Chapter 1: Introduction

1.1 Background and motivation

Energy consumption increases rapidly all over the world due to increased urbanization and industrialization processes. The rate of global energy utilization will increase significantly as the world population is expected to increase from 7.6 billion in 2017 to 9.8 billion in 2030 (UN Department of Economic and Social Affairs). With the immense demand for energy, rapid depletion of conventional sources of energy, and enhanced global warming, there must be alternative energy sources to meet all the future global energy demands without having a negative impact on the environment. Carbon emission is also a major concern that is associated with the use of primary energy resources (Coal, natural gas, and crude oil), which has a severe impact on climate change, i.e., global warming, ocean acidification, and carbon fertilization. The increase in carbon emissions due to the use of primary resources by nearly 2 times from 1973 to 2019 can be seen in Fig.1.1 (IEA, CO_2 Emissions from Fuel Combustion, 2021) [1]. If the carbon emission persists at the same rate, then the earth will become unlivable in the coming future.

Therefore, scientific communities are looking for renewable energy resources which are infinitely available such as solar, geothermal, wind, ocean, and many others, to meet the future energy demand. Fig.1.2 shows the share of different energy sources in the world's total energy supply from 1973 to 2019 (IEA, World Energy Balances, 2021). The total energy supply has increased about 2.4 times, i.e., 254 Exajoule to 606 EJ from 1973 to 2019. But now, the use of primary sources is now decreasing or remains constant and renewable energy resources are significantly increasing now. This indicates that the scientific community is now searching and implementing new ideas and technology through which the use of primary sources of energy can be minimized or replaced by a renewable source of energy. Furthermore, transferring renewable energy without utilizing electricity is another research concern.

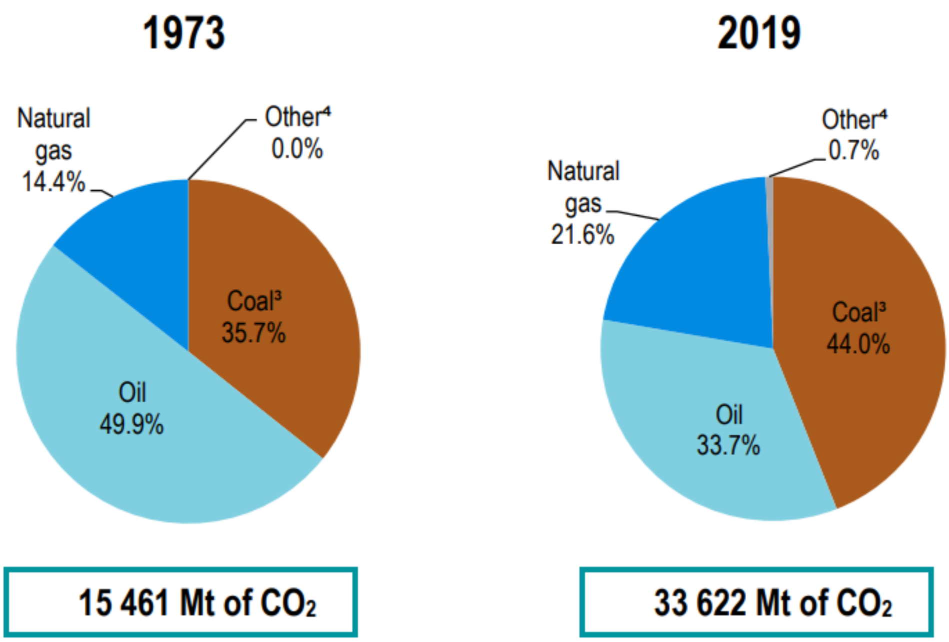

Fig. 1.1. Fuel share of CO_2 emissions from fuel combustion, 1973 and 2019 (IEA, CO_2 Emissions from Fuel Combustion, 2021) [1]

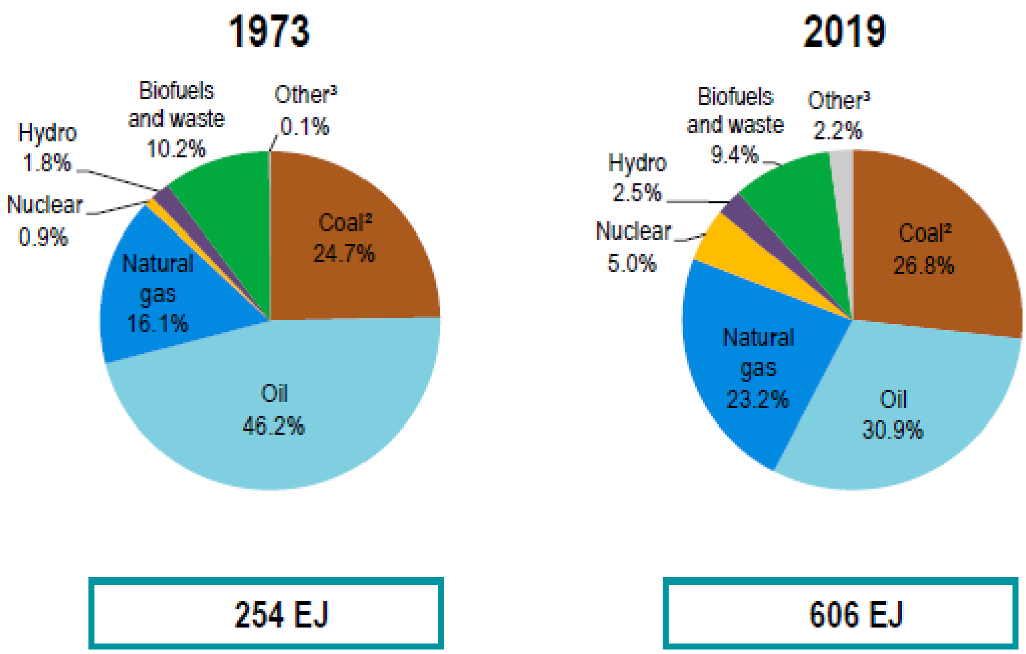

Fig. 1.2: Share of world total energy supply by source, 1973 and 2019 (IEA, World Energy Balances, 2021) [1]

Over a few decades, the research on the Natural Circulation Loop (NCL) system has increased significantly because it saves high-grade energy due to its passive nature as it does not require any mechanical device or active power source for its operation. This concept (NCL) is gaining more visibility because it can be implemented in various sectors, i.e., power generation (solar thermal and nuclear power plants), refrigeration, solar heating system (water and oil heating), cooling of heat generation devices (engine block, electronics, transformer cooling), chemical industries, and process heating. Some of the emerging applications of the natural circulation system, which can utilize renewable energy, are passive cooling of aircraft and vehicles and building ventilation. Thus, the natural circulation has an energy-saving potential that can utilize renewable energy and also minimize the use of high-grade energy for its operation. So this has motivated to select the present research topic.

1.2 Natural circulation loop

The natural circulation loop is a passive system that transfers the heat from a high-temperature source to a low-temperature sink without using any external motive force or mechanical device. It consists of a heater (high-temperature source), a heat exchanger (low-temperature sink) and piping, which forms a closed loop for the circulation of the fluids, as shown in Fig. 1.3. The primary function of a natural circulation loop (NCL) is to transfer the heat from the source to a sink with the help of buoyancy-driven flow. The important necessary condition to generate a buoyancy-driven flow is that the heat sink is always mounted at a higher elevation than the heat exchanger. The working principle of NCL is described here, as the heat is supplied in the heater in the form of heat flux, the fluid temperature inside the heating section increases and becomes lighter. Similarly, in the heat exchanger, the fluid gets cooled and becomes denser. So, the density difference is established between the left vertical and right vertical arm, and hydrostatic pressure difference is generated at the bottom of the horizontal leg at points 1 and 2 Shown in Fig.1.3. $P_2 = \rho_c g H$ and $P_1 = \rho_h g H$, where ρ_h and ρ_c is the density of the fluid on the left and right vertical arm, H is the loop height and g is the acceleration due to gravity. $P_2 > P_1$, causing the buoyancy-driven pressure force, which drives the flow. However, the friction force is also acting due to the pipe wall surface, which opposes the motion of the fluid flow. At a steady-state, these forces balance each other, hence the flow rate in the NCL loop can be enhanced by increasing buoyancy force, which can be increased by increasing density difference and loop height, and reducing the frictional force by increasing diameter and using less viscous fluids. Natural circulation loop (NCL) has several advantages due to the absence of a mechanical device (pump) it improves safety and reliability and reduces maintenance and operational cost. However, it has some disadvantages, i.e., low mass flow rate, instability or flow reversal, and less stability than the forced flow.

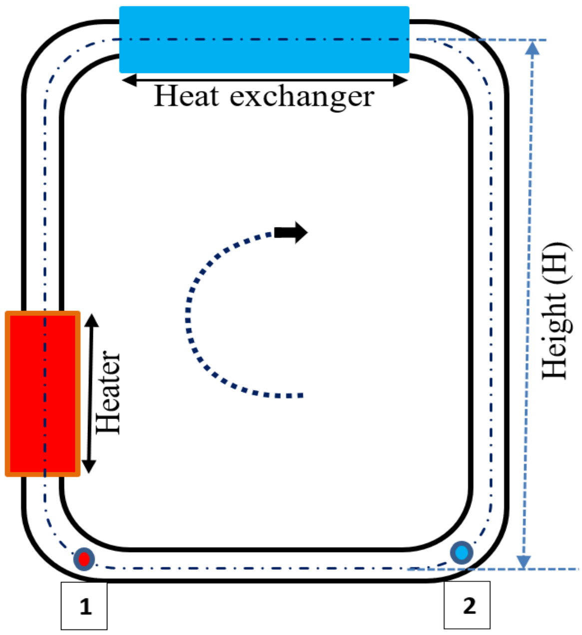

Fig. 1.3 Schematic diagram of rectangular Single phase natural circulation loop

It is very difficult to say when exactly the commercialization of the natural circulation system has been started as a heat transport system. The first time it was used in the automobile industry to cool the engine blocks (Japiske 1973). Over the years, natural circulation systems have found various engineering applications such as solar water heating systems, chemical process industry, geothermal energy extraction, nuclear power plants, transformer cooling, and cooling of electronic devices. Some of the major applications are shown in Fig.1.4 [2].

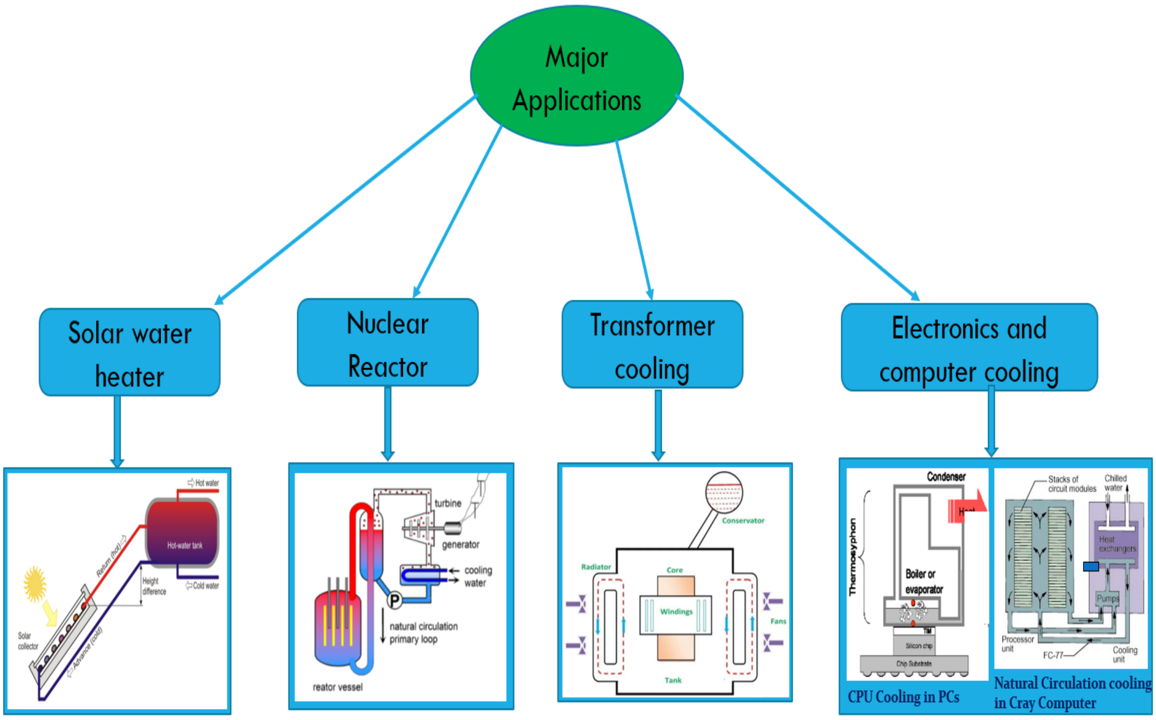

Fig. 1.4: Application of natural circulation loop

Based on the type of application and working temperature range, different working fluids can be used in a single-phase natural circulation loop (SPNCL) under atmospheric conditions shown in Table 1.1.

Table 1.1 Temperature range, application and working fluid of SPNCL

Operating temperature range	Applications	Working Fluid

Low-temperature, below 100^{o}C	Milk chilling, Chemical industries, Solar water heater	Water, EG, PG
Medium temperature, below 100^{o}C to 250^{o}C	Chemical industries: Soaps, Synthetic rubber, Processing heat Cooking Industries	Thermal oil: Therminol-VP1, Paratherm-CR, Dowtherm-Q Vegetable oil: Soyabean, Canola oil, Sunflower oil
High temperature below above 250^{o}C	In Nuclear Industry: Cooling of Nuclear reactor	Molten salt, Liquid metal

In the available literature, most of the work has been done using water for low temperatures below 100 ^{o}C, and molten salts and liquid metals for high temperatures above 250 ^{o}C in a single-phase natural circulation loop under atmospheric conditions. There are very few literatures that advocate for working fluids in the medium temperature range of application. So, various working fluids such as thermal oils (Thermal oil: Therminol-VP1, Paratherm-CR, Dowtherm-Q) and vegetable oils (Soyabean, Canola oil, Sunflower oil), can be used as a potential working fluid for the medium temperature range of application in single-phase natural circulation loop at atmospheric conditions.

1.3 Mono and hybrid nanofluids

Nowadays, the use of nanofluid over conventional fluid has a very powerful impact on the thermal performance of the system. It improves the heat transfer capability of the system due to enhanced thermophysical properties of base fluids, which makes the system more compact. Nanofluids are engineered by dispersing nanoparticles, having average sizes below 100 nm, in conventional heat transfer fluids coined by Choi in 1995. Nanofluids provide a significant improvement in the heat transfer properties even at a very small fraction of nanoparticles for stable, homogenous, and uniformly dispersed nanofluids. Therefore, the preparation of nanofluid is a very important step. The different types of nanoparticles that can be used for the preparation of nanofluids such as metals (Cu, Al, Zinc, Ag, etc.), metal oxides (Al_2O_3, CuO, SiO_2, MgO, etc.), allotropes of carbon (CNT, Graphene, etc.) metal carbides (SiC, TiC, etc.). The stability of the nanofluid is improved by adding some surfactants in the base fluids such as CTAB, Gun, SDS, Arabic, CMC, etc. The nanofluids may be broadly categorized into two groups, (i) mono-nanofluids, prepared by adding only one type of nanoparticles in the base fluid, (ii) hybrid nanofluids, dispersed two or more than two types of nanoparticles in the base fluid. For the preparation of nanofluids, two methods are available, the single-step method and the two-step method. The two-step method is mostly used over a single step instead of having agglomeration and stability issues because the single step has the following disadvantages (i) a small quantity of nanofluids can be prepared, (ii) Some residual product remains in the prepared nanofluid, and (iii) Expensive compared to two-step method. The following procedures are used for the preparation of mono or hybrid nanofluids through a two-step method. Firstly, different nanoparticles are prepared as dry powders. Then they are mixed in the base fluid through magnetic or mechanical stirring. A suitable surfactant is used as per requirement. After that, the solution is sonicated and then characterized using different techniques to assure the proper (homogeneous) mixing and stability of the hybrid nanofluids. Both mono and hybrid nanofluids are thus prepared to provide improved heat transfer characteristics due to an increase in thermal conductivity, Brownian motion, proper dispersion, agglomeration, solid/liquid interface layering, thermophoresis, the improved thermal network between the solid nanoparticle and fluid molecules, nanofin and nanoporous effects at the heat transfer surface. The reason behind this improvement can be summarized as [3]: (i) More heat transfer surface between nanoparticles and fluid, (ii) Collision between the nanoparticles, (iii) Increment in the thermal conductivity due to the interactive effect of different nanoparticles, and (iv) Proper dispersion of the nanoparticles in the base fluid, creating micro turbulences. In addition to nanofluids, hybrid (binary and ternary) nanofluids have gained more attention recently due to significant improvement in heat transfer characteristics and stability that may be caused by the synergistic effect of hybridization. Moreover, the hybrid nanofluids also provide combined thermal, physical, and chemical properties of different materials, whereas a single nanoparticle does not fulfill all the requirements. Therefore, in hybrid nanofluids, both nanoparticles compromise their properties and provide better thermo-physical, chemical, and rheological properties at a low cost that making it preferable over nanofluids for different applications It is supposed that hybrid nanofluid has better thermophysical properties over mono nanofluid, which has motivated to implement hybrid (binary and ternary) nanofluids in single-phase natural circulation loop.

1.4 Objective and novelty of the thesis

The single-phase natural circulation loop (SPNCL) is used for many engineering applications due to the various advantages discussed above, Water and oil-based hybrid nanofluids can be a potential working fluid in the temperature range of 30^{o}-250^{o}, which can be used in various industrial applications such as in solar water heating, chemical industries: soaps, synthetic rubber, process heat, and cooking industries. However, based on the literature review, few experimental and numerical studies have been conducted using water-based mono nanofluid. So, as far as the author's knowledge, none of the numerical and experimental studies are available using water-based and oil-based hybrid nanofluids having different shapes of nanoparticles in the open literature. Moreover, no study is available on the effect of different assumptions such as Boussinesq approximation, property variation, bend effect, heat loss, axial fluid, and wall conduction on the transient and steady-state characteristics of SPNCL for different working fluids (water, brines, and hybrid nanofluids). Therefore, the numerical and experimental investigations have been planned to assess the transient and steady-state performance characteristics of SPNCL using water and oil-based hybrid nanofluids for low and medium temperature ranges. Hence the objectives of the present research are summarized as:

1. To develop a numerical code to analyze the thermo-hydraulic performance of a single-phase natural circulation loop using various water and oil-based hybrid nanofluids.
2. To investigate the effect of different assumptions related to Boussinesq approximation, property variation, bend effect, heat loss, axial fluid, and wall conduction on the transient and steady-state characteristics for different fluids. Also, to check the validity of this assumption for higher temperature application.
3. Preparation, characterization, and stability test of mono/hybrid nanofluids
4. Experimentation on SPNCL using water-based mono/hybrid nanofluids.
5. Experimentation on SPNCL using oil-based mono/hybrid nanofluids.

The novelty of the thesis is that the present work deal with the numerical and experimental investigation of the energetic and exergetic performances of a single-phase natural circulation loop using water and oil-based hybrid nanofluids. In this study, the effect of different types and shapes of the nanoparticles, geometric parameters (diameter and height), loop inclination, loop aspect ratio (height to width), operating parameter (Heater power input, Coolant inlet temperature), and different nature of heat flux distributions (uniform, linear, non-linear, sinusoidal, and Gaussian) in the heating section on the performance parameter has been investigated. The present work also numerically investigates the effect of different assumptions related to Boussinesq approximation, property variation, bend effect, heat loss, axial fluid, and wall conduction on the transient and steady-state characteristics of different fluids.

1.5 Thesis structure

The present thesis has been organized into seven chapters.

Chapter 1 Includes Background and motivation, Natural circulation loop and hybrid nanofluids, and thesis objective and novelty.

Chapter 2 Provides the numerical and experimental literature review on the single-phase natural circulation loop related to the geometric and operating parameters and working fluid used.

Chapter 3 provides a numerical analysis of the one-dimensional steady state and transient performances for Vertical Heating Horizontal Cooling (VHHC) SPNCL with water, water-based binary and ternary hybrid nanofluids, and thermal oils as the working fluids. The parametric investigation includes the effect of geometrical parameters like diameter, height, loop aspect ratio (height to width), loop inclination, nanoparticle shapes, and power input on the SPNCL performance parameters such as mass flow rate, effectiveness of heat exchanger, and total entropy generation rate.

Chapter 4, includes a detailed investigation of the effect of different assumptions related to Boussinesq approximation, property variation, bend effect, heat loss, axial fluid and wall conduction on the transient and steady-state characteristics. The effect of assumptions on the performance parameters for different working fluids (water, brines, and hybrid nanofluids) and the effect of different heat flux distributions, like the uniform, linear, non-linear, sinusoidal, and Gaussian, applied to heater have also been explored.

Chapter 5 consists of a detailed explanation of the preparation and characterization of nanoparticles and hybrid nanofluids, experimental setup and procedure, data analysis, and uncertainty analysis based on defined performance parameters. Finally, a detailed explanation of the effect of power input, coolant inlet temperature, and loop inclination (left and Clockwise) on the performance parameter, i.e., mass flow rate, effectiveness of the heat exchanger, and total entropy generation rate, has been presented.

Chapter 6 includes an experimental investigation that shows the transient and steady-state performance of SPNCL using Therminol VP1 and Soyabean oil, and their based mono/binary hybrid nanofluids. A detailed study of the effect of power input, and loop inclination (left and Clockwise) on the performance parameter, i.e., mass flow rate, effectiveness of the heat exchanger, and total entropy generation rate, has been presented.

Chapter 7 concludes the findings of the present investigation and possibilities for future work.