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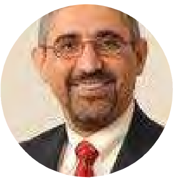

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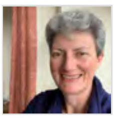

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Review

Design of rectangular single-phase natural circulation loop based on working fluid and geometry parameters to enhancement stability and mass flow rates: A research review

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ABSTRACT

This literature review examines diverse experimental and numerical investigations of single-phase natural circulation loops, with particular emphasis on rectangular configurations. The analysis focused on two critical aspects: mass flow rate and instability phenomena. The examination of instability is categorized into three main sections: (1) The influence of geometric parameters and operational variables on single-phase natural circulation loop stability, (2) Methods for improving single-phase natural circulation loop stability through loop configuration modifications and component additions, and (3) stability mapping approaches for single-phase natural circulation loops. The study also explores how nanofluid implementation as a working medium affects mass flow characteristics and system stability. Our paper synthesizes contemporary developments in natural circulation loop studies, drawing parallels with passive cooling mechanisms in nuclear facilities. We seek to comprehensively assess present conditions and obstacles in enhancing mass flow and stability characteristics within single-phase natural circulation loops. Additionally, this analysis offers guidance for developing rectangular loops with optimized configurations, operational protocols, and geometric specifications.

1. Introduction

Natural circulation loop (NCL) represents fluid movement through channels driven solely by natural phenomena, eliminating the need for external driving mechanisms (Vijayan and Austregesilo, 1994). The flow dynamics arise from the interaction between buoyancy forces in heated sections and frictional resistance in cooled portions (Swapnalee and Vijayan, 2011). Heat addition generates buoyancy effects that enhance flow circulation (Holstein and Fitzjohn, 1989). Natural circulation systems have demonstrated significant advantages across multiple applications, particularly in nuclear power plant passive cooling systems (PCS) (Vijayan), (Bae et al., 2023). Following the 2011 Fukushima Daiichi incident, ongoing validation of nuclear reactor safety technologies incorporating PCS as backup cooling mechanisms during transient

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conditions remains essential (Kosai and Yamasue, 2019). Despite the long-standing development of passive residual heat dissipation mechanisms, numerous parameters require verification and validation, including initial and boundary conditions influencing natural circulation (NC) flow patterns; current systems still exhibit flow instabilities that could compromise reactor piping system integrity. Therefore, PCS implementation in nuclear safety systems demands continued research efforts (Huang and Ma, 2019).

Passive cooling mechanisms represent an essential component in modern nuclear reactor safety design, particularly for advanced generation reactors (generation III/III + or generation IV) (Shin et al., 2015). Notable examples of nuclear facilities incorporating passive cooling systems include the SMART reactor, engineered by KAERI (Korean Atomic Energy Research Institute) (Chung et al., 2003) and NuScale, developed by NuScale Power USA (Fakhrarei et al., 2021). These facilities exemplify small modular reactor (SMR) technology. SMART's design incorporates a passive residual heat removal system (PRHRS), engineered to extract residual core heat during shutdown operations, maintaining temperatures below cladding material melting thresholds (International Atomic Energy Agency, 2016). NuScale represents an SMR variant featuring 77 MWe power modules, allowing the integration of up to 12 units in a single cooling reservoir. Each unit consists of an integrated water-cooled reactor housed within a sealed, high-pressure containment structure submerged in a water pool. During system blackout (SBO) events, core decay heat dissipation occurs passively through a decay heat removal system (DHRS) utilizing dual helical steam generators with 2×100 % capacity (Ingersoll et al., 2014).

Flow stability and rate parameters have emerged as crucial research focuses due to their substantial impact on NCL efficiency (Vijayan, 2002). Elevated flow rates facilitate rapid hot fluid displacement by a cooler medium, enhancing convective heat transfer and flow characteristics (Wen and Ding, 2006). Reynolds number elevation induces turbulence in NC flow patterns. This phenomenon accelerates heat transfer processes and optimizes heat removal efficiency, determining thermal energy transfer rates between systems. During active system failures in nuclear reactors, natural circulation mass flow rates become critical in preventing core melt scenarios through adequate heat transfer. Beyond flow rate considerations, natural circulation systems must achieve an optimal balance between flow velocity and operational stability (Aguirre et al., 2005), (Pilehvar et al., 2020). System stability remains paramount for maintaining consistent operational conditions (Durga Prasad et al., 2007). Excessive flow rates may generate substantial pressure reductions, potentially destabilizing systems or compromising piping infrastructure (Boure et al., 1973) through enhanced vibration effects and resultant equipment degradation. Researchers have explored various approaches to achieve stable NC flow conditions through loop configuration modifications and working fluid adaptations.

A comprehensive review of the fundamental aspects of Natural Circulation Loops (NCLs) has been conducted by Tilehnoee et al. (Hashemi-Tilehnoee et al., 2025), with a focus on single-phase and two-phase flow dynamics and the thermal-hydraulic performance of various working fluids and geometric configurations. This review aims to identify key trends and challenges in NCL design, particularly in enhancing the safety and efficiency of passive thermal energy storage and cooling systems. This analysis synthesizes multiple research findings regarding thermal-hydraulic parameter effects and geometric variations on natural circulation flow rates and stability characteristics. Additionally, we examine nanofluid applications in NCL performance enhancement as an emerging research direction. Our investigation concentrates on rectangular loop configurations and single-phase natural circulation loop (SPNCL) operational parameters. We present a systematic mapping of key issues addressed across scientific literature. This work consolidates recent NCL research developments, particularly regarding nuclear reactor passive cooling applications. Our review encompasses experimental studies, numerical analyses, and computational fluid dynamics modeling approaches. We aim to deliver a thorough examination of current research progress in NC phenomena while identifying scientific challenges for future NCL investigations. The paper concludes by outlining proposed research directions based on planned experimental investigations.

2. Research parameters

Nuclear power facilities incorporate multiple safeguarding mechanisms designed to prevent accidents and minimize environmental radiation exposure. These protective systems undergo regular maintenance cycles, inspections, and continuous enhancement to exceed safety requirements established by national regulatory authorities and the International Atomic Energy Agency (IAEA). Critical events that may impact nuclear facilities include external power interruptions, backup generator malfunctions, cooling system failures, containment breaches, and seismic activities. These protective mechanisms serve three essential safety functions: reaction management, thermal regulation, and radioactive material containment.

During emergency scenarios such as seismic events, reactor systems initiate automatic shutdown procedures. Efficient residual heat dissipation becomes crucial to prevent reactor core degradation and subsequent radioactive material release. Under these circumstances, emergency diesel generators (EDG) typically activate to facilitate coolant circulation for rapid temperature reduction. However, the 2011 Fukushima Daichi incident demonstrated how tsunami impacts rendered EDG systems inoperative, resulting in cooling pump failure. To mitigate similar scenarios, contemporary designs incorporate passive cooling mechanisms that maintain thermal management through natural circulation principles when active systems fail. The Fukushima Daichi experience has significantly influenced research trajectories in passive cooling system development, as illustrated in Fig. 1.

Fig. 1 illustrates three fundamental passive cooling strategies implemented during active system failures: (1) Passive emergency core cooling system (Passive-ECCS), (2) Passive containment cooling system (Passive-CCS), and (3) Passive residual heat removal system (Passive-RHRS). Advanced light-water reactors incorporate Passive-ECCS designs (Bae et al., 2023). enabling response capabilities across various accident scenarios while providing redundancy for reactor shutdown despite subsystem failures. Passive-CCS represents a key safety feature in advanced pressurized water reactor (APWR) designs (Ha et al., 2017). utilizing natural phenomena for environmental heat dissipation during design basis accidents to prevent containment overpressurization (Wang, 2013). Passive-RHRS integrates into reactor safety systems, facilitating core cooling through working fluid circulation without electrical power requirements. This system plays a fundamental role in nuclear power plant decay heat management (Shakil et al., 2019). specifically maintaining sub-melting point cladding temperatures during shutdown conditions (Liao et al., 2022).

Natural circulation mass flow characteristics depend on multiple variables, including elevation differences, density gradients, and flow resistance factors. Variations in these parameters significantly influence passive system operational behavior. Our investigation examines these parameters to evaluate their impact on PRHRS performance under natural convection conditions. Research initiatives have employed simplified loop configurations to model PRHRS, including vertical U-loop (Welander, 1957) and toroidal loop (Creveling et al., 1975) designs. Rectangular configurations (Welander, 1957), (Keller, 1966), emerge as preferred geometries, offering advantages in pressure drop characteristics, manufacturing feasibility, instrumentation requirements, and phenomenon comprehension (VIjayan et al., 2019).

Contemporary research efforts continue exploring innovative rectangular loop designs and configurations (Cammarata et al., 2003). Investigations examine various parameters, including operational conditions, geometric specifications, and working fluid characteristics in single-phase and two-phase regimes, aiming to optimize natural

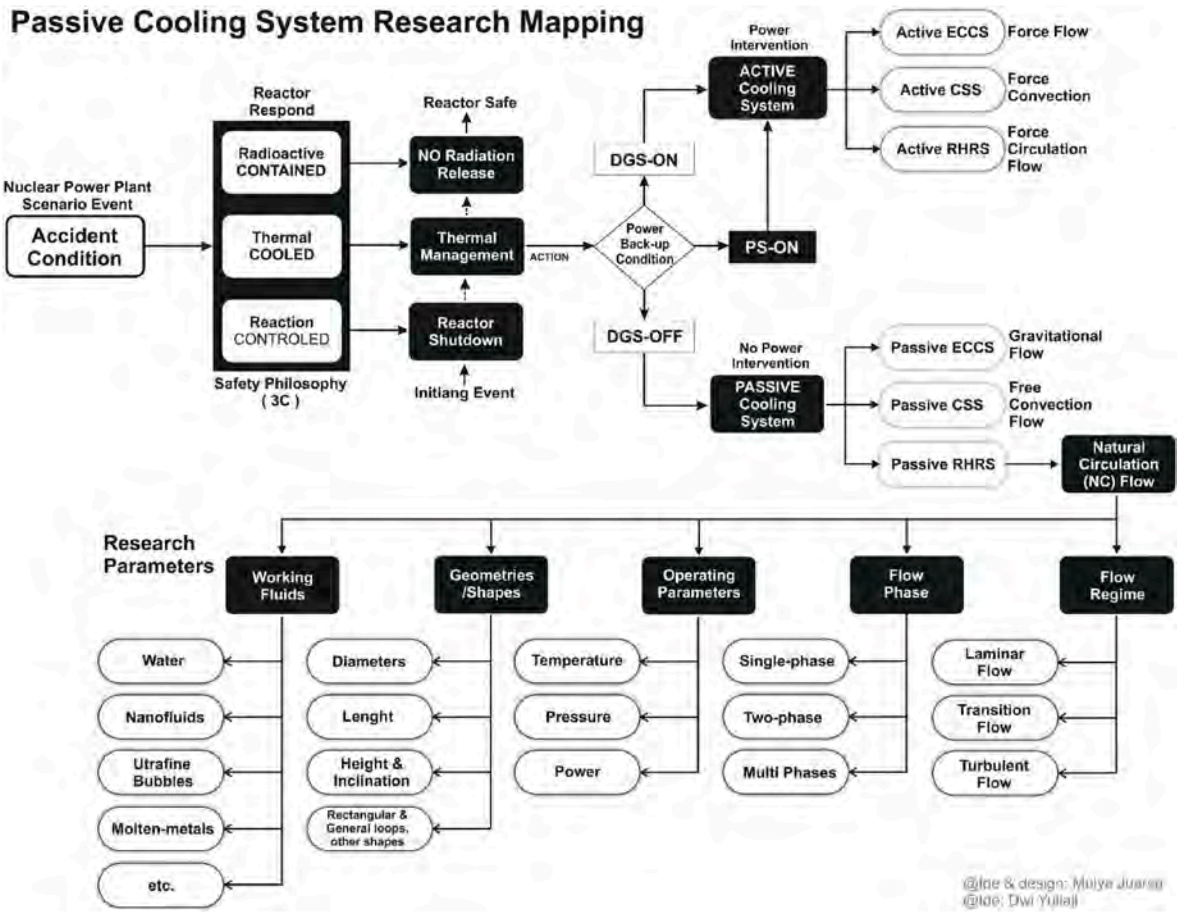

Fig. 1. Passive cooling system research mapping.

circulation performance through enhanced mass flow rates and reduced instability. Significant contributions to rectangular loop natural circulation research include studies by Holman and Boggs (1960), Bernier and Baliga (1992), Ho et al. (1997), Vijayan et al. (2001), Cammarata et al. (2003), Mousavian et al. (Moussavian et al., 2003), Ho et al. (2005) Zhang et al. (2010), Juarsa et al. (2018a).

3. Instability characteristics of rectangular single-phase natural circulation loop

Flow instability represents a significant research focus, as geometry and operational parameters substantially influence flow dynamics and stability characteristics in both single-phase and two-phase NCL systems (Astyanto et al., 2022). System performance can be adversely affected by various instability manifestations, including oscillatory behavior, chaotic patterns, and flow direction reversals (Wahidi and Yadav, 2021). The inherent non-linear processes in natural circulation mechanisms make these systems particularly susceptible to instability, where any perturbation in driving forces can significantly impact flow characteristics. Fig. 2 illustrates the fundamental concepts of stability assessment. Systems exhibiting steady-state convergence are classified as stable, with decay ratio (DR) serving as the primary indicator. Stability conditions are defined as: stable when $DR < 1$, neutrally stable at $DR = 1$, and unstable when $DR > 1$ (VIjayan et al., 2019).

This section presents a systematic analysis of instability research. Given the extensive literature available, investigations can be categorized into experimental studies and numerical analyses. Our review synthesizes influential parameters, methodological approaches, and key findings, organized chronologically and classified by research objectives. The investigation of instability encompasses three primary areas:

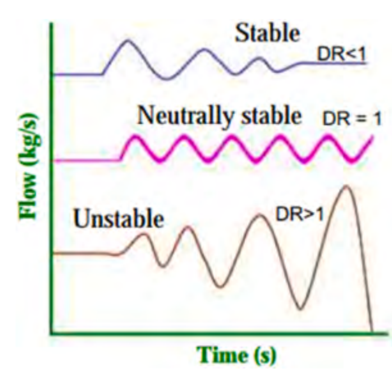

Fig. 2. Instability definition (VIjayan et al., 2019).

(1) Geometric and operational parameter effects on SPNCL stability characteristics, (2) Stability enhancement methodologies through loop configuration modifications and component integration, and (3) SPNCL stability mapping approaches. Contemporary research developments are incorporated into this analysis. Fig. 3 illustrates various rectangular loop configurations and terminology.

3.1. *Effects of various geometry and operation parameters on SPNCL stability*

Initial investigations into single-phase natural circulation loop stability emerged during the 1960–1970 period. Pioneering theoretical frameworks were established independently by Keller (1966) and Welander (1967). Concurrent experimental investigations were initiated

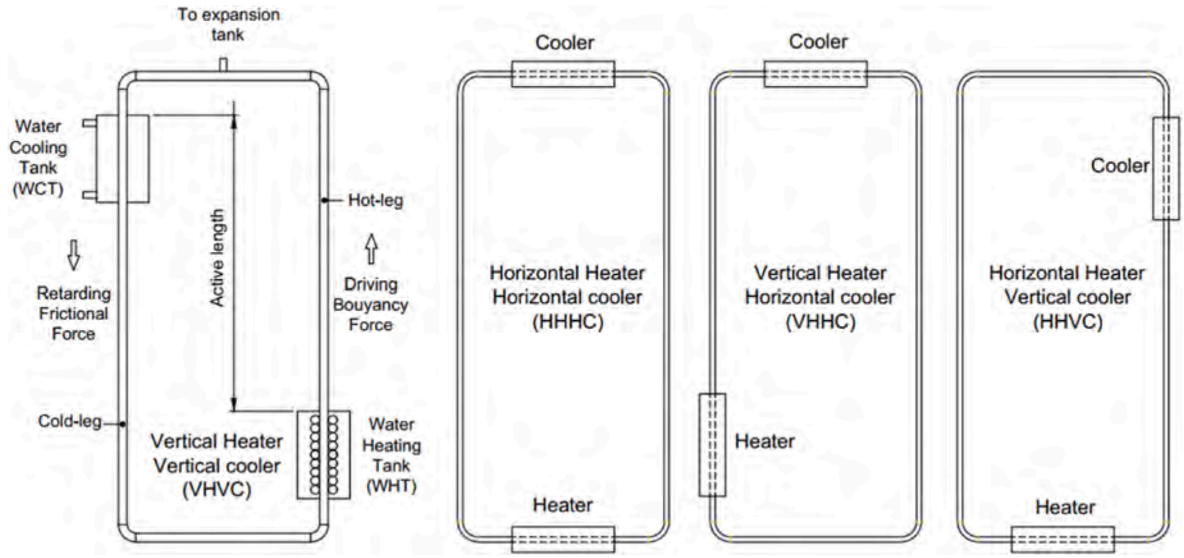

Fig. 3. General terminologies on rectangular loop.

by Creveling et al. Creveling et al. (1975) who developed a vertical-plane glass toroidal apparatus featuring differential heating between upper and lower sections. Their empirical observations revealed an inherent susceptibility of single-phase circulation systems to periodic flow variations. These oscillatory patterns manifested as cyclical fluctuations in both mass transport rates and thermal distributions throughout the system. Analysis demonstrated the critical influence of thermal gradients between heating elements and coolant media, alongside geometric parameters, on system stabilization characteristics. The research established that minimal parametric adjustments could precipitate transitions between stable and unstable flow regimes. Through systematic investigation, Creveling et al. developed comprehensive stability criteria delineating operational boundaries. Their experimental findings substantiated the theoretical predictions of Keller and Welander, establishing that flow instabilities manifest in conventional fluids under standard atmospheric conditions and moderate thermal states. This discovery challenged contemporary assumptions restricting single-phase instability phenomena to critical thermodynamic regions.

Further advancement in understanding NCL instability emerged through seminal work by Vijayan et al. (1995), which has since become foundational literature in the field. Their experimental methodology employed three distinct rectangular configurations with varying diametrical dimensions to examine oscillatory behavior patterns. Results demonstrated a positive correlation between heating power intensity and flow reversal frequency. Additionally, the investigation revealed regime-dependent oscillation characteristics, exhibiting regular patterns at lower power inputs and transitioning to irregular behavior at elevated power levels. The research highlighted the significant impact of energy transfer rates on thermohydraulic system dynamics.

Subsequent research by Misale et al. (2007) established correlations between power input parameters and loop orientation angles on system stability characteristics. Optimal thermal performance was documented at 25W power input with vertical orientation (0-degree inclination). Complementary findings were reported by Naveen et al. (2014a), who investigated operational parameter effects, particularly heater power and loop geometry, on initialization dynamics. Their analysis confirmed the substantial influence of these variables on both system stability and temporal response characteristics. Additional research demonstrated that temperature differentials between heated and cooled sections significantly modulate oscillation patterns and amplitudes (Devia and Misale, 2012).

System stability in SPNCL configurations is fundamentally influenced by multiple geometric parameters, including loop diameter, vertical height, aspect ratio, total path length, inclination angle, and heat exchanger orientation. Comprehensive research by Vijayan et al. (2008), examined diameter-dependent effects on circulation patterns and stability characteristics. Their findings established that larger diameter configurations generally enhance both stability and flow rates, though with important qualifications. Specifically, while smaller-diameter systems typically maintain stable operation across broader conditions, larger-diameter configurations may exhibit instability under specific operational parameters.

Research conducted by Basu et al. al (Basu et al., 2013a). examined SPNCL stability by evaluating various operational and geometric variables, including internal diameter, height of the loop, overall length, and heating section length. Their findings revealed that while extending the loop's vertical dimension creates instability through enhanced buoyancy effects, it simultaneously generates increased friction that helps offset this destabilization. Beyond geometric considerations, scientific investigations emphasized how heater-cooler positioning impacts SPNCL performance, as demonstrated in research by Vijayan et al. (2007). Their analysis of different heater and cooler configurations in a rectangular SPNCL determined that a horizontal heater-horizontal cooler (HHHC) arrangement yielded maximum flow rates but minimal stability, whereas vertical heater-vertical cooler (VHVC) positioning achieved optimal stability levels.

Beyond operational and geometric parameters, the system's stability is influenced by material properties of the loop, including the thermal capacity of walls, thermal conductivity of loop walls, and fluid-wall friction interactions. Research performed by Jiang and Shoji (2003) Exploring how loop wall thermal conductivity affects flow stability in natural circulation systems demonstrated that walls with enhanced thermal conductivity, exemplified by copper-based loops, demonstrate superior efficiency in eliminating thermal disruptions, thereby preventing the development of disturbances leading to Lorenz chaos. Their investigation revealed that increased wall thermal capacity promotes flow stabilization and minimizes temperature variations. The presence of axial conduction may result in subtle temperature gradients throughout the loop, influencing flow characteristics (Misale et al., 2000). Additional experimental and numerical investigations (Misale et al., 1999, 2000; Naveen et al., 2014b, 2015; Vijayan et al., 2005; Basu et al., 2008, 2013b; Garibaldi and Misale, 2008; Angelo et al., 2012; Wang et al., 2013; Goudarzi and Talebi, 2015, 2018; Saha et al., 2015; Misale, 2016; Kudariyawar et al., 2016; Krishnani and Basu, 2017; Juarsa et al., 2018b, 2019; Antariksawan et al., 2019; Cheng et al., 2019;

Bello et al., 2021; Bertani et al., 2021) examining the impact of various geometric and operational parameters on SPNCL stability are comprehensively detailed in Table 1.

Based on Table 1, numerous studies have advanced the understanding of natural circulation through experiments and simulations, identifying key influences—such as heating power, loop geometry, and working fluid—on flow stability and performance. Researchers have developed dimensionless correlations and analytical models that predict flow rates, stability thresholds, and transient behaviors like start-up and flow reversal, overcoming limitations of conventional 1D models. CFD and system codes like RELAP5 provide detailed insights into 3D effects such as secondary flows and thermal stratification. Experimental data from facilities like FASSIP-01 and FASSIP-02 offer valuable validation for passive cooling systems in nuclear safety. Together, these efforts form a solid foundation for designing more stable and efficient natural circulation systems.

Although providing valuable insights, most studies have methodological limitations. Many numerical models still rely on one-dimensional approaches that neglect three-dimensional effects, minor losses (such as those at elbows and fittings), wall dynamics, and axial conduction, reducing prediction accuracy, especially under transitional or unstable conditions. Some studies lack sufficient experimental data or in-depth quantitative validation, making it difficult to objectively assess model limitations. In experiments, flow measurement is often indirect (based on temperature data), particularly at low velocities, which can reduce data accuracy. Furthermore, many studies are limited to specific geometries (such as rectangular loops), working fluids (water), and small scales, so extrapolating results to larger systems or advanced fluids (such as nanofluids) requires further validation. In general, despite significant progress, more comprehensive approaches and stronger experimental validation are still needed to address complex flow dynamics.

3.2. Stability enhancement SPNCL with modification loop shape or equipped with other components

This section presents research findings focused on improving SPNCL stability through loop shape modifications, component additions, or working fluid alterations via air injection. The relevant studies are detailed as follows:

Research by Misale & Frogheri (Misale and Frogheri, 2001), explored SPNCL characteristics by implementing an orifice in the vertical sections (hot-leg and cold-leg) to concentrate pressure drop. Their analysis of temperature, pressure, and flow measurements under varying operational conditions demonstrated that increased flow resistance due to the orifice successfully reduced oscillation amplitude, thereby suppressing oscillations. Similar findings were reported by Elton et al. (2021) in their investigation of orifice plates as flow restrictors for enhancing stability in large-diameter natural circulation loops. Their work confirmed that flow restrictors effectively mitigate typical instabilities in natural circulation systems, with various orifice plate ratios substantially enhancing loop stability thresholds.

In their research, Basu et al. (2012) established a comprehensive model for SPNCL featuring constant heat flow heating and convective cooling, applicable across various geometries. After validating their model against experimental data, they conducted comparative analyses between rectangular and toroidal loops of identical dimensions. Their findings indicated that while rectangular loops achieved higher flow rates, toroidal configurations demonstrated superior stability characteristics due to reduced buoyancy forces, offering broader and more stable operational ranges.

Experimental analysis by Misale et al. (2020), compared single-loop and parallel-connected loop systems with independent heat sources under various configurations and parameters. Their investigation revealed stable behavior in both configurations, with hot-leg and cold-leg temperature differentials showing nonlinear relationships to power increases across both systems. Their results indicated minimal performance impact from parallel loop connections, though effectiveness improved with rising heat sink temperatures.

Wahidi & Yadav (Wahidi and Yadav, 2021), conducted comparative studies between standard Natural Circulation Loops (R-NCL) and those incorporating modified Tesla valves (T-NCL). Their research demonstrated superior flow stabilization in T-NCL systems compared to conventional R-NCL configurations, with T-NCL systems also showing marked reductions in temperature oscillations. Recent investigations by Chandan et al. (2023). examined flow and stability characteristics in air-injection-equipped SPNCL systems. Their research documented flow rate variations between systems with and without air injection, revealing enhanced Heat transfer fluid (HTF) flow rates due to void buoyancy effects. Bottom-position air injection at 40 cc/min yielded 5.2-fold flow rate increases compared to baseline cases, while 80 cc/min and 120 cc/min injections produced 6.5-fold and 8.9-fold increases, respectively. However, their findings advised against top injection due to high ΔP oscillation amplitudes and minimal flow rate improvements. Table 2 provides a comprehensive overview of experimental and numerical studies focusing on SPNCL stability enhancement.

Although orifices and Tesla valves effectively reduce instability, their implementation increases system pressure drop, resulting in diminished flow rates. Similarly, while toroidal loops demonstrate enhanced stability, they suffer from reduced buoyancy force. These limitations highlight the importance of exploring instability reduction methods that preserve boundary conditions, such as working fluid modifications, to achieve stability improvements without compromising flow rate performance.

3.3. Single-phase rectangular natural circulation loop stability mapping

This section examines stability characteristics by analyzing how geometric and operational parameters influence the boundaries between stable and unstable SPNCL regions (Ruiz et al., 2015). Common research approaches for closed-loop geometries typically represent stability maps as functions correlating the modified Grashof number (Grm) with the Stanton number (Swapnalee and Vijayan, 2011). The Grashof number represents the relationship between buoyancy forces driving fluid movement and the opposing friction forces, while the Stanton number (St) quantifies the ratio between fluid heat transfer and thermal capacity. Key studies in this area include:

In examining non-uniform diameter loops, Vijayan (2002) determined that stability depends not only on the modified Stanton number (Stm) and the ratio $(Gr_m)^{b/(3-b)}/(NG)^{3/(3-b)}$, but also on geometric parameters, specifically the relationship between total length (Lt) and loop diameter (D). Research by Mousavian et al. (2004) employed numerical analysis alongside the RELAP5 system code to model natural circulation loops and evaluate linear stability through the Nyquist criterion application. Their findings produced a rectangular loop stability map illustrating how stable and unstable region boundaries correlate with loop geometry and fluid flow parameters.

Through their investigation of single-phase natural circulation loop dynamics, Pilkhwal et al. (2007) evaluated the effectiveness of one-dimensional models and computational fluid dynamics (CFD) in predicting observed phenomena. Their research showed that despite certain constraints, one-dimensional approaches using GENLOOP and RELAP5 could accurately forecast natural circulation steady states to thermal power and loop configuration. Kumar et al. (2011) developed an innovative 1-D model for simulating startup and transient behaviors in single-phase natural circulation loops with horizontal heaters. Their work emphasized the crucial role of appropriate wall friction factor correlations in predicting NCL dynamics, noting that traditional forced flow correlations prove inadequate, particularly at low Grashof numbers where natural convection effects become significant. Their model successfully captured hysteresis phenomena, demonstrating how stability thresholds vary with heat addition patterns.

Research by Swapnalee & Vijayan (Swapnalee and Vijayan, 2011)

Table 1
Summary of effects of various geometry and operation parameters on the stability of SPNCL.

Authors	Determinant	Method	Findings	Advantages	Disadvantages
Vijayan et al. (Vijayan et al., 1995)	Power input	Numerical	Demonstrated that flow reversal frequency increases with heightened heater power, exhibiting periodic patterns at lower power levels and transitioning to chaotic behavior at higher intensities.	Developed a numerical model for single-phase natural circulation instabilities, including wall thermal capacitance and flow regime transitions.	The model has limitations in predicting chaotic oscillation frequencies and is highly sensitive to nodalization and initial conditions.
Misale et al. (Misale et al., 2007)	Inclination and power input	Experimental	Revealed that power input and loop orientation significantly influence stable behavior, particularly regarding temperature differentials across the heat sink regions.	A successful initial experiment demonstrating stable operation in a single-phase natural circulation mini-loop under varying heating power and loop inclination.	Low flow velocities, indirect measurements, and the one-dimensional model's limitations reduce accuracy at low power and high inclination.
Naveen et al. (Naveen et al., 2014a)	Power input	Numerical	Heater power and loop geometry significantly impact start-up dynamics, i.e., system stability and response time.	Developed a pseudo-conductivity model that successfully simulates start-up from rest in SPNCL, which cannot be captured by classical 1-D models	The model still uses simplified assumptions for wall dynamics and friction laws, resulting in lower accuracy when predicting the flow initiation time and the initial flow peak.
Devia & Misale (Devia and Misale, 2012)	Heat sink temperature	Numerical	Highlighted the critical nature of reducing temperature variations between heating and cooling conduits to optimize system performance.	Combining experiments and CFD to reveal thermo-hydraulic behavior and local, three-dimensional parameters that are difficult to measure directly.	CFD analysis is less accurate in predicting the timing and number of oscillations between flow reversals, producing more repetitive patterns than those observed in experiments
Vijayan et al. (Vijayan et al., 2008)	Loop diameter	Experimental	Increasing the loop diameter will increase stability and flow rate. Smaller loops are more stable, while larger loops show instability at certain conditions.	Comprehensive data on loop diameter effects in single- and two-phase natural circulation, with a general correlation for various sizes	Limited to rectangular loop geometry and water as the working fluid, so extrapolation to other systems must be done with caution
Basu et al. (Basu et al., 2013a)	Loop height,	Numerical	Increasing the vertical length of the loop has a destabilizing effect due to increased buoyancy but also induces greater friction, which can counteract the destabilizing effect.	An analytical model to evaluate the influence of geometric and operational parameters on the performance and stability of a single-phase natural circulation system.	The model neglects minor losses at elbows and fittings, potentially reducing the accuracy of flow and stability predictions.
Vijayan et al. (Vijayan et al., 2007)	Heater and cooler orientation	Experimental	Horizontal heater-cooler (HHHC) configurations maximize flow rates but exhibit minimal stability, while vertical heater-cooler (VHVC) arrangements demonstrate superior stability characteristics.	Presents a linear and non-linear stability analysis directly compared with experimental data to understand single-phase natural circulation.	Linear analysis tends to be conservative and predicts a larger unstable zone because it neglects 3D effects, local losses, and wall damping.
Jiang & Shoji (Jiang and Shoji, 2003)	Loop material	Experimental	Loops with higher thermal conductivity (copper) can stabilize the flow in natural circulation loops.	This study shows that wall thermal conductivity plays a key role in flow stabilization, with copper more effectively damping thermal disturbances than other materials.	The study used a one-dimensional approach and indirect temperature data, making it less capable of accurately capturing local flow dynamics and three-dimensional effects.
Misale et al. (Misale et al., 2000)	Power input, wall thermal capacity	Numerical	Higher thermal capacity tends to stabilize the flow and reduce temperature fluctuations. Axial conduction can lead to smaller temperature differences along the loop, affecting the flow pattern.	Successfully analyzed transient and steady-state behavior of single-phase natural circulation using a 2D numerical method, offering deeper insight than 1D models.	The numerical model does not include 3D effects such as secondary flows and local turbulence, making it less accurate in predicting complex flow dynamics.
Misale et al. (Misale et al., 1999)	Power input	Numerical	The flow rate increases with increasing power; however, at higher power levels, oscillations and flow reversals occur, which disturb the heat removal process	Determination of the instability threshold and evaluation of system code performance (CATHARE and RELAP5) in predicting loop behavior.	System codes (CATHARE and RELAP5) failed to accurately predict the stability map due to their 1D approach, which cannot capture multidimensional effects.
Naveen et al. (Naveen et al., 2014b)	Wall friction factor	Experimental	Established direct correlations between system flow and various parameters, including aspect ratio, loop diameter, and wall thickness. Their research also identified wall friction as a crucial factor affecting flow dynamics and system stability.	Proposes a new friction factor correlation for diabatic conditions, providing more accurate predictions of experimental data compared to conventional correlations.	The model still uses a one-dimensional approach and neglects inlet geometry effects and Wall dynamics, which may affect accuracy under flow transition conditions.
Vijayan et al. (Vijayan et al., 2005)	Non-dimensional number	Numerical	Indicated that maintaining consistent Grm/NG ratios between models and prototypes enables accurate simulation of steady-state behavior in both single and two-phase natural circulation systems.	Developed a universal dimensionless correlation to predict the flow rate in single-phase and two-phase natural circulation, applicable to various loop sizes and operating conditions.	The proposed correlation, based on experimental and literature data under specific boundary conditions, requires further validation for systems with different geometries or working fluids.
Basu et al. (Basu et al., 2008)	Loop height, inner diameter & wall thickness	Numerical	Loops with smaller heights and diameters are favorable for higher effectiveness, but this comes at the cost of reduced flow rates.	This study shows that high-conductivity wall materials like copper dampen temperature gradients and enhance natural circulation stability	The study used a 1D model that ignores 3D effects like secondary flow, limiting its accuracy in capturing complex flow dynamics

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Table 1 (*continued*)

Authors	Determinant	Method	Findings	Advantages	Disadvantages
Garibaldi & Misale (Garibaldi and Misale, 2008)	Working fluid and loop height	Experimental	The flow velocity of FC43 is almost twice that of water. Increasing the loop height reduces the flow velocity because the increase in frictional losses is greater than the increase in buoyancy force.	Valuable experimental data on the influence of working fluid, geometry, and loop inclination on small-scale natural circulation.	Applicable to laminar flow conditions and small-scale miniloops with small diameters.
Angelo et al. (Angelo et al., 2012)	Power input	Numerical	The model reveals velocity fluctuations in the heat exchanger caused by flow contraction and expansion, which the 1D model fails to capture.	Provides a comprehensive review of analytical and numerical methods for various natural circulation system designs, including applications in nuclear reactors and thermosiphons.	The review is general and does not present experimental data or new models, so its limitation lies in the lack of technical depth for specific cases.
Basu et al. (Basu et al., 2013b)	Excitations of input power	Numerical	Observed that sudden power input increases could trigger initial flow reversals, particularly when the elevated power levels fall within unstable operational zones.	The study analyzes the transient response of a natural circulation system to various dynamic excitations, providing important insights into its dynamic behavior	The study uses a one-dimensional numerical model that neglects three-dimensional effects, making it less accurate for complex flows
Wang et al. (Wang et al., 2013)	Temperature	Numerical	Compressible 3D CFD models effectively simulate natural circulation loops' flow and heat transfer characteristics, capturing phenomena such as secondary flow and thermal stratification.	The study evaluates the capability of CFD in simulating flow and heat transfer characteristics in natural circulation systems, which is important for passive safety systems in NPPs	The absence of experimental data and in-depth quantitative validation limits the ability to objectively evaluate the CFD model's limitations.
Naveen et al. (Naveen et al., 2015)	Expansion tank	Experimental	The presence of an expansion tank can improve the stability of natural circulation loops. Without an expansion tank, loops tend to experience greater instability.	The study develops a numerical model using a pseudo-conductivity approach to predict start-up from rest, a phenomenon that conventional models cannot capture.	The model uses simplified heater and friction assumptions, reducing accuracy in predicting flow initiation and peak.
Goudarzi & Talebi (Goudarzi and Talebi, 2015)	Loop dimension, power input	Experimental	Loop dimensions (Lt/D) and heater power significantly impact system stability, efficiency, and entropy generation.	The study combines stability analysis with entropy generation minimization to provide a more comprehensive evaluation of natural circulation system performance.	The study was conducted numerically using a one-dimensional model, making it less capable of capturing three-dimensional effects and complex local flow dynamics.
Saha et al. (Saha et al., 2015)	Ambient temperature	Experimental	Determined that fluid inertia significantly impacts initial transient behavior, with moderate power levels producing observable periodic oscillation patterns.	The study proposes a new dimensionless correlation to predict natural circulation flow and compares it with experimental data, showing good agreement.	It does not provide sufficient details on the experiment or numerical model, making it difficult to evaluate the validity or reproduce the results.
Misale (Misale, 2016)	Power steps	Experimental	Power changes affect thermohydraulic behavior in the loop, including temperature distribution and flow patterns.	Presents experimental data on flow instabilities and proposes a simple correlation for oscillation frequency versus input power in a single-phase natural circulation loop.	Limited methodological detail hinders a full assessment of the experimental setup and limits the reproducibility of the results
Kudariyawar et al. (Kudariyawar et al., 2016)	Heater-cooler orientation	Numerical	Identified heat flux and loop geometry as primary factors influencing flow stability, noting that increased heat flux typically leads to enhanced flow instability.	Presents a 3D CFD analysis of steady-state behavior, compared with experimental correlations for various flow regimes	The simulation requires high computational time, and its results are limited to a single fluid and single-phase flow
Krishnani & Basu (Krishnani and Basu, 2017)	Loop tilting	Numerical	The loop's inclination reduces the adequate gravitational acceleration, reducing local buoyancy effects, a more uniform temperature profile, and suppressing flow fluctuations and instability.	The study develops a 3D model showing that a 30° tilt effectively suppresses flow instability with minimal impact on steady-state flow.	The model uses a 1D correlation that may miss property variations and 3D effects, causing small prediction discrepancies.
Goudarzi & Talebi (Goudarzi and Talebi, 2018)	Heater and Cooler orientation	Numerical	HHVC-oriented loops perform best in terms of stability and heat removal capability measured by entrainment dissipation compared to VHVC loops, which perform worst.	The study develops a 1D transient model that accurately predicts a rectangular NCL's response to various power excitation profiles.	The model uses a first-order upwind scheme with numerical diffusion, which may reduce accuracy for complex transients like flow reversal.
Juarsa et al. (Juarsa et al., 2018b)	Temperature differences (heater-cooler)	Experimental	Established a positive correlation between temperature differentials in hot and cold sections and natural circulation flow velocities.	Provides an analytical method to estimate flow in the FASSIP-02 loop, aiding passive safety system design.	Relies solely on analytical calculations, lacking experimental validation for instabilities and transients.
Antariksawan et al. (Antariksawan et al., 2019)	Sink temperature	Numerical	Stable and steady SPNCL circulation was observed in the FASSIP-01 loop, with friction losses affecting the mass flow rate.	Demonstrates stable natural circulation in FASSIP-01 and validates RELAP5 with good agreement.	Non-uniform heater flux and loop diameter may affect flow and validation accuracy.
Cheng et al. (Cheng et al., 2019)	Heating and cooling fluids	Experimental	Discovered that secondary fluid mass flow rates have minimal impact on mini-loop thermal performance characteristics.	The experiment demonstrates high stability and provides Nusselt number and driving temperature data for the natural circulation mini-loop.	The flow velocity is very low and not measured directly, reducing the accuracy of quantitative analysis.

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Table 1 (*continued*)

Authors	Determinant	Method	Findings	Advantages	Disadvantages
Juarsa et al. (Juarsa et al., 2019)	Heater power and heating sink system flow	Experimental	An increase in coolant flow in the cooling area accelerates the response time from flow instability to stability.	Experimentally investigates heater power and cooling flow effects on stabilization time in the FASSIP-01 natural circulation system.	Only assesses response time, lacking analysis of steady-state flow or instability phenomena.
Bello et al. (Bello et al., 2021)	Temperature variation and power input	Experimental	Documented stable temperature oscillations at heated channel entry and exit points, with temperature distributions maintaining stability under low flux conditions.	The study provides detailed experimental data on the effects of temperature and heating power variations on single-phase natural circulation at low pressure.	The study is limited to a single fluid and does not include two-phase effects or other geometric variations.
Bertani et al. (Bertani et al., 2021)	Power input	Experimental	Increased power results in faster establishment of natural circulation, with lower flow instability at higher power levels.	The study experimentally investigates natural circulation start-up in single- and two-phase conditions, identifying transient phases and the effects of heater power and initial mass inventory.	The flow rate is not measured directly but estimated, limiting the accuracy of flow dynamics and stability boundary data.

introduced an advanced flow equation for single-phase natural circulation loops accommodating multiple friction laws. Their analysis revealed an absence of stable zones in subcritical regions when Stanton numbers fell below 7 during turbulent flow conditions in their test configuration. The researchers acknowledged that certain experimental data points appearing in predicted unstable regions might be attributed to simplified linear stability analysis assumptions, particularly the omission of heat loss and wall effects. Independent work by Seyyedi et al. (2019) investigated the influence of asymmetrically positioned heaters on natural circulation dynamics. Their findings demonstrated that asymmetric heater placement substantially impacts flow patterns and thermal distribution throughout the loop system. They observed that positioning heaters closer to one loop side generated enhanced temperature differentials and stronger flows in that region. Their research provided comprehensive stability mapping across various flow conditions (laminar, transitional, and turbulent). Additionally, they identified key stability determinants beyond Grashof and Stanton numbers, including Reynolds number, loop configuration, inclination angles, and heater-cooler orientations.

The work of Luzzi et al. (2017) focused on developing and validating a hybrid semi-analytical and numerical framework for analyzing vertical loop single-phase natural circulation dynamics. Their model validation incorporated experimental data from natural circulation systems, employing dimensionless stability maps for system stability assessment. Their research generated comprehensive stability maps enabling a deeper understanding of SPNCL asymptotic behavior to various parameters, including power input, geometric configuration, loop dimensions and shape, component positioning, and operational conditions.

Experimental investigations by Elton et al. (2020) examined stability threshold variations across different SPNCL operational protocols using a square rectangular loop featuring horizontal heating and cooling arrangements. Their research, utilizing de-mineralized water, analyzed stability thresholds across multiple operational scenarios: idle state initiation, steady-state power enhancement, and unsteady-state power reduction. Their findings emphasized operational procedure dependency on stability thresholds, highlighting cooling conditions as crucial stability factors. In subsequent research, Elton et al. (2022) explored the effects of implementing orifice plates with varying ratios ($\beta = Dor/Di$). Employing one-dimensional linear stability analysis, they evaluated the stabilizing impact of orifice implementations. Their research confirmed that orifice plate integration enhanced stability in large-diameter NCL systems, effectively mitigating typical flow instabilities. A comprehensive overview of SPNCL stability mapping research is presented in Table 3.

Analysis of stability mapping research summarized in Table 3, examining geometric and operational parameter effects, indicates a research gap regarding stability mapping to modified working fluids. Future research directions should therefore explore Stanton number versus Grashof number relationships, considering both loop inclination geometry parameters and alternative working fluids, specifically water combined with nanoparticles or ultrafine bubbles.

4. Effects of nanofluids on single-phase rectangular natural circulation loop

Literature examination reveals that nanofluid implementation, when compared with water, enhances flow rates while reducing NCL instability. The mechanism behind nanofluid-induced mass flow rate enhancement can be understood through the Grashof number equation, which represents the relationship between buoyancy and viscous forces:

$$Gr = \frac{g\beta\Delta T L^3}{\nu^2} \tag{1}$$

Nanofluids exhibit superior thermal conductivity (k) and lower thermal capacity (Cp) compared to water, enabling enhanced heat absorption. Consequently, the temperature differential in nanofluids (ΔT_{nf}) exceeds that of water (ΔT_{water}). After heat source exposure. While increased fluid temperature corresponds to stronger buoyancy forces, elevated nanofluid concentrations simultaneously increase viscous resistance forces, which depend on viscosity and friction factors. Higher nanofluid concentrations intensify these viscous resistance forces, including friction factors, potentially impeding fluid flow (Ho et al., 2014). Therefore, increased nanofluid concentration benefits require sufficient input power or temperature to maintain low viscosity. System behavior depends on the dominance between buoyancy and friction forces - predominant buoyancy forces enhance mass flow rates, while dominant friction forces reduce them (Sahu and Sarkar, 2019a). These forces are influenced by input power (temperature), particle characteristics (size and shape), and nanoparticle concentration (Ali et al., 2018), (Sahu and Sarkar, 2019a). Optimal nanoparticle concentration varies depending on multiple parameters. Fig. 4 illustrates nanofluid-induced flow rate enhancement across various operational and geometric parameters from multiple studies.

In NCL applications, elevated *Gr* values enhance flow rates and influence system stability (Thomas and Balakrishna Panicker Sobhan, 2011). Nanofluids demonstrate superior stability as working fluids due to their higher thermal expansion coefficient (β) compared to water. This coefficient measures volumetric or density changes in response to temperature variations. Enhanced thermal expansion coefficients grant nanofluids improved thermal stability, maintaining strength at elevated temperatures. While no universal instability equation exists, natural circulation system stability can be expressed through a fluid mass flow equation relating instability to flow rate effects on thermal stability and circulation dynamics:

$$\frac{dQ}{dt} = \frac{\Delta T \,.\, \Delta\rho}{\mu \,.\, L} \tag{2}$$

Table 2
Summary of experimental and numerical studies on stability enhancement SPNCL.

Authors	Determinant	Method	Findings
Misale & Frogheri (Misale and Frogheri, 2001)	Localized Pressure-drop (using orifice)	Experimental	Revealed that enhancing loop flow resistance effectively reduces oscillation amplitude, leading to oscillation suppression.
Elton et al. (Elton et al., 2021)	flow restrictors (Orifice)	Experimental	The implementation of flow restriction devices enhances system stability by extending effective loop length and raising stability thresholds
Basu et al. (Basu et al., 2012)	Loop shape	Numerical	Demonstrated that under identical conditions, rectangular configurations achieve higher flow rates compared to toroidal designs, though toroidal systems exhibit enhanced stability characteristics
Misale et al. (Misale et al., 2020)	Connected loop	Experimental	Showed that both individual and interconnected natural circulation systems maintain stable operation, with performance enhancement correlating to increased heat sink temperatures
Chandan et al. (Chandan et al., 2023)	Air Injection	Experimental	Documented increased heat transfer fluid circulation rates resulting from air injection-induced void buoyancy effects.
Misale et al. (Misale et al., 2021)	Connected loop	Experimental	Connected rectangular natural circulation loops with different inner diameters are always stable; larger diameters reduce temperature difference and slightly increase interaction between loops, but the connection effect remains small due to dominant friction, especially in smaller diameters.
Wahidi et al. (Wahidi and Yadav, 2021)	Twin Tesla-type valves	Experimental	Established that natural circulation loops incorporating modified Tesla valves demonstrate superior flow stabilization compared to conventional designs.
Bocanegra et al. (Bocanegra et al., 2024)	Connected loop and Working fluid	Experimental	Three parallel-connected natural circulation loops (NCLs) with different working fluids (water, glycol solution, and FC-43) are always stable.

This equation demonstrates that circulation flow instability occurs when flow rate changes (dQ/dt) inadequately compensate for temperature (ΔT) and density (Δρ) differentials. Insufficient Q values may trigger instability, resulting in temperature and pressure oscillations. Conversely, excessive or fluctuating Q values might induce dynamic instability.

Table 3
Summary of studies on single-phase rectangular natural circulation loop stability mapping.

Authors	Determinant	Method	Findings
Vijayan (Vijayan, 2002)	Uniform and non-uniform diameter loop	Numerical	Established that non-uniform diameter loop stability is influenced by geometric configurations and the modified Stanton number (Stm), along with the ratio $(Grm)^{b/(3-b)}/(NG)^{3/(3-b)}$
Mousavian et al. (Mousavian et al., 2004)	Non-dimensional number (Gr_m and St_m)	Numerical	Utilized the Nyquist criterion to generate rectangular loop stability maps, delineating stable and unstable regions based on loop geometry and fluid flow parameters.
Pilkhwal et al. (Pilkhwal et al., 2007)	Power, Heater-cooler orientation	Numerical	A dimensionless stability map showing stable and unstable states influenced by thermal power and loop geometry affects the system's stability.
Kumar et al. (Kumar et al., 2011)	Mixed convection, Wall friction	Numerical	Wall friction and mixed convection affect the flow pattern. Higher wall friction tends to stabilize the flow by reducing velocity fluctuations.
Misale et al. (Misale et al., 2011)	Heat-sink temperature	Experimental	Varying the heat-sink temperature can switch the system between stable and unstable flow regimes without changing the power input.
Swapnalee & Vijayan (Swapnalee and Vijayan, 2011)	Non-dimensional number	Experimental	Demonstrated through stability mapping that turbulent flow conditions with Stanton numbers below 7 ($Stm < 7$) exhibit no stable zones in subcritical regions
Luzzi et al. (Luzzi et al., 2017)	Numerik 1D dan CFD 3D	Numerical	Employed semi-analytical linear analysis techniques to examine natural circulation loop asymptotic behavior through dimensional stability mapping, facilitating the identification of stability conditions across various system configurations
Seyyedi et al. (Seyyedi et al., 2019)	Heater position	Experimental	Asymmetric positioning of the heater can affect the performance and stability of the circulation loop.
Elton et al. (Elton et al., 2020)	Operating procedure	Experimental	indicated that stability thresholds are dependent on operational procedures, with cooling conditions playing a crucial role in determining overall system stability.
Elton et al. (Elton et al., 2022)	Orifice ratio (β)	Experimental	This study produced stability maps showing stable and unstable conditions using different orifice β ratios.

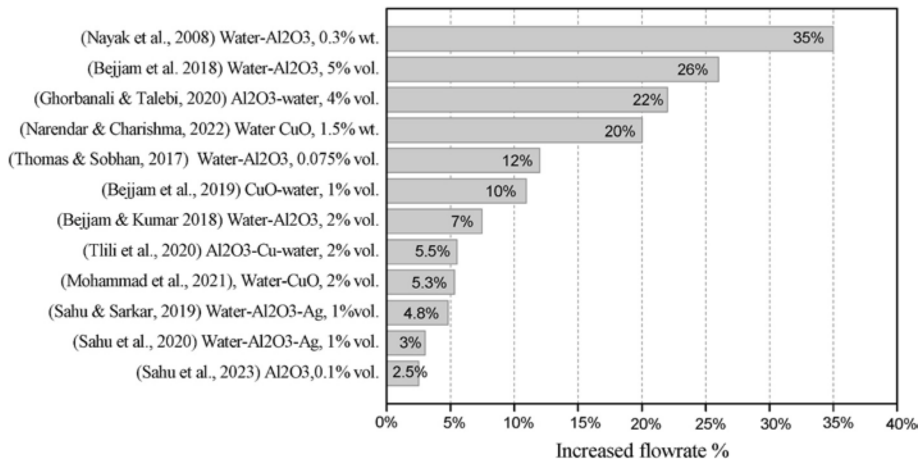

Fig. 4. Mass flow rate enhancement of nanofluids compared to water.

4.1. Experimental research on the effects of nanofluids as working fluid in SPNCL

Pioneering experimental investigations into rectangular loop performance utilizing nanofluid working media were conducted by Nayak et al. (2008), (Nayak et al., 2009). Their research examined Al_2O_3 nanofluids at varying concentrations (0.3–2 % by weight, 40–80 nm particle size). Their findings demonstrated that natural circulation flow enhancement and instability reduction correlated with nanoparticle concentration levels. Flow rate improvements ranged from 20 % to 35 %, varying with nanoparticle concentration and operational parameters. Notably, flow instability suppression was observed even at minimal concentrations (0.3 % by weight Al_2O_3). Similar findings regarding enhanced mass flow rates and stability through nanofluid implementation were documented by numerous researchers, including Misale et al. (2012). Koca et al. also reported the effect of using nanofluids on increasing mass flow rate and flow stability. (Koca et al., 2017), Thomas & Sobhan (Thomas and Sobhan, 2018), Bejjam et al. (2019), Doganay & Turgut (Doganay and Turgut, 2015), Veeramachaneni et al. (2022), Sahu et al. (2023), Sudi et al. (2023).

Contrasting observations emerged from Ho et al. (2014) research utilizing Al_2O_3-water mixtures. Their investigation focused on working fluid modifications and temperature differential effects between cold and hot walls, examining various Al_2O_3 nanoparticle concentrations (0 %, 0.1 %, 0.5 %, 1 %) under controlled temperature conditions (cold wall: 4°C-25 °C, hot wall: 50°C-110 °C). Their findings indicated adverse effects of increased nanofluid concentration on flow rates, with Reynolds number reductions of approximately 44 % at 0.1 % concentration and 52 % at 1 % concentration. They attributed these reductions to enhanced viscosity from nanoparticle addition, though noting minimal

Table 4
Summary of experimental studies on effects of nanofluids on single-phase rectangular natural circulation.

Authors	Nanofluids	Parameters	Lt/D (mm)	Findings
Nayak et al. (Nayak et al., 2008)	Water-Al_2O_3	Particle concentration (0.3, 1, 2 %wt.)	7456/ 26.9	Demonstrated that flow rates increase in relation to nano-powder concentration and operational parameters.
Misale et al. (Misale et al., 2012)	Water-Al_2O_3	Particle concentration (0.5 & 3) %vol.	888/4	The mini-loop has stable thermal performance for all working fluids. At a mini-loop inclination of 75°, the nanofluid experiences a slight improvement.
Koca et al. (Koca et al., 2017)	Water-Ag 5 %wt, also PVP with 1.25 wt %, diluted with DIW to 0.25, 0.5, 0.75, and 1 wt %.	Particle concentration,	1048/ 4.75	The Ag-water nanofluid showed good thermal stability, meaning that its thermal properties remained consistent during long-term operation.
Thomas & Sobhan (Thomas and Sobhan, 2018)	Water-Al_2O_3 Water-CuO	Type and concentration of nanoparticles	600/10	revealed that Al_2O_3-water nanofluid at 0.075 % concentration improved steady-state mass flow by 12 %, while CuO-water at 0.05 % volume achieved a 14 % enhancement.
Bejjam et al. (Bejjam et al., 2019)	Water-SiO_2 Water-CuO Water-Al_2O_3	Working fluids, Particle concentration	10400/ 12	CuO-distilled water had the highest mass flow rate, with an increase of 10.95 % compared to water.
Doganay & Turgut (Doganay and Turgut, 2015)	Water-Al_2O_3	Inclination, Heat sink temperature, Particle size	1048/ 4.75	The highest velocity was obtained in the 1 % Al_2O_3, 10 nm nanofluid sample, 20 °C heatsink temperature, and 0° inclination.
Veeramachaneni et al. (Veeramachaneni et al., 2022)	Hybrid nanofluid Water -(copper–graphene)	The mass ratio between copper and graphene	500/3	The 7.6 % increase in merit indicates that hybrid nanofluids have higher performance than water
Sahu et al. (Sahu et al., 2023)	mono/hybrid nanofluids	Type nanoparticle (Water-Al_2O_3, Water-Al_2O_3-CuO, Water-Al_2O_3-SiC Water-Al_2O_3-MWCNT) with a 0.1 %	5000/ 25.4	Hybrid nanofluids help improve natural circulation systems' stability, reducing temperature and flow fluctuations. Higher concentrations enhance heat transfer but can also increase viscosity, affecting flow.
Sudi et al. (Sudi et al., 2023)	Water-Al_2O_3	Nanoparticle concentration (0.00, 0.005& 0.01 % vol.)	2150/ 10	The use of water-Al_2O_3 nanofluid in NCL increases the heat transfer efficiency. so that the loop filled with nanofluid (0.01 %) transitions to a lower heat flux than the loop filled with water
Ho et al. (Ho et al., 2014)	Water-Al_2O_3	Particle concentration (0.1, 0.5, 1 %wt.)	1214/4	Observed an inverse relationship between nanoparticle concentration and Reynolds number.

impact. Table 4 presents comprehensive experimental findings regarding nanofluid effects on single-phase rectangular natural circulation across multiple studies.

The nanomaterials listed in Table 4 vary in type and properties, which influence their thermal and flow behavior in natural circulation. Metal oxides (e.g., Al_2O_3, CuO, SiO_2) are commonly used due to their stability and moderate enhancement of thermal conductivity with low viscosity increase. Metallic nanoparticles (e.g., Ag) offer higher thermal conductivity but require stabilizers to maintain dispersion. Hybrid and carbon-based nanofluids (e.g., Cu-graphene, MWCNT) provide improved heat transfer and flow stability, though often with higher viscosity and dispersion challenges. These differences affect heat transfer rates, flow velocity, and system stability.

4.2. *Numerical studies on the effects of nanofluids as a working fluid in SPNCL*

Contemporary computational advances have sparked widespread research interest in nanofluid effects on SPNCL through numerical analysis. These computational approaches enable more comprehensive research capabilities while reducing costs compared to traditional experimental methods, establishing numerical analysis as an effective tool for demonstrating nanofluid advantages over conventional working fluids.

Numerical investigations by Bejjam & Kumar (Bejjam and Kumar, 2018) projected that 5 % nanofluid concentrations could achieve 26 % mass flow rate improvements compared to water systems. Their subsequent research (Bejjam and Kiran Kumar, 2019). also highlighted thermal performance enhancements. Similar mass flow rate improvements were documented by Ghorbanali & Talebi (Ghorbanali and Talebi, 2020), Sahu et al. (2020a), Tlili et al. (2020), Mohammad (Mohammad et al., 2022), and Çobanoglu (Çobanoğlu et al., 2021). While higher nanofluid concentrations enhanced heat transfer capabilities, Narendra & Charishma (Narendar and Tejo Satya Charishma, 2022) noted increased viscosity impacts on flow characteristics. Çobanoglu & Karadeniz (Çobanoğlu and Karadeniz, 2020) determined that while nanofluid viscosity significantly influenced SPNCL characteristics, thermal conductivity effects remained limited.

Research focus has extended beyond concentration effects to examine nanoparticle type impacts. Sahu & Sarkar (Sahu and Sarkar,

Table 5
Summary of Numerical studies on the effects of nanofluids on single-phase rectangular natural circulation.

Authors	Nanofluids	Parameters	Lt/D (mm)	Findings
Bejjam & Kumar (Bejjam and Kumar, 2018)	Water-Al_2O_3	Concentration of nano-particles	5440/15	Established that natural circulation loop mass flow rates rise with increased heat input, identifying 5 % as the optimal particle concentration level
Bejjam & Kumar (Bejjam and Kiran Kumar, 2019)	Water-Al_2O_3	Concentration of nano-particles (1&2 %)	5440/15	Confirmed that nanofluid thermal performance varies with nanoparticle concentration
Sahu & Sarkar (Sahu and Sarkar, 2019b)	Hybrid nanofluid. Water+ 1 % vol. (Al_2O_3-TiO_2), (Al_2O_3-CNT), (Al_2O_3-Ag), (Al_2O_3-Cu), (Al_2O_3-CuO), (Al_2O_3-graphene)	Type of nanoparticles	4070/ (20–30)	Documented superior steady-state mass flow rates and effectiveness in Al_2O_3-Ag nanofluids compared to alternatives, noting positive correlations between flow rates and loop dimensions (diameter and height), while observing decreased performance with increased loop inclination and heating/cooling.
Çobanoglu & Karadeniz (Çobanoğlu and Karadeniz, 2020)	Water-Al2O3	Consentration nanopartikel (1–3 vol %), loop diameter (3–6 mm)	1046/(3, 4, 4.75, 5, 6)	Nanofluid's viscosity significantly influences on the characteristics and performance of SPNCL. In contrast, the influence of thermal conductivity on the characteristics of SPNCL was found to be limited.
Ghorbanali & Talebi (Ghorbanali and Talebi, 2020)	Al_2O_3-water, Water-TiO_2	Particle concentration, Nanoparticle type	7560/26.9	The mass flow rate improvement over water is about 22 % for Al_2O_3 nanofluids and 10 % for TiO_2 nanofluids.
Sahu et al. (Sahu et al., 2020a)	Mono/Hybrid nanofluids	Type of nanoparticle, loop	7230/26.9	Revealed that Al_2O_3+Ag hybrid nanofluid achieved 3 % flow rate improvement, while Al_2O_3+Graphene demonstrated 25.4 % effectiveness increase and 14.3 % reduction in total entropy generation compared to water-based systems
Tlili et al. (Tlili et al., 2020)	Water-Al_2O_3 Water-Cu Water-Al_2O_3.Cu	Heat input, type of nanofluids, Loop diameter & height, Inclination,	5000/30	Identified positive correlations between steady-state mass flow rates and various parameters including heater power, loop dimensions, and nanoparticle concentration, while noting loop tilt angle effects on temperature distribution and stability.
Çobanoglu (Çobanoğlu et al., 2021)	Water-Al_2O_3	Nanoparticle concentration		Observed that mass flow rates increase with higher nanoparticle concentrations and input power, with negligible changes in flow rates for pipe diameters below 4 mm, but significant increases beyond this threshold. Similar findings applied to Aspect Ratio variations.
Mohammad (Mohammad et al., 2022)	Water-CuO	Nanoparticle concentration	4200/NA	Documented that CuO/water nanofluid enhanced mass flow rates by 5.33 % at 2 % volumetric concentration, though increasing concentration to 3 % reduced heat transfer effectiveness due to dominance effects.
Sahu et al. (Sahu et al., 2020b)	Tri-hybrid nanofluids	Nanoparticle shape: Cu (spherical), Graphene (platelets), Al_2O_3 (spherical), and CNT (cylindrical)	7230/26.9	demonstrated that tri-hybrid nanofluids enhance system stability and thermal performance under various conditions, with nanoparticle shape significantly impacting performance and Al_2O_3 + Cu + CNT/water showing optimal results.
Sahu et al. (Sahu et al., 2021)	Ternary Hybrid Nanofluids	Nanoparticle shape: Cu (spherical), Graphene (platelets), Al_2O_3 spherical), and CNT (cylindrical)	7230/26.9	Revealed that ternary hybrid nanofluids accelerate flow initiation and minimize fluctuations, with steady-state mass flow rates varying based on nanoparticle morphology.
Narendar & Charishma (Narendar and Tejo Satya Charishma, 2022)	Water-Al_2O_3 Water-CuO	Nanoparticle concentration (0.5, 1, and 1.5) %Wt	420/25.4	Nanofluids help improve system stability and reduce temperature and flow fluctuations. Higher concentrations promote fantastic heat transfer but can also increase viscosity, affecting flow

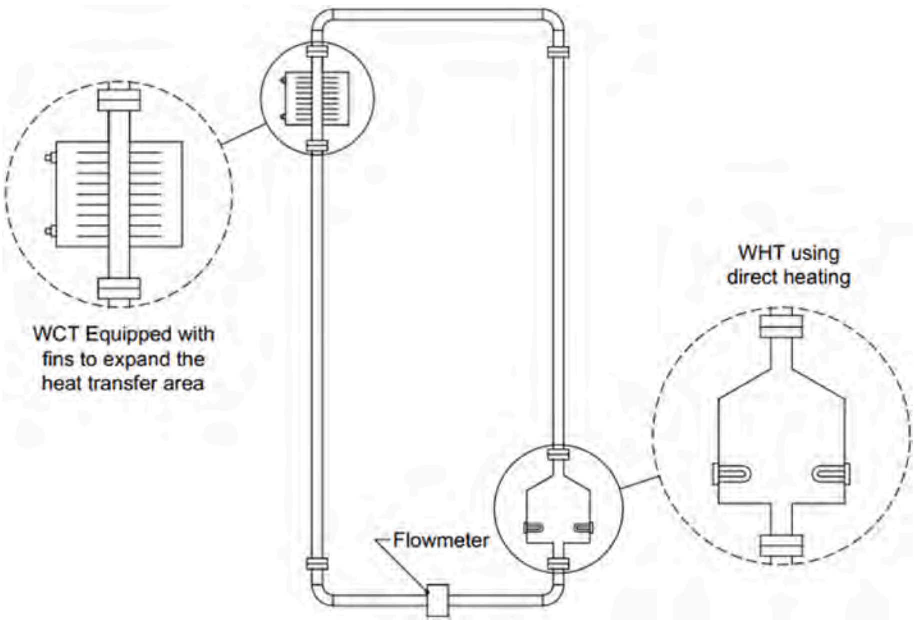

Fig. 5. Configuration 1 FASSIP-06-V0 variation of inclination and working fluid.

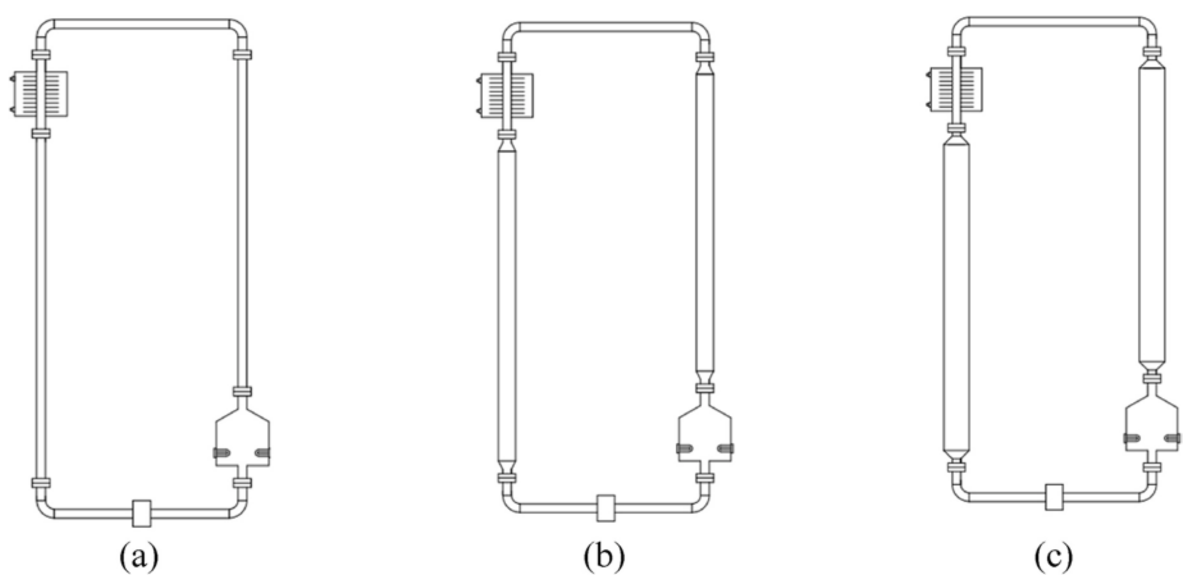

Fig. 6. Configuration 2 FASSIP-06-V1 variation of working fluid and loop diameter (a) 1-1 inches (b) 2-2 inches (c) 3-3 inches.

2019b) investigated hybrid nanofluid performance, identifying superior mass flow rates and effectiveness in water-Al_2O_3-Ag compositions. Particle shape effects were explored by Sahu et al. (2020b), revealing significant performance variations. Their research identified optimal performance in tri-hybrid systems combining water + Al_2O_3 (spherical) + Cu (spherical) + CNT (cylindrical). Further investigations by Sahu et al. (2021) demonstrated ternary hybrid nanofluids' capacity to accelerate flow initiation and reduce fluctuations, with steady-state mass flow rates varying according to particle morphology. Table 5 provides a comprehensive overview of numerical studies examining nanofluid effects on single-phase rectangular natural circulation.

5. Discussion and Further Research

While extensive experimental, numerical, and CFD modeling research has examined rectangular geometry SPNCL, a complete understanding of parameter effects and physical mechanisms driving enhanced mass flow rates and reduced instability remains incomplete, necessitating continued experimental investigation. Comprehensive analysis of existing studies reveals that natural circulation flow rates fluctuate based on the relative dominance between buoyancy and friction forces. Predominant buoyancy forces enhance mass flow rates, while dominant friction forces diminish them. Consequently, mass flow rate enhancement strategies must consider buoyancy force augmentation, including the implementation of lower-density working fluids like

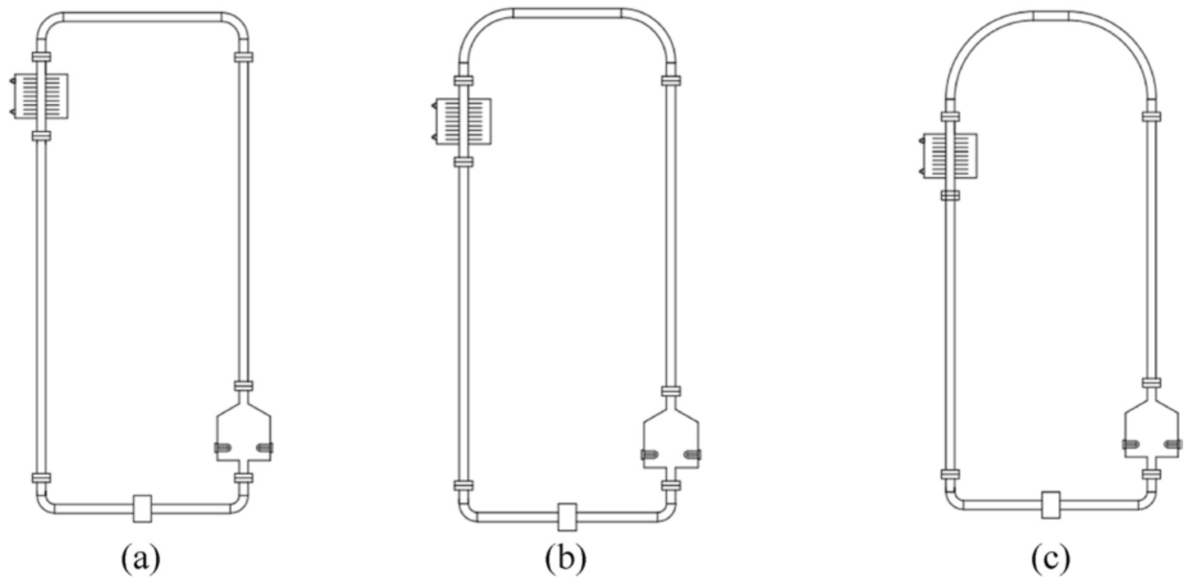

Fig. 7. Configuration 3 FASSIP-06-V3 variation of working fluid and elbow radius (a) 100 mm, (b) 200 mm, (c) 300 mm.

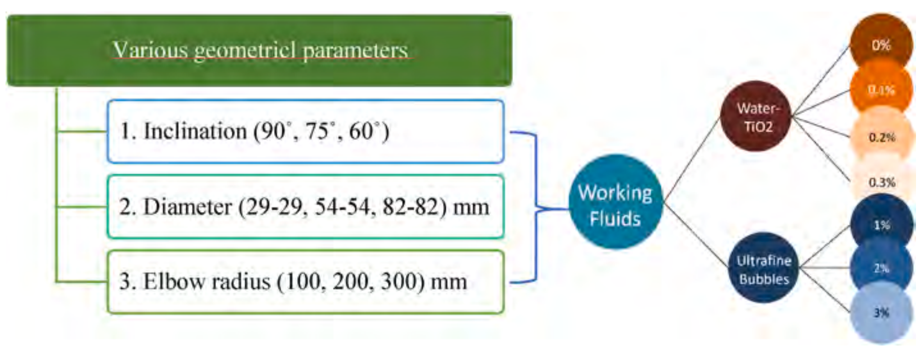

Fig. 8. Proposed experiment scenario.

ultrafine bubbles (UFB), though further investigation of UFB thermal properties remains necessary. Additionally, research priorities include both flow rate enhancement and heat transfer improvement through working fluid optimization, such as water-nanoparticle mixtures at specific ratios for instability reduction.

Natural circulation flow instability presents an inherent challenge. Researchers face the task of categorizing thermal-hydraulic parameters that significantly influence mass flow rates and stability, particularly for nuclear reactor safety thermal management innovations. Literature analysis identifies four crucial experimental parameters affecting flow rates and instability: phase characteristics, operational conditions, geometric configurations, and working fluid properties. Future research initiatives utilize the FASSIP-06 SOLOMOTION (System Analysis Loop Modeling Variation) facility, illustrated in Figs. 5–7, featuring three modular configurations. This facility incorporates direct-modeled heating components and indirect-modeled cooling components with pipe-mounted fins, accommodating pipe diameters from 1 to 3 inches in various combinations. The experimental configurations include:

* *Configuration 1*

Implements a stainless steel rectangular loop (850 mm width, 2500 mm height, 1-inch diameter) with non-direct heating and fin-enhanced heat transfer areas in both WHT and WCT. This setup enables natural circulation experiments using diverse working fluids (water, nanofluids, nanobubbles) with variable loop inclination angles, as shown in Fig. 5.

* *Configuration 2*

Features three rectangular loops (850 mm width, 2500 mm height) constructed from stainless steel, incorporating vertical sections with 1-inch, 2-inch, and 3-inch diameters. This arrangement creates both uniform diameter loops (UDL) for 1-inch sections and non-uniform diameter loops (NDL) for 2-inch and 3-inch sections, facilitating water-based natural circulation studies across varying diameters, as illustrated in Fig. 6.

* *Configuration 3*

Comprises three stainless steel rectangular loops (850 mm width) with varying heights determined by different elbow radii. The intersection points between vertical and horizontal loops feature adjustable top elbow radii ranging from 100 mm to 200 mm, as depicted in Fig. 7.

Several working fluids are employed in experimental studies, including water, nanofluids, and ultra-fine bubbles (UFBs). Studies have demonstrated that the incorporation of nanoparticles into base fluids enhances thermal characteristics, specifically thermal conductivity, heat capacity (Angayarkanni and Philip, 2015), and heat transfer coefficient (Wen and Ding, 2006). Researchers have explored nanofluid applications in natural circulation systems to examine their impact on circulation dynamics and flow instabilities (Nayak et al., 2008). The selection of TiO_2 nanoparticles for suspension was influenced by their superior heat transfer capabilities, long-term stability, and safety considerations. Combining water and TiO_2 creates a consistently dispersed solution that prevents particle clustering. This uniform distribution enhances heat transfer efficiency while minimizing potential system blockages and sediment formation (Yang and Hu, 2017), (Sezer et al., 2019).

The incorporation of UFBs was selected primarily due to their low-density properties, as they are expected to generate significant buoyant forces that exceed frictional resistance. Experimental findings indicated that water containing oxygen nanobubbles demonstrated accelerated cooling, achieving a temperature reduction from 80 °C to 34 °C within approximately 12 min (Senthilkumar et al., 2021). UFBs exhibit strong negative zeta potential characteristics, resulting in bubble dimensions that remain relatively constant despite temperature fluctuations (Zhang et al., 2020). Research conducted by Chandan et al. (2023) revealed that introducing air into SPNCL enhanced fluid circulation rates through void buoyancy effects. The introduction of air at 40 cc/min resulted in a 5.2-fold increase in flow rate. Furthermore, air injection served to improve thermal efficiency and acted as a stabilizing mechanism in HHHC loop systems. Fig. 8 illustrates the experimental configuration incorporating both geometric and working fluid variables.

The system's performance evaluation involves both linear and non-linear analytical approaches, utilizing dimensionless parameters including Reynolds, Grashof, and Stanton numbers. These parameters are calculated for each experimental variation. The relationship between Reynolds and Grashof numbers is graphically represented to illustrate the predominant forces affecting fluid movement. Stability mapping, distinguishing between stable and unstable regions, is achieved through non-linear analysis of modified Grashof versus modified Stanton numbers.

Flow rate measurement accuracy requires appropriate analytical methodologies for data interpretation. The presence of a flowmeter is shown in Figs. 5–7, where proper selection is essential to ensure accuracy and stable hydraulic conditions. In the context of flow rate measurement, we recommend the use of ultrasonic flowmeters and electromagnetic flowmeters, depending on operational conditions and fluid properties. Ultrasonic flowmeters have the advantage of being non-invasive, causing no pressure drop and being easy to install (clamped-on), but their accuracy is highly dependent on pipe conditions and fluid homogeneity (Afandi et al., 2024). On the other hand, electromagnetic flowmeters provide high accuracy for conductive fluids such as water or nanofluids, with resistance to changes in viscosity and density, although they require permanent installation and sufficient fluid conductivity. Meanwhile, the ideal installation for both types of flowmeters is on the horizontal adiabatic cold-leg section, with sufficient straight pipe length—at least 10 diameters before the flowmeter and 5 diameters after the flowmeter. This installation helps achieve a fully developed flow profile and minimizes measurement errors caused by flow disturbances. Placing the device after the cooler also protects the sensor from high temperatures that may exceed its operational limits.

Flow rate and pressure differential measurements, recorded at 1-s intervals, undergo wavelet analysis. This analytical approach characterizes flow patterns by decomposing time-frequency signals into eight distinct levels. The analysis incorporates probability distribution function (PDF) for data distribution assessment, power spectral density (PSD) for frequency and magnitude evaluation, and discrete wavelet transform (DWT) for frequency and amplitude representation. Wavelet analysis serves as a post-processing tool capable of characterizing fluctuations related to bubble formation and wave dynamics (IGNB. Catrawedarma et al., 2021).

6. Conclusion remarks

This comprehensive review examines single-phase natural circulation loops (SPNCL) with rectangular geometries, focusing on passive nuclear cooling. While existing studies highlight the influence of phase characteristics, operational conditions, geometric configuration, and working fluid properties on flow stability and heat transfer, the core of this work lies in Section 4: Discussion and Further Research, which extends beyond a mere summary by proposing a targeted experimental framework. This section introduces the FASSIP-06 SOLOMOTION facility, designed with three modular configurations to systematically investigate the effects of inclination angles (90°, 75°, 60°), pipe diameters (29–82 mm), elbow radii (100–300 mm), and advanced working fluids such as TiO_2-water nanofluids and ultrafine bubbles (UFBs)—both of which show promise in enhancing buoyancy forces and improving flow stability. The use of non-intrusive ultrasonic flowmeters, installed on straight horizontal sections downstream of the cooler, and wavelet-based signal analysis of 1-s interval data enable high-accuracy, disturbance-free data collection. By integrating these elements, Section 4 provides a novel, actionable research roadmap, making it the central and most significant contribution of the paper.

Nomenclature

		Acronyms	
A	Flow area (m^2)	APWR	Advanced pressurized water reactor
c_p	Specific heat capacity (J/kg°C)	CCS	Containment cooling system
D	Hydraulic diameter (m)	CFD	Computational fluid dynamics
Gr	Grashof Number (−)	CL	Cold−leg
H	Loop height(m)	CNT	Carbon nanotube
k	Thermal conductivity (W/m°C)	DHRS	Decay heat removal system
L	Length (m)	DR	Decay ratio
m	Mass (kg)	DWT	Discrete wavelet transform
NG	Geometrical ratio number (−)	ECCS	Emergency core cooling system
P	Pressure (Pa)	EDG	Emergency diesel generators
Q	Volumetric flow rate (m^3/s)	FASSIP	Fasilitas simulasi sistem pasif (Indonesian)
Re	Reynolds Number (−)	HHHC	Horizontal heater horizontal cooler
St	Stanton Number (−)	HHVC	Horizontal heater vertical cooler
t	Time (s)	HL	Hot−leg
T	Temperature (°C)	HTF	Heat transfer fluid
v	Velocity (m/s)	IAEA	International atomic energy agency
		KAERI	Korean tomic energy research institute
Greek symbols		NC	Natural circulation
Δ	Refers to the difference	NCL	Natural circulation loop
β	*Thermal expansion coef*. (1/K)	NDL	Non-uniform diameter loop
ρ	Density (kg/m^3)	PCS	Passive cooling systems
μ	Dynamic viscosity ($N.s/m^2$)	PDF	Probability distribution function
		PRHRS	Passive residual heat removal system
Subscripts		PSD	Power spectral density
m	Modified	SBO	Station blackout
nf	Nanofluids	SMART	System integrated modular advanced reactor
t	Total	SMR	Small modular reactor
		SPNCL	Single-phase natural circulation loop
		UDL	Uniform diameter loop
		UFBs	Ultrafine bubbles
		VHHC	Vertical heater horizontal cooler
		VHVC	Vertical heater vertical cooler
		WCT	Water cooling tank
		WHT	Water heating tank

CRediT authorship contribution statement

Roy Waluyo: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Deendarlianto:** Supervision, Methodology, Conceptualization. **Indarto:** Validation. **Dwi Yuliaji:** Data curation. **Veronica Indriati Sri Wardhani:** Resources. **Akhmad Afandi:** Investigation. **Muhammad Ganjar Putra:** Data curation. **Ryan Oktaviandi:** Data curation. **Sunandi Kharisma:** Visualization. **Shendy Akbar Maryadi:** Visualization. **Achilleus Hermawan Astyanto:** Resources. **Mulya Juarsa:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

Data will be made available on request.

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