## ANNEXURES

### Annexure A

#### Chemical compositions of the raw materials and raw meal

<table>
<thead>
<tr>
<th>Component</th>
<th>Limestone (wt %)</th>
<th>Sweetener Limestone (wt %)</th>
<th>Laterite (wt %)</th>
<th>Raw Meal (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>45.9</td>
<td>49.28</td>
<td>-</td>
<td>44.2</td>
</tr>
<tr>
<td>SiO₂</td>
<td>14</td>
<td>4.5</td>
<td>8</td>
<td>12.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.6</td>
<td>1.5</td>
<td>42</td>
<td>3.9</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.6</td>
<td>2.4</td>
<td>30</td>
<td>2.36</td>
</tr>
<tr>
<td>MgO</td>
<td>0.6</td>
<td>0.2</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>SiO₃</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### Chemical compositions clinker

<table>
<thead>
<tr>
<th>Component</th>
<th>(wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>63.86</td>
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<tr>
<td>SiO₂</td>
<td>22.2</td>
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<tr>
<td>Al₂O₃</td>
<td>6.8</td>
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<tr>
<td>Fe₂O₃</td>
<td>4.2</td>
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<tr>
<td>MgO</td>
<td>0.8</td>
</tr>
<tr>
<td>SiO₃</td>
<td>0.65</td>
</tr>
<tr>
<td>Free lime</td>
<td>1.1</td>
</tr>
<tr>
<td>Ignition loss</td>
<td>0.39</td>
</tr>
</tbody>
</table>

#### Chemical compositions of dust

<table>
<thead>
<tr>
<th>Component</th>
<th>(wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>63.5</td>
</tr>
<tr>
<td>SiO₂</td>
<td>25.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.16</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.91</td>
</tr>
<tr>
<td>MgO</td>
<td>0.4</td>
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</table>

#### Chemical compositions of exhaust gas

<table>
<thead>
<tr>
<th>Component</th>
<th>(vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>26.03</td>
</tr>
<tr>
<td>O₂</td>
<td>4.22</td>
</tr>
<tr>
<td>H₂O</td>
<td>4.84</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.04</td>
</tr>
<tr>
<td>N₂</td>
<td>64.87</td>
</tr>
</tbody>
</table>
Annexure B

Energy calculation of the raw mill (Production rate of 117 tonnes per hour)

For the energy analysis the reference enthalpy is considered to be zero at 0°C for the calculation. The various input and output energy calculations given as follow.

Input Energy

1. **Infiltrated air**
   Mass flow rate, \( m_{ia} = 24114 \text{ kg/hr} \)
   Temperature, \( T_{ia} = 30^\circ\text{C} \)
   Specific heat, \( c_{p_{ia}} = 0.9655 \text{ kJ/kg K} \)

   Infiltrated air heat energy, \( Q_{ia} = m_{ia} \times c_{p_{ia}} \times T_{ia} \)
   \[ = 698431.2 \text{ kJ/hr} \]

2. **Gas**
   Mass flow rate, \( m_g = 96458 \text{ kg/hr} \)
   Temperature, \( T_g = 30^\circ\text{C} \)
   Specific heat, \( c_{p_g} = 1.0812 \text{ kJ/kg K} \)

   Heat energy of gas, \( Q_g = m_g \times c_{p_g} \times T_g \)
   \[ = 37544540.26 \text{ kJ/hr} \]

3. **Limestone**
   Mass flow rate, \( m_l = 96426 \text{ kg/hr} \)
   Temperature, \( T_l = 30^\circ\text{C} \)
   Specific heat, \( c_{p_l} = 0.7664 \text{ kJ/kg K} \)

   Heat energy of limestone, \( Q_l = m_l \times c_{p_l} \times T_l \)
   \[ = 2217026.59 \text{ kJ/hr} \]
4. **Sweetener limestone**
   Mass flow rate, \( m_{sl} = 11344 \text{ kg/hr} \)
   Temperature, \( T_{sl} = 30^\circ \text{C} \)

   Specific heat, \( c_{p_{sl}} = 0.7632 \text{ kJ/kg K} \)

   Heat energy of sweetener limestone, \( Q_{sl} = m_{sl} \times c_{p_{sl}} \times T_{sl} \)

   \[ = 259732.22 \text{ kJ/hr} \]

5. **Laterite**
   Mass flow rate, \( m_{lt} = 5672 \text{ kg/hr} \)
   Temperature, \( T_{lt} = 30^\circ \text{C} \)

   Specific heat, \( c_{p_{lt}} = 0.745 \text{ kJ/kg K} \)

   Heat energy of laterite, \( Q_{lt} = m_{lt} \times c_{p_{lt}} \times T_{lt} \)

   \[ = 126769.2 \text{ kJ/hr} \]

6. **Material returned from separator**
   Mass flow rate, \( m_{rs} = 234000 \text{ kg/hr} \)
   Temperature, \( T_{rs} = 78^\circ \text{C} \)

   Specific heat, \( c_{p_{rs}} = 0.8142 \text{ kJ/kg K} \)

   Heat energy of material returned from separator, \( Q_{rs} = m_{rs} \times c_{p_{rs}} \times T_{rs} \)

   \[ = 14860778.4 \text{ kJ/hr} \]

7. **Moisture in limestone**
   Mass flow rate, \( m_{ml} = 1929 \text{ kg/hr} \)
   Temperature, \( T_{ml} = 30^\circ \text{C} \)

   Specific heat, \( c_{p_{ml}} = 4.178 \text{ kJ/kg K} \)

   Heat energy of moisture in the limestone, \( Q_{ml} = m_{ml} \times c_{p_{ml}} \times T_{ml} \)

   \[ = 241780.86 \text{ kJ/hr} \]
8. **Moisture in sweetener limestone**  
Mass flow rate, $m_{sm} = 1361 \text{ kg/hr}$  
Temperature, $T_{sm} = 30^\circ C$  
Specific heat, $c_{p_{sm}} = 4.187 \text{ kJ/kg K}$  
Heat energy of moisture in the sweetener limestone, $Q_{sm} = m_{sm} \times c_{p_{sm}} \times T_{sm}$  
= 170587.74 kJ/hr

9. **Moisture in laterite**  
Mass flow rate, $m_{tm} = 284 \text{ kg/hr}$  
Temperature, $T_{tm} = 30^\circ C$  
Specific heat, $c_{p_{tm}} = 4.187 \text{ kJ/kg K}$  
Heat energy of moisture in laterite, $Q_{tm} = m_{tm} \times c_{p_{tm}} \times T_{tm}$  
= 35596.56 kJ/hr

10. **Dust**  
Mass flow rate, $m_d = 2973 \text{ kg/hr}$  
Temperature, $T_d = 360^\circ C$  
Specific heat, $c_{p_d} = 0.9971 \text{ kJ/kg K}$  
Heat energy of dust, $Q_d = m_d \times c_{p_d} \times T_d$  
= 1067138.33 kJ/hr

11. **Heat from electrical energy**, $Q_e = 2223 \text{ kW}$  
= 8002800 kJ/hr

Total energy input to the raw mill,  
$Q = Q_{da} + Q_g + Q_t + Q_{st} + Q_{lt} + Q_{rs} + Q_{mi} + Q_{sm} + Q_{tm} + Q_d + Q_e$  
= 65225181.37 kJ/hr
Output energy

1. **Infiltrated air**
   Mass flow rate, \( m_{ia} = 24114 \text{ kg/hr} \)
   Temperature, \( T_{ia} = 88^\circ \text{C} \)
   Specific heat, \( c_{p_{ia}} = 0.9908 \text{ kJ/kg K} \)
   Heat energy of infiltrated air, \( Q_{ia} = m_{ia} \times c_{p_{ia}} \times T_{ia} \) \( \text{(A)} \)
   \[ = 2102514.46 \text{kJ/hr} \]

2. **Gas**
   Mass flow rate, \( m_g = 96458 \text{ kg/hr} \)
   Temperature \( T_g = 88^\circ \text{C} \)
   Specific heat, \( c_{p_g} = 0.9745 \text{ kJ/kg K} \)
   Heat energy of gas, \( Q_g = m_g \times c_{p_g} \times T_g \) \( \text{(B)} \)
   \[ = 8271954.85 \text{kJ/hr} \]

3. **Steam**
   Mass flow rate, \( m_{st} = 2989 \text{ kg/hr} \)
   Temperature, \( T_{st} = 88^\circ \text{C} \)
   Specific heat, \( c_{p_{st}} = 1.962 \text{ kJ/kg K} \)
   Heat energy of steam, \( Q_{st} = m_{st} \times c_{p_{st}} \times T_{st} \) \( \text{(C)} \)
   \[ = 516068.78 \text{kJ/hr} \]

4. **Raw meal**
   Mass flow rate, \( m_{rm} = 350415 \text{ kg/hr} \)
   Temperature, \( T_{rm} = 88^\circ \text{C} \)
   Specific heat, \( c_{p_{rm}} = 0.8232 \text{ kJ/kg K} \)
   Heat energy of raw meal, \( Q_{rm} = m_{rm} \times c_{p_{rm}} \times T_{rm} \) \( \text{(D)} \)
   \[ = 25383247.68 \text{kJ/hr} \]
5. **Moisture**

Mass flow rate, \( m_m = 585 \text{ kg/hr} \)

Temperature, \( T_m = 88^\circ \text{C} \)

Specific heat, \( c_{p_m} = 4.195 \text{ kJ/kg K} \)

Heat energy of moisture, \( Q_m = m_m \times c_{p_m} \times T_m \) \( \cdots \cdot (E) \)

\[
= 215958.6 \text{ kJ/hr}
\]

Efficiency of the raw mill, \( \eta = \frac{A+B+C+D+E}{\text{Total input energy}} \)

\[
= 55.94\%
\]

7. **Heat loss from raw mill**

a) **Drying room**

Inner diameter of drying room, \( D_i = 4.2 \text{ m} \)

Outer diameter of drying room, \( D_o = 4.28 \text{ m} \)

Length of drying room, \( L = 2.5 \text{ m} \)

Drying room temperature, \( T_{in} = 133.07 ^\circ \text{C} \)

Surface temperature, \( T_s = 72 ^\circ \text{C} \)

Surrounding Temperature, \( T_{\infty} = 30 ^\circ \text{C} \)

Outer surface heat transfer coefficient, \( h_a = 5.8 \text{ W/ W/m}^2\text{K} \)

(Film temperature \( T_f = 50 ^\circ \text{C} \)

Velocity of air = 2 m/sec

Density of air \( \rho = 1.06 \text{ kg/m}^3 \)

Dynamic viscosity of air \( \mu = 20.1 \times 10^{-6} \text{ Ns/m}^2 \)

Prandtl number \( Pr = 0.698 \)

Thermal conductivity of air \( k = 0.02826 \text{ W/mK} \)

Reynold’s number \( Re = \frac{D_o V}{\mu} \)
Diameter $D_o = 4.28$ m

Nusselt number $N_u = 0.0266 \times (Re^{0.805}) \times Pr^{0.333}$

(Frank, 2001)

Outer surface heat transfer coefficient

$$h_o = \frac{N_u k}{D_o} \approx 5.8 \text{ W/ m}^2\text{K}$$

Inner surface heat transfer coefficient, $= 6.8 \text{ W/ m}^2\text{K}$

(Velocity of air $V = 2.5$ m/sec

Bulk mean temperature of air $T_b = 113^\circ$C

Density of air $\rho = 0.946$ kg/m$^3$

Dynamic viscosity of air $\mu = 21.87 \times 10^{-6}$ Ns/m$^2$

Prandle number $Pr = 0.688$

Thermal conductivity of air $k = 0.0321$ W/mK

Reynold’s number $Re = \frac{\rho D_o V}{\mu} = 454184$

Diameter $D_{in} = 4.2$ m

As per Gnielinsky correlation (Frank, 2001),

$$N_u = 0.214 \times (Re^{0.8} - 100) \times Pr^{-0.4} \times (1 + \frac{D_{in}}{D_o})^2$$

Heat transfer coefficient $h_{in} = \frac{N_u k}{D_{in}} = 6.8 \text{ W/ m}^2\text{K}$

Thermal conductivity material, $k = 52$ W/m $^0$C

Emissivity of the raw mill surface, $\varepsilon = 0.8$

Stefan Boltzmann constant $= 5.67 \times 10^{-8}$ W/m$^2$K$^4$

i) Heat loss with convection due to the inside temperature and the surface temperature ($Q_{cv1}$)

$$= \pi D_{in} h_{in} L (T_{in} - T_s)$$

$$= 13752.05 \text{ Watts}$$
ii) The heat loss with conduction due to the temperature difference between inner and outer surface \((Q_{cd})\)

\[
Q_{cd} = \frac{(T_{in} - T_s)}{\ln \left( \frac{r_o}{r_i} \right)}
\]

where \(r_i = \) inside radius of raw mill

\(r_o = \) outer radius of the raw mill.

\[= 2642371.65 \text{ Watts} \]

iii) Heat losses with the convection from the outer surface to the environment \((Q_{cv2})\)

\[
Q_{cv2} = \pi D_o h_o L (T_s - T_\infty)
\]

\[= 8184.47 \text{ Watts} \]

iv) Heat losses with radiation occur from the outer surface to the environment \((Q_{ra})\)

\[
Q_{ra} = \pi D_o \epsilon \sigma (T_s^4 - T_\infty^4)
\]

\[= 8744.83 \text{ Watts} \]

Drying room total heat loss = \(Q_{cv1} + Q_{cd} + Q_{cv2} + Q_{ra}\)

\[= 2673053.01 \text{ Watts} \]

\[= 9622990.8 \text{ kJ/hr} \]

b) Grinding room

Inner diameter of grinding room, \(D_{in} = 4.2 \text{m}\)

Outer diameter of grinding room, \(D_o = 4.28 \text{m}\)

Length of grinding room, \(L = 10 \text{ m}\)

Grinding room temperature, \(T_{in} = 108.98^\circ \text{C}\)

Surface temperature \(T_s = 82^\circ \text{C}\)

Inner surface heat transfer coefficient, \(= 6.8 \text{ W/ W/m}^2\text{K}\)
Outer surface heat transfer coefficient, $h_a = 5.8 \text{ W/ W/m}^2\text{K}$

The thermal conductivity material, $k = 52 \text{ W/m}^0\text{C}$

Emissivity of the raw mill surface, $\varepsilon = 0.8$

Stefan Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$

i) Heat losses with convection due to the inside temperatures and the surface temperature

$$= \pi D_{in} h_a L (T_{in} - T_s)$$

$$= 24301.98 \text{ Watts}$$

ii) The heat loss with conduction due to the temperature difference between inner and outer surfaces ($Q_{cd}$)

$$= \frac{(T_{in} - T_s)}{\ln \frac{D_{in}}{2L}} \frac{L}{k}$$

$$= 4669473.53 \text{ Watts}$$

iii) Heat losses with the convection from the outer surface to the environment ($Q_{cv2}$)

$$= \pi D_o h_a L (T_s - T_\infty)$$

$$= 40532.63 \text{ Watts}$$

iv) Heat losses with radiation occur from the outer surface to the environment ($Q_r$)

$$= \pi D_o \varepsilon \sigma (T_s^4 - T_\infty^4)$$

$$= 45436.13 \text{ Watts}$$

Grinding room total heat loss $= Q_{cv1} + Q_{cd} + Q_{cv2} + Q_r$

$$= 4779744.27 \text{ Watts}$$

$$= 17207079.36 \text{ kJ/hr}$$

Total heat loss from the raw mill ($Q_{total}$)

$$= \text{Drying room heat loss} + \text{Grinding room heat loss}$$

$$= 26830070.19 \text{ kJ/hr}$$
Exergy calculation of raw mill (Production rate of 117 tonnes per hour)

For incompressible substances such as solids, both the constant pressure and constant volume specific heats are identical.

\[ c_p = c_v = c \]

Internal energy change and enthalpy change values are (Bejan, 1988)

\[ \Delta u = \int_1^2 c(T) = c_{avg} (T_2 - T_1) \]

\[ \Delta h = \Delta u + v\Delta p \]

where \( c_{avg} \) is the average specific heat, \( v \) is the specific volume and \( \Delta p \) is the pressure change. Pressure change in the unit is negligible so that enthalpy change is equal to internal energy change of the material. The enthalpy values of the input and output materials can be expressed in terms of reference temperature \( (T_o) \).

\[ \Delta h_{in} = c_{avg}(T_1 - T_o) \]

\[ \Delta h_{in} = c_{avg}(T_2 - T_o) \]

where \( T_1 \) and \( T_2 \) are the input and output temperatures of the materials and \( T_o \) is the reference temperature.

For incompressible substances the entropy change is

\[ s_2 - s_1 = c_{avg} \ln \frac{T_2}{T_o} \] (Rosen et al., 2005).

For ideal gases the entropy change is (Rosen et al., 2005).

\[ s_2 - s_1 = c_{p,avg} \ln \frac{T_2}{T_o} - R \ln \frac{P_2}{P_o} \]

where \( R \) = Gas constant
Since the pressure of the input and output materials are equal, $\Delta s$ the values for input and output materials are expressed as

$$\Delta s_{in} = c_{p_{avg}} \ln \frac{T_1}{T_0}$$
$$\Delta s_{out} = c_{p_{avg}} \ln \frac{T_2}{T_0}$$

After obtaining the entropy and enthalpy values of the input and output materials, the exergy values of the input and output materials can be calculated from

$$\Delta \psi_{in} = \Delta h_{in} - T_0 \Delta s_{in}$$
$$\Delta \psi_{out} = \Delta h_{out} - T_0 \Delta s_{out}$$

where $\psi$ is the specific exergy

For the exergy analysis of the raw mill the reference temperature and pressure are assumed to be 298 K ($T_0$) and 101 kPa (dead state condition) respectively.

**Input Exergy.**

1. **Infiltrated air**
   Mass flow rate, $m_{i\alpha} = 24114$ kg/hr
   Temperature, $T_{i\alpha} = 303$ K
   Specific heat, $c_{p_{i\alpha}} = 0.9655$ kJ/kg K

   Enthalpy change, $\Delta H_{i\alpha} = m_{i\alpha} \times c_{p_{i\alpha}} \times (T_{i\alpha} - T_0)$
   $$= 116504.2 \text{ kJ/hr}$$

   Entropy change, $\Delta S_{i\alpha} = m_{i\alpha} \times c_{p_{i\alpha}} \times \ln \left(\frac{T_{i\alpha}}{T_0}\right)$
   $$= 387.38 \text{ kJ/hr}$$
Exergy of infiltrated air, \( Ex_{ia} = \Delta H_{ia} - T_0 \times \Delta S_{ia} \)
\[ = 965.77 \text{ kJ/hr} \]

2. **Gas**

Mass flow rate, \( m_g = 96458 \text{ kg/hr} \)

Temperature, \( T_g = 633 \text{K} \)

Specific heat, \( c_{pg} = 1.0812 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_g = m_g \times c_{pg} \times (T_g - T_0) \)
\[ = 34937280.52 \text{ kJ/hr} \]

Entropy change, \( \Delta S_g = m_g \times c_{pg} \times \ln\left(\frac{T_g}{T_0}\right) \)
\[ = 78569.97 \text{ kJ/hr} \]

Exergy of the gas, \( Ex_g = \Delta H_g - T_0 \times \Delta S_g \)
\[ = 11523428.22 \text{ kJ/hr} \]

3. **Limestone**

Mass flow rate, \( m_l = 96426 \text{ kg/hr} \)

Temperature, \( T_l = 303 \text{K} \)

Specific heat, \( c_{pl} = 0.7632 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_l = m_l \times c_{pl} \times (T_l - T_0) \)
\[ = 369504.43 \text{ kJ/hr} \]

Entropy change, \( \Delta S_l = m_l \times c_{pl} \times \ln\left(\frac{T_l}{T_0}\right) \)
\[ = 1229.66 \text{ kJ/hr} \]

Exergy of the limestone, \( Ex_l = \Delta H_l - T_0 \times \Delta S_l \)
\[ = 3065.63 \text{ kJ/hr} \]
4. **Sweetener limestone**

Mass flow rate, $m_{sl} = 11344$ kg/hr

Temperature, $T_{sl} = 303$K

Specific heat, $c_{p_{sl}} = 0.7632$ kJ/kg K

Enthalpy change, $\Delta H_{sl} = m_{sl} \times c_{p_{sl}} \times (T_{sl} - T_0)$

$$= 43288.7 \text{ kJ/hr}$$

Entropy change, $\Delta S_{sl} = m_{sl} \times c_{p_{sl}} \times \ln \left( \frac{T_{sl}}{T_0} \right)$

$$= 144.06 \text{ kJ/hr}$$

Exergy of the sweetener limestone, $E_{x_{sl}} = \Delta H_{sl} - T_0 \times \Delta S_{sl}$

$$= 359.15 \text{ kJ/hr}$$

5. **Laterite**

Mass flow rate, $m_{lt} = 5672$ kg/hr

Temperature, $T_{lt} = 303$K

Specific heat, $c_{p_{lt}} = 0.745$ kJ/kg K

Enthalpy change, $\Delta H_{lt} = m_{lt} \times c_{p_{lt}} \times (T_{lt} - T_0)$

$$= 21128.2 \text{ kJ/hr}$$

Entropy change, $\Delta S_{lt} = m_{lt} \times c_{p_{lt}} \times \ln \left( \frac{T_{lt}}{T_0} \right)$

$$= 70.31 \text{ kJ/hr}$$

Exergy of the laterite, $E_{x_{lt}} = \Delta H_{lt} - T_0 \times \Delta S_{lt}$

$$= 175.29 \text{ kJ/hr}$$
6. Material returned from separator for recirculation.

Mass flow rate, \( m_{rs} = 234000 \text{ kg/hr} \)

Temperature, \( T_{rs} = 351 \text{ K} \)

Specific heat, \( c_{prs} = 0.8142 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_{rs} = m_{rs} \times c_{prs} \times (T_{rs} - T_0) \)
\[
= 10097708.4 \text{ kJ/hr}
\]

Entropy change, \( \Delta S_{rs} = m_{rs} \times c_{prs} \times \ln \left( \frac{T_{rs}}{T_0} \right) \)
\[
= 31187.2 \text{ kJ/hr}
\]

Exergy of the material returned from separator, \( Ex_{rs} = \Delta H_{rs} - T_0 \times \Delta S_{rs} \)
\[
= 803923.22 \text{ kJ/hr}
\]

7. Moisture in the limestone

Mass flow rate, \( m_{ml} = 1929 \text{ kg/hr} \)

Temperature, \( T_{ml} = 303 \text{ K} \)

Specific heat, \( c_{pml} = 4.178 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_{ml} = m_{ml} \times c_{pml} \times (T_{ml} - T_0) \)
\[
= 40296.81 \text{ kJ/hr}
\]

Entropy change, \( \Delta S_{ml} = m_{ml} \times c_{pml} \times \left( \frac{T_{ml}}{T_0} \right) \)
\[
= 134.1 \text{ kJ/hr}
\]

Exergy of moisture in the limestone, \( Ex_{ml} = \Delta H_{ml} - T_0 \times \Delta S_{ml} \)
\[
= 334.33 \text{ kJ/hr}
\]
8. **Moisture in the sweetener limestone**

Mass flow rate, \( m_{sm} = 1361 \text{ kg/hr} \)

Temperature, \( T_{sm} = 303 \text{K} \)

Specific heat, \( c_{p_{sm}} = 4.187 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_{sm} = m_{sm} \times c_{p_{sm}} \times (T_{sm} - T_0) \)

\[ = 28431.29 \text{ kJ/hr} \]

Entropy change, \( \Delta S_{sm} = m_{sm} \times c_{p_{sm}} \times \left(\frac{T_{sm}}{T_0}\right) \)

\[ = 94.62 \text{ kJ/hr} \]

Exergy of moisture in the sweetener limestone, \( E_{x_{sm}} = \Delta H_{sm} - T_0 \times \Delta S_{sm} \)

\[ = 235.88 \text{ kJ/hr} \]

9. **Moisture in laterite**

Mass flow rate, \( m_{tm} = 284 \text{ kg/hr} \)

Temperature, \( T_{tm} = 303 \text{K} \)

Specific heat, \( c_{p_{tm}} = 4.187 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_{tm} = m_{tm} \times c_{p_{tm}} \times (T_{tm} - T_0) \)

\[ = 5932.76 \text{ kJ/hr} \]

Entropy change, \( \Delta S_{tm} = m_{tm} \times c_{p_{tm}} \times \left(\frac{T_{tm}}{T_0}\right) \)

\[ = 19.74 \text{ kJ/hr} \]

Exergy of moisture in the laterite, \( E_{x_{tm}} = \Delta H_{tm} - T_0 \times \Delta S_{tm} \)

\[ = 49.22 \text{ kJ/hr} \]
10. Dust

Mass flow rate, \( m_d = 2973 \text{ kg/hr} \)

Temperature, \( T_d = 633\text{K} \)

Specific heat, \( c_{p_d} = 0.9971 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_d = m_d \times c_{p_d} \times (T_d - T_0) \)
\[ = 993031.50 \text{ kJ/hr} \]

Entropy change, \( \Delta S_d = m_d \times c_{p_d} \times \left(\frac{T_d}{T_0}\right) \)
\[ = 2233.22 \text{ kJ/hr} \]

Exergy of the dust \( Ex_d = \Delta H_d - T_0 \times \Delta S_d \)
\[ = 327533.43 \text{ kJ/hr} \]

11. Exergy related to electrical work \( Ex_e = 8002800 \text{ kJ/hr} \)

Total input exergy

\[
Ex = Ex_{ia} + Ex_g + Ex_i + Ex_{st} + Ex_{lt} + Ex_{rs} + Ex_{mt} + Ex_{sm} + \]
\[ + Ex_{im} + Ex_d + Ex_e \]
\[ = 20662870.14 \text{ kJ/hr} \]

Output exergy

1. Infiltrated air

Mass flow rate, \( m_{ia} = 24114 \text{ kg/hr} \)

Temperature, \( T_{ia} = 361\text{K} \)

Specific heat, \( c_{p_{ia}} = 0.9908 \text{ kJ/kg K} \)

Enthalpy change, \( \Delta H_{ia} = m_{ia} \times c_{p_{ia}} \times (T_{ia} - T_0) \)
\[ = 1506268.95 \text{ kJ/hr} \]

Entropy change, \( \Delta S_{ia} = m_{ia} \times c_{p_{ia}} \times \ln \left(\frac{T_{ia}}{T_0}\right) \)
\[ = 4585.38 \text{ kJ/hr} \]

Exergy of the infiltrated air, \( Ex_{ia} = \Delta H_{ia} - T_0 \times \Delta S_{ia} \ -----(A) \)
\[ = 139825.45 \text{ kJ/hr} \]
2. **Gas**

Mass flow rate $m_g = 96458$ kg/hr

Temperature, $T_g = 361$K

Specific heat, $c_{p,g} = 0.9745$ kJ/kg K

Enthalpy change, $\Delta H_g = m_g \times c_{p,g} \times (T_g - T_0)$

$$= 5929794.13 \text{ kJ/hr}$$

Entropy change, $\Delta S_g = m_g \times c_{p,g} \times \ln \left( \frac{T_g}{T_0} \right)$

$$= 18051.47 \text{ kJ/hr}$$

Exergy of the gas $Ex_g = \Delta H_g - T_0 \times \Delta S_g$ \(\text{--------}(B)\)

$$= 550456.9 \text{ kJ/hr}$$

3. **Steam**

Mass flow rate, $m_{st} = 2989$ kg/hr

Temperature, $T_{st} = 361$K

Specific heat, $c_{p,\text{st}} = 1.962$ kJ/kg K

Enthalpy change, $\Delta H_{st} = m_{st} \times c_{p,\text{st}} \times (T_{st} - T_0)$

$$= 369458.33 \text{ kJ/hr}$$

Entropy change, $\Delta S_{st} = m_{st} \times c_{p,\text{st}} \times \ln \left( \frac{T_{st}}{T_0} \right)$

$$= 1124.7 \text{ kJ/hr}$$

Exergy of steam, $Ex_{st} = \Delta H_{st} - T_0 \times \Delta S_{st}$ \(\text{--------}(C)\)

$$= 34296.45 \text{ kJ/hr}$$
4. **Raw meal**

Mass flow rate, \( m_{rm} = 350415 \) kg/hr

Temperature, \( T_{rm} = 361 \) K

Specific heat, \( c_{p_{rm}} = 0.8232 \) kJ/kg K

Enthalpy change, \( \Delta H_{rm} = m_{rm} \times c_{p_{rm}} \times (T_{rm} - T_0) \)
\[
= 18210612.01 \text{ kJ/hr}
\]

Entropy change, \( \Delta S_{rm} = m_{rm} \times c_{p_{rm}} \times \ln \left( \frac{T_{rm}}{T_0} \right) \)
\[
= 55436.71 \text{ kJ/hr}
\]

Exergy of the raw meal, \( Ex_{rm} = \Delta H_{rm} - T_0 \times \Delta S_{rm} \text{--------(D)} \)
\[
= 1690473.02 \text{ kJ/hr}
\]

5. **Moisture**

Mass flow rate, \( m_m = 585 \) kg/hr

Temperature, \( T_m = 361 \) K

Specific heat, \( c_{p_m} = 4.195\)kJ/kg K

Enthalpy change, \( \Delta H_m = m_m \times c_{p_m} \times (T_m - T_0) \)
\[
= 154606.73 \text{ kJ/hr}
\]

Entropy change, \( \Delta S_m = m_m \times c_{p_m} \times \ln \left( \frac{T_m}{T_0} \right) \)
\[
= 470.65 \text{ kJ/hr}
\]

Exergy of the moisture, \( Ex_m = \Delta H_m - T_0 \times \Delta S_m \text{--------(E)} \)
\[
= 14351.99 \text{ kJ/hr}
\]

**Exergy efficiency**

\[
\text{Exergy efficiency of the raw mill} = \frac{A+B+C+D+E}{\text{Total input exergy}}
\]
\[
= 11.76\%
\]

**Loss of exergy** = 88.24%
Annexure D

Calculations of useful energy and exergy due to the clinker formation (1 kg of clinker) in the kiln system.

The useful heat and useful chemical exergy due to clinker formation have been calculated using the data of the enthalpies of reactions of the raw meal to form clinker (Rosemann et al., 1987) and the standard chemical exergy values of the gas and solid flows in cement kiln plant (Morris and Szargut, 1996) are shown below.

Standard chemical exergy values of the gas and solid flows in cement plant (Morris and Szargut 1996)

<table>
<thead>
<tr>
<th>Species</th>
<th>Chemical Exergy (kJ/k mole)</th>
<th>Species</th>
<th>Chemical exergy (kJ/k mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3(s, )$</td>
<td>200400</td>
<td>$\text{CaSO}_4(s, )$</td>
<td>8200</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3\text{SiO}_2(s)$</td>
<td>15400</td>
<td>$\text{Fe}_2\text{O}_3(s)$</td>
<td>16500</td>
</tr>
<tr>
<td>$\text{CO}(g)$</td>
<td>275100</td>
<td>$\text{H}_2(g)$</td>
<td>236100</td>
</tr>
<tr>
<td>$\text{CO}_2(g)$</td>
<td>19870</td>
<td>$\text{H}_2\text{O}(l)$</td>
<td>900</td>
</tr>
<tr>
<td>$\text{CaCO}_3(s)$</td>
<td>1000</td>
<td>$\text{H}_2\text{O}(g)$</td>
<td>9490</td>
</tr>
<tr>
<td>$\text{CaCO}_3\cdot\text{MgCO}_3(s)$</td>
<td>15100</td>
<td>$\text{K}_2\text{O}(s)$</td>
<td>413100</td>
</tr>
<tr>
<td>$\text{CaO}(s)$</td>
<td>101200</td>
<td>$\text{MgO}(s)$</td>
<td>66800</td>
</tr>
<tr>
<td>$\text{CaO}\cdot\text{Al}_2\text{O}_3(s)$</td>
<td>275400</td>
<td>$\text{MgCO}_3(s)$</td>
<td>37900</td>
</tr>
<tr>
<td>$2\text{CaO}\cdot\text{Al}_2\text{O}_3(s)$</td>
<td>460400</td>
<td>$\text{N}_2 (g)$</td>
<td>690</td>
</tr>
<tr>
<td>$3\text{CaO}\cdot\text{Al}_2\text{O}_3(s)$</td>
<td>500600</td>
<td>$\text{O}_2(g)$</td>
<td>3970</td>
</tr>
<tr>
<td>$\text{CaO}\cdot\text{SiO}_2(s)$</td>
<td>23600</td>
<td>$\text{Na}_2\text{O}(s)$</td>
<td>296200</td>
</tr>
<tr>
<td>$2\text{CaO}\cdot\text{SiO}_2(s, )$</td>
<td>95700</td>
<td>$\text{SO}_2(g)$</td>
<td>313400</td>
</tr>
<tr>
<td>$3\text{CaO}\cdot\text{SiO}_2(s)$</td>
<td>219800</td>
<td>$\text{SiO}_2$</td>
<td>1900</td>
</tr>
<tr>
<td>$\text{CaS}$</td>
<td>844600</td>
<td>$\text{Fe}_2\text{O}_3\cdot\text{SiO}_2$</td>
<td>18400</td>
</tr>
<tr>
<td>$4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$</td>
<td>667000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the investigated process the actual amount of reacting raw meal = 1.49 kg to produce 1kg of clinker. Its contents of various components, in kg, are as follows:

<table>
<thead>
<tr>
<th></th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>SiO₃</th>
<th>Loss of Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>0.658</td>
<td>0.19</td>
<td>0.058</td>
<td>0.035</td>
<td>0.0045</td>
<td>0.0045</td>
<td>0.54</td>
</tr>
</tbody>
</table>

It’s CaCO₃ and MgCO₃ components have been estimated as follows:

CaCO₃ content = 1.176 kg
MgCO₃ content = 0.009 kg

In the burning zone of the kiln (1450°C) the chemical reactions of calcined material takes place and clinker is formed. The four clinker phases such as tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate (C₃A) and tetracalcium aluminoferrite (C₄AF) are calculated based on Bogue calculation (Nicholas, 1990) using the clinker analysis data of the plant.

\[
\begin{align*}
C_3S &= 4.07 \text{CaO} - 7.6024 \text{SiO}_2 - 1.4297 \text{Fe}_2\text{O}_3 - 6.7187 \text{Al}_2\text{O}_3 \\
C_2S &= 8.6024 \text{SiO}_2 + 1.0785 \text{Fe}_2\text{O}_3 + 5.0683 \text{Al}_2\text{O}_3 - 3.071 \text{CaO} \\
C_3A &= 2.6504 \text{Al}_2\text{O}_3 - 1.692 \text{Fe}_2\text{O}_3 \\
C_4AF &= 3.0432 \text{Fe}_2\text{O}_3
\end{align*}
\]

The estimated values of the clinker phases are (in wt %) as follows:

C₂S 39 %, C₃S 36.6 %, C₃A 11.4 % and C₄AF 13%

The amounts of formed clinker phases in 1 kg of clinker are given as:
0.39 kg C₂S, 0.366 kg C₃S, 0.114 kg C₃A and 0.13 kg C₄AF
The table given below shows the detailed calculation of energy and exergy during the formation of 1 kg of clinker in the cement plant.

<table>
<thead>
<tr>
<th>Reaction name</th>
<th>Reaction</th>
<th>Enthalpy of reaction $Q_k = m_k \times \Delta h_r$ (kJ/kg of clinker)</th>
<th>Exergy of chemical reaction $E_{Ch} = m_k \times \psi_{ch}$ (kJ/kg of clinker)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcinations process</td>
<td>CaCO$_3$ → CaO + CO$_2$</td>
<td>2093.28</td>
<td>1499.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enthalpy $\Delta h_r = 1780$ kJ/kg CaCO$_3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = 1275.1$ kJ/kg CaCO$_3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 1.176$ kg CaCO$_3$/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>MgCO$_3$ dissociation</td>
<td>MgCO$_3$ → MgO + CO$_2$</td>
<td>12.56</td>
<td>5.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enthalpy $\Delta h_r = 1395$ kJ/kg MgCO$_3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = 610$ kJ/kg MgCO$_3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 0.009$ kg MgCO$_3$/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>β-C$_2$S formation</td>
<td>2CaO$+$SiO$_2$ → β-C$_2$S</td>
<td>-368.55</td>
<td>-370.51</td>
</tr>
<tr>
<td>(Intermediate compound)</td>
<td></td>
<td>Enthalpy $\Delta h_r = -732$ kJ/kg β-C$_2$S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = -735.9$ kJ/β-C$_2$S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 0.5$ kg β-C$_2$S/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>C$_3$S formation</td>
<td>β-C$_2$S + CaO → C$_3$S</td>
<td>12.95</td>
<td>12.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enthalpy $\Delta h_r = 35$ kJ/C$_3$S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = 33.16$ kJ/C$_3$S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 0.366$ kg C$_3$S/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>C$_3$A formation</td>
<td>3CaO + Al$_2$O$_3$ → C$_3$A</td>
<td>2.75</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enthalpy $\Delta h_r = 25$ kJ/C$_3$A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = 18.69$ kJ/C$_3$A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 0.114$ kg C$_3$A/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>C$_4$AF formation</td>
<td>4CaO + Al$_2$O$_3$ + Fe$_2$O$_3$ → C$_4$AF</td>
<td>3.25</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enthalpy $\Delta h_r = 25$ kJ/C$_4$AF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical exergy $\psi_{ch} = 28.57$ kJ/C$_4$AF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass $m_k = 0.13$ kg C$_4$AF/kg-clinker</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1756.24</td>
<td>1152.53</td>
</tr>
</tbody>
</table>
Annexure E

Exergy calculation of kiln system (Production rate of 1400 tonnes per day)

For the exergy analysis the reference temperature and pressure are assumed to be $T_0 = 298$ K and 101 kPa (dead state condition) respectively.

Input Exergy

1. Raw meal

   Mass of raw meal per kg of clinker, $(m_k)_{rm} = 1.49$ kg / kg of clinker

   Temperature, $T_{rm} = 328$ K

   Specific heat, $c_{p_{rm}} = 0.7919$ kJ/kg-K

   Enthalpy change, $(\Delta H_k)_{rm} = (m_k)_{rm} \times c_{p_{rm}} \times (T_{rm} - T_0)$
   
   $= 35.4$ kJ/kg-clinker

   Entropy change, $(\Delta S_k)_{rm} = (m_k)_{rm} \times c_{p_{rm}} \times ln \left( \frac{T_{rm}}{T_0} \right)$
   
   $= 0.1132$ kJ/kg-clinker K

   Exergy of raw meal, $(Ex_k)_{rm} = (\Delta H_k)_{rm} - T_0 \times (\Delta S_k)_{rm}$
   
   $= 1.67$ kJ/kg-clinker

2. Primary air

   Mass of primary air per kg of clinker, $(m_k)_{pa} = 0.418$ kg/kg-clinker

   Temperature, $T_{pa} = 344$ K

   Specific heat, $c_{p_{pa}} = 0.9843$ kJ/kg-K

   Enthalpy change, $(\Delta H_k)_{pa} = (m_k)_{pa} \times c_{p_{pa}} \times (T_{pa} - T_0)$
   
   $= 18.93$ kJ/kg-clinker

   Entropy change, $(\Delta S_k)_{pa} = (m_k)_{pa} \times c_{p_{pa}} \times ln \left( \frac{T_{pa}}{T_0} \right)$
   
   $= 0.0591$ kJ/kg-clinker K

   Exergy of Primary air, $(Ex_k)_{pa} = (\Delta H_k)_{pa} - T_0 \times (\Delta S_k)_{pa}$
   
   $= 1.33$ kJ/kg-clinker
3. **Cooler inlet air**

Mass of cooler air per kg of clinker, \((m_k)_{ca} = 3.667\) kg/kg-clinker

Temperature, \(T_{ca} = 308\) K

Specific heat, \(c_{p_{ca}} = 0.9681\) kJ/kg-K

Enthalpy change, \((\Delta H_k)_{ca} = (m_k)_{ca} \times c_{p_{ca}} \times (T_{ca} - T_0)\)

\[35.5\] kJ/kg-clinker

Entropy change, \(\Delta S_{k_{ca}} = (m_k)_{ca} \times c_{p_{ca}} \times \ln\left(\frac{T_{ca}}{T_0}\right)\)

\[= 0.1172\] kJ/kg-clinker K

Exergy of cooler air, \((Ex_k)_{ca} = (\Delta H_k)_{ca} - T_0 \times (\Delta S_k)_{ca}\)

\[= 0.58\] kJ/kg-clinker

4. **Infiltrated air**

Mass of infiltrated air per kg of clinker, \((m_k)_{ia} = 0.8146\) kg/kg-clinker

Temperature, \(T_{ia} = 308\) K

Specific heat, \(c_{p_{ia}} = 0.9681\) kJ/kg-K

Enthalpy change, \((\Delta H_k)_{ia} = (m_k)_{ia} \times c_{p_{ia}} \times (T_{ia} - T_0)\)

\[= 7.81\] kJ/kg-clinker

Entropy change, \(\Delta S_{k_{ia}} = (m_k)_{ia} \times c_{p_{ia}} \times \ln\left(\frac{T_{ia}}{T_0}\right)\)

\[= 0.026\] kJ/kg-clinker K

Exergy infiltrated air, \((Ex_k)_{ia} = (\Delta H_k)_{ia} - T_0 \times (\Delta S_k)_{ia}\)

\[= 0.13\] kJ/kg-clinker

5. **Chemical exergy of coal**

\[= [\text{Calorific value} + \text{heat of evaporation} \times (\text{percentage of Moisture})] \times \Phi\]

where \(\Phi = 1.0437 + 0.1882 \times (h/c) + 0.0610 \times (o/c) + 0.0404 \times (n/c)\)

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and c, h, o, and n are the mass fractions of Carbon, Hydrogen, Oxygen, and Nitrogen respectively (Kotas, 1985).

Chemical Exergy of coal = \((20763+2315\times0.035) \times 1.0722\)
\[= 21658.32 \text{ kJ/kg}\]

Coal consumption in kiln = 0.183 kg/kg of clinker

Chemical exergy of coal \((Ex_k)_c = 21658.32\times0.183\)
\[= 4089.92 \text{ kJ/kg of clinker}\]

Proximate analysis of coal = (Fixed carbon-43%, Ash- 25%, Volatile matter-28.5% and Moisture-3.5%) and Ultimate analysis of coal (Carbon-57.58%, Hydrogen – 3.7%, Nitrogen-1.54%, Oxygen-7.18%, Sulphur 0.5%, Mineral matter 26% and Moisture-3.5%)

6. Total input exergy of the kiln system
\(= (Ex_k)_{rm} + (Ex_k)_{pa} + (Ex_k)_{ca} + (Ex_k)_{ia} + (Ex_k)_c\)
\[= 4093.63 \text{ kJ/kg-clinker}\]

Output exergy

1. **Preheater Exhaust gas**

Mass of the preheater exhaust gas per kg of clinker,
\[m_{k_{eg}} = 2.56 \text{ kg/kg of clinker}\]

Temperature, \(T_{eg} = 657\text{K}\)

Specific heat, \(c_{p_{eg}} = 1.0878 \text{ kJ/kg-K}\)

Change in enthalpy, \((\Delta H_k)_{eg} = (m_k)_{eg} \times c_{p_{eg}} \times (T_{eg} - T_0)\)
\[= 999.72 \text{ kJ/kg-clinker}\]

Change in entropy, \((\Delta S_k)_{eg} = (m_k)_{eg} \times c_{p_{eg}} \times ln\left(\frac{T_{eg}}{T_0}\right)\)
\[= 2.2016 \text{ kJ/kg-clinker K}\]

Exergy of preheater exhaust gas, \((Ex_k)_{eg} = (\Delta H_k)_{eg} - T_0 \times (\Delta S_k)_{eg}\)
\[= 343.65 \text{ kJ/kg-clinker}\]
2. **Dust**

Mass of dust per kg of clinker, $m_{kd} = 0.0476$ kg / kg of clinker

Temperature, $T_d = 657$K

Specific heat, $c_{pd} = 1.0093$ kJ/kg-K

Change in enthalpy, $(\Delta H_k)_d = (m_k)_d \times c_{pd} \times (T_d - T_0)$

= $27.03$ kJ/kg-clinker

Change in entropy, $(\Delta S_k)_d = (m_k)_d \times c_{pd} \times ln(T_d/T_0)$

= $0.0595$ kJ/kg-clinker K

Exergy of dust, $(Ex_k)_d = (\Delta H_k)_d - T_0 \times (\Delta S_k)_d$

= $9.29$ kJ/kg-clinker

3. **Clinker**

Clinker discharge, $(m_k)_{cli} = 1$ kg/kg-clinker

Temperature, $T_{cli} = 368$K

Specific heat, $c_{pcli} = 0.8308$ kJ/kg-K

Change in enthalpy, $(\Delta H_k)_{cli} = (m_k)_{cli} \times c_{pcli} \times (T_{cli} - T_0)$

= $58.16$ kJ/kg-clinker

Change in entropy, $(\Delta S_k)_{cli} = (m_k)_{cli} \times c_{pcli} \times ln(T_d/T_0)$

= $0.1753$ kJ/kg-clinker K

Exergy of clinker, $(Ex_k)_{cli} = (\Delta H_k)_{cli} - T_0 \times (\Delta S_k)_{cli}$

= $5.92$ kJ/kg-clinker
4. **Cooler hot air**

Mass flow of cooler hot air per kg of clinker,

\[
m_{k_{co}} = 2.82 \text{ kg / kg of clinker}
\]

Temperature, \( T_{co} = 473 \text{K} \)

Specific heat, \( c_{p_{co}} = 1.0226 \text{ kJ/kg-K} \)

Change in enthalpy,
\[
(\Delta H_k)_{co} = (m_k)_{co} \times c_{p_{co}} \times (T_{co} - T_0)
\]
\[
= 504.65 \text{ kJ/kg-clinker}
\]

Change in entropy,
\[
(\Delta S_k)_{co} = (m_k)_{co} \times c_{p_{co}} \times \ln\left(\frac{T_{co}}{T_0}\right)
\]
\[
= 1.3323 \text{ kJ/ kg-clinker K}
\]

Exergy of cooler hot air,
\[
(Ex_k)_{co} = (\Delta H_k)_{co} - T_0 \times (\Delta S_k)_{co}
\]
\[
= 107.63 \text{ kJ/kg-clinker}
\]

5. **Coal mill gas**

Mass flow of the coal mill gas per kg of clinker,

\[
m_{k_{cm}} = 0.125 \text{ kg / kg of clinker}
\]

Temperature, \( T_{cm} = 591 \text{ K} \)

Specific heat, \( c_{p_{cm}} = 1.0482 \text{ kJ/kg-K} \)

Enthalpy change,
\[
(\Delta H_k)_{cm} = (m_k)_{cm} \times c_{p_{cm}} \times (T_{cm} - T_0)
\]
\[
= 39.96 \text{ kJ/kg-clinker}
\]

Entropy change,
\[
(\Delta S_k)_{cm} = (m_k)_{cm} \times c_{p_{cm}} \times \ln\left(\frac{T_{cm}}{T_0}\right)
\]
Exergy of coal mill gas, \((Ex_k)_{cm} = (\Delta H_k)_{cm} - T_0 \times \Delta S_k_{cm}\)

\[= 12.44 \text{ kJ/kg-clinker}\]

Exergy efficiency of the kiln system

\[\text{Exergy efficiency of the kiln system} = \frac{\text{Clinker formation exergy} + \text{Exergy carried by clinker}}{\text{Total input exergy}}\]

\[= \frac{1152.53 + 5.92}{4093.63} = 28.3\%\]

(The clinker formation exergy is calculated and given in the Annexure D as 1152.53 kJ/kg-clinker)

6. **Exergy due to heat transfer**

   a) Convection radiation heat loss from kiln surface,

   \[Q_k = 305.96 \text{ kJ/kg-clinker} \] (From Table 4.4)

   Surface temperature of kiln, \(T_s = 573\text{K}\)

   Exergy

   \[= \left(1 - \frac{T_0}{T_s}\right) \times Q_k\]

   \[= 147 \text{ kJ/kg-clinker}\]

   b) Convection radiation heat loss from preheater surface,

   \[Q_k = 5.81 \text{ kJ/kg-clinker} \] (From Table 4.4)

   Surface temperature of preheater, \(T_s = 353\text{K}\)

   Exergy

   \[= \left(1 - \frac{T_0}{T_s}\right) \times Q_k\]

   \[= 0.9 \text{ kJ/kg-clinker}\]
c) Convection radiation heat loss from cooler surface, 
\[ Q_k = 2 \text{ kJ/kg-kg-clinker} \text{ (From Table 4.4)} \]
Surface temperature of cooler surface, \( T_s = 355 \text{K} \)
Exergy 
\[ = \left(1 - \frac{T_o}{T_s}\right) \times Q_k \]
\[ = 0.32 \text{ kJ/kg-clinker} \]

Total exergy due to heat transfer in the kiln system = (a) + (b) + (c) 
\[ = 148.06 \text{ kJ/kg-clinker} \]

7. Irreversibility of the kiln system = 2314.1 kJ/kg-clinker