and non-equilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5 development effort was to create a code that captures essential first-order effects for accurate system transient predictions while remaining sufficiently simple and cost-effective to enable parametric and sensitivity studies [21].
The RELAP5 nodalization of the DYNASTY loop is shown in Fig. 4. The DYNASTY loop is modeled by means of the RELAP5 hydrodynamic components PIPE, SNGLJUN (single junction), BRANCH and TMDPVOL (time-dependent volume). The number of control volumes composing the pipes in the numerical model is chosen such that each control volume has a length of 100 millimeters. The left leg (GV1 in Fig. 4) is realized by a pipe with 35 control volumes, linked to the cooler with a single junction. The cooler is modeled with a pipe of 21 nodes. The GO1 leg (PIPE-101) is composed of a pipe with 31 nodes, linked to the left leg with the single junction 199 and with the single junction 499 to the right leg, GV2. In the bottom horizontal pipe, the mass flow rate meter introduces high concentrated pressure drops and is simply modeled as a junction in the PIPE-101 center. As shown in Section 3, even with such a simplified model being adopted, the predictions remain accurate. The right leg is modeled with a vertical pipe with 29 nodes and a branch connecting this vertical pipe (PIPE-403) to the horizontal leg (PIPE-401). The branch links the two pipes and connects the loop to the atmosphere, which is modeled as a TMDPVOL with a pressure of 1 bar and a temperature of 25 °C. The control volumes composing the loop have an internal diameter of 38 mm, as in the actual facility.

The heat structure of the cooler was initially modeled using a simple pipe with an associated table of HTCs versus time. Inspired by Benzoni et al.'s work for the DYMOLA model [4], a more complex model was later developed, incorporating a dedicated hydrodynamic system to simulate the fan. This system includes a TMDPJUN that injects air into a pipe thermally coupled to the cooler through a heat structure, with the air mass flow rate value based on the referenced test case. Due to the lack of detailed characterization of the cooling system and the difficulty of accurately reproducing such a complex system without extensive model tuning, the authors retained the simpler model with the HTC table.
Additional heat structures are implemented to account for the input power and heat losses in both heated and non-heated pipes. Since the facility was not thermally insulated from the environment during the ex-

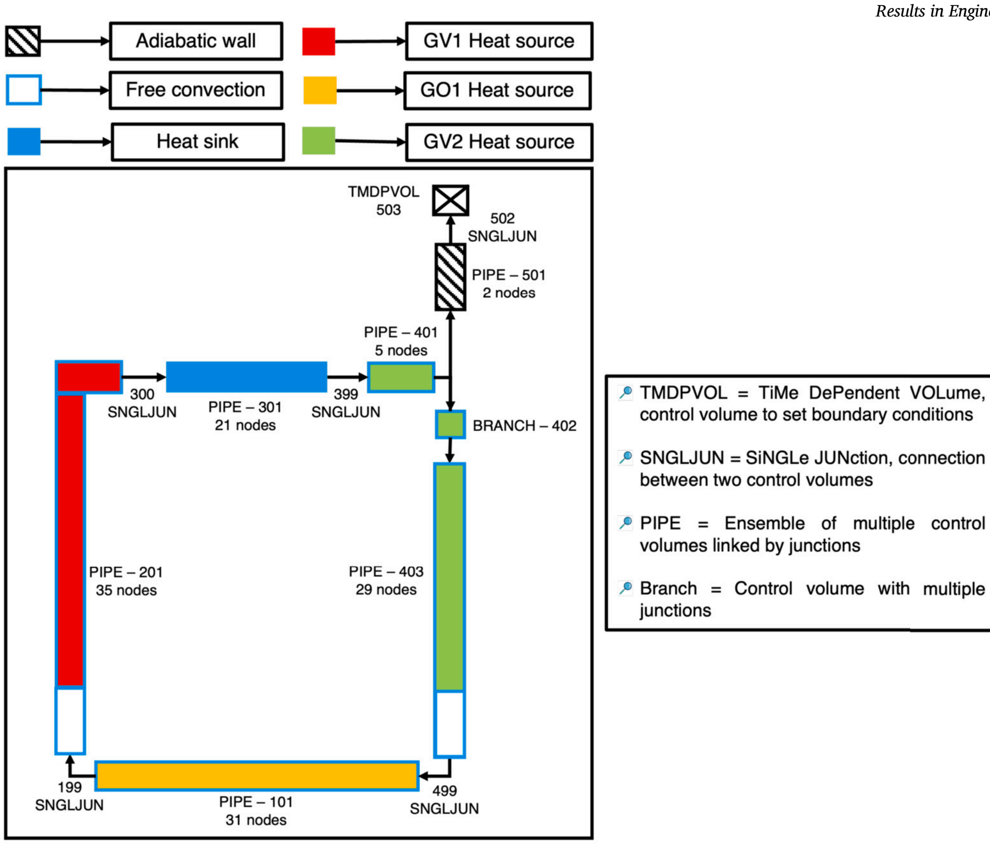



**Fig. 4.** Nodalization of the DYNASTY loop adopted in the RELAP5/MOD3.3 simulations.

perimental campaign, heat losses significantly influence the dynamics of NC. In the heat structure representing the heat source, efforts have been undertaken to reproduce the electric heating strips accurately. The heating strips are reproduced by interposing a layer of copper into two layers of fiberglass, whose dimensions were directly measured in the Energy Laboratories at Politecnico di Milano. The entire thermal-hydraulic system, including the heater section, accounts for thermal losses through with the external environment set at a given temperature. This exchange follows a HTC versus temperature table derived from the free convection Churchill-Chu correlation, which is suitable for the range of applicability of the current experimental case [17]. The concentrated pressure drop coefficients of elbows, flanges and the tee, found at the top of the right leg, are calculated from Idelchik [16]. The pressure drop coefficient of the mass flow rate meter is computed from its technical data sheet. In the RELAP5 input file, the material properties are implemented using the function/table option, selecting AISI316 for the piping.
Initial and boundary conditions were implemented using standard RELAP5 input structures. Hydrodynamic components and heat structures were initialized through their respective input fields. Boundary conditions for the hydrodynamic volume TMDPVOL-503 were defined directly via dedicated input lines specifying pressure and temperature. Environmental heat losses were modeled by assigning the ambient air temperature ($T_{air}$) and the HTC through general table data, using the correlation previously described. Similarly, the applied power input was specified using general table entries. A complete overview of the initial and boundary conditions used in the model is reported in Table 1 and Table 2, respectively.

### 2.2. Model validation protocol

To validate the novel RELAP5 model of the DYNASTY loop, three experimental cases were selected, corresponding to three different heating configurations of the DYNASTY loop. The multiplicity of the experimental cases was selected to investigate the robustness of the model and its adaptability to different testing configurations. Specifically, the selected cases feature VHHC, HHHC, and DH configurations.
For the validation of the model, both qualitative and quantitative approaches were employed. Graphical comparisons between simulation results and experimental data were used to visually assess the accuracy of the model in capturing transient and steady-state behaviors. Additionally, the RMSE (Eq. (1)) was calculated to provide a quantitative measure of the discrepancy between simulation predictions and experimental measurements:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_i^{\mathrm{exp}} - y_i^{\mathrm{sim}}\right)^2} \tag{1}$$

where $y_i^{\mathrm{exp}}$ and $y_i^{\mathrm{sim}}$ represent the experimental and simulated values at the $i$-th data point, respectively, and $N$ is the total number of data points considered.
Table 3 reports the sequences of events during the VHHC, HHHC, and DH experimental tests. The same timeline was implemented in the numerical simulations. The parameters utilized for the model's validation are summarized in Table 4. Pressure data are not available from the experiments.

### 2.3. Sensitivity studies

To support the validation process, two separate sensitivity studies were carried out to determine the optimal nodalization and numerical method settings for the RELAP5 model. These analyses aim to ensure both accuracy and numerical stability across the different experimental configurations.
The first study focuses on assessing the model's robustness with respect to the numerical methods available in RELAP5 [32]. Four different schemes were tested: Method 1 employs an explicit coupling of heat

**Table 1**
RELAP5 initial conditions for the HHHV, HHHC, and DH validation tests.

| | HHHV Test | | | HHHC Test | | | DH Test | | |
|---|---|---|---|---|---|---|---|---|---|
| | T (°C) | P (bar) | w (kg/s) | T (°C) | P (bar) | w (kg/s) | T (°C) | P (bar) | w (kg/s) |
| *Components* | | | | | | | | | |
| PIPE-101 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| SNGLJUN-199 | – | – | 0 | – | – | 0 | – | – | 0 |
| PIPE-201 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| SNGLJUN-300 | – | – | 0 | – | – | 0 | – | – | 0 |
| PIPE-301 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| SNGLJUN-399 | – | – | 0 | – | – | 0 | – | – | 0 |
| PIPE-401 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| BRANCH-402 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| PIPE-403 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| SNGLJUN-499 | – | – | 0 | – | – | 0 | – | – | 0 |
| PIPE-501 | 24 | 1 | 0 | 24 | 1 | 0 | 24 | 1 | 0 |
| *Heat structures* | | | | | | | | | |
| HS PIPE-101 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS PIPE-201 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS PIPE-301 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS PIPE-401 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS BRANCH-402 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS PIPE-403 | 24 | – | – | 24 | – | – | 24 | – | – |
| HS PIPE-501 | 24 | – | – | 24 | – | – | 24 | – | – |

**Table 2**
RELAP5 Boundary conditions for the HHHV, HHHC, and DH validation tests.

| Hydrodynamic component | HHHV Test | | HHHC Test | | DH Test | |
|---|---|---|---|---|---|---|
| | T (°C) | P (bar) | T (°C) | P (bar) | T (°C) | P (bar) |
| TMDPVOL-503 | 24 | 1 | 24 | 1 | 24 | 1 |
| **Heat structures** | **HHHV Test** | | **HHHC Test** | | **DH Test** | |
| | $T_{air}$ (°C) | Power (W) | $T_{air}$ (°C) | Power (W) | $T_{air}$ (°C) | Power (W) |
| HS PIPE-101 | 17 | 0 | 20 | 1369 | 19 | 1369 |
| HS PIPE-201 | 17 | 2068 | 20 | 0 | 19 | 2068 |
| HS PIPE-301 | 17 | 0 | 20 | 0 | 19 | 0 |
| HS PIPE-401 | 17 | 0 | 20 | 0 | 19 | 672.3 |
| HS BRANCH-402 | 17 | 0 | 20 | 0 | 19 | 672.3 |
| HS PIPE-403 | 17 | 0 | 20 | 0 | 19 | 672.3 |
| HS PIPE-501 | 17 | 0 | 20 | 0 | 19 | 0 |

**Table 3**
Sequences of events during the VHHC, HHHC, and DH validation tests.

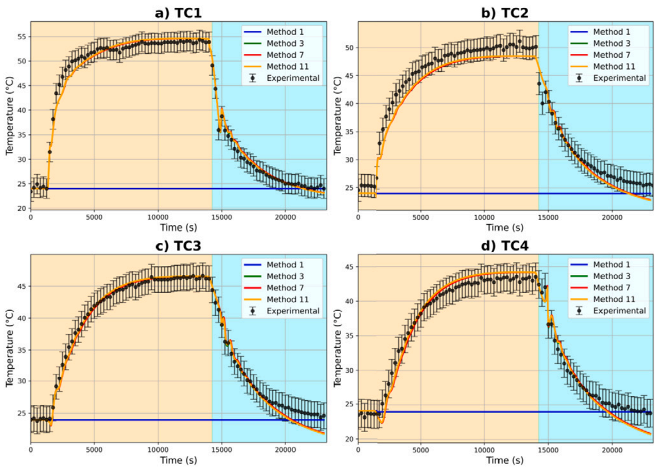
| VHHC Test | | HHHC Test | | DH Test | |
|---|---|---|---|---|---|
| Time (s) | Event | Time (s) | Event | Time (s) | Event |
| 0 | Start of data acquisition<br>Average fluid temperature 24 °C,<br>Average wall temperature 19 °C,<br>Mass flow rate -0.2 g/s | 0 | Start of data acquisition<br>Average fluid temperature 23 °C,<br>Average wall temperature 18 °C,<br>Mass flow rate -0.2 g/s | 0 | Start of data acquisition<br>Average fluid temperature 23 °C,<br>Average wall temperature 18 °C,<br>Mass flow rate -0.2 g/s |
| 1380 | Power start up<br>GV1 power 2068 W, air flow rate 3 $m^3/s$ | 120<br>GO1 power 1369 W, air flow rate 3 $m^3/s$ | Power start up<br>Total DH power 5508 W, air flow rate 3 $m^3/s$ | 540 | Power start up |
| 14100 | Power shutdown | 14040 | Power shutdown | 9540 | Power shutdown |
| 14460 | Inversion of the mass flow rate | 22080 | Data acquisition shutdown | 20040 | Data acquisition shutdown |
| 23280 | Data acquisition shutdown | | | | |

**Table 4**
Experimental parameters selected for model's validation.

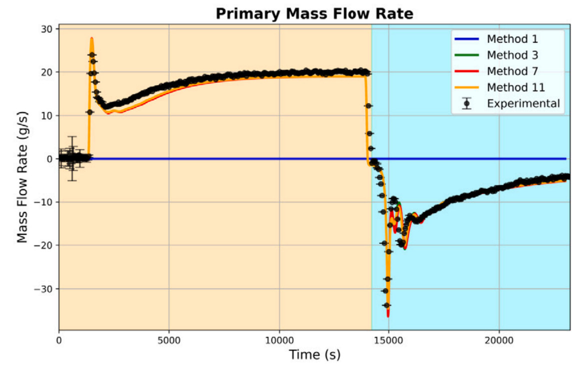
| Quantity | Unit | Description |
|---|---|---|
| TC1 | °C | DYNASTY temperature before the cooler |
| TC2 | °C | DYNASTY temperature after the cooler |
| TC3 | °C | DYNASTY temperature on the bottom right corner |
| TC4 | °C | DYNASTY temperature on the bottom left corner |
| MFR | g/s | DYNASTY mass flow rate |

conduction/transfer and hydrodynamics; Methods 3 and 11 utilize semi-implicit and nearly implicit schemes, respectively, both featuring time step control to synchronize thermal and hydrodynamic solvers; Method 7 applies a fully implicit scheme to both domains, similar to Methods 3 and 11.

The second study investigates the impact of spatial discretization by varying the control volume length among 5 cm, 10 cm, and 20 cm. This nodalization sensitivity ensures that the chosen mesh size strikes an appropriate balance between solution accuracy and computational efficiency.




(a) Impact of the RELAP5 numerical methods on the tempera-ture field for the VHHC case.




(b) Impact of the RELAP5 numerical methods on the mass flow rate for the VHHC case.

**Fig. 5.** Effect of RELAP5 numerical method settings on the VHHC case.

**Table 5**
RMSE between RELAP5 simulations and experimental data for each case and numerical method.

| Case | Method | TC1 (°C) | TC2 (°C) | TC3 (°C) | TC4 (°C) | $TC_{avg}$ (°C) | MFR (g/s) |
|---|---|---|---|---|---|---|---|
| VHHC | M1 | 21.14 | 17.91 | 14.95 | 12.73 | 16.68 | 14.85 |
| VHHC | M3 | 1.50 | 2.04 | 1.35 | 1.60 | 1.62 | 2.34 |
| VHHC | M7 | 1.52 | 2.07 | 1.33 | 1.58 | 1.62 | 2.38 |
| VHHC | M11 | 1.50 | 2.04 | 1.35 | 1.60 | 1.62 | 2.27 |
| HHHC | M1 | 12.96 | 12.57 | 10.66 | 13.35 | 12.38 | 23.23 |
| HHHC | M3 | 1.77 | 1.34 | 1.50 | 2.00 | 1.65 | 3.70 |
| HHHC | M7 | 1.76 | 1.35 | 1.48 | 1.99 | 1.64 | 3.75 |
| HHHC | M11 | 1.72 | 1.26 | 1.46 | 1.94 | 1.60 | 3.10 |
| DH | M1 | 40.74 | 38.26 | 40.07 | 37.98 | 39.26 | 29.72 |
| DH | M3 | 2.67 | 2.41 | 3.82 | 2.23 | 2.78 | 4.70 |
| DH | M7 | 2.82 | 2.54 | 4.00 | 2.30 | 2.92 | 4.71 |
| DH | M11 | 2.67 | 2.41 | 3.82 | 2.23 | 2.78 | 4.67 |

## 3. Results and discussion

### 3.1. Sensitivity study on numerical methods

As illustrated in Figs. 5a and 5b, the numerical methods generally produce consistent and accurate results, confirming the robustness of the RELAP5 model for both temperature and mass flow rate predictions in the VHHC case. In particular, Methods 3, 7, and 11 yield nearly identical temperature RMSEs (Table 5), with average values around 1.62 °C and mass flow rate RMSEs between 2.27 and 2.38 g/s. In contrast, Method 1 stands out as a clear outlier, with significantly higher RMSEs, up to 21.14 °C for TC1 and an average temperature RMSE of 16.68 °C, along with a large mass flow rate RMSE of 14.85 g/s. This substantial discrepancy can be attributed to Method 1 being an explicit numerical scheme, which requires much smaller time steps to maintain accuracy and stability. Without such adjustments, it becomes unreliable for transient simulation.

A similar trend is observed across the HHHC and DH cases. For the former case, Method 1 shows an average temperature RMSE of 12.38 °C and a mass flow error of 23.23 g/s, whereas the other methods maintain average temperature RMSEs below 1.7 °C and flow rate RMSEs between 3.10 and 3.75 g/s. The most pronounced difference occurs in the DH case, where Method 1 yields temperature RMSEs exceeding 40 °C across all sensors, compared to below 3 °C for the remaining methods. Mass flow RMSEs also decrease significantly from 29.72 g/s with Method 1 to below 4.8 g/s with the improved schemes.

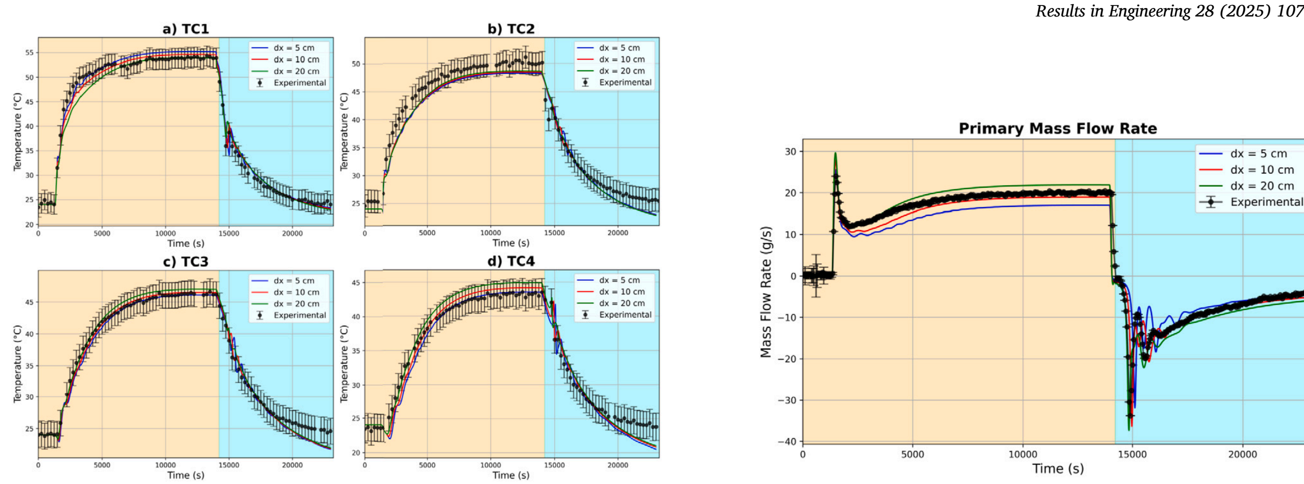
These findings demonstrate that while Methods 3, 7, and 11 provide consistent and accurate results across all tested configurations, Method 1 is inadequate for transient NC analysis due to its instability and lower fidelity under typical time step settings.

Among the methods evaluated, Method 11 shows the lowest overall RMSE values across temperature and mass flow rate, and is therefore the selected numerical method.

### 3.2. Sensitivity study on nodalizazion impact

For the VHHC case, only minor discrepancies are observed across different nodalization schemes, for both the heating and cooling transients, in terms of temperature field and mass flow rate, as shown in Figs. 6a and 6b, respectively. The RELAP5 model demonstrates resilience to changes in nodalization, maintaining an accurate representation of NC dynamics despite variations in control volume lengths. Quantitatively, the temperature RMSE (Table 6) remains low across all nodalizations, with average values of 1.62 °C, 1.71 °C, and 1.73 °C for the 10 cm, 5 cm, and 20 cm nodalizations, respectively. Mass flow RMSEs are slightly more sensitive, with the 20 cm scheme yielding the most accurate result at 2.32 g/s, compared to 3.77 g/s and 2.38 g/s for the 5 cm and 10 cm cases.

Figs. 7a and 7b show the sensitivity analysis for the HHHC case. All three nodalizations (5 cm, 10 cm, and 20 cm) result in accurate temperature and mass flow predictions, with only small variations. Quantitatively, the 5 cm case provides the lowest average temperature RMSE of 1.54 °C, slightly outperforming both the 10 cm and 20 cm nodalizations, which yield RMSEs of 1.64 °C and 1.55 °C respectively. On a sensor-by-sensor basis, the 5 cm model also exhibits the lowest RMSE for three out of four thermocouples.




(a) Impact of nodalization on the temperature field for the VHHC case. (b) Impact of nodalization on the mass flow rate for the VHHC case.

**Fig. 6.** Effect of RELAP5 nodalization settings on thermal-hydraulic predictions for the VHHC case.

**Table 6**
RMSE between RELAP5 simulations and experimental data for each case and noding.

| Case | Noding | TC1 (°C) | TC2 (°C) | TC3 (°C) | TC4 (°C) | $TC_{avg}$ (°C) | MFR (g/s) |
|---|---|---|---|---|---|---|---|
| VHHC | 5 cm | 1.59 | 2.12 | 1.39 | 1.72 | 1.71 | 3.77 |
| VHHC | 10 cm | 1.52 | 2.07 | 1.33 | 1.58 | 1.62 | 2.38 |
| VHHC | 20 cm | 1.83 | 2.03 | 1.38 | 1.70 | 1.73 | 2.32 |
| HHHC | 5 cm | 1.74 | 1.17 | 1.43 | 1.84 | 1.54 | 2.49 |
| HHHC | 10 cm | 1.76 | 1.35 | 1.48 | 1.99 | 1.64 | 3.75 |
| HHHC | 20 cm | 1.67 | 1.20 | 1.47 | 1.84 | 1.55 | 2.86 |
| DH | 5 cm | 2.79 | 2.58 | 4.03 | 2.33 | 2.93 | 5.02 |
| DH | 10 cm | 2.82 | 2.54 | 4.00 | 2.30 | 2.92 | 4.71 |
| DH | 20 cm | 2.85 | 2.47 | 3.91 | 2.32 | 2.89 | 4.86 |

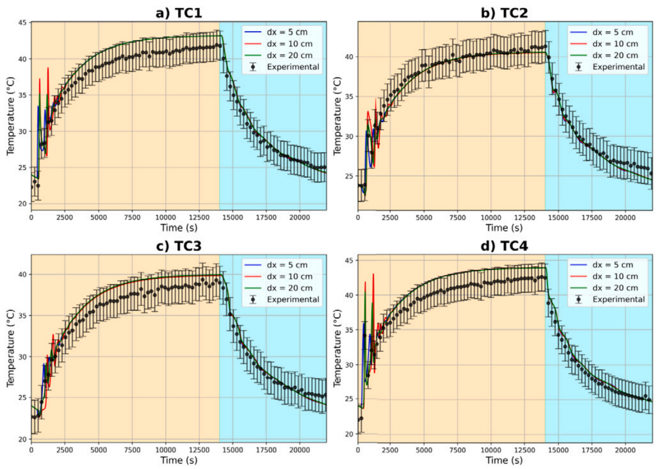
In terms of mass flow rate, the 5 cm discretization again shows the best agreement, with an RMSE of 2.49 g/s, compared to 3.75 g/s for the 10 cm model and 2.86 g/s for the 20 cm case. Figs. 7a and 7b confirm this trend, as the blue line (5 cm) closely tracks the experimental data over the entire transient, including both heating and cooling phases. These results demonstrate that, despite the expected increase in computational cost, the 5 cm nodalization offers the most accurate performance for the HHHC case and is therefore recommended for model validation.
The DH case results, presented in Figs. 8a and 8b, confirm the robustness of the RELAP5 model under varying nodalizations, even in long transients with distributed internal heating. All nodalizations yield nearly identical temperature fields, with RMSEs narrowly ranging between 2.89 °C and 2.93 °C, indicating negligible sensitivity to spatial discretization.
Mass flow rate predictions are similarly consistent, with RMSEs varying slightly between 4.71 g/s and 5.02 g/s. All three nodalizations (5 cm, 10 cm, and 20 cm) accurately capture the flow evolution, with only minor differences during the initial rise and post-peak phases. The 10 cm mesh performs marginally better overall, but deviations remain limited.
The 5 cm nodalization provides the lowest average temperature RMSE in both the HHHC and DH cases, and the lowest mass flow RMSE in the VHHC case (3.77 g/s). However, it introduces slight numerical noise in the cooling transient of the VHHC case.
The 10 cm nodalization, while not always the lowest in RMSE, offers the best compromise between accuracy, stability, and computational cost. It maintains consistently low temperature RMSEs (e.g., 1.62 °C in VHHC and 1.64 °C in HHHC) and provides stable, reliable trends across all simulations, as confirmed by Figs. 6, 7, 8. Therefore, the 10 cm configuration is selected for the validation phase.

### *3.3. The VHHC validation case*

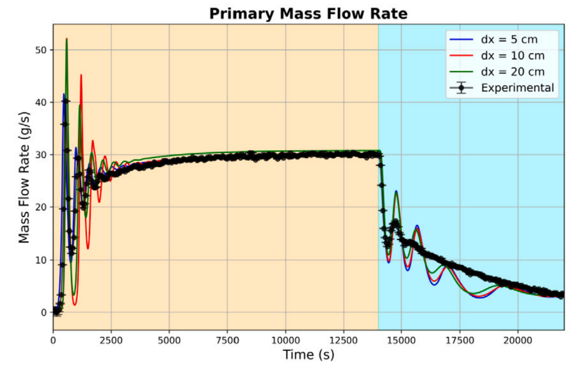
The comparison of the calculated results against the experimental data for the VHHC case is reported in Figs. 9a and 9b. At the top left of Fig. 9a, the temporal evolution of the TC1 temperature is shown. The RELAP5 model accurately captures the initial heating transient and closely follows the experimental profile during the steady-state phase, which extends up to approximately 14000 seconds. The model also successfully reproduces the cooling transient when the power is shut off, both qualitatively and quantitatively.
Similar performance is observed for the other thermocouples, shown in Figs. 9a. The RMSE values confirm the model's predictive accuracy: the temperature deviations across TC1–TC4 remain below 2.1 °C, with the lowest RMSE observed at TC3 (1.33 °C) and the highest at TC2 (2.07 °C). These values indicate that the model maintains a high level of precision across different positions within the loop.
Fig. 9b shows the mass flow rate validation. The RELAP5 model reproduces the transient behavior of the flow, correctly tracking the flow ramp-up, the steady regime, and the subsequent decrease during cooling. The RMSE for the mass flow rate is 2.35 g/s, which, considering the full dynamic range of the system, indicates satisfactory agreement.
Overall, the VHHC case validation demonstrates that the model can capture the main thermal-hydraulic dynamics of the system with high fidelity, supported by both low RMSE values and good qualitative behavior throughout all stages of the transients.

### *3.4. The HHHC validation case*

The second experimental case considered for the validation of the DYNASTY RELAP5 model investigates NC under the HHHC heating configuration. The comparison between numerical predictions and experimental data is shown in Figs. 10a and 10b.

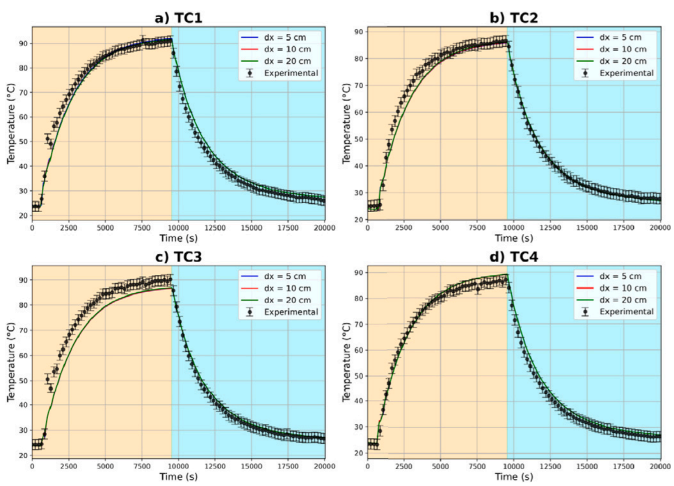



(a) Impact of nodalization on the temperature field for the HHHC case.

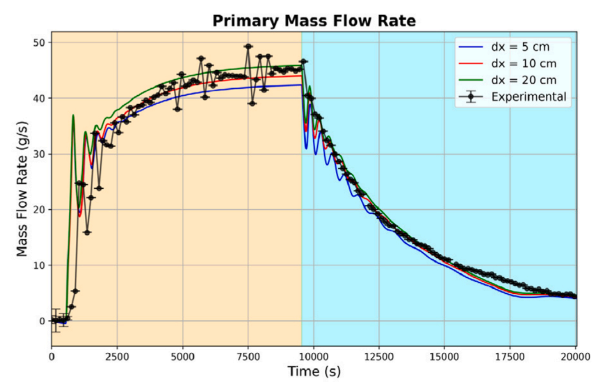



(b) Impact of nodalization on the mass flow rate for the HHHC case.

**Fig. 7.** Effect of RELAP5 nodalization for the HHHC case.

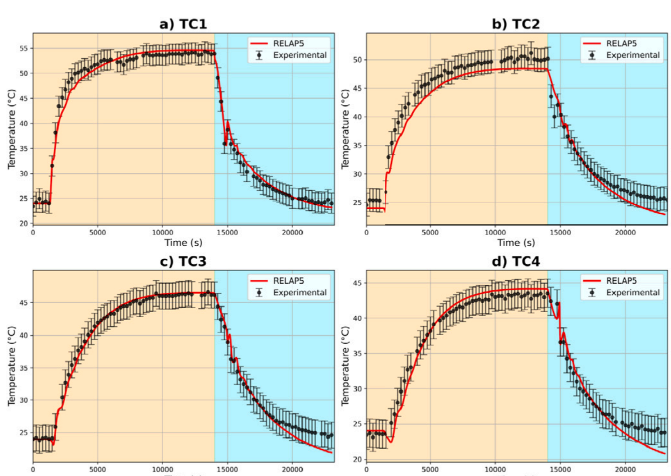



(a) Impact of nodalization on the temperature field for the DH case.

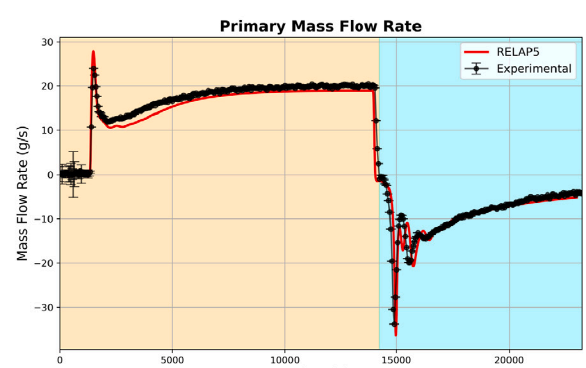



(b) Impact of nodalization on the mass flow rate for the DH case.

**Fig. 8.** Effect of RELAP5 nodalization for the DH case.

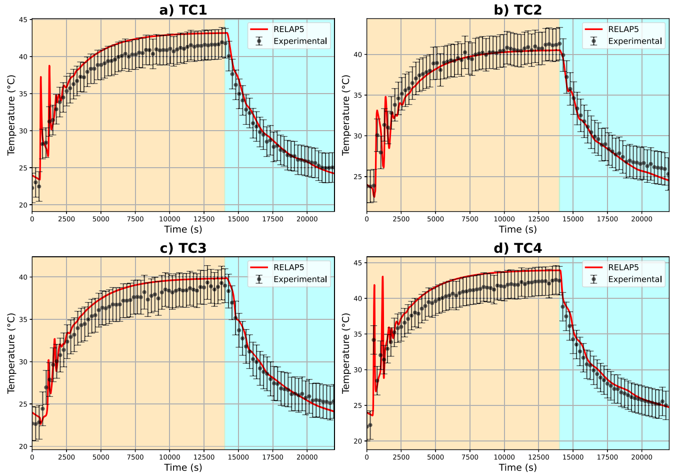



(a) Temporal evolution of DYNASTY temperatures in the VHHC case.

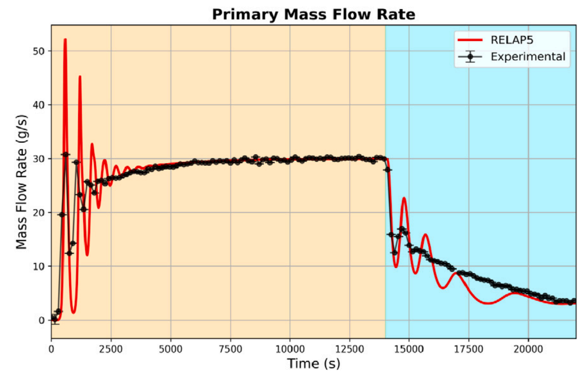



(b) Temporal evolution of mass flow rate in the VHHC case.

**Fig. 9.** Comparison of thermal-hydraulic quantities over time for the VHHC case.




(a) Temporal evolution of DYNASTY temperatures in the HHHC case.




(b) Temporal evolution of mass flow rate in the HHHC case.

**Fig. 10.** Comparison of thermal-hydraulic quantities over time for the HHHC case.

Fig. 10a presents the temporal evolution of the measured temperatures at various locations. The RELAP5 model demonstrates a strong predictive capability, accurately reproducing the heating and cooling transients across all sensors. RMSE values confirm the quality of the simulation: temperature deviations range between 1.35 °C and 1.99 °C across the four thermocouples. Specifically, TC2 shows the lowest RMSE (1.35 °C), while TC4 exhibits the highest (1.99 °C), highlighting the model's consistency in tracking spatially distributed thermal responses under different heating conditions.

Fig. 10b shows the mass flow rate evolution. The RELAP5 simulation captures the general behavior well, with good agreement during both the steady-state and cooling phases. Initial flow oscillations are overpredicted in amplitude; however, the timing and frequency are reasonably matched. The early oscillations observed in the mass flow rate are likely not due to flow meter simplifications, but rather to the model's limited ability to reproduce the system's thermal inertia during the transient startup phase. Specifically, the accumulation of heat in the lower leg of the loop is not immediately converted into fluid motion, as the onset of NC is delayed compared to the experiment. This delay results in a sharper temperature rise for TC1 and TC4 thermocouples, which in turn induces a sudden increase in driving buoyancy forces and a corresponding spike in the mass flow rate. Once NC is fully established, the model behavior aligns well with the experimental data. The steady-state conditions are qualitatively captured, as shown in Fig. 10b, indicating that the model correctly reproduces the system dynamics after the initial transient phase. The RMSE for mass flow rate in this case is 3.75 g/s, which, while slightly higher than in the VHHC configuration, remains acceptable given the dynamic nature of the flow response in the HHHC regime.

In summary, the RELAP5 model provides accurate and robust predictions in the HHHC configuration, with temperature RMSEs remaining below 2 °C and good agreement observed for mass flow dynamics across all transient phases.

### 3.5. The DH validation case

The results related to the model validation for the DH case are reported in Fig. 11a and Fig. 11b. RELAP5 satisfactorily captures both the qualitative and quantitative evolution of the experimental parameters across the entire transient. The model demonstrates good predictive capability, especially considering the long duration and complexity of the transient (over 23000 seconds).

Quantitatively, the RMSEs for temperature range from 3.28 °C (TC1) to 7.25 °C (TC3), with TC3 showing the highest deviation among all validation cases. TC4 and TC2 present intermediate discrepancies, with RMSEs of 5.23 °C and 6.42 °C, respectively. In terms of mass flow rate, Fig. 11b shows that RELAP5 replicates the overall trend quite well, with an RMSE of 5.31 g/s (Table 7). The code accurately reproduces the general dynamics of the flow during both heating and cooling phases. However, it predicts a slightly earlier increase in the flow rate during the initial transient and shows more pronounced oscillations compared to the experimental signal. These flow oscillations are partially present in the experimental data, although more damped. Additional discrepancies are observed just after the onset of the cooling transient, where RELAP5 introduces small mass flow rate oscillations that are not observed experimentally.

**Table 7**
RMSE between RELAP5 simulations and experimental data for each parameter and experiment.

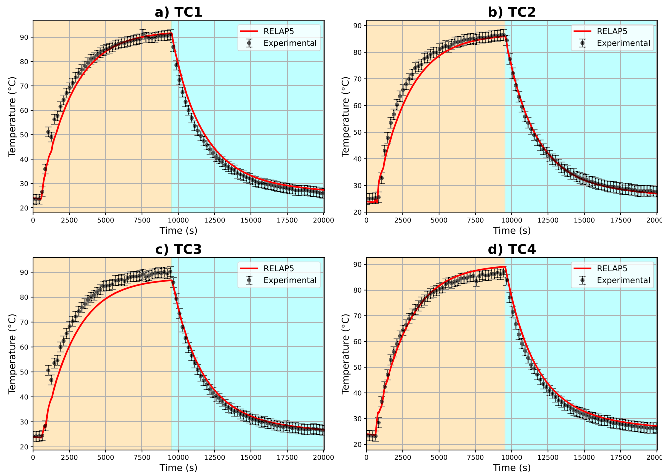
| Sensor | Unit | VHHC | HHHC | DH |
|---|---|---|---|---|
| TC1 | °C | 1.52 | 1.76 | 3.28 |
| TC2 | °C | 2.07 | 1.35 | 6.42 |
| TC3 | °C | 1.33 | 1.48 | 7.25 |
| TC4 | °C | 1.58 | 1.99 | 5.23 |
| w | g/s | 2.35 | 3.75 | 5.31 |

These deviations in both the temperature field and mass flow rate are likely due to a combination of factors. One is the model's limited ability to capture the thermal inertia of the system, particularly during the initial heating phase, leading to an anticipated onset of NC. Another factor could be a non-optimal representation of pressure losses in specific loop segments, particularly the GV2 leg, as well as unaccounted thermal losses resulting from incomplete insulation and the lack of detailed heat loss characterization from the facility. Further experimental characterization of the system's local pressure losses and thermal boundaries is planned to improve model accuracy and fidelity.

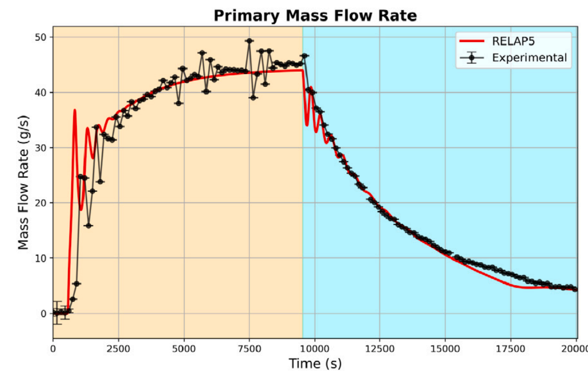
In conclusion, despite the complexity of the DH case and the absence of detailed boundary loss characterization, the RELAP5 model demonstrates acceptable agreement with experimental data, with temperature RMSEs generally below 7.5 °C and mass flow RMSE within 5.5 g/s, providing a reliable foundation for future improvements and analysis.

### 3.6. RELAP5-DYMOLA benchmark on the VHHC experimental case

Fig. 12a compares the simulation results from RELAP5 and DYMOLA with experimental data from VHHC case for the four thermocouples. RE-

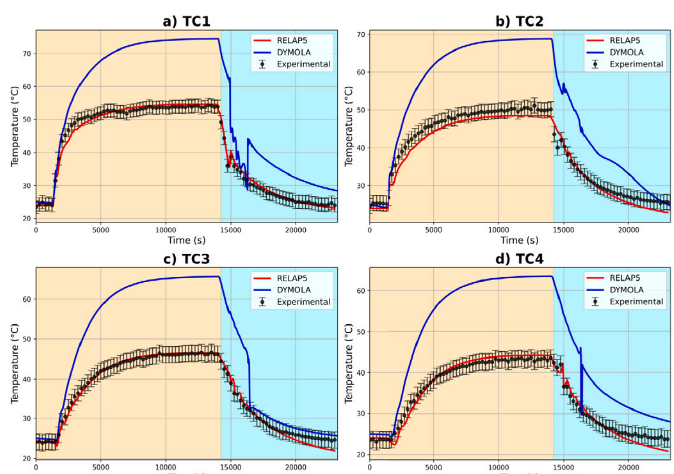



(a) Comparison of the temporal evolution of the DYNASTY temperatures in the DH case.

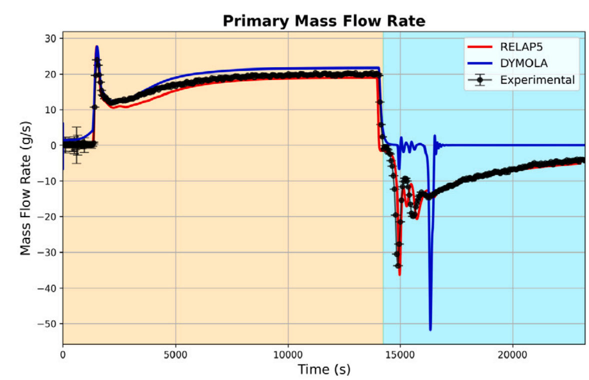



(b) Temporal evolution of mass flow rate in the DH case.

**Fig. 11.** Thermal-hydraulic behavior comparison over time for the DH case.




(a) Benchmark of the temporal evolution of the DYNASTY temperatures in the VHHC case.




(b) Benchmark of the temporal evolution of mass flow rate in the VHHC case.

**Fig. 12.** RELAP5-DYMOLA benchmark over time for the VHHC case.

LAP5 demonstrates consistently better agreement with the experimental temperatures, particularly during the steady-state condition and the cooling transient. In contrast, DYMOLA tends to overestimate steady-state temperatures and exhibits a faster thermal response, resulting in larger deviations from the experimental results, especially after the onset of cooling.

These discrepancies can be attributed to differences in the modeling approaches. First, the heater in RELAP5 is represented with a detailed heat structure, copper encased in fiberglass, which more accurately captures the system thermal inertia and heat transfer characteristics. DYMOLA, on the other hand, models heat losses using a constant HTC, whereas RELAP5 employs a table-based correlation that reflects the variation of the free convection HTC with the external pipe temperature. This simplification in DYMOLA reduces accuracy, particularly during the cooling phase, when heat loss dynamics become more significant. Overall, the comparison underscores the importance of detailed heat structure modeling and accurate heat loss characterization for reliable thermal system simulations.

Fig. 12b compares the mass flow rate predictions from RELAP5 and DYMOLA against experimental data. Both codes successfully capture the general trend during the heating transient and the steady-state condition. However, a significant discrepancy emerges during the cooling transient: only RELAP5 accurately predicts the flow reversal, reproducing both the initial oscillations and the subsequent slow decrease in flow rate with a slope comparable to the experimental data.

It is important to note that in NC systems, the mass flow rate is primarily driven by the temperature difference between the heat source and the sink. In DYMOLA, although the predicted mass flow rate may appear accurate, this can result from compensating errors in the temperature field. Specifically, the model tends to overpredict temperatures at both ends of the loop, and these overestimations cancel out when only the temperature difference is considered. This masks underlying inaccuracies in the thermal behavior. The cooling transient, in particular, highlights this limitation: DYMOLA does not adequately capture the system's thermal inertia, leading to deviations in the predicted flow. This underscores the importance of accurately modeling both the absolute temperature distribution and the hydraulic response to ensure reliable predictions in transient NC scenarios.

## 4. Conclusions

In conclusion, this study presents and validates a novel RELAP5 model of the DYNASTY facility against experimental data from past campaigns with various heat source configurations (including VHHC, HHHC, and DH). The following key findings summarize the main contributions of this study:

- A comprehensive RELAP5 model of the DYNASTY NC loop was successfully developed and validated against experimental data from multiple heating configurations, demonstrating reliable predictive capability.
- Enhanced modeling of heat sources and detailed characterization of heat losses substantially improved the agreement between simulations and experiments, particularly during transient phases.
- Sensitivity analyses on nodalization and numerical schemes confirmed the robustness and numerical stability of the model, guiding optimal modeling choices for future applications.

While RELAP5 has proven highly effective for one-dimensional thermal-hydraulic modeling and validation of passive safety systems, it presents certain limitations when considering three-dimensional phenomena. The code's inherently 1D framework restricts its ability to capture complex flow structures, localized phenomena, and spatially varying fields (e.g., multidimensional mixing or stratification effects). To overcome the inherent 1D limitations of RELAP5, coupling with computational fluid dynamics tools is often adopted, enabling more detailed spatial resolution and physics fidelity in integrated system analyses [28]. Moreover, the RELAP5 model could be coupled with other codes for multiphysics analysis, as extensively documented in the scientific literature [19] [12].

Future developments for the DYNASTY facility should prioritize the accurate characterization of pressure drops and thermal losses to the environment to minimize their impact on experimental results. Moreover, better characterization of heat transfer in the fan will help to resolve deviations between model predictions and experimental data. A focused evaluation of the mass flow rate meter will also enhance the accuracy of the facility modeling. Addressing these aspects will refine the models and reduce uncertainties in the experimental investigations. In parallel, experiments using glycol, whose Prandtl number closely resembles that of molten salts, are currently under development to better approximate the thermal-hydraulic behavior of the MSFR. In the longer term, given that the DYNASTY facility is designed to safely host molten salts, future campaigns will aim to use these fluids directly, bringing the experimental conditions even closer to real reactor scenarios.

Overall, in the context of advancing nuclear safety, this study offers valuable contributions to the validation of passive safety system models based on NC, addressing critical modeling challenges and paving the way for enhanced reliability and safety in next-generation reactor systems.

## Nomenclature

### Acronyms

| | |
|---|---|
| **DH** | Distributed Heating |
| **DYNASTY** | DYnamics of NAtural circulation for molten SalT internallY heated |
| **HHHC** | Horizontal Heater Horizontal Cooler |
| **HTC** | Heat Transfer Coefficient |
| **IHG** | Internal Heat Generation |
| **LFR** | Lead-cooled Fast Reactor |
| **MSFR** | Molten Salt Fast Reactor |
| **NC** | Natural Circulation |
| **RMSE** | Root Mean Square Error |
| **SMR** | Small Modular Reactor |
| **SNGLJUN** | Single Junction |
| **SPES3** | Simulatore Pressurizzato per Esperienze di Sicurezza |
| **TMPDVOL** | Time-dependent volume |
| **VHHC** | Vertical Heater Horizontal Cooler |

## CRediT authorship contribution statement

**Andrea Missaglia:** Writing – original draft, Validation, Methodology, Formal analysis. **Gabriele Benzoni:** Writing – review & editing, Formal analysis. **Carolina Introini:** Writing – review & editing. **Marco Enrico Ricotti:** Writing – review & editing. **Antonio Cammi:** Writing – review & editing, Methodology, Conceptualization. **Francois Foulon:** Writing – review & editing.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References

[1] D.N. Basu, S. Bhattacharyya, P. Das, A review of modern advances in analyses and applications of single-phase natural circulation loop in nuclear thermal hydraulics, Nucl. Eng. Des. 280 (2014) 326–348.
[2] A. Battistini, A. Cammi, S. Lorenzi, M. Colombo, M. Fairweather, Development of a cfd–les model for the dynamic analysis of the dynasty natural circulation loop, Chem. Eng. Sci. 237 (2021) 116520.
[3] G. Benzoni, Natural circulation modeling and experimental validation of the dynasty facility, 2020.
[4] G. Benzoni, C. Introini, S. Lorenzi, A. Cammi, Preliminary validation of the 1D modeling of the dynasty natural circulation loop against results from water experimental campaign, Prog. Nucl. Energy 155 (2023) 104486.
[5] G. Benzoni, C. Introini, S. Lorenzi, L. Loi, A. Cammi, 1d modelling and preliminary analysis of the coupled dynasty–edynasty natural circulation loop, Front. Energy Res. 11 (2023) 1165179.
[6] A. Bersano, C. Lombardo, F. Alblouwy, I. Karppinen, A. Silde, K. Nikitin, B. Grosjean, F. Morin, J. Martin, F. Weyermann, Benchmark exercise on elsmor passive heat removal system, Nucl. Eng. Des. 419 (2024) 112961.
[7] A. Cammi, M. Cauzzi, L. Luzzi, A. Pini, et al., Dynasty: an experimental loop for the study of natural circulation with internally heated fluids, in: Proceedings of the 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT), 2016, pp. 11–13.
[8] A. Cammi, L. Luzzi, A. Pini, The influence of the wall thermal inertia over a single-phase natural convection loop with internally heated fluids, Chem. Eng. Sci. 153 (2016) 411–433.
[9] M.T. Cauzzi, Modelling and experimental investigation of natural circulation in presence of distributed heating, 2019.
[10] K. Cheng, T. Meng, C. Tian, H. Yuan, S. Tan, Experimental investigation on flow characteristics of pressure drop oscillations in a closed natural circulation loop, Int. J. Heat Mass Transf. 122 (2018) 1162–1171.
[11] S. Deanesi, Multiphysics analysis of accidental transients for a molten salt fast reactor, 2021.
[12] S. Dong, J. Wei, W. Wang, K. Zhang, R. Pan, S. Wang, H. Chen, Development and application of three-dimensional multi-physics and multi-scale coupling program for lead cooled fast reactor, Ann. Nucl. Energy 219 (2025) 111486.
[13] ELSI, http://www.elsi.it/en/products/thermocouple/ELSI_TC_Q1_UK.pdf, 1998.
[14] Endress-Hauser, https://www.it.endress.com/en/field-instruments-overview/flow-measurement-product-overview/Product-Coriolis-flowmeter-Proline-Promass-80F, 2017.
[15] X. Hou, Z. Sun, W. Lei, Capability of relap5 code to simulate the thermal-hydraulic characteristics of open natural circulation, Ann. Nucl. Energy 109 (2017) 612–625.
[16] I.E. Idelchik, Handbook of Hydraulic Resistance, 1986, Washington.

[17] F.P. Incropera, D.P. DeWitt, T.L. Bergman, A.S. Lavine, et al., Fundamentals of Heat and Mass Transfer, vol. 6, Wiley, New York, 1996.

[18] Y.S. Jeong, S.B. Seo, I.C. Bang, Natural convection heat transfer characteristics of molten salt with internal heat generation, Int. J. Therm. Sci. 129 (2018) 181–192, https://doi.org/10.1016/j.ijthermalsci.2018.01.036.

[19] P. Kakaei, M. Zangian, M. Abbasi, Multi-physics core analysis and verification of nuscale reactor with coupling parcs/relap, Ann. Nucl. Energy 193 (2023) 110021.

[20] P. Lorusso, S. Bassini, A. Del Nevo, I. Di Piazza, F. Giannetti, M. Tarantino, M. Utili, Gen-iv lfr development: status & perspectives, Prog. Nucl. Energy 105 (2018) 318–331.

[21] A. Mangal, V. Jain, A. Nayak, Capability of the relap5 code to simulate natural circulation behavior in test facilities, Prog. Nucl. Energy 61 (2012) 1–16.

[22] F. Mascari, B. Woods, K. Welter, F. D'Auria, et al., Validation of the trace code against small modular integral reactor natural circulation phenomena, in: 18th Int. Top. Meet. on Nuclear Reactor Thermal-Hydraulics (NURETH-18), Portland (or, US), Aug. 18-22, 2019, in: American Nuclear Society, vol. 804, 2019, pp. 6701–6716.

[23] S. Nasiri, G. Ansarifar, M. Esteki, Design of the carem nuclear reactor core with dual cooled annular fuel and optimizing the thermal-hydraulic, natural circulation, and neutronics parameters, Ann. Nucl. Energy 169 (2022) 108939.

[24] D. van Nijen, Investigation of natural circulation capabilities of the Molten Salt Fast Reactor, Ph.D. thesis, Bachelor of Science Thesis, Delft University of Technology Delft, 2018.

[25] E. Novarese, G. Benzoni, C. Introini, S. Lorenzi, L. Savoldi, a. Cammi, Stability analysis on two single-phase coupled natural circulation loops, Available at, SSRN 4748047.

[26] D. Papini, D. Grgić, A. Cammi, M.E. Ricotti, Analysis of different containment models for iris small break loca, using gothic and relap5 codes, Nucl. Eng. Des. 241 (2011) 1152–1164.

[27] A. Pini, A. Cammi, M. Cauzzi, F. Fanale, L. Luzzi, An experimental facility to investigate the natural circulation dynamics in presence of distributed heat sources, Energy Proc. 101 (2016) 10–17.

[28] P.C. Puviani, T. Del Moro, B. Gonfiotti, D. Martelli, F. Giannetti, R. Zanino, M. Tarantino, A novel ansys cfx–relap5 coupling tool for the transient thermal-hydraulic analysis of liquid metal systems, Prog. Nucl. Energy 180 (2025) 105590.

[29] S. Rassame, T. Hibiki, M. Ishii, Esbwr passive safety system performance under loss of coolant accidents, Prog. Nucl. Energy 96 (2017) 1–17.

[30] J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J.L. Kloosterman, et al., The molten salt reactor (msr) in generation iv: overview and perspectives, Prog. Nucl. Energy 77 (2014) 308–319.

[31] B. Sutharshan, M. Mutyala, R.P. Vijuk, A. Mishra, The AP1000TM reactor: passive safety and modular design, Energy Proc. 7 (2011) 293–302.

[32] The RELAP5 Code Development Team, RELAP5/MOD3.3 Users Manual, Rockville, Maryland and Idaho Falls, Idaho 2002.

[33] K. Welter, J.N. Reyes Jr, A. Brigantic, Unique safety features and licensing requirements of the nuscale small modular reactor, Front. Energy Res. 11 (2023) 1160150.

[34] H. Zhang, Research on the Versatility of Arctic Marine Nuclear Power Plant, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2021, 012031.