Heat Balance Analysis in Cement Rotary Kiln

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Abstract: The purpose of this study is optimizing the air and fuel quantities at kiln considering design parameters of the cement plant by keeping adequate safety factors at each level of calculations to assure that neither production rate nor quality of the clinker vary. Analysis of Heat balance was used to determine the sources of heat loss from the kiln system. Based on the collected data, an energy balance is applied to the kiln system. The physical properties and equations can be found in Perry’s handbook. The reference enthalpy is considered to be zero at 0°C for the calculations. The kiln has a capacity of 1000 ton-clinker per day. It found that the major heat loss is Heat losses by the kiln exhaust gas (2.33%), hot air from the cooler stack (7.28%), Radiation from kiln surfaces (11.71%). Some possible ways to recover the heat losses are introduced and discussed and they are Electricity generation, Heat recovery from kiln surface and Pre-heating raw material before the clinkering process.

Keywords: Rotary Kiln, Design Parameters, Exhaust Gas, Radiation

1. Introduction

Heat balance on a kiln can offer extremely useful information on the thermal performance of the system [1]. Heat balance show where or how the fuel heat is consumed based on the simple principle of input = output [2, 3]. Unnecessary energy losses can be easily detected, the principle of heat balance may be easily transferred to another system such as preheater, cooler, and drying system. Therefore the use of this study can be extended to another system than cement kiln [3].

Various reasons or circumstances may cause a need for a heat balance measurement. The following situations may justify a heat balance:
1. Performance test,
2. Recoding of kiln performance before/after a modification,
3. Unusually high heat consumption or abnormal kiln operational data,
4. Kiln optimization campaign.

Although the specific heat consumption proper could also be determine by measuring nothing but fuel heat and clinker production, a complete heat balance does offer to considerably more information and security [5]. The consistency of the measured data is proved much better, and the balance shows clearly where the heat is consumed. A heat balance is obviously a very efficient tool assessment of thermal efficiency [6].

A heat balance does not only mean calculation of heat balance items. The complete procedure usually includes the following steps:

1.1. Preparation

The extent of works to be done depends on the completeness and reliability which is desired. A careful planning and preparation are recommendable. The following basic items must be clarified:
1. What has to be measured (kiln and location of measuring/sampling points).
2. Duration of test?
3. The frequency of measurements (continuous recording, spot measurements, time intervals, etc)?
4. Necessary log sheets for manual recording ready?
5. Data recording system (electronic, pen recorder etc) available?
6. The flow of information among the test team?
7. Calibration and checks of instruments and scales done (flowmeters, orifice plates, ventsores,do-cell, thermocouples, etc.?
8. Temporary measuring equipment available? Complete?
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Correct span? Functioning properly?
9. For example:
   a. Pitot tube
   b. U-tube manometer
   c. Mobile thermometer
   d. Radiation pyrometer
   e. Orsat / gas analyzer
   f. Sampling equipment for gas
   g. Sampling procedure for solids (e.g. meal, dust, clinker) clarified?

1.2. Execution

An important precondition for a good test is steady kiln operation. The test should only be started if the system has reached a constant equilibrium state. During the test, variations of operating parameters should be avoided. For the measuring techniques, reference is made to the corresponding paper.

It is recommended to check completeness and reliability of measurements already during the test, afterward missing or uncertain information may create problems at the final evaluation.

1.3. Evaluation

This step is the scope of this paper. Evaluation of data means to establish a heat balance calculation according to the principle “input = output”

1.4. Discussion

A heat balance is such must bring some practical conclusions otherwise it would be only of academically interest. The following items may be considered:

1. Acceptable (normal) heat consumption?
2. Are heat balance items normal for given kiln system?
3. Measures in order to improve the heat economy of the system?

The last item can become quite an extensive work and the economic feasibility must be considered as well. Such subject, however, is beyond the scope of this paper. Summarizing, it is obvious that the 3rd step “evaluation” is only a limited part in the whole context [7].

2. Methods of Testing Calculations

2.1. Assumptions

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

1. The system is assumed to be steady state, steady flow & open.
2. Kinetic & Potential energy changes of input and output materials are negligible.
3. Ambient conditions are constant throughout the study i.e. T0 = 301 K.
4. Raw material and coal material composition do not change & feed rate of both are constant.
5. The natural convection is taken into account as the velocity of atmospheric air is < 3 m/s.
6. Average kiln surface temperature does not change throughout the study.
7. The gases inside the kiln are assumed to be ideal gases.

### Table 1. Equations used to calculate the rotary kiln Heat balance.

<table>
<thead>
<tr>
<th>Heat Output</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of Formation</td>
<td>Q = 2.2 A + 6.48 M + 7.646 C - 5.1165 S - 0.59 F</td>
</tr>
<tr>
<td>Heat in Preheater Exit Dust</td>
<td>Q = m_d * C_p,d(t_d - t_r)</td>
</tr>
<tr>
<td>Heat in Preheater Exit Gases</td>
<td>Q = m_e * C_p,e(t_e - t_r)</td>
</tr>
<tr>
<td>Heat in Clinker from Cooler Discharge</td>
<td>Q = m_c * C_p,c(t_c - t_r)</td>
</tr>
<tr>
<td>Heat in Evaporation of Raw Meal Moisture</td>
<td>Q = m_m * L</td>
</tr>
<tr>
<td>Heat Input</td>
<td></td>
</tr>
<tr>
<td>Heat of fuel Combustion</td>
<td>Q = CV * X</td>
</tr>
<tr>
<td>Heat in Kiln Feed</td>
<td>Q = m_f * C_p,f(t_f - t_r)</td>
</tr>
<tr>
<td>Heat in Cooling Air</td>
<td>Q = m_c_a * C_p,(t_c_a - t_r)</td>
</tr>
<tr>
<td>Heat in Primary Air</td>
<td>Q = m_p * C_p,(t_p - t_r)</td>
</tr>
<tr>
<td>Sensible Heat of Fuel</td>
<td>Q = m_fuel * C_p,(t_fuel - t_r)</td>
</tr>
</tbody>
</table>

| Ox(%) | 3.5  |
| CO(%)  | 0.01 |

Dust from cyclones (ton/hour): 10
Pitot measurements, kg/sec: 24.94
Production (tonne per day) based on clinker weight.

2.2. Basic data

2.2.1. Kiln Dimensions

| Diameter (m): | 3.4 |
| Length (m):   | 63  |

2.2.2. Preheater4Stage Cyclone with Calciner

| Feed temperature (°C): | 50 |
| Raw Meal Feed rate (tph): | 70 |
| Raw Meal Moisture (%): | 0.5 |
| Gas after preheater (°C): | 320 |

Orsat measurements:

| CO2(%) | 28 |

2.2.3. Firing System

i. Fuel: Gasoline
Calorific value (kcal/kg): 8000
ii. Kiln primary air
Temperature (°C): 40
Pitot measurements (kg air/kg clinker): 0.073
iii. Calciner primary air
Temperature (°C): 40
Flow rate (kg air/kg clinker): 0.009

2.2.4. Grate Cooler
i. Exhaust air:
  Temperature (°C): 240
  Pitot measurements (kg air/sec): 11.34
ii. Clinker from cooler
  Temperature (°C): 140
iii. Cooling air
  Flow rate, kg/kg clinker: 2.4
  Temperature (°C): 37

2.3. Analysis of Clinker

Table 2. The chemical composition of clinker sample.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>64.40</td>
</tr>
<tr>
<td>SiO₂</td>
<td>21.46</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>04.85</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>04.79</td>
</tr>
<tr>
<td>MgO</td>
<td>03.63</td>
</tr>
<tr>
<td>SO₃</td>
<td>00.50</td>
</tr>
<tr>
<td>LOI</td>
<td>00.79</td>
</tr>
<tr>
<td>K₂O</td>
<td>00.50</td>
</tr>
<tr>
<td>Na₂O</td>
<td>00.26</td>
</tr>
</tbody>
</table>

Mean specific heats between 0 and T°C
\[ Cp = A + B \cdot T \cdot 10^{-6} + C \cdot T^2 \cdot 10^{-9} \text{kcal/kg°C} \]

Table 3. Values of coefficients.

<table>
<thead>
<tr>
<th>Component</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.196</td>
<td>118</td>
<td>-43</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.443</td>
<td>39</td>
<td>28</td>
</tr>
<tr>
<td>N₂</td>
<td>0.244</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>O₂</td>
<td>0.218</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Air</td>
<td>0.237</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Raw Meal</td>
<td>0.206</td>
<td>101</td>
<td>-37</td>
</tr>
<tr>
<td>Clinker</td>
<td>0.186</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>0.262</td>
<td>390</td>
<td>0</td>
</tr>
</tbody>
</table>

3. Results

3.1. Basis
1. 1kg of clinker
2. Reference Temperature 0°C

3.2. Heat Outputs

3.2.1. Heat of Formation
Considering loss free clinker as loss-free meal feedstock under equilibrium condition
Loss-free feedstock composition:

\[ \text{SiO}_2 = 21.46\% \]
\[ \text{Al}_2\text{O}_3 = 4.85\% \]
\[ \text{Fe}_2\text{O}_3 = 4.79\% \]
\[ \text{CaO} = 64.4\% \]
\[ \text{MgO} = 3.63\% \]
\[ Q = 2.2 \cdot A + 6.48 \cdot M + 7.646 \cdot C - 5.1165 \cdot S - 0.59 \cdot F \]
\[ Q = 2.2 \cdot 0.196 + 6.48 \cdot 0.218 + 7.646 \cdot 0.443 - 5.1165 \cdot 0.244 - 0.59 \cdot 0.237 \]
\[ Q = 413.75 \text{kcal/kg clinker} \]

\[ \text{Mean Specific heat:} \]
\[ \text{Cp}_d = A + B \cdot T \cdot 10^{-6} + C \cdot T^2 \cdot 10^{-9} \text{kcal/kg°C} \]

From table 3:
\[ A = 0.206, B = 101, C = -37 \]

Therefore:
\[ \text{Cp}_d = 0.2305 \text{kcal/kg°C} \]
\[ t_d = 330°C \]
\[ t_r = 0°C \]
\[ Q_d = m_d \cdot \text{Cp}_d \cdot (t_d - t_r) \]
\[ Q_d = 0.24 \cdot 0.2305 \cdot (330 - 0) \]
\[ = 18.25 \text{kcal/kg clinker} \]

3.2.2. Heat in Preheater Exist Dust
1. Gross dust loss=8.5tph
2. Clinker output rate= 42tph
Dust in Preheater Exit Gas = 12/1000
\[ = 0.24 \text{ kg dust/kg clinker} \]

\[ \text{Mean Specific heat:} \]
\[ \text{Cp}_d = A + B \cdot T \cdot 10^{-6} + C \cdot T^2 \cdot 10^{-9} \text{kcal/kg°C} \]

From table 3:
\[ A = 0.206, B = 101, C = -37 \]

Therefore:
\[ \text{Cp}_d = 0.2305 \text{kcal/kg°C} \]
\[ t_d = 330°C \]
\[ t_r = 0°C \]
\[ Q_d = m_d \cdot \text{Cp}_d \cdot (t_d - t_r) \]
\[ Q_d = 0.24 \cdot 0.2305 \cdot (330 - 0) \]
\[ = 18.25 \text{kcal/kg clinker} \]

3.2.3. Heat in Preheater Exist Gases
\[ Q_e = m_e \cdot \text{Cp}_e \cdot (t_e - t_r) \]
Pitot measurements of kiln exit gases =24.94 kg/sec
Clinker Production = 1000tpd
\[ = 11.6 \text{ kg/sec} \]
\[ m_e = 24.94/11.6 \]
\[ = 2.15 \text{ kg/kg clinker} \]

\[ \text{Exit gas composition:} \]
\[ O_2 = 2.8\% \]
\[ CO_2 = 26.3\% \]
\[ CO = 0.03\% \]

Assuming balance gases as N₂
\[ N₂ = 70.87\% \]

\[ \text{Table 5. Determination of gases weight fraction.} \]

<table>
<thead>
<tr>
<th>Gas</th>
<th>vol.fraction</th>
<th>WT.fraction</th>
<th>WT.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>0.028</td>
<td>0.028*32/22.4=0.04</td>
<td>2.77</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.263</td>
<td>0.263*44/22.4=0.516</td>
<td>35.77</td>
</tr>
<tr>
<td>CO</td>
<td>0.0003</td>
<td>0.0003*28/22.4=0.000375</td>
<td>0.026</td>
</tr>
<tr>
<td>N₂</td>
<td>0.7087</td>
<td>0.7087*28/22.4=0.8859</td>
<td>61.434</td>
</tr>
<tr>
<td>Total</td>
<td>1.0</td>
<td>1.4422</td>
<td></td>
</tr>
</tbody>
</table>

The specific heat of exist gas is the sum of specific heats of individual gas composition. Considering that waste gases in terms of weight percentage comprise of 2.77% O₂, 35.77% CO₂ and 61.46%N₂.

\[ \text{Cp}_e = (2.77/100)(0.218 + 30*269 \cdot 10^{-6}) + (35.77/100)(0.196 + 118 * 269 \cdot 10^{-6}) - (43 * 2692 * 10^{-9}) + (61.46/100)(0.244 + 2 * 269 * 10^{-6}) \]
\[ = 0.2402 \text{kcal/kg°C} \]

Heat in preheater exist gas
3.2.4. Heat in Clinker from Cooler Discharge

\[ Q_c = m \cdot C_p c \cdot (t_c - t_r) \]

- \( m \) = wt. of clinker
- \( C_p c \) = mean specific heat of clinker, kcal/kg°C
- \( t_c \) = temperature of clinker, = 120°C
- \( C_p c = 0.186 + 54 \times 140 \times 10^{-6} = 0.1935 \text{ kcal/kg°C} \)

\[ Q_c = 1 \times 0.1935 \times (140-0) = 27.1 \text{ kcal/kg clinker} \]

3.2.5. Heat in Cooler Exhaust Air

\[ Q_{ce} = m_{ce} \cdot C_{p_{ce}} \cdot (t_{ce} - t_r) \]

- \( m_{ce} = \frac{11.34}{11.6} = 0.98 \text{ kg air/kg clinker} \)
- \( t_{ce} = 340°C \)
- \( C_{p_{ce}} = 0.237 + 23 \times 340 \times 10^{-6} = 0.2425 \text{ kcal/kg°C} \)

\[ Q_{ce} = 0.98 \times 0.2425 \times 240 = 57.041 \text{ kcal/kg clinker} \]

3.2.6. Heat in Evaporation of Raw Meal Moisture

\[ Q_{er} = m_{mr} \cdot L_{water} \]

- \( m_{mr} = 1.66 \text{ kg/kg clinker} \)
- \( L_{water} = 597 \text{ kcal/kg} \)

\[ Q_{er} = 1.66 \times 597 = 995.6 \text{ kcal/kg clinker} \]

3.2.7. Radiation and Conventional Losses

- Kiln: 45.7 kcal/kg clinker
- Preheater: 40.7 kcal/kg clinker
- Cooler: 5.2 kcal/kg clinker

Total heat loss by radiation and convention: \( Q = 91.6 \text{ kcal/kg clinker} \)

3.3. Heat Input

3.3.1. Heat of Fuel Combustion

\[ Q = CV \cdot X \]

- \( X \) = fuel consumption, = 0.118 kg fuel/kg clinker
- \( CV = 8000 \text{ kcal/kg} \)

\[ Q_{fuel} = 8000 \times 0.118 = 944 \text{ kcal/kg clinker} \]

3.3.2. Heat in Kiln Feed

\[ Q = m_i \cdot C_p (t_i - t) \]

- \( m_i = \) amount of kiln feed = 70 tph = 1.66 kg/kg clinker
- \( t_i = \) temp. of kiln feed = 50°C
- \( C_p = 0.206 + 101 \times 50 \times 10^{-6} = 0.211 \text{ kcal/kg°C} \)

\[ Q = 1.66 \times 0.211 \times (50 - 0) = 17.51 \text{ kcal/kg clinker} \]

3.3.3. Heat in Cooling Air

\[ Q = m_{co} \cdot C_p (t_{co} - t_r) \]

- \( m_{co} = \) amount of cooling air = 27.84 kg/sec = 2.4 kg/kg clinker
- \( t_{co} = \) temp. of cooling air = 37°C
- \( C_p = 0.237 + 23 \times 37 \times 10^{-6} = 0.238 \text{ kcal/kg°C} \)

\[ Q = 2.4 \times 0.238 \times (37 - 0) = 21.12 \text{ kcal/kg clinker} \]

3.3.4. Heat in Primary Air

\[ Q = m_p \cdot C_p (t_p - t) \]

- \( m_p = \) total primary air (kiln & calciner)
- Primary air to kiln = 0.073 kg/kg clinker
- Primary air to Calciner = 0.009 kg/kg clinker

\[ m_p = \text{Total Primary Air} = 0.082 \text{ kg/kg clinker} \]
- \( t_p = \) Temperature of Primary air = 40°C
- \( C_p = 0.237 + 23 \times 40 \times 10^{-6} = 0.238 \text{ kcal/kg°C} \)

\[ Q = 0.082 \times 0.238 \times (40 - 0) = 0.8 \text{ kcal/kg clinker} \]

3.3.5. Sensible Heat of Fuel

\[ Q = m_{fuel} \cdot C_p (t_{fuel} - t) \]

Mean \( C_p \) of gasoline = 0.53 kcal/kg.°C

\[ Q = 0.118 \times 0.53 \times (55 - 0) = 3.44 \text{ kcal/kg clinker} \]

3.4. Total Heat Inputs and Outputs

Total Heat Inputs = 986.87 kcal/kg clinker

Total Heat Outputs = 783.11 kcal/kg clinker

Calculation of Heat loss

\[ Q_{loss} = Q_{total inputs} - Q_{total outputs} = 986.87 - 783.11 = 203.76 \text{ kcal/kg clinker} \]
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Figure 1. Flow diagram show the kiln and preheater system.

Heat balance of kiln
Clinker output: 1000tpd

Table 6. Summary of total heat balance of kiln.

<table>
<thead>
<tr>
<th>Items</th>
<th>Kcal/kg clinker</th>
<th>Percentage%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat through fuel combustion</td>
<td>944</td>
<td>95.66</td>
</tr>
<tr>
<td>Sensible heat in kiln feed</td>
<td>17.51</td>
<td>1.77</td>
</tr>
<tr>
<td>Sensible heat in fuel</td>
<td>3.44</td>
<td>0.35</td>
</tr>
<tr>
<td>Sensible heat in air (cooling air and primary air)</td>
<td>21.92</td>
<td>2.22</td>
</tr>
<tr>
<td>Total heat input</td>
<td>986.87</td>
<td>100</td>
</tr>
<tr>
<td>Heat output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat in ph exit gases</td>
<td>170.42</td>
<td>21.76</td>
</tr>
<tr>
<td>Heat in dust in ph exit gases</td>
<td>18.25</td>
<td>2.33</td>
</tr>
<tr>
<td>Theoretical heat of reaction</td>
<td>413.75</td>
<td>52.83</td>
</tr>
<tr>
<td>Heat in cooler exhaust air</td>
<td>57.04</td>
<td>7.28</td>
</tr>
<tr>
<td>Heat in clinker leaving cooler</td>
<td>27.1</td>
<td>3.46</td>
</tr>
<tr>
<td>Heat in evaporation of moisture rawmeal</td>
<td>4.95</td>
<td>0.63</td>
</tr>
<tr>
<td>Radiation and convection losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. kiln45.7kcal/kg clinker</td>
<td>91.6</td>
<td>11.71</td>
</tr>
<tr>
<td>2. preheater40.7kcal/kg clinker</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. cooler5.2kcal/kg clinker</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total heat output</td>
<td>783.11</td>
<td>100</td>
</tr>
</tbody>
</table>

Net specific heat of fuel combustion= 1000 kcal/kg clinker

4. Discussion

Based on the collected data, an energy balance is applied to the kiln system. 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 6. It is clear that the total
energy used in the process is 986.87 kJ/kg-clinker, and the main heat source is Gasoline, giving a total heat of 944 kJ/kg-clinker (95.66%). Also, the energy balance given in Table 6 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 203 kJ/kg-clinker of energy difference from the input heat. This difference is nearly 20% 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.

4.1. General Remarks
1. It was found that the gases out at a high temperature of 330°C caused damage in the filter bags.
2. Radiation affects the performance of workers near the kiln.

4.2. Heat Recovery from the Kiln System
The overall system efficiency can be defined by η = \( \frac{Q_o}{Q_{\text{total input}}} \) = 0.42 or 42%, which can be regarded as relatively low. Some kiln systems operating at full capacity would declare an efficiency of 55% based on the current dry process methodology. The overall efficiency of the kiln system can be improved by recovering some of the heat losses [9]. The recovered heat energy can then be used for several purposes, such as electricity generation and preparation of hot water. There are a few major heat loss sources that would be considered for heat recovery.

These are heat losses by (1) preheater exhaust gas (21.76%), (2) hot air from the cooler stack (7.28%) and (3) radiation from kiln surfaces (11.7%). In the following section, there are some possible ways for recovering this wasted heat energy:

4.2.1. Electricity Generation
There are many ways in which heat wasted to the environment is captured and utilized for preheating and electricity generation. One of the most accessible and in turn the most cost-effective heat losses are the kiln exhausts gas and cooler discharge. The exhaust gas from the kilns is on average, 330°C, and the temperature of the air discharged from the cooler stack is 240°C. These streams are directed into the waste heat recovery generator which will convert the available energy into electricity. Thus this, in turn, reduces the electrical demand of the plant [10, 11].

4.2.2. Pre-heating
Apart from power production, one of the most effective methods of waste heat recovery is to preheat the raw material before the clinkering process. Preheating is usually achieved by directing gas streams into the raw material just before the grinding mill, which helps in increasing the temperature of the raw material and also lead to more efficient grinding process [12].

4.2.3. Heat Recovery from Kiln Surface
The hot surface of the kiln is another source of waste heat recovery, in which heat loss occurs by convection and radiation which is about 11.71% of the input energy. The use of the secondary shell on kiln surface can significantly reduce this loss which will reduce fuel consumption and increase the overall system efficiency by approximately 5-6% [13].

5. 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 sights about the reasons for the low overall system efficiency.

According to the results obtained, the system efficiency is 42%. The major heat loss sources have been determined as preheater exhaust gas (21.76% of total input), cooler exhaust (7.28% of total input) and combined radioactive and convective heat transfer from total kiln surfaces (11.71% of total input).

For the first two losses, a conventional West heat recovery steam generation system (WHRSG) system is proposed. For the kiln surface, a secondary shell system has been proposed and designed.

References


