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Review on Waste Energy Recovery Systems

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Abstract: Today the demand of energy is increasing tremendously, but available energy lacks in supply. Hence, there is no option for proper and efficient utilization and conservation of energy. In this paper the main stress is given on energy conservation by using technique of utilizing waste heat. A review of recovery and utilization of waste energy systems is presented. The thermal treatment of waste with the heat recovery provides us with clean and reliable energy in the form of heat as well as power. This has contributed to primary energy savings in conventional utility systems.

Keywords: Rnakine cycle, Heat pump, Cogeneration, Trigeneration.

I. INTRODUCTION

Electric energy is an essential ingredient for the industrial and all-round development of any country. It can be adapted easily and efficiently to industrial applications and domestic purposes. The consumption of electrical energy is a reliable indicator of a country’s state of development. We are not faced with a vicious cycle of increasing fuel consumption to maintain our standard of living has been demonstrated very forcefully by R. Stobaugh [1]. It is around 170 units per annum for India against 9000 units in USA and 4000 units in UK [2]. In U. S. industrial plants, the energy that is being discharged to the air and rivers of America can be a new and substantial energy supply through the use of appropriate energy productivity technologies [3-4]. Power sector has grown at a phenomenal rate during the last four decades to meet the rapidly growing demand for electricity as a commercial fuel. Electric utilities have in the past adopted the conventional approach of adding new generating capacities to meet the demand [5]. However, financial constraints aggravated by sub-optimal operations of the existing facilities of power generation and supply have resulted in both energy and peak shortages since mid-seventies. Rapid growing trend brings about the crucial environmental problems such as contamination and greenhouse effect. The alternative energy sources, cost-effective use of the exhaustible sources of energy, and the re-use of the usually wasted forms of energy have encouraged research and development effort in this field. Currently, 80% of electricity in the world is approximately produced from fossil fuels (coal, petroleum, fuel-oil, natural gas) fired thermal power plants, whereas 20% of the electricity is compensated from different sources such as hydraulic, nuclear, wind, solar, geothermal and biogas [6]. Use significant amounts of energy in the form of heat, which is rarely utilized efficiently through a large number of industrial processes. Thus the use of heat exchangers and other forms of heat equipment to enable waste heat to be recovered is a considerable scope. To conserve the depletable energy sources and to recover wasted energy are currently active areas of research.

Cogeneration presents an important option to meet the demand for electricity and heat in a most cost-effective manner. It is defined as the combined generation of electric (or mechanical) and thermal energy from the same initial energy source. Electricity generated can be used to meet the internal electric requirements and thus reduce the demand for utility power and additionally the surplus, if any could be sold to the utilities. Cogeneration thus provides an alternative to the conventional utility power and reduces the overall emissions from the power sector [7]. However, the total fuel consumption is significantly reduced when “co-generation” or “combined heat and power” (CHP) is applied.

Combined cooling, heating and power (CCHP) systems, provide another alternative for the world to solve energy-related problems, such as energy shortages, the economy and conservation of energy, energy supply security, emission control, etc. A CCHP is the simultaneous production of mechanical power (often converted to electricity), heating and/or cooling from one primary fuel, and is an extension of CHP (combined heat and power, also defined as cogeneration) by coupling with thermally activated cooling technologies that take the waste heat from CHP for

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producing cooling [8-10]. The conventional way to provide electricity and heat is to purchase electricity from the local grid and generate heat by burning fuel in a boiler. But in a CHP system, by-product heat, which can be as much as 60–80% of total primary energy in combustion-based electricity generation, is recycled for different uses.

II. WASTE ENERGY RECOVERY

The forms of combustible fuel but unburned, sensible heat discharge from drain water, the sensible and latent heat discharge from flue gases takes by industry that is the wasted energy [11]. That the other more effective steps, like process changes, process control, and maintenance improvement, such as adjusting the excess-air rate, and streamlining of operations, must be considered before investing in heat recovery equipment emphasized for effective energy management. In the time of decision-making process, payback-period and life-cycle cost concepts are considered [12]. By the installation of combustion equipment to utilize the wasted fuel, the waste energy can be recovered, and the provision of heat recovery equipment to regain sensible and latent heat. During the past two decades to re-use the wasted heat more effort has been expended [13]. Analyses of heat recovery systems suitable for industrial plants have been suggested in this context [14]. An overview of available waste heat equipment, as well as of current applications was presented [11]. Charts, tables and curves were made available to assist the engineer in selecting the appropriate heat recovery system [15]. A survey of the waste heat related industries, refuse incineration, swage incineration, industrial incineration, foundries, glass furnaces, and cement factories provided enough opportunities for waste heat recovery concluded by Gitterman and Zwickler [16]. They suggested especially in arid zones that the recovered waste heat be used for water desalination. The use of waste heat recovered from the incineration of solid wastes to be used in connection with desalination of water by the reverse-osmosis process is a further study on the same subject suggested by R. E. Bailie [17].

One ways to pipe waste thermal generated in nuclear power plants to locations up to 40 km away has investigated by Kirvela and Seppala [18]. They concluded that saturated high pressure steam may be produced from ovens, furnaces, turbines, incinerators, and combustion equipment by the use of heat pipes. The production of fresh water from sea is another application of waste energy was considered [19]. To drive vapour compression equipment for desalination use waste heat gained from aluminium smelting furnaces has proposed by Weinberg and Fisher. For heating greenhouses from the cooling water from electric generators is the possibility of utilizing waste heat has given by Boyd [20]. The various applications in the process industry, where steam generated by the use of waste heat from a cogeneration facility could be used have proposed by Salt [21]. Bilgen [22] presented exergetic and engineering analyses as well as a simulation of gas turbine-based cogeneration plants consisting of a gas turbine, heat recovery steam generator and steam turbine. Reddy and Butcher [23] analyzed waste heat recovery based power generation system based on second law of thermodynamics.

Gaseous streams represent the largest and most readily exploited source of recoverable heat has pointed out by Brooks and Reay [24]. The waste heat boilers are most appropriate at temperatures above 3000C, and that economizers can be used to recover sensible heat only has asserted by same authors. Various types of heat exchangers that may find use as waste heat recovery equipment has discussed by Kiang [11,] and Shook [25]. For gas-to-gas heat recovery many kinds of equipment available studied by Sims [26]. Kiang [11] suggested for high temperature gases, use of gas-to-gas heat exchangers, including the heat wheel. He remarked the importance of material selection as regards the effect of corrosion. He indicated the advantages of the heat pipe heat exchangers over other type. G. Shultz and R. Hough [27-28] discussed the use of gas-to-gas heat exchangers in the form of heat recovery wheels, heat pipes, and recuperators was investigated in connection with energy retrieval from the exhaust air of buildings. Emphasize the factors to consider when specifying a system, and concentrated on flue-gas heat recovery equipment by Shook [25]. The use of gas-to-gas heat exchanger for preheating combustion air to about 120^0C above the ambient, described by Tipton and Huges [29]. By the use of stack gases, and resulted in a 6% reduction in fuel consumption was achieved. The use of liquid-to-liquid heat exchanger for heat recovery from high pressure gas compressor proposed by Sternlicht [30]. He also concluded that intercooling of compressor stages and by inlet gas precooling the thermal efficiency of the gas turbine can be improved. Equipment for heat recovery at high temperatures, recuperative and regenerative techniques reviewed by Nicholoson [31].

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The extent from a given stream of hot gases is limited by the state of cleanliness of the gas stream to which heat can be recovered. The problems associated with corrosion, erosion, fouling, and thermal fatigue because of contaminated streams. Because of these factors reduce efficiency of heat recovery system and limit the lifetime of heat recovery equipment. The amount of latent heat recovered from exhaust gases depends on the permissible lower temperature limit to which these gases may be cooled. Oxides of sulphur and nitrogen containing in polluted gas stream are rarely cooled below 150^0C to avoid the formation of sulphuric and nitric acids. The heat recovery equipments are attack by dilute solution of all these acids.

III. UTILIZATION OF WASTE HEAT

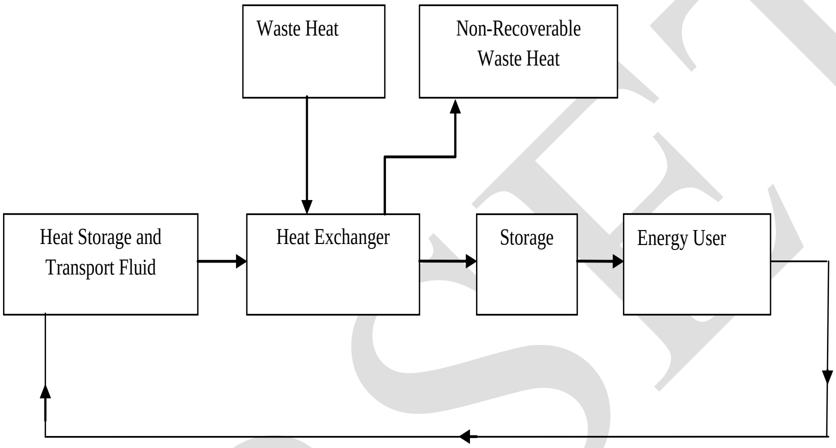

Fig. 1 One way to utilize waste heat

There are a large number of methods through which this energy can be recovered and utilized. We can reduce the cost of waste disposal. The quality of waste heat is usually low temperature but not always. Different heat exchanger devices can be used, depending on the temperature level of the wasted heat and the proposed application to facilitate the use of the recovered heat,. Figure -1. shows a schematic of possible energy utilization methods. When there is a time span between energy recovery and use, energy storage is needed. For maximum benefits from recovered energy, application of heat recovery should be physically close to the source of waste heat.

1. Cogeneration (CHP):

Co-generation was initially introduced in Europe and the USA around 1890. During the first decades of the 20th century, most industries had their own power generation units with a steam furnace-turbine, operating on coal. This course has now been reversed not only in the USA but also in Europe, Japan etc., mainly due to the abrupt rise of fuel prices since 1973, and the energy policy motives provided at a National level. Cogeneration is the generation of electricity and process steam is another technology for waste heat utilization [12, 13, 32-36]. Cogeneration accounts for 7 % of total global power production and more than 40 % in some European countries [37, 38]. Conventional power generation on average is only 35% efficient and up to 65 % of the energy potential is released as waste heat. More recent combined cycle generation can impose this to 55% excluding losses for the transmission and distribution of electricity. Cogeneration reduces this loss by using heat for industry, commerce and home heating/cooling. In conventional electricity generation, further losses of around 5-10% are associated with the transmission and distribution (T&D) of electricity from relatively remote power stations via the electricity grid; but in case of cogeneration the electricity generated is normally used locally thus T&D losses will be negligible. Thus the efficiency of cogeneration plant can reach 90% or more & it offers energy savings ranging 15-40% when compared to con-ventional power stations [39]. The book 'Handbook for Cogeneration and Combined Cycle Power Plants' by Boyce [40] covers all major aspects of power plant design, operation, and maintenance. It covers cycle optimization and reliability, technical

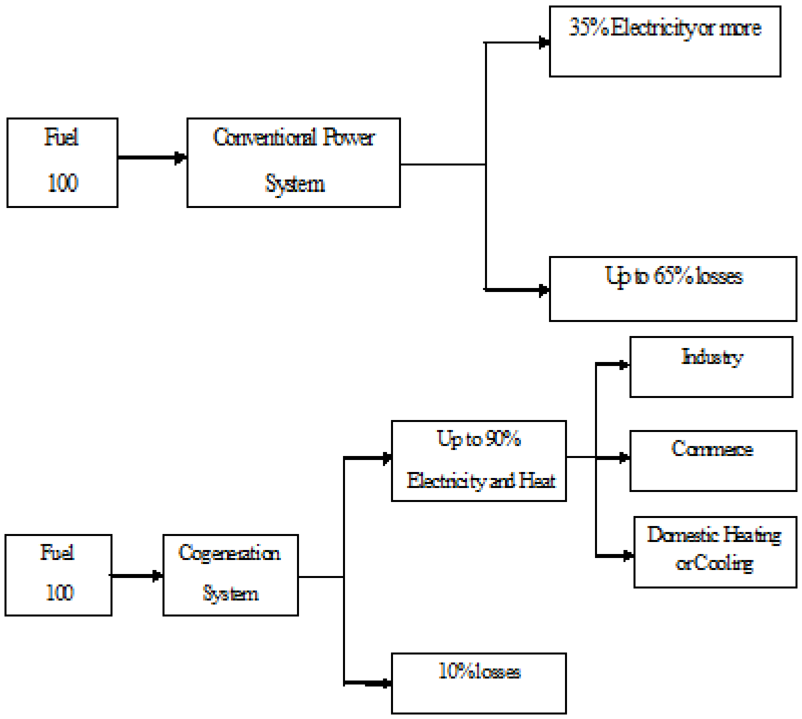

Fig. 2 Comparison between Conventional and Cogeneration power system

details on sizing, plant layout, fuel selection, types of drives, and performance charac-trics of all major components in a cogeneration or combined cycle power plant. In addition to energy, conservation cogenerat-ion yields significant environme-ntal benefits through using fossil fuels more efficiently as shown in Figure - 2.

Kamate and Gangavati [41] studied exergy analysis of a heat-matched bagasse-based co-generation plant of a typical 2500 tcd sugar factory, using backpressure and extraction condensing steam turbine is pre-sented. Dai et al. [42] was done exergy analysis for each cogen-eration system is examin-ed, and a parameter optimization for each cogeneration system is achieved by means of genetic algorithm to reach the maximum exergy efficiency. Khaliq and Kaushik [43] presented thermo-dynamic methodology for the performance evaluation of combustion gas turbine cogen-eration system with reheat. The energetic and exergetic efficiencies have been defined. The effects of process steam pre-ssure and pinch point tempe-rature used in the design of heat recovery steam generator, and reheat on energetic and exergetic efficiencies have been investigated. The paper 'Exergetic and Engineering Analyses of Gas Turbine Based Cogeneration Systems' by Bilgen [44] presents exergetic and engineering analyses as well as a simulation of gas turbine-based cogeneration plants. Two cogeneration cycles, one consisting of a gas turbine and the other of a gas turbine and steam turbine has been analyzed. The results showed good agreement with the reported data. Cogeneration technologies that have been widely commercialized include steam turbines, gas turbine with heat recovery and reciprocating engines with heat recovery boiler.

1.1 Steam Turbine Cogeneration Systems:

The two types of steam turbines most widely used are the backpressure and the extraction-condensing types, as shown in Figure - 3. The choice between backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors. The extraction points of steam from the turbine could be more than one, depending on the temperature levels of heat required by the processes. Another variation of the steam turbine topping cycle cogeneration system is the extraction-back pressure turbine that can be employed where the end-user needs thermal energy at two different temperature levels. The full-condensing steam turbines are usually incorporated at sites where heat rejected from the process is used to generate power.

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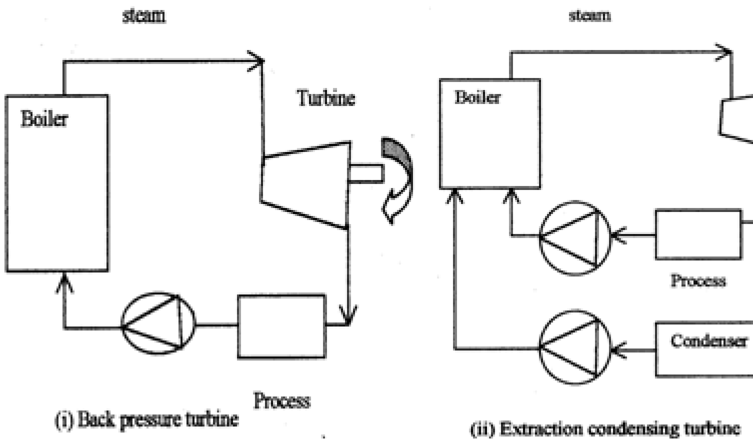

(i) Back pressure turbine (ii) Extraction condensing turbine

Fig. 3 Schematic diagram of steam turbine cogeneration

The specific advantage of using steam turbines in comparison with the other prime movers is the option for using a wide variety of conventional as well as alternative fuels such as coal, natural gas, fuel oil and biomass. The power generation efficiency of the cycle may be sacrificed to some extent in order to optimize heat supply. In backpressure cogeneration plants, there is no need for large cooling towers. Steam turbines are mostly used where the demand for electricity is greater than one MW up to a few hundreds of MW. Due to the system inertia, their operation is not suitable for sites with intermittent energy demand.

1.2 Gas Turbine Cogeneration Systems:

Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature in the exhaust stack can be recovered for various heating and cooling applications, as shown in Figure - 4. Though natural gas is most commonly used, other fuels such as light fuel oil or diesel can also be employed. The typical range of gas turbines varies from a fraction of a MW to around 100 MW [45]. It has probably experienced the most rapid development in the recent years due to the greater availability of natural gas, rapid progress in the technology, significant reduction in installation costs, and better environmental performance.

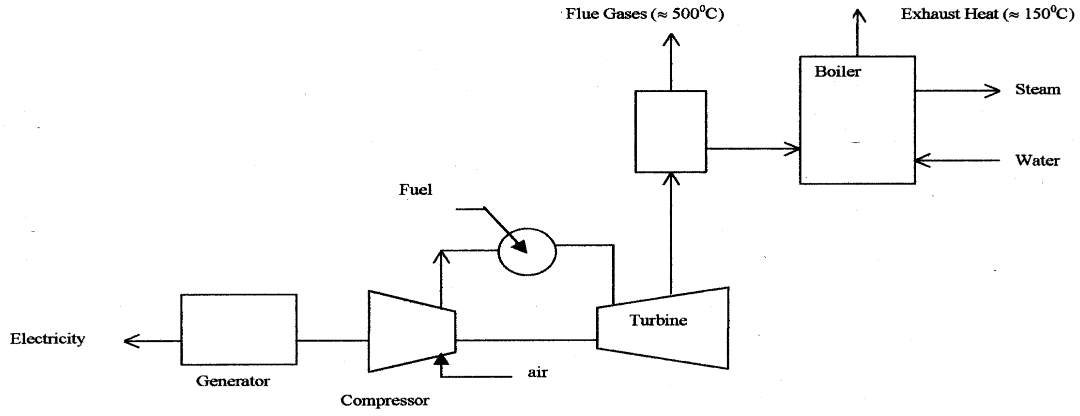

Fig. 4 Schematic diagram of gas turbine cogeneration

Gas turbine has a short start-up time and provides the flexibility of intermittent operation. Though it has a low heat to power conversion efficiency, more heat can be recovered at higher temperatures. If the heat output is less than that required by the user, it is possible to have supplementary natural gas firing by mixing additional fuel to the oxygen-rich exhaust gas to boost the thermal output more efficiently. On the other hand, if more power is required at the site, it is possible to adopt a combined cycle that is a combination of gas turbine and steam turbine cogeneration. Steam generated from the exhaust gas of the gas turbine is passed through a backpressure or extraction-condensing steam turbine to generate additional power. The exhaust or the extracted steam from the steam turbine provides the required thermal energy.

Khaliq and Kaushik [46] presented second-law efficiency of gas fire thermal power plant varying the number of reheat process and compression ratio in gas turbine. The first-law efficiency of the adiabatic turbine increases with the increase in pressure ratio. The second-law efficiency decreases with the pressure ratio, but increases with the cycle temperature ratio since a greater proportion of the available work lost at the higher temperature may be recovered. Kanoglu and Dincer [47] studied the performance assessment of various cogeneration systems through energy and exergy efficiencies. Chen and Tyagi [48] were presented parametric study of an irreversible cycle model of a regenerative-intercooled-reheat Brayton heat engine along with a detailed. The power output and the efficiency are optimized with respect to the cycle temperatures for a typical set of operating conditions. It is found that there are optimal values of the turbine outlet temperature, inter cooling, reheat and cycle pressure ratios at which the cycle attains the maximum power output and efficiency. Kaushik and Tyagi [49] explained in his paper a parametric study of an irreversible regenerative Brayton heat engine with isothermal heat addition has been performed with external as well as internal irreversibility. It is seen that the effect of the isobaric side effectiveness is rather pronounced for the power output and the corresponding thermal efficiency.
Gas turbine exhaust recovery was considered to be one of the rich areas of research for heat recovery and utilization [50-52]. Among the ideas suggested for utilizing the gas turbine waste are: for water distillation [50] for boosting the turbine output by air pre-cooling [52], and for the purposes of heating and cooling.

1.3 Reciprocating Engine Cogeneration Systems:

Also known as internal combustion (I. C.) engines, these cogeneration systems have high power generation efficiencies in compar-ison with other prime movers. There are two sources of heat for re-covery: exhaust gas at high temperature and engine jacket cooling water system at low te-mperature, as shown in Figure - 5. As heat recovery can be quite efficient for smaller systems, these systems are more popular with smaller energy cons-uming facilities, particularly those hav-ing a greater need for electricity than thermal energy and where the quality of heat required is not high, e.g. low pressure steam or hot water. Though diesel has been the most common fuel in the past, the prime movers can also operate with heavy fuel oil or natural gas.

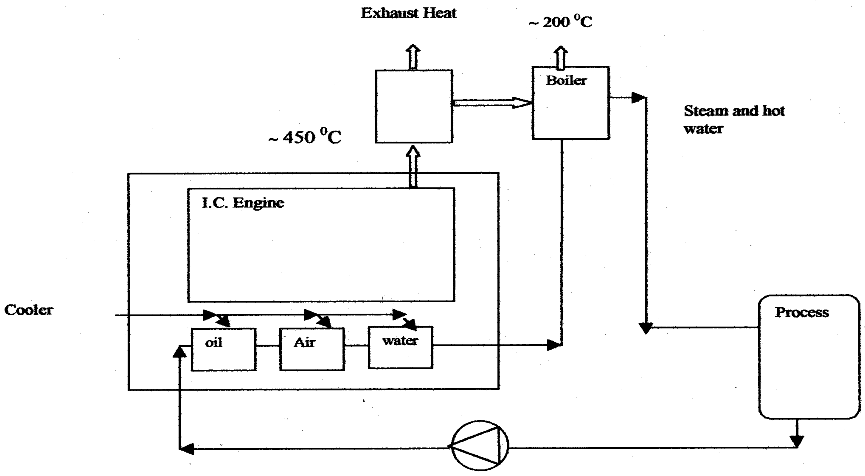

Fig. 5 Schematic diagram of reciprocating engine cogeneration

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In urban areas where natural gas distribution network is in place, gas engines are finding wider application due to the ease of fuel handling and cleaner emissions from the engine exhaust. These machines are ideal for intermittent operation and their performance is not as sensitive to the changes in ambient temperatures as the gas turbines. Though the initial investment on these machines is low, their operating and maintenance costs are high due to high wear and tear. To improve appreciably the diesel engine performance Diesel engine waste was found, and utilization of waste heat recovery, both transport and stationary diesel engines were examined [53].

2. Rankine cycle:

Power generation is one of the major areas of utility for waste heat recovery [54-59]. To produce electricity or shaft power Rankine cycle can be employed efficiently at low temperatures, with suitable working fluids [12]. The overall efficiency of a low-grade energy Rankine cycle using R113 and R114 has studied by several researchers [60, 61]. Thermodynamic properties and Rankine cycle performance for several working fluids are studied by Devotta and Holland [61]. The performance of the cycle as a function of pressure ratio, the difference between boiler and condenser temperatures and the boiler temperatures are considered in his paper. The basic computer program for selecting the suitable fluid for Rankine cycle, based on the given waste heat data is developed by Badr et al. [62]. For selecting a steam turbine unit utilizing waste heat presented a graphical method by Johnson [63]. The waste heat steam boiler efficiency can be found, and approximate steam-turbine efficiency can be calculated through graphical method. Zubair and Habib [64] performed second law based thermodynamic analysis of the regenerative-reheat Rankine cycle power plants. They have taken thermodynamic parameters from the Ghazlan Power Plant in Saudi Arabia [65]. Kotas [66] explained in this work the concept of exergy used to define criteria of performance of thermal plant.

3. Heat pumps:

The heat pump receives low-grade energy in the evaporator, take mechanical work via a compressor, and heat is then rejected for use in condenser. It is another device for utilization of waste heat as shown in Figure - 6. Thus the heat pump up-grades the heat at its evaporator to a relatively higher-grade useful heat. It is characterized by a high COP (Coefficient of Performance), which is defined as:

$$\mathrm{COP} = \frac{\text{useful heat at the condenser}}{\text{work done on the compressor}}$$

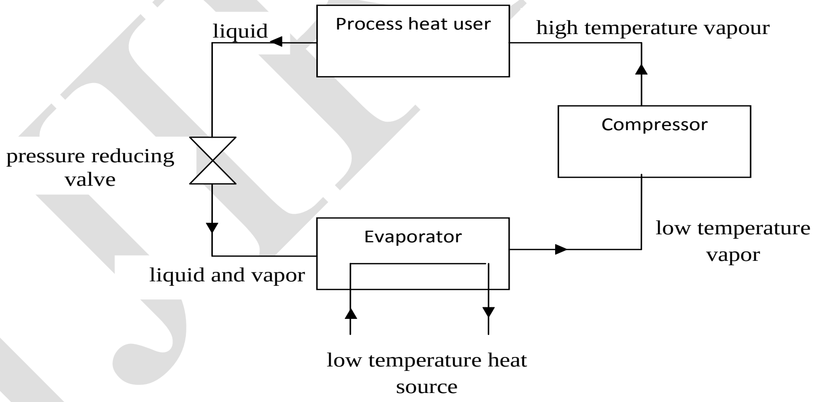

Fig. 6 Heat Pump

The applications of heat pumps for waste heat recovery have investigated by Steimle [67]. Fundamentals of heat pump design and applications are presented by Reay and Machichael [68,]. The applications of heat pumps in distillation columns are discussed by Mergens [69]. He concluded that the installation of a heat pump can reduce the amount of energy required to boil liquids by 15 to 30%. Steward [70] was made the thermodynamic optimization of heat pumps for particular situations and give Expressions for the coefficient of performance of systems of heat pumps operating in series between fluid streams. Selecting the appropriate heat pumps for analyzing data were developed [71, 72] through computer programs. The possibility of cascading heat pumps was investigated by Gupta [73]. Applications of heat

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pumps in industry [74-76], with special reference to distillation [77], as well as in residential applications [77-79] were reported. Kolin'ko [78] was studied the effective use of secondary energy sources via heat pump plants. Investigation of solar-assisted heat pumps is another and older sector employing heat pumps for both heating and cooling. In the area of solar-assisted heat pumps are useful and helpful for waste heat recovery and utilization studied in many researches. Tleimat and Kugle [79, 80] were concluded that low-grade energy collected by a fiat-plate collector can be up-graded using heat pumps in his paper.

3.1 Absorption heat-pumps:

For the cooling purposes absorption cycle may be employed, in this case a heat source may be substituted for shaft work. To produce nearly pure refrigerant that flows into the condenser the waste heat is used in the generator. This refrigerant produces the cooling effect in the evaporator after expansion. A flow diagram for the lithium bromide-water absorption cycle [81] as shown in Figure - 7. Since cooling is the objective here, the COP is defined as:

$$\text{COPref} = \frac{\text{cooling effect in the evaporator}}{\text{heat added at the generator}}$$

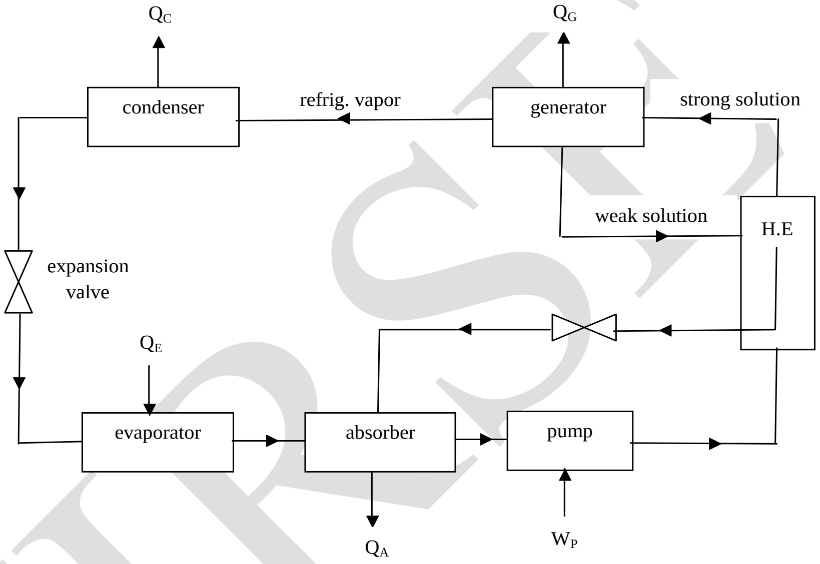

Fig. 7 Simple absorption refrigeration systems

The absorption heat pump is identical to the absorption refrigeration cycle, but here the objective is to extract thermal energy from the condenser, and the absorber [82-90]. The total heat output is approximately 1.5 times the heat supplied. Heppenstall [82] presented the operation principles, performance, advantages, and practical difficulties of the absorption heat pump. To utilize the output heat is the objective of the heat pump; the COP is now defined as:

$$\text{COPab} = \frac{\text{heat rejected by the condenser and absorber}}{\text{heat supplied to the generator}}$$

For use in absorption heat pumps different fluid mixtures were suggested and studied. Tyagi [83], Kaushik et al. [84-85], and Chaudhari et al. [86, 87] has investigated the performance of absorption heat pumps using ammonium-salts, water-lithium bromide, and water--calcium chloride mixtures. Chaudhari et al. [88] has also studied a simulation model of an advanced absorption heat pump for solar heating. He has also listed and classified the references in the field of absorption heat pumps [89]. The performance of a single stage lithium bromide-water absorption heat pump, and studied the importance of the effectiveness of the solution heat exchanger and circulation ratio on cycle performance analyzed by Jeng et al. [89]. Herold and Radermacher [90] were presented thermodynamic differences between vapour compression and absorption heat pumps.

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4. Trigeneration (CCHP):

A typical CCHP system is shown in Figure - 8. It is comprised of a gas turbine, generator, heat recovery steam generator (HRSG), and an absorption chiller. The gas turbine is driven by natural gas and the mechanical work is further converted into electric power by the generator. At the same time, the absorption chiller, which is driven by the recovered heat from HRSG in the form of steam or hot water, generates cooling power in summer and heat in winter. A slight difference between CCHP and CHP is that thermal or electrical/mechanical energy is further utilized to provide space or process cooling capacity in a CCHP application.

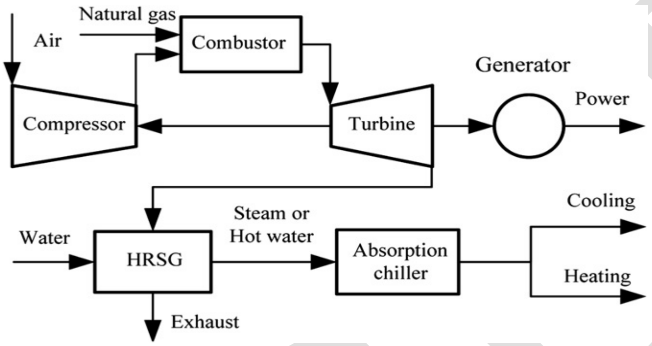

Fig. 8 Schematic diagram of a typical CCHP system.

In some literature, CCHP systems are also referred to as trigeneration and building cooling heating and power (BCHP) systems [91-93]. While CHP profits from more than 100 years of experience and is a well established technology, the development of CCHP is quite slow and mostly limited to combine absorption chillier with large-scale power generation systems until the mid 1980s. The fast development of thermally activated cooling technologies together with reduction of their market price, and the commercial success of distributed energy resources (below 1 MW) technologies in the last two decades, have contributed to strengthen and spread the on-site application of CCHP technology. CCHP is a promising technology that is becoming economically feasible for the local production of cooling, heating and power [94-97]. Khaliq [98] was proposed conceptual trigeneration system based on the conventional gas turbine cycle for the high temperature heat addition while adopting the heat recovery steam generator for process heat and vapour absorption refrigeration for the cold production.

IV. CONCLUSION

The above review that considerable potential exists for recovering some of the wasted energy in industrial processes, and of using it to improve plant performance. Research and development efforts seem to be focused especially on heat exchangers that utilize heat pipes, Rankine cycle and heat pumps.

The use of Rankine cycles with low-grade thermal sources offers significant potential for energy productivity. The new perspective on Rankine cycles is that they are viable technology for our energy future. They can technically and economically provide useful energy from currently wasted thermal streams and from renewable sources. Heat pump technologies are widely used for upgrading ambient heat from sustainable sources, such as air, water, the ground and waste heat, to heating temperatures. They can be used for residential and commercial space heating, cooling and water heating, refrigeration and in many industrial processes.

Now a day cogeneration getting popularity due to rapidly increasing demand for electricity, constraints faced by the authorities to finance additional power generating capacities, and the growing concern to limit the environmental emission and pollution associated with the use of energy. Cogeneration is presently being recommended when there is plan for expansion of existing facilities, development of new industrial zones, replacement of outdated steam

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generation systems, or when the cost of energy is high and there is scope for selling power. Beside district heating and air-conditioning, cogeneration has great potential in different industries such as: paper; dairy; brick; refinery operations such as ethylene production and enhanced oil recovery; and chemical complexes including salt refineries, chlorine production, caustic soda plants and natural gas based methanol plants.

Existing and potential technologies of trigeneration are available. These technologies contain both improved conventional approaches, like steam turbines, reciprocating engines, combustion turbines and electric chillers, as well as relatively new technologies such as fuel cells, micro-turbines, Stirling engines, sorption chillers and dehumidifiers. The CCHP world market has grown rapidly in the last decade, despite the fact that development levels differ from country to country. CCHP development in the US and Europe restarted recently, after a short period of slow growth.

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