Chapter 1

Introduction

Father of thermodynamics, Sadi Carnot said that man is the weakest animal on the earth yet dominates the entire world…. only because of power. Best power plant cycle is the one in which when cycle is completed the source should come to the initial point (same T, P). According to Carnot’s theory at least four processes are needed for a thermodynamic cycle. Best power cycle is the one for which the PV diagram will be a CIRCLE (very difficult to get). Heat addition and rejection should be at high and low temperatures. He said that ‘don’t do any experimentation on power plant cycles unless the theoretical analysis’.

1.1 CURRENT ENERGY SCENARIO

The world energy consumption will increase by 56% from 2010 to 2040 as per International Energy Outlook (IEO2013). The energy use in the world at 2010 is 524 quadrillion British thermal units (Btu). It increases to 630 quadrillion Btu in 2020 and to 820 Btu in 2040 (Fig.1.1). The organisation for Economic Co-operation and Development (OECD) is an international forum of developed countries, co-ordinates and improves the economic and social status around the world. Non-Organization for Economic Cooperation and Development (non-OECD) is the countries outside the OECD where the energy demand increases by strong population and economic growth. In OECD and non-OECD countries the energy growth increases by 17% and 90% respectively. In 2010 the net electricity generation in the world is 20.2 trillion kWh and in 2040 is expected to reach 39.0 trillion kWh with 93% increase according to IEO2013 data. But the electricity demand in non-OECD countries is slow compare to OECD countries. OECD countries are with well established electricity markets and mature consumption pattern whereas in non-OECD countries presently many people do not have right to use electricity.

The world’s fastest growing energy sources are renewable energy and nuclear power, both increases about 2.5% every year. In 2040, mostly 80% of world energy use is supplied by fossil fuels. In the outlook the fastest growing fossil fuel is the natural gas. The natural gas consumption is increased about 1.7% per year globally. After 2030, the usage of coal will go faster than petroleum and other liquid fuels. For
the past two decades India and China are the fastest growing countries around the world. The India’s economy has been raised to an average of 6.4% from 1990 to 2010 every year. Coal remains as the second-largest energy source as per the projections of world energy markets by fuel type (IEO2013). The world coal consumption at 2010 is 147 quadrillion Btu and in 2020 it is 180 quadrillion Btu. The increase is averaged to 1.3% per year. However coal is not considered as the cleaner energy source. In longer term the growth is decelerated as policies and regulations to encourage the cleaner energy source. As a consequence of China’s industrial activities and shale gas development, the usage of coal diminishes.

Fig.1.1 World energy consumption, 1990-2040 (Quadrillion Btu)

The following are the development factors in the power sector (Ministry of power).

i) Rural electrification
ii) Generation
iii) Transmission
iv) Distribution
v) Recovery of cost of services and targeted subsidies
vi) Technology development and Research and Development (R & D)
vii) Competition aimed at consumer benefits
viii) Financing power sector programmes including private sector participation
ix) Energy conservation
x) Environmental issues
xi) Training and human resources development
xii) Cogeneration and non-conventional energy sources.

There are possibilities still to improve the power sector with certain ideal approaches. Presently the focus is on to eliminate interrupted power supply to the consumers.

1.2 THERMAL POWER PLANT

Power plant are classified as per the source as conventional power plants and non-conventional power plants. In conventional power plants, the fuel is coal, oil, natural gas or any other similar. Solar thermal, solar photovoltaic, biogas, biomass, geothermal, wind, ocean thermal energy conversion, wave, tidal, thermo-ionic generator and magneto hydro dynamic (MHD) power plant etc. are in the category of non-conventional.

Thermal power plant works on heat engine principle and converts heat into electricity with Carnot limitation. The various thermal power plants are steam power plant, diesel power plant, gas turbine power plant, nuclear power plant and combined cycle power plant etc. In steam engines, power plant works on Rankine cycle. In I.C. engine based power plants, the cycles are Otto, diesel or dual. In case of gas turbine it is Brayton cycle. Nuclear power plant works on the principle of fission and fusion. Power cycles have been classified into two groups: (i) vapor power cycle and (ii) gas power cycle.

The vapour power cycles are Carnot, Rankine, regenerative, reheat and binary vapor cycle. Otto cycle, diesel cycle, dual combustion cycle, Stirling cycle and gas turbine cycle are gas power cycles. Carnot cycle is a standard of comparison for all cycles. As the wet vapor is difficult to compress to a saturated state, this cycle is difficult to operate in practice even though the efficiency of this cycle is high.
Rankine cycle is a steam cycle which uses steam as a working fluid. Work output of Rankine cycle is greater than Carnot cycle. The size of the Rankine cycle depends on the steam flow rate. Rankine cycle has got low efficiency due to isothermal heat supply in the boiler. In Rankine cycle, pump work is smaller compared to the compressor work in Carnot cycle. By increasing the supply temperature and decreasing the average temperature at which heat has rejected, the Rankine cycle efficiency increases. The working of the Rankine cycle can also be improved by increasing boiler pressure, superheating and reducing condenser pressure. The efficiency of Rankine cycle approaches closer to Carnot cycle, when the superheated temperature rise gets reduced. The other methods for increasing the cycle efficiency of the Rankine cycle are: regenerative feed heating, reheating of steam and use of binary vapor. In reheat cycle, the steam is extracted from the turbine before expansion and used for reheating. With this cycle, the dryness fraction of steam at exhaust can be raised so that blade erosion can be reduced. With reheating, output of the turbine increases and the turbine blades will not get damaged. But reheating requires additional maintenance. The efficiency of the regenerative cycle increases with the average temperature of heat addition, reduced heat rate and by using small size condenser. Regenerative cycle requires greater maintenance as with the increased number of heaters.

In a binary vapor power cycle, two working fluids have been used one with good high-temperature characteristics and another with good low-temperature characteristics. Binary vapor cycle is used to increase the overall plant efficiency. The components considered should not be toxic and dangerous to human life. The binary fluid considered must be non-corrosive to the metals used in power plants. The mercury-steam cycle may receive favourable attention as the possibilities of improving steam cycle are reducing and consequently the cost of the fuel is increasing. But more amount of mercury is required which is costly. Among the discussed cycles, it is clearly intended to concentrate on performance boost of the chosen cycle favouring increased power generation.

The performance of the power plant can also be increased by the carbon dioxide trans-critical Rankine power cycle. It has got better temperature glide matching characteristics between sensible waste heat source and working fluid in
vapor generator. It has desirable qualities such as moderate critical point, little environment impact and low cost. Ultra-supercritical (USC) steam conditions are paying attention in reducing power plant emissions includes green house gases from coal fired power plants (Cziesla et al., 2009).

Organic Rankine cycle (ORC) is the alternate measurement proving as an improvement of the Rankine cycle. The ORC uses organic, high molecular mass fluid with a liquid-vapor phase change or boiling point, occurring at a lower temperature. The ORC has proved to be a system for thermodynamic conversion of recovered sensible heat into electrical energy. In ORC’s pure fluid must be selected according to the source temperature level. ORC systems employ iso-pentane, iso-butane, or a number of other hydrocarbons. The utilization of organic fluid as working components, will allow recovering heat from low temperature sources. Low temperature sources include biomass combustion, industrial waste heat, geothermal resources, solar ponds etc. With the potential integration in distributed generation systems and favourable characteristics, ORC is considered as an opponent to conventional steam power cycles. It is used in geothermal power plants and suitable for low temperature applications (Vijayaraghavan, 2003).

Recently the role renewable power technologies are increasing in India. Fig. 1.2 shows a simple layout of solar Rankine cycle for power production. In producing electricity, solar energy is utilized for steam generation. In March 2010, India had 10.2 MW photovoltaic systems and 2.5 MW stand-alone systems. In 2020, 22 GW of electricity is proposed to be generated from solar energy as the target is set by solar mission (20 GW grid-connected, 2 GW off-grids). In Rajasthan, India has good concentrated solar power (CSP) potential. The maintenance required by solar cells is little and are non-polluting. In comparison with other renewable sources, solar cells have got more advantages. The wind and water power depends on turbines which are noisy, expensive with high initial cost and depends on weather conditions.
Affairs about safekeeping of energy supplies and the environmental consequences of greenhouse gas emissions have motivated government policies that support a proposed increase in renewable energy sources. From 2010 to 2040, 2.8% growth per year happens with renewable energy sources as it is considered as the fastest growing sources of electricity generation (IEO2013). Nearly 80% of the proposed increment in renewable electricity generation is by hydropower and wind power. Electricity generation from nuclear power increases from 2620 billion kWh in 2010 to 5492 billion kWh in 2040. Due to non-continuous supply of solar and wind energy, the economic competitiveness of those resources have been obstructed.

The decomposing, matter imitated from plants or animals obtainable on a renewable basis are biomass. It includes wood and agricultural crops, herbaceous and woody energy crops and municipal organic wastes. Of the world total primary energy supply, about 10% of it is accounted by biomass-energy in 2009. Bio energy plays an important role in heat and power and meets the future energy demand (International Energy Agency, 2013).
The heat underneath the earth's surface is tapped by geothermal energy. Geothermal energy potential is mainly accessed in Himalaya region, Jammu and Kashmir and Himachal Pradesh. Geothermal energy has not been realized as a clean, secure energy alternative because of issues with resources, technology, and low natural gas prices. Geothermal energy benefits the nation by helping to solve energy reliability and security, economic development, and air quality. Compared with conventional coal-fired plants, emission of carbon dioxide, sulphur dioxide and nitrogen oxide are less.

1.3 KALINA POWER PLANTS

Kalina cycle system (KCS) is a competitive system to the ORC in heat recovery plants. It is a modified Rankine cycle rather a reversed vapor absorption refrigeration system utilizing low temperature energy source. KCS utilizes binary mixture as working fluid. The zeotropic mixture has a temperature distribution parallel to that of the thermal reservoir. Transition from liquid to vapor phase occurs at a constant pressure and temperature, without any change in the composition. KCS is efficient than Rankine cycle due to varying boiling and condensation nature. Conventional steam cycle boils and condenses at a constant temperature, hence less performance compared to KCS. The mixture of working fluids has the tendency to boil at varying temperature and due to this it matches with the hot source. This closeness leads to recover energy with low source temperature. The condensation of two component working fluid happens over a range of temperatures which provides additional heat recovery in the condensation system.

Figure 1.3 shows the temperature entropy plot for Rankine and Kalina cycles. In Fig. 1.3(a), the heat addition and heat rejection happens at constant temperature during phase change for Rankine cycle. Whereas in Kalina cycle the heat addition in boiler and heat rejection in condenser happens at variable temperature as shown in Fig.1.3(b). State ‘a’ is the bubble point temperature and state ‘b’ is the dew point temperature. In condenser state ‘4’ is the start of phase change and state ‘1’ is the end of phase change. The mean heat addition of source temperature ($T_{ma}$) for Kalina cycle is higher than Rankine cycle. The mean heat rejection ($T_{mr}$) for Kalina cycle is lower than the Rankine cycle. It is possible to maintain low pinch point in the Kalina system, which is difficult in steam Rankine cycle. With the increase in source
temperature and with decrease in sink temperature the overall Kalina cycle efficiency is increased to 1.6 – 1.9 times more than the Rankine cycle efficiency. Multiple pressure systems could recover more energy, resulting in complex design and cost. The condenser pressure can be much higher which eliminates vacuum maintenance at condenser. Expansion in turbine, results in nearly saturated vapor for a two component fluid cycle compared to wet steam in Rankine cycle, requiring protection of blades in the last few stages. Conventional equipments such as steam turbines and heat recovery steam generators (HRSGs) can be used in Kalina cycle plant.

![Fig. 1.3 Temperature - entropy plot (a) Rankine cycle (b) Kalina cycle](image)

Figure 1.4 shows the temperature concentration diagram of ammonia-water mixture. In addition to the Rankine cycle components Kalina cycle involves separator. In Organic Rankine cycle (ORC) and steam Rankine cycle there is no separator. One working fluid is continuously moving all the components from starting to ending. In KCS, the expansion in turbine with a high ammonia concentration needs very low condensing temperature. But at this condition condenser requires low cooling water temperature. It is not possible to condense ammonia at atmospheric conditions. Accomplishing it is very difficult, hence requires alternate solution. The difficulty in condensation is overcome by the incorporation of separator as shown in Fig. 1.5. The ammonia-water mixture is separated into enriched (high concentration) ammonia mixture and lean (low concentration) ammonia mixture. The lean ammonia mixture is mixed with the high concentration of ammonia mixture from turbine
exhaust thus reduces the concentrations at condenser inlet. The condensation temperature is increased with the decrease in ammonia mixture concentration. Now the condensation happens with ordinary cooling water in the condenser. The complexity arises because of the separator.

![Fig. 1.4 Temperature – ammonia concentration diagram for ammonia-water mixture at pressure of 10 bar](image)

The advantage of KCS is the use of recuperation with heat recovery from the turbine exhaust. The temperature at state ‘9’ in Fig. 1.5 is enough high at 60 °C to 70 °C, which can be used in regenerator and so the boiler heat load can be decrease. In Rankine cycle the steam is expanded at low temperature. There is no possibility of adding the recuperator after turbine in ORC or steam Rankine cycle. The addition of recuperator is possible only in Kalina cycle plant to increase the efficiency (Fig. 1.6). In the cement production process, Kalina cycle produces 40% higher thermal efficiency compared to conventional steam and organic Rankine cycles without affecting the environment.
Fig. 1.5 Use of separator in producing low concentration ammonia mixture at condenser

Fig. 1.6 Increase in efficiency with recuperator
Ammonia is environmentally benign and does not promote ozone depletion or global warming like organic fluids. In Kalina cycle, ammonia as working fluid has zero oxygen depletion potential and near zero global warming potential and is inflammable. Whereas the ORC working fluids have bad magnitude than ammonia in environmental performance and many are highly inflammable. In organic fluids emissions and spills do occur, guiding to serious hazards if not controlled by proper safety procedures and planning. According to the literature, impressive performance advantages of Kalina cycles over ORCs have been claimed. Leibowitz and Mlcak (1997), concluded that the KCS-34 results an improvement of 25% net output compared to the hydrocarbon ORC cycle. Mlcak et al. (2002) claimed that Kalina plant generates 30-50% more power from a given heat source than ORC plant.

1.3.1 EXISTING KALINA PLANTS

Table 1.1 Overview of the Kalina power plants located throughout the world.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Year</th>
<th>Power output, MW</th>
<th>Project</th>
<th>Country</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1991</td>
<td>6.5</td>
<td>Canoga Park</td>
<td>USA</td>
<td>Power plant gas turbine</td>
</tr>
<tr>
<td>2</td>
<td>1998</td>
<td>4.5</td>
<td>Fukuoka</td>
<td>Japan</td>
<td>Incinerator</td>
</tr>
<tr>
<td>3</td>
<td>1999</td>
<td>3.5</td>
<td>Kashima</td>
<td>Japan</td>
<td>WHR from a steel plant</td>
</tr>
<tr>
<td>4</td>
<td>2000</td>
<td>2.0</td>
<td>Husavik</td>
<td>Iceland</td>
<td>Geothermal plant</td>
</tr>
<tr>
<td>5</td>
<td>2006</td>
<td>4.0</td>
<td>Fuji oil</td>
<td>Japan</td>
<td>WHR from a oil refinery</td>
</tr>
<tr>
<td>6</td>
<td>2009</td>
<td>3.4</td>
<td>Unterhaching</td>
<td>Germany</td>
<td>Geothermal plant</td>
</tr>
<tr>
<td>7</td>
<td>2009</td>
<td>0.6</td>
<td>Bruchsal</td>
<td>Germany</td>
<td>Geothermal plant</td>
</tr>
<tr>
<td>8</td>
<td>2009</td>
<td>50.0</td>
<td>Tibet</td>
<td>Tibet</td>
<td>Geothermal plant</td>
</tr>
<tr>
<td>9</td>
<td>2010</td>
<td>50.0</td>
<td>Shanghai World Expo</td>
<td>China</td>
<td>Solar thermal plant</td>
</tr>
<tr>
<td>10</td>
<td>2010</td>
<td>50.0</td>
<td>Taiwan</td>
<td>Taiwan</td>
<td>Geothermal plant</td>
</tr>
<tr>
<td>11</td>
<td>2012</td>
<td>8.6</td>
<td>Khaipur</td>
<td>Pakistan</td>
<td>WHR from a cement plant</td>
</tr>
</tbody>
</table>

Table 1.1 presents the current status of Kalina cycle projects in various countries. Canoga Park demonstration plant has been the first Kalina cycle plant uses waste heat power plant and as a combined cycle power plant, designed with turbine inlet vapor conditions of 515 °C. It has been tested between 1992 and 1997 both as a waste heat plant and as a combined plant.

A second demonstration Kalina cycle generating plant in 1999 has been part of a waste–to-energy facility in Fukuoka, Japan. This 4.5 MW power plant was a
retrofit to a fluidized municipal incinerator. In 2002, another waste heat recovery plant has been built inside the Tokyo bay Fuji oil refinery yielding up to 3.9 MW of electric power. Siemens has completed the construction of first geothermal power plant, utilizing binary cycle with ammonia-water mixture to produce electricity built in the town of Unterhaching with electrical power output as 3.4 MW.

In December 2009, another geothermal plant has been built in Germany, in Bruchsal with the electrical power of 500 kW. The first commercial plant has been built in Japan in 1999 by Sumitomo metal Kashima steelworks. It produces 3.1 MW using waste heat from the steel plant. The first geothermal power plant has been built at Husavik, Iceland in 2000. It produces a net output of 2.0 MW. The plant is a combined heat and power plant.

The performance problems after the erection of plant are rectified by the engineers with suitable remedies. In Canoga park plant, the performance of the vapor turbine was low with the under performance of the turbine’s control stage. Improper specifications resulted low condenser performance. The labyrinth seals on the turbine shaft and the packing rings in the feed pump were eroded resulting excessive leaks. Corrosion in the turbine was occurred between the turbine housing and the first stage nozzle vanes at Husavik geothermal plant. By installing a stainless steel ring between the first stage nozzle and the turbine housing, this problem has been recovered. In the exhaust section of the turbine, material losses were identified. Erosion was noticed on the low pressure side of the turbine sealing. Ammonia leakage was observed through the axial sealing of the turbine.

1.4 OBJECTIVES OF THE CURRRENT WORK

The main objective of the current work is to examine for KCSs at various heat recovery levels with the possibility of improved performance. The heaters arrangements in source are investigated. Kalina cycle has been focused and evaluated to generate power at hot sink temperature. Parametric analysis has been made on the Kalina cycles considered. The parameters and methodology, not considered by others have been developed. The results have been simulated using MATLAB software. The power generation cycles suitable for three different temperature ranges have been assessed.
1.5 SCOPE OF PRESENT WORK

Projections for future electricity demand are very uncertain, because of the anticipated persistence of India’s dynamic development. Gross domestic product (GDP) development, industry structure, population growth and income levels are important drivers for energy and electricity demand. Growing energy demand and developing non-polluting energy conversion systems are the probabilities to meet the challenges of energy crisis. A power cycle is an energy conversion system in which one form of energy has been converted into another usable form. Power generation cycle is a set of repetitious processes that has the same starting and ending point in terms of state properties. It is difficult to erect the power plant without the thermodynamic design and the analysis.

Kalina cycle configurations for low, medium and high temperatures in power generation have been focused in this work. In assessing, a power cycle the properties of the working fluid must be known. The properties of binary ammonia-water mixture have been developed for various pressures, temperatures and concentrations. In determining the properties of the working fluid, computer codes in MATLAB have been prepared. These property codes works as function programme in the main program of the Kalina systems. At given values of temperature, pressure and concentration, the property data for enthalpy, entropy, volume and exergy have been developed. Using mass, energy and exergy balances the performance of the KCS has been evaluated at Indian atmospheric conditions.

The binary working fluid method is complicated compared to pure substance as it involves the function of pressure, temperature and concentration. The current work simplifies this complex nature of method and analyzes the basic processes for power generation solutions.

The methodology for low temperature Kalina cycle system (LTKCS) has been modified and developed at efficient operational conditions. The regular design of serially connected high temperature regenerator (HTRGN) and boiler in a LTKCS has been replaced with parallel heaters and compared with each other. The influence of vapor fraction, separator temperature, turbine concentration and solar beam
radiation has been studied on performance of the plant. The key parameters are optimized to get a high performance with minimized collector’s cost.

Thermodynamic development and assessment of a medium temperature Kalina cycle system (MTKCS) has been examined to augment the power from a medium temperature heat recovery. There is no throttling device in this plant as the separator is located at low pressure side. The key parameters have been addressed for performance results.

Thermodynamic development and assessment for a high temperature Kalina cycle system (HTKCS) suitable up to 550 °C with an improved heat recovery has been focused. The cycle has three pressure levels i.e. high pressure (HP), intermediate pressure (IP) and low pressure (LP). The superheated vapor expands from HP to LP and the separator is located at IP. The work develops a simple and new method for thermodynamic evaluation. Separator inlet condition, turbine inlet condition and solar radiation have been identified as key parameters for the plant evaluation.

1.6 LAYOUT OF THE THESIS

Chapter 2: In this chapter, literature has been reviewed in the area of aqua-ammonia properties, KCS, exergy analysis, innovation in power cycles and combined power and cooling systems. The low temperature cycles have been discussed in the order of developments. Diverse innovations in Kalina cycle have been reviewed. The MTKCS plant has been identified as an innovative development having more merits. A review on exergy analysis is carried out to highlight the importance of second law of thermodynamic evolution to Kalina cycle. Based on the reported literature on KCS plants, the problem has been defined.

Chapter 3: In this chapter, the methodology to solve cycle processes, LTKCS, MTKCS and HTKCS plants has been developed. The formulations involved in separator, turbine, pump and heat exchanger have been detailed. For the three systems, first law and second law calculations are discussed. The assumptions made in each system have been summarized. The procedure concerned in calculating the solar plant efficiency has been discoursed. The sizing and economics of plants are developed.
Chapter 4: In this chapter, the results of separation process, and parameters influencing the performance of LTKCS, MTKCS and HTKCS plants are discussed. The thermodynamic results are validated with the plant operation data. The results are analyzed to identify the optimum operation conditions. The key parameters are identified and analyzed with the selected range in the operational parameters. Influence of solar beam radiation with supply temperature on plant performance and collector cost has been investigated. The area and detailed cost for heat exchangers, turbine and pump are summarized. Specifications are developed at the optimized operational conditions.