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Validation of SPACE Code for Flashing-Induced Instability Using CIRCUS Experiments

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1. Introduction

Small modular reactors (SMRs) are increasingly recognized for their enhanced safety and economic potential, largely owing to their reliance on passive safety systems that can function without external power or operator intervention. Among these, the passive containment cooling system (PCCS) was introduced and developed since the early 1990s, with applications in advanced reactor concepts such as the AP1000, ESBWR, and VVER-1200 [1, 2, 3]. PCCS utilizes gravity-driven natural circulation and large external water pools as ultimate heat sinks, providing long-term decay heat removal through a simplified and cost-effective approach.

However, natural circulation inherently relies on relatively weak driving forces, making PCCS susceptible to flow instabilities. One of the critical instability phenomena that can occur in PCCS is flashing-induced instability (FII). FII arises when superheated coolant undergoes rapid phase change, causing abrupt fluctuations in void fraction and flow rate. This can cause mechanical vibration, thermal fatigue, system control failure, disturb heat transfer leading to reduced performance, potential structural damage, and ultimately threaten structural integrity and overall safety.

This issue is even more pronounced for SMRs, where compact layouts and greater reliance on passive systems amplify the sensitivity to such instabilities. Therefore, it is vital to understand and address the phenomena during the design stage. In this context, it is crucial that the SPACE code [4], the safety analysis code, can accurately capture and predict FII. Demonstrating this capability not only enhances confidence in the code but also ensures a reliable foundation for assessing SMR designs against instability risks.

2. Mechanism of flashing-induced instability

Flashing-induced instability occurs in natural circulation boiling water reactors when the hydrostatic head decreases along a tall chimney or riser. As the heated coolant ascends, it becomes superheated above the local saturation temperature, leading to flashing in the unheated riser section. The sudden vapor generation increases void fraction, enhancing buoyancy and raising the natural circulation flow rate as shown in Figure 1. This increased flow subsequently lowers the inlet coolant temperature, suppressing flashing and reducing the driving force. The reduced flow then causes coolant superheating again, initiating another flashing event. This feedback loop produces self-sustained oscillations in flow rate. In general, FII can be suppressed by increasing system pressure or modifying chimney design.

A similar mechanism can arise in PCCS, where long vertical risers and natural circulation are employed to transfer heat from the containment to external water pools. Under such conditions, flashing in the riser section may trigger flow oscillations analogous to those in boiling water reactors. Consequently, understanding the onset and behavior of FII within PCCS configurations is essential, as such instabilities could compromise long-term heat removal capability and, in turn, system safety.

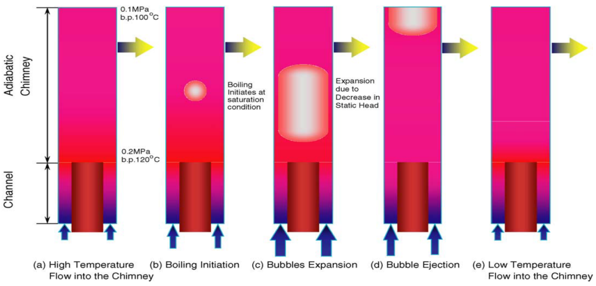

Figure 1 Mechanism of flashing-induced instability [5]

3. Methodology

3.1. Experimental facility

The CIRCUS facility, constructed at Delft University of Technology in the Netherlands, is a steam–water loop designed to investigate natural-circulation boiling water reactor (BWR) behavior. The loop consists of four electrically heated parallel channels forming the core section, a 3 m long adiabatic riser, a buffer vessel for inlet temperature control, a steam dome to maintain system pressure at saturation conditions, a heat exchanger for condensation, and a downcomer equipped with a regulating valve as shown in Figure 2. This configuration reproduces the essential hydraulic features of a natural-circulation-cooled BWR, enabling controlled studies of flashing-induced instabilities under low-pressure, low-power startup conditions. A comprehensive instrumentation system, including magnetic flow meters, thermocouples, and pressure sensors, provides detailed measurements of flow, temperature, and pressure transients throughout the facility [6].

Experimental investigations at the CIRCUS facility have clearly identified the onset and progression of FII as the system transitions from single-phase to two-phase natural circulation. Results demonstrated that instabilities develop as the system crosses into the two-phase natural circulation regime, with flashing in the riser acting as the dominant driving mechanism. The experiments further confirmed that increasing system pressure has a stabilizing effect, while the compressible volume of the steam dome provides a feedback mechanism that reduces oscillation amplitude.

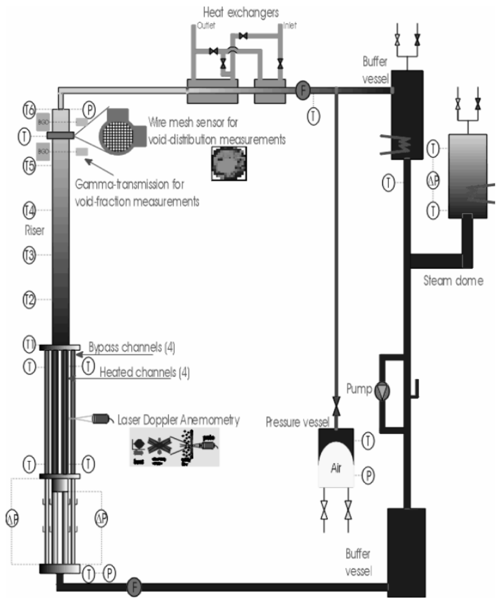

Figure 2 Schematic of CIRCUS facility [6]

3.2. SPACE code modeling

SPACE code version 3.3.2 was used to validate the FII phenomena. The nodalization is illustrated in Figure 3. The core section, consisting of four parallel heated channels, was modeled using PIPE components. The riser located above the core was also modeled as a PIPE component with its geometry reflecting the experimental configuration. Heat removal in the condenser was implemented using heat structure element, and the auxiliary heater in the buffer vessel was similarly modeled to ensure temperature control at the core inlet. Since detailed secondary-side information was unavailable, heat structure elements were adjusted such that the inlet temperature matched the measured data. The steam dome was modeled as a pressure boundary condition to maintain the system pressure. The downcomer outlet flow area was adjusted to stabilize the mass flow rate at approximately 0.097 kg/s, consistent with experimental conditons.

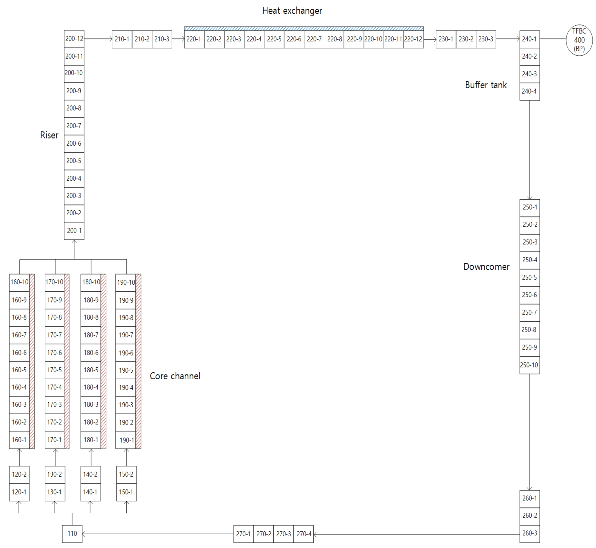

Figure 3 Nodalization of the CIRCUS facility

4. Results

Validation was performed for three experimental cases previously analyzed using RELAP5 [7], as summarized in Table 1. Figures 4, 5, 6 show the comparison of flow oscillations with increasing inlet temperature. As the inlet temperature increased, the length of the incubation period decreased, leading to a higher oscillation frequency. This trend was consistent with experimental observations. Moreover, both the oscillation period and amplitude predicted by SPACE closely matched the measured data, confirming the capability of the code to capture the flashing-induced instability mechanism. These findings suggest that SPACE can be effectively applied to qualitative assessments of natural circulation instabilities in reactor systems, especially under conditions where flashing plays a dominant role.

Table 1 Simulated CIRCUS test cases [7]

Experiment	System pressure (bar)	Total power (kW)	Inlet temperature (°C)	Steam dome water level (cm)
M06	1.0	8.0	85.5	28.0
M07	1.0	8.0	87.3	28.0
M08	1.0	8.0	90.4	28.0

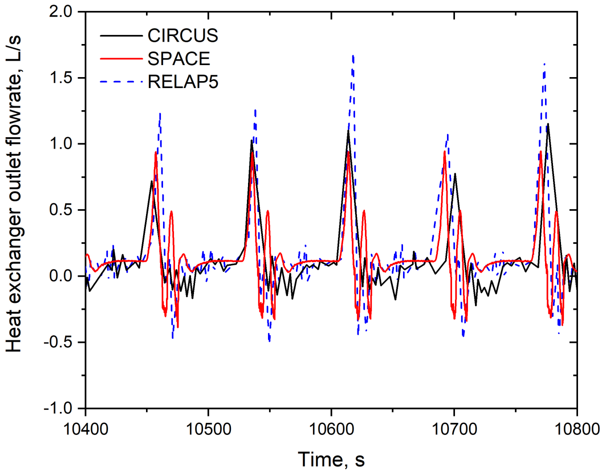

Figure 4 Comparison between calculated and measured flow rates at the heat exchanger outlet (M06)

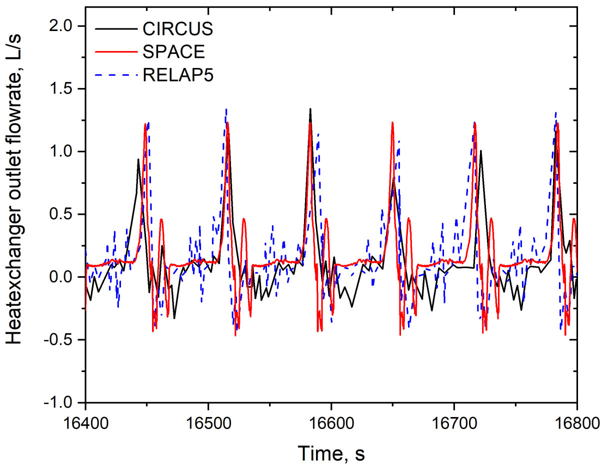

Figure 5 Comparison between calculated and measured flow rates at the heat exchanger outlet (M07)

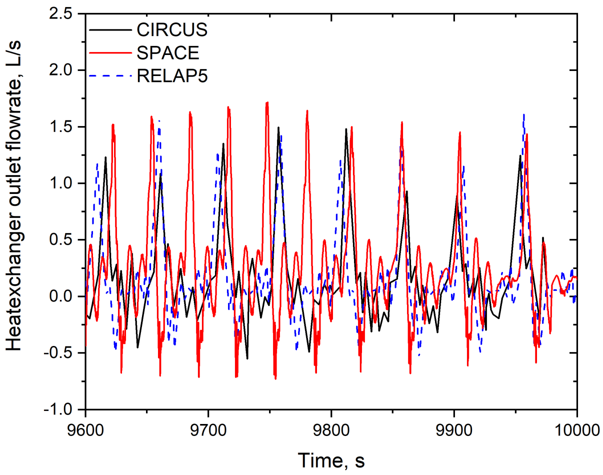

Figure 6 Comparison between calculated and measured flow rates at the heat exchanger outlet (M08)

An extended comparison was performed for flow oscillation periods under a broader range of subcooling conditions (Figure 7). The SPACE results demonstrated strong agreement with experimental data across the entire domain, with deviations generally within 10%. Notably, the oscillation period was reproduced with a mean absolute percentage error (MAPE) of 7.34%, indicating quantitative reliability. Both in the low subcooling region, where single-phase circulation was absent, and in the transitional region, where alternating single- and two-phase circulation occurred, the predicted oscillation periods matched the experimental data well.

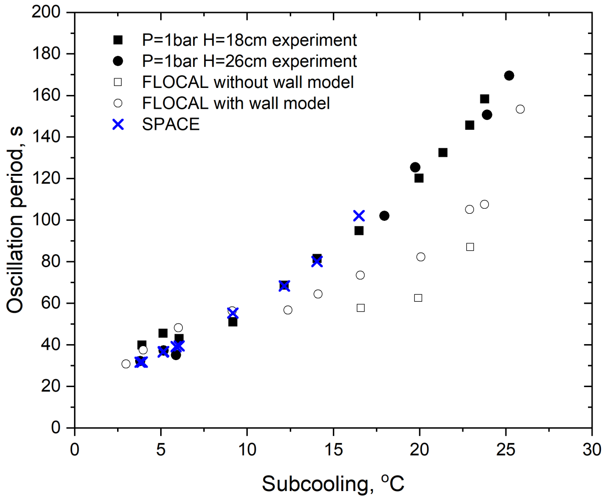

Figure 7 Comparison of oscillation period trends with respect to subcooling

The predicted stability boundary is shown in Figure 8. While SPACE captured the overall trend of the stability transition, it predicted the onset of stable flow at slightly lower subcooling conditions than observed experimentally. This indicates that the code tended to overestimate the extent of the stable regime, thereby underpredicting the system's instability region.

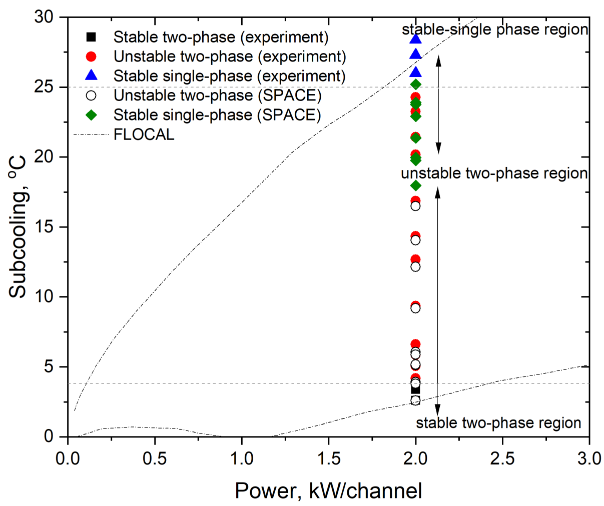

Figure 8 Comparison of stability boundaries (P = 1 bar, H = 0.18 m)

5. Conclusions

A validation study of the SPACE code has been performed against the CIRCUS flashing-induced instability experiments conducted under low-pressure natural circulation conditions. The comparisons demonstrate that SPACE is able to reproduce the essential characteristics of the observed flow oscillations. In particular, the calculated oscillation frequency increased with core inlet temperature, which is consistent with the experimental trend. The predicted oscillation period and amplitude also showed good agreement with the measured data, with the mean absolute percentage error of the oscillation period remaining within approximately 7%.

Although the overall stability behavior was well captured, SPACE tended to predict an earlier transition to stable flow at lower subcooling compared with the experiments. This tendency indicates a slight underestimation of the instability region, which is likely attributable to the simplified representation of the steam dome as a constant-pressure boundary. Nevertheless, the results confirm that SPACE is capable of qualitatively assessing flashing-induced instabilities in natural circulation systems. The code provides valuable insights into the dynamic characteristics of FII and can be utilized as a practical tool for reactor safety evaluation. Future work should focus on refining the modeling of system feedback mechanisms and extending the validation database to enhance the predictive capability of SPACE for a broader range of instability phenomena.

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