A CASE STUDY: THE WASTE HEAT RECOVERY AND UTILIZATION FOR POWER
GENERATION IN A CEMENT PLANT (PHASE-1)

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Abstract: Cement production is one of the most energy intensive industrial processes. A considerable amount of the energy input is lost through different parts of the processing units such as pre-heater stack, rotary kiln shell and clinker cooler stack. The recovery and utilization of waste heat not only conserves fuel, usually fossil fuel, but also reduces the amount of waste heat and greenhouse gases dumped to the environment. Several different medium-temperature waste heat power generation for cement production have been developed in the past years, including the Steam Rankine Cycle, the Organic Rankine Cycle and the Kalina Cycle. The Steam Rankine Cycle approach is the common approach that used in many plants. The Organic Rankine Cycle and the Kalina Cycle are not widely used in commercial applications in cement plant. The aim of this case study was generating power by utilizing waste heat from the dual sources using Steam Rankine Cycle. In the present work a WHRPG system is designed to recover waste heat for power generation purpose in the cement manufacturing process. Waste gas from the pre-heater with amount of 440,673 kg/hr at 335°C temperature and clinker cooler with amount of 298,667 kg/hr at 305°C temperature are exists. Those sources of waste heat have a lot of sensible heat and can be used for steam generation and this superheated steam which is produced in both boilers are used to rotate impulse steam turbine shows that the proposed technology can produce 7.35MW which yields considerable impact on the turnover. The methodology of this WHRPG cycle system using an approximate cement industries data will be presented in the future work.

Keywords: Waste heat, power generation, heat recovery, cement, clinker, kiln.
1. INTRODUCTION

1.1. Background

Cement production is one of the most energy intensive industrial processes. A considerable amount of energy input is lost through different parts of the processing units such as preheater stack, rotary kiln shell and clinker cooler stack. The recovery and utilization of waste heat not only conserves fuel, usually fossil fuel, but also reduces the amount of waste heat and greenhouse gases dumped to the environment. The priority in the cement industry is to minimize the increase in energy expenditure, to be more efficient and good competitor both internally and internationally. Also in current circumstances, both the availability and cost of energy is becoming challenge to local industrial hubs.

In many countries, energy costs represent the largest component of direct production cost for cement. Energy cost represents as much as 40% to 60% of cement direct production cost. Energy cost is incurred due to the need for large quantities of thermal heat for the clinkerization, calcination and drying processes and electrical energy for operation of motors for grinding mills, fans, conveyers and other motor driven equipment. Although the fuel use and energy use will depend on the type of process, equipment, system efficiency and fuel heating value, typical requirements for coal use is in the range of 150-250 kg per metric tons of cement and typical requirements for electrical energy use is in the range of 80-125 kW hr per metric tons of cement.

Cogeneration systems have been successfully operating in cement plants in India, China and South-east Asian countries. WHRPG technology started from the late 1960s in Europe and the United States, it was put into practical utility in the mid-1970s and the application of this technology reached a climax in the early 1980s and has become popular since then. The technology of WHRPG technology is utilizing the low-grade steam (low pressure, low temperature) generated by industrial waste heat temperature between 120°C and 400°C, to push the specially designed low-parameter steam turbine generator unit to generate electricity.

Japan is much more mature in the research and development of this technology. Since the world oil crisis in 1973, the government of Japan has paid closer attention to energy conservation and began to promote the outside pre-clinker kiln (up to 90%) and waste heat power generation. In February, 1981, Japan Sumitomo Cement Company put a set of two
1320 kW heat generators, which were the first sets of heat generating units in Japan, into operation. China has been engaged in waste heat utilization technology for a long time. The first low temperature WHRPG project in China was a 6,480kW waste heat generator which is provided by Kawasaki for 4000 t/d clinker production. The first case of the national production of the waste heat power generation project was constructed to produce 3000kW by Shanghai Triumph and Nanjing Cement Design Institute.

Now a days, in various countries throughout the world it is becoming more common for combined heat and power (CHP) plant to be installed by recovering the waste heat, which can also produce hot water for domestic heating as a means of utilizing low grade heat and improving the overall efficiency of the CHP. It is less common to install heat recovery systems on existing process plant for use in domestic heating systems. Till recent times, energy generation from waste heat recovery technique was an alien idea to local industry. But now most factories are planning to have such technologies. Now a day as the country is transforming from agriculture based economy to industry based economy, the number of industries is increasing all over the country resulting in huge energy utilization. This further leads to the need of energy efficiency and waste heat recovery activities. This can help the country to reduce its fossil fuel consumption, thus improving energy security and improving the country’s balance of payments.

1.2. Statement of the problem

The cement production process is highly energy intensive in a conventional Cement plant the substantial energy contained in the waste heat is not utilized but lost. This substantial energy loss occurs at the pre-heater stage (where exhaust gasses from the heaters are cooled and waste heat is vented into the atmosphere) and during the cooling of clinker product at the air quenching coolers (AQC) stage. In the dry process cement plants nearly 40 percent of the total heat input is rejected as waste heat from exit gases of preheater and grate cooler. Even for an optimized cement process, significant heat loss, mainly caused by the heat of the waste gases, still occurs.

In most of the plants part of the waste heat is utilized for drying of raw material and coal, but even after covering the need for drying energy in most of the cases, the remaining waste heat is rejected to the environment resulting in energy lose, air pollution and acid rain to the surrounding environment. Cogeneration of power besides mitigating the problem of
power shortage also helps in energy conservation as well as reducing greenhouse gas emissions. In existing plants cogeneration technologies based on bottoming cycles have potential to generate up to 15-30 percent of the power requirement of a plant. Such a development assumes considerable significance and potential in Ethiopian cement industry in order to achieve economy and environmental compatibility.

2. PROCESS DESCRIPTION

2.1. Process description of cement production

Cement is manufactured by intimately mixing together calcareous and argillaceous and silica alumina or iron oxide bearing materials, burning them at clinkering temperature and grinding the resultant clinker so as to produce cement. To manufacture 1 ton of Portland cement about 1.5 to 1.7 tons raw materials, 0.13 ton coal and 1 ton clinker must be ground to dust fineness. The production process of cement has three major stages. The first stage is mixing and crushing stage which is responsible to mix certain proportion of clay and limestone and to crush them to powder form. The second and the most important stage is pyro processing which consumes more than 90% of total energy. This stage includes preheater, calciner, kiln and cooler. Clinker as nodular and well mixed form is the main product of this stage which then is sent to final grinding and crushing stage of the cement mill.

![Figure 1: Cement manufacturing process](image-url)
with additives and then is sent to packaging stage. The schematic PFD of DMC plant is shown in Figure below.

As mentioned before, pyro processing is the most important stage in terms of energy and pollution management in cement plant. In this stage, raw materials which are mixture of clay and limestone is crushed and mixed in the first crushing stage reaching to 90µ sieve grain size. This solid mixture enters to the pre-heater at 50°C. The pre-heater stages consist of 5 stages of double string cyclones which are used to preheat raw materials and separate them from the pre-heater gas. In this stage, feed stream with 50°C is heated up to 950°C by heat exchange with flue gases entering at 1100°C from calciner. Flue gases then leave the pre-heater stage at 322.7°C and 347.5°C from each preheater stack and discharged to the environment. Such a high temperature is a valuable source of thermal heat. Solid stream at 950°C leaves pre-heater stage and is fed to claciner where two reactions occur to convert 95% of CaCO$_3$ and all amount of MgCO$_3$ to CaO and MgO respectively. These endothermic reactions which are the major source of CO$_2$ production in cement plant require too much thermal energy.

The main reactions of each section are given in below, along with other data as operating temperature and heat of reaction. The reaction products are solid materials which consist of remained CaCO$_3$, CaO, MgO, and the other materials. This solid stream enters to the kiln at 1100°C, where $C_2S$, $C_3S$, $C_3A$ and $C_4AF$ are produced as four major components of clinker under several chemical and physical (phase change) reactions presented in Table 1. The required thermal heat is provided by combustion of coal fuel and hot air sent from coolers. The clinker enters the cooler at 1450°C and is cooled down to 80°C - 100°C. Ambient air which is sent to hot clinker is separated to three streams and different temperatures by ducts. One stream at 1100°C is sent to the kiln, another one at 1000°C is launched to calciner and the last one at 305°C is discharged to the environment as the second major source of thermal heat loss in cement plant. Then, clinker is transported to the finish mill by a conveyor belt to be ground into fine powder cement. A small amount of gypsum is added during grinding to control the set properties of the produced cement.

2.2. **Types of energy used in cement production process**

For each of the process steps within the boundary, the major energy use at that step of clinker production the combustion of fuel to generate the heat required, not the electricity
used to rotate the kiln. Fuel coal and electricity are the main sources of energy in the cement production. Generally, energy use is classified in three categories:

- Electricity use for raw material preparation
- Fossil fuel use for clinker production, and
- Electricity use for cement grinding (or finish grinding).

### Table 1: Clinker formation reaction in kiln system

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Equation of reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatilization of water</td>
<td>H₂O(l) → H₂O (v)</td>
</tr>
<tr>
<td>Kaolinite decomposition</td>
<td>Al₂O₃·2SiO₂·2H₂O→Al₂O₃ + 2SiO₂ + H₂O</td>
</tr>
<tr>
<td>MgCO₃ decomposition</td>
<td>MgCO₃→MgO + CO₂</td>
</tr>
<tr>
<td>CaCO₃ dissociation</td>
<td>CaCO₃→CaO + CO₂</td>
</tr>
<tr>
<td>Formation of intermediate products</td>
<td>CaO + Al₂O₃→CA</td>
</tr>
<tr>
<td>Formation of C₂F</td>
<td>2CaO + Fe₂O₃→C₂F</td>
</tr>
<tr>
<td>Formation of C₂S</td>
<td>2CaO + SiO₂→C₂S</td>
</tr>
<tr>
<td>Clinkering reactions</td>
<td>CA + C₂F + CaO → C₄AF</td>
</tr>
<tr>
<td>Formation of C₃A</td>
<td>2CA + CaO → C₃A</td>
</tr>
<tr>
<td>Formation of C₃S</td>
<td>C₂S + CaO → C₃S</td>
</tr>
<tr>
<td>Overall reactions</td>
<td>Kiln Meal → Clinker</td>
</tr>
</tbody>
</table>

i) **Electrical Energy:**

The major electrical energy consumption areas are mill drives, fans and conveying systems. About 30% of electric power is consumed for finish grinding, and a little 30% each is consumed by the clinker burning process. Typical distribution of electrical energy for a cement plant operating is at 93kWh per MT of cement.

ii) **Thermal Energy:**

Thermal energy accounts for almost half the energy costs incurred in cement manufacture. A variety of fuels such as coal, gas and oil are used in the cement plant. The major use of thermal energy is in the kiln and pre calciner. In plants using coal, an external coal or oil fired furnace is used for generation of hot air required for coal mills.

### 2.3. Fuel used in cement kiln system

Fuels that have been used for primary firing include coal and heavy fuel oil. High carbon fuels such as coal are preferred for kiln firing, because they yield a high luminous flame. The
clinker is brought to its peak temperature mainly by radiant heat transfer and hot flame is essential for this.

2.4. Energy requirement in cement production process

The cement industry is essentially a chemical process industry entailing various engineering unit operations. Thus raw meal grinding, mixing, burning and cement grinding are the main operations entailed in the manufacture of cement. There are different types of equipment available for transportation of materials, crushing and grinding of materials, mixing of materials. The thermal efficiency of the pre-heater depends on the number of the stages in the pre-heater and the capacity of the flow ratio of the gas and the kiln feed of materials.

The fed entering to the calciner is 95% calcined before it enters the rotary kiln. The hot combustion air for the calciner arrives in a tertiary duct directly from the cooler, bypassing the kiln. In clinker burning, the raw meal is fed to the kiln system where it is dried, preheated, calcined and sintered to produce cement clinker. Thermal energy mainly coal, is consumed in the kiln for the pyro processing of limestone to produce clinker. Theoretically only 430Kcal/ Kg clinker of heat is required for burning 1 Kg of clinker, but in practice twice or more times this is necessary. The shell heat loses from the rotary kiln can represent a considerable proportion of the total energy loss, specially, in kiln plants with small throughout the heat loss through the shell of rotating the kiln lies in the range of 200-600 KJ/kg of clinker depending on the productivity of the kiln and if the kiln system have with or without tertiary air duct.

3. INDUSTRIAL WASTE HEAT RECOVERY

3.1. Introduction

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose. Waste heat recovery refers to the recuperation of heat that is discharged as a byproduct from one process to provide supplemental energy needed by another process. Captured and reused waste heat is an emission free substitute for costly purchased fuels or electricity. Heat recovery options can be broadly classified into three strategies.

- Recycling energy back into the process
- Recovering energy for other on-site uses
• Using it to generate electricity in combined heat and power systems.

3.2. Sustainable development through waste heat recovery

Industrial waste heat refers to energy that is generated in industrial processes without being put to practical use. Many industrial processes require large quantities of thermal energy, much of which is eventually exhausted to the environment, either to the atmosphere or water. Recovering this waste heat represents the largest opportunity for reducing industrial energy consumption. The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat. Waste heat reduces losses by improving equipment efficiency or installing waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat in industrial processes for heating or for generating mechanical or electrical work. A sustainable energy system is one which balances energy production and consumption with minimal negative impact on the environment. The multi-criteria decision-making procedure for any sustainable energy system includes: technology (primary energy ratio), economy (investment cost), environment (CO₂ emission) and society (job creation).

3.3. Commercial Waste Heat Recovery devices

Waste Heat Boilers

Waste heat boilers are ordinarily water tube boilers in which the hot exhaust gases from cement kiln, furnace, gas turbines, incinerators and etc. pass over a number of parallel tubes containing water. The water is vaporized in the tubes and collected in a steam drum from which it is drawn off for use as heating or processing steam. Because the exhaust gases are usually in the medium temperature range and in order to conserve space, a more compact boiler can be produced if the water tubes are finned in order to increase the effective heat transfer area on the gas side. The pressure at which the steam is generated and the rate of steam production is depends on the temperature of waste heat available. The pressure of a pure vapor in the presence of its liquid is a function of the temperature of the liquid from which it is evaporated. If the waste heat in the exhaust gases is insufficient for generating the required amount of process steam, auxiliary burners which burn fuel in the waste heat boiler or an after-burner in the exhaust gases flue are added.
**Figure 2: Two-pass water tube WHR boiler**

**Economizer**

In case of boiler system, economizer can be provided to utilize the flue gas heat for pre-heating the boiler feed water. 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.

**Figure 3: Economizer**

**Regenerator**

The Regeneration which is preferable for large capacities has been very widely used in glass, cement kiln and steel melting furnaces. Important relations exist between the size of the regenerator, time between reversals, thickness of brick, conductivity of brick and heat storage ratio of the brick. In a regenerator, the time between the reversals is an important aspect. Long periods would mean higher thermal storage and hence higher cost.
The Heat Pipe comprises of three elements – a sealed container, a capillary wick structure and a working fluid. The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum. Thermal energy applied to the external surface of the heat pipe is in equilibrium with its own vapor as the container tube is sealed under vacuum. Thermal energy applied to the external surface of the heat pipe causes the working fluid near the surface to evaporate instantaneously. The vapor then travels to the other end the pipe where the thermal energy is removed causing the vapor to condense into liquid again, thereby giving up the latent heat of the condensation.

3.4. Factors affecting the waste heat recovery

The amount of heat in the waste gases that can be utilized or recovered depends primarily on the waste gas mass flow rate, temperature of the waste heat gas and thermal capacity of the waste gas. Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Depending on the
above parameters, for a 5,000 t/d kiln, it is expected to be in the range of 6 MW to 14 MW net electricity generations through a WHRPG technologies. Factors that influence these parameters or otherwise affect the design capacity of the power plant include the following:

**Heat Quantity and heat Quality:** The quantity or heat content is a measure of how much energy is contained in a waste heat stream. The quantity of waste heat contained in a waste stream is a function of both the temperature and the mass flow rate of the stream:

\[
\dot{E} = \dot{m} C_p \Delta T
\]

Where \(\dot{E}\) is the waste heat loss (KJ/hr); \(\dot{m}\) is the waste stream mass flow rate (Kg/hr)

**Waste stream composition**

Although chemical compositions do not directly influence the quality or quantity of the available heat, the composition of the stream affects the recovery process and material selection. The composition and phase of waste heat streams will determine factors such as thermal conductivity and heat capacity, which will impact heat exchanger effectiveness. Meanwhile, the process specific chemical makeup of off gases will have an important impact on heat exchanger designs, material constraints, and costs.

**Minimum allowable temperature**

The minimum allowable temperature for waste streams is often closely connected with material corrosion problems. Depending on the fuel used, combustion related flue gases contain varying concentrations of carbon dioxide, water vapor, NOX, SOX, unoxidized organics, and minerals. If exhaust gases are cooled below the dew point temperature, the water vapor in the gas will condense and deposit corrosive substances on the heat exchanger surface. The most common method for preventing chemical corrosion is designing heat exchangers with exhaust temperatures well above the dew point temperature.

### 3.5. Benefits of waste heat recovery

Benefits of waste heat recovery can be broadly classified in two categories:

**Direct benefits**

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.
Indirect benefits

Reduction in pollution:
A number of toxic combustible wastes such as CO gas, sour gas, carbon black off gases, Acrylonitrile and other plastic chemicals releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

Reduction in equipment sizes:
Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced, results in reduction in equipment sizes of all flue gas handling equipment’s such as fans, stacks, ducts, burners, etc.

Reduction in auxiliary energy consumption:
Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

4. TECHNOLOGIES OF HEAT RECOVERY SYSTEMS

4.1. Steam (Conventional) Rankine cycle
The most commonly used system for power generation from waste heat involves using the heat to generate steam in a waste heat boiler, which then drives a steam turbine. Steam turbines are one of the oldest and most versatile prime mover technologies. Heat recovery boiler and steam turbine systems operate thermodynamically as a Rankine Cycle, as shown in below figure.

Figure 6: waste heat recovery through steam Rankine
In the steam Rankine cycle; the working fluid water is first pumped to elevated pressure before entering a heat recovery boiler. The pressurized water is vaporized by the hot exhaust and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where heat is removed by condensing the vapor back into a liquid. The condensate from the condenser is then returned to the pump and the cycle continues.

4.2. Organic Rankine Cycle

It is one of the methods to convert thermal energy to electrical energy. It is a closed loop system filled with an organic liquid having a low boiling temperature. The Organic Rankine cycle (ORC) is named for its use of an organic, high molecular mass fluid with a liquid-vapor phase change, or boiling point, occurring at a lower temperature than the water - steam phase change. The fluid allows Rankine cycle heat recovery from lower temperature sources such as biomass combustion, industrial waste heat, geothermal heat, solar ponds etc. The low - temperature heat is converted into useful work that can itself be converted into electricity. The working principle of the organic Rankine cycle is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally re- condensed. In the ideal cycle, the expansion is isentropic and the evaporation and condensation processes are isobaric. In the real cycle, the presence of irreversibility lowers the cycle efficiency.

**Figure 7: WHR through Organic Cycle system**

The fluid allows Rankine cycle heat recovery from lower temperature sources such as biomass combustion, industrial waste heat, geothermal heat, solar ponds etc. The low - temperature heat is converted into useful work that can itself be converted into electricity. The working principle of the organic Rankine cycle is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally re- condensed. In the ideal cycle, the expansion is isentropic and the evaporation and condensation processes are isobaric. In the real cycle, the presence of irreversibility lowers the cycle efficiency.
4.3. Kalina Cycle

The Rankine cycle has also been improvised using binary fluid of ammonia and water as the working fluid in place of only water for improving the overall efficiency of conventional systems. This system is called ‘Kalina Cycle’. In this system efficiency gains of up to 50% for low temperature heat sources (200-280°C) and up to 20% for higher temperature heat sources have been claimed as compared to conventional Rankine cycle based power plants. Kalina cycle takes advantage of the ability of ammonia-water mixture at any given pressure to boil or condense at a ‘Variable’ temperature. Moreover, conventional axial flow turbines can be used in these plants as molecular weights of ammonia and water are almost similar. Further, the turbines used may be smaller in size and hence less costly as back pressure turbines can be used as condensing turbines.

Figure 8: Kalina Cycle Waste heat recovery system
Table 2: Summary of waste heat recovery power generation technologies

<table>
<thead>
<tr>
<th>S. No</th>
<th>Thermal Conversion Technology</th>
<th>Temperature Range</th>
<th>Typical Sources of Waste Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steam Rankine Cycle</td>
<td>Medium, high</td>
<td>Exhaust from gas turbines, reciprocating engines, furnaces and cement kiln.</td>
</tr>
<tr>
<td>2</td>
<td>Kalina Cycle</td>
<td>Low, medium</td>
<td>Gas turbine exhaust, boiler exhaust, cement kilns</td>
</tr>
<tr>
<td>3</td>
<td>Organic Rankine Cycle</td>
<td>Low, medium</td>
<td>Gas turbine exhaust, boiler exhaust, heated water, cement kilns</td>
</tr>
<tr>
<td>4</td>
<td>Thermoelectric Generation</td>
<td>Medium- high</td>
<td>Not yet demonstrated in industrial applications</td>
</tr>
<tr>
<td>5</td>
<td>Piezoelectric generation</td>
<td>Low</td>
<td>Not yet demonstrated in industrial applications</td>
</tr>
<tr>
<td>6</td>
<td>Thermal Photovoltaic</td>
<td>Medium- high</td>
<td>Not yet demonstrated in industrial Applications</td>
</tr>
</tbody>
</table>

4.4. Selection of WHRPG technology

Several different medium temperature waste heat power generation technologies for cement production have been developed in the past few years, including Steam Rankine Cycle, the Organic Rankine Cycle and the Kalina Cycle. The Steam Rankine Cycle approach is the most common approach that is used in existing on-site power plant. The organic Rankine Cycle and Kalina Cycle are not yet in commercial applications in cement plant. Because of the availability, low cost and easy thermodynamic properties the working fluid, low maintenance, easy for installation, high production of power and environmental friendly as comparing with the other technologies Steam Rankine Cycle is preferable and selected.

Technical/ Technological Barriers

- No availability of proven technology indigenously.
- Design of waste heat recovery boiler suitable to withstand high dust load in the waste gases.
- High performance risk due to lack of demonstration.
- Viability remains to be established.
- High cost of technology and access to funds.
- Depressed cement marketing scenario.
- Lack of incentives for adoption of technology.
5. WASTE HEAT RECOVERY POWER GENERATION

5.1. Process description of power generation

Fully condensed, basic working fluid (water) with parameters as at point 1, corresponding to a state of saturated liquid, enters into a feed pump, P1, where its pressure is increased, obtaining parameters as at point 2, corresponding to a state of a sub cooled liquid. Stream 2 now passes through a preheater (regenerator), HX-3, where it is heated and vaporized in counter flow by a returning stream of condensing working fluid (9-10, see below) and gives parameters as at point 3, corresponding to a state of vapor-liquid mixture. Stream 3 is divided into streams 4 and 5 which are then sent into a heat recovery vapor generator, (AQC), HX-1 and heat recovery vapor generator (SP-boiler), where it is heated, fully vaporized and superheated, in counter flow with a stream of hot air (50-51) and a stream of exhaust gas (40-41) respectively. The working fluid enters and leaves at the same pressure, which means no pressure drop in both boilers. Therefore, both streams 6 and 7 are now superheated and then combined by the valve corresponding to a state of superheated steam as at point 8. The adjusted operating condition of the steam is now sent in to the turbine (TR-1), where it expands, producing work and obtaining parameter as at point 10, corresponding to a state of super vapor and to a parameter of 9, which is used to produce mechanical energy. Stream 10 is now sent into regenerator (HX-3), where it desuperheated, providing heat for process stream 2-3 and obtains parameters as at point 11, corresponding to a state of liquid-vapor mixture (see, below). Thereafter, stream 11 is sent into the final condenser (HX-4), where it is cooled and fully condensed by a stream coolant (30-31, water,) and obtains parameters as at point 1 (see below). Generally, the summarized process of power generation using conventional Rankine cycle is as follows: The water exiting the condenser and makeup water is pumped to the regenerator where it is preheated. Then, the hot water directly enters to the AQC boiler and meanwhile to the SP-boiler to produce steam. The steam is now superheated, heated to a temperature above its saturation temperature at the actual pressure conditions. The superheated steam expands in the turbine, generating power. This line reflects the turbine at its operating efficiency. The expansion decreases the steam temperature and pressure. The steam/water exiting the turbine is condensed to liquid form in the condenser.
5.2. Source of waste heat in cement kiln system

In general 54% of the fuel energy consumption is required for the chemical reaction of the kiln fed to produce clinker. About 16% of the fuel energy consumption is consumed for drying of the raw materials in the raw mill. The total of this energy percent gas about 70% corresponded to the useful energy. The remaining 30% of the energy is needed to cover energy losses, (wall heat loss, kiln exhaust gas, cold clinker and other losses). There are a few major heat loss sources that would be considered for heat recovery. These heat losses are:

i. Cement rotary kilns surface:

Whole section kilns Surface temperature can be up to 260-280 °C when rotary kilns works, air- cooled method is currently used and a lot of heat is directly distributed into the
atmosphere, which not only causes a waste of a lot of heat, but also causes high temperatures pollution around the kiln. According to the needs of enterprises, waste heat recovery can be used to heat water or air, and hot water can be used for life and refrigeration.

ii. Grate cooler waste gas process:
Cold air is sent to grate cooler to cool the material 80 up to 100°C, and cold air is heats to hot air of 305°C, then excretes from grate cooler tail, then enters to kiln head dust collector, and finally discharge into atmosphere by exhaust fan.

iii. Preheater waste gas process:
Waste gases of preheater outlet from the two double strings preheater, 322.7 and 347.5 °C lose occur then discharged into atmosphere. The average temperature of the flue gas is 335°C.

5.3. Connection of WHRPG with cement production lines
Cement kiln waste heat power systems encounter one major requirement which complicate the cost effective utilization. The technical difficulty in utilizing both sources of heat from cement kiln in a single unified power system, this is caused by the differences in the initial, and especially in the final temperatures of the two heat sources. Thus, the efficacy of any power system utilizing heat from a cement kiln depends not only on the system's thermal efficiency, but also on the system's ability to utilize the maximum amount of heat from these two different heat sources. Therefore, any power system utilizing heat from a cement kiln will have at least two parallel boilers, because the flue gas and the hot air cannot be mixed.

Connection of AQC-boiler: Because the waste gas temperature of grate cooler terminal is low, and direct utilization efficiency is low, the air is taken from the central part of grate cooler, the waste gas of 305 0C enters AQC boiler. The waste gas was cooled to about 110°C by AQC boiler. Both 1100C and grate cooler tail waste gas about 1400C return to kiln head dust collecting system.

Connection of SP-boiler: The average temperature of preheater waste gas is about 335 0C, and it enters directly into SP-boiler. The waste gas was cooled to 210 0C by SP-boiler. Then the waste gas enters raw mill and provides drying heat source for it. The SP-boiler is equivalent to bypass of gas conditioning tower.
5.4. Expansion chamber for dust removal

An expansion chamber is an apparatus for the removal of solid particles from a stream of gas, in particular (but not limited to) gas used as a heat source in a power system. An example of this situation can be found in power systems based on the use of waste heat from cement plants, where the hot gas is heavily laden with abrasive cement dust. Removal of these particles by various sorts of filters cause substantial difficulties; such a filter would have to operate at very high temperature and in the case that a large amount of solid particles is high, the filter becomes clogged in a short time, causing substantial maintenance problems. The use of cyclone separation apparatus is problematic in that it causes substantial losses of pressure in the stream of gas. Moreover, abrasive solid particles can cause substantial erosion in the cyclone apparatus itself.

A stream of gas, laden with solid particles and moving at high speed enters into the inlet duct of the apparatus. Due to the high velocity of the gas the kinetic energy of the stream is high, which enables the stream to carry solid particles. This stream then enters into an expanding duct. As the cross-section of the expanding duct increases, the velocity of the stream decreases and according to Bernoulli’s Principle, the pressure of the stream increases. The decrease in the velocity of the stream corresponds to a reduction of its kinetic energy (in proportion to the second power of velocity). Therefore the ability of the stream to carry solid particles is drastically decreased. Thereafter, the low velocity stream enters into a separation chamber where, due to the low velocity of the gas, the solid particles fall down into dust collector, located at the bottom of the separation chamber. Due to the fact that the pressure in the collection chamber is elevated, the solid particles in the dust collector is easily removed through openings the bottom of the dust collector. Thereafter, the gas from the separation chamber enters into a converging duct, where its velocity increases and pressure decreases. Thereafter, the stream of gas enters into an outlet duct and can be directed as needed. An expansion chamber used for dust removal has the following advantages compared to conventional filters:

- It can separate a substantial quantity of solid particles without causing blockage of a filter.
- It can easily work with high temperature or low temperature gas without need for special high temperature filters.
• It has no moving parts and as a result is reliable.

![Figure 10: Expansion chamber for dust removal subsystem](image)

5.5. Basic unit operations of WHRPG

**AQC and SP boilers**

AQC boiler will be installed next to the kiln head of the cement line, producing superheated steam and a dedusting chamber will be set up to alleviate the boiler abrasion. For AQC boiler, the heat-receiving surface of the boiler is divided into three stages: The first stage is main superheated steam stage, and the second stage is low pressure superheated steam stage, and the third stage is hot water stage.

SP boiler will be connected to the pre-heater exit, producing a superheated steam. For SP boiler, the heat-receiving surface of the boiler is divided into three stages: The first stage is main superheated steam stage, second stage is low pressure superheated steam stage and the water after being deaerated is pumped to AQC boiler second and third stage. Then, the outgoing hot water from AQC third stage is used as feed water of AQC boiler second stage and SP boiler first stage. The superheated steam produced in AQC boiler first stage and SP boiler second stage merge together and then is introduced to the turbine main stream inlet. At the same time, the low pressure superheated steam produced in AQC boiler second stage and SP boiler second stage merge together, and then is introduced to the turbine supplement inlet. The main stream and low pressure steam is used to promote the turbine for power generation. Exhaust steam of turbine after work is condensed to water, and then pumped to a deaerator, thus a complete thermodynamic circulation system forms.
Turbine
The purpose of the turbine is to change the potential energy of pressurized gasses into rotational kinetic energy. The stream of high-pressure vapor of organic fluid expands in the turbine, causing its internal part to rotate. The rotor is connected by a shaft to the generator which changes rotational kinetic energy into electricity. The expansion process is considered adiabatic and a steady state of operation is assumed. Knowing the isentropic efficiency of the turbine (\( \eta_t \)), which is given by the manufacturer, generated power can be calculated as follows
\[
\dot{w}_{\text{gen}} = \dot{m}_{\text{wf}} (h_1 - h_2) = \dot{m}_{\text{wf}} \eta_t (h_1 - h_{2s})
\]
Where state 2s corresponds to exhaust from ideal isentropic turbine

Condenser
Water-cooling unit adopts water as cooling medium for exhaust steam condensation, which is composed of condenser, condensate pump, cooling tower and water basin. Water from basin is pressurized and sent to condenser for heat absorption, and exhaust steam from turbine is condensed. The water absorbed heat and turned back to the cooling tower for cooling with the help of mechanical draft fans.

Pump
This is used to deliver cooling water from condenser to heat exchanger by application of pressure difference. Using the same assumptions that were used for the turbine, power consumed by the feed pump can be calculated.
Technical consideration for power generation

The various considerations for the design of appropriate cogeneration scheme for a particular plant will need in-depth study of the following technical details

Availability of waste heat for power generation

The heat available for recovery entirely depends on the design of the cement plant and its configuration. The pyro process system design itself plays a crucial role. The parameters that are important are plant capacity, heat consumption, type of system such as preheater kiln or pre-calciner kiln, either with one string or two strings of preheater, number of stages of preheater and type of clinker cooler. Next aspect is the drying and grinding system utilized for raw materials and fuel. Some of the crucial parameters are the quantity of material to be ground their moisture content, their grind ability, type of grinding system etc.

Location of waste heat boiler

Another factor that could be important is the location of heat recovery unit in the process circuit, namely before or after process fan, in the down-comer at an elevated position or at ground level, and before or after the pollution control device such as electrostatic precipitator or a bag filter. These could play a role in estimating the heat that could be recovered as well as in the design and layout of plant.

Suitability of waste heat recovery boiler

The waste gases from preheater and cooler exhaust contain high dust concentrations. Accordingly the waste heat recovery boiler should be able to withstand high dust loads. Moreover, the operating conditions in cement plants require design of waste heat recovery boilers which should be able to withstand the problems of heavy coating formation resulting in drastic reduction of capacity and the wear of tubes due to coarse clinker particles. As such, the characterization of the dust in the waste gases with regard to particle size, stickiness, abrasiveness should be studied in detail for evaluation of the suitability/design of the waste heat recovery boiler.

Maximum flue gas temperature

There is a limit at the upper scale of the temperature of the waste gases for cement plant application as the flue gases contain dust comprising. These components make the dust sticky and aggressive at temperatures more than 400°C which is considered as the highest
gas temperature for steam production. The material used for waste heat boiler tubes and plates is also not too expensive if the gas temperature is less than 400°C.

**Quantity of heat recovery**

Ideally, higher the temperature of the gases, the better the heat transfer efficiency, as the gases at higher temperatures can be cooled down to a much lower temperature in the waste heat recovery boiler. The critical parameters such as steam flow rate, pressure and superheat gas outlet temperature are to be optimized for each plant in order to achieve maximum power generation.

**CONCLUSION**

In this work, the use of medium grade waste heat energy from a cement manufacturing plant (which is currently being rejected into the environment, thus causing energy wastage and environment pollution) to generate electricity using Steam Rankine Cycle system proposed in this work has been established to be an economically viable and environmentally friendly project. Although, the use of exhaust waste heat to generate power using the Steam Rankine Cycle has been in existence for a long time throughout the world, but many countries, has never used previously. Therefore, this project through its theoretical study has been able to establish that this same technology can be adequately transferred to other processes where waste heat is in existence. The waste heat rejected from the AQC stack and pre-heater exhaust stack can be used to drive a heat source Steam Rankine Cycle system to generate about 7.35MW (net) which is about 18%of the electricity needed in the cement manufacturing industry approximately. Therefore, further research was carried out to determine the exact values of heat using the existing cement plant details and the phase 2 results will be presented very soon. This will not only generate more insight into the operation of the system but will also reposition of this college as a center for the study of the waste heat to electricity process.

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