CHAPTER **1**	**INTRODUCTION**

In view of the stratospheric ozone layer depletion and global warming problems caused by conventional synthetic refrigerants, the use of natural and environment friendly substances such as ammonia, hydrocarbons etc in refrigeration and air conditioning applications is increasing. However, some of the natural refrigerants being suggested are flammable (e.g. hydrocarbons), toxic (e.g. ammonia) or both. Hence when these flammable and/or toxic refrigerants have to be used in commercial and industrial refrigeration systems, it is essential to minimize the amount of refrigerant used in the system for a given cooling/heating capacity. Also it may be essential to avoid the presence of these substances in locations occupied by people such as supermarkets, auditoriums etc. In such cases, one can confine the flammable or toxic refrigerant to the refrigerant plant (which can be located away from the occupied zone) and transfer heat from the conditioned space (supermarket, cold storage, auditorium etc.) to the plant using a harmless secondary fluid. Traditionally fluids such as water, solutions of brines, glycols, alcohols etc. have been used as working fluids in secondary loops. However, due to some favourable properties, carbon dioxide has the potential to offer itself as a long term substitute with respect to environmental and personal safety. CO_2 can be used advantageously as secondary fluid in both forced circulation and natural circulation loops. However, natural circulation loops offer certain advantages over forced circulation systems, particularly in small-to-medium capacity systems.

1.1 Indirect cooling systems:

There are many types of refrigeration and air conditioning systems. The same system can be put into different categories depending on varied definitions. For example, a plant can be defined as either a single stage system (based on the charged refrigerants) or a two-stage system (based on the system configuration). However, the distinction of direct and indirect systems is the most important one among all of them, because a completely new concept has been introduced by the definition. Due to its advantages, more and more supermarkets and auditoriums are using indirect systems for both retrofitting and new installation.

The difference between direct cooling systems and indirect cooling systems, also known as secondary refrigeration, lies in the physical separation between the primary circuit, where the cold is generated, and the secondary system, where cooling takes place. The cold generated in the primary circuit is transported by the heat transfer fluid to the space where food or other products must be cooled. In indirect refrigerant systems a heat transfer fluid is needed, which has two basic functions : not only must it transfer the cold, the heat transfer fluid, also called secondary fluid, must also protect the system against corrosion. Secondary refrigerating circuit which has been integrated with a basic refrigeration system is shown in fig.1.1. Indirect refrigeration systems however, require an additional heat exchanger and a secondary refrigerant pump, typically resulting in increased energy requirements over equivalent direct systems [Kruse 2004, Clarke et al.2008]. However, the secondary refrigerant pump can be eliminated by using a buoyancy driven natural circulation loop.
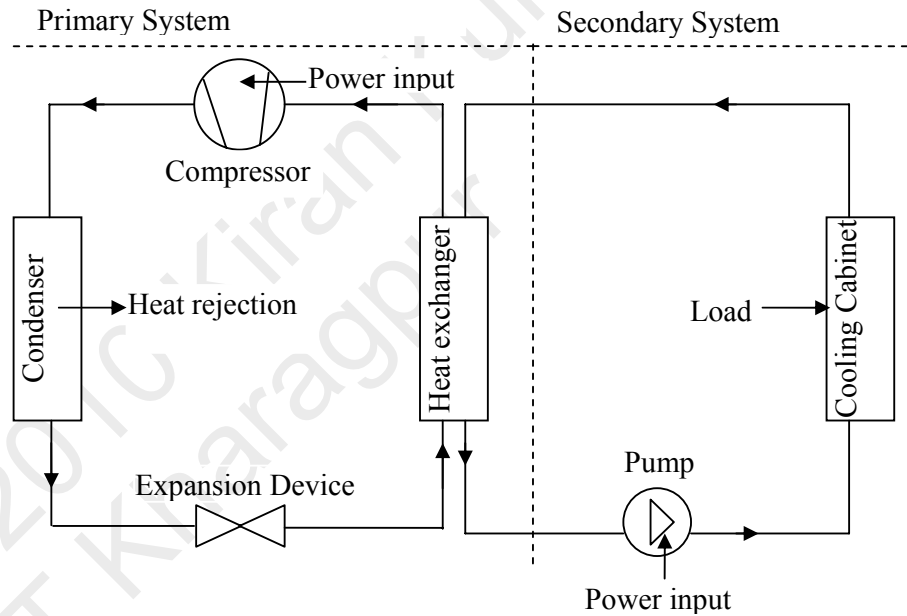
Fig.1.1: Indirect refrigeration system

1.1.1 Advantages of indirect refrigeration systems:

- A toxic and/or flammable but environment friendly refrigerant can be used in the primary circuit, which is confined to the plant room.

- Refrigerant charge can be minimized in the primary circuit, which can lead to the reduction of both capital cost and refrigerant leakage.

- Smaller primary cooling circuits further benefit in fewer legally mandatory maintenance and checking operations.

- Compact factory built units can be used for different kinds of purpose; the installation work can be simplified, which leads to a further reduction of initial investment.

- A secondary system is also simpler to modify, which makes it extremely interesting for production processes requiring flexibility.

1.1.2   Disadvantages of indirect refrigeration systems:

- One more heat exchanger and several circuit pumps are added to systems, which will increase costs. An added temperature difference may result in a higher energy demand. However, as mentioned before, use of a natural circulation secondary loop can avoid circulating pumps.

- The difficulty of selecting a suitable secondary refrigerant. Aqueous solutions and non-aqueous heat transfer liquids are two main categories of liquid secondary refrigerants that are used. However, they have both positive and negative effects. On the contrary, some phase changing secondary refrigerants, such as carbon dioxide, look very promising.

1.2 Natural Circulation Loops:

Heat transfer loops are categorized into forced circulation loop in which an external pump is used to drive the flow, or natural circulation loops (NCL). NCL is a thermal system in which flow is driven by thermally generated density gradient so that pump is not required. These NCL are some times called as thermosyphons, natural convection loops. Of course, Japikse [1973] made a clear distinction between natural circulation loops, where the flow is generally in one direction around the loop, and "thermosyphon" where, the flow is upward along the wall of the tube with an

associated downward return flow in the core. In natural circulation loops, simultaneous heating and cooling cause the density gradient which results in buoyancy that drives the fluid. Usually heat source is located below the heat sink to promote natural circulation. When both the heat source and heat sink conditions are maintained constant, steady state circulation is expected to be achieved, which can continue indefinitely, if the integrity of the loop is maintained.

Natural Circulation loops can have various configurations. The classification has been made on the basis of state of working fluid, interaction with surroundings, shape, inventory, number of channels and body force field. Figure 1.2 shows an elaborate classification of NCL [Vijayan 2007]. Systems which are open to the atmosphere and exchange both inventory as well as energy with atmosphere are called open loops and loops which exchange only energy with surroundings are called closed loops. Geothermal heat extraction systems are example of open loops and solar heaters are example of closed loops. Depending on the application, shape of the NCL can be toroidal, rectangular, figure of eight etc. It is to be noted that loop fluid may exist in single phase, two phases or in supercritical stage. It is also to be noted that the fluid may be in different phases at different positions of the same loop. Eventhough supercritical fluid should come under single phase loop category, large changes in the properties at that state draw interest of many researchers. Two phase can be achieved either by boiling or by flashing. Depending on the system inventory one can obtain single phase, two phase or reflux condensation. By decreasing the system inventory one can obtain two phase flow in loop. Further decrease in inventory causes circulation to break down and reflux condensation may set in. In reflux condensation circulation may not take place but heat may be carried by the vapour at centre of tube and condensate falls along the tube walls [Gross 1992]. Some times it may be required to use more number of channels in the loop. So, based on the number of channels one can categorise loops into single channel or multi channel loops. Generally in nuclear reactor cooling system it is required to use more number of parallel channels. Natural circulation system functions under the influence of a body force field. Two types of body force fields are relevant to NCL. They are gravity and

centrifugal force fields. Most loops in common use work in gravity force field and are static. However, centrifugal force field can be advantageously employed in cooling of rotating machinery. It should be mentioned that a loop can be any combination of above. For example, a nuclear reactor core cooling system can be multi channel, rectangular, two phase, and closed loop using gravitational force.

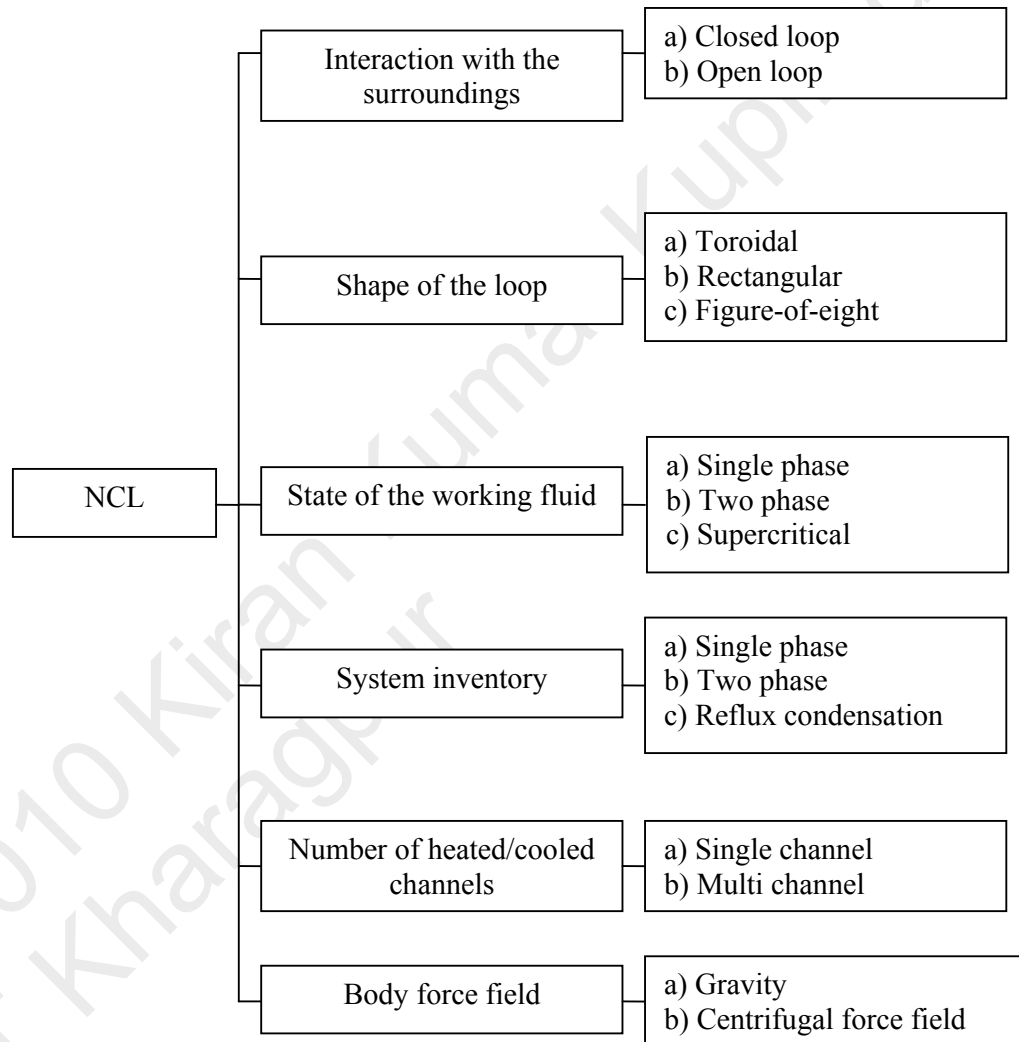|	Interaction with the surroundings	a) Closed loop b) Open loop
	Shape of the loop	a) Toroidal b) Rectangular c) Figure-of-eight
NCL	State of the working fluid	a) Single phase b) Two phase c) Supercritical
	System inventory	a) Single phase b) Two phase c) Reflux condensation
	Number of heated/cooled channels	a) Single channel b) Multi channel
	Body force field	a) Gravity b) Centrifugal force field

Fig. 1.2 : Classification of Natural Circulation Loops [Vijayan 2007]

Apart from the above classification it can be further classified depending on mode of heat transfer at heat source and heat sink. Depending upon the application in

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various engineering fields, heat can be transferred as constant heat flux, radiative heat exchange or at constant temperature. For theoretical studies loop may be considered with point heat source and heat sink where the effects of fluid flow at heat source and heat sink are ignored. Figure 1.3 shows the commonly used NCL configurations for theoretical studies.
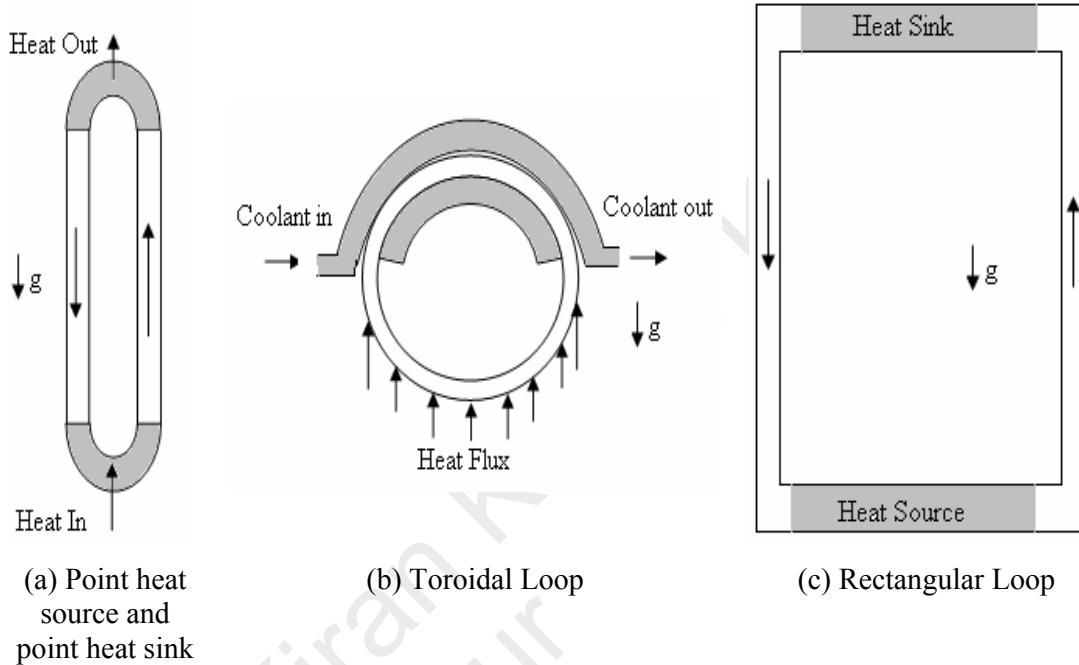

| (a) Point heat source and point heat sink | (b) Toroidal Loop | (c) Rectangular Loop |

Fig. 1.3: Different NCL models

1.2.1 Advantages of NCL:

Simplicity

Simplicity is the primary advantage of a natural circulation loop. The elimination of active power supplies and pumps can greatly simplify the construction, operation and maintenance of the system. Furthermore, elimination of the pumps also eliminates all safety issues associated with the failure of the circulating pumps.

Better flow distribution

Another advantage is that the flow distribution in parallel channel cores is much more uniform in a natural circulation system. However, use of pumps cause maldistribution of pressure in the headers leading to maldistribution of flow in the parallel channels.

Flow characteristics

As there is no prime mover, the two phase region of the loop need not be restricted to a specified zone. In principle two phase flow may occur throughout the entire length of the loop [Rao, 2002].

Safety aspects

Since natural circulation loops work on a natural physical law, it is not expected to fail like the fluid moving machinery such as pumps. This aspect of NCL has enabled its application in many systems where safety is of utmost importance. Apart from this, because of the low head requirements, natural circulation loops tend to have large volumes and relatively low power densities compared to forced circulation systems of the same power rating. As a result, the thermal response of natural circulation loop is slow; giving operators ample time to respond to plant upsets.

1.2.2 Disadvantages of NCL:

Some of the disadvantages of natural circulation loops are listed below:

Low driving head

The primary disadvantage of a natural circulation system is that the driving head is low. To increase the flow rate at a fixed power would require either an increase in the loop height or a decrease in the loop resistance, either of which might increase plant costs.

Low mass flux and instability effects

In general, the mass flux through a natural circulation loop is low. As a result, the allowable maximum channel power is low leading to a larger core volume compared to a forced circulation system of the same rating. Furthermore, large volumes can result in zonal control problems and stability. This is attributable to the nonlinear nature of the natural circulation phenomenon, where any change in the driving force affects the flow which in turn affects the driving force that may lead to an oscillatory behavior. Fortunately, these problems are rather well understood now. Size optimisation results in enhanced exit qualities.

Low critical heat flux

The low mass flux also has an impact on the critical heat flux of system. Since flow in natural circulation reactors is low, they tend to use the maximum allowable exit quality to minimize their size. In the process, their critical heat flux value tends to be significantly lower than that of forced circulation systems.

Specification of a start-up and operating procedure

Natural circulation systems are to be started up from stagnant low pressure and low temperature condition. During the pressure and power raising process, passing through an unstable zone has to be avoided as instability can cause premature critical heat flux occurrence. Under the circumstances, it is essential to specify a start-up procedure that avoids the instability. Selection of the pressure at which to initiate boiling and appropriate procedures for raising pressure and power is central to the specification of a start-up procedure. In addition, it may become essential to control the inlet subcooling as a function of power. For a cold start-up (first start-up) an external source for pressurization may be required. For these reasons, the selection of a start-up procedure for a natural circulation loop is not always an easy task. In summary Table 1.1 presents the highlights of advantages and disadvantages.

Table 1.1: Advantages and disadvantages of NCL

Advantages	Disadvantages
Simplicity and low cost	Low driving head
Pumps are eliminated	Lower maximum power per channel
Possibility of improved flow distribution	Potential instabilities
Better two phase characteristics	Low critical heat flux
Large thermal inertia	Specific start-up procedures required

1.2.3 Applications of NCL:

Traditional applications of NCL are in solar water heaters, geothermal power extraction, coffee machines, cooling of transformers, rotating machinery, nuclear reactors, etc.

Emerging fields of application are

- Cooling of electronic systems like computers. Natural circulation loops for computer cooling can be made with very low inventory of working fluid.

- As a secondary loop in indirect cooling systems such as supermarket refrigeration etc.

1.3 Selection of working fluids for natural circulation loops:

There are several fundamental requirements that any secondary refrigerant must satisfy. These are:

- Low viscosity
- High volumetric heat capacity
- High specific heat
- High thermal conductivity
- High density
- Less corrosive, chemically stable, non toxic etc.

The freezing point can be considered as the starting point to choose a secondary refrigerant, and it should be below the operating temperature of the system with a comfortable safety margin. For optimum design of secondary refrigeration system it is essential to find the balance between viscosity, specific heat and thermal conductivity.

1.3.1 Commonly used secondary fluids:

Commonly used secondary fluids can be divided into two categories, namely aqueous (i.e. water based) and non-aqueous. Water can also be used as secondary fluid for above $0^{o}C$ applications. Aqueous solutions are generally either salt based or alcohol based products. These are fluids which suffer from one or more non-favorable effects like corrosiveness, toxicity, high Ph value etc. Non-aqueous solutions are commercially available chemicals. Table 1.2 shows a comparison between conventional secondary fluids in terms of relevant properties. All the properties in the Table 1.2 are at $0^{o}C$. From Table 1.2 it is seen that viscosity of the aqueous solutions is very high compared to CO_2. Moreover thermal expansion coefficient, which is a key property in natural circulation systems, is very low for aqueous solutions.

Table 1.2: Property comparison of different secondary fluids [CoolPack Software, 1999]

Fluid	ρ (kg/m^3)	c (kJ/kg^{o}C)	k (W/m^{o}C)	μ (*10^{-5}) (Pa-s)	β (K^{-1})	T$_{freezing}$ (^{0}C)
Calcium chloride [#](29.4%)	1293.2	2.718	0.529	596.6	0.000114	-55
Ethanol [#](90%)	839.2	2.417	0.213	218.144	0.000247	-80
Ethylene glycol [@](90%)	1131.4	2.312	0.272	3374.1	0.000293	-29.17
Magnesium chloride [#](20.6%)	1187.6	3.016	0.512	550.4	0.000714	-33.6
Methanol[#](90%)	816.8	2.597	0.243	137.2	0.000557	-80
Potassium carbonate [#](38.4%)	1418.7	2.65	0.508	901	0.000098	-35.5
Sodium chloride[#](23.1%)	1181.8	3.314	0.543	304.72	0.00009	-21.2
Syltherm XLT	862.6	1.598	0.107	186.2	0.000963	-93
Freezium[#](50%)	1387.5	2.646	0.475	461.8	0.000597	-58.61
Propylene glycol [@](90%)	1069.7	2.479	0.235	12200.88	0.00089	-51.1
Tyfoxit [@](98%)	1252.7	2.854	0.423	828	0.00047	-55
Water[*]	999.8	4.2196	0.561	178.54	-0.00006	0
Carbon dioxide	927.43	2.5923	0.110	9.9	0.007398	-56.6[$]

[*] Water properties are at 0.1^{o}C

[#] Composition % by mass

[@] Composition % by volume

[$] Triple point temperature

Note: all properties at specified composition and 0°C

1.3.2 Suitability of CO_2 as a secondary fluid:

From Table 1.2 it is seen that compared to other fluids CO_2 offers very low viscosity and very high coefficient of thermal expansion. Due to these favourable properties one may expect CO_2 to perform well as secondary fluid also. In addition to these, CO_2 is an environmental friendly working fluid with zero ODP and negligible GWP (Table 1.3). Also it is non-toxic and acts as a flame retardant, thus perfectly safe

for use. However, unlike other working fluids the operating pressures are very high in CO_2 systems. The phase diagram of CO_2 is shown in Fig. 1.4 on P-T plane. Due to low critical temperature, systems based on CO_2 operate near or even above critical point. However, it will be seen that near or above critical operation offers certain advantages that are unique to CO_2 systems.
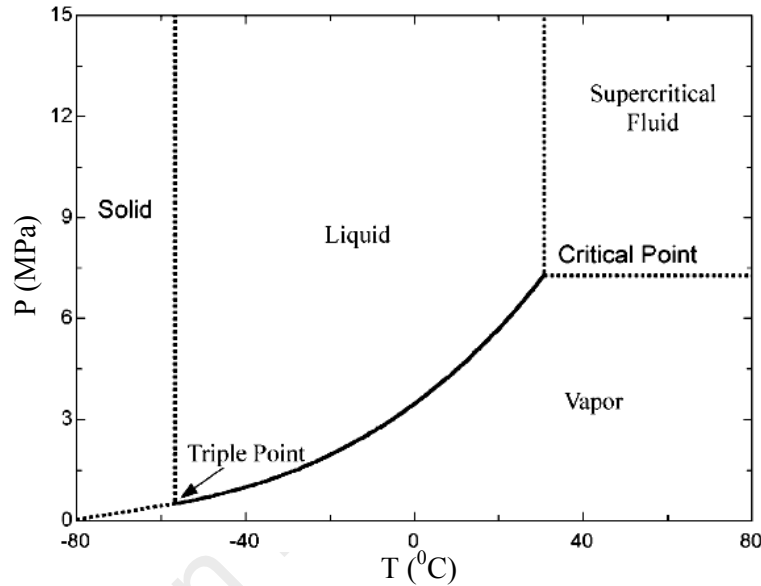

Fig. 1.4. Phase diagram of CO_2 [Kim et al., 2004]

Table 1.3 CO_2 Properties – A comparison [Lorentzen et al.1993; Riffat et al. 1997]

Refrigerant	R12	R22	R134a	R600a	R717	R744
ODP	0.82	0.055	0.0	0.0	0.0	0.0
GWP$_{IPCC\ value}$ (100 yrs)	8100	1700	1300	0.0	0.0	1
Flammable	No	No	No	Yes	Yes	No
Toxic	No	No	No	No	Yes	No
Molecular weight	120.9	86.5	102.03	58.0	17.03	44.01
Normal boiling point (^{0}C)	-29.8	-40.8	-26.2	-11.6	-33.3	-78.4
Critical pressure (bar)	41.1	49.7	40.7	36.4	114.27	73.8
Critical temperature (^{0}C)	112.0	96.0	101.1	134.7	133.0	31.2
Saturation pressure at 0 ^{0}C (bar)	3.09	4.98	2.93	1.56	4.29	34.8

1.4 Objective of the present work:

        The main objectives of the present study are:

- To establish the feasibility of CO_2 in natural circulation loop based secondary refrigeration systems.

- Develop mathematical models to simulate the performance of various types of CO_2 based natural circulation loop systems.

- To optimize the relevant design and operating parameters of natural circulation loops for a given application.

- To design a NCL based system using the models developed and to fabricate an experimental test rig.

- To carry out parametric studies on the experimental NCL test rig.

- To validate the mathematical model with experimental results.

1.5 Structure of thesis:

        Chapter 1 presents a brief introduction to indirect refrigeration systems, secondary fluids etc.

        A comprehensive review of relevant literature is presented in chapter 2. It includes survey on heat transfer loops, indirect cooling systems, NCL and different applications of NCL etc.

        Chapter 3 deals with the comparison of CO_2 with some selected secondary fluids. This comparison is made both for laminar and turbulent flow conditions and for liquid and vapour phases.

        Chapter 4 first presents a simple analysis of CO_2 based natural circulation loops for different applications by considering point heat source and point heat sink. Then the analysis is extended by replacing point heat source and heat sink with heat exchangers. Parametric studies on steady state single phase and two phase CO_2 based natural circulation loops are presented in this chapter.

        In chapter 5 theoretical results obtained on a vapour compression water cooler coupled to a natural circulation loop that uses CO_2 as secondary fluid are presented. This is followed by theoretical results obtained on a room air conditioner that is

coupled to a CO_2 based natural circulation loop (NCL). The results obtained on the NCL based system are compared with the base room air conditioner system that cools the room directly.

The detailed experimental study is presented in chapter 6. Tests have been carried out to study the system performance and validate the numerical results. Test rig has been designed based on the simulated results. Tests have been conducted to study the system performance by varying the operating parameters. The chapter concludes with the validation of numerical results presented in Chapter 4 with the experimental results.

The dissertation concludes with important findings based on this study. The major conclusions and recommendations for future work are presented in Chapter 7.