CHAPTER II

LITERATURE REVIEW

2.1 Cement Industry and Cement Production Energy

Fog et al. (1983) stated that the energy sources in a cement plant can be classified as primary sources, i.e. oil, coal, gas, other fuels and electricity, and secondary sources, i.e. waste heat from one phase of the process which can be recovered and utilized in another phase. The theoretical heat requirement for the production of clinker, the main substance of cement, is estimated at about 1.75 ± 0.1 MJ per kg clinker. The actual heat requirement is higher, and it depends on the type of process applied. Cement production processes are generally distinguished into wet process, semi-wet process, semi-dry and Lepol process, and dry process. For the production of clinker, the two types of kilns used are rotary kilns and shaft kilns (Hendriks et al., 2004).

The world's average primary energy intensity is approximately 4.8 MJ/kg cement, with the most energy intensive regions being Eastern Europe and the former Soviet Union, followed by the North America and the Middle East (Hendriks et al., 2004). Table 2.1 presents the global energy consumption for cement production for different regions and countries around the world.

Table 2.1
Global energy consumption for cement production

Region/Country	Cement Production (Tg)	Clinker/ Cement Ratio	Primary Intensity (MJ/kg)	Primary Energy (PJ)
China	423	83%	5.0	2117
Europe	182		4.1	749
OECD Pacific	151		3.5	533
Other ASIA	124		4.9	613
Middle East	111		5.1	563
North America	88		5.4	480
EE/FSU	101		5.5	558
Latin America	97		4.7	462
India	62	89%	5.0	309
Africa	41		4.9	201
World Total	**1381**		**4.8**	**6585**

Source: Hendriks et al., 2004

2.2 Air Pollutants and Greenhouse Gas Emissions from the Cement Production Process

The three major air pollutants released in a cement production process are nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). The emission of NO_x is the result of combustion of fuels at high temperatures in cement kilns. CO is a possible result of poor solid-fuel feed systems, leading to sub-stoichiometric combustion. During the manufacturing of cement, quarrying operations, the crushing and grinding of raw materials and clinker, and the kiln line ash result in PM emissions (U.S. EPA Sector Strategies Program, 2006).

The U.S. Environmental Protection Agency (EPA) Sector Strategies 2006 Performance Report (2006) stated that in the U.S., the EPA's National Emissions Inventory (NEI) estimates that this sector alone released 214,000 tons of NO_x emissions and 44,000 tons of PM emissions in 2002.

In the cement sector, the burning of fossil fuels (predominantly coal) during pyroprocessing and the chemical reactions (calcination) that convert limestone into clinker result in the emission of CO_2 (U.S. EPA Sector Strategies Program, 2006). Hendriks et al. (2004) also stated that the global cement industry contributes approximately 20% of all man-made CO_2 emissions, and is consequently responsible for around 10% of man-made global warming. The cement plant releases about one tonne of CO_2 for every tonne of cement produced, half of it from the fuel it burns and the other half from the calcination process.

The average world carbon intensity of carbon emissions from cement production is 0.81 kg CO_2/kg cement produced. While China is the largest emitter of carbon, the most carbon intensive cement region in terms of carbon emissions per kg of cement produced is India, followed by North America and China (Hendriks et al., 2004). Table 2.2 presents the global carbon emission from cement production for different regions and countries around the world.

Table 2.2
Global carbon emission from cement production

Region/ Country	Cement Production (Tg)	Process Carbon Emissions (Tg CO_2)	Carbon Emissions Energy Use (Tg CO_2)	Total Carbon Emissions (Tg CO_2)
China	423	175	197	372
Europe	182	73	56	129
OECD Pacific	151	65	41	105
Other ASIA	124	56	179	105
Middle East	111	51	44	95
North America	88	39	40	78
EE/FSU	101	42	38	80
Latin America	97	41	30	71
India	62	28	30	60
Africa	41	18	15	33
World Total	**1381**	**587**	**830**	**1126**

Source: Hendriks et al., 2004

2.3 Cement Process Description

Cement is produced by chemically combining calcium carbonates, silica, alumina, iron ore, and small amounts of other materials. These ingredients are chemically altered through intense heat to form a compound with binding properties. Raw materials including limestone, chalk and clay will pass through a crusher after they are treated. They are then converted to fine powder in proper portion in mills. Clinker is produced from treating raw materials by heating, which consists of three parts: pre-heaters, furnace and cooler. The clinker produced will be ground and mixed with gypsum and sent for packing (Avami and Sattari, 2007).

Two different production systems are categorized, i.e. the wet process and the dry process. Most cement production plants nowadays utilize the dry process, as it has been proven to be more energy efficient compared to the wet process. As opposed to the wet process, the raw materials are ground, mixed, and fed into the kiln in their dry state in the dry process (Avami and Sattari, 2007). Table 2.3 presents the energy requirement for operational equipments in a typical process, while Figure 2.3 illustrates a typical flow diagram in a dry process.

Table 2.3
Energy required by different process phases

Process sections	**Electricity(KWh/ton)**	
	Dry	**Wet**
Raw material treatment & Crushing	4	3
Meshing	44	10
Fans & coolers	23	25
Dust collector	6	8
Cement milling	45	45
Transportation	8	58
Total electricity required (KWh/ton)	130	99
Fuel burned in Furnaces(lit/ton)	112.5	156

Source: Avami and Sattari, 2007

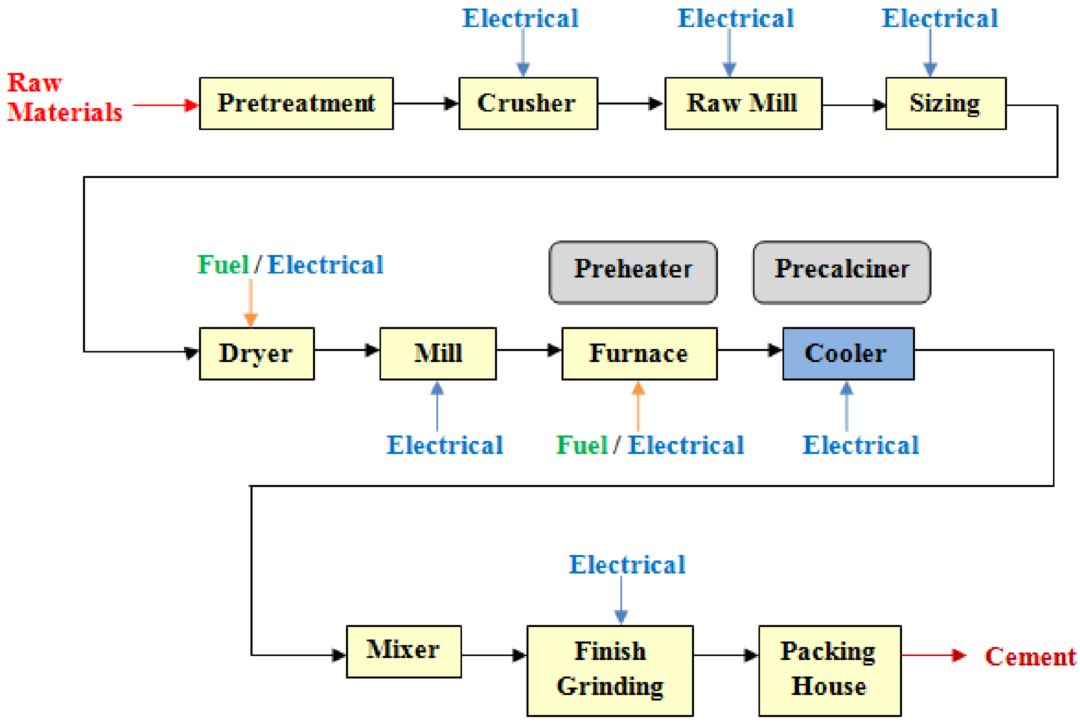

Figure 2.3
Flow diagram of a typical dry process in cement production
Source: Avami and Sattari, 2007

2.4 Clinker Cooler

The clinker burning system consists of three parts, i.e. the clinker cooler, the rotary kiln, and the suspension pre-heater (Touil et al., 2005). The function of a clinker cooler in a cement plant is twofold, i.e. to reduce the temperature of the clinker to a level that is acceptable for further transport, and to grind and recover energy from the sensible heat of the hot clinker by heating the cooling air. There are various types of clinker coolers that were previously used, but the four main types used for clinker cooling in the present day are the grate coolers, the planetary coolers, the shaft coolers, and the rotary coolers (Worrell et al., 2008).

Almost all modern kilns utilize the grate cooler, a modern variant of cooler. Grate coolers have the advantage of being large in capacity to allow large kiln capacities and having efficient heat recovery, when compared to the more conventional planetary coolers. Tertiary heat recovery, which is required for pre-calciners, is impossible with planetary coolers, limiting the heat recovery efficiency. Grate coolers have been proven to recover more heat than do the other types of coolers. For large capacity plants, grate coolers are preferred (Worrell et al., 2008). Figure 2.2 presents the schematic of a typical grate clinker cooler.

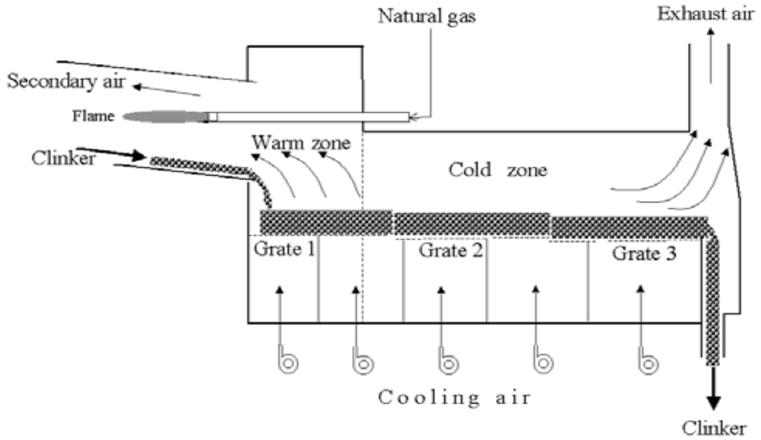

Figure 2.4
Grate clinker cooler schematic
Source: Touil et al., 2005

In the clinker burning system, the clinker comes out of the rotary kiln at a high temperature of 1380°C and it is cooled by fresh incoming air at a temperature of 65°C through a cross-flow heat exchanger with the top of the highly refractory steel grate. Movement of the grates causes the advancement and the spreading out of the clinker in a layer of which its thickness depends on grate speed (Touil et al., 2005). After passing over the layer of clinker, hot air from the recuperation zone is used as main burning air (secondary air) and as precalciner fuel (tertiary air), while the remaining air is sent to the stack through multiclones or ESP. Once clinker leaves the kiln it must be rapidly cooled to ensure maximum yield of the compound that contributes to the hardening properties of cement (Energy Efficiency Guide for Industry in Asia, 2005). The cooler is divided into two zones, i.e. hot and cold zones, due to the air depression created at the inlet and the outlet of the heat exchanger (Touil et al., 2005).

2.5 Energy Efficiency Improvement Opportunities for Grate Clinker Coolers

The energy consumption in the clinker cooler is governed by the energy required to drive the clinker bed, as well as the heat losses to the surroundings from the cooler. For the grate clinker cooler, the bed can be transported using two types of grates, i.e. travelling grate or reciprocating grate (Mundhara and Sharma, 2005). All coolers heat the secondary air required for the kiln combustion process and sometimes also the tertiary air for the pre-calciner. The highest temperature portion of the remaining air is usually used as tertiary air for the pre-calciner (Worrell et al., 2008).

The efficiency of a clinker cooler mainly depends on how effectively the heat is recovered from the clinker and the losses from the cooler surface, i.e. through conduction, convection, or radiation to the surroundings (Mundhara and Sharma, 2005). Worrell et al. (2008) stated that improving heat recovery efficiency in the cooler will result in fuel savings, and may also influence product quality and emission levels.

In order to improve the efficiencies of the clinker cooler used in cement industries, one should choose the optimum cooling air, the clinker input rate, the clinker bed depth, the clinker inlet temperature, the cooler length, the number of openings for air, and the grate speed (Mundhara and Sharma, 2005; Worrell et al., 2008). Worrell et al. (2008) also stated that controlling the distribution of cooling air over the grate may result in lower clinker temperatures and high air temperatures, resulting in additional heat recovery. Additional heat recovery consequently reduces energy use in the kiln and pre-calciner, due to higher combustion air temperatures.

2.6 Energy Analysis of the Grate Clinker Cooler

Rasul et al. (2005) presented a model to assess the thermal performance of a Portland cement industry in Indonesia on the basis of mass and energy balance. The clinker cooler was considered as a separate component for energy balance in order to estimate the efficiency of the cooler and the quantity of energy that can be recovered from the cooler.

Steady-state operation of the plant, fixed boundary conditions around the kiln, suspension pre-heater and cooler, flow rate of clinker product equal to the charged flow rate at any time, and analysis of heat balances according to to JIS R030 with reasonable modifications, were among the assumptions made during the data collection from the industry. The reference temperature was set at the ambient temperature of 25˚C, i.e. the sensible heat of mass flows at 25˚C becomes zero. Heat of transformation, i.e. combustion, evaporation, formation was also analyzed on the basis of the reference temperature (Rasul et al., 2005).

From the results, it was apparent that only 30.32% of the sensible heat of the clinker from the kiln can be recovered through the secondary air fed to the kiln, and 20.88% through the tertiary air fed to the pre-calciner. The unaccounted losses of the cooler were found to be fairly high, i.e. 18.9%, which was mainly due to convection and radiation losses from the uninsulated cooler. The loss due to sensible heat of the cooler outlet gas was determined to be as high as 24%. The first law efficiency of the clinker cooling system calculated was 81.2%, while its heat recovery efficiency was 51.2% (Rasul et al., 2005). Figure 2.6 presents the energy flow diagram of the clinker cooler.

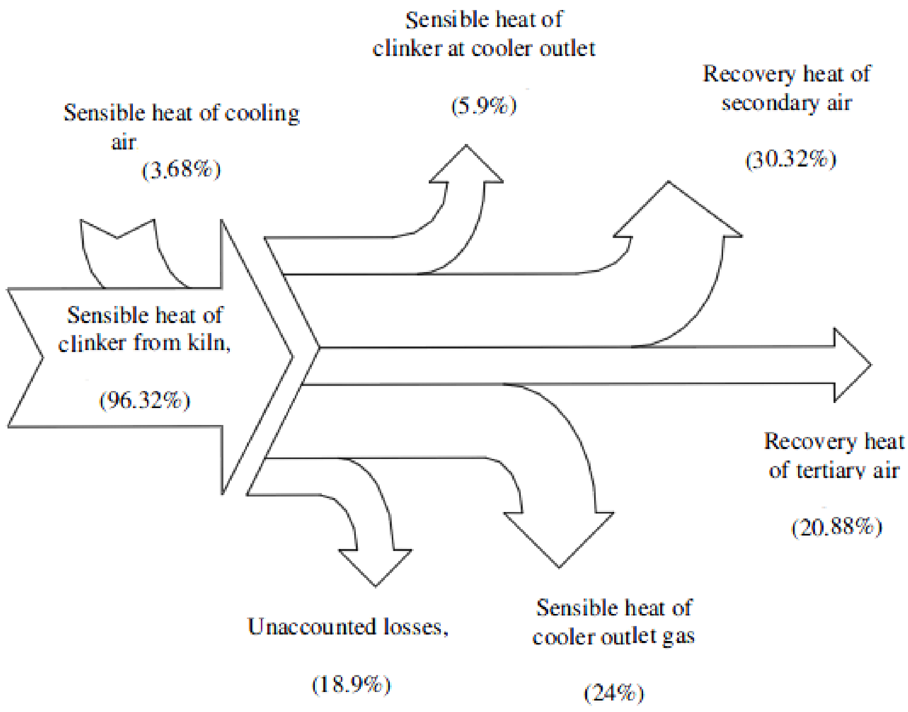

Figure 2.6
Energy flow diagram of the clinker cooling system
Source: Rasul et al., 2005

2.7 Exergy and Entropy Production Analysis of the Grate Clinker Cooler

Touil et al. (2005) applied the concept of exergy analysis to a grate cooler of a cement production facility in Algeria. A clinker cooler model was developed based on a set of assumptions and the specific exergies of various streams were calculated according to the real operating conditions of the Meftah cement factory. The identification of the sources of exergy losses and their quantification allow the improvement and the optimization of such energy process. It was considered that losses due to the flow of heat dissipation of the cooler are rejected to the ambient air with temperature T_0.

It was found that the transiting thermomechanical exergy of air and clinker traversing the cooler can be neglected, as they only constitute 0.44% of the overall exergy input. The exergy efficiency of the clinker cooler remains lower than 50%, whereas the energy efficiency calculated for the similar system was nearly 85%. This stresses the importance of the exergetic approach in the optimization of an energy process. Cooling causes internal exergy losses of 50.68%, which signifies the irreversibility of heat exchange between the air and the clinker (Touil et al., 2005).

The interest of this study was to determine the causes of the thermodynamic imperfections in heat transfer. The utilizable energy of secondary air represents 43.80% of the total exergy input. The exhaust air conveys external exergy loss of 5.08%, whose recovery can contribute to the improvement of the exergetic performance of this system (Touil et al., 2005). Figure 2.7 depicts the cooling exergy flow for the grate cooler from the results obtained by the studies performed by Touil et al. (2005).

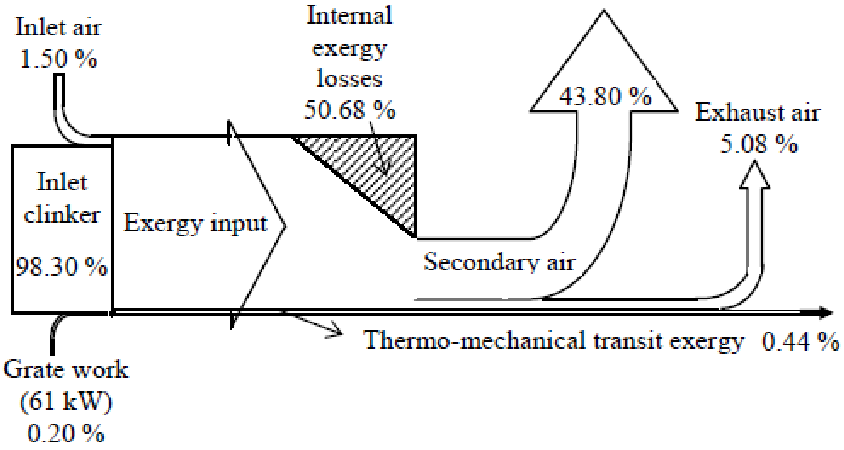

Figure 2.7
Exergy flow diagram of the clinker cooling system
Source: Touil et al., 2005

2.8 Operational Parameters of the Grate Clinker Cooler

The efficiency of the cooler plays a key role as it functions to recover heat from the hot clinker and pre-heat the air used for combustion in calciner and rotary kiln. Heat from the clinker that comes out of the cooler will not be recovered again, representing actual loss of the system. The optimum values of operational parameters of the cooler are needed to decrease the energy consumption (Mundhara and Sharma, 2005).

Detailed computational models were developed by Mundhara and Sharma (2005) to simulate the operational parameters for grate coolers. The model presented was based on the expression for calculating the heat transfer between cement clinker and air particles. In order to improve the efficiency of the cooler used in the cement industry, the operational parameters such as the optimum cooling air rate, the clinker input rate, the clinker inlet temperature, the cooler length, the number of openings for air, and the grate speed must be determined.

The length and the height of the clinker bed in the grate cooler were subdivided into individual balance segments for the calculation of heat transfer, using the finite volume method. It was assumed that the mass flow rate of solids remained unchanged throughout the system and the mass flow rate through each balance segment is the same as the inlet mass flow rate of the solids. The cooler undergoes a steady-state process, therefore there was no accumulation of energy in any subdivision (Mundhara and Sharma, 2005).

Several simulations were carried out by changing operational parameters of the cooler to find the effect of each parameter on the performance of cooler. These parameters include cooler height, mass flow rate of solid clinker, mass flow rate of air, and grate speed (Mundhara and Sharma, 2005). Table 2.7 presents the summary of the results, discussions and conclusions for some of the simulations ran.

Table 2.7
Summary of results, discussions and conclusions of the grate clinker cooler computational modelling

Case	Results	Discussion	Conclusion
Case 1: Temperature variation of cement clinker along the length of cooler at various heights.	At the initial length, the heat transfer is more at the bottom layers of clinker bed compared to the upper layers of clinker bed.	As the air moves upward the temperature of air increases and after reaching a certain bed height it becomes equal to the solid temperature, where no more heat transfer can take place.	The temperature of the top layer of solids should be maximum.
	As the length of cooler increases, the heat transfer increases at the top layers of clinker and decreases at the bottom layers of clinker. The air, which goes up to the top layers, will be at a lower temperature.	After a certain length, the bottom layers of solids have reached a temperature equal to the inlet temperature of the air. Therefore no more heat transfer can take place at these layers.	The maximum heat transfer will take place in the upper part of the bed.
Case 2: Temperature variation of air along the length of cooler at various heights.	At the initial length, the heat transfer is more at the bottom layers of air compared to the upper layers of air.	As the air moves upward, the temperature of air increases and after a certain bed height it reaches a temperature equal to the solid temperature and no more heat transfer can take place.	The temperature of the top layer of air should be maximum.
	As we move along the length of cooler, it is observed that the heat transfer is increasing at the top layers of air and decreasing at the bottom layers of air.	After a certain length, the bottom layers of solids has reached to a temperature equal to the inlet temperature of air, and no more heat transfer heat transfer can take place at these layers. Now the air, which goes to top layers, will be at a lower temperature.	The maximum heat transfer will take place in the upper part of the bed.
Case 3: Temperature variation of air along the length of cooler at various heights.	At the initial height, the heat transfer is more at the cooler entrance layers of air compared to the cooler exit layers of air.	As the solid moves along the length, the temperature of solid decreases and after a certain length it reaches to a temperature very close to the air temperature. Therefore no more heat transfer can take place at this place.	The maximum heat transfer will take place in the region where the high temperature solid goes to the cooler exit layers.
	As we move along the height of the cooler it is observed that the heat transfer is increasing at the cooler exit layers of air and decreasing at the cooler entrance of air.	After a certain height the temperature of cooler entrance air has reached at a temperature equal to the inlet temperature of solid. Hence, no more heat transfer can take place at these layers.	

(Mundhara and Sharma, 2005)

Table 2.7, continued
Summary of results, discussions and conclusions of the grate clinker cooler computational modelling

Case	Results	Discussion	Conclusion
Case 4: The clinker and air temperature variation along the length with mass flow rate of solid.	As the mass flow rates of solid are increased, the temperature of solids increases.	As the solid mass flow rate is increased, the heat input increases but there is no increment in heat transfer between solid and air. Consequently, the air doesn't get any extra amount of heat from solid and therefore the air temperature remains constant with mass flow rate of solid. But as the heat input increases, the solid temperature also increases.	An optimum value of mass flow rate of solid is required so that the recovery of energy is maximum in the cooler at a reasonable plant output.
	As the mass flow rate is increased, there is no variation of air temperature with mass flow rate of solid.		
Case 5: The variation of average caloric temperature of clinker and air temperature in free board region along the length of cooler at different mass flow rates of air.	As the mass flow rates of air is increased the outlet temperature of solid decreases.	More energy is able to be recovered from the solids.	The optimum mass flow rate of air for which energy recovery is maximum and the mass flow rate of air and its temperature is suitable for coal burning in rotary kiln and calciner needs to be determined.
	With the increase in air mass flow rate the outlet temperature of air decreases.	As the air mass flow rate is increased, more heat from the solids is able to be recovered.	
Case 6: The variation of average calorific temperature of clinker and air temperature variation in free board region with grate speed.	As the grate speed is increased, first the air outlet temperature increases with grate speed and after a value of grate speed it starts to decrease.	As the grate speed is increased, the residence time of solids will decrease, resulting in lower amount of heat transfer.	At a certain grate speed the heat transfer will be at a maximum.
	As the grate speed increases, the solid bed height will decrease so as to increase the rate of heat transfer.	The solid bed height will decrease so as to increase the rate of heat transfer	

(Mundhara and Sharma, 2005)