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Numerical Analysis of the Rectangular Natural Circulation Loop of IPEN/CNEN-SP in the Dymola Software

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1. Introduction

The Natural Circulation (NC) circuits play a crucial role in nuclear engineering, particularly in nuclear reactors. Their significance stems from their ability to act as a passive safety feature, highlighted by the International Atomic Energy Agency (IAEA), providing core cooling even in critical operational conditions or lack of external power. This feature is particularly valuable given the independence of these systems from human actions, often associated with failures in nuclear accidents.

In the context of nuclear reactor generations, natural convection circuits have been widely studied in second and third-generation plants, notably in Pressurized Water Reactors (PWR), where their application can reduce the number of required equipment, plant size, and overall deployment costs. Moreover, the effectiveness of these systems in handling core residual heat during safe or emergency shutdowns has contributed significantly to the safety and efficiency of these nuclear facilities.

In the realm of Nuclear Power Plants used in ships and submarines for naval propulsion and electricity generation, natural circulation faces additional challenges. The operational conditions of these vessels, subject to tidal fluctuations, movements due to navigation, and significant inclinations in submarines, introduce complex variables that can affect the performance of the natural circulation cooling system. These conditions require an in-depth understanding of the phenomenon under movement, particularly concerning heat transfer, to ensure the safety and effectiveness of these embedded reactors.

At the Institute of Energy and Nuclear Research (IPEN), numerous studies have been conducted on natural circulation, including recent works highlighting the coherence between experimental and numerical results. This article seeks to contribute to this body of knowledge, focusing on the numerical analysis of the performance of the natural circulation cooling system in embedded nuclear reactors. The work aims to validate the use of Dymola software, a prominent Modelica-based tool for numerical simulations, compared to experimental data and previous simulations conducted with RELAP5 software.

The underlying motivation for this work lies in the validation of an object-oriented language for numerical simulations, comparing it with previous RELAP5/MOD3.3 results to ensure its applicability in future circuit simulations. General objectives include the development of a comprehensive numerical model to represent thermo-hydraulic phenomena under various operational conditions, thereby contributing to the advancement of scientific and technological research in the thermo-hydraulics of nuclear reactors onboard ships.

The investigation into natural circulation in single-phase systems has been addressed by various researchers over the decades. Initially, ALSTAD et al. (1956) proposed an iterative method based on finite differences to predict temperature and flow in natural circulation circuits in single-phase regime, highlighting its effectiveness in predicting the transient behavior of the flow. Later, KELLER (1966) identified periodic oscillations in a one-dimensional thermal convection model, contributing to the understanding of these phenomena. WELANDER (1967) expanded these theoretical analyses, exploring oscillatory instability in closed circuits. ZVIRIN (1982) and GREIF (1988) provided comprehensive reviews on natural circulation, discussing analytical and numerical methods for different circuit geometries.

Subsequent studies broadened the perspectives. HUANG and ZELAYA (1988) investigated the thermal performance of a rectangular thermosyphon loop, while SHARMA et al. (2002) modeled transient behavior using the RELAP5/MOD3.2 code, providing detailed analyses of influential factors. MOUSAVIAN et al. (2004) compared three distinct methods in modeling, indicating the effectiveness of varied approaches. GARTIA, VIJAYAN, and PILKHWAL (2006) proposed a correlation for steady-state two-phase flow, experimentally and numerically validated.

MARTIN and TAYLOR (1992) evaluated the RELAP5/MOD3 code in both single-phase and two-phase flows, while SABUNDJIAN et al. (2010) also simulated experiments in single-phase and two-phase regimes, highlighting the reliability of results obtained in the RELAP5/MOD3.2 code. ANGELO et al. (2012) conducted a three-dimensional analysis, emphasizing the need for coupling between one-dimensional and three-dimensional models. These studies, addressing different aspects of natural circulation, form a solid foundation for comprehensive understanding and advancement in the modeling of these systems. For this, the commercial software ANSYS-CFX® was used for numerical simulation and comparison with experimental results.

MANGAL, JAIN, and NAYAK (2012) developed a comparative model of two circuits using the RELAP5/MOD3.2 code, revealing limitations of the code in representing two-phase flow in parallel channels. MISALE (2016) investigated single-phase behavior, observing thermal oscillations and emphasizing the influence of the circuit's thermal inertia. BRAZ FILHO et al. (2017) evaluated linear equation solvers in the RELAP5/MOD3.3 and RELAP5-3D codes, highlighting the influence of solver choice on predicting two-phase circulation phenomena. VINHAS (2018) and FRENZEL (2019) confronted experimental data with RELAP5/MOD3.2 simulations, revealing that, although the code can predict the general flow behavior, there are challenges in representing instabilities characteristic of natural circulation. These studies, addressing different aspects of natural circulation, offer valuable insights for the advancement in modeling and understanding these complex systems.

The Natural Circulation Loop (NCL) at IPEN is a rectangular closed system, filled with demineralized water and suspended by steel cables in a metal structure to ensure integrity during experiments. Its dimensions are 2,600 mm in height and 850 mm in width, excluding the expansion tank. The tubes, made of Pyrex glass, have a constant circular section, connecting the heater to the heat exchanger, with an internal diameter of 38.1 mm and a thickness of 4.4 mm. The heater, composed of two electric resistances, operates with a total power of 7,800 W, with one of them adjustable by a voltage variator.

These characteristics allow experiments in both single-phase and two-phase regimes in the circuit. The schematic diagram of the IPEN can be visualized in Figure 1.

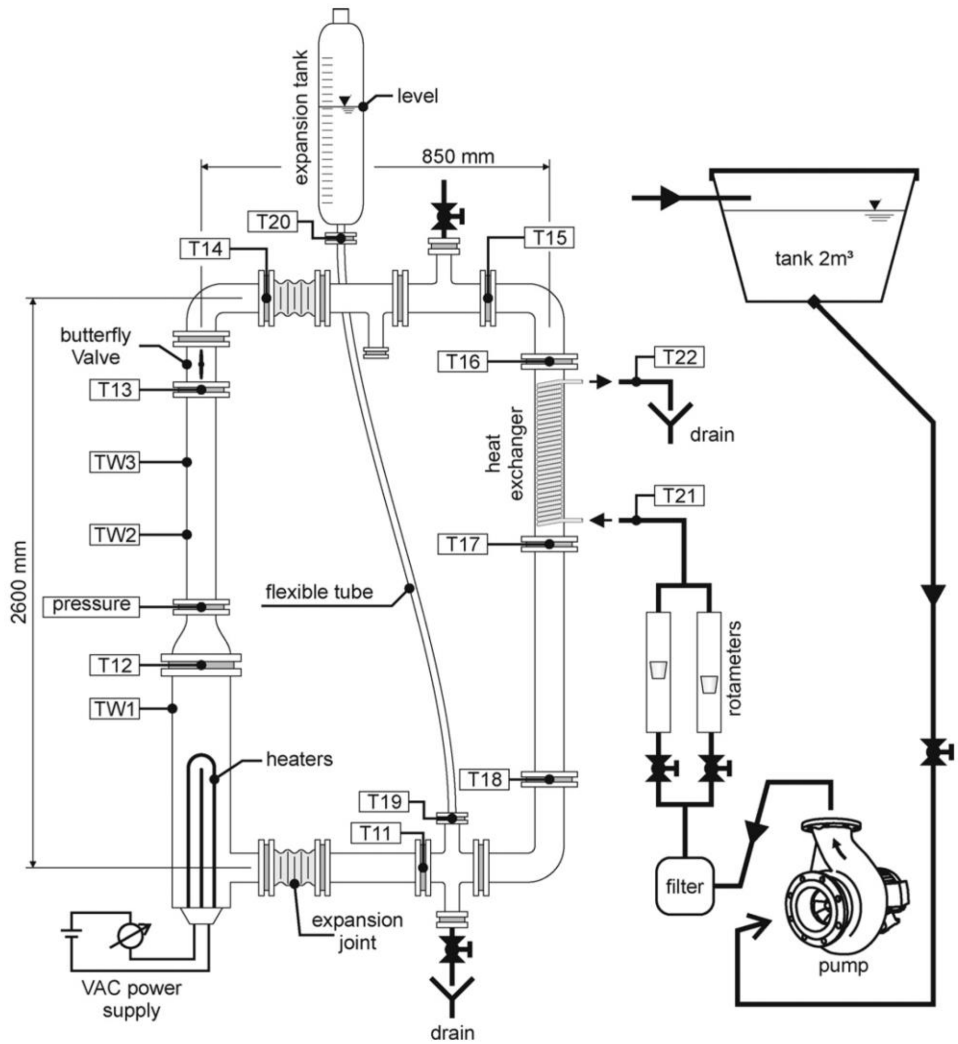

Figure 1 – Schematic diagram of the Natural Circulation Loop at IPEN.

Fonte: ANGELO et al. (2012).

2. Methodology

The methodology developed to configure the Natural Circulation Loop of IPEN in the object-oriented Dymola software involved the following steps:

Firstly, the geometric representation of the Natural Circulation Loop in Dymola was performed. Modelica and TRANSFORM libraries were utilized for each circuit component, such as pipes, heater, heat exchanger, expansion tank, and steel cables. The geometry was modeled according to the real dimensions of the circuit. Figure 2 represents the final configuration of Natural Circulation Loop modeling in Dymola.

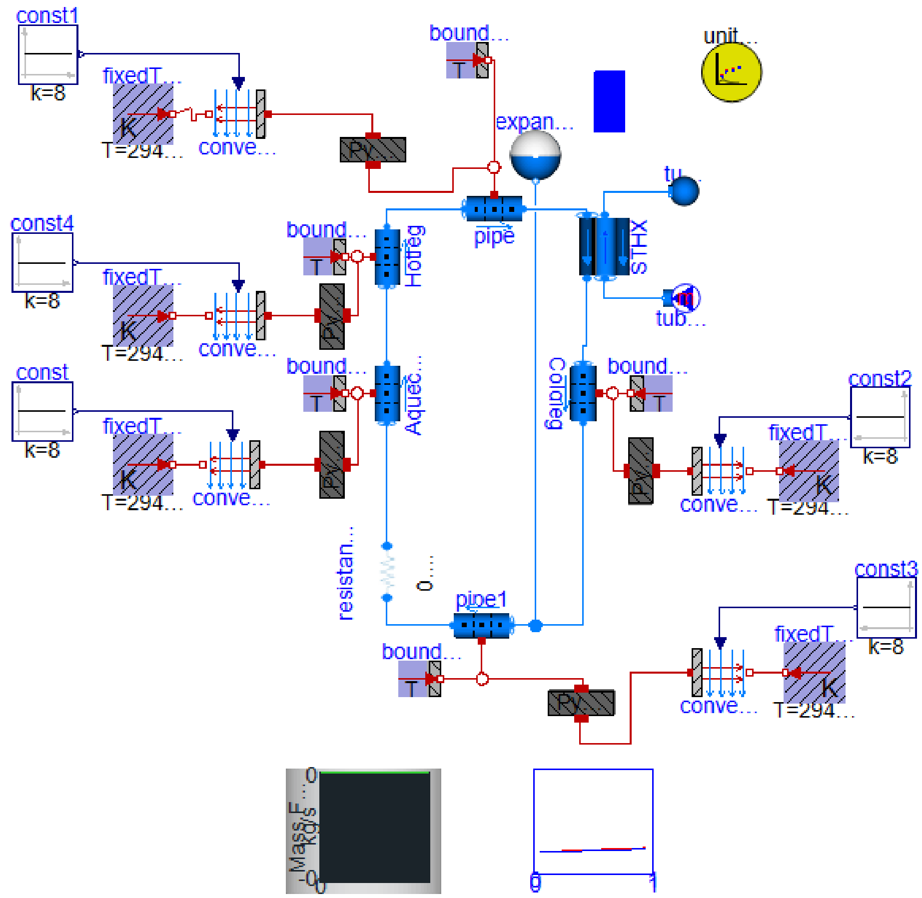

Figure 2 – Modeling of the Natural Circulation Loop at IPEN in Dymola.

Source: author.

Following geometric modeling, specific materials were assigned, such as Pyrex glass for the pipes, circuit fluid, etc. Additionally, the necessary thermal properties to simulate the behavior of the circulating fluid were incorporated. Connections between components were established, reflecting the actual topology of the Natural Circulation Loop. Proper nodalization was implemented to capture points of interest, such as fluid inlets and outlets, connections of the heater, and heat exchanger. For this purpose, ten nodes were created in each component to extract information at specific positions of the Natural Circulation Loop.

The system's dynamics were modeled, taking into account thermal and hydraulic interactions. Differential equations of mass, momentum, and energy conservation were incorporated into the models developed by the libraries, describing the thermal and dynamic behavior of the model. During modeling, there is the possibility to alter the power in the heater before starting the simulation, according to the desired simulation, allowing for the simulation of different operating conditions, including single-phase and two-phase flow regimes.

This methodology provided a virtual representation of the Natural Circulation Loop in Dymola, enabling dynamic simulations and detailed analyses of the thermal-hydraulic behavior of the system under various conditions.

3. Results and Discussion

Single-phase regime

From the simulations of the model in Dymola, it was possible to observe an excellent agreement with the experimental and numerical results of the Instituto de Pesquisas Energéticas e Nucleares (IPEN) Natural Circulation Loop in RELAP5/MOD3.3. The simulation results in Dymola demonstrate a good accuracy in reproducing the observed behavior in other literature works, especially in the works of SABUNDJIAN et al. (2010), ANGELO (2012) and FRENZEL and SABUNDJIAN (2019).

The results obtained from the Dymola simulation for a 1000W power input into the heater recorded an increase in fluid temperature at the heater outlet. The analysis focused on the upper horizontal (pipe) and lower horizontal (pipe1) pipes, particularly observing the temperature reduction after passing through the heat exchanger. In all analyzed cases, it was possible to track the variations in the fluid temperature of the Natural Circulation Loop as it enters the natural circulation mode, as predicted by literature works. Figure 3 illustrates the fluid heating at node 10 of the heater.

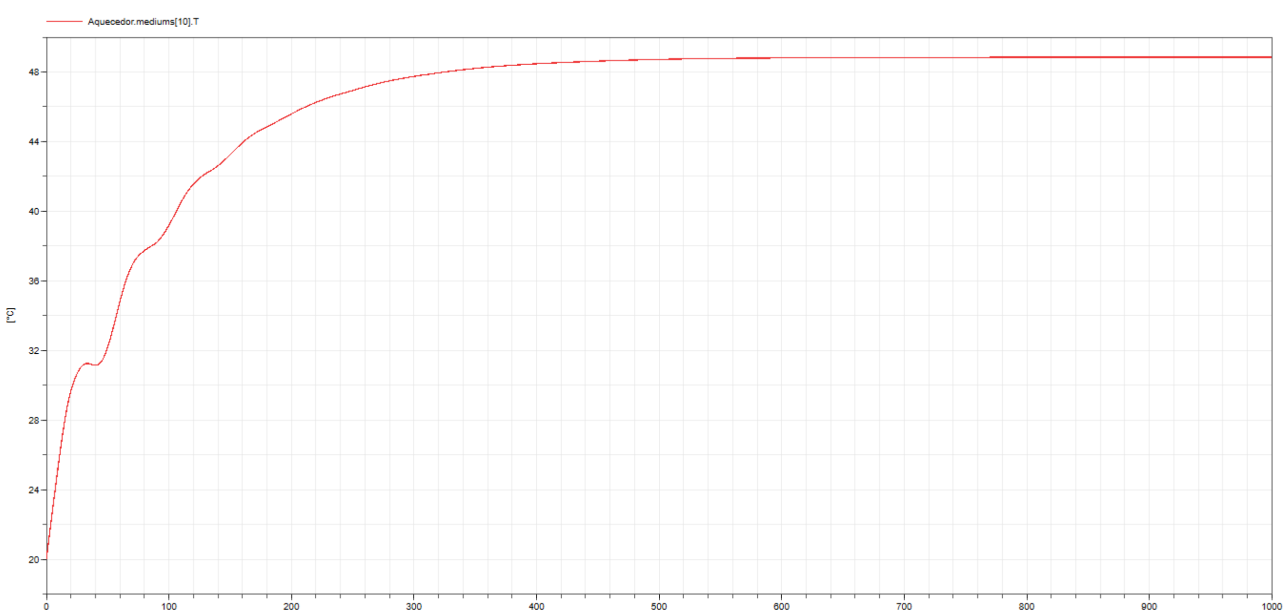

Figure 3 – Simulation of the IPEN NCL for 1000W in the Dymola software for the heater.

Source: author.

For a heater power of 1000W, a dynamic response in the system was observed, reflected in temperature changes along the pipes. The analysis of the working fluid's behavior after the heat exchanger in the cold leg revealed patterns consistent with expectations in natural circulation situations, supporting the findings in the specialized literature. In Figure 4, the temperature variation in the horizontal pipes is observed, demonstrating the temperature change in the Natural Circulation Loop. The number in brackets represents the node position in each pipe, with 1 for the inlet node and 10 for the outlet node of the pipe.

The thermal-hydraulic behavior of the Natural Circulation Loop, simulated in Dymola, demonstrated the significant influence of increasing fluid heating power and temperature variations along the circuit. The transition to the natural circulation mode was clearly identified by the observed temperature patterns, indicating the occurrence of the phenomenon in accordance with theoretical-experimental expectations.

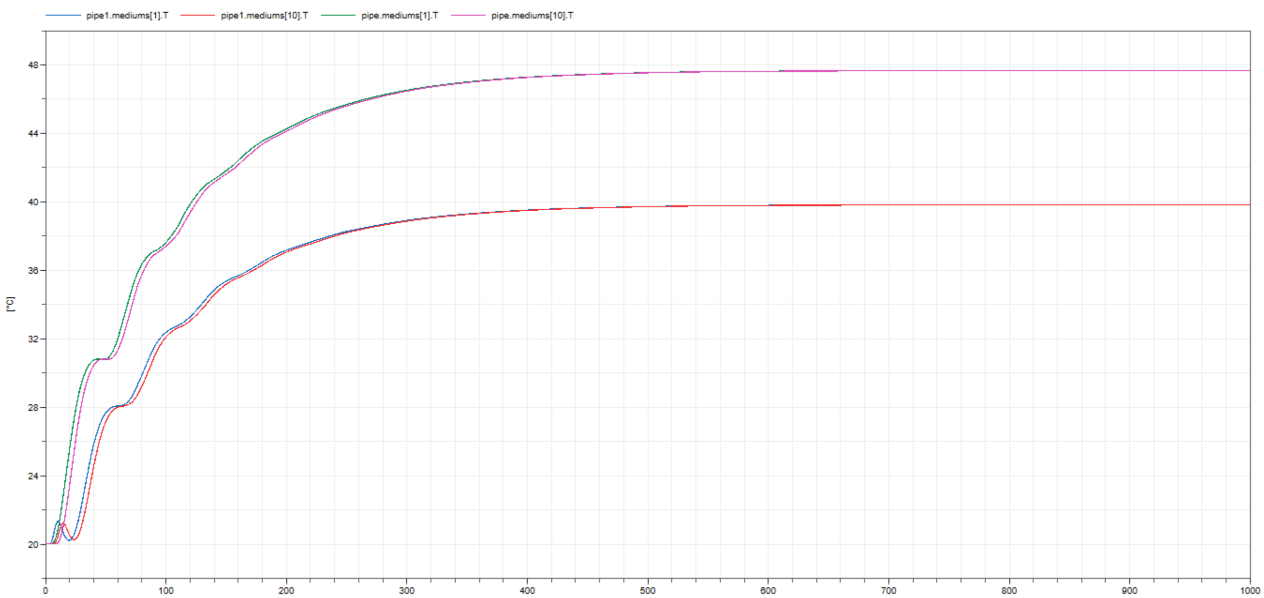

Figure 4 – Simulation of the IPEN NCL for 1000W in the Dymola for upper and lower horizontal pipes.

Source: author.

These results validate the model's ability in Dymola to faithfully represent the behavior of the Natural Circulation Loop in a single-phase regime. The agreement with patterns observed in the literature strengthens the reliability of the model and contributes to a thorough understanding of the thermal-hydraulic performance of the Natural Circulation Loop under different operational scenarios.

Two-phase regime

In the Dymola simulation, when increasing the power at the heater outlet to 7800W, results were observed indicating a transition to the two-phase regime in the Natural Circulation Loop. The analysis of the upper (pipe) and lower (pipe1) horizontal pipes, for the same previous positions, revealed not only a sharp increase in temperatures but also the manifestation of typical instabilities of the two-phase regime, providing valuable insights into the system's behavior. Figure 5 shows both heating and the appearance of instabilities in the fluid at nodes 1 (inlet) and 10 (outlet) of the heater.

In this new heater power configuration, two-phase instabilities began to manifest, evidenced by the rise in fluid temperature along the Natural Circulation Loop. Abrupt increases and decreases in temperatures were observed, indicating the presence of oscillations in the two-phase flow. These oscillations are characterized by disturbances in temperature and flow distribution, manifesting as regions of instability.

It was also possible to observe instability regions in the horizontal pipes, at node 1 of the upper horizontal pipe (pipe.mediums[1]), and at node 10 at the exit of the lower horizontal pipe (pipe1.mediums[10]), forming more prominently. These points stand out as critical points where biphasic conditions caused intense variations in the thermo-hydraulic properties of the fluid. These observations are consistent with what is expected for biphasic regimes, where abrupt changes in flow and heat transfer are intrinsic characteristics of this type of flow.

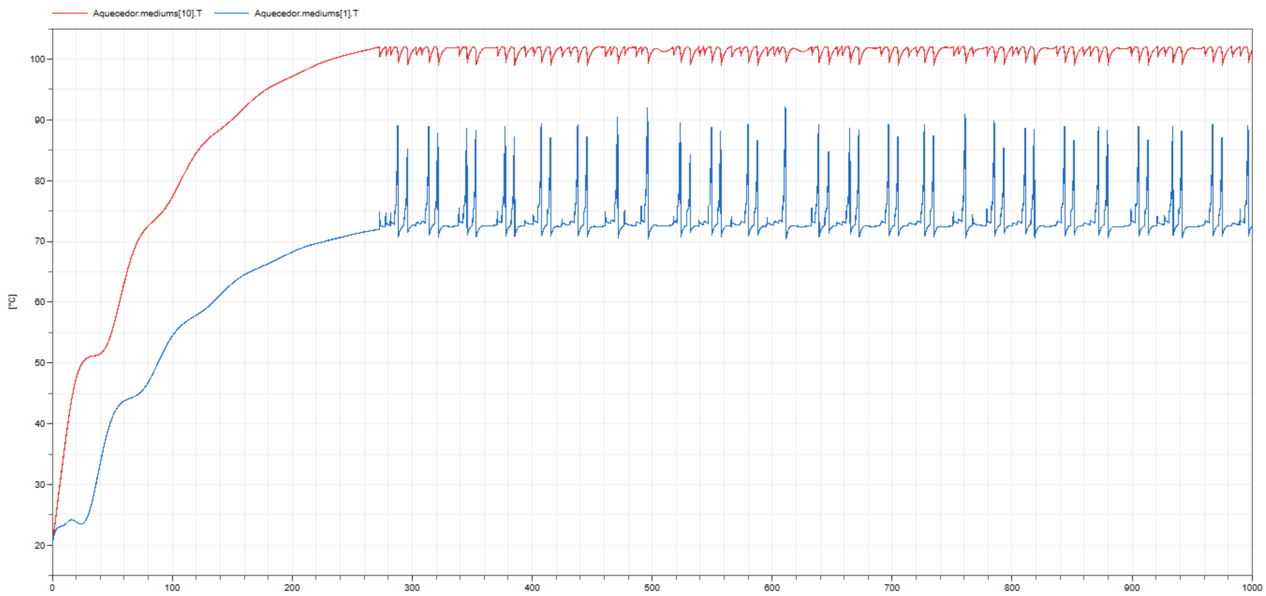

Figure 5 – Simulation of the IPEN NCL for 7800W in the Dymola for the heater.

Source: author.

Figure 6 – Simulation of the IPEN NCL for 7800W in the Dymola for the upper and lower horizontal pipes.

Source: author.

The appearance of instability regions in the biphasic regime during the Dymola simulation reflects the sensitivity of Dymola to capture operational conditions and the occurrence of instabilities in the NCL. This analysis provides a detailed understanding of how the system responds to a substantial increase in heating power, allowing the identification of critical behaviors associated with biphasic flow. A comparison of flow rates observed in monophasic and biphasic flows can be seen in Figure 7.

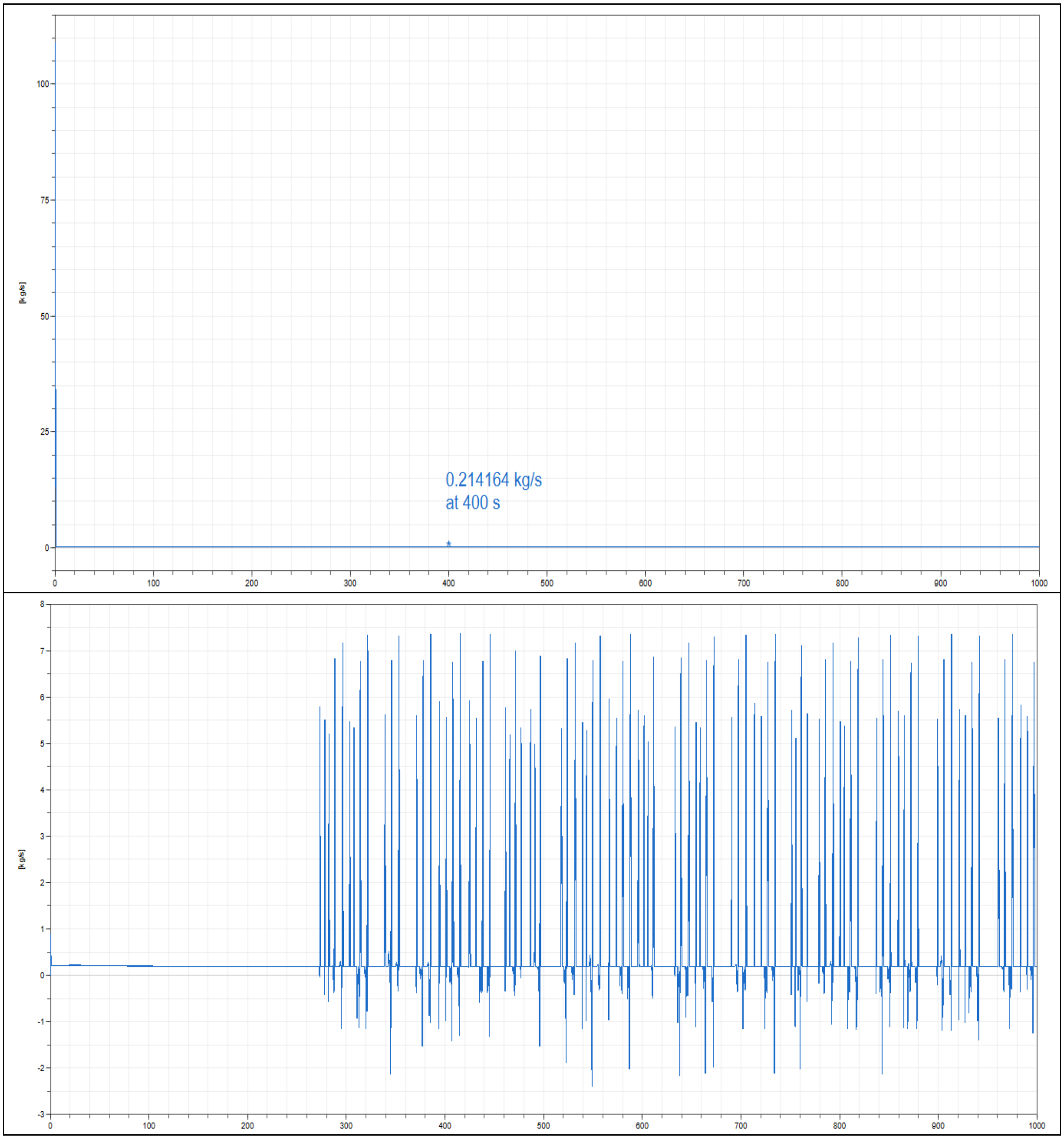

Figure 7 – Comparison of flow rates of Single-phase and Two-phase regimes of the IPEN NCL in the Dymola.

Source: author.

The successful simulation of the biphasic regime in Dymola provides valuable information for optimizing the performance of the NCL under conditions that replicate extreme situations, consolidating the reliability and applicability of the developed model. However, improvements in the model and adjustments to implement sensors for temperature measurement at specific locations in the NCL are possible enhancements to be implemented.

4. Conclusions

In conclusion, the study on natural circulation developed in Dymola presents significant advancements in understanding the behavior of the Natural Circulation Loop (NCL) under different operational conditions. The obtained results provide valuable insights into the system's response to power variations, highlighting the transition to the two-phase regime and the manifestation of associated instabilities.

Strengths of this study include the Dymola model's ability to simulate the thermo-hydraulic characteristics of the NCL accurately and dynamically. The representation of instabilities in the two-phase regime and variations in temperatures along the circuit align with existing knowledge in the literature, converging to validate the developing model.

Potential improvements can be directed towards enhancing the model's accuracy, considering additional factors such as the influence of external disturbances and variations in fluid properties. Additionally, expanding the study to include vessel inclinations would be a valuable extension, providing a more comprehensive understanding of the NCL's behavior in scenarios closer to operational reality, an area still underexplored in the works conducted at IPEN.

Advancements in modeling are underway to prepare the system to account for vessel inclinations, aiming to replicate more realistic conditions found in naval environments. This expansion of modeling will allow for a more in-depth analysis of the effects of inclination on natural circulation, contributing to the practical application of the study in maritime contexts.

In summary, the study in Dymola represents a solid foundation for future investigations, emphasizing the importance of dynamic and accurate modeling in understanding the behavior of natural circulation systems. The continuous pursuit of improvements and expansions in modeling will ensure the ongoing relevance and applicability of this work in the optimization and safety of embedded nuclear reactors.

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