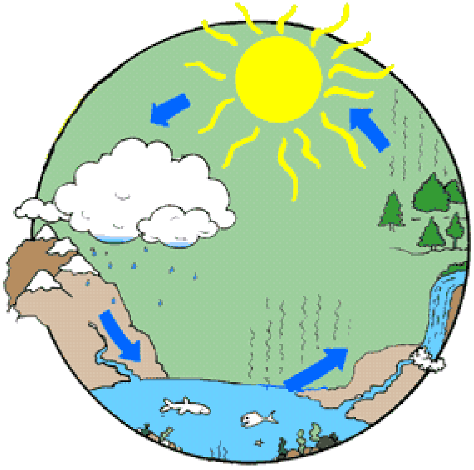
Chapter 1

Introduction

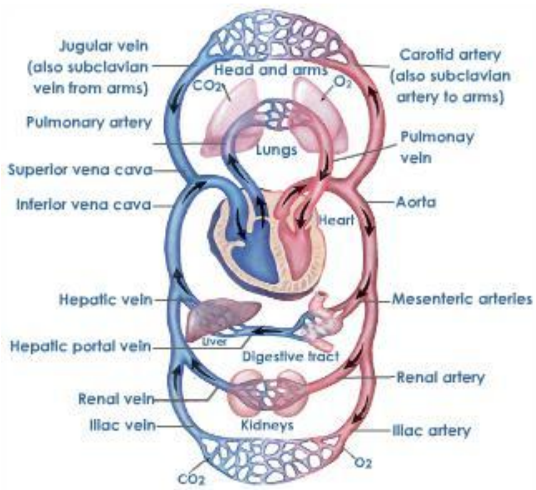
1.1. Understanding natural circulation

In engineering sense, the term *circulation* generally refers to the transport of a fluid through a closed circuit. Very common examples can be the atmospheric and oceanic circulations in the nature and blood circulation in human body (Fig. 1.1). However, there is a fundamental difference between the two citations. In the later case, there is a central component in the form of heart to pressurize the fluid and thereby to externally impart enough driving energy for circulation. In the other case, however, the circulation takes place solely due to the density difference in different parts of the medium (air or water) caused by thermal imbalance. Such kind of phenomena is referred to as *natural circulation*, in contrary to the *forced or assisted circulation* for the other case. Gebhart (1973) used the terminology ‘internal natural convection’ to describe *flows arising in a body of fluid contained in a cavity or completely bounded by surfaces*. The most distinctive features of natural circulation systems are their high sensitivity to the operating conditions and susceptibility to unstable operation, mainly due to the completely coupled nature of flow and temperature fields. Flow rates in such systems are much smaller compared to the cases with assisted circulation (flow imposed by prime movers like pumps or fans). As a result, identical orders of momentum and viscous effects and strong dependence on body forces become important characteristics of a natural circulation loop.

The phenomenon of natural circulation offers a very efficient option of fluid transport within a closed system without employing any mechanical drives. It is possible to construct a closed circuit with heating at one location and cooling at some other location, heat sink being located at higher elevation than the source. That establishes an unstable density gradient in the system and hence, under the influence of gravity, forces the warmer, and hence lighter, fluid to rise up and cooler, heavier fluid to come down. Hence thermal energy can be transported from high-temperature source to low-temperature sink without bringing them in direct contact with each other and also without using any prime mover. Such systems are commonly known as Natural Circulation Loops (NCLs). Sometimes the term *thermosyphon* is also used loosely to describe a NCL. Early definition of *thermosyphon* by Davies and Morris (from Japikse, 1973) includes all circulating fluid systems where motion is caused by



(a) Water evaporation from oceans and rainfall completes a natural cycle (courtesy: http://www.co.kane.il.us)



(b) Blood circulation in human body forced by the heart (courtesy: http://babycolorshq.blogspot.com)

Fig. 1.1: Examples of Natural and Assisted Circulations in Everyday World

density difference in a body force field. Japikse (1973) more rationally considered the systems with intrinsic function of removing heat from a prescribed source and transporting over a prescribed path to a prescribed sink and defined *thermosyphon* as *a prescribed circulating fluid system driven by thermal buoyancy forces*. However, he also made a clear distinction between NCL, where the flow is generally in one direction around the loop, and thermosyphon, where the flow can be upward along the heated wall with associated return flow along the cooler wall or down the core (Fig. 1.2). One appropriate example of such a thermosyphon system can be evacuated tube solar water heaters (Budihardjo *et al.*, 2007). However, the conventional NCL with loop-type design has found plenty more applications in energy conversion and transfer systems, mainly to take advantage of the distinctive location of source and sink. NCLs have been employed very successfully in a wide variety of industrial and engineering fields including solar heaters (Close, 1962; Mertol *et al.*, 1981a; Ong, 1974; Shitzer *et al.*, 1977; Zvirin *et al.*, 1977), thermosyphon reboilers (McKee, 1970; Sarma *et al.*, 1973), electronic chip cooling (Tuma and Mortazavi, 2006), turbine blade cooling (Cohen and Bayley, 1955), chemical process industries (Joshi, 2001; Nottenkamper*et al.*, 1983), geothermal energy extraction processes (Kreitlow *et al.*, 1978), closed loop pulsating heat pipe (Khandekar and Groll, 2004; Khandekar and Gupta, 2007; Tong *et al.*, 2001), nuclear power generation and plenty more. Other novel ideas for application of NCLs are models of thermal springs of Virginia

(Torrance, 1979), low velocity corrosion studies (Hamilton *et al.*, 1954), heat dissipation employing the so-called 'liquid fins' (Madejski and Mikielewicz, 1971), in the study of deterministic chaos (Wang, 1992) and recently in the field of refrigeration (Kaga *et al.*, 2008) as well.

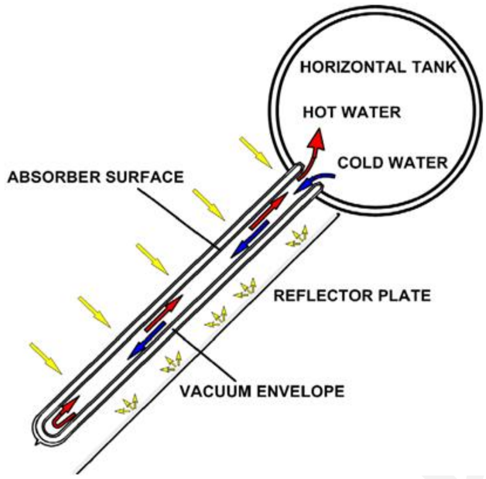


Fig. 1.2: Evacuated Tube Solar Water Heater – An Example of Thermosyphon (Budihardjo *et al.*, 2007)

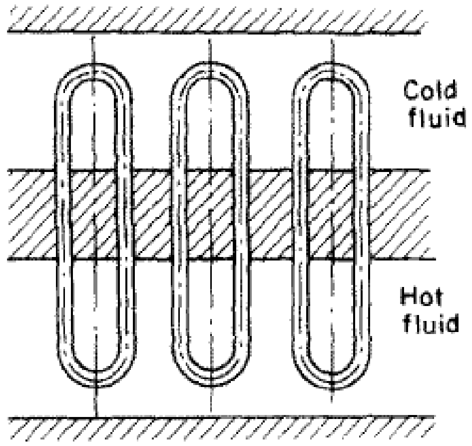
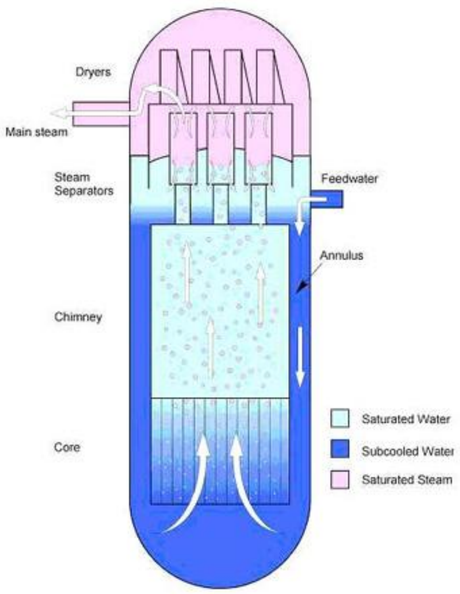


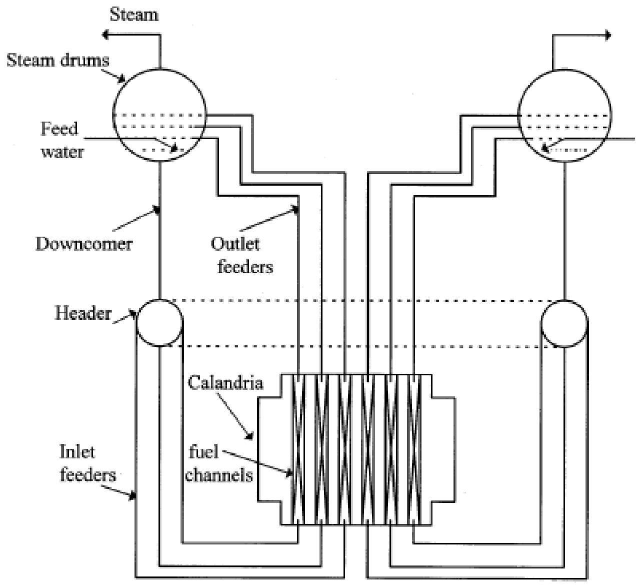
Fig. 1.3: Liquid Fins (Madejski and Mikielewicz, 1971) – An Innovative Application of Natural Circulation Loop

1.2. NCL in nuclear applications

In the context of twenty-first century world, probably the most important application of natural circulation loops is in connection with passive cooling of nuclear reactor core. Majority of the early-day reactors used to operate on assisted circulation or forced circulation mode for complete control on flow rate and compact design. However, following the disastrous incidents at Three-Mile Island (Samuel, 2004) and Chernobyl (Medvedev, 1991) owing to Loss-of-Coolant Accident (LOCA), sweeping changes were brought about in emergency response planning, reactor operator training, human factors engineering, radiation protection and in many other areas related to nuclear plant operation and safety. Accordingly, the focus of nuclear scientists has shifted back to the natural circulation mode, mainly to enhance the passive safety of the reactor, and thereby opening up a wide area of dynamic research and development. The emergency core cooling mechanism of Dodewaard nuclear reactor of Netherlands (Van Der Hagen *et al.*, 1997) and Economic Simplified Boiling Water Reactor (ESBWR) (Hinds and Maslak, 2006) designed by General Electric are fine examples of NCL in nuclear power applications. The Advanced Heavy Water Reactor (AHWR) (Sinha and Kakodkar, 2006) of India (Fig. 1.4) is also worth mentioning here. AHWR is a 750 MWth pressure tube type boiling light water cooled and heavy water moderated reactor with the objective to burn thorium in the core from a combination of $(Th\text{-}U^{233})O_2$ and $(Pu\text{-}Th)O_2$ as fuel. Its most striking feature is the adoption of natural circulation for core cooling during start-up, power raising, rated power condition and accidental measures, thereby no dependence on prime movers during any stage of operation leading to enhanced passive safety of the system. The world has observed numerous instances of NCL application in nuclear field in recent times and the extent of use is only going to expand in future. Emergence of NCL in nuclear field has nearly revamped the entire technology promising a bright future.



(a) Natural circulation flow in ESBWR
(Courtesy: http://www.ge-energy.com)

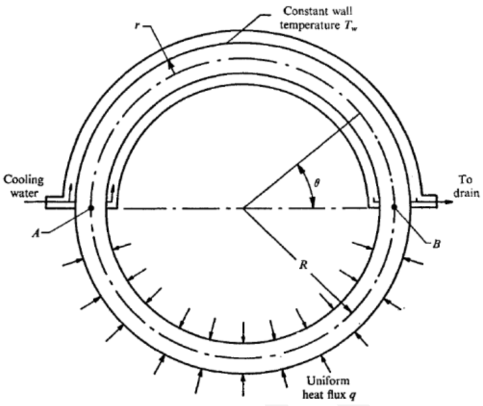


(b) Primary heat transport system of AHWR
(Nayak *et al.*, 2000a)

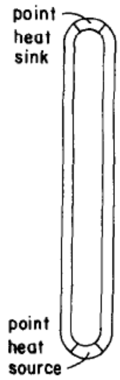
Fig. 1.4: Examples of Application of Natural Circulation in Nuclear Plants

1.3. Different configurations of NCL

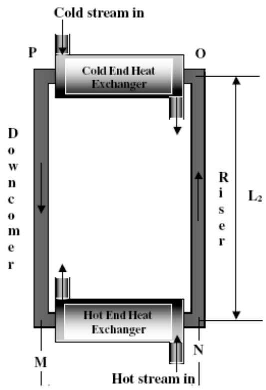
From theoretical point of view, natural circulation flow can be achieved with the presence of any suitable body forces such as electromagnetic, centrifugal or gravitational forces. However, almost all the practical applications concern the use of buoyancy created by gravity forces. Buoyancy always corresponds to a difference in density in adjacent parts of the same system. Now density difference can be achieved either by thermal effects or by introduction of a lighter phase in the flow domain. The later kind of system is commonly known as Air-lift Loop (ALL) and has found widespread application in chemical process industries (Merchuk and Berzin, 1995; Young *et al.*, 1991). The term NCL is typically attached with thermal loops having distinct heating and cooling zones. Heat addition to the loop fluid can be in the form of specified heat flux (*e.g.* use of electrical heaters around the pipe) or convective heat transfer with a warmer fluid in heat exchanger or combined radiation and convection (*e.g.* water evaporation in riser tubes inside the furnace of a water-tube boiler). Heat rejection is generally in the convective mode. It is also possible for the loop fluid to undergo a phase change depending upon the rate of heat transfer. In power station boilers, the vapour is separated from the two-phase mixture and extracted for running the turbine. Makeup liquid is provided at the same rate to maintain the mass balance in the circuit. Considering the practical importance, different NCL configurations have been proposed to accommodate corresponding applications. Examples of a few important configurations have been shown in Fig. 1.5.



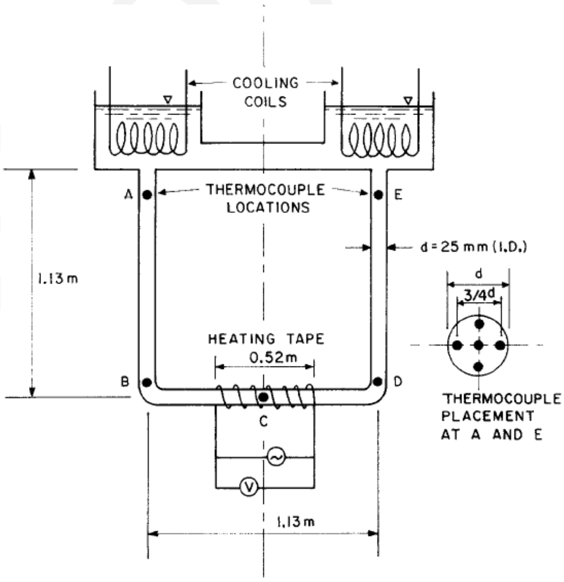
(a) Toroidal NCL
(Creveling *et al.*, 1975)



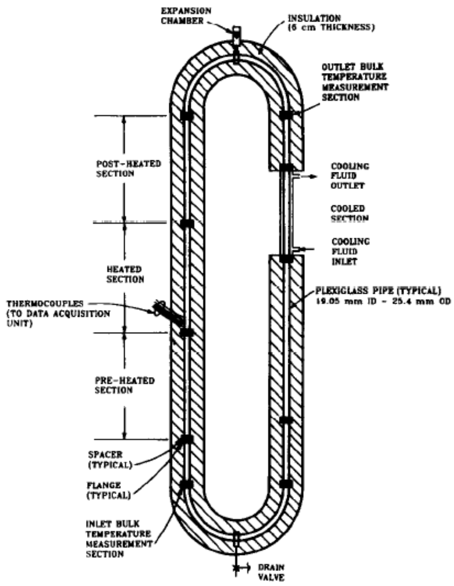
(b) Rectangular NCL with point heat source & sink
(Welander, 1967)



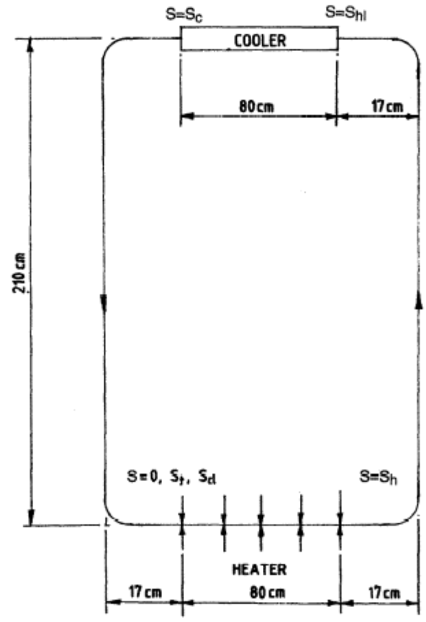
(c) Rectangular NCL with end heat exchangers
(Rao *et al.*, 2005)



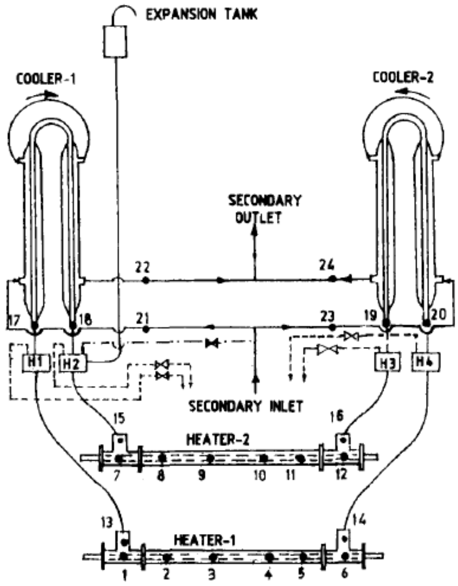
(d) Open-type rectangular NCL
(Bau and Torrance, 1981)



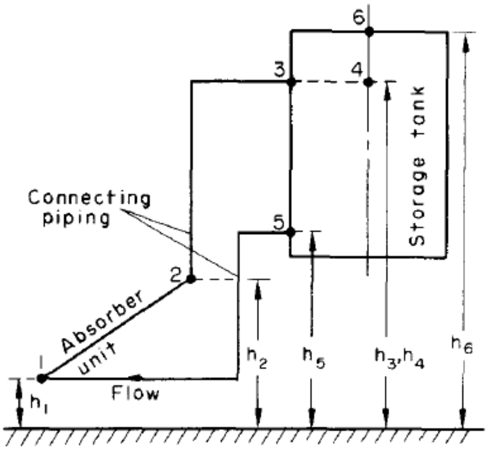
(e) Semi-rectangular NCL with vertical heat transfer sections (Bernier and Baliga, 1992)



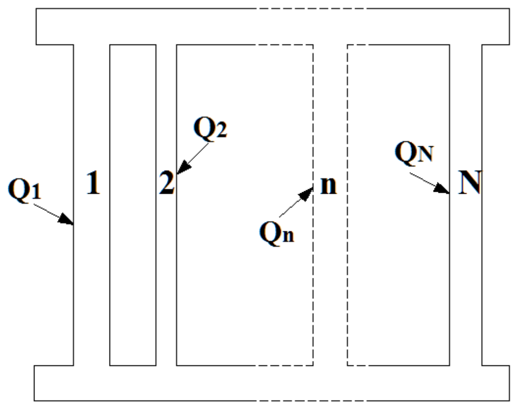
(f) Closed-type rectangular NCL (Nayak *et al.*, 1995)



(g) Figure-of-eight loop with throughflow (Vijayan and Date, 1992a)



(h) Typical solar water heating system (Ong, 1974)



(i) Multiple path thermosyphon (Chato, 1963)

Fig. 1.5: Various Geometric Configurations of Natural Circulation Loop

1.4. Brief overview of available literature

Natural circulation systems essentially offer an assured and highly reliable heat transport mechanism, characterized by enhanced passive safety with respect to thermal failure. The absence of prime mover makes it a suitable option in a number of typical applications. For example, a two-phase NCL can be operated without bothering about the problem of cavitation and pump malfunctioning. Mechanical drives also introduce noise and vibration into the system, whereas NCL comes across as a serene relief. However, due to the strong coupling between momentum and thermal fields, it is not possible to predict desirable operating conditions in the natural circulation domain just by some thumb-rules. The system performance generally depends very strongly on each of the geometric and operating parameters and the slightest change in any may induce dramatic shift in operation. Hence intricate and comprehensive design calculations are mandatorily required to match the precise requirement of the concerned application.

Due to the strong dependence of the flow field on operating conditions, NCL systems are always susceptible to flow oscillations and possible flow reversals. Intense interaction between buoyancy and frictional forces dominate the events. Different modes of flow instability have been observed for almost all kinds of configuration. Along with periodic flow reversals, even flow bifurcation and chaotic behaviour can also appear. The phenomena are generally more severe for two-phase NCLs, compared to their single-phase counterparts. As there is no direct controlling mechanism, proper zone of operation is needed to be identified at the design level itself. That poses a real challenge to the researchers and over the years, a large number of researchers have worked upon natural circulation and related effects. Both experimental and theoretical findings have been reported. Comprehensive reviews on natural circulation systems and thermosyphons have been presented by McKee (1970), Ostrach (1972), Japikse (1973), Zvirin (1981), Mertol and Greif (1985), Norton and Probert (1986) and Greif (1988). It is truly an arduous job to have elaborate discussion on each of the available studies within the scope of a few pages. Hence, in the present section, effort has been made to mention some of the most significant contributions from the literature and to gather some idea about the gradual development of concept regarding natural circulation loops and associated configurations.

1.4.1. Concept of natural circulation and flow instability

The concept of fluid motion due to bottom heating and top cooling evoked from the works of Lord Rayleigh (1916). Pioneering studies were focused on the stability of fluid movement bounded between infinite parallel plates, initially at rest and onset of motion due to a temperature gradient in the direction of body force. Reduction of Orr-Sommerfeld equation to the instructive case of infinite Reynolds number (Re) or zero viscosity for a parallel flow field yielded the inviscid perturbation differential equation or the so called Rayleigh equation (Schlichting and Gersten, 2004) having the form:

$$(U - c)(\varphi'' - \alpha^2 \varphi) - U''\varphi = 0 \tag{1.1}$$

Here U represents the basic flow velocity in longitudinal direction, α is the wave number and c is the propagation speed. $\varphi(y)$ represents the amplitude function of the disturbance wave, historically referred to as the Tollmien-Schlichting wave (White, 2003). Based on Eq. (1.1), Lord Rayleigh postulated that velocity profiles with points of inflection are unstable. Later, Tollmien (from Schlichting and Gersten, 2004) proved that the presence of points of inflection in velocity profile is a sufficient condition for flow instability. The introduction of viscous effects suppresses the amplification of disturbances for infinitely large Reynolds number and a finite region of unstable waves exists. Instability generally arises after a critical temperature gradient has been reached and a stationary cellular structure of motion can be observed (Chandrasekhar, 1961). Under suitable boundary conditions, a secondary structure arises where fluid motion forms rolls, undergoing a Hopf bifurcation and becoming oscillatory (Busse and Clever, 1979).

Zvirin (1985) presented an excellent discussion on the initiation on motion in a natural circulation system. He summarized the types of instabilities in such loops as,

(a) onset of local closed cell of Rayleigh-Bénard type, when a certain critical Rayleigh number (Ra) is exceeded, similar to other thermal instabilities
(b) onset of global flow around the loop with further heating
(c) instability of steady flow in the loop, associated with oscillation growth
(d) multiple steady-state solutions, indicating meta-stable instabilities

Hence the motion in any thermosyphon is always induced by thermal instabilities and general working of any energy transfer device working on NCL associates the favorable instability of the second kind. However, the third and the fourth kinds of instabilities are commonly the matter of concern and are required to be avoided for practical operations.

Most of the early reports on observation of instability in free convection flows concern near-critical fluids. Creveling *et al.* (1975) has presented a complete chronological development of such kind of studies till the 1960s. Studies have been reported on pressurized ammonia, water, R-12 and R-114. It was, generally, assumed that flow instability appears due to the large variation in fluid properties in the vicinity of critical point, without giving much thought to the system dynamics. Hence, it was not expected for the fluid to exhibit any unstable behaviour under ordinary temperatures.

Keller (1966) was the first to theoretically find the periodic motion in a simplified rectangular loop, where heating element was assumed at the mid-point of lower arm and cooling element at the mid-point of the upper arm. Under certain operating conditions, the system behaves like a self-excited oscillator. Inertia was found to have negligible effect on such oscillations, as they merely require an interplay between friction and buoyancy. Welander (1967) developed the concept on a configuration consisting of point heat source and heat sink, connected by parallel vertical branches, and proposed a 1-D model to predict the steady-state and stability behaviour assuming friction as a linear function of flow rate. Zones of stable and unstable operation through the neutral curve were predicted as well. A numerical experiment for unstable cases exhibited growth of oscillations and flow reversal. He also presented a plausible explanation for the emergence of instability using the well-celebrated theory of 'warm and cold pockets of fluids'. The fluid was considered to behave as a pendulum, *with its mass centre towards the 'cold pocket'*.

The first physical observation of instability with water as the working fluid under normal temperatures is credited to Creveling *et al.* (1975). They carried out the experiment on a toroidal loop with distributed heating and cooling, each occurring over half of the loop length. Under specific operating conditions, unstable system response with repeated flow reversal was observed. Accompanying theoretical analysis using proposed friction factor and heat transfer coefficient satisfactorily reproduced the experimental result. Two different regimes of stable operation were found, with the region of instability matching the transition from laminar to turbulent flow. Creveling *et al.* (1975) were strongly in accord with the argument of Welander (1967) regarding the origin of instability.

Sen and Treviño (1982) developed a one-dimensional model of an NCL having arbitrary shape and general nature of heat flux to or from the loop. Considering a general power law-based frictional relation, they showed that the loop could have both forward and reverse flow under any particular situation, steady-state flow direction being governed by the initial conditions. By subjecting the loop to both point and distributed heat fluxes in their subsequent work (Sen and Treviño, 1983), they explained that steady-state flow is possible only under certain conditions and even that might be pulsating in nature. Analytical expression for steady-state velocity with convective cooling was also proposed for the same loop.

1.4.2. Natural circulation in solar thermal systems

Most of the early applications of NCLs relate to solar water heaters. Desa (1964) was probably the first one to work upon solar heating systems employing natural circulation. Mean water temperature variation throughout the day was predicted by carrying out an energy balance. Close (1962) proposed a mathematical model to predict the steady-state values for mean water temperature and system mass flow rate. Gupta and Garg (1968) improved Close's analysis by incorporating a plate efficiency factor to account for the thermal efficiency of the collector and approximating ambient temperature and radiation intensity employing Fourier series expansion. Ong (1974) analyzed the thermal performance of similar systems employing finite-difference technique. Important variables such as the plate efficiency, heat transfer coefficient, friction factor and water properties were allowed to vary depending on local temperature and measured values of ambient temperature and radiation intensity were employed, thereby giving a more realistic prediction. Computed results generally agreed well with accompanying experiment during the main insolation period. The method was improved subsequently by Ong (1976) incorporating more realistic temperature distribution in the storage tank and absorber plate. It resulted in much better comparison with test data, showing small discrepancy during early morning heat-up and late evening cool-down periods. Assumption of zero heat capacity of the glass, and other structural components had some role to play here.

Zvirin *et al.* (1977) presented a simplified model only suitable for noon-time analysis and showed that the assumption of linear temperature variation was reasonably valid during that period. They also suggested the range of validity of such assumption. Their work was supported by experimental results of Shitzer *et al.* (1979), who found that temperature distribution inside the collector tube was almost linear throughout the day. In fact, in absence of any hot water consumption, temperature distribution inside the storage tank was also found to be more or less uniform. These results proved that the thermosyphonic flow rate closely follow the incident solar radiation. Mertol *et al.* (1981a) developed an analytical detailed loop model (DLM) to analyze the performance of solar heaters with heat exchanger in the storage tank and propylene glycol as the working medium to solve the freezing problem under specific weather conditions. They studied system performance as function of heat exchanger characteristics, working fluid, flow resistance and tank elevation and predicted that loop performance would be around 90% compared to a thermosyphon without heat exchanger.

Morrison and Ranatunga (1980a) analyzed the transient response of a solar heater with a step change in insolation. Long time delays were observed for the thermosyphon flow to pick up, however, without affecting much the overall collection capability. In an accompanying paper (Morrison and Ranatunga, 1980b), they focused on some methods for improving predictions from conventional models. They observed that, in general, flow rates were underestimated for low Reynolds number ($Re < 300$) and overestimated at higher Re and showed that the effect of friction in developing flow region could have significant effects. They also postulated that, for a low rate of circulation, it might be possible for the velocity and temperature profiles to deviate from the assumed forced flow conditions. Appearance of a peak in the velocity profile close to the heated wall, with a dip or recirculation at the centre was a real possibility.

1.4.3. Investigations on Toroidal NCLs

Since Creveling *et al.* (1975) established the phenomenon of instability in NCL under ordinary temperatures, number of researchers have worked on this particular topic, as it offers an excellent thermo-fluidic problem with simple background. Majority of the reported studies concerns a torus in a vertical plane as the geometry, mostly down to the fact that regular nature of the flow path results in mathematical simplicity. A number of intricate concepts regarding steady-state and stability behaviour of NCL were expatiated through toroidal geometry. Hence, despite limited practical applicability, a meticulous discussion on evolution of toroidal NCLs and associated findings need to be reported.

Creveling *et al.* (1975) presented the stability map for a toroidal loop heated from below and cooled from the top. Damerrel and Schoenhals (1979) extended their work to investigate the effect of angular shift in the heated and cooled sections on flow rate and loop stability. Zone of sustained oscillations were observed for displacement between $+6°$ to $-6°$, with an input heat flux range of ~ 500 to 9500 W/m^2 for zero tilt angle to the limiting case of ~ 4000 W/m^2 for $\pm 6°$. A simple theoretical model with laminar flow and assumed heat transfer relation predicted two possible steady-state solutions for each tilt angle, equal in magnitude but opposite in direction. Favorable agreement between predictions and experimental observations was achieved for tilt angle between $60°$ and $140°$. However, flow rate was generally over-predicted for less than $60°$ angular shifts. They found reverse flow to appear for $0°$ to $60°$ tilt angles due to rapid cooling of fluid near the wall, having maximum effect for direct bottom heating and designated this phenomenon to be responsible for such over-prediction. Maximum flow rate was also attained for zero inclination. However, a similar theoretical analysis by Sen *et al.* (1985a) presented an exact expression for steady-state velocity and showed that maximum velocity might not always appear for direct bottom heating. The flow was predicted to have zero, one, two or three steady-state velocities.

Britt and Wood (1983) carried out experiments on toroidal NCL and their findings were well in agreement with Creveling *et al.* (1975). Their study confirmed three distinct zones of operation, namely, stable flow at low power, oscillations at intermediate power and back to stable flow at high power. Recirculation was also observed due to faster change in temperature of fluid elements in contact with the wall compared to those close to centerline. A $90°$ angular shift of the loop showed no flow reversals.

Greif *et al.* (1979) studied the transient and stability behaviour of a similar toroidal loop employing finite-difference technique. However, they assumed the flow field to be laminar and assumed friction factor to be $16/Re$ to study the dynamic performance. Resultant stability map was different than predicted earlier (Creveling *et al.*, 1975) for obvious reasons. The transient response for stable, neutrally stable and unstable cases corresponded well with their locations on the linearized stability map. The period of oscillation was found to be close to the time taken by a fluid element to circulate around the loop.

Mertol *et al.* (1982) carried out a two-dimensional analysis for a toroidal loop, where both friction factor and heat transfer relations were expressed as non-monotonic functions of Graetz number (Gz). Variations were considered in both radial and axial directions and finite-difference technique was employed. The average velocity was found to increase with Gz initially, till it reached a maximum and then decreased, due to the increased friction and smaller temperature differential with higher velocity. Computed steady-state results exhibited excellent agreement with the experimental result of Creveling *et al.* (1975). However, their model failed to predict the flow reversal, as was observed earlier (Damerell and Schoenhals, 1979). As a further improvement, three-dimensional steady-state analysis of toroidal NCL has been reported by Lavine *et al.* (1987). They showed that 1-D and 2-D analyses over-predicted the total buoyancy and hence average axial velocity by 31 and 47 percent respectively. Some real-time phenomena, *e.g.*, stream-wise flow reversal, secondary motion and non-axisymmetric temperature profiles were predicted well.

Three different types of heating conditions were considered by Pacheco-Vega *et al.* (2002) in a toroidal thermosyphon, namely, known heat flux, known wall temperature and mixed heating. Solution for the first case exhibited super-critical Hopf bifurcation, whereas the other two showed both sub- or super-critical bifurcations. The behaviour changed from sub- to super-critical with increase in tilt angle, which showed a natural stabilizing effect. Their numerical experiment confirmed the presence of chaotic behaviour with the mixed heating mode.

In a separate work, Zvirin (1979) proved that viscous dissipation increased the temperature level and flow rate for a toroidal loop under steady-state due to the additional heating of loop fluid. Stable zone of operation reduces slightly due to viscous heating under turbulent conditions. Bau and Torrance (1983) have also reported similar results. However, they proved that viscous dissipation and pressure work have opposing effect on flow and are of comparable magnitude. Axial conduction was found to have an obvious stabilizing effect (Mertol, 1980) on the system due to reduction in thermal gradients leading to weaker buoyancy and lower flow rates. Similar effect of axial conduction was also hinted by Sen *et al.* (1985a) for situations, where flow was observed in experiments despite zero possible solution. Gordon *et al.* (1987) observed through their theoretical analysis that highly conducting fluid may yield zero flow through the loop, whereas reduced conduction effects resulted in multiple solutions. Stability maps were also constructed with three different working fluids to demonstrate the effect of axial conduction. Through a more elaborate conduction model, Sen *et al.* (1989) identified the lower boundary of heating for ensuring flow through the loop. Beyond that limit, either two stable solutions or oscillatory motion were predicted for different working conditions in a toroidal loop with symmetric heating. With asymmetric heating, however, flow can be initiated with any heat flux. Stabilizing effects were also observed with the application of through flow, *i.e.*, continuous addition and removal of fluid from the loop (Mertol *et al.*, 1980). Detailed stability behaviour of toroidal loop with parallel-flow heat exchanger has been reported by Mertol *et al.* (1983).

The Lorenz system has recently been applied for predicting system stability by a separate group of authors (Gorman, *et al.*, 1986; Hart, 1984; Sen *et al.*, 1985b). The transient governing equations were converted to an infinite set of ordinary differential equations, which was transformed to a 'master' problem of three non-linear ordinary differential equations, along with an infinite set of linear 'slave' problems. Representative forms of decoupled equations for both known heat flux and known wall temperature cases were developed by Sen *et al.* (1984), assuming both friction factor (f) and Nusselt number (Nu) as power law functions of Reynolds number (Re). Angular variations of temperature were expressed in terms of Fourier series with unknown time-dependent coefficients. Steady, periodic and chaotic motions were found for various parameter ranges. Sen et al. (1992) presented a summary of findings based on similar approach for toroidal loops with a prescribed heat flux. Singer *et al.* (1991), Boskovic and Krstic (2001) used active feedback control to suppress or induce chaos, thereby suggesting mechanisms for controlling chaotic instability in convection loops. Jiang and Shoji (2003) added the influence of wall thermal conductivity into the Lorenz model and highly conducting wall was found to have a stabilizing effect on the system. The Rayleigh number value characterizing the appearance of instability exhibited strong dependence on wall thermal conductivity. However, Lorenz model does have the drawback of assumed nature of velocity and temperature profiles. Burroughs *et al.* (2005) derived a model, such that the first Fourier modes exactly decoupled from all other Fourier modes, resulting in a system of three coupled non-linear partial differential equations completely describing the system behaviour. Fourier-Chebyshev spectral methods were used for numerical solution. Their result predicted stable periodic flow at much lower Prandtl number (Pr) and both sub- and super-critical Hopf bifurcation depending upon Pr.

1.4.4. Transformation towards rectangular geometry

For real-life application, the toroidal geometry of natural circulation loops does not have much significance. Hence, with the development in knowledge related to the underlying physics of natural circulation, focus has shifted to more realistic geometric configurations, which can be realized in practice. As a first effort, Holman and Boggs (1960) investigated the heat transfer to R-12 near the critical point in an NCL. Their system consisted of two vertical branches, a horizontal section at the bottom with large curvatures at the corners and a curved connector at the top. Lower portion of one vertical branch was electrically heated, whereas a cooling heat exchanger was mounted around the upper part of other vertical arm. They observed pressure fluctuation of the order of 20 to 30 psi (≈ 136 to 204 kPa) close to critical point. Fluctuations subsided with increase in coolant flow rate, but intensified with decrease in coolant flow or increase in supplied heat flux.

Model of Welander (1967) of point heat source and point heat sink connected by vertical branches was a significant stride for analyzing NCLs with ordinary fluids. That model can also be viewed as a lumped representation of rectangular loops. Zvirin and Greif (1979) attempted transient analysis for a similar configuration. Assuming linear temperature distribution, their results asymptotically approached the steady-state solution of Welander (1967). However, their analysis failed to predict any instability, even for the range of parameters earlier found to yield unstable solutions. Therefore they concluded that the stability characteristics strongly depend on the shape of temperature distribution. Assumption of linear temperature profile was found to be unsuitable even for predicting the steady-state values close to the limits of operation (Zvirin *et al.*, 1977). A number of other studies on solar heaters (Mertol *et al.*, 1981a; Morrison and Ranatunga, 1980b) were also important steps in shift from circular geometry.

Hallinan and Viskanta (1985, 1986) conducted detailed experiments on a rectangular natural circulation loop having de-ionized water under atmospheric pressure with tube bundles as source in one vertical arm and as sink in the other. Flow visualization was done by injecting fluorescent dye. Laminar to turbulent transition was found to occur around $Re = 340$. Friction parameter was found to be a straight-line function of Re and comparable with forced-flow situations. Correlations for average heat transfer coefficient were proposed based on experimental findings. Their work was a major contribution towards the implementation of natural circulation for passive safety in nuclear plants.

Experimental investigation on rectangular NCL was also reported by Huang and Zelaya (1988). They experimented on a loop with vertical electrical heating and vertical convective cooling and water as the working fluid. Initial oscillations were observed to damp out and give only stable flow. Overall heat transfer coefficient was calculated from energy balance and was found to be almost identical to that with near-critical R-12 (Holman and Boggs, 1960). Ho *et al.* (1997) analyzed the effect of anomalous behaviour of water on the performance of a similar configuration. Unique density inversion of water around 4 °C was found to have significant impact on heat transfer and major modification was suggested at the modelling level to have accurate prediction.

In a more generalized study, Ramos *et al.* (1985) investigated rectangular loops with variable area. Assuming Poiseuille flow through the loop, they showed that flow was possible only with heat source at a lower elevation than heat sink and such system would always have multiple steady-state solutions. Experimental observation of the appearance of multiple steady-states in a tilted square loop was done by Acosta *et al.* (1987). Heating and cooling were in opposite arms of the loop. Different types of flow patterns appeared with variation of tilt angle. They showed that it is possible to have two distinct stable states for certain heat supplies and tilt angles. Such observation has already been reported for toroidal loops earlier (Damerell and Schoenhals, 1979; Sen *et al.*, 1985a). Appearance of instability with small changes in tilt angle was also demonstrated.

Bernier and Baliga (1992) observed that 1-D models were accurate when the flow approached fully-developed condition throughout the loop. However, with strong local convection effects in the heated and cooled sections, the velocity and temperature profiles are bound to be distorted, with strong 3-D effects. As a compromise between accuracy and computational cost, they proposed a 1-D/2-D model to couple the detailing of mixed convection effects in the heated and cooled sections with simplified model for the other sections. Numerically and experimentally they studied a system with vertical heat-exchanging sections, connected by two circular 180° bends. Reasonable agreement was achieved and their model showed improvement over conventional 1-D models.

Chen (1985) studied the stability of a rectangular loop, heated over lower horizontal arm and cooled over upper horizontal arm. He introduced the concept of a modified Grashof number (Gr_m) incorporating the influences of loop diameter and geometry and suggested a critical value of Gr_m for instability to appear. Oscillations were observed to occur over a narrow range depending upon the frictional parameter. Aspect ratio was found to have important role in determining the stable zone of operation and system was more susceptible to instability as aspect ratio approached unity. Vijayan *et al.* (1992b) carried out detailed experimentation on three rectangular NCLs. All the loops had configuration similar to that studied by Chen (1985), but differed only in diameter, namely, 6 mm, 11 mm and 23.2 mm. Test was conducted over wide range of heater power and cooling water flow rate. No instability was observed for loops with 6 mm and 11 mm diameter over the entire test range. However, the third loop exhibited unstable oscillations and flow reversals for certain input combinations. Steady-state results for all three loops plotted on a $Re - Gr_m$ plane fell on parallel straight line.

Vijayan *et al.* (1991) presented a number of very crucial observations. They found that, for a given Reynolds number, the pressure loss coefficient measured under natural circulation condition exceeded that under forced circulation condition by as much as 30%. Similarly, the measured Nusselt number (Nu) value greatly exceeded the value calculated with available forced flow correlations. They attributed such effects to the presence of secondary flow. They also felt the necessity of defining non-loop specific characterizing parameters in order to compare the results from different experimental studies performed on various geometries, as most of the available data were either in dimensional form or in terms of loop-specific parameters. They used equivalent diameter and equivalent cross-sectional area of the loop to define Re and Gr_m and proposed a generalized relationship of the form

$$Re = 6.077 \times 10^{-3} (pGr_m)^{1/2.3444} \tag{1.2}$$

p being a loop-dependent constant. Such representation allowed them to compare the data from seven geometrically dissimilar loops. Comparisons exhibited appreciable agreement with all, except some deviation with the results presented by Creveling *et al.* (1975). They noted the presence of about 50% heat loss in corresponding experiment and identified that as reason for such divergence. They also observed that the form of proposed correlations could be applied to real systems with possible modification in the exponents, but maintaining the geometrical shape and magnitude of modified Grashof number, thereby providing a basis for system scaling.

As a further development, Vijayan and Austregesilo (1994) postulated that, in order to have satisfactory scaling to simulate steady-state, transient and stability behaviours of natural circulation, equalities of Gr_m, ratio of diameter-to-length, ratio of length-to-height, ratio of total length-to-heater length and modified Stanton number (St_m) were essential. Hence, if the experimental model has identical heights to the prototype, identical loop diameter, heating length and total loop length need to be maintained, thereby differing from the old concept of power-to-volume scaling philosophy (Karwat, 1985). Their model has the advantage of having only two independent physical similarity groups. The experimental results from all the three loops of Vijayan *et al.* (1992b) can now be represented with a single straight line on $Re - Gr_m(d/L)$ plane and correspondingly they proposed a friction factor relationship suitable for natural circulation systems as,

$$f = 22.26\, Re^{-0.6744} \tag{1.3}$$

A large number of available experimental data was successfully correlated following their approach, thereby justifying the application of non-loop specific parameters.

Vijayan (2002) generalized the earlier observations a bit further by introducing a geometric parameter (N_G) to counter loops with non-uniform diameter. It can be viewed as the contribution of the geometry to the friction number and hence, independent of the flow field. Using fully-developed flow correlation for friction factor, relationship between Re and Gr_m was proposed for both laminar and turbulent conditions. Excellent agreement was achieved for laminar flow, in particular, for both uniform and non-uniform diameter loops. The same relationship has also been applied to study the behaviour of a rectangular mini-loop by Misale *et al.* (2007), with laminar friction factor and modification in the expression of Gr_m to counter the loop inclination. Stable flow was observed in all of their experiments with a loop of 4 mm inner diameter. Corresponding experimental data was in good agreement with the relation proposed by Vijayan (2002), proving its pertinence over a wide range of scales.

Rectangular NCL having heat source in convective mode has also been studied quite actively. London and Kays (1951) first proposed the idea of fluid-coupled indirect heat exchange system and explained a number of advantages of such system over direct-type heat exchangers. Rao (2002) and Rao *et al.* (2002, 2005) have analyzed the influence of heat exchange parameters on a rectangular NCL with counter-flow heat exchanger on both heater and cooler sides. They observed that both heat exchangers should have identical transfer units under steady-state to have maximum flow rate. Recently, Kiran Kumar and Ram Gopal (2009) studied a similar system with CO_2 as the working medium and predicted a more compact loop compared to systems with water as working medium. For a given set of inputs, optimum values of heat exchanger length and tube diameter were also predicted. Optimum diameter for downcomer was found to be smaller than riser.

1.4.5. Stability issues related to rectangular NCL

As the concept on rectangular natural circulation loops gradually developed, more emphasis was exercised on development of specialized computational techniques and higher-order analytical models, in order to predict the stability behaviour and dynamic response more precisely. Rectangular NCLs finding direct application to nuclear plants, both for normal and accidental heat removal, thus concurrently acting as working medium and passive safety option, it is all the more important to ensure stable zone of operation. General focus is to construct a neutral stability map in terms of generalized parameters. Both linear and non-linear analyses have been employed. In the former, the non-linear governing equations are perturbed and linearized to find the characteristic equation for the system, which is generally an algebraic equation. Investigations of the roots of that equation suggest whether the system is stable, unstable or neutrally stable. In non-linear analyses, numerical methods are used to observe the transient response of the system after being perturbed from a steady-state and growth or decay of the resultant oscillations determines the nature of the system. Linear stability analysis provides a very efficient and prompt option of finding the neutrally stable points, which can be very time-consuming with non-linear methods. However, to ascertain the nature of instability, to observe the growth of oscillations and to judge the evolution of transients during the start-up period, in particular, non-linear methods are required.

With the advancement in computational techniques, a number of codes have been developed following both linear and non-linear methods. NUFREQ (Peng *et al.*, 1986) and DENSITY-PARA (Xiao *et al.*, 1993) are examples of codes developed following linear stability analysis. SPORTS (Chatoorgoon, 1986) and RAMONA (Rohatgi *et al.*, 1993) were developed for non-linear stability analysis. Application of commercial software, *e.g.*, RELAP5, CATHARE2, ATHLET, FLUENT etc was also attempted by various authors. Some pioneering experimental and theoretical results are generally used for validation purpose of all such codes.

The neutral stability curve corresponding to the experimental findings of Vijayan *et al.* (1992b) has been presented in the same paper following linear stability analysis. Nayak *et al.* (1995) developed a 1-D mathematical model to predict the dynamic behaviour of the same loop. Transient response of the loop with application of perturbation at the steady-state was observed for any specified $St_m - Gr_m$ combination. Amplitude and frequency of oscillations remaining constant signified neutral stability. The locus of all such points was joined to form the neutral stability curve. A similar curve was also prepared following linear stability analysis and both the curves were in close agreement with each other. Vijayan *et al.* (1995) observed the dearth in available literature concerning numerical study of unstable oscillatory flow with repetitive flow reversal, thereby requiring repetitive switching of frictional correlations between laminar and turbulent regimes. Hence they used the thermal-hydraulic code ATHLET, which solves 1-D mass, momentum and energy conservation equations for both single-phase and two-phase systems. Radial conduction equation for the pipe wall was also solved to counter the damping effect of wall conductance. Reasonable agreement was observed in relation to steady-state data of corresponding experimental results (Vijayan *et al.*, 1992b), with some over-prediction of flow rates. However, for proper prediction of stability, fine nodalization was required. System with coarse grid failed to predict instability, when experiment exhibited unstable oscillations. The authors observed that required size of nodes should be such that amplification of instabilities should not get hampered.

Mousavian *et al.* (2004) experimentally observed the behaviour of a rectangular NCL and attempted theoretical prediction of stability map using a number of different techniques, namely, finite-difference transient analysis, linear stability analysis, Nyquist criterion and RELAP5 system code. Hot and cold leg temperatures were found to have strong dependence on flow regime, secondary side conditions and power level and hence Gr_m and St_m were identified as the characterizing parameters along with the geometry. Similar to Vijayan *et al.* (1995), they also observed dependence of stability response on the nodalization, finer nodes being a pre-requisite. Stability map was prepared based on linear stability analysis and identical map with non-linear method was predicted. Any comparison, however, was not shown between linear and non-linear stability maps. Some sample results with RELAP5 was shown. Generally, they under-predicted the results for lower powers and over-predicted for higher powers, which was attributed to the used heat transfer and fluid flow correlations.

The numerical aspects of stability analysis for single-phase NCLs have been studied in depth by Ambrosini and Ferreri in a series of published works. In one of their early studies (Ambrosini and Ferreri, 1998) they pointed out the influence numerical diffusion and truncation error could have on the shape and position of neutral stability curve. They selected Welander's problem as the base case, assuming flow field to be turbulent, and both the grid sizing and adopted numerical methodology were found to have strong effects on linear stability prediction. Among first-order methods, explicit upwind scheme was found to be more suitable compared to its implicit counterpart, as diffusion decreases with increasing number of nodes and keeping Courant number (Co) close to numerical stability limit of one. Implicit methods were found to be much more diffusive, particularly with larger time steps, thereby nullifying the unconditional stability of the scheme. Second-order explicit schemes were found to be very fast and accurate. In a subsequent work (Ambrosini and Ferreri, 2000), they included a rectangular and a toroidal loop under the purview of the same analysis and similar trends were observed in terms of adopted technique. Use of explicit upwind scheme with detailed special discretization or second-order method was stressed upon, in contrary to implicit methods. The choice of frictional relations on neutral stability curve was also shown to have strong effect. Use of properly evaluated wall friction factor was strongly recommended by Ambrosini *et al.* (2004), emphasizing the transition between laminar and turbulent regime in particular. They contradicted the earlier concept of under-prediction of friction in natural circulation systems with forced flow relations (Zvirin, 1981; Vijayan and Austregesilo, 1994) and supported the discussion of Vijayan (2002) to conclude that the applicability of any closure law was geometry-specific. They were unable to identify a particular relation functional for all NCLs, rather emphasized the use of detailed and efficient higher-order numerical techniques, thereby eliminating the need of area-averaged correlations. Use of FLUENT was demonstrated as an option.

Ambrosini and Ferreri (2003) proposed an ad-hoc technique to minimize the effects of truncation errors by defining a low-diffusion numerical scheme, a particular form of *donor cell rule*, to analyze the stability behaviour of the loop of Welander (1967) and the same for a rectangular loop. They kept the control volume formulation and upwind nature of first-order explicit method and made use of the low diffusive nature of second-order schemes. Excellent predictions were obtained even with ‘very coarse’ grids and the results were found to be relatively insensitive to the selection of time step.

Cammarata *et al.* (2003) proposed an alternative option of analyzing the stability behaviour of rectangular loops with the Lorenz system, similar to toroidal loops (Gorman, *et al.*, 1986; Hart, 1984; Sen *et al.*, 1985b), thus eliminating the sources of errors inherent in special discretization. Their model was obtained through Fourier series expansion of temperature field, gravity function and heating boundary conditions. All modes higher than the third were eliminated as a compromise between model complexity and accuracy. The model was linearized around the equilibrium point and computation of the sign of the real part of complex eigen values of Jacobian matrix identified the stability nature of the system. They recommended their model as a useful tool for design and operation of rectangular NCLs.

A number of theoretical and experimental investigations have been reported in the last decade aiming at suppression of unstable oscillations in a rectangular loop. Fichera and Pagano (2003) applied the model of Cammarata *et al.* (2003) for design and experimental testing of model-based feedback control strategies. A traditional proportional-derivative controller was applied on the model. Both the flow velocity and temperature difference across the heating section were used as the feedback variable, though only the latter was used in experiment. Despite a slight mismatch, both experimental and simulated results suggested stabilization of system dynamics. Muscato and Xibilia (2003) developed an identical model and tested both proportional and proportional-derivative controllers. All types of feedback controllers were found capable of stabilizing the system. Derivative action reduced the settling time slightly, but did not exhibit any significant impact. Control based on temperature difference was found to be superior due to higher bandwidth and lower noise of temperature sensor compared to flow sensor.

Misale and Frogheri (1999, 2001) analyzed the influence of introducing additional pressure drop in the flow path in form of orifices on unstable oscillations. Pressure drop was found to have a stabilizing effect, particularly for smaller orifices. With a decrease in the orifice opening, the stabilizing capability was enhanced and hence the amplitude of oscillations and damping period reduced. Recently Bodkha *et* *al.* (2010) experimented with the use of different spool pieces in the loop and that exhibited very encouraging results in terms of suppressing loop instability. Nayak *et al.* (2009) demonstrated the influence of addition of Al_2O_3 nanofluid in the circuit. Distinct increase in steady-state loop flow rate was observed based on concentration of nanofluid and accordingly unstable oscillations were suppressed significantly.

Vijayan *et al.* (2007) studied the role of orientation of heating and cooling sections on loop stability. Though horizontal heater-cooler gives highest flow rate, that was found to be most unstable. A conditionally stable hysteresis region was observed, where stability threshold depended upon heat addition path. Vertical heater-cooler orientation was identified as the most stable one. Generalized stability equation was found to give a conservative prediction compared to experiments. Pilkhwal *et al.* (2007) applied different 1-D models and one multi-dimensional CFD code (FLUENT) on similar configuration. The CFD code was found to be an excellent option for predicting the observed pulsating behaviour at low powers.

1.4.6. Studies on different alternative loop configurations

Along with the conventional shape of circle and rectangle, number of alternative geometric and physical configurations has been discussed by various researchers to suit the requirements of different applications. Sen and Fernández (1985c) considered the general situation of multiple tubes connected between two common points, each having the same cross-section but varying lengths and orientations. Expressions for temperature profiles along each arm were developed for both known heat flux and known temperature distribution. They proved that the resultant set of transcendental equations could be solved only after considering axial conduction. Non-conducting assumption leads to an inconsistent set, which could be evaluated only for the special cases of single-loop or loops having all but one identical branch. Their observation was improved by Sen *et al.* (1988) studying a double loop in the shape of a torus with diametral branch near the center. Coupling their analytical model with real experiments, they postulated that the effect of axial conduction at high flow velocities is confined in narrow thermal boundary layers near branch junctions. However, with lower flow rate, the effect spread over larger regions and must be taken into consideration despite the conduction term having order-of-magnitude difference with convection term outside the boundary layer. Large change in flow through the branches for small difference in their orientation (by tilting) was also demonstrated. As a variation of their geometry, Satou *et al.* (2001) evaluated a loop with insulated connecting tube between both sides (θ-loop), which can be viewed as a simplification of multiple cooling loops in a LMFBR. Such a loop was observed to have a different bifurcation structure compared to the single loop. Appearance of chaos corresponded to a higher value of Rayleigh number (Ra). Such stabilizing effect was attributed to reduction in pressure difference between two sides of the loop and flow in the connecting tube. Salazar *et al.* (1988) presented another variation of LMFBR through thermally-coupled conjugate loops and analyzed coupled square loops to show the possible existence of four steady-state velocities, two in either direction for each loop.

Use of an open-loop NCL (where *all or part of the circulating fluid may be exchanged with an external reservoir*) for geothermal energy extraction was demonstrated by Kreitlow *et al.* (1978) analyzing heat transfer in the downhole heat exchanger. They developed an analytical model of convection through and around a wellbore casing perforated at different depths. Temperature measurement of uncased well showed a substantial temperature gradient with highest temperature at the bottom and much lower at static water level. Torrance (1979) investigated flow in an open loop connecting two reservoirs with a 1-D analytical model. The limits of very narrow (vertical) to wide (elliptical) loop were examined and the latter one achieved higher exit temperature with long residence time at or near the maximum depth of the loop. Virginia thermal springs region was selected as the standard and reasonable theoretical prediction was made. This work was extended by Bau and Torrance (1981) with detailed experimentation to examine starting transients and loop stability. Quiescent initial state was always found to be unstable when heated from below. Linear stability analysis revealed zero value for critical Rayleigh number to initiate motion and always stable steady-state motion was attained upon symmetric heating. Secondary flow was found to have a strong role in diffusing the oscillation peaks during initial transients.

Theoretical analysis for a rotating open loop has been performed by Stremler *et al.* (1994) employing one-dimensional approximation. Centrifugal force was also considered as the body force, along with buoyancy. Critical heat flux corresponding to flow initiation was observed to be very low for any practical concern. Two different solutions for steady-state velocity were found, one in the direction of pressure gradient and the other opposite to it. Linear stability analysis indicated that one of them was always stable and hence possibility of a time-independent solution co-existing with a constant amplitude oscillation was demonstrated.

Another configuration with a very important practical application was the figure-of-eight design employed in CANDU-type of pressurized heavy water reactors. Vijayan and Date (1990) first analyzed such geometry with throughflow to counter the feed and bleed required in a practical system. They were the first to develop an experimental apparatus for methodical analysis of the effect of throughflow on thermosyphon. ±15% agreement was obtained between theoretical prediction and experimental data. Steady-state flow rate was observed to decrease with increase in throughflow, with accompanying increase in efficiency of throughflow. Highest flow rate correspond to the minimum distance in the direction of the flow between feed and bleed locations. Throughflow was also observed to induce asymmetry of temperature in the loop. Vijayan *et al.* (1991) presented a detailed discussion on associated frictional losses and presented a generalized correlation, as has been discussed in §1.4.4. Vijayan and Date (1992a) identified the limits of stability for such configuration using both linear stability analysis and finite-difference method, along with experimental observations. The two methods predicted slightly different neutral stability curve which was attributed to the use of separate values of heat transfer coefficient. Linear stability analysis was found suitable only to predict the threshold of instability, but was unable to provide any physical explanation. Non-linear analysis was found to be better suited for predicting conditional stability, *i.e.*, steady oscillation growth or flow reversal after first oscillation.

Loop with multiple parallel channels is another widely-used configuration, mostly in large power generation systems. Chato (1963) was the first to investigate a generalized model with several vertical parallel channels connected by two constant temperature headers. Tests were carried out with a three-channel system and existence of metastable condition was demonstrated. Laminar to turbulent transition was predicted at a lower *Re* and partial reverse flow was observed. Theoretical and experimental study of a loop with electrical heating and two parallel arms with convective cooling was undertaken by Zvirin *et al.* (1981). About 30% discrepancy was noted between two sets of results and that was attributed to the 3-D nature of the real flow field. Oscillations were observed with possible instability and flow reversals. Characteristic transient time was estimated to be close to the time taken by a fluid particle to circulate around the loop.

A few other configurations of NCL have also been utilized to some areas of research. But, generally, those are application-specific and do not contribute much to the knowledge about natural circulations.

1.4.7. Instability in two-phase NCLs

Single-phase NCLs are always limited by the saturation point criterion for the concerned fluid. With increase in source strength or suitable modification in the geometrical structure, phase change can be initiated in the system. Circulating fluid then generally undergoes boiling or flashing at one section of the loop and condensation or phase separation at some other part. Much larger density difference between a single-phase liquid and a two-phase mixture is capable of generating stronger buoyancy, resulting in larger circulation and enhanced system yield. The potential of two-phase thermosyphons for cooling of gas turbine rotor blades was manifested by Schmidt (1951) a long way back. However, the growth of such systems was relatively sluggish early on, mainly due to the lack of knowledge regarding the impact of multiphase interactions and resultant instability on a self-sustaining phenomenon such as natural circulation. Appearance of unstable oscillations in a two-phase NCL for intermediate power ranges and around the boiling point of the water was reported by Wissler *et al.* (1956) as early as 1956. Hence, all initial studies were focused on identification and quantification of two-phase instabilities and development of physics-based modelling techniques. With improvement in computational resources, very accurate prediction of two-phase behaviour is possible now and multiphase NCLs are finding applications in very critical fields such as nuclear reactor core cooling and electronic chip cooling.

An excellent description of different possible instabilities in a two-phase system was elaborated by Fukuda and Kobori (1979). They experimented with a 14 MW heat transfer loop consisting of steam drum, condenser, subcooler, preheater, pump, two parallel vertical heated sections and associated piping. Two markedly different forms of instabilities were observed in the experiments. However, their theoretical exercise pointed out at least eight different types of instabilities possible with either gravitational or frictional pressure drop dominating each of those. Three of them were classified as static or Ledinegg instability, where the adiabatic vertical risers play major role and gravitational pressure drop is crucial. Mathematically it was attributed to the negative slope of loop pressure drop and can be expressed as,

$$\partial \Delta p / \partial J_{inlet} < 0 \tag{1.4}$$

Frictional pressure drop was found to be dominant in other five types and they were classified as dynamic or density-wave instability. Their comprehensive coverage is still very much valid for conceptualizing two-phase instability in NCL.

Cohen and Bayley (1955) reviewed different methods of gas turbine blade cooling and suggested thermosyphon to be the most attractive option. They also observed that wide range of energy could be transferred from the hot to the cold end of the loop without bothering about the quantity of coolant. Another successful early-day application of two-phase thermosyphon was demonstrated by Long (1963) to keep permafrost frozen. He observed great increase in heat flow out of the ground throughout the year without much increase in heat flow into the ground.

Some of important contributions towards the development of modern-day two-phase thermosyphon are worth mentioning here. Lee and Mital (1972) performed an experimental study, followed by simplified theoretical analysis, to understand the effects of different system variables on the performance of a two-phase thermosyphon. They observed that the heat transfer coefficient was a strong function of loop pressure and rapidly increased with temperature, but relatively insensitive to the quantity of working fluid. That also increased with decrease in evaporator to condenser length ratio. Use of water and R-11 as separate working showed identical results. However, R-11 was suggested as an option for low-temperature applications. Maximum heat transfer rate was predicted from a simple analysis and that closely matched the experimental trends. Dobran (1985) also predicted the existence of a maximum heat flux associated with flooding limits through a lumped parameters representation of boiling thermosyphon. Linear stability analysis showed that as the critical heat flux value exceeded, the liquid pool dried out, leading to instability due to flooding.

Cundy and Ha (1983) experimented with a closed loop incorporating an evaporator at the bottom and a condenser at the side of the loop, connected by an adiabatic riser. The vapour was forced to travel through the adiabatic portion by a U-shaped vapour barrier. Unpredictable and fluctuating temperature rise at the start-up was reported. They also stressed upon the importance of simultaneous downward flow of vapour and condensate, which enhanced the heat transfer by thinning and removing condensate film. Manero *et al.* (1987) developed a toroidal loop with evaporator and condenser at the opposite ends. Four qualitatively different regions were observed, with intense bubbling accompanied by liquid carryover in the forth region. Bubble frequency was observed to be inversely proportional to the heat rate. A low-grade heat recovery thermosyphon was developed by Cheng and Rovang (1987), where they operated even with supercritical steam in the riser. Optimum performance was achieved with saturated mixture having quality close to unity. System flow rate was found to be very small even with large heat supply. Duffey and Sursock (1987) discussed the role of natural circulation relevant to LOCA in PWRs and reviewed the then available test data. Flow rate was found to be strongly dependent on liquid inventory or system void and much lesser on power levels.

Bau and Torrance (1981) observed oscillations with initiation of boiling in their open loop as discussed in §1.4.6. With sufficiently large heat supply, water temperature attained saturation and remained there until convective flow quenched boiling with influx of cold water. Occasionally, saturation temperature plateau was followed by a short dry-out period before quenching. Large amplitude oscillations were observed sporadically, signifying formation and escape of large vapour bubbles. Two different zones of periodic circulation, with continuous circulation in between, were observed by Kyung and Lee (1994) in their open NCL with R-113 as working fluid. Stable operation corresponded to churn or whispy-annular flow in the riser. System flow rate exhibited a maximum with increase in heat flux, though void fraction continually increased. Effect of inlet restriction, exit restriction and inlet subcooling on system stability map was also explained. Appearance of both static and dynamic instabilities in parallel channels was explained by Duffey *et al.* (1993). CHF was found to be preceded by static instability except with large additional inlet losses, orificing or throttling. Transient characteristics of natural circulation system driven by flashing were studied by Tanimoto *et al.* (1998). Condensation-induced flashing was found to induce larger degree of instability in the system. Enhancement in heat transfer due to the combined effect of evaporation of liquid film and secondary flow in a rectangular NCL with coiled heated section was reported by Yi *et al.* (2003). A generalized correlation to estimate the steady-state flow rate for a two-phase NCL has been proposed by Gartia *et al.* (2006). A dimensionless group Gr_m/N_G was identified as the similarity parameter and comparison was shown for five different cases.

First generation models of two-phase NCLs were based on homogeneous equilibrium (HEM) approach, where both the phases were considered to be at uniform velocity and temperature. Ramos *et al.* (1985) employed such a model coupled with *sharp interface approximation* to study the effect of vertical distance between evaporator and condenser on loop flow rate. Chen and Chang (1988) improved their model considering vapour quality as a linear function of flow distance. Furutera (1986) presented a discussion on the validity of such models to predict density-wave oscillation in a natural circulation boiling channel. Though his findings showed reasonable agreement with experimental data, homogeneous flow condition is far from reality in most of the practical systems. Hence separated-flow models followed, where both phases were allowed to have different velocities, with velocity ratio being derived from some typical correlation. But that was promptly over-shadowed by the more realistic drift-flux model (Zuber and Findlay, 1965), which characterizes velocity ratio with two parameters. Rao *et al.* (2006) presented a comparison between HEM and TEDFM for predicting the steady-state performance of a rectangular two-phase NCL and a large deviation was observed, with TEDFM apparently the more accurate one. Therefore a large number of theoretical studies have been reported for two-phase NCLs following drift-flux approach. Jeng and Pan (1999) employed that in an analytical model to estimate the steady-state parameters with flow pattern change and subcooled boiling under consideration and possibility of multiple steady-state solution was predicted with high inlet subcooling. Use of drift flux model to predict the thermo-hydraulic instability during low pressure start-up was demonstrated by Inada *et al.* (2000) and a decent agreement with test data was exhibited. Influence of friction factor multiplier, drift velocity and void distribution parameter while predicting flow stability was explained by Nayak *et al.* (2007) using a four-equation drift flux model. Increase in drift velocity was found to suppress the instabilities.

However, there can be a number of situations where the coupling between phases is very weak and velocity ratio cannot be determined from local flow conditions. To deal with such intricate flow simulations, the two-fluid model was introduced (Ishii and Mishima, 1984), where the two phases are treated separately in terms of two sets of conservation equations for balancing the mass, momentum and energy of both phases. Interaction terms are employed for coupling the mass, momentum and energy transport across the interface being estimated with proper averaging methods. The key factor inherent in the success of two-fluid model is in the choice of appropriate interaction relations and that depends on availability of large experimental data set and accompanying sophistication in computational methods. Hence the focus of modern-day researchers has concentrated on evolution of multi-scale CMFD. As example of one such modelling effort, one can mention about the ASTAR project (Staedtke *et al.*, 2005). Most of the present commercial thermal-hydraulic codes being 1-D in nature, introduction of CMFD is an excellent step towards transformation to gigantic 3-D system codes and its scope and capability are only going to flourish with time.

Similar to single-phase NCLs, most of the research for appraisal of stability issues in two-phase NCLs follows the linear stability approach (Lee and Lee, 1991; Nayak *et al.*, 2002, 2006). However, the non-linear mode of analysis, mainly to judge the nature of transients under unstable condition, has recently become quite popular. Rizwan-Uddin and Dorning (1988) were the first to report a strange attractor in a boiling channel subjected to periodically forced flow. Similarly, Lahey (1991) observed a chaotic attractor during non-linear analysis of autonomous density wave instabilities. He introduced a Galerkin nodal approximation to transform the partial differential conservation equations to a set of non-linear ordinary differential equations and that approach was followed in several subsequent studies. Lin and Pan (1994) investigated non-linear dynamics of a two-phase NCL to identify the characteristics of limit cycle oscillations and transient response to step change in power supply. Chang and Lahey (1997) presented dynamic modelling of a BWR loop with heated wall dynamics and neutron kinetics, where they observed chaotic behaviour in presence of an adiabatic riser. Heated wall dynamics was found to have a significant destabilizing effect. Similar approach to evaluate the non-linear dynamics has been followed in a number of other investigations (Lee and Pan, 1999, 2005) as well.

1.4.8. Entrainment in two-phase NCLs with phase separation

Entrainment of phases is one of the most important practical challenges regarding the operation of two-phase natural circulation loops with phase separation. This problem is more commonly encountered in power boilers and nuclear reactors.

Use of mechanical phase-separators in steam drums of water-tube boiler may result in significant amount of pressure losses, which is very much undesirable in natural circulation. Hence, gravity separation has been recommended in systems such as AHWR (Sinha and Kakodkar, 2006). However, under such situations, some liquid droplet may get carried away with the gaseous stream and some gas bubbles may get entrained into the return liquid line; the first kind is termed as *carryover*, whereas the latter is known as *carryunder*.

Droplet carryover is generally the outcome of the dynamic interaction of phases and two major kinds of carryover have been observed in practice, namely, film entrainment and pool entrainment. The former one is the entrainment of droplets from liquid film, mainly by shear, and is typified by the presence of a wavy interface along the direction of the flow. Paleev and Filippovich (1966) were probably the first to characterize it through systematic experimental observations. Ishii and Grolmes (1975) have studied inception criterion for such entrainment in detail and the critical velocity for onset of entrainment was reported to depend upon film Reynolds number and viscosity number. Increase in gas velocity was found to result in wavy interface due to the Kelvin-Hemholtz instability. Film carryover is also of great importance in the study of reflood processes for PWRs. Sobajima and Ohnuki (1982) proposed a correlation for mass effluent rate out of the core using the void fraction distribution characteristics.

Pool entrainment results from the entrainment of droplets from the surface of any liquid pool due to the bursting of bubbles and break-up of liquid jet. Yeh and Zuber (1960) have described details of the associated processes quite vividly. Newitt *et al.* (1954) identified two distinct group of bubbles produced due to such bubble bursting, namely, film drops and jet drops. Gunther *et al.* (2003) have shown that the number and distribution of droplets are mainly governed by the size of the bubbles bursting at the interface. The entire phenomenon is generally characterized by randomness and uncertainty and only statistical measures are able to provide some idea about pertinent influencing factors. The most established approach to characterize droplet carryover has been proposed by Kataoka and Ishii (1984). They expanded entrainment as a function of gas-phase superficial velocity, pool dimensions, height from the interface and fluid properties and employed the data of Garner *et al.* (1954) to tune the correlations. Nayak *et al.* (2000b) developed an AHWR steam drum simulation employing the Kataoka and Ishii model and proposed a maximum permissible steam velocity to limit carryover. More et al. (2005) have recently proposed a more pertinent correlation for entrainment analysis in separator drum. The experimental studies of Cheng and Teller (1961) and Shieh *et al.* (1990) are also worth mentioning here.

In a stark comparison, research related to carryunder is scarce. Data analysis by Wazzan *et al.* (1982) on a real PWR steam generator has shown a maximum of about 1.23% of carryunder at full load, which may cause cavitation for assisted circulation systems. The effect is even more detrimental in NCLs, as the presence of bubbles in the return line reduces the buoyancy head and so the circulation through the circuit is adversely affected. However, apart from a few data analysis from Wazzan *et al.* (1984, 1988) on forced circulation PWRs, which found negligible carryunder at all loads, hardly any methodical study is available. Petrick (1961) proposed an analytical model of carryunder in natural circulation BWRs. He considered a configuration comprising two concentric tubes, where the inner one was the riser, surrounded by annular downcomer tube. A correlation for the quality ratio was developed and compared successfully with an atmospheric air-water loop test data. Test results from a high-pressure steam-water loop also compared well with the model prediction. Jain et al. (2002) have proposed a similar analysis in case of an AHWR.

1.5. Motivation of the present thesis

A meticulous survey of the available literature suggests that the domain of natural circulation is very well addressed in nearly all aspects of the phenomenon and at a first glance, the field seems almost saturated. However, a careful analytic mind can find a few vestiges which, despite being of primal consequence in relation to realistic applications, have hardly received the due prerogative and they deserve a thorough exploration. Most of the reported theoretical studies focus primarily on dimensionless groups, mostly to stress upon the generality of the model. That is definitely admirable for proposing new correlations, say for friction factor or loop flow rate, to allow the newly developed relation to be used over a wider range. That is also excellent for judging the performance and checking the compatibility of a system in light of previous works. However, when a particular system is concentrated upon, it is generally desirable to understand the expected system behaviour in terms of physically meaningful parameters, *i.e.*, geometric or kinetic variables. For example, the neutral stability curves for single-phase NCLs are most commonly offered on $Gr_m - St_m$ plane, the magnitudes of concerned dimensionless groups being strongly dependent on different choices, *e.g.*, reference conditions, heat transfer correlations, property relations, etc. Hence, it is difficult to get a realistic feel about their values without thorough analysis. On the other hand, if the concerned curves are made available in terms of physical variables, that would be readily adoptable to practitioners. The set of operating conditions required to have optimum output or the limiting values of parameters to avoid unstable oscillations can be best defined in terms of physical variables. Obviously that may hamper the generality a bit. But a suitably defined model, obeying the fundamental conservation laws and not subjected to any unjustifiable simplifying assumption, is always expected to predict identical trends for all the systems, only differing in magnitude.

Hence the present work focuses on analysis of natural circulation systems with emphasis on physical variables. The tune is set at the very beginning to investigate the behaviour in terms of real parameters. A number of important areas have been ear-marked from the survey of available literature as summarized below:

(a) Both toroidal (Creveling *et al.*, 1975; Damerell and Schoenhals, 1979; Lavine *et al.*, 1987; Mertol *et al.*, 1981b; Sen *et al.*, 1985b) and rectangular (Hallinan and Viskanta, 1985, 1986; Nayak *et al.*, 1995; Ramos *et al.*, 1985; Vijayan *et al.*, 1991, 1992b) geometries have found plenty of individual attention for NCL applications. However, a systematic comparison of their performance under steady-state and dynamic conditions and henceforth identification of their relative complexity is not present in the literature.

(b) Researchers have used different standards and formats for analyses of their own systems and some sort of unification seems necessary for standardization.

(c) Rectangular NCL with distinct heating and cooling sections, despite having wide-spread applications, has not received due attention from physical point of view.

(d) Wall thermal conductivity seems to have an important role, particularly for suppressing system instabilities (Jiang and Shoji, 2003; Vijayan, 2002). However, a dedicated analysis appears to be missing from the reported studies.

(e) A number of experiments suffer from the errors induced due to the loss of energy to the surroundings, as was mentioned by Vijayan *et al.* (1991). Systematic approach to categorize the influence of such losses has not been attempted.

(f) Possibility of the appearance of subcooled boiling and thermal non-equilibrium in a single-phase NCL has not been considered in any reported work.

(g) Nearly all the two-phase rectangular NCLs studied so far contain a boiling and a phase-separating section, similar to power loops. But loops with exclusive boiling and condensing parts can have significant application in large-scale PWRs to micro-scale electronic cooling.

(h) The domain of entrainment in two-phase NCLs, *i.e.*, carryover and carryunder, require more intense focus with nuclear plant as the targeted application. Detailed experimental analysis is essential with properly developed test facility.

The present body of work aims at extenuating some of the above mentioned issues. Attempt has been made to develop a unified model with specific correlations suitable for both rectangular and toroidal geometry and compare the steady-state and transient performance for both kinds of system. Rectangular geometry with horizontal heating/boiling and horizontal cooling/condensation has been concentrated upon, mainly due to the attraction of its complicacy. Analysis starts with single-phase loops and gradually two-phase has been introduced into the domain. Effect of thermal non-equilibrium has also been included. Finally, influence of the appearance of carryunder and carryover in an NCL has been studied and a scaled down well instrumented experimental facility has been designed and developed. Early results obtained from this test rig have also been presented.

1.6. Organization of the thesis

Arrangement of the thesis can be presented as,

(1) The phenomenon of natural circulation is included in chapter one exploring the range of applicability in engineering systems. Some of the important findings from the available literature are presented as well.

(2) A unified model has been developed in the second chapter and validated for different geometries. Steady-state and transient behaviours of rectangular and toroidal geometries have been compared.

(3) Influences of controlling parameters and operating conditions on dynamic response and stability performance of a rectangular NCL have been studied in the third chapter.

(4) Influences of wall thermal conductivity and heat loss to the surrounding from a single-phase rectangular NCL have been explored in the next chapter.

(5) A model of rectangular NCL with subcooled boiling has been considered and steady-state behaviour has been studied in chapter five.

(6) Development of a scaled experimental facility for studying carryover and carryunder phenomena is discussed in chapter six along with early test data obtained from this test rig.

(7) Finally the summarized conclusions from this entire study are presented and some of the possible future areas of investigation have been identified.