Review on Waste Heat Recovery from Flue Gas and Its Application in CO$_2$ Capture

Y Nandakishora$^1$, R K Sahoo$^2$ and S Murugan$^3$

$^1,^2,^3$ Department of Mechanical Engineering, National Institute of Technology Rourkela, Odisha, India

E-mail: nandakishora1992@gmail.com

Abstract. CO$_2$ capture and storage (CCS) is a promising technology to mitigate CO$_2$ emission from fossil-fuelled power plants. The three existing CO$_2$ capturing technologies popularly used in the fossil-fuelled thermal plants are pre-combustion, oxy-fuel combustion, and post-combustion. Absorption, adsorption, membranes, chemical looping, and cryogenic are the prominent methods used in post-combustion technique. The cost reduction and energy savings are the two important challenges in CCS. Secondary power generation by using an organic Rankine cycle (ORC) from waste heat available from flue gas and CO$_2$ capturing units is an attractive option. A comprehensive review of research works carried out pertaining to the integration of ORC in power plants in the recent past is presented in this paper.

Abbreviation

| Abbreviation | Description |
|--------------|-------------|
| APC          | absorption power cycle |
| ASU          | air separation unit |
| CCS          | carbon capture and storage |
| CO$_2$       | carbon dioxide |
| CTM          | coal-to-methanol |
| EES          | engineering equation solver |
| IGCC         | integrated gasification combined cycle |
| MEA          | monoethanolamine |
| NGCC         | natural gas combined cycle |
| ORC          | organic Rankine cycle |
| TMC          | transport membrane condenser |
| WHR ORC      | waste heat recovery organic Rankine cycle |
| WHWRS        | waste heat and water recovery system |

Nomenclature

| Symbol | Description |
|--------|-------------|
| $h$    | specific enthalpy kJ/kg |
| $m$    | mass flow rate kg/s |
| $Q$    | heat flow W |
| $W$    | power kW |
| $\eta_t$ | thermal efficiency |
1. Introduction

Carbon dioxide (CO₂) emission has been continuously increasing in the last few decades leading to a concentration in the atmosphere of over 400 ppm. The reduction of CO₂ emission from the thermal power plants run on fossil fuels is necessary to fulfill the national and international regulations [1]. Carbon Capture and Storage (CCS) is one of the promising methods to reduce CO₂ emission from thermal power plants [1]. Pre combustion, oxy-fuel combustion, and post-combustion are three existing CO₂ capture strategies are used in thermal power plants. The existing CO₂ capture technologies are absorption, adsorption, membranes, chemical looping, and cryogenic, etc. [2]. CO₂ capture is an additional burden to the thermal power plants due to additional capital cost and energy penalties [3-6]. Among the different post-combustion technologies, monoethanolamine (MEA) is the most proven technology. In this process, CO₂ is absorbed from flue gases using chemical solvents. This technology consumes more energy and water [7-10].

Integration of Organic Rankine Cycle (ORC) is one of the methods to increase plant efficiency by producing additional electrical energy from available waste heat in the power plants, and CO₂ capturing units [1, 11, 12]. In a 600MW power plant, the flue gas temperature at the exit was found to be around 150°C [12, 14]. Several methods are available to recover heat or recover water from the exhaust gas, such as absorption systems, waste heat boilers and heat exchangers, and ORC [15]. Fossil-fuelled power plants suffer from a significant water consumption. The waste heat recovery from the exhaust flue gas of coal-fired power plants leads to its condensation and gives a solution to the above-mentioned problem [12]. If the waste heat recovery organic cycle (WHR ORC) system is installed to 600MW coal power plant with a flue gas temperature of 150°C, it can produce about 6.7MW power by recovering 50% of the water from flue gas by cooling the flue gas to 40°C at the evaporation temperature of 30°C for R134a [14].

2. Organic Rankine cycle

ORC is a power-producing cycle used for extracting work from a low-temperature waste heat source by using a low boiling point of organic working fluid [16]. In an ORC system, a high molecular mass organic fluid is used as a working fluid with a lower boiling point than the water [26]. The ORC energy systems have been widely used to convert thermal energy available in solar, waste heat, geothermal, biomass, and ocean thermal to electrical energy [16, 11].

Figure 1 shows the different stages, such as the preheating stages, the evaporation stages, and the superheating stages of the ORC evaporator. The condensation stages of organic fluid is also similar, but the heat source is replaced by the cooling water. A counter-flow heat exchanger is used to transfer heat from a heat source to organic fluid. The T₃ and T₅ are the temperatures of the heat source at the inlet and outlet, respectively; T₁ and T₄ are the temperatures of the organic fluid at the inlet and outlet, respectively [16].
Figure 1. Different heat transfer stages in ORC evaporator [16]

Figure 2 shows the location of a waste heat recovery heat exchanger in the flue gas line. The counter flow and inline tubes are used to reduce the pressure drop in the flue gas line. The sub-cooled working fluid is converted into high-temperature vapor while passing through the heat exchanger by utilizing heat from flue gas [11].

Figure 2. Schematic diagram of the location of waste heat recovery heat exchanger in the flue gas line [11]
Figure 3 shows the schematic diagram of the ORC configuration, and Figure 4 shows the T-s diagram of ORC [17]. The ORC system consists of four key components: an evaporator, an expander, a condenser, and a pump. The four thermodynamic processes of ORC are: isentropic expansion (1-2), isobaric cooling (2-5), isentropic compression (5-6), and isobaric heating (6-1). At point 1, the organic working fluid is at high temperature and high pressure. At this condition, fluid enters the expander and transfers energy by an isentropic expansion of the working fluid. The expanded working fluid enters the condenser, in which the working fluid is cooled at a constant pressure to a liquid state. The liquid working fluid is drawn from the condenser and compressed to high pressure in the pump, and sent to the evaporator. In the evaporator, high-pressure liquid working fluid is converted into vapor of high temperature at constant pressure by utilizing heat from the waste source. Finally, the evaporator's steam is fed back to the expander, and the cycle is repeated. In actual cases, the expansion and compression do not follow the isentropic process [17].

![Figure 3. Schematic diagram of the ORC configuration [17]](image)

The selection of an appropriate organic working fluid mainly depends on the temperature of the waste heat source. It also depends on the specific application. Some potential ORC working fluid: N-Butane, R236ea, R245fa, R134a, R1234ze, R123, and R1233zd [1, 11]. Out of R236ea, R245fa, R134a, R1234ze, R123, and R1233zd are non-flammable and environmentally friendly working fluids [11].
Table 1 gives the comparison of different ORCs used for waste heat recovery from a 1000 MW boiler [11].

| Working fluid | P_{T,in}/MPa | T_{T,in}/°C | Power out/kW | Thermal efficiency/% |
|---------------|--------------|-------------|--------------|----------------------|
| R1234ze       | 2.74         | 125         | 3570.6       | 12.85                |
| R236ea        | 2.09         | 113.67      | 3783.0       | 13.61                |
| R245fa        | 1.63         | 111.84      | 3845.9       | 13.84                |
| R1233zd(E)    | 1.31         | 110.69      | 3876.9       | 13.95                |
| R123          | 0.97         | 109.60      | 3937.7       | 14.17                |
| R134a         | 3.85         | 125         | 3502.0       | 12.60                |
| R1234ze       | 3.82         | 125         | 3576.5       | 12.87                |
| R236ea        | 1.97         | 125         | 4025.5       | 14.48                |
| R123          | 0.93         | 125         | 4118.6       | 14.82                |
| R1233zd(E)    | 1.25         | 125         | 4074.6       | 14.66                |
| R134a         | 4.26         | 125         | 3484.8       | 12.54                |
| R245fa        | 1.55         | 125         | 4070.6       | 14.65                |

Nemade and Ponsankar [30] performed a simulation study of the ORC system coupled with the thermal power plant flue gas. The efficiency and effect of pump pressure on the ORC plants were assessed with the help of the ASPEN V9 simulator. In this study, the pump pressure was changed from 5 bar to 20 bar, and power output was analyzed. The study revealed that the maximum power output was observed at 20 bar pressure [30]. Zhou et al. [31] conducted an experimental study to find the cycle efficiency of the ORC system. From the experimental result, it revealed that the energetic efficiency, cycle efficiency, and power output depended on evaporating pressure and heat source temperature. The cycle efficiency
of the ORC system was inversely proportional to the superheat degree of the working fluid. The maximum efficiency of the ORC was found to around 8.5% [31]. Li et al. [36] conducted an experimentally economic analysis of the ORC plant (16.3 kW) to extract power from a low waste heat source. The influence of the parameters on economics, such as the installation of components, loan ratio, profit, and interest rate on electricity production costs are analyzed. The results of the study revealed that the lowest electricity production cost was found to be around 0.46 Yuan/(kW • h) [36].

3. Waste heat recovery from CO\(_2\) capture section

Figure 5 shows the relative energy flows of MEA-based CO\(_2\) capture [12]. The extraction of work from the waste heat, which is generated in the CO\(_2\) capture systems, is more useful to increase the plant's efficiency. In this process, a low boiling point fluid is used as a working fluid to drive the low-temperature turbine [12].

Tola and Finkenrath [1] carried out a simulation study using commercial software packages Gate Cycle and HYSYS to know the power plant and CO\(_2\) capture unit's performance. The waste heat sources were available in the natural gas combined cycle with the solvent-based CO\(_2\) capture were CO\(_2\) compressor intercoolers, amine reboiler, condensate cooling, lean solvent coolers, stripper condenser, and exhaust gas cooler. The flue gas was cooled to 30-50 °C before sending it to the absorber in an amine-based CO\(_2\) capturing system, and this was one of the major sources of low heat. This low heat was used to produce power by using ORC, and it increased the efficiency of the total plant. Novotny et al. [18] conducted a study on waste heat recovery from oxy-fuel combustion-CCS, post-combustion-CCS, and IGCC-CCS plants by utilizing ORC and absorption power cycle (APC). The major sources of heat from post-combustion amine bicarbonate CCS plants are de absorber and cooling heat from the compression train. The major sources of heat from oxy-fuel combustion-CCS were waste heat obtained from ASU (Air separation unit) air compressor and compression and conditioning of CO\(_2\). The major sources of heat from IGCC-CCS ASU air compressors, gasifier O\(_2\) and N\(_2\) compressors, coal dryer outlet vapors, syngas cooling, CO\(_2\) compression, and flue gas aftercooler. Compared to all the three cases, the efficiency was found to be maximum (4.2 percentage points) for IGCC-CCS plants with waste heat recovery [18].
Farajollahi and Hossainpour [27] conducted a simulation study on integrated ORC in 350MW capacity thermal power plant with MEA based post-combustion CO₂ capture and compression. The processes were developed by using the Aspen HYSYS software package. In this study, three waste heat sources were considered, which were; flue gas, steam cooler before reboiler, and CO₂ compression intercoolers. The study revealed that the total power plant efficiency reduced from 40.55% to 31.26% after the installation of CO₂ capture and compression. The total power plant efficiency was found to be 33.4% for the best configuration. The ORC system added 17.38 MWe extra power, and it helped to compensate for the loss of energy penalty due to the implementation of CO₂ capture and compression to thermal plants [27]. Liu et al. [29] proposed an ORC system to recover waste heat from the coal-to-methanol (CTM) conversion process with CO₂ pre-combustion capture. The CTM model was developed and investigated with the help of the Aspen Plus simulator. The simulation of the proposed process was done by considering the energy and economic point of view. The major heat source of ORC was hot water from the water gas shift unit and CO₂ compressor intercooler. The study revealed that the ORC, which was invested in the proposed CTM with the CO₂ capture process, would be able to produce around 4.8 MW, and its payback period is around 2.7 years [29].

Romeo et al. [33] conducted a simulation study of the ORC system integrated into the CO₂ capture unit to the energy penalty associated with CO₂ capture. In this study, a theoretical 600 MWₜh plant with an oxy-fuel combustion CCS unit was integrated with a two-stage ORC system that was simulated with the help of engineering equation solver software (EES). The efficiency of the power plant was reduced by 11 points after the addition of Oxy-fuel CCS. The major sources of waste heat in the oxy-fuel combustion CCS plant were CO₂ and ASU compressors. By combining the ORC system the oxy-fuel combustion plant efficiency was found to increase by 2.8%. The efficiency of the CCS also found be higher with the oxy-fuel combustion plant and the ORC system [33]. Patiño et al. [35] conducted a simulation study of natural gas combined cycle (NGCC) power plant integrated with MEA-based post-combustion carbon capture and CO₂ compression. In this study, Aspen plus software and SYNHEAT model were used. Also, a study was done on the heat exchanger network to decrease the energy impact of the post-combustion carbon capture process. The ORC system was thermally coupled with a 453 MWₑ, NGCC-CCS to reduce the energy penalty associated with CO₂ capture. The study result revealed that around 1.651 MWₑ additional power was generated by ORC [35]. Table 2 shows the summary of waste heat recovered from the CCS unit.

Table 2. Summary of waste heat recovery from CCS unit

| Authors and year | Objective / Nature of work | Key point | Reference |
|------------------|-----------------------------|-----------|-----------|
| Henderson (2015) | Study of different power plant with CO₂ capture heat integration | - The primary waste heat sources from supercritical plants are (i) CO₂ inter cooling, (ii) CO₂ cooling, (iii) direct contact cooling water, (iv) lean solvent, (v) flue gas, (vi) stripper overhead condenser | [12] |
| Tola and Finkenrath (2015) | Performance study of an ORC which was used for recovery of waste heat from CO₂ capture unit | - The flue gas was cooled to 30-50°C before sending it to the absorber; this is a major source of low heat. - The efficiency of NGCC CCS power plant with ORC shows around 2.5 % higher than NGCC plant | [1] |
Farajollahi and Hossainpour (2017) Application of ORC in post-combustion CO2 capture unit
- The ORC system produces around 17.38 MWe additional power by utilizing waste heat from flue gas, CO2 compression intercoolers, and steam cooler before reboiler [27]

Novotny et al. (2017) Utilization of waste from CCS plants to reduce its energy penalty
- A comparative study was done on waste heat recovery from oxy-fuel combustion-CCS, post-combustion-CCS, and IGCC-CCS plants by utilizing ORC and absorption power cycle (APC).
- The maximum efficiency (4.2 percentage points) found for IGCC-CCS plants with waste heat recovery [18]

Liu et al. (2011) Application of an ORC in coal to methanol production plant with CCS
- The major heat source considered was CO2 compressor intercooler and hot water from the water gas shift unit
- The power produced by using waste heat from coal-to-methanol with the CO2 capture process was found to be around 4.8 MW
- The payback period was of ORC waste heat recovery unit was found to be around 2.7 years [2]

Romeo et al. (2016) Application of an ORC in CCS to reduce its energy penalty
- The energy penalty of a theoretical 600 MWth plant with an oxy-fuel combustion CCS unit with an ORC waste heat recovery system was increased by 2.8% [33]

Patiño et al. (2017) Thermal integration of an ORC in NGCC plant with a post-combustion carbon capture unit
- The additional energy generated in the NGCC-CCS power plant (453 MWe) with an ORC waste heat recovery was found to be around 1.651 MWe [35]

4. Water recovering from power plant flue gas
Fossil fuel-based power plants consume more amount of water. Therefore, the power plants can cause an environmental impact, and their locations are minimal by water availability. Water recovery from flue gas in the power plants could contribute to reduces water requirements [14]. A 600 MW, coal-fuelled power plant releases 45 ton/min of flue gas, including 7.2 ton/min of moisture [14]. Separating water from flue gas other constitutes like O2, CO2, N2, and SO2 is usually done by lowering the gas mixer up to the water vapor's dew point in the flue gas [19]. The power plant (600 MW) flue gas contains around 16% vol of the water vapor at the exit. The energy and water have simultaneously been recovered by adding a waste heat and water recovery system (WHWRS) to a power plant. WHWRS can able to produce energy of about 4-6 MW e by recovering 50% water [12].

Figure 6 shows a schematic of the waste heat and water recovery system implemented to recover waste heat and water from the low-temperature power plant flue gas. This system consisted of two sequencing
processes: (i) power generation unit and (ii) water recovery unit. Initially, the flue gas is cooled by utilizing waste heat to produce power and further cooled till dew point to recover water by using low-temperature evaporators [12].

Figure 6. Schematic of waste heat recovery united with water recovery system [12]

Figure 7. Schematic of bare tube heat exchanger testing rig [20]
Jeong et al. [20] conducted an experimental and analytical study of water condensation in a condensing heat exchanger, the test rig shown in Figure 7. The flue gas was passed through a series of water-cooled heat exchangers to cool up to the dew point of moisture. The temperature of flue gas and cooling water at inlet and outlet were found to be 149.5 °C to 32 °C and 31 °C to 51.8 °C, respectively. The experimentation was conducted by varying the mass flow rate of flue gas and cooling water. This study revealed that the condensation efficiency of the predicted analytical model matches with experimental results [20].

![Figure 8. Image of a membrane condenser [15]](image)

Figure 8 shows the working principle of membrane condenser which is used to recover waste heat and water from the thermal power plant flue gas [15]. Zhao et al. [15] conducted an experimental investigation on simultaneous recovering of waste heat and water condensation from flue gas with the aid of a tubular ceramic membrane condenser. It also studied the effect of operational factors such as flow rates of fluids, temperatures of fluids, and humidity of flue gas on the performance of membrane condensation. The study revealed that when the mass flow rate of flue gas was increased, the performance of the membrane was reduced due to the reduced residence time [15].

Soleimanikutanaei et al. [21] conducted numerical modeling of transport membrane condenser (TMC), used to recover waste heat and water. The membrane was made up of nano-scale porous ceramic tubes, and it recovered both heat and water. Modeling and simulation were done with the help of computational fluid dynamics by considering a mixed model. The study was conducted to the effect of parameters such as recovery efficiency, pitches of TMC, the flow rate of fluids, and humidity of flue gas on recovering waste heat and water. The numerical results obtained from this study revealed that the mixed model’s accuracy was improved [21]. Cheng et al. [22] also conducted an experimental study of recovering water from flue gas which was obtained from a coal-fired power plant with the aid of TMC. This study revealed that the maximum total heat transfer coefficient and maximum water flux could reach 1068.2 W/(m²*K) and 22.23 kg/(m²*h) [22]. Table 3. Summary of waste heat and water recovery from the thermal power plant.
Table 3. Summary of waste heat and water recovery from the thermal power plant

| Authors and year | Objective / Nature of work | Key point | Reference |
|------------------|-----------------------------|-----------|-----------|
| Kim et al. (2018) | Simultaneous recovery of waste heat and water from power plant flue gas | • 600MW capacity coal power plant releases 45 ton/min of flue gas, including 7.2 ton/min of moisture  
• The WHR ORC system can produce around 6.7MW of additional power, and it recovers 50% of the water in flue gas by cooling the flue gas to 40℃ | [14] |
| Shamsi et al. (2019) | The optimization of WHWRS for flue gas | • WHWRS can produce about 4-6 MWe by recovering 50% water by cooling the flue gas to 40 °C | [13] |
| Zhao et al. (2017) | Application of membrane condenser to the recovery of waste heat and water from flue gas | • The study revealed that when the mass flow rate of flue gas was increased, the performance of the membrane was reduced due to the reduced residence time | [15] |
| Soleimanikutanaei et al. (2019) | Analysis of TMC to the recovery of waste heat and water from flue gas | • The membrane was made up of nano-scale porous ceramic tubes, and it recovered both heat and water. | [21] |
| Cheng et al. (2020) | Experimental study of TMC, which was used to recovery of waste heat and water from flue gas | • The heat recovery efficiency of a membrane heat exchanger was found to be higher than that of conventional heat exchangers | [22] |

5. Thermodynamic model of the organic Rankine cycle system
The thermodynamic model of each component of the ORC system is given below [23-25]:

The following equations held to calculate the heat gain by working fluid in the evaporator

\[ Q_{in} = h_1 - h_6 \] (1)

Work produced in the expander:

\[ W_T = h_1 - h_{2s} \] (2)

Work required to operate pump:

\[ W_p = h_6 - h_5 \] (3)

Heat rejected to the in condenser:

\[ Q_{con} = h_2 - h_5 \] (4)

Net work produced:

\[ W_{net} = W_T - W_p \] (5)

Thermal efficiency of the cycle

\[ \eta_{th} = \frac{W_{net}}{Q_{in}} \] (6)

Exergy flow rates are calculated at all k component and each j states, expressed as [28,32,34]
\[ \Psi_{kj} = \dot{m}[h_{kj} - h_0 - T_0(s_{kj} - s_0)] \]  
(7)

Where subscript “0” referred to the dead state, taken at \( T_0 = 20 \) °C and \( P_0 = 101 \) kPa. 

The rate of exergy destruction rate \( \dot{I}_a \) was calculated for each k component [28]

\[ \dot{I}_k = \Psi_{kj} - \Psi_{ke} - \dot{W}_k \]  
(8)

The second law efficiency for a cycle can be calculated [28] as:

\[ \eta_{II} = 1 - \frac{\dot{I}_{tot}}{\Psi_{g}} \]  
(9)

Where \( \dot{I}_{tot} \) is the exergy destruction summed across all k components of the cycle, expressed as:

\[ \dot{I}_{tot} = \sum_{k=1}^{k} \dot{I}_a \]  
(10)

6. Conclusions

Fossil fuelled power plant emits CO\(_2\) into the environment along with other pollutants. The mitigation of CO\(_2\) is more challenge due to additional capital cost and energy utilization. Waste heat recovery from the power plant flue gas and CO\(_2\) capturing units by producing power by using ORC gives benefits. Along with energy production, recovery of water from flue gas may solve the water problem in the power plants. WHWRS can produce about 4-6 MW\(_e\) from flue waste heat which is emitted from a 600 MW power plant by recovering 50% water. The IGCC-CCS plants are found to pose a maximum waste recovery efficiency (4.2 percentage points) compared to oxy-fuel and post-combustion CO\(_2\) capture strategies. From this study, it can be concluded that recovery of waste heat from the power plant flue gas and CCS unit would increase the plant's efficiency. Also, recovery of water from power plant flue substitutes water scarcity in the power plants.

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