WASTE HEAT RECOVERY SYSTEM (WHRS) FOR CEMENT INDUSTRY - A CASE STUDY FOR HADHRAMOUT CEMENT FACTORY, ARABIAN YEMEN CEMENT COMPANY LIMITED (AYCCL) – MUKALLA – HADHRAMOUT

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Key words: Cement Plant, Rotary kiln system, Energy Balance, Heat Balance, Heat Recovery

Abstract

Waste Heat Recovery (WHR) is the process of recovering heat discharged as a byproduct of one process to provide heat needed by a second process. So it is the capture and the use of energy contained in fluids or gasses that would otherwise be lost to a facility. In simplistic terms, waste heat can be interpreted as heat rejected heat that has already been paid for and is now being rejected from a facility to the environment. This heat still has energy and usefulness to the facility in terms of preheating another process or cooling using absorption system or heating a building. Recovery and reuse of this heat has the potential for significant reduction of energy costs and improving the profitability of any business. Engineers have intensive research work in taking a systematic approach to defining and implementing waste heat recovery projects for industrial, commercial, and institutional facilities where these opportunities exist.

Among these facilities where (WHRS) has potential is the Cement Industries. Cement industry is considered from the important industries in Yemen. As this industry is directly related with building and construction industries in the country. In Yemen there are eight cement factories distributed in different parts of the country. Cement industry is one of the high energy consuming industries.

The specific average energy consumption is estimated as 100 – 150 equivalent kg of oil per produced ton of cement, and the energy cost may reach 40 – 60% of the total production cost. To ensure the proper selection of the right waste heat recovery system (WHRS) technologies, their correct dimensioning and smart positioning, all of which leads to enormous savings in money and adds up to a significant enhancement in a plants’ economy, Lower capital and operation costs.

Waste Heat recovery in cement industry is the use of the waste heat from furnace (kiln) and the clinker in the preheating processes. In this study the energy saving using heat exchanger heat
recovery system for the Arabian Yemen Cement Company Limited (AYCCL) for pre-heating processes is considered. Data of Mukalla weather has been used as the basis of this analysis. Other technical data for the different heat equipment are taken from site i.e. (AYCCL).

It can be concluded that heat recovery system proved its importance in the cement industry application where there is a possibility of heat recovery from the exhaust air from the furnace burning process and the Clinker to the preheating processes. Findings showed that approximately 13.3% of the total input energy could be recovered; (7.5 MW) (in case of steam cycle), For the kiln surface, a secondary shell system has been proposed and designed. Therefore, it is recommended to use the Waste heat recovery system (WHRS) in cement industry in Yemen so as to achieve energy saving as well as to reduce the running cost of the system beside the other advantages.
Secondary shell application to the current kiln surface.

Rotary kiln covered by special insulation. (China).

Another application of kiln radiation and convection waste heat recovered for domestic using. (China).

Distribution of cement production cost, AYCCL 2012.

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1. Raw material and clinker components and their percentages.
2. Complete Energy Balance of the Kiln system.
3. Complete thermal calculations (equations & parameters).
1. Introduction

Waste heat from cement kilns is usually used for drying of raw materials and fuel. Depending on the humidity of the raw materials and the cooler technology, additional waste heat is available from the kiln gases (pre-heater exit gas) and cooler exhaust air. This heat can be used for steam and electric power production. Waste heat recovery from hot gases and hot kiln surfaces in a kiln system are known as potential ways to improve overall kiln efficiency [3].

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

There are several exhaust streams in the cement manufacturing operation that contain significant amounts of heat energy, including the kiln exhaust, clinker cooler, and kiln pre-heater and pre-calciner. In certain cases, it may be cost effective to recover a portion of the heat in these exhaust streams for power generation. Power generation can be based on steam cycle or organic Rankin Cycle (i.e. conversion of heat into work). In each case a pressurized working fluid (Water for steam cycle or an organic compound for the organic Rankin cycle) is vaporized by the hot exhaust gases in the heat recovery boiler, or heater, and then expanded through a turbine that drives a generator. Based the heat recovery system and kiln technology, 7 – 8 kWh/ton cement can be produced from hot air from the clinker cooler, and 8 – 10 kWh/ton cement from kiln exhaust[12]. Total power generation can range from 7 – 20 kWh/ton cement. Steam turbine heat recovery system were developed and first implemented in Japan and are being widely adopted in Europe and China [11]. Installation costs for steam system ranges from $2 – 4? Annual ton cement capacity with operating costs ranging from $0.2 – 0.3/annual cement capacity [12].

Generally, only long dry kilns produce exhaust gases with temperature high enough to make heat recovery for power economical. Heat installation in Europe and China has included long dry kilns with pre-heater. Heat recovery for power generation may not possible at facilities where the waste heat is used to extensively dry the raw materials; it is usually more economic and efficient to use the exhaust heat to reduce the moisture content of raw materials with very high moisture [12].

It is possible to meet 25- 30 % of the plants total electrical needs through this type of cogeneration. An example, a 4100 ton/day cement plant in India, installed a waste heat recover power plant using the exhaust from preheater and clinker cooler. The power plant was rated at 8 megawatt (MW). Capital investment was 18.7 million, and CO2 emission reductions were reported to be 49000/yr. [13].

This paper focuses on the energy recovery of a horizontal rotary kiln system, which has been used in the Arabian Yemen Cement Company Ltd (AYCCL) Hadhramout Yemen 4000 ton/day. A detailed thermodynamic analysis of the kiln system is first given, and then, possible approaches of heat recovery from some major heat loss sources are discussed.
2. Basic Concept

Waste flue gases emissions from cement kiln are mainly concentrated in exhaust emissions from kiln head cooling machine (cooler) and kiln end preheat machine (Preheater). A clinker cooling machine waste heat boiler (AQC for short) makes use of the waste heat less than 400°C from cement kiln head clinker cooling machine and a kiln end preheat machine waste heat boiler (SP for short) makes use of the waste heat less than 300°C from kiln end preheat machine. The two boilers set generate superheated steam which is sent to the steam turbine to expand to do work. In other words the heat energy is converted to mechanical for power generation as shown in Figure 1.

Fig. 1 Shows the Schematic of Waste Heat Recovery for Power Generation.

3. Waste heat availability

In the dry process plants, nearly 40% of the total heat input is rejected as waste heat from exist gases of pre-heater and cooler also from kiln shell by convection plus radiation. The quantity of heat lost from pre-heater exhaust gases ranges from 628 to 754 kJ/kg clinker at temperature range of 260 to 280 °C. In addition, 209 to 335 kJ/kg clinker heat is lost at a temperature range of 200 to 300°C from exhaust gases of grate cooler. These waste heats have various applications such as drying of raw materials, coal and power generation. In most of the plants part of the waste heat is utilized for drying of raw material and coal like AYCCL Plant, but even after covering the need for drying energy in most of the cases, there is still waste heat available which can be utilized for electrical power generation.

To know an availability of waste heat which can be utilized for electrical power generation. Should be estimated energy and mass balance or you can say energy auditing with analyzing the mass and energy should be estimated. By other means, it can be said ENERGY AUDITING by analyzing the kiln system thermodynamics, which is discussed below.
4. Energy auditing and heat recovery

4.1 Data Gathering and main (thermal) calculations.

Table 1: Raw material and clinker components and their percentages*

<table>
<thead>
<tr>
<th>Component</th>
<th>Raw Materials, %</th>
<th>Clinker, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2, %</td>
<td>13.15</td>
<td>22.25</td>
</tr>
<tr>
<td>Al2O3, %</td>
<td>3.76</td>
<td>5.50</td>
</tr>
<tr>
<td>Fe2O3, %</td>
<td>1.94</td>
<td>3.90</td>
</tr>
<tr>
<td>CaO, %</td>
<td>43.25</td>
<td>66.00</td>
</tr>
<tr>
<td>MgO, %</td>
<td>1.25</td>
<td>1.65</td>
</tr>
<tr>
<td>K2O, %</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Na2O, %</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>SO3, %</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>H2O, %</td>
<td>1.31</td>
<td>-</td>
</tr>
<tr>
<td>Organics</td>
<td>0.90</td>
<td>-</td>
</tr>
<tr>
<td>Ignition loss</td>
<td>35.97</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.00</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

* Ref. Aycl Lab.
Fig. 2. Control volume, various streams and components for kiln system.

Fig. 3. Mass balance of the kiln system
Table. 2 Complete Energy Balance of the Kiln system.

<table>
<thead>
<tr>
<th>Q. Sr.</th>
<th>Description</th>
<th>Equations used</th>
<th>Data</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(KJ/Kg-clinker)</td>
</tr>
<tr>
<td>1</td>
<td>Combustion of coal</td>
<td>( Q_1 = m_c H_c )</td>
<td>( m_c = 0.115 \text{ kg/kg cli} , H_c = 23028.5 \text{ kJ/kg} )</td>
<td>2792.06</td>
</tr>
<tr>
<td>2</td>
<td>Sensible heat by coal</td>
<td>( Q_2 = m_c h_c, h_c = CT )</td>
<td>( m_c = 0.115 \text{ kg/kg cli} , C = 1.15 \text{ kJ/kg °C} , T = 50°C )</td>
<td>6.61</td>
</tr>
<tr>
<td>3</td>
<td>Heat by raw material</td>
<td>( Q_3 = m_{rm} h_{rm}, h_{rm} = CT )</td>
<td>( m_{rm} = 1.667 \text{ kg/kg cli} , C = 0.86 \text{ kJ/kg °C} , T = 50°C )</td>
<td>71.68</td>
</tr>
<tr>
<td>4</td>
<td>Organics in the kiln feed</td>
<td>( Q_4 = FK h_{Os} )</td>
<td>( F = 0.10, h_{os} = 21036 \text{ kJ/kg}, K = 0.9 % ) (Ref.[7])</td>
<td>18.93</td>
</tr>
<tr>
<td>5</td>
<td>Heat by cooling air</td>
<td>( Q_5 = m_{ca} h_{ca} )</td>
<td>( m_{ca} = 2.1 \text{ kJ/kg cli} , h_{ca} = 30 \text{ kJ/kg}, (T = 50°C) )</td>
<td>63.00</td>
</tr>
</tbody>
</table>

**Total heat input** 2952.29 705.11 100.0

**Heat outputs :**

<table>
<thead>
<tr>
<th>Q. Sr.</th>
<th>Description</th>
<th>Equations used</th>
<th>Data</th>
<th>Result</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(KJ/Kg-clinker)</td>
</tr>
<tr>
<td>6</td>
<td>Formation of clinker</td>
<td>( Q_6 = 17.196(\text{Al}_2\text{O}_3) + 27.112(\text{MgO}) + 32(\text{CaO}) - 21.405(\text{SiO}_2) - 2.468(\text{Fe}_2\text{O}_3) ) (Clinker composition is given in Table 1)</td>
<td>1762.65</td>
<td>420.98</td>
</tr>
<tr>
<td>7</td>
<td>Kiln exhaust gas</td>
<td>( Q_7 = m_{eg} C_{P-eg} T_{eg} )</td>
<td>( m_{eg} = 2.094 \text{ kJ/kg cli} , C_{P-eg} = 1.1071 \text{ kJ/kg °C} , T = 275°C )</td>
<td>637.47</td>
</tr>
<tr>
<td>8</td>
<td>Moisture in raw material and coal</td>
<td>( Q_8 = m_{H_2O} \left( h_{fg}(50°C) + h_{276°C} - h_{5°C} \right) )</td>
<td>( m_{H_2O} = 0.008835 \text{ kg/kg cli} ) (in coal+raw material) ( h_{fg(50°C)} = 2591 \text{ J/kg} ) , ( h_{276°C} = 3104 \text{ J/kg} )</td>
<td>16.53</td>
</tr>
<tr>
<td>9</td>
<td>Hot air from cooler</td>
<td>( Q_9 = m_{air-co} h_{air-co} )</td>
<td>( m_{air-co} = 0.940 \text{ kg/kg cli} ) , ( m_{air-co} = 220 \text{ kJ/kg °C} ) , ( T = 300°C )</td>
<td>216.20</td>
</tr>
<tr>
<td>10</td>
<td>Heat loss by dust</td>
<td>( Q_{10} = (m_{dust-preheater} + m_{dust-air co}) h_{dust,ave} )</td>
<td>( m_{dust-preheater} = 0.042 \text{ kg/kg cli} ) , ( m_{dust-air co} = 0.006 \text{ kg/kg cli} ) , ( m_{dust,ave} = 275 \text{ kJ/kg} ) (Ref.[7])</td>
<td>13.20</td>
</tr>
<tr>
<td>11</td>
<td>Clinker discharge</td>
<td>( Q_{11} = m_{cl} h_{cli,T=110°C} )</td>
<td>( m_{cl} = 1 \text{ kg/kg cli} ) , ( h_{cli} = 86 \text{ kJ/kg} ) (Ref.[7])</td>
<td>86.00</td>
</tr>
</tbody>
</table>
### Convection & Radiation from kiln surface

\[ Q_{12} = \frac{1}{m_{cl}} \left[ A \right]_{\text{kiln}} h(T - T_a) \]

- \( h = \text{combine Convection & Radiation coff. From chart.} = 21.5 \text{ kcal/m}^2 \text{ C hr} \)
- \( A = 1092 \text{ m}^2 \), \( T = 300 \), \( T_a = 35 \text{ C} \)
- \( m_{\text{cl}} = 166666.67 \text{ kg/h} \) (Ans. X 4.18)

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<tbody>
<tr>
<td>12</td>
<td>Convection &amp; Radiation from kiln surface</td>
<td>( Q_{12} )</td>
<td>184.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>43.98</td>
</tr>
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<td></td>
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<td>6.24</td>
</tr>
</tbody>
</table>

### Convection & Radiation from cooler surface

\[ Q_{13} = \frac{1}{m_{cl}} \left[ A \right]_{\text{col}} h(T - T_a) \]

- \( h = \text{combine Convection & Radiation coff. From chart.} = 12.5 \text{ kcal/m}^2 \text{ C hr} \)
- \( A = 230 \text{ m}^2 \), \( T = 120 \), \( T_a = 35 \text{ C} \)
- \( m_{\text{cl}} = 166666.67 \text{ kg/h} \) (Ans. X 4.18)

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<tbody>
<tr>
<td>13</td>
<td>Convection &amp; Radiation from cooler surface</td>
<td>( Q_{13} )</td>
<td>6.14</td>
</tr>
<tr>
<td></td>
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<td>1.47</td>
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<td></td>
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<td>0.21</td>
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### Unaccounted losses

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<tbody>
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<td>14</td>
<td>Unaccounted losses</td>
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<td>29.96</td>
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<tr>
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<td></td>
<td></td>
<td>7.16</td>
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<td>1.01</td>
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**Total heat output**

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<td></td>
<td></td>
<td></td>
<td>2952.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>705.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100.0</td>
</tr>
</tbody>
</table>

Overall system Thermal Efficiency or (Energy efficiency for the kiln system) \( \eta = 59.70 \% \)
4.2 Mass balance

The average compositions for dried coal and pre-heater exhaust gas are shown in Fig. 2. Based on the coal composition, the net heat value has been found to be 24278.8 kJ/kg-coal. It is usually more convenient to define mass/energy data per kg clinker produced per unit time. The mass balance of the kiln system is summarized in Fig. 3. All gas streams are assumed to be ideal gases at the given temperatures.

4.3 Energy balance:

In order to analyze the kiln system thermodynamically, the following assumptions are made:

1. Steady state working conditions.
2. The change in the ambient temperature is neglected.
3. Cold air leakage into the system is negligible.
4. Raw material and coal compositions do not change.
5. Averaged kiln surface temperatures do not change.

Based on the collected data from AYCCL site, an energy balance is applied to the kiln system. The physical properties and equations can be found in Peray’s handbook [1]. The reference enthalpy is considered to be zero at 0 °C for the calculations. The complete energy balance for the system is shown in Table 2. It is clear from Table 2 that the total energy used in the process is 2952.29 kJ/kg-clinker, and the main heat source is the coal, giving a total heat of 2792.07 kJ/kg-clinker (94.57%). Also, the energy balance given in Table 2 indicates relatively good consistency between the total heat input and total heat output. Since most of the heat loss sources have been considered, there is only a 30 kJ/kg-clinker of energy difference from the input heat; this difference is nearly 1.01% of the
total input energy and can be attributed to the assumptions and nature of data. The 
distribution of heat losses to the individual components exhibits reasonably good 
agreement with some other key plants reported in the literature [3].

4.4 Kiln system efficiency & waste heat.

The overall system efficiency can be defined by $\eta = \frac{Q_6}{Q_{\text{Total input}}} = \frac{1762.65}{2952.29} = 0.597$ or 59.7%, which can be regarded as relatively low. The overall efficiency of the kiln 
system can be improved by recovering some of the heat losses. The recovered heat energy 
can then be used for several purposes, such as electricity generation and preparation of hot 
water.

4.5 Sources of waste heat

Large amounts of coal are consumed in the production of cement, especially in the 
calcination process, so the temperature of the exhaust gas from the kiln head to the back 
end is very high, so the recovery of the waste heat is necessary to improve the energy 
utilization efficiency. The places which released heat are discussed below.

4.5.1 Exhaust gas from the kiln terminal (22%),

The temperature of the exhaust gas from the kiln terminal is about 275°C. This heat can 
be reused by employing a waste heat recovery system.

4.5.2 Exhaust gas from the head of the kiln (7.6%)

The temperature of the exhaust gas at the kiln head is about 300°C, which is high enough 
for a waste heat recovery system to be useful at exist condition (w/out modification 
which it showed in Fig. 9 Sec. 5.3 to getting some improvement.

4.5.3 Heat diffusion from cement kiln shell (7 %)

The cement rotary kiln is the primary place where the calcination process occurs, so most 
of the energy is consumed here. The temperature in the kiln needs to be about 1450°C to 
ensure that the cement producing process is functioning properly. The temperature of the 
kiln shell surface is also very high and can be up to 350°C with a mean temperature of 
about 300°C. Between heat convection and radiation, much heat is released into the 
atmosphere. Fire bricks are set around the kiln to prevent heat dissipation; but the kiln 
shell cannot tolerate temperatures higher than 400°C. So at the same time, excess heat in 
the kiln shell must be promptly radiated away.

5. Waste heat recovery system

The thermodynamic cycle system that is most suitable to convert waste heat into power 
is the **Rankine cycle** in its various working fluid-specific forms:

- Traditional water-steam Rankine cycle.
- Organic Rankine cycle (ORC).
- Ammonia-water Rankine cycle (The so-called Kalina cycle).

Because the temperature of the exhaust gas is not high especially at Pre-heater exhaust gas, the efficiency of the waste heat recovery system is limited. Kalina cycle is thought to have better performance for electricity generation by recovering low-temperature waste heat than other cycles [4], and the reasons for selection Kalina Cycle will be introduced in sec.7.

A waste heat boiler for cement plants has been studied by many researchers, and this mature technology is already used in the cement industry.

In this study, a suspension pre-heater (SP) boiler was placed at the back end of the kiln to recover heat from the exhaust gas at 270°C and an air quenching cooler (AQC) boiler was added to recover the heat of the exhaust gas from the clinker cooler at 380°C (after exhaust system modified). The inlet air of the SP boiler comes from the final stage of the pre-heater (C1-stage), and its temperature is about 260°C–280°C.

5.1 The second generation of WHR power generation technology

5.1.1 Characteristics of the second generation system.

For most (over 80%) AQC of production lines that had been completed can absorb heat in 380-400°C or even higher, the systems which the outlet temperature of SP C1 cyclone is below 330°C will send the low-temperature superheated steam (below 300°C) like our plant (AYCCL) from SP boiler to AQC boiler, the AQC boiler has a superheater which can mix the steam (from AQC and SP boilers) and heat it to 360-380°C (the temperature will increase 50-60°C than original steam), and then, the heated steam will enter the turbine to generate power. This process can improve the power generation by around 8-10% than the first process Fig.5 shows process diagram of second generation system [5].
Fig. 5. Illustrate Process diagram of second generation system

Fig. 6. Shows Suspension Pre-heater (SP) Boiler with gas flow diagram
Fig. 7. Shows Air Quenching Cooler (AQC) Boiler with gas flow diagram

5.2 Thermal calculations.

The basic data of the cement plant is given below. The data is based on standard engineering practices.
1) The data is based on a dry process cement plant with a cement output of 4000 t/d clinker.
2) The energy consumption of the clinker is 2952.29 kJ/kg. The temperature of the raw mill drying process is 125°C & coal mill 170°C.
3) The flow rate of the exhaust gas from the kiln terminal is 281,670 N m3/h (Calculated 330,000 Nm3/h for one ID fan). The mean temperature is 275°C, but decreases to 185°C when it leaves the SP boiler.
4) The exhaust gas from the kiln head is 391,000 Nm3/h and the average temperature is 300°C, which decreases to 185°C when it leaves the AQC boiler.
5) The mean temperature of the cement kiln shell is about 320°C.
6) The Boiler, Turbine and generator efficiencies are set as 85%, 85% & 89% respectively.

The calculation results show that the generating capacity of the whole system is 7.5MW, these calculations for traditional steam cycle, Figure 8 shows process diagram with final assumptions and calculations.
Fig. 8 Shows process diagram with final assumption and calculation

Table 3: Show complete thermal calculations (equations & parameters)

<table>
<thead>
<tr>
<th>SP Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
</tr>
<tr>
<td>Input Data:</td>
</tr>
<tr>
<td>Mass of hot gases,</td>
</tr>
<tr>
<td>Temp. of hot gases, Tg</td>
</tr>
<tr>
<td>Stack Temp. (first assumption)</td>
</tr>
<tr>
<td>Stack Temp. (after balancing)</td>
</tr>
<tr>
<td>Density, ρ</td>
</tr>
<tr>
<td>WHR Boiler Efficiency</td>
</tr>
<tr>
<td>Boiler Pressure</td>
</tr>
<tr>
<td>Superheated Temp.</td>
</tr>
<tr>
<td>Enthalpy for superheated steam, h</td>
</tr>
<tr>
<td>Inlet water to boiler,</td>
</tr>
<tr>
<td>Enthalpy for inlet water, h</td>
</tr>
<tr>
<td>Saturated Temp., tst</td>
</tr>
<tr>
<td>Punch Temp. tp</td>
</tr>
<tr>
<td>Sensible heat, h</td>
</tr>
</tbody>
</table>

Calculations:

1) Quantity of heat available | kW | 16599.752 | Q=mCp(tg-ts) |
2) Mass of steam | kg/s | 5.05 | Boiler eff. = (mass of steam)(change of enthalpy in boiler)/heat supplied. |
### Designation | Unit | Quantity | Note and additional information
--- | --- | --- | ---
**Input Data :**
Mass of hot gases, | m³/hr | 391,000 | At normal operation, but (Fan design capacity 520,000 m³/hr)
Temp. of hot gases, | °C | 380 |
Stack Temp. (first assumption) | °C | 100 |
Stack Temp. (after balancing) | °C | 184.89 |
Density, | Kg/m³ | 1.2 | Fan Designer used 1.3 (ideal condition)
WHR Boiler Efficiency | - | 0.85 | Assumed
Boiler Pressure | Bar | 10 | Assumed
Superheated Temp. | °C | 250 | choose after trial methods,
Enthalpy for superheated steam, h | KJ/kg | 2942.6 | From Steam tables at 10 bar & 250 °C
Inlet water to boiler, | °C | 35 | Assumed
Enthalpy for inlet water, h | KJ/kg | 146.6 | From Steam tables at 35 °C
Saturated Temp., t_st | °C | 179.88 | From Steam tables at 10 bar
Punch Temp. tp | °C | 184.88 | + 5 deg.
Sensible heat, h | KJ/kg | 762.5 | From Steam tables at 10 bar
Fraction, x | - | 0.9 |
h_f | KJ/kg | 191.8 | at 01 bar & x = 0.9 (steam leaving assumption)
h_f | KJ/kg | 2392.1 | at 01 bar & x = 0.9 (steam leaving assumption)
Turbine Efficiency | - | 0.85 | Assumed
Generator Efficiency | - | 0.89 | Assumed

**Calculations:**
1) Quantity of heat available | kW | 37953.07 | Q=mC_p(t_g-t_s)
2) Mass of steam | kg/s | 11.54 | Boiler eff. = (mass of steam)(change of enthalpy in boiler)/heat supplied.
3) Produced Power (by turbine) | kW | 6898.66 | Power = (m)(h-h_f+x(h_f-g)) only from AQC boiler.
5) Output Power (by turbine) | kW | 8428.57 | With additional mass of steam which produced from SP Boiler. with eff. 85 %
6) Output Power (by generator) | kW | 7501.42 | With additional mass of steam which produced from SP Boiler. with eff. 89 %

59.70 t/h, 0.9MPa and 350 °C

**5.3 System Description (process):**

The exhaust gas from the kiln is, on average, 275°C, and the temperature of the air discharged from the cooler is 320°C but after duct modification with first chamber of cooler it will 380°C Figure 9. illustrate this modification. Both streams would be directed through a waste heat recovery steam generator (WHRSG), traditional steam cycle
considered here, and the available energy is transferred to water via the WHRSG. The schematic of a typical WHRSG cycle is shown in Fig.5. The available waste energy is such that steam would be generated. Because of various losses and inefficiencies inherent in the transfer of energy from the gas stream to the water circulating within the WHRSG, not all of the available energy will be transferred. A reasonable estimate on the efficiency of the WHRSG must be made. The Boiler, Turbine & generator efficiencies are set as 85%, 85 % & 89 % respectively. As the gas passes through the WHRSG, energy will be transferred and the gas temperature will drop. Targeting a pressure of 10 bars at the turbine inlet. The minimum stream temperature at the WHRSG’s exit would be higher than the corresponding saturation temperature, which is roughly 180 °C. As a limiting case, we assume the exit temperatures to be 185°C. After exiting the WHRSG, the energy of those streams can be recovered by using a compact heat exchanger. Hence, the final temperature can be reduced as low as possible. According to the final temperatures of both streams, the final enthalpies have been calculated. Therefore, the available heat energy would be:

\[ Q = 7501.42 \text{ kW} = 7.5 \text{ MW} \]

The next step is to find a steam turbine generator set that can utilize this energy. Since a steam turbine is a rotating piece of machinery, if properly maintained and supplied with a clean supply of dry steam. Considering steam turbine generator set 1000 kW. If we assume that the useful power generated is 6500 kW = 6.5 MW.

6. Heat recovery from kiln surface

The hot kiln surface is another significant heat loss source, and the heat loss through convection and radiation dictates a waste energy of 6.3% of the input energy. On the other hand, the use of a secondary shell on the kiln surface can significantly reduce this heat loss. Since the kiln surface needs to be frequently observed by the operator so as to see any local burning on the surface due to loss of refractory inside the kiln, we would not consider insulating the kiln surface, unless found a good solution for this issue.
The basic principle of the secondary shell is shown in Fig. 11. For the current rotary kiln, \( R_{klin} = \frac{\text{m}}{2.35} \), a radius of \( R_{\text{shell}} = \frac{\text{m}}{2.55} \) can be considered and Kiln surface area will be \( = 819.5 \text{ m}^2 \) (for 75% as effective area). Since the distance between the two surfaces is relatively small (440 mm), a realistic estimation for the temperature of the secondary shell can be made. We assume \( T_2 = 300 \degree \text{C} = 573 \text{ K} \). We would consider stainless steel for the material of the secondary shell since it has relatively low surface emissivity and thermal conductivity. The heat transfer rate by radiation is then calculated using the following equation [1]:

\[
Q_r = \frac{A_{klin} \sigma (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2} \left( \frac{R_{klin}}{R_{\text{shell}}} \right)}
\]

Where \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \), \( T_1=\text{Ts}=613 \text{ K} \), \( \varepsilon_1 = 0.78 \) (for oxidized kiln surface) and \( \varepsilon_2 = 0.35 \) (lightly oxidized stainless steel).

\[Q_r \approx 521 \text{ kW}\]

This heat loss is to be transferred through the insulation on the secondary shell. Therefore, assuming a reasonable temperature for the outer surface of the insulation, we can determine the required thickness of insulation. For glass wool insulation, the thermal conductivity is taken as 0.05 W/m K. Therefore, the resistance of the insulation layer would be,

\[
\text{Resistance of insulation} = \frac{\ln \left( \frac{R_{\text{ins}}}{R_{\text{shell}}} \right)}{2k_{\text{ins}} \pi R_{klin}} = \frac{\ln \left( \frac{R_{\text{ins}}}{2.55} \right)}{17} .44
\]

Assuming a temperature difference of \( \Delta T_{\text{ins}} = 240 \degree \text{C} \) (which means an outer surface temperature of 60 \degree \text{C} ) \( R_{\text{ins}} \) can be determined:

\[\Delta T_{\text{ins}} = Q \times (\text{resistance of insulation})\]

\[
240\degree \text{C} = 521000 \times \frac{\ln \left( \frac{R_{\text{ins}}}{2.55} \right)}{17} .44
\]
We found $R_{ins} = 2.6 \, \text{m}$, and the thickness of insulation would be

$$e = R_{ins} - R_{shell} = 0.1 \, \text{m} = 10 \, \text{cm}$$

It should be noted that when the secondary shell is added onto the kiln surface, the convective heat transfer would presumably become insignificant. This is because of the fact that the temperature gradient in the gap would be relatively very low, e.g., $0.45^\circ\text{C/cm}$ [1]. Therefore, the total energy savings due to the secondary shell would be

$$(184.14 \, \text{kJ/kg-clinker}) \times (46.3 \, \text{kg-clinker/s}) = 8525.7 \, \text{kW}$$

from the convective & radiation heat transfer.

Therefore, we can safely conclude that the use of a secondary shell on the current kiln surface would save at least $8.5 \, \text{MW}$, which is $6.3\%$ of the total input energy. This energy saving would result in a considerable reduction of fuel consumption (almost $6.5\%$) of the kiln system, and the overall system efficiency would increase by approximately $5\%$.

![Fig.12 Shows Rotary Kiln covered by special insulation. (China)](image1)

![Fig.13 Shows another application of kiln radiation and convection waste heat recovered for domestic using. (China)](image2)

7. **Energy & Cost savings with some major Benefits.**

Normally, more than half of the cost of cement production is spent on energy consumption. It will be much more if the cost of energy goes up. Therefore, the project of
using waste heat to generate electricity is a fairly good way to cut down the whole production cost. Figure. 16 Shows the mix of cement production cost (AYCCL 2012).

Fig. 14  Distribution of cement production cost, AYCCL 2012

7. Benefits by Energy Saving (Summary):

- Increase overall thermal use efficiency 4.8-6.4 %.
- Waste heat power generation amount 39-52 kWh per ton clinker.
- Lower clinker cost 7-10 % $ / ton from exist cost.
- Annual energy saving 50-70 % kWh from exist energy.
- The waste heat power generation system will also help to decrease the generation of CO2 generation up to 33%-50% emission reduced. [9]

8. Results & Conclusions

A detailed energy audit analysis, which can be directly applied to any dry kiln system, has been made for a specific key cement plant. The distribution of the input heat energy to the system components showed good agreement between the total input and output energy and gave significant insights about the reasons for the low overall system efficiency. According to the results obtained, the system efficiency is 59.7 %. The major heat loss sources have been determined as kiln exhaust (22 % of total input), cooler exhaust (7.6% of total input) and combined radiative and convective heat transfer from kiln surfaces (7 % of total input). For the first two losses, a conventional WHRSG system is proposed. Calculations showed that 7.5 MW of energy could be recovered (in case of steam cycle), but 9.75 MW (in case of Kalina Cycle). For the kiln surface, a secondary shell system has been proposed and designed. It is believed that the use of this system would lead to 8.5 MW of energy saving from the kiln surface.
The payback period for the two systems is expected to be less than 1.5 year in the first case and less than 2.5 years in second case. The above results are obtained using the provided data and their calculations, they may vary depending upon plant conditions and other economics factors.

9. References: