CHAPTER III

METHODOLOGY

3.1 Energetic & Exergetic Analyses

The first law of thermodynamics states that energy is a thermodynamics property that can change from one form to another during an interaction, but its total amount remains unchanged. Energy is always conserved, but it cannot be created nor destroyed. The change in the content of energy of a body or a system is equal to the difference between the energy input and the energy output (Saidur et al., 2007).

Exergy can be viewed as the ability to produce work. The second law of thermodynamics states that exergy has both quality and quantity, and actual processes occur in the direction of decreasing quality of energy. Exergy is a measure of the maximum capacity of an energy system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings (Cengel, 2006). The surroundings of the energy source plays a major role in determining the availability of work that can be extracted from it. A large difference between the energy source and its surroundings will result in higher capacity of available work. Eventhough the energy of a system is also proportional to the difference between the energy source and its surroundings, energy and exergy are different in the sense that exergy is only conserved in a reversible process, but is always consumed in an irreversible process (Saidur et al., 2007).

The energy analysis is a traditional approach which uses energy balance to estimate various energy conversion processes. Based on the first law of thermodynamics, energy analysis does not give any information on the degradation of energy that occurs in such processes. Hence, exergy analysis is frequently used in addition to energy analysis in evaluating industrial processes (Worrell et al., 2008).

Exergy analysis is a modern thermodynamic method that is able to identify the types, locations and magnitudes of thermal losses, which will consequently allow the evaluation and improvement in the design of thermodynamic systems (Worrell et al., 2008). Exergy is a measure of the quality of energy streams. The exergy concept is able to provide an estimate of the theoretical minimum energy requirement in a process. Consequently, this provides information on the maximum savings that could be achieved through improved processes (Sogut et al., 2009).

3.1.1 Energy & Exergy Analyses Data

The specific heat capacities, the mass balance, the temperature and the pressure values of the input and output materials were firstly determined before the energy and exergy analyses of the grate clinker cooler takes place. The base case grate clinker cooler input and output data are theoretical data taken from studies done by Rasul et al. (2005), Kolip et al. (2010) and Mundhara and Sharma (2005). Table 3.1.1 summarizes the theoretical input and output data of the base case grate clinker cooling sytem.

Table 3.1.1
Summary of input and output data of the base case clinker cooler

No.	Material	Mass flow rate (kg/kg clinker)	C_p(kJ/kg.˚C)	T (˚C)
1	Hot Clinker	1.00	1.06	1300
2	Cooling air	2.55	1.01	45
3	Secondary air	0.45	1.14	850
4	Tertiary air	0.42	1.13	650
5	Cooled Clinker	1.00	0.92	115
6	Exhaust air	1.68	1.03	220

(Rasul et al., 2005; Kolip et al., 2010, Mundhara and Sharma, 2005)

The reference temperature is taken as the ambient temperature of 25˚C. In order to thermodynamically analyze the cooler system, the following assumptions were made:

i. Steady state working conditions.

ii. The change in ambient temperature is neglected.

iii. Cold air leakage into the system is negligible.

iv. Clinker compositions do not change.

v. Kinetic and potential energy changes of input and output materials are negligible.

vi. Energy losses happening in the pipeline connections among units are ignored.

vii. All gas streams are assumed to be ideal gases at the given temperatures.

3.1.2 First Law Analysis of the Grate Clinker Cooler

For a general steady state and steady-flow process, the mass balance equation is in the rate form as shown below (Sogut et al., 2009):

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3.1}$$

where $\dot{m}$ is the mass flow rate, and the subscript *in* stands for inlet and *out* for outlet.

The general energy balance is (Sogut et al., 2009):

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{3.2}$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \tag{3.3}$$

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the rate of net energy transfer *in* and *out* respectively, by heat, work and mass, $\dot{Q} = \dot{Q}_{net;in} = \dot{Q}_{in} - \dot{Q}_{out}$ is the rate of net heat input, $\dot{W} = \dot{W}_{net;out} = \dot{W}_{out} - \dot{W}_{in}$ is the rate of net work output, and *h* is the enthalpy per unit mass (Sogut et al., 2009).

Table 3.1.2 presents the summary of energy input and output of the clinker cooler, while Figure 3.1.2 presents the schematic of energy balance for the grate clinker cooler.

Table 3.1.2
Energy input & output of the clinker cooler

Symbol	Description	Formula Used	Unit
$\dot{Q}_{ic}$	rate of sensible heat of clinker from kiln to cooler	$\dot{m}_{cl}$ x C_{cl} x $(T_{cl1} - T_a)$	kJ/kg.ck
$\dot{Q}_{ca}$	rate of sensible heat of cooling air	$\dot{m}_a$ x C_a x $(T_{ac} - T_a)$	kJ/kg.ck
$\dot{Q}_{pk}$	recovery heat rate of kiln secondary air	$\dot{m}_{as}$ x C_a x $(T_{a2} - T_a)$	kJ/kg.ck
$\dot{Q}_{pc}$	recovery heat rate of tertiary air from cooler	$\dot{m}_{at}$ x C_a x $(T_{a3} - T_a)$	kJ/kg.ck
$\dot{Q}_{oc}$	rate of sensible heat of clinker at cooler outlet	$\dot{m}_{cl}$ x C_{cl2} x $(T_{cl2} - T_a)$	kJ/kg.ck
$\dot{Q}_{exh}$	rate of sensible heat of cooler exhaust air	$\dot{m}_{exh}$ x C_a x $(T_s - T_a)$	kJ/kg.ck

(Rasul et al., 2009)

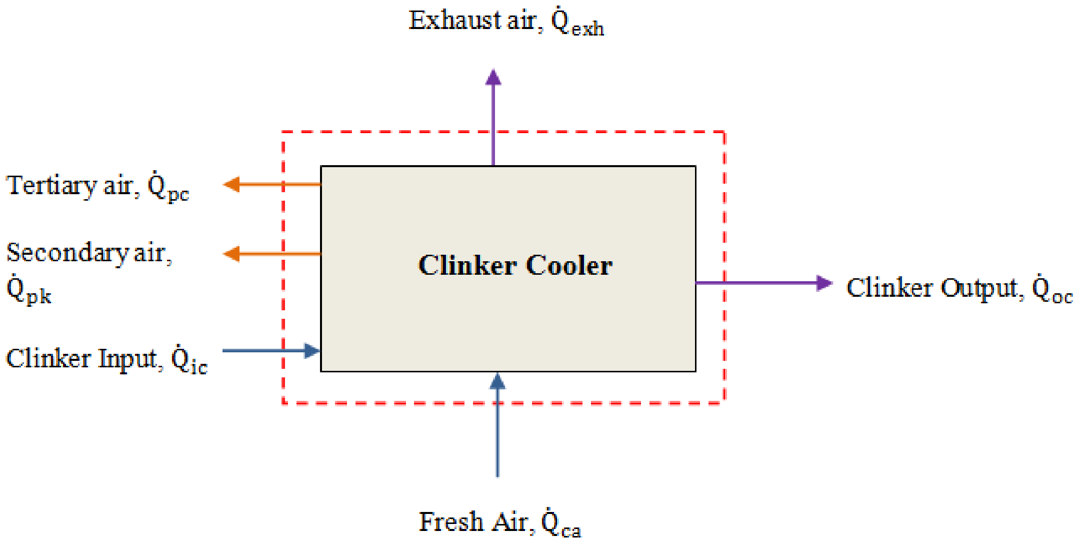

Figure 3.1.2
Energy balance schematic of the grate clinker cooler
(Rasul et al., 2009)

In order to estimate the efficiency of the cooler and the quantity of energy that can be recovered, the clinker cooler is considered separately for energy balance. Heat input into the cooler is (Rasul et al., 2005):

$$\dot{Q}_{hi} = \dot{Q}_{ic} + \dot{Q}_{ca} \tag{3.4}$$

where $\dot{Q}_{ic}$ is the rate of sensible heat of clinker from the cooler to the kiln, and $\dot{Q}_{ca}$ is the rate of sensible heat of cooling air (Rasul et al., 2005).

Heat output from the cooler is (Rasul et al., 2005):

$$\dot{Q}_{ho} = \dot{Q}_{pk} + \dot{Q}_{pc} + \dot{Q}_{oc} + \dot{Q}_{exh} \tag{3.5}$$

where $\dot{Q}_{pk}$ is the recovery heat rate of kiln secondary air, and $\dot{Q}_{pc}$ is the recovery heat rate of tertiary air from the cooler. On the other hand, $\dot{Q}_{oc}$ is the rate of sensible heat of clinker at the cooler outlet, and $\dot{Q}_{exh}$ is the rate of sensible heat of the cooler exhaust air (Rasul et al., 2005).

Energy efficiency is the ratio between the amount of energy output and the amount of input energy to system, i.e. (Sogut et al., 2009)

$$\eta_I = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \tag{3.6}$$

The energy recovery efficiency of the secondary and tertiary air can be expressed as (Rasul et al., 2005):

$$\eta_{recovery,\ cooler} = \frac{\dot{Q}_r}{\dot{Q}_{ic}+\dot{Q}_{ca}} \tag{3.7}$$

3.1.3 Second Law Analysis of the Grate Clinker Cooler

The general exergy balance for an ideal system can be expressed as (Sogut et al., 2009):

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \Delta \dot{E}x_{sys} \text{ or} \tag{3.8}$$

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} = \Delta \dot{E}x_{sys} \tag{3.9}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location *k*; $\dot{W}$ is the work rate, and ψ is the flow exergy (Bejan, 1988). Figure 3.1.3 presents the exergy flow of the clinker cooler.

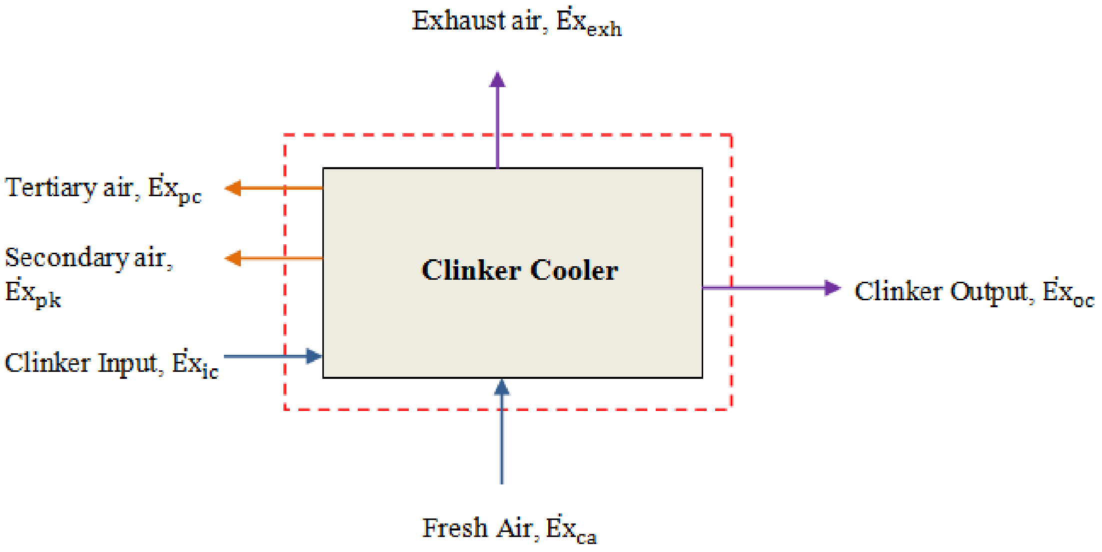

Fig. 3.1.3
Exergy balance schematic of the grate clinker cooler
(Touil et al., 2005)

The steady state exergy balance of the open system of clinker cooling is thus (Touil et al., 2005):

$$\dot{E}x_d = (\dot{E}x_{ic} + \dot{E}x_{ca}) - (\dot{E}x_{oc} + \dot{E}x_{pk} + \dot{E}x_{pc} + \dot{E}x_{exh}) \tag{3.10}$$

$$= \left(\dot{m}_{ck}\bar{e}_{ck,in} + \dot{m}_a\bar{e}_a\right) - \left(\dot{m}_{ck}\bar{e}_{ck,out} + \dot{m}_{as}\bar{e}_{as} + \dot{m}_{at}\bar{e}_{at} + \dot{m}_{aexh}\bar{e}_{exh}\right) \tag{3.11}$$

The exergy efficiency expresses all exergy input as exergy consumed, and all exergy output as exergy utilized, i.e. (Sogut et al., 2009)

$$\eta_{II,1} = \frac{\dot{E}x_{recovered}}{\dot{E}x_{in}} \tag{3.12}$$

Flow exergy is the work obtainable by taking the substance through reversible processes from its initial state temperature T_0 and the pressure P_0 of the environment. Flow exergy may be expressed as follows (Sogut et al., 2009; Cengel, 2006):

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3.13}$$

where *h* is the specific enthalpy and *s* is the specific entropy. The subscript zero indicates properties at the dead state.

The rate of exergy destroyed or the irreversibility rate is defined as follows (Sogut et al., 2009):

$$\dot{I} = \dot{E}x_{destroyed} = T_0\dot{S}_{gen} \tag{3.14}$$

where $\dot{S}_{gen}$ is the rate of entropy generation, while the subscript zero again denotes conditions of the reference environment or dead state (Bejan, 1988).

The specific exergies at (T,P) of the clinker and the humid air are respectively expressed by Equations (3.15) and (3.16) (Touil et al., 2005):

$$e_{ck} = \left(\bar{h}_{ck} - \bar{h}_0\right) - T_0(\bar{s}_{ck} - \bar{s}_0) \tag{3.15}$$

$$e_a = \left(\bar{h}_a - \bar{h}_0\right) - T_0(\bar{s}_a - \bar{s}_0) \tag{3.16}$$

The dead state is characterized by (T_0, P_0), where T_0 is the ambient temperature, i.e. 298K, and P_0 is the atmospheric pressure, i.e 1.013 kPa. In this case, both the kinetic and potential exergies are neglected (Touil et al., 2005).

3.2 Cost Benefit

3.2.1 Potential Energy & Cost Savings

The change in cooler efficency by optimizing its operational parameters will result in potential energy saving, in the form of fuel consumed. The potential energy savings obtainable by optimizing the operational parameters of the grate clinker cooler are taken from the results of the analyses performed. They are divided into energy savings through secondary air to the rotary kiln, tertiary air to the pre-calciner, and other channels, i.e. raw materials and coal drier, cooling air pre-heater and primary air pre-heater.

The amount of cost savings through the substitution of heat supplied with the recovered heat is estimated with the formulas below:

$$\mathrm{CS} = \mathrm{ES} \times \mathrm{EC} \tag{3.17}$$

where *CS* is cost saving in US Dollars per kg clinker, *ES* is energy saving in kJ per kg clinker, and *EC* is the energy cost. The average fuel energy cost is taken as USD 4.664/GJ (Price et al., 2009).

3.2.2 Payback Period

Payback period according to capital budgeting refers to the period of time required for the return on an investment to repay the sum of the original investment (Park, 2007). Although primarily a financial term, the concept of a payback period occasionally extends to other uses, such as energy payback period, i.e. the period of time over which the energy savings of a project equal the amount of initial investment cost incurred and the energy expended since project inception.

A simple payback period in this analysis can be calculated with the formula below (Saidur and Mahlia, 2010):

$$\mathrm{SPP} = \frac{\mathrm{IIC}}{(\mathrm{CS}-\mathrm{IC})} \tag{3.18}$$

where *IIC* and *IC* are the initial investment costs and the incremental costs, respectively.

3.2.3 Present Value

Present value can be defined as the value on a given date of a future payment or series of future payments, discounted to reflect the time value of money and other factors such as investment risks. The cumulative present value of annualized savings can be expressed in mathematical form as follows (Park, 2007):

$$PV = \sum_{n=0}^{15} \frac{A_n}{(1+d)^n} \tag{3.19}$$

where A_n is the net cash flow at end of period *n* and *d* is the discount rate per year (%).

3.2.4 Capital Recovery Factor

Capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time (Saidur and Mahlia, 2010). It is the correlation between the real discount rate and the lifespan of the energy efficient clinker cooler (Park, 2007).

Using the real discount factor *d* (%), the capital recovery factor is (Park, 2007):

$$CRF = \frac{d}{(1-(1+d)^{-L_m})} \tag{3.20}$$

where L_m is the lifespan of the upgrades in years.

3.2.5 Cost of Conserved Energy

The cost of conserved energy can be used to evaluate the cost effectiveness and the technical potential for energy efficiency improvement in a Portland cement plant. It is an analytical tool that captures both the engineering and the economic aspects of energy conservation. It shows the energy conservation potential as a function of the marginal cost of energy conserved (Price et al., 2009).

The cost of conserved energy (CCE) can be calculated as follows (Price et al., 2009):

$$\text{CCE} = \frac{(\text{annualized capital cost} + \text{annual change in operations \& } \textit{maintenance costs})}{\text{annual energy savings}} \tag{3.21}$$

where annualized capital cost is (Price et al., 2009):

$$\text{ACC} = \text{Capital Cost x CRF} \tag{3.22}$$

3.3 Emission Reduction

An important benefit from optimizing the energy efficiency of a cement production process is the reduction in emission of major air pollutants such as NO_x, CO and PM, as well as the greenhouse gas CO_2. Energy savings are most likely to reduce the amounts of fuel consumed.

The cummulative amount of emissions associated with energy savings that can be reduced can be estimated using the following formula (Saidur and Mahlia, 2010):

$$\text{ER}_i^{\,c} = \text{ES}_i^{\,c} \text{ x } (\text{PE}_i^{\,1} \text{ x } \text{EM}_p^{\,1} \text{ x } \text{PE}_i^{\,2} \text{ x } \text{EM}_p^{\,2} \text{ x } \text{PE}_i^{\,3} \text{ x } \text{EM}_p^{\,3} \text{ x } \text{PE}_i^{\,4} \text{ x } \text{EM}_p^{\,4}) \tag{3.23}$$

where $\text{EM}_p^{\,1}$ = NO_x, $\text{EMPE}_p^{\,2}$ = CO, $\text{EM}_p^{\,3}$ = PM, and $\text{EM}_p^{\,4}$ = CO_2. Alternatively, individual emission reduction can also be estimated by breaking up the equation into its constituents. *PE* is the percentage of electricity generation in year *i* of fuel type *n*.