Chapter 2: Literature review

The growing energy demand requires a reliable passive device like a natural circulation loop (NCL) is needed for the recovery, transfer, and use of the generated heat in a closed loop. The potential applications for NCL are in solar heaters [4-7], cooling of turbine blades [8], geothermal energy extraction [9], decay heat removal from the core of a nuclear reactor [10-11], cooling of an electronic chip [12-13], and refrigeration system [14-15]. Mostly, single-phase NCL (SPNCL) is preferred in such applications for simplicity. However, some of the major drawbacks of SPNCL are low mass flow rate and flow instability. Thus, for enhancing the reliability of SPNCL, the accurate prediction of transient and steady-state behavior is crucial. Several parameters influence the stability and the performance of SPNCL, such as geometric parameters, operating parameters, and working fluids. A literature review showed that natural circulation had been the subject of extensive research. In view of practical importance, different configurations of NCL have been proposed, such as a toroidal loop and rectangular loop. For example, the solar water heating loop and its applications have been reviewed by Japikse [17], Zvirin [18], Greif [19] and Basu et al. [20]. The presented literature review mainly emphasizes the numerical and experimental studies for SPNCL and these are presented subsequently.

2.1 Experimental Studies

Natural circulation loop systems are susceptible to flow oscillations because of the flow field's significant dependency on operating and geometric parameters and working fluids. For practically all configurations, several flow instabilities, including periodic flow reversals, flow bifurcation, and even chaotic oscillations, have been reported.The first experiment was performed by Creveling et al. [21] to analyze the flow instability and/or reversal in a toroidal-shaped water loop and reported that there were two ranges of heat input in which the system was stable: a low heat input range ($q < 0.11$ W/cm2) in which the flow seemed laminar, and a high heat input range which was in turbulent flown regime ($q > 0.70$W/cm2). At intermediate values of the heating, the flow was found to be unstable approximately between 0.11 and 0.70 W/cm2. Damerell and Schoenhals [22] investigated the effects of an angular displacement (tilt) [$\theta + \pi \leq \theta \leq \theta + 2\pi$] between heated and cooled sections of the toroidal loop on its flow and stability. They found that tilting the loop minimizes the instabilities occurring in the toroidal loop. The performance and stability of the solar heater were investigated by Zvirin and Shitzer [23,24]. The first experimental investigation using a rectangular loop was done by Hallinan and Viskanta [25,26]. Fluorescent dye was injected into the DI water to visualize the flow regimes. They observed that laminar to turbulent regime changes at very low Reynolds as 340. In single-phase NCLs, the suppression of unstable oscillations is a practical concern; therefore, Numerous studies have tried to suppress the instability by varying geometrical and operating parameters. Misale and Frogheri [27] experimentally studied the effect of pressure drop on the stability of a natural circulation loop by placing three different diameters (6, 10, 14 mm) of an orifice in the vertical column of the loop and found that pressure drop has a stabilizing effect, but there is a significant reduction in the mass flow rate which reduces the heat transfer capability. Vijayan et al. [28] experimentally studied the effect of the heater and cooler orientation on the steady state and stability behaviour of the single phase natural circulation loop (SPNCL). They found that the maximum mass flow rate was achieved when the heater and cooler were placed horizontal, but it was found to be least stable and the orientation having a vertical heater and a vertical cooler was found to be most stable, but they had minimum mass flow rate. Garibaldi and Misale [29] experimentally studied the effect of the geometric parameter and different working fluids on the thermal performance of rectangular SPNCL. They observed that FC43 has a velocity almost twice as compared to water at the same power input. The velocity in the tallest loop is lower, probably due to a higher increase in shear forces overcoming the increase in buoyancy forces. Misale et al. [30] investigated experimentally the effect of thermal boundary condition on the dynamic behaviour of a rectangular SPNCL. They have considered the two working fluids (distilled water and FC43) and the effect of sink temperature on the stability behaviour of SPNCL. They found that the distilled water is more stable than FC43 and stability can also be achieved by varying only the sink temperature without varying heater power. Misale [31] experimentally investigated the influence of power step on the thermo-hydraulic behaviour of the natural circulation loop and found that the loop shows unstable behavior for both constant and variable power supply. Vijayan [32] developed a correlation in terms of a single non-dimensional parameter (Gr_m/N_G), which predicts the steady state behaviour of both uniform and non-uniform diameter of the loop. Vijayan et al. [33] experimentally studied the effect of loop diameter on the flow stability of NCL and found that decreasing the loop diameter enhances the stability. Misale et al. [34] experimentally studied the dynamic response of NCL by varying the sink temperature and found that stability can be attained by decreasing the sink temperature without changing heater power. This may not be practically feasible as it is restricted by ambient temperature. The stability is achieved at the expense of increasing the pressure drop, which reduces the mass flow rate or is economically infeasible.

The majority of researchers employed water as their working fluid in the aforementioned literature. The operating limit of the water is constrained at higher power input in the subcritical region due to its lower boing point. Using supercritical water at high pressure is the best solution to run a natural circulation loop that uses water at a high temperature, but the cost and risk associated with it is high. Several works of literature using supercritical CO_2 have also been carried out by many researchers [35-39]. Kumar and Gopal [40] investigated the different working fluids for SPNCL for low-temperature application (-35°C to 10°C). The selected working fluids are 1. MA: aqueous solution of methyl alcohol of 40 percent by weight, 2. EG: aqueous solution of ethylene glycol of 50 percent by weight, 3. S-XLT: polydimethylsiloxane, silicon oil (Slytherm XLT, Dow Corning), 4. R-744: carbon dioxide, 5. R-717: ammonia.6.R22:chlorodifluoromethane, 7. R-134a: 1,1,1,2-tetrafluoroethane, 8. R-600a: iso-butane, 9. R-290: propane, 10. water (H2O). They found that CO_2 shows the best performance among all other selected working fluids and can be considered as a suitable working fluid in natural convection loops for refrigeration and air conditioning applications. Several researchers have investigated Liquid metal [41-43] and molten salt [44-46] as a working fluid in the nuclear industry and solar thermal power plants, which is suitable for high operating temperature range (250 °C to 800 °C) in SPNCL system.

Recently the use of nanofluid over conventional fluid has had a very powerful impact on the thermal performance of the system. It improves the heat transfer capability of the system due to enhanced thermophysical properties, which makes the system more compact. Therefore, for better performance of single-phase NCLs, it is crucial to enhance the thermophysical properties of loop fluid, both in terms of heat transfer and system stability. Recently, nanofluids have been used in NCL by many researchers. Nayak et al. [47] experimentally investigated the effect of water and Al_2O_3/water nanofluid on natural circulation behaviour in a rectangular loop. They reported that significant enhancement in mass flow rate and instability is suppressed even at a low concentration of nanoparticles. They also reported that mass flow rate and suppression of instability is dependent on the concentration of nanoparticle used. They also found that the instability is suppressed in all cases and mass flow rate with nanofluid is higher than that with water and CuO nanofluid has a higher mass flow rate at higher power (> 250 W) and TiO_2 nanofluid has a higher flow rate at lower power (< 250 W) than other nanofluids [48]. The steady natural circulation flow rate was found to be increased with nanoparticle concentration [49]. Misale et al. [50] studied the effect of loop inclination and sink temperature on the thermal performance of a natural circulation mini loop with Al_2O_3/water nanofluid and water and reported that the mini loop is stable for both fluids and the thermal performance (temperature difference between hot and cold leg, average fluid temperature and overall heat transfer coefficient) is reduced by increasing loop inclination and increases with heat sink temperature. Ho et al. [51] experimentally showed that Al_2O_3–water nanofluid could markedly enhance the heat-transfer performance (average heat transfer effectiveness) of NCL. Doganay et al. [52] experimentally studied the thermal performance of SPNCL with Al_2O_3/water nanofluid and concluded that the effectiveness factor increases with an increase in particle concentration and loop inclination at all power ranges. Koca et al. [53] experimentally investigated the thermal characteristics of Ag/water nanofluid in SPNCL and found that effectiveness is improved by 11% with 1% weight concentration of nanofluid compared to water. Thomas and Sobhan [54] also recently reported superior heat transfer capabilities in the rectangular NCL by using nanofluids. Experimental research on the dynamic behavior of water-based nanofluids, including silicon dioxide (SiO_2), copper oxide (CuO), and alumina (Al_2O_3) nanoparticles, was done by Bejjam et al. [55] at different volume concentrations ranging from 0.5 % to 1.5 %. In order to investigate the state reaching time, the effect of various power inputs and cold fluid inlet temperatures were chosen as input parameters. It was discovered that, when compared to water, utilising various nanofluids as working fluids in the loop lowered reaching time by 12-27 %. Nanofluid enhances thermal performance parameters of mass flow rate, Rayleigh number, and average Nusselt number by 10.95%, 16.64%, and 8.10%, respectively, as compared to water. At the same power input condition, CuO-water nanofluid performs better compared to other nanofluids. Cobanoglu and Karadeniz [56] studied the effect of different pipe diameters (3–6 mm) of water-based Al_2O_3 nanofluid (1–3 vol.%). The effect of the thermal conductivity on SPNCmL characteristics is found to be limited for the investigated cases. However, viscosity affects the SPNCmL characteristics significantly as the viscosity values differ greatly for both the measured and Einstein correlation's data. Thermo-hydraulic performance is also evaluated by calculating the dimensionless heat transfer coefficient. Some important literatures are shown in the Table 2.1.

Table 2.1 Some important experimental investigations on SPNCL

Authors	**Studied parameters**	**Result**
Misale and Frogheri [27]	Influence of pressure drop by using orifice on the behavior of a single-phase natural circulation loop. Loop diameter = 20 mm Orifice diameter: :6, 10 and 14 mm	(1) The pressure drops stabilize the loop behavior. (2) Mass flow is reduced.
Vijayan et al. [28]	Effect of the heater and cooler orientation: HHHC= Horizontal heater horizontal cooler HHVC=Horizontal heater horizontal cooler VHHC= Vertical heater horizontal cooler VHVC= Vertical heater vertical cooler	(1) Mass flow is higher for HHHC followed by HHVC, VHHC, VHVC. (2) Stability for VHVC is higher followed by VHHC, HHVC, and HHHC.

Vijayan et al. [33]	Effect of loop diameter on the Steady State and stability behavior of SPNCL.	(1) Mass flow rate increases with increase in diameter. (2) Instability increases with larger diameter loops.
Misale et al. [50]	Effect of loop inclination and sink temperature on the thermal performance on mini loop using Al_2O_3/water nanofluid	Thermal performance (temperature difference between hot and cold leg and overall heat transfer coefficient) is reduced by increasing loop inclination and increases with heat sink temperature.
Misale et al. [30]	Influence of thermal boundary conditions on the dynamic behavior: (1) Effect of heat sink temperature (2) Effect of working fluids Loop fluid: Water, FC43	(1) Water shows more stable behavior than that of FC43. (2) Decreasing the sink temperature increases the stability behavior.
Nayak et al. [47]	Effect of water-based Al_2O_3 nanofluid on stability and mass flow rate.	Flow instabilities are suppressed and also the mass flow rate is enhanced with nanofluids.
Bejjam et al. [55]	Steady-state and transient characteristics: Parameter variation: Power input, Coolant inlet temperature	Steady-state reaching time is reduced by 12–27% using nanofluids. Thermal performance parameters like

	Nanoparticles: Al_2O_3, CuO and SiO_2 Loop fluid: Water Volume concentration: 0.5% to 1.5%.	mass flow rate, Rayleigh number, and Nusselt number of nanofluid-based NCL are improved by 10.95%, 16.64%, and 8.10%, respectively.
Koca et al. [53]	Effect of nanofluid on effectiveness Ag/water nanofluid in SPNCL	Effectiveness is improved by 11% with a 1% weight concentration of nanofluid as compared to water.

2.2 Theoretical and numerical studies

Numerous theoretical and numerical studies have been performed to understand the dynamic behaviour and stability of NCL. The first theoretical investigation was carried out by Keller[57] using rectangular loop NCL and they observed periodic oscillations and concluded that inertia is not responsible for this oscillation, which is due to the interplay between buoyancy and frictional force. Welander [58] theoretically explained the mechanism causing instability of a loop consisting of a point heat source (top) and heat sink (below). Sen and Trevi˜no [59] modelled 1-D code and reported that Both forward and backward behaviour is possible in a condition in the loop, and mainly depends on the initial condition given in the loop. As the reasons behind instability behaviour of SPNCL are exposed, the researchers are attracted towards the problem and are making an effort to control the instability behaviour of NCL Chen [60] theoretically showed that the aspect ratio (height/width) has a significant influence on flow stability of NCL and found least stable as aspect ratio approaches to unity. Mousavian et al. [61] performed a numerical analysis using the RELAP5 system code of HHHC rectangular single-phase natural circulation loop to observe the transient and stability behaviour of the loop. Several investigations on NCL related to the effects of geometric and operating parameters have been reported. Sadhu et al. [62] investigated the effect of geometry and operating parameters on the stability behaviour of NCL with CO_2 and found the ambient effect is significant and the axial conduction effect is negligible. Cammi et al. [63] developed a new methodology based on Information Entropy to evaluate the dynamic behaviour of NCL. It provides information to identify the stable and unstable transient and also shows a stability map of a given dynamic system. Rao et al. [64] numerically investigated the dynamic response of NCL with end heat exchangers for various excitations such as sinusoidal, step, exponential and ramp excitations. Basu et al. [65] analyzed the influence of loop shape on the stability of the Single Phase NCL (SPNCL) and found that the rectangular loop is less stable than the toroidal loop. Basu et al. [66] studied the dynamic behaviour of rectangular NCL on the different nature of heat input excitations and found that modified exponential excitation is best for increasing or decreasing power input. Basu et al. [67] studied the influence of geometry (diameter, height, total loop length) on the stability response of a single-phase natural circulation loop. They observed that (1) Decreasing loop diameter stabilizes the flow but also reduces the steady-state flow rate drastically. (2) Increasing vertical height enhanced stability margin and a slightly enhanced steady-state flow rate. They also reported that stability increase with an increase in loop width and heater length. Misale and Devia [68] performed a numerical investigation on the thermo-hydraulic behavior of HHHC SPNCL for different heat sink temperatures. Krishnani and Basu [69] studied the influence of heater power, sink temperature and loop inclination on the stability of the system and found that the instability increases with increasing heater power and sink temperature and decreases with increasing loop inclination. Most of the 1-D codes are developed based on the conventional forced flow correlations for heat transfer coefficient and friction factor. Vijayan and Austregesilo [70] found a higher friction factor for the natural circulation loop as compared to the force flow correlation. Huang and Zelaya [71] informed that force flow correlation could predict the behavior of the rectangular loop well if local losses due to bend and fitting are accounted for accurately. Ambrosini et al. [72] studied the effect of truncation error on the numerical prediction of linear stability boundaries in a single-phase natural circulation loop. Ambrosini et al. [73] investigated the effect of wall friction and provided an appropriate friction law for laminar and turbulent flow, which provide higher friction factors than in forced flow. Pilkhwal et al. [74] studied stability analysis of a single-phase natural circulation loop with 1-D and 3D CFD and concluded that the 3D CFD model could predict stability behaviour better than 1-D and provide improved modelling capabilities since it does not use any correlation of heat transfer and friction factor. Swapnalee et al. [75] investigated SPNCL, which obeys multiple friction law, and provided a friction factor correlation for the laminar, transition and turbulent flow rectangular SPNCL. They reported that the laminar regime occurs at Re < 898, the transition regime occurs at 898 < Re < 3196 and the turbulent flow regime occurs at Re > 3196. The effect of wall thermal inertia [76-79], Heat loss to the ambient [80], and Boussinesq approximation [81] on the performance of SPNCL was reported in the literature; details are shown in Table 2. Some numerical works were conducted by researchers using liquid metal [82-85], molten salt [86-88] and thermal oils [89-91] as a working fluid in the nuclear industry and solar thermal power plant applications. Some numerical studies based on nanofluid-based SPNCL are available. Kumar et al. [92] finite difference method is used to discretize the one-dimensional homogeneous loop model to study the mass flow rate, momentum and, energy behaviour at steady state condition nanofluid (Al_2O_3-water) is considered as the loop fluid and water is considered as the external fluid (hot and cold). Parameter variation- Cold and hot inlet temperature, heat transfer rate decreases with increase in cold water inlet temperature, heat transfer rate increases with increase in hot water inlet temperature, heat transfer rate increases with loop height. Bejjam and Kumar [93-94] numerically studied the effect of loop inclination on the thermal performance of Al_2O_3/water nanofluid-based SPNCL and reported that steady state mass flow rate, heat transfer coefficient, Rayleigh number and effectiveness increase with particle concentration. Through theoretical study, Devi et al. [95] found that Fe_3O_4/water nanofluid-based NCL size is reduced by 4% at 1% concentration and the size reduction is more at higher concentrations. Karadeniz and Doganay [96] numerically investigated the performance of mini loop SPNCL using Al_2O_3-DIW nanofluid on the effect of different heater powers (10, 30, 50 W), volumetric concentrations (1%, 2% and 3 %), and inclination angles (0^o, 30^o, 60^o and 75°). Some important investigations are shown in Table 2.2.

Table 2.2 Some important numerical investigations on SPNCL

Author	Studied parameters	Findings
Cammi et al. [76]	Wall thermal inertia	The unstable region reduces by introducing the thermal inertia of the wall material.
Misale et al. [77]	Thermal capacity and axial conduction	Increasing wall heat capacity and conductivity augments the average fluid temperature, resulting in an increase in velocity and Nusselt number.

Lin et al.[78]	Wall thermal conductivity and thickness	Higher thermal conductivity and thick wall markedly enhance the buoyancy-induced flow at the lower modified Rayleigh number.
Cheng et al.[79]	Effect of wall thermal resistance	The lower thermal conductivity of the tube material significantly influences the thermo-hydraulic performance of SPNCL.
Basu et al. [80]	Heat loss from the loop wall to ambient	Higher ambient temperature increases the effectiveness of the heat exchanger.
Basu et al. [66]	Nature of power input excitations: (1) Step, (2) Ramp, (3) Exponential profiles, and (4) newly-defined modified exponential Signal.	The exponential excitation was the best for decreasing or increasing heat input.
Krishnani et al.[81]	Boussinesq approximation	Boussinesq approximation offered an extremely conservative estimate of stability and recommended avoiding transient analysis by using Boussinesq approximation, particularly at higher power.
Basu et al. [67]	Influence of geometry (diameter, height, total loop length) and Minor friction loss	(1) Decreasing loop diameter stabilizes the flow but also reduces the steady-state flow rate drastically.

	on the stability response of single-phase natural circulation loop.	(2) Increasing vertical height enhanced stability margin and a slightly enhanced steady-state flow rate. (3) Total loop length enhances stability but reduces steady-state flow rate. (4) Minor frictional losses due to bends and fittings suppress flow instability. Whereas it deteriorates the steady-state mass flow rate.
Basu et al. [65]	Performance comparison of rectangular loop and toroidal loop under steady-state and transient conditions.	A rectangular loop showed a high mass flow rate but was less stable than the toroidal loop.

2.3 Research gaps

Based on the above literature review, the following research gaps have been identified:

- These days, using nanofluid instead of traditional fluid has a significant impact on the system's thermal performance. There are very few investigations that demonstrate the impact of nanofluids on the performance of SPNCL. Generally, they reported that the nanofluids enhance the mass flow rate and effectiveness of SPNCL system. However, the effect of shape of the nanoparticles and the use of hybrid nanofluid are not yet reported. So, there is a need of detailed investigation for the same on the performance of SPNCL.

- Most of the reported studies are based on water up to a temperature of 100 ^{o}C. A limited investigation reports the performance of SPNCL, under atmospheric conditions, with molten salts and liquid metals for a high temperature above 250 ^{o}C. There are even few literatures, which advocate for the available working fluids in the medium temperature range of applications. Therefore, the need for literature identifying or using the potential working fluid is realized for the medium temperature range (100 ^{o}C to 250 ^{o}C). Therefore, it is worth investigating the possible working fluids such as thermal oils (Thermal oil: Therminol-VP1, Paratherm-CR, Dowtherm-Q) and vegetable oils (Soyabean, Canola oil, Sunflower oil) as potential candidates for SPNCL under atmospheric conditions.
- The effects of heat loss, conduction (axial conduction in fluid, wall conduction and heating coil conduction), property variation, bend, non-uniform heat flux distribution, and non-Boussinesq have some impact on the performance and stability of SPNCL. For numerical modeling in practice, many of the above-mentioned effects are being neglected. Therefore, investigations are necessary to assess the individual effect and combined effect of each parameter on transient and steady-state characteristics of SPNCL for different working fluids, to verify the validity of these assumptions, and to improve the predictive capability. Hence, the relative effect of all these phenomena in simulation should be studied extensively. However, to the best of the author’s knowledge, no such study is available in the literature.
- Effect of heater power input, height to width ratio, loop inclination, coolant inlet temperature on the energetic i.e. mass flow rate (predict heat transport capacity),

the effectiveness of the heat exchanger (predict heat transfer capability) and exergetic, i.e., total entropy generation rate (predict exergy of the system) performance parameter of SPNCL using hybrid nanofluid is not available in the open literature