CHAPTER 1
INTRODUCTION

1.1 Cogeneration

The increasing concern for depleting energy sources and greenhouse gas emission from power generating stations has forced the industrial community to look for alternative way of using energy more efficiently. Cogeneration in this regard provides a cost effective way of achieving the above objective. Cogeneration is simultaneous production of power and useful thermal energy from the same energy source. The thermal energy so produced can be used for process heating, producing process steam, producing chilled water for cooling and refrigeration. Cogeneration captures the thermal energy and utilizes it for some useful purpose which otherwise would have wasted in a traditional thermal power plant. Consequently, a cogeneration system provides much higher efficiency than those of the separate systems and in situations, where both process heat and electric energy are required; cogeneration is an option that should always be practiced [1].

1.2 Need for cogeneration

Thermal power plants are a major source of electricity supply in India. Conventional thermal power plants burn fuel either to convert water into steam to drive a steam turbine (ST) or burn gas to make it expand to drive a gas turbine (GT). Electricity generation in conventional thermal power plants is usually inefficient in the sense that they convert only about a third of the fuel's chemical energy into useful energy and the remaining is lost as waste heat. As such, more energy goes to waste than production of useful electricity in most of the thermal power plants. Moreover, many chemical and process industries such as paper mills, textile mills, sugar mills, oil refineries, cryogenic systems, steel manufacturing and food processing plants rely heavily on process heating/cooling besides being a huge consumer of electricity. Having two separate units, one for the power and the other for process heat would not only unnecessarily increase the cost of the plant but it would also incur heavy energy loss which is thermodynamically wasteful. Cogeneration plants utilize energy more effectively and their utilization factor is as high as 80% or higher [2]. Fuel consumption reduces and less fuel is required to generate the same amount of power and process heat as separate generation of electricity and heat through use of individual power station and heating boilers. Lower fuel consumption also helps reducing emission of greenhouse gases, particularly CO_2 emission from a cogeneration plant. Therefore, it is economical and also logical from engineering point of view to use cogeneration plants whenever there is requirement of both power and process heating/cooling.

1.3 Benefits of usage of cogeneration

Some benefits of using cogeneration have already been pointed out in the above paragraph. Some other benefits of cogeneration plants are more elaborately discussed below.

Reduced fuel and utility costs: Efficient energy utilization causes reduction in fuel consumption, thereby reducing the need for fuel supply and other logistics required for fuel transportation and storage. A cogeneration plant can provide on–site power and thermal energy with much lower cost and facilities, particularly in places where purchased power from utilities is otherwise expensive [3]. Hence, there is immense savings in the annual operational and maintenance costs. Additionally, losses associated with transmission and distribution of electricity from distant power plants are mitigated in a cogeneration plant.

Environmental benefits: Increased efficiency and lower fuel consumption of the cogeneration process makes it highly sensitive to the environment. Emissions of CO_2 and other greenhouse gases including nitrogen oxides, sulfur dioxide and particulate emissions are greatly reduced in cogeneration plants.

Fuel flexibility: Cogeneration plants are operated with waste heat or low grade energy. Hence, low quality fuels such as bio–mass, wood or wood waste and other renewable can be used. Otherwise also, cogeneration gives a wide range of fuel choices including coal, natural gas, fuel oil, gasoline and high speed diesel etc.

Energy reliability: Cogeneration plants, since they produce on–site electricity and thermal energy simultaneously from a single plant, therefore, the risk of electric grid disruptions is eliminated and energy reliability is enhanced. Disruption from weather, natural disasters, mechanical failures, and other troubles are also significantly reduced in cogeneration plants. Cogeneration plants have the ability to operate in parallel with existing utility and provide quality backup power. They are also capable of running even when there is a power outage in the grid. The increased energy reliability provided by cogeneration plants is especially important in many facilities and process industries with continuous power supply demand [3].

Extended lifespan of equipment: Wear and tear on mechanical equipment such as boilers is less in a cogeneration plant. This increases the operational life of the equipment. When a cogeneration plant is put into service, existing equipment is often relegated to serve as a back–up and this helps in prolonging the lifespan of existing equipment.

1.4 Cogeneration systems

The following are some common cogeneration systems that are used in industry for commercial production of power and process heat applications [3, 4].They are classified according to the type of prime–mover they use.

1. ST based cogeneration systems

(i) Back pressure (Non–condensing) ST cycle

(ii) Extraction and condensing ST cycle

2. GT based cogeneration systems

3. Internal combustion engine (ICE) based cogeneration systems

4. Fuel cell (FC) based cogeneration systems

5. Micro gas turbine (MGT) based cogeneration systems

6. Hybrid FC–GT/MGT based cogeneration systems

1.4.1 ST based cogeneration systems

The most common among the ST based cogeneration systems are the backpressure and extraction condensing types, the choice depends on the process heat and power load requirements and economic factors. The advantage of ST based systems over other prime movers is that a wide variety of fuels such as coal, natural gas, fuel oil and biomass can be used in these systems. However, due to the system inertia, their operation is limited only to sites with intermittent energy demand.

In back pressure ST based cogeneration system (Fig. 1.1), the exhaust steam from the turbine is utilized for process heating. The process heater replaces the condenser of the plant, thus eliminating the need of the condenser and hence no heat is rejected as waste heat. If the focus is laid on process heating, then, the steam flow rate and exhaust steam pressure can be carefully adjusted to meet the process heat requirements. However, in that case, it will lose control over the power requirement. Therefore, in a back pressure turbine, there is little scope of adjustment with variation of power and process heat load.

In extraction condensing type cogeneration system (Fig. 1.2), steam is extracted from the turbine at some intermediate pressure for passing it through the process heater. The extraction pressure and amount of steam extraction may be varied based on the process heat requirement. Therefore in this system, control of electrical power is possible and it is independent of the thermal load.

ST based combined heating and power (CHP) systems are available in a variety of sizes ranging from 500 kW to 350 MW [3]. They are highly efficient and reliable with a long working life, which make them suitable for numerous cogeneration applications in agriculture sector, ethanol plants, sugar mills, lumber mills, paper/pulp mills, manufacturing and oil refining industries. The disadvantages are that they have slow start up and cannot attain high power to heat ratio.

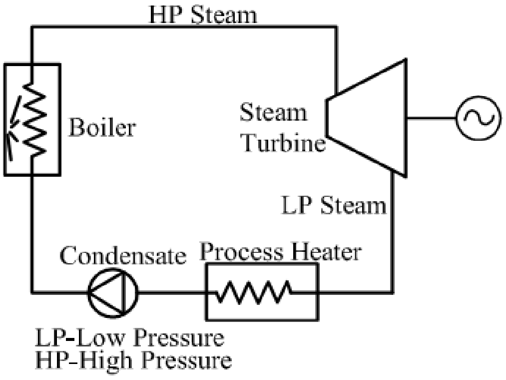

Fig. 1.1 ST based cogeneration systems (back pressure type)

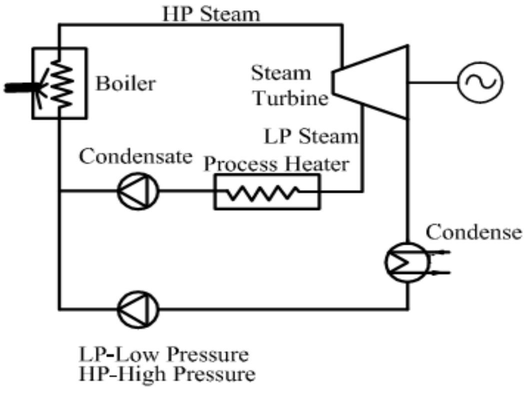

Fig. 1.2: ST based cogeneration systems (extraction type)

1.4.2 GT based cogeneration systems

In GT based cogeneration systems, the thermal energy of high temperature turbine exhaust gases is recovered in a heat recovery steam generator (HRSG) for producing steam. The process steam generated in the HRSG is used for heating/cooling applications or for further production of electricity in the combined cycle (CC) mode using a bottoming ST cycle. GT in combination with the HRSG and the ST represents the state of the art CC technology with efficiencies up to 60% in various plant capacities ranging from medium to large scale power generation [5–7]. Otherwise also, the GT exhaust heat can be used for preheating combustion air and fuel in a recuperative GT cycle. Majority of the recuperative GT plants use recuperator for the purpose of preheating combustion air prior to its entry to the GT combustor as a means of improving system efficiency [8]. In dual recuperated cycle [5, 9], GT exhaust heat is used for preheating combustion air and steam generation simultaneously. Fuel preheating is also one of the many techniques that are used for achieving higher efficiency [5, 8,10] from GT plant. Over the years, GT cogeneration technology has seen rapid development due to a number of factors such as low capital cost, high flexibility and reliability, early commissioning, low capital and maintenance cost, compact size, easy starting and better environmental performance [11, 12].

Natural gas is the most common fuel used in the combustor of a GT plant, although, other fuels such as light fuel oil or diesel can also be employed. Natural gas firing produces less CO_2 than liquid or solid fuels [12]. GT cogeneration is suitable for textile mills, paper/pulp mills, refineries, food processing, chemical, petrochemical, manufacturing and agricultural industries [3, 11]. It can also be used in district energy systems for space heating and air conditioning purpose.

Increase in turbine inlet temperature (TIT) through development of advanced high–temperature blade material with superior thermal barrier coatings; advanced inlet duct and compressor inlet design; improved compressor and turbine efficiencies; improved turbine blade cooling techniques (closed loop water/steam cooling);better blade cooling mediums; intercooling and reheat either separately or in combination with the simple GT cycle using higher cycle pressure ratio; improved heat recovery in the HRSG, minimization of stack gas temperature; best shaft system configuration, steam injected gas turbine (STIG), humid air turbine (HAT) are the various technologies that can be employed to improve the performance of GT based power plants and cogeneration systems at feasible costs [8, 13]. A typical GT based cogeneration system is shown in Fig. 1.3.

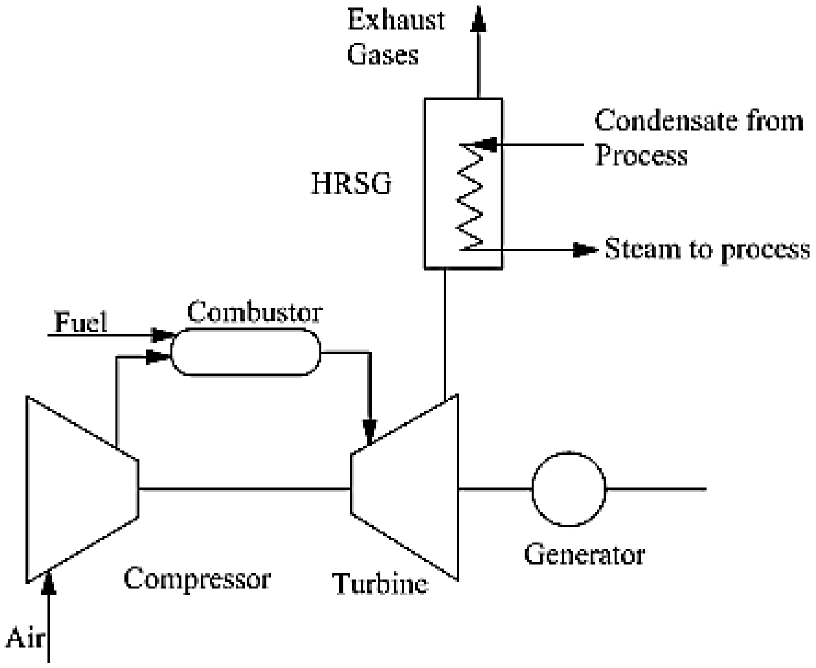

Fig. 1.3: GT based cogeneration system

1.4.3 ICE based cogeneration systems

Reciprocating ICEs are suitable for small–scale cogeneration applications such as residential, commercial, institutional and small–scale industrial applications [14]. The engine exhaust (medium–grade) and engine coolant (low–grade) are the main sources of waste heat from an ICE [15–17]. Small amount of heat recovery may also be possible from the hot lubricating oil [18, 19], exhaust gas recirculation cooler and charge air cooler [17]. Waste heat may be recovered from each of these sources simultaneously and used for process/space heating, space cooling, and air conditioning and even for producing electricity.

The thermodynamic cycles that can be used to generate electricity from ICE exhaust heat are the Kalina cycle, supercritical/ transcritical Rankine cycle, organic Rankine cycle (ORC) and Goswami cycle. Among these, the Kalina cycle and ORC are the potential candidates for using ICE exhaust heat, because these are simple in operation and have the ability to operate efficiently between small to moderate temperature differences [17, 20].ORC's provide an attractive combination of efficiency and affordability for ICE waste heat recovery. Selection of the cycle expander and the working fluid are the keys to performance of an ORC [17]. In an ORC, the working fluid is organic while in the Kalina cycle, it uses a variable composition mixture such as ammonia–water(NH_3–H_2O) binary mixture. Tanscritical carbon–dioxide power cycle [21–23] and thermoelectric power generation systems [24, 25] may also be driven by low grade heat source such as ICE exhaust heat [17]. ICE exhausts are also feasible and potential energy sources for absorption refrigeration systems [26–30].

ICE based cogeneration systems are ideal for intermittent operation and their performance is not affected by changes in ambient temperatures as in a GT based systems. Initial investment cost of these systems is low, but the operating and maintenance costs are high due to high wear and tear. Fig. 1.4 and Fig. 1.5 show two typical ICE based cogeneration systems. In the schematic shown in Fig. 1.4, engine exhaust is used for producing hot water/steam while in Fig. 1.5; cooling effect is produced by utilizing engine exhaust heat.

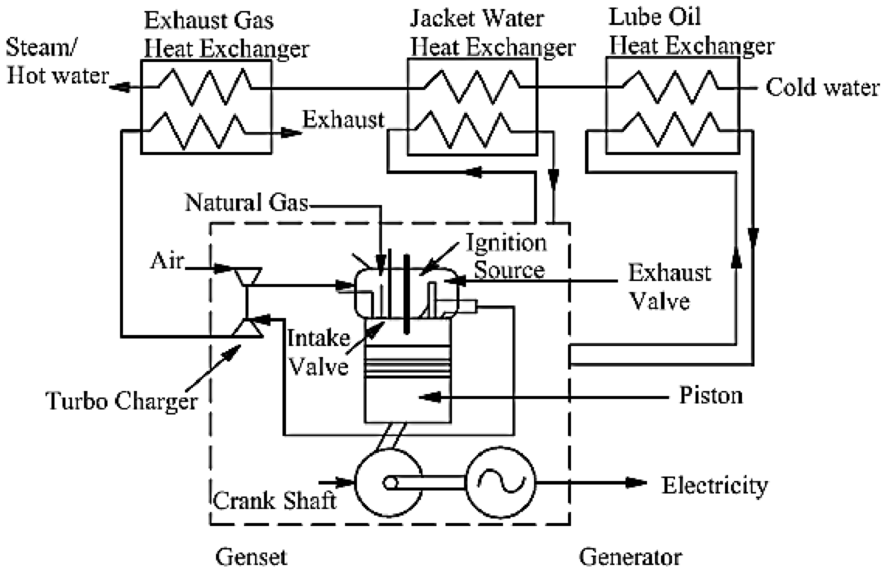

Fig. 1.4: ICE based cogeneration system [19]

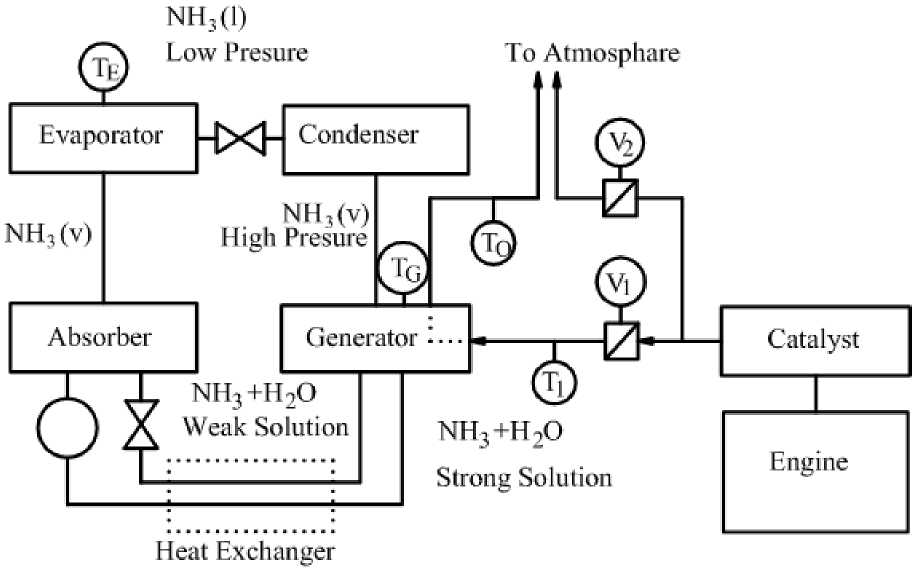

Fig. 1.5: Engine exhaust driven absorption refrigeration system [30]

1.4.4 Fuel cell based cogeneration systems

Fuel cells produce electricity from hydrogen–rich fuels through electrochemical processes. The heat generated during the fuel cell's electrochemical reaction can be recovered and used for various purposes. Unlike in conventional power systems, where fuel needs to be combusted to generate heat for further conversion into mechanical and electrical energy, a fuel cell power system avoids direct fuel combustion and converts the chemical energy of fuel directly to electrical energy through an electrochemical kinetic process. As such, efficiency of a fuel cell system is not subject to the limitations of Carnot cycle as in the case of a conventional heat engine. Fuel cell power generation system is an emerging technology and is expected to be one of most efficient energy conversion system in the future with flexible fuel utilization and very low pollutant emissions [31].

There are various types of fuel cells viz. Alkaline fuel cell (AFC), Direct methanol fuel cell (DMFC), Phosphoric acid fuel (PAFC), Sulfuric acid fuel cell (SAFC), Proton–exchange membrane fuel cell (PEMFC), Molten carbonate fuel cell (MCFC), Solid oxide fuel cell (SOFC), Protonic ceramic fuel cell (PCFC) etc. These fuel cells are basically characterized by their range of operating temperature, applications, type of electrolyte used and the nature of the fuel used. AFC, DMFC, PAFC, SAFC and PEMFC are characterized by their low to medium temperature (50–210°C) whereas MCFC, SOFC and PCFCs have high operating temperature in the range of 600–1000°C

[32]. Among the various types of fuel cell, the high temperature fuel cells have better potential to achieve higher efficiency for electricity production. They are suitable for both large power plants and small cogeneration unit [31]. Moreover, the high operating temperatures allow direct internal reforming of fuels that reduces the system complexity involved with low–temperature power plants which require hydrogen generation in an additional process step. One of the most notable advantages with the high temperature fuel cells, particularly the SOFCs, is that they can be integrated with bottoming GT/ST/combined cycles to generate further power from high temperature exhaust stream [33].

1.4.5 MGT based cogeneration systems

MGTs are small GTs with outputs ranging in size from 30 to 100 kilowatts [4]. MGTs are more appropriate for small–scale applications, particularly for distributed power generation because of their compact size, low weight, small number of moving parts, lower noise, fuel flexibility as well as low emissions [34]. They are reasonably efficient, have low maintenance costs, low vibration level and short delivery time. When more power is required, multiple units can be synchronized to meet the additional power demand.

The integration of MGT and absorption chillers is emerging as a new technology to produce electricity, heating and cooling simultaneously for small scale distributed generation in grid connected or isolated locations [35–37]. In these systems, the MGT exhaust gas is the heating medium to drive the absorption chiller. That the MGT exhaust can be used for heating or cooling application is schematically shown in Fig. 1.6.

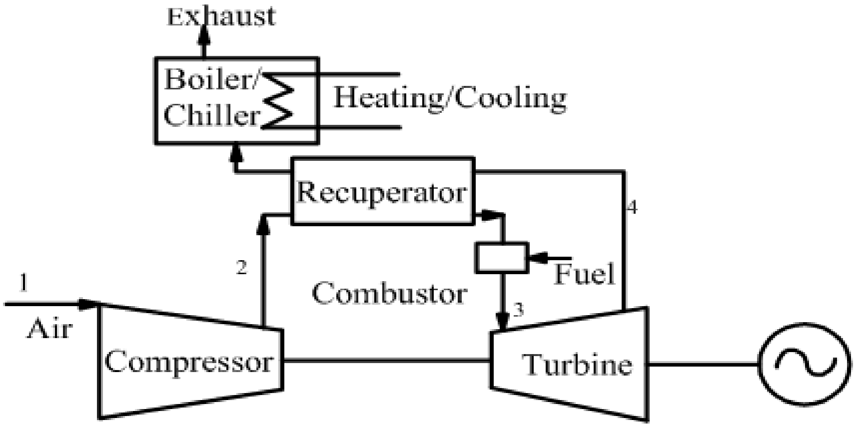

Fig. 1.6: MGT based cogeneration system [34]

1.4.6 Hybrid FC–GT/MGT based cogeneration systems

FC provides very good opportunity for hybrid systems especially for distributed generation. Any combination of a FC and a heat engine can be considered as hybrid FC system [33]. In a hybrid FC system, the heat energy of the FC off–gas is used to generate further electricity in a heat engine, which could be either a GT or a ST or the combined GT–ST cycle. Among the various FC hybrid schemes, the SOFC–GT system is the one that is being studied extensively with theoretical models and also with the help of experiment [38].

In a hybrid SOFC–GT system, the power output from the bottoming GT plant is usually less and therefore, small sized MGTs are more suitable for integration with SOFC in such plants [39–41]. In hybrid SOFC–GT/MGT systems, the high pressure air from the compressor is fed to the cathode and the fuel (natural gas) is fed to the anode. In the cathode, oxygen diffuses through the electrode and reaches the electrode/electrolyte interface, where the oxygen is electrochemically transformed into oxygen ions by consuming the electrons transported through the external circuit. The solid ceramic electrolyte in a SOFC conducts only the oxygen ions and do not conduct electron, hence the electrons flow via the external circuit from the anode to the cathode. The oxygen ion is transported through the electrolyte to the anode side. At the anode, diffused H_2 reacts with the oxygen ions producing water and releasing electrons along with electrical energy and heat. The residual fuel from the SOFC is burnt in an afterburner and the gases leaving the burner are expanded in the GT/MGT to produce further electricity. The following schematic (Fig. 1.7) shows a FC based cogeneration system where it uses a SOFC integrated GT cycle to produce power and an ORC at the bottom to produce further electricity by utilizing GT exhaust heat.

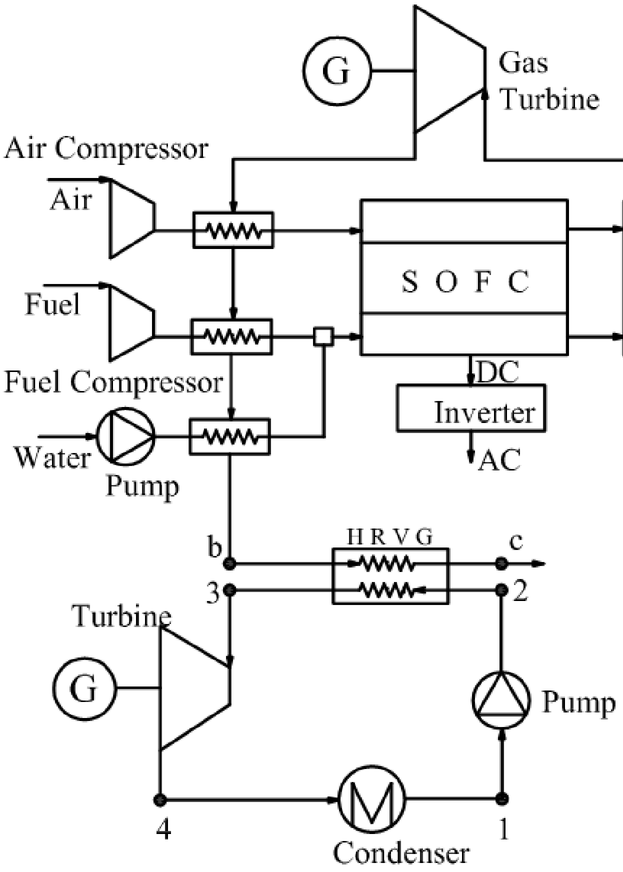

Fig. 1.7: Combined SOFC–GT–ORC hybrid power system [42]

1.5. ST based vapour power cycle

In a steam power plant, the energy released by burning of fuel (coal, oil, natural gas) is transferred to water to produce steam at high pressure and temperature in the boiler. The superheated steam then expands in the ST to produce shaft work and electricity in coupling with an electric generator. ST based thermal power plants generally operates on Rankine cycle and often termed a vapour power cycle (VPC). There are various methods that are used for increasing efficiency of VPC. Among these, the following are very commonly employed [2, 43, 44].

(i) increasing the boiler pressure,

(ii) lowering the condenser pressure,

(iii) superheating the steam to high temperatures,

(iv) regeneration, the process of preheating boiler feed water by steam extraction

(v) reheating of steam after expansion in the ST to some intermediate pressure

(vi) reheat regenerative VPC (RRVPC) etc.

Use of reheat regenerative VPC is very common in thermal power plants. A typical RRVPC is shown in Fig. 1.8.

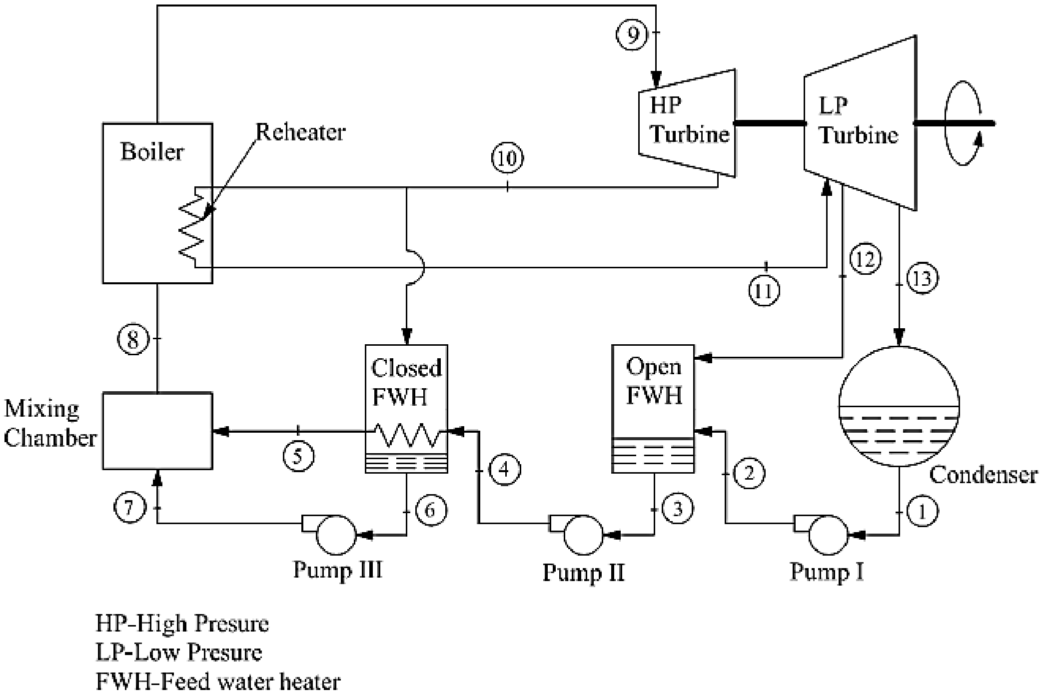

Fig. 1.8: A typical RRVPC [2]

The components in Fig. 1.8 are the HP and LP turbines, boiler, condenser, pumps, open feed water heater (FWH), closed FWH and the mixing chamber. Often thermodynamic performance of such ST based VPCs are evaluated with the help of first (energy) and second law (exergy) of thermodynamics [44–52].

Theoretical energy and exergy based parametric analysis helps to identify the parameters that maximize the system performance and minimize the irreversible losses. Details regarding energy and exergy analyses of thermal systems are described later in section 1.8.

Reheat cycle in steam power plants are usually employed to increase the dryness fraction of steam and avoid excessive moisture content at ST exhaust. Effect of reheating alone on thermal efficiency of VPC is usually small. Reheating consists of passing the steam through a high pressure (HP) turbine, then returning it to a special superheater (reheater), and resuperheating it before the steam is expanded further in the low–pressure (LP) turbine.

Regeneration is the process in which the boiler feed water is heated by steam extracted from ST at some intermediate pressure. This is accomplished by using a number of feed water heaters. Some large steam power plants use as many as 5 to 9 feed water heaters [2, 43]. The optimum number of feed water heaters is determined from economic considerations. The incremental increase in thermal efficiency or savings in fuel costs achieved with each additional heater must justify the added capital cost of the heater. Alternately, pre–heating of feed water can also be achieved by utilizing the exhaust heat of the flue gas in an economizer. Due to regeneration, there is a considerable saving in the amount of fuel consumed and the efficiency of the cycle is improved significantly. Modern steam power plants use both reheating and regeneration for obtaining combined advantages of the reheat regenerative configuration [43].

Performance of ST based VPC depends on operating parameters such as boiler pressure (BP), ST inlet temperature (STIT), number of pumps, feed water heaters, condenser pressure, fuel flow rate (FFR) and air flow rate (AFR) etc.

1.6 Refrigeration systems

The following are the basic refrigeration systems that are used in refrigeration and HVAC industry.

(i) Vapour compression refrigeration system (VCRS)

(ii) Vapour absorption refrigeration system (VARS)

(iii) Gas cycle refrigeration system (GCRS)

(iv) Ejector refrigeration systems (ERS)

(v) Thermoelectric refrigeration systems

In VCRS, the refrigerant is vapourized and condensed alternately and compressed in the vapour phase. The system has the advantage of high COP and large cooling capacity over the other refrigeration systems. Chlorofluorocarbons (CFCs) used in VCRS however have large degree of ozone depletion potential (ODP)and global warming potential (GWP). CFCs, therefore, nowadays are substituted with HCFCs, HCs and HFCs which have relatively less ODP and GWP. Continuous efforts are therefore being made by the research community to evaluate performance of VCRS with low ODP/GWP refrigerants having superior thermo physical and heat transfer properties [53–55].

In VARS, the refrigerating effect is produced by using a refrigerant absorbent pair and low grade energy (heat) instead of high grade electrical energy as in VCRS [56]. In a common single effect VARS, the refrigerant is vapourized in the evaporator which then goes to the absorber where the refrigerant vapour is absorbed by a weak solution of the refrigerant in the solvent. The strong refrigerant solution from the absorber is then pumped to the generator via a solution heat exchanger (SHE), where heat is added from a source. The vapour then passes through a condenser and an expansion valve and finally to the evaporator to complete the cycle. Selection of appropriate refrigerant and absorbent pair is very crucial in a VARS. The most widely used refrigerant and absorbent pairs in VARSs are the ammonia–water (NH_3–H_2O) and water–lithium bromide (H_2O–LiBr). The H_2O–LiBr pair is used mainly for air–conditioning and chilling applications over 4°C because of the ice formation problem at low temperature and crystallization of LiBr at moderate concentration. On the other hand, NH_3–H_2O is used for large capacity industrial applications requiring low temperature for process cooling below 0°C.

Usually, VCRS outperforms VARS, but the advantage with VARS is that it can be operated with waste heat stream, non–conventional energy sources such as solar or geothermal energy. VARSs are available in various configurations ranging from half effect to triple effect. The half effect cycle presents the lowest COP; COP increases with increase in number of stages and thus highest COP is obtained with the triple effect configuration [57]. In the double and triple effect (multi effect) cycles, generation of refrigerant vapour is distributed among two and three number of generators respectively. Multi effect (double and triple effect) absorption refrigeration cycles are also available in series, parallel and reverse parallel flow configurations. Details of all these configurations and their differences can be found in the Refs. [57–60]. The schematics of the single effect and double effect (series, parallel and reverse parallel flow) system configurations are shown in Figs. 1.9–1.12.

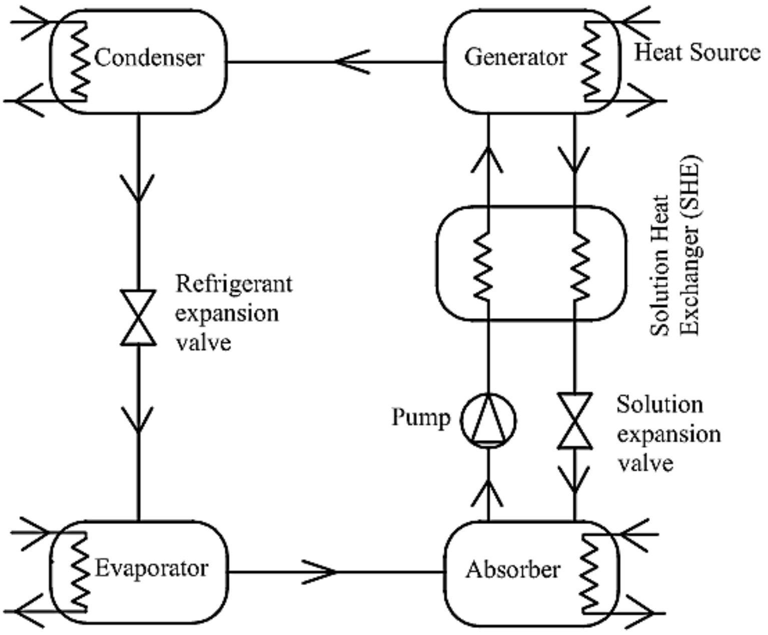

Fig. 1.9: Single effectVARS [56]

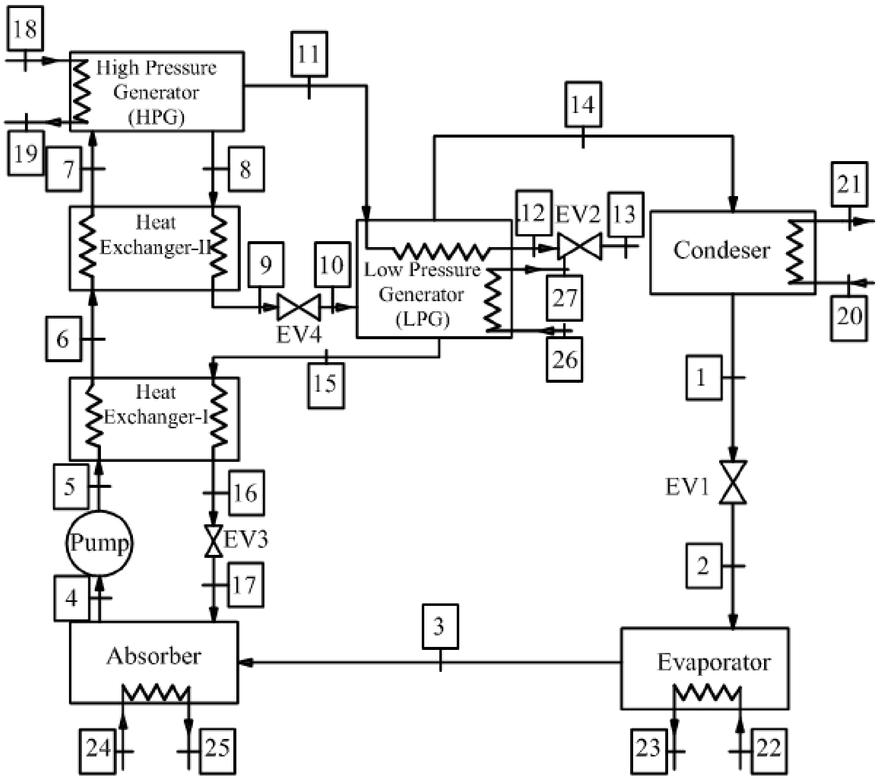

Fig. 1.10: Double effect VARS (series configuration) [57]

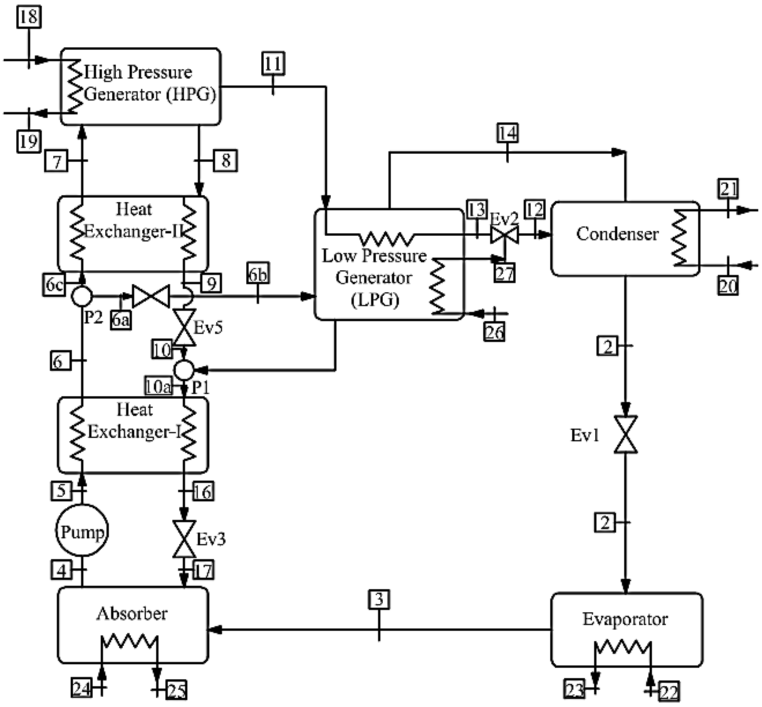

Fig. 1.11: Double effect VARS (parallel configuration) [57]

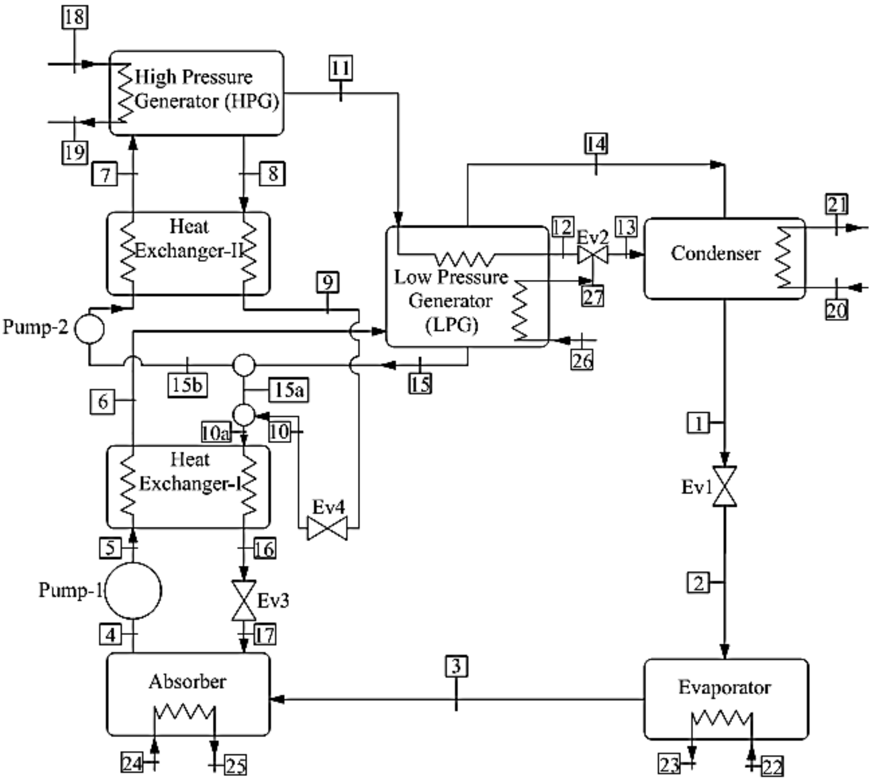

Fig. 1.12: Double effect VARS (reverese parallel configuration) [57]

The difference among the double effect series, parallel and reverse flow configurations is visible in the above schematics. In the series flow configuration, the strong refrigerant solution from the absorber is pumped directly to the high pressure generator (HPG) while in the parallel flow, the solution is distributed among the low pressure generator (LPG) and the HPG. In the reverse parallel flow configuration, the solution first goes to the LPG for partial vapour generation and the remaining solution is again pumped to the HPG [57].

Cascaded vapour compression–absorption systems are also investigated [61–65]. These are obtained by coupling VCRS with VARS and they offer advantages of both vapour compression and vapour absorption systems. It is possible to reduce consumption of a considerable amount of high grade electrical energy because the topping cycle is a heat driven VARS and low temperature can be achieved without using a conventional two stage vapour compression cascade refrigeration systems in which two separate VCR systems are coupled. However, the structure of such a compression–absorption cascaded system is more complex and bulky, but the overall operating cost is relatively low because of simultaneous usage of electricity and heat energy for refrigeration [65].

Another well–known refrigeration system is the gas cycle refrigeration system (GCRS) in which the refrigerant remains in the gas phase throughout. GCRS works on reversed Brayton cycle and uses simple and lighter components which make them suitable for air craft cooling. Regenerative GCRS is used for liquefaction of gases and cryogenic applications. COP of these systems are however low compared to VCRS.

Ejector refrigeration system (ERS) is another thermally driven cooling system (Fig. 1.13), where there is an ejector which increases the pressure of the refrigerant vapour without consuming mechanical energy [66]. The ejector eliminates the need of a compressor of a VCRS; and thus with ejector and other devices, it offers a simple cooling configuration [67–71]. ERSs have been developed in various capacities for applications in many engineering fields [67–71] but its lower COP is the main disadvantage. To improve COP of the simple ejector cycle, more complex cycles with additional jet pump [72], combined ejector–VCRS [73–75], hybrid absorption–ejector refrigeration system [76]and combined vapour compression–absorption–ejector refrigerator systems [77] have been developed and investigated. Significant effort has also been made to develop solar driven ejector refrigeration systems [75, 78–80].

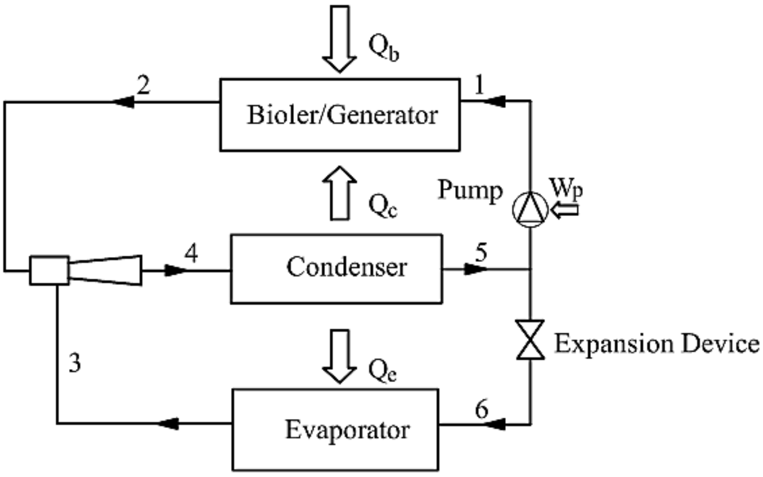

Fig. 1.13 Ejector refrigeration system [66]

The working of a thermoelectric refrigerator is based on Peltier effect. In a circuit containing two junctions of two dissimilar conductors or semiconductors, heat may be transferred from one junction to the other by applying a DC source. Semiconductors are better than metals for producing Peltier effect [81] and in a practical thermo–electric refrigerator, n and p type semiconductors are connected in series (Fig. 1.14). The heat from the refrigerated space is transferred through semiconductor elements to the hot–side heat sink which rejects the heat to the environment. Thermo–electric refrigerators are simple, quiet in operation, small in size, and reliable. But due to their low COP, they cannot compete with the conventional refrigeration cycles. However, they have their specific preferred applications in electronic, medical, telecommunications and space applications.

Thus, it was seen that all these basic refrigeration systems have their specific advantages and disadvantages. A detail comparison among these systems can be found in the Ref. [81].

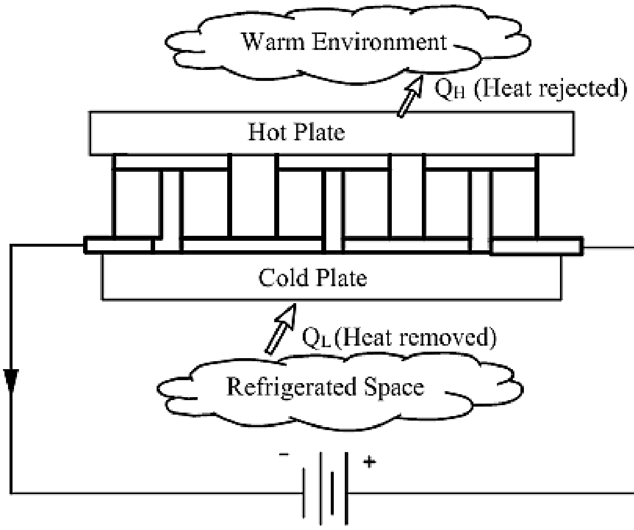

Fig. 1.14: Thermoelectric refrigerator

1.7 Combined power and cooling (CPC) system

Combined power and cooling (CPC) system is a cogeneration system that produces power and cooling simultaneously from one single plant. The advantage is that such a combined plant can supply the whole range of energy demand from only power to only cooling and is also capable of producing power and cooling at different ratios [82]. CPC leads to significant improvement of overall energy conversion efficiency and reduction in cost of cooling. Power and cooling can be produced simultaneously from the same thermodynamic cycle using a multi–component mixture. There are combined power and refrigeration cycles such as those proposed by Goswami et al. [83–85], Wang et al. [86], Zheng et al. [87], Liu and Zhang [88], Zhang and Lior [89] which uses NH_3–H_2O binary mixture as working fluid. A typical binary mixture based CPC system is shown in Fig. 1.15. In this type of CPC cycle, superheated NH_3vapour expands in a turbine to produce power while at the same time it also produces cooling due to expansion of vapour to very low temperatures.

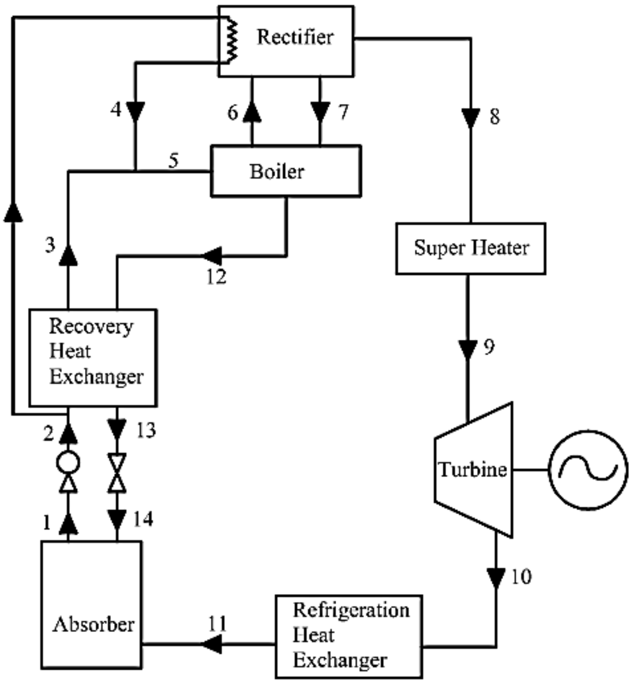

Fig. 1.15: A typical binary mixture based CPC cycle [85]

As discussed earlier in section 1.4, combined production of power and cooling is also possible through recovery of waste heat from ICEs [15, 26–30] and GT/MGT based thermal power plants [90–92]. In GT based CPC systems, absorption cooling cycles are used as bottoming cycles to produce cooling and for improving performance of GT based power plants through inlet air cooling. Solar energy driven absorption cooling systems are also gaining significant importance.

1.8 Energy and exergy analyses of thermal systems

Performances of thermal systems are usually quantified in terms of thermal efficiency, specific fuel consumption, coefficient of performance (COP) etc. These are determined by applying the first law of thermodynamics or energy balance to the system components, called energy analysis. The first–law based performance parameters in their definitions ignore the best possible performance of a system under reversible conditions. Hence, they are not actual measure of the system performance. Moreover, an energy analysis provides only a quantitative measurement of energy balance in a device or a system. Through energy analysis, it is not possible, to identify processes in the system that cause unrecoverable degradation of the thermodynamic state of the working fluid used in the system. In order to correlate the first law based system performance with the performance under reversible conditions, it is necessary to carry out system performance analysis on the basis of second law of thermodynamics. Thermodynamic analysis based on second law of thermodynamicsis called second law analysis or exergy analysis. Exergy of a system is a composite property linked with the state of the surroundings and it indicates the extent of departure of a system from the equilibrium state. It is the measure of quality and usefulness of energy. It refers to the maximum useful work that can be obtained from a system when it reaches thermal, mechanical and chemical equilibrium with the reference environment. In exergy analysis, exergy balance is applied to determine exergy destruction (or irreversibility) in various system components and the second law efficiency of a thermal system. Second law efficiency in its definition incorporates the best possible performance of the system under reversible conditions.

Suppose in a steam power plant, if an energy analysis is carried out, it would provide information about the heat supplied in the boiler, energy loss in the condenser and the thermal efficiency of the plant. Further, it would indicate that energy loss in the condenser is mainly responsible for low efficiency of the plant because a large amount of energy is lost in transferring heat to the cooling water in the condenser. This information obtained from energy analysis in no way gives any idea about the real usefulness of the low temperature cooling water and the exergy loss in the condenser. It would be possible only through exergy analysis to quantify that there is hardly any exergy loss in the condenser compared to the boiler irreversibility due to fuel combustion and heat transfer between combustion gas and water though large temperature difference. Exergy analysis plays an important role in

(i) determining magnitudes, location and causes of irreversibility in a thermal system,

(ii) analyzing the effect of various design, operating and thermodynamic parameters on the exergy destruction,

(iii) specifying the maximum possible performance of thermal systems and identify those aspects of processes that are significant to overall performance,

(iv) identifying methods for reduction of exergy destruction.

Performance of ST based VPC [44, 47–49, 51, 52], VCRS [54], VARS [57], NH_3–H_2O based CPC system [84], GT based tri–generation system [37] has been analyzed on the basis of exergy in many studies.

1.9 Motivation

From the discussion above in all the preceding sections, it was clear that cogeneration systems offer a number of benefits over individual production of power and thermal energy in separate stations. One to one discussion was provided for all possible cogeneration systems starting from the ST based to the hybrid SOFC–GT based systems in sections 1.4.1–1.4.6. A good number of previous thermodynamic analyses performed on ST and GT based thermal power plants, CHP systems, VCRS, VARS, NH_3–H_2O based CPC systems and exhaust heat driven CPC systems with bottoming VARS were referred in the preceding sections.

In so far as CPC systems are concerned, a lot of thermodynamic analyses have been done particularly on Goswami cycle [83–85], where power and cooling are produced simultaneously in a single thermodynamic cycle using mostly binary mixture of ammonia and water. As it was seen that other NH_3–H_2O based CPC cycle configurations [86–89] have also been proposed and analyzed. Thermodynamic analysis of CPC cogeneration systems that use waste heat from topping ICE and GT based power plants for driving coupled VARS were also previously performed. Solar energy assisted absorption cooling systems are also studied and discussed.

VARS in particular is more suitable for heat integration with the topping heat engine cycle. Many thermodynamic analyses have been done on VARS alone considering different sources of heat for the generator such as hot water [93], hot natural gas [94], high–pressure steam [95–97] etc. Sometimes, the analysis is done without being shown what the generator heat source is. This can possibly be done in a situation where the source of heat is assumed to be available for supply of heat to the generator and as such it has nothing to do with the performance of the topping system that provides the heat for running the bottoming VARS. However, when a VARS is integrated with the heat providing system, the performance of the two systems become interdependent; the performance of one will affect the other. E.g. performance analysis of some location specific combined solar powered VARSs have been reported [98–101]. The works of

Havelsky [15] and Manzela et al. [28] provide detail energetic performance calculations for both the ICE (topping cycle) and the VARS (bottoming cycle) simultaneously.

In ST based thermal power plants, steam is produced in abundance and sometimes lost unused at some intermediate/low pressure. Thermodynamic analysis for few Rankine cycle based steam power plants are found in Refs. [45–52,102,103]. Unfortunately, no such study on cogeneration system is available involving combination of the steam turbine based vapour power (Rankine) cycle and the H_2O–LiBr vapour absorption refrigeration cycle. Steam is a good heating medium and it is very commonly used as a heat source for driving VARS. Liang et al. [104] proposed a cogeneration system based on combined steam based Rankine–absorption refrigeration cycle to recover waste heat from engine coolant for water preheating and waste heat from engine exhaust gas for producing superheated steam. This superheated steam was used to drive a ST for generating power. The steam from the ST outlet was condensed in the condenser, and the heat rejected in the condenser was the source of heat for the NH_3–H_2O based absorption cycle.

Detail thermodynamic modelling and analysis of such a combined VPC and H_2O–LiBr VARS both on the basis of first (energy) and second law (exergy) of thermodynamics could be very useful in studying the effect of operating parameters of the topping VPC as well as bottoming VARS. Further, a performance comparison of systems with and without VARS is also possible as it would indicate the details regarding performance of the systems with and without VARS integration. There are two possibilities, either steam can be extracted from the ST or the exhaust heat of boiler flue gas of the VPC can be used. In thermal power plants, hot flue gas are sometimes used for preheating of boiler feed water in the economizer and combustion air in an air preheater. Similarly it can also be used for driving the generator of a VARS. However, one needs to be careful in selecting the type of VARS for it to be driven with boiler flue gas as there are various types of VARS ranging from half effect to triple effect type. This requires a systematic approach and this is with this motivation, the research in the current study is carried out to analyze two configurations of combined VPC and H_2O–LiBr absorption refrigeration systems thermodynamically with the help of energy and exergy analysis.

1.10 Research objectives

The following are the overall objectives of this research work.

1. Conduct literature review on individual VARS and VCRS and also on the state of the art CPC cycles.
2. To develop thermodynamic model and perform energy and exergy analyses for a novel combined RRVPC and a single effect H_2O–LiBr VARS operated by steam extracted from the ST of the topping RRVPC.
3. To compare the performance of two RRVPC based CPC systems, one with the single effect H_2O–LiBr VARS and the other with a R134a based VCRS as bottoming cycles.
4. To develop thermodynamic models for two combined RRVPC based CPC systems one with the double effect H_2O–LiBr VARS and the other with a single effect H_2O–LiBr VARS and provide performance comparison between the two systems.

1.11 Chapter wise thesis structure

The thesis consists of seven chapters. The present chapter provides the introduction along with motivation and research objectives. The remaining chapters in this thesis are organized as follows:

- A detailed review on previous studies related to VARS, ST based VPC, binary mixture based and waste heat driven CPC systems is presented in Chapter 2. The scope of the present research work is highlighted at the end.

- Chapter 3 presents a detailed energy based thermodynamic modeling and analysis for a novel combined RRVPC and a single effect steam driven H_2O–LiBr VARS proposed in this research. A parametric analysis is presented to show the effect of parameters such as boiler pressure, fuel flow rate, VARS cooling load (CL) and component operating temperatures on performance of the topping RRVPC and bottoming VARS. Further, the system performance variation is shown for the system without VARS to compare and quantify the effect of VARS integration in the plant.

Comparative performance analysis is also provided for the RRVPC alone with and without a regenerative feed water heater in the plant.

Chapter 4 describes the exergy based thermodynamic modelling of the combined RRVPC and single effect H_2O–LiBr VARS. The parametric variation of the exergetic performance parameters such as exergy efficiency of the individual power cycle and VARS, energy utilization factor (EUF) of the CPC system and irreversibility of the system components are shown against the system operating parameters. Irreversibility distribution among various RRVPC and VARS components are also presented in this chapter.

Chapter 5 presents thermodynamic modelling and comparative performance analysis of the CPC system with VCRS and VARS as bottoming cycles. At the beginning, a brief literature review on previous thermodynamic analyses performed on VCRS and combined absorption–compression refrigeration systems is presented**.** Next, the motivation behind carrying out the comparative performance analysis for the VARS and VCRS integrated CPC systems is highlighted. This is followed by description of the thermodynamic calculations of the topping RRVPC and bottoming VARS. At last, the performance of the two CPC systems with VCRS and VARS is highlighted to provide a comparative assessment.

In Chapter 6, a novel combined RRVPC and boiler flue gas driven double effect H_2O–LiBr VARS is proposed. The thermodynamic modelling required for the energetic and exergetic performance calculations of this novel CPC system is presented in detail. Energy and exergy analysis of the proposed CPC system is performed to show the performance variation of both the topping RRVPC and the bottoming VARS with changing boiler flue gas temperature. Further, the performance of double effect VARS integrated CPC system is compared with a similar system integrated with a single effect VARS.

In Chapter 7, the important observations made from this research are summarized and concluded. The possible scope of future research in the given research topic is also recommended at the end.

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