Theoretical Study on Solar Integrated Waste Heat Recovery Systems for Power Industries

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Abstract - *In recent years, energy and environmental problems are becoming increasingly prominent. Industrialization of any country is necessary for its economy, but it also causes environmental toxicity. Energy Intensive industries like, cement, steel, glass and metal forming etc. are responsible for environment's severe deterioration and high energy prices. Approximately 20-50% of total energy input is dumped into atmosphere from different industrial process. Numerous technologies have been proposed for waste heat recovery like Tri-Generation (combined power, heating and refrigeration effect) system, Organic Rankine cycle (ORC) systems and Co-generation systems. The waste heat recovery from industries and power plants has tremendous potential of re-powering the plant. Efficient heat recovery technology can create new market opportunities in the field of energy conservation.*

Key Words: **Solar energy, WHR, ORC, Kalina model, Trigeneration**

1. INTRODUCTION

Nowadays due to 40% predicted increase in energy consumption of the world, more environmental concerns form of global warming, acid rains, air, water and soil pollution, ozone depletion, forest devastation and radioactive substances emissions. Utilizing waste heat attempts to derive energy out of renewable resources as low grade thermal heat sources have motivated the use of advanced energy recovery systems. The present research issue provides the concept and employment of low global warming potential (GWP) and ozone depletion potential (ODP) values type chemicals (refrigerants) based utilities for IWH recovery application. The key benefits of WHR technologies are reduced environment impact, generation of process heating, power and cooling effect with low operating cost and the opportunity of renewable energy systems for heat recovery in energy efficient manner.

A recuperator, recovering waste heat from flue gases, the heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre-heated, the other side contains the waste heat stream. Heat pipe is a thermal energy absorbing and transferring system and have no moving parts and hence require minimum maintenance. Heat pipe can transfer up to 100 times more thermal energy than copper. The heat pipe heat recovery systems are capable of operating at 315oC with 60% to 80% heat recovery capability. Economizer provides to utilize the flue gas heat for pre-heating the boiler feed water in boiler. On the other hand, in an air pre-heater, the waste heat is used to heat combustion air. In both the cases, there is a corresponding reduction in the fuel requirements of the boiler. For every 220 C reduction in flue gas temperature by passing through an economizer or a pre-heater, there is 1% saving of fuel in the boiler. For every 60 C rise in feed water temperature through an economizer or 200C rise in combustion air temperature through an air pre-heater, there is 1% saving of fuel in the boiler unit. Heat Recovery Steam Generator is an energy recovery heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process (cogeneration) or used to drive a steam turbine (combined cycle). HRSG provides the thermodynamic link between the gas turbines and steam turbines in a combined-cycle power plant. All units shown in fig-1, 2, 3, 4.

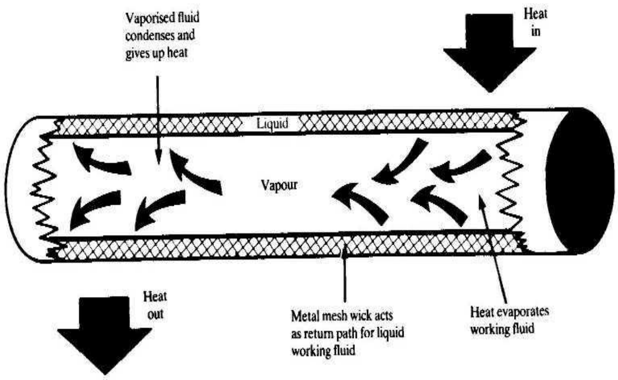

Fig-1: Heat Pipe Exchanger [1]

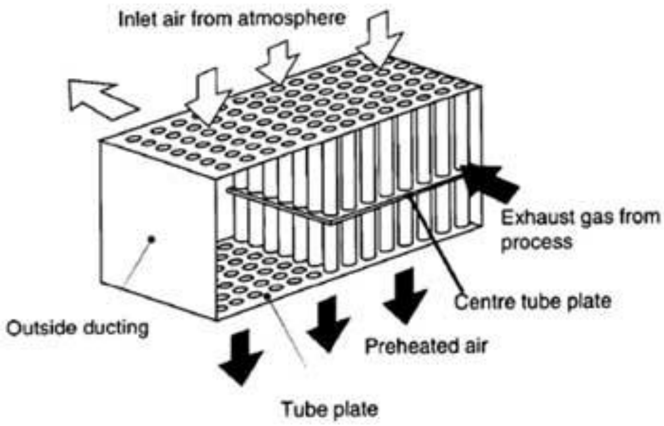

Fig-2: Recuperator [1]

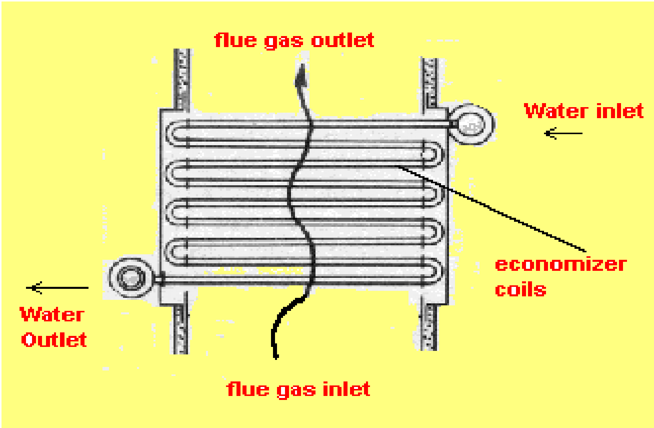

Fig-3: Economizer [1]

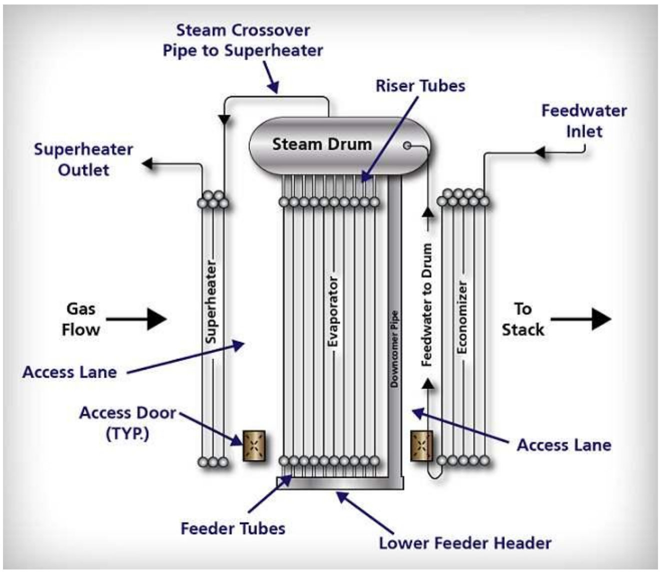

Fig-4: HRSG [2]

2. THERMODYNAMIC CONCEPT OF WASTE HEAT RECOVERY TECHNOLOGY

2.1 Combined and cogeneration system (heating-power generation concept)-

Cogeneration or combined heat and power (CHP) is use to generate electricity and useful heat or process heat at the same time through coupling of two different power cycles like gas turbine and steam turbine systems. In power generation, the production of electricity, some energy must be discarded as waste heat, but in cogeneration this thermal energy is put to use. Bazques and Strom and Maidment and Tozer have reviewed a number of combined energy production plants operating in supermarkets. They analyzed different schemes of combined energy production including different cooling and engine technologies [3, 4]. BEE [1] summarized the popularity of topping and bottoming cycle concept of co-generation system which are suitable for manufacturing processes that require heat at high temperature in furnaces and kilns, and reject heat at significantly high temperatures. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries. Bottoming cycle plants are much less common than topping cycle plants. The waste gases coming out of the furnace is utilized in a boiler to generate steam, which drives the turbine to produce electricity [1, 5].

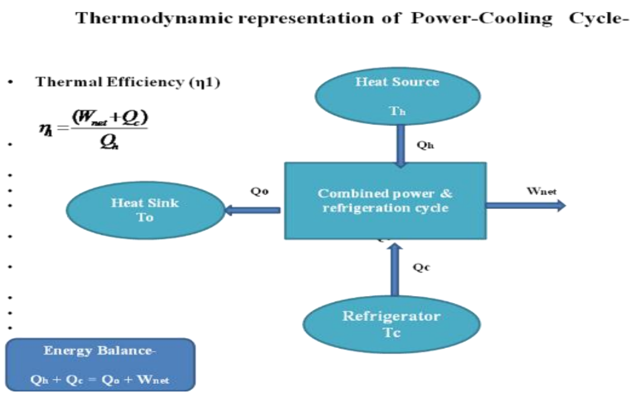

Fig-5: Thermodynamic concept of power-cooling system

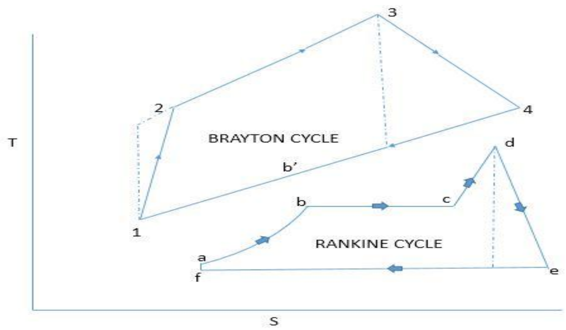

Fig-6: Combined Power Cycle [5]

2.2 Trigeneration system

Tri-generation technology provide simultaneously three forms of output energy; electrical power, heating and cooling. Trigeneration is also known as CCHP (Combined Cooling, Heating and Power) or CHRP (Combined Heating, Refrigeration and Power). In essence, trigeneration systems are CHP (Combined Heat and Power) or co-generation systems, integrated with a thermally driven refrigeration system to provide cooling as well as electrical power and heating. Trigeneration systems can have overall efficiencies as high as 90% compared to 33%-35% for electricity generated in central power plants. [1, 6].

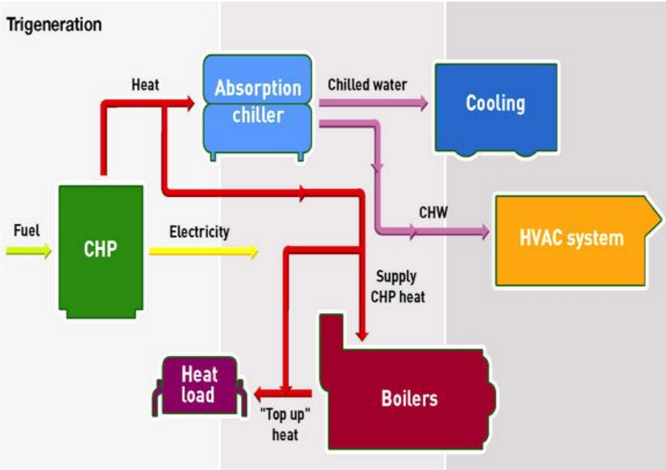

Fig-7: Trigneration System layout [1]

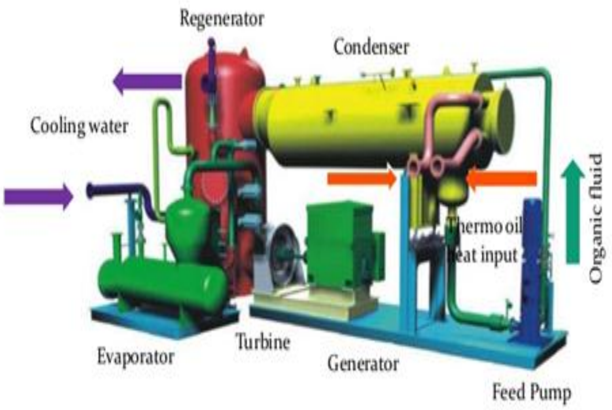

Fig-8: ORC components [7]

2.3 Organic rankine cycle (ORC)

Chen and Goswami [7] reviewed the different thermodynamic systems for utilization of discard heat, like Organic Rankine Cycle (ORC).The ORC applies the principle of the steam Rankine cycle, but uses organic working fluid with low boiling points, instead of steam, to recover heat from a lower temperature source. The cycle consists of an expansion turbine, condenser, a pump, a boiler and a superheated (provide superheat is needed).Different form of combined with ORC as a bottoming cycle, ORC with different pure working fluids such as HCFC123 (CHCl2CF3), PF5050 (CF3(CF2)3CF3), HFC-245fa (CH3CH2CHF2), HFC-245ca (CF3CHFCH2F), isobutene ((CH3)2C=CH2), n-pentane and aromatic hydrocarbons, have been studied for organic Rankine cycles for power plants, cement industry, desalination, process industry, and manufacturing industry. Working fluid classified as a Dry fluid, wet fluid or isentropic fluid. Isentropic or dry fluid was suggested for ORC to avoid liquid droplet impingement in turbine blade during the expansion. If the fluid is too dry the expanded vapor will leave the turbine with substantial superheat, which is a waste and add to the cooling load in. The cycle efficiency can be increased using this superheat to preheat the liquid after it leaves the feed pump and before it enters the boilers [7, 8-11].

2.4 Binary fluid power system (Kalina model)

Aleksander Kalina developed binary fluid based power and cooling system in between 1970 and 1980.Kalina cycles system (KCS) uses ammonia-water (Binary fluid) mixture based working fluid used as source for power and cooling. In this cycle ammonia is the refrigerant and water as is the absorbent due to the high difference in their boiling point and high enthalpy. In the Kalina cycle, the used binary fluid mixture results in a good thermal match in the boiler due to the non-isothermal boiling created by the shifting mixture composition. Several studies have shown that the kalina cycle performs substantially better than a steam Rankine cycle system. A second law analysis showed that by using a binary fluid, the Kalina cycle reduced irreversibility in the boiler, resulting in improved efficiency of the cycle. One drawback of the Kalina cycle is the fact that high vapor fraction is needed in the boiler, however, the heat exchanger surface is easy to dry out at high vapor fraction as, resulting in lower overall heat transfer coefficients and a larger heat exchange area. Another drawback relates to the corrosivity of ammonia. Impurities in liquid ammonia such as air or carbon dioxide can cause stress corrosion cracking of mild steel and also ammonia is highly corrosive towards copper and zinc [5, 12]. Goswami proposed in 1998 [7] a novel thermodynamic cycle that uses binary mixture to produce power and refrigeration simultaneously in one loop. This cycle, Fig-9a is a combination of Rankine power and absorption cooling cycle. The binary mixture first used was ammonia-water and later on new binary fluids were proposed and studied.

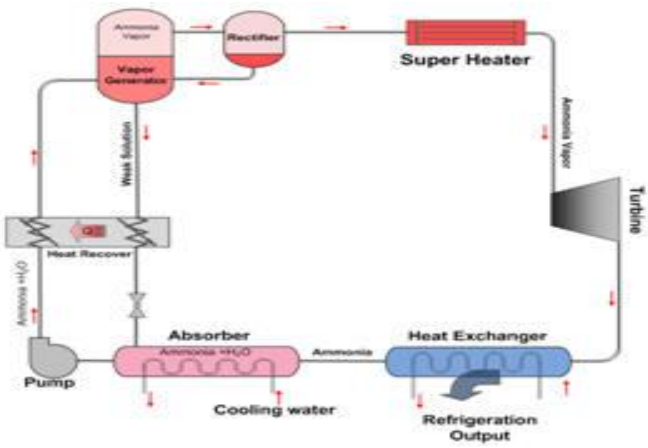

Fig-9a: Goswami Cycle [7].

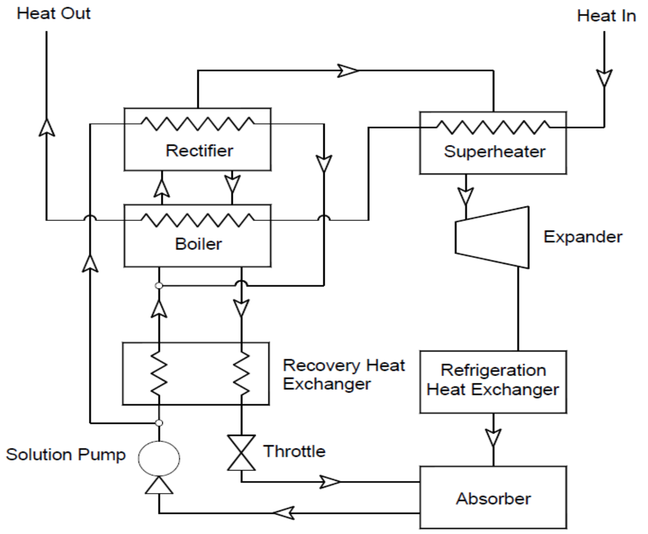

Fig-9b: Schematic of the power-cooling cycle [5]

3. TECHNOLOGICAL OVERVIEW ON WHR SYSTEMS

Present Literature review focus on low grade energy recovery systems, working fluid and their selection criteria with fluid properties and technological development. The working fluid is one of the most important components of a Rankine cycle power system. Intense research of non-geothermal ORC use took place in this country during the early 1970's through the early 1980's. ORC heat engines were reconsidered for utilizing solar resources and conserving other resources by recovering energy from waste heat. In one an ORC was integrated with a large truck engine to recover heat from the exhaust and save on fuel costs with the idea of replacing the automobile internal combustion engine with an ORC system was explored [13, 14]. Mechanical cooling systems were one of the more productive research areas that dealt with the conversion of solar thermal energy. A significant amount of the published literature regarding ORC conversion of solar thermal energy comes from this and related work [15]. The concept started as an alternative to solar-driven, absorption, air conditioning cycles which have a limited coefficient of performance. Essentially, mechanical work produced by a solar-driven ORC would be used to drive vapor compression air conditioning equipment, with the potential of a higher COP than absorption equipment [15-17].More recent research in the area has largely taken place internationally [18-21]. Two approaches have been noted: one is to develop and design systems around high-speed turbo-machinery with a shaft integral generator and circulation pump , thus reducing costs by simpler design, and the other, more recent idea is to adapt mass-produced (cheap) displacement compressors for use as reasonably efficient expanders [21-24]. The lineage that the power cooling cycle is derived from initially intended for utility-scale bottoming cycle duty. The first study of an absorption based power cycle was performed by Maloney and Robertson who concluded no significant advantage to the configuration. Several decades later, Kalina reintroduced the idea of an ammonia-water power cycle as a superior bottoming cycle option over steam Rankine cycles [25-28].The ammonia-water based power cycles have been proposed for solar utilization, geothermal, ocean thermal energy conversion, and other forms of heat recovery. While it was the interest brought about by Kalina's proposal that led to the introduction of the power-cooling cycle, it is somewhat ironic that the original suggestion for its implementation is more similar to the original Maloney-Robertson implementation [7, 8].Referring to Fig-9a & 9b of power-cooling cycle, basic solution fluid is drawn from the absorber and pumped to high pressure via the solution pump. Before entering the boiler, the basic solution recovers heat from the returning weak solution in the recovery heat exchanger. In the boiler, the basic solution is partially boiled to produce a two-phase mixture; a liquid, which is relatively weak in ammonia, and a vapor with a high concentration of ammonia. This two-phase mixture is separated and the weak liquid is throttled back to the absorber. The vapor's ammonia concentration is increased by cooling and condensate separation in the rectifier. Heat can be added in the superheater as the vapor proceeds to the expander, where energy is extracted from the high-pressure vapor as it is throttled to the system low-pressure. The vapor rejoins the weak liquid in the absorber where, with heat rejection, the basic solution is regenerated. [29-31]. Later studies concluded that the cycle could be optimized for work or cooling outputs and even for efficiency. Optimization studies began to appear, optimizing on the basis of various efficiency definitions, minimum cooling temperature, working fluid combination, and system configuration. Also, an experimental study was described by Tamm and Goswami [10] which generally verified the expected boiling and absorption processes. Goswami and Xu [30] presented the first theoretical analysis of the power-cooling cycle. Turbine inlet temperatures of 400 – 500 K were considered along with absorption temperatures of 280 – 320 K. Cooling production suffered with increased turbine inlet and absorption temperatures, and benefited with increased boiler pressure. Many of the operating trends of importance in this work were introduced here. Optimization studies began to appear following this work, which identified the balance of effects that dictate cycle operation. Lu and Goswami [8] optimized the ideal cycle conditions using various objectives, work output, cooling output, first and second law efficiencies. All operating parameters, efficiencies, power/cooling output, etc., were found to decrease with increasing heat rejection temperatures. At high heat source temperatures, 440 K, no cooling was possible at conditions optimized for second law efficiency. A contrast between work optimized and cooling optimized cases was provided. Important differences in the cooling optimized case versus the work optimized one were higher vapor concentration, lower turbine inlet temperature, low vaporization fraction (16.5 % vs. 91.2 %), and a lower basic solution concentration. Minimum cooling temperatures were also optimized, and a minimum turbine exhaust temperature of 205 K was identified under the assumptions considered [32]. The appropriate efficiency expressions for the cycle was tackled by Vijayaraghavan and Goswami [33]. Vijayaraghavan, et al introduced a satisfactory second law efficiency definition based upon ideal Lorenz cycle performance which accounts for sensible heat addition and rejection behavior. However, they concede that ultimately the value of work and cooling will be decided by the end application .Both first and second law efficiency analyses were performed for the cycle. A second law efficiency of 65.8 % was determined [33-35].

4. CONCLUSIONS

- All power and heavy process industries emit heat during generation or industrial process which can be released into the environment through cooling towers, flue gas, or by other means. By-product heat at moderate temperatures (100–180 °C, 212–356 °F) can also be used in absorption refrigerators for cooling.
- The organic Rankine cycle applications in waste heat recovery. Working fluid properties and selection (including pure fluids and mixtures) was reviewed. Also some important physical properties of the working fluids for ORC and the performance of the system were introduced. Different applications of ORC systems including solar thermal, biomass ORC, solar thermal reverse osmosis desalination, geothermal application, and waste heat recover from industrial process were intensively investigated.
- The paper also concludes the solar thermal energy application for waste heat recovery with the cooling generation effect like vapor absorption and adsorption refrigeration systems. These systems mostly applicable for space cooling purpose.
- There are lot of organic chemicals and refrigerants available in literature for power and cooling application in heat/energy recovery system. Most applicable 134a used in present technologies for energy recovery systems.R-1234ze and R-1234yf are Low global warming fluids available to replace R-134a in WHR technologies.
- Increased reliability and security of energy supply. Lower energy cost: the 75 % saving of operation cost compared to conventional unit and higher overall efficiency: 24 % higher than conventional unit. Fuel energy losses reduced to approximately 4 % as against around 28 % in case of conventional system.
- The waste heat recovery from industries and power plant have huge potential for re-powering of plant and new market scope for employment of efficient heat recovery technology in respect of energy conservation and environment aspect.

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BIOGRAPHY

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