CHAPTER IV

RESULTS & DISCUSSIONS

4.1 Energy Analysis of the Base Case Clinker Cooler

The energy analysis for the base case grate clinker cooler is performed by using the formulas in Table 3.1. The mass balance of the system first needs to be analyzed to show that the clinker cooling process is a steady process, i.e. the total mass input into the system is equivalent to the total mass output of the system. The study then proceeds to the energy balance of the system, for which the total energy input of the system should be equal to the total energy output of the system. The next two subchapters present the sample of calculations for the mass balance and energy balance, as well as the calculations for the energy efficiency and the energy recovery efficiency of the grate clinker cooling system.

4.1.1 Mass Balance

The mass balance of the grate clinker cooler is conceived on the law of mass conservation using equations below:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{4.1}$$

$$(\dot{m}_{ic} + \dot{m}_{ca}) - (\dot{m}_{as} + \dot{m}_{at} + \dot{m}_{oc} + \dot{m}_{exh}) = 0 \tag{4.2}$$

$$\left(1.00\,\frac{kg}{kg.ck} + 2.55\,\frac{kg}{kg.ck}\right) - \left(0.45\,\frac{kg}{kg.ck} + 0.42\,\frac{kg}{kg.ck} + 1.00\,\frac{kg}{kg.ck} + 1.68\,\frac{kg}{kg.ck}\right) = 0 \tag{4.3}$$

4.1.2 *Energy Balance*

The energy balance of the grate clinker cooler is conceived on the law of energy conservation using equations as follows:

$$\sum \mathrm{E_{in}} - \sum \mathrm{E_{out}} = 0 \tag{4.4}$$

$$(\dot{Q}_{ic} + \dot{Q}_{ca}) - (\dot{Q}_{pk} + \dot{Q}_{pc} + \dot{Q}_{oc} + \dot{Q}_{exh}) = 0 \tag{4.5}$$

$$\left(1351.5\ \frac{kJ}{kg,ck} + 51.5\ \frac{kJ}{kg.ck}\right) - \left(423.2\frac{kJ}{kg.ck} + 296.6\ \frac{kJ}{kg.ck} + 82.8\ \frac{kJ}{kg.ck} + 337.4\ \frac{kJ}{kg.ck}\right)$$

$$= 262.9\ \frac{kJ}{kg.ck} \ \leftarrow \textit{unaccountable losses} \tag{4.6}$$

The energy efficiency of the clinker cooler:

$$\eta_{cooler,I} = \frac{(\dot{Q}_{pk}+\dot{Q}_{pc}+\dot{Q}_{oc}+\dot{Q}_{exh})}{\dot{Q}_{ic}+\dot{Q}_{ca}}$$

$$= \frac{\left(423.2\frac{kJ}{kg.ck}+296.6\ \frac{kJ}{kg.ck}+82.8\ \frac{kJ}{kg.ck}+337.4\ \frac{kJ}{kg.ck}\right)}{1351.5\ \frac{kJ}{kg.ck}+51.5\ \frac{kJ}{kg.ck}} = 81.3\% \tag{4.7}$$

The energy recovery efficiency of the clinker cooler:

$$\eta_{recovery,\ cooler} = \frac{\dot{Q}_r}{\dot{Q}_{ic}+\dot{Q}_{ca}} = \frac{\dot{Q}_{pk}+\dot{Q}_{pc}}{\dot{Q}_{ic}+\dot{Q}_{ca}} = \frac{423.2\frac{kJ}{kg.ck}+296.6\ \frac{kJ}{kg.ck}}{1351.5\ \frac{kJ}{kg.ck}+51.5\ \frac{kJ}{kg.ck}} = 51.3\% \tag{4.8}$$

Table 4.1.2
Energy analysis summary of the base case clinker cooler

	Material	**Mass Flow Rate (kg/kg clinker)**	**Cp (kJ/kg.˚C)**	**T (˚C)**	**Q (kJ/kg.ck)**	**%**
Input	Hot Clinker	1.00	1.06	1300.0	1351.5	96.3
	Cooling air	2.55	1.01	45.0	51.5	3.7
Output	Secondary air	0.45	1.14	850.0	423.2	30.2
	Tertiary air	0.42	1.13	650.0	296.6	21.1
	Cooled Clinker	1.00	0.92	115.0	82.8	5.9
	Exhaust air	1.68	1.03	220.0	337.4	24.1
	Unaccountable losses				262.9	18.7

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

Table 4.1.2 presents the summary of energy analysis of the base case clinker cooler using the theoretical input and output data in Table 3.1.1. The mass input, for which in this case is taken as kg/kg clinker, is the same as the mass output of the system at 3.55 kg/kg clinker. The individual specific heat of each material depends on the temperature of the material. The total energy output of this system at a value of 1403 kJ/kg clinker is equal to the total energy input, taking into account the unaccountable losses of the system. These losses are primarily due to heat losses via convection and radiation heat transfers.

From Equation 4.7, the energy efficiency of the system is 81.3%. This figure represents the overall performance of the grate clinker cooling system, for which heat energy contained in the exhaust air and the cooled clinker are still considered to be recovered regardless of the end use. Equation 4.8 shows that the energy recovery efficiency of the system is much lower at 51.3%. This is due to the fact that for energy recovery efficiency, only the heat energy recovered and used at other phases of clinker production is taken into account. The energy recovery efficiency of the system plays a bigger role in the improvement of the clinker cooler, as the increase in its value translates to energy and cost saving.

4.2 Exergy Analysis of the Base Case Clinker Cooler

The exergy analysis for the base case grate clinker cooler is almost similar to its energy analysis counterpart. The mass balance of the system is adopted from the energy analysis, since the only difference between the exergy and energy analyses lies in the state of the system's surroundings. The irreversible process of clinker cooling produces entropy, which consequently leads to exergy destruction. The next subchapter presents the sample of calculations for the exergy balance, as well as the calculations for the exergy efficiency and the exergy recovery efficiency of the grate clinker cooler.

4.2.1 Exergy Balance

The steady state exergy balance of the open system of clinker cooling:

$$T_0\dot{S}_{gen} = \dot{E}x_d = (\dot{E}x_{ic} + \dot{E}x_{ca}) - (\dot{E}x_{oc} + \dot{E}x_{pk} + \dot{E}x_{pc} + \dot{E}x_{exh})$$

$$= \left(\dot{m}_{ck}\bar{e}_{ck,in} + \dot{m}_a\bar{e}_a\right) - \left(\dot{m}_{ck}\bar{e}_{ck,out} + \dot{m}_{as}\bar{e}_{as} + \dot{m}_{at}\bar{e}_{at} + \dot{m}_{aexh}\bar{e}_{exh}\right) \quad (4.9)$$

where Specific exergy of *hot clinker*,

$$\dot{m}_{ck}\bar{e}_{ck,in} = \dot{m}_{ck}\left[\left(\bar{h}_{ck,in} - \bar{h}_0\right) - T_0(\bar{s}_{ck,in} - \bar{s}_0)\right] \quad (4.10)$$

$$= \left(1.00\,\frac{kg}{kg.\,ck}\right)\left[\left(1351.5\,\frac{kJ}{kg}\right) - \left(525.5\,\frac{kJ}{kg}\right)\right] = 826.0\,\frac{kJ}{kg.\,ck}$$

Specific exergy of *cooling air*, assuming $P_a = P_o$,

$$\dot{m}_a\bar{e}_a = \dot{m}_a\left[\left(\bar{h}_{ca} - \bar{h}_0\right) - T_0(\bar{s}_{ca} - \bar{s}_0)\right] \quad (4.11)$$

$$= \left(2.55\,\frac{kg}{kg.ck}\right)\left[\left(20.2\,\frac{kJ}{kg}\right) - \left(19.6\,\frac{kJ}{kg}\right)\right] = 1.7\,\frac{kJ}{kg}$$

Specific exergy of *cooled clinker*,

$$\dot{m}_{ck}\bar{e}_{ck,out} = \dot{m}_{ck}\left[\left(\bar{h}_{ck,out} - \bar{h}_0\right) - T_0(\bar{s}_{ck,out} - \bar{s}_0)\right] \quad (4.12)$$

$$= \left(1.00\,\frac{kg}{kg.ck}\right)\left[\left(82.8\,\frac{kJ}{kg}\right) - \left(72.4\,\frac{kJ}{kg}\right)\right] = 10.4\,\frac{kJ}{kg}$$

Specific exergy of *secondary air*, assuming $P_{as} = P_o$,

$$\dot{m}_{as}\bar{e}_{as} = \dot{m}_{as}\left[\left(\bar{h}_{as} - \bar{h}_0\right) - T_0(\bar{s}_{as} - \bar{s}_0)\right] \quad (4.13)$$

$$= \left(0.45\,\frac{kg}{kg.ck}\right)\left[\left(940.4\,\frac{kJ}{kg}\right) - \left(450.7\,\frac{kJ}{kg}\right)\right] = 220.4\,\frac{kJ}{kg}$$

Specific exergy of *tertiary air*, assuming $P_{at} = P_o$,

$$\dot{m}_{at}\bar{e}_{at} = \dot{m}_{at}\left[\left(\bar{h}_{at} - \bar{h}_0\right) - T_0(\bar{s}_{at} - \bar{s}_0)\right] \quad (4.14)$$

$$= \left(0.42\,\frac{kg}{kg.\,ck}\right)\left[\left(705.2\,\frac{kJ}{kg}\right) - \left(380.7\,\frac{kJ}{kg}\right)\right] = 136.7\,\frac{kJ}{kg}$$

and Specific exergy of *exhaust air*, assuming $P_{exh} = P_o$,

$$\dot{m}_{exh}\bar{e}_{exh} = \dot{m}_{exh}\left[\left(\bar{h}_{exh} - \bar{h}_0\right) - T_0(\bar{s}_{exh} - \bar{s}_0)\right] \tag{4.15}$$

$$= \left(1.68\frac{kg}{kg.ck}\right)\left[\left(200.8\frac{kJ}{kg}\right) - \left(154.5\frac{kJ}{kg}\right)\right] = 77.8\frac{kJ}{kg}$$

Therefore, the rate of exergy destroyed:

$$\dot{E}x_d = \left[(\dot{E}x_{ic} + \dot{E}x_{ca}) - (\dot{E}x_{oc} + \dot{E}x_{pk} + \dot{E}x_{pc} + \dot{E}x_{exh})\right]$$

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

$$= \left[\left(826.0\frac{kJ}{kg.ck} + 1.7\frac{kJ}{kg.ck}\right) - \left(10.4\frac{kJ}{kg.ck} + 220.4\frac{kJ}{kg.ck} + 136.7\frac{kJ}{kg.ck} + 77.8\frac{kJ}{kg.ck}\right)\right]$$

$$= 382.2\frac{kJ}{kg.ck}$$

Based on the second law analysis, the exergy efficiency of the clinker cooler:

$$\eta_{II,1} = \frac{\left(\dot{m}_{ck}\bar{e}_{ck,out} + \dot{m}_{as}\bar{e}_{as} + \dot{m}_{at}\bar{e}_{at} + \dot{m}_{aexh}\bar{e}_{exh}\right)}{\left(\dot{m}_{ck}\bar{e}_{ck,in} + \dot{m}_a\bar{e}_a\right)} = \frac{445.3\frac{kJ}{kg.ck}}{827.7\frac{kJ}{kg.ck}} = 53.8\% \tag{4.16}$$

The exergy recovery efficiency of the clinker cooler:

$$\eta_{II,2} = \frac{\left(\dot{m}_{as}\bar{e}_{as} + \dot{m}_{at}\bar{e}_{at}\right)}{\left(\dot{m}_{ck}\bar{e}_{ck,in} + \dot{m}_a\bar{e}_a\right)} = \frac{357.1\frac{kJ}{kg.ck}}{827.7\frac{kJ}{kg.ck}} = 43.2\% \tag{4.17}$$

Table 4.2.1
Exergy analysis summary of the base case clinker cooler

	Material	Mass Flow Rate (kg/kg clinker)	Cp (kJ/kg.˚C)	T (˚C)	Ex (kJ/kg.ck)	%
Input	Hot Clinker	1.00	1.06	1300.0	826.0	99.8
	Cooling air	2.55	1.01	45.0	1.7	0.2
Output	Secondary air	0.45	1.14	850.0	220.4	26.6
	Tertiary air	0.42	1.13	650.0	136.7	16.5
	Cooled Clinker	1.00	0.92	115.0	10.4	1.3
	Exhaust air	1.68	1.03	220.0	77.8	9.4
	Total Exergy losses				382.2	46.2

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

Table 4.2.1 presents the summary of exergy analysis of the base case clinker cooler using the theoretical input and output data in Table 3.1.1, and the energy analysis results obtained from subchapter 4.1. The mass input, adopted from the energy analysis, remains balanced at 3.55 kg/kg clinker on each side of the equation. The total exergy output of this system at a value of 445.3 kJ/kg clinker is 382.2 kJ/kg clinker less than the total exergy input. This figure represents the total amount of exergy destruction of the clinker cooling process. It also includes the exergy destruction related to the energy that is lost through convection and radiation heat transfers.

From Equation 4.16, the exergy efficiency of the system is 53.8%. Similar to the energy efficiency of the system, this figure represents the overall performance of the grate clinker cooling system, for which exergy contained in the exhaust air and the cooled clinker are still considered to be recovered regardless of the end use. The exergy efficiency of the grate clinker cooling system is relatively low compared to its energy efficiency at 81.3%. This confirms that at the given system surroundings, not all energy contained within the system can be converted to useful work. The exergy of the system is always destroyed in the irreversible clinker cooling process, for which its constituents are brought to a state of equilibrium with the surroundings.

Equation 4.17 shows that the exergy recovery efficiency of the system is much lower at 43.2%. This is due to the fact that for exergy recovery efficiency, only the exergy recovered and used at other phases of clinker production is taken into account. Similar to the energy recovery efficiency, the exergy recovery efficiency of the system also plays a bigger role in the improvement of the clinker cooler. Exergy recovery efficiency represents the real room for improvement for the system.

4.3 Operational Parameter: Mass Flow Rate of Cooling Air

4.3.1 Change in First & Second Law Efficiencies of the Grate Clinker Cooling System

Variation in mass flow rate of cooling air will cause the change in outlet temperature of clinker, due to an increase or decrease in the rate of heat transfer between the two mediums. Theoretically, as we increase the mass flow rate of cooling air, we are able to recover more heat energy from the solid clinker. The increase in mass flow rate of cooling air will also cause a slight decrease in the outlet temperature of air, i.e. the secondary and the tertiary air temperatures, and the exhaust air temperature (Mundhara and Sharma, 2005).

Figure 4.3.1 (a) and Figure 4.3.1 (b) present the temperature profiles of solid clinker and cooling air along the length of cooler at different mass flow rate of cooling air, respectively. The temperature variation of clinker and air are estimated from the corresponding variations in the figures borrowed from the computational results obtained in the study performed by Mundhara and Sharma (2005).

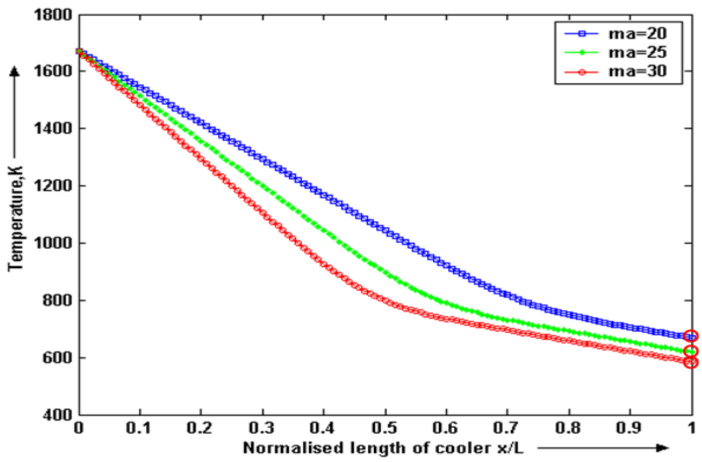

Figure 4.3.1 (a)
Variation of average caloric temperature of the clinker along the length of cooler at different mass flow rate of cooling air
Source: Mundhara and Sharma, 2005

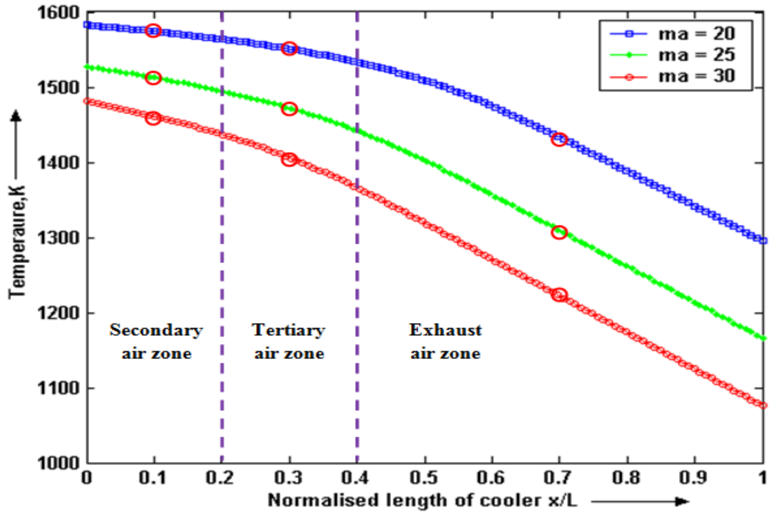

Figure 4.3.1 (b)
Variation of air temperature at freeboard region along the length of cooler at different mass flow rate of cooling air
Source: Mundhara and Sharma, 2005

For the air temperature profile, the cooler is divided into three regions, i.e. the secondary air zone, the tertiary air zone and the exhaust air zone. On the other hand, for the clinker temperature profile, this would not be necessary as only the temperature at the outlet is of interest. For this analysis, only the temperature variations between the circled points, and not the entire profile, are taken into account in order to estimate the cooler's performance with variation in its parameters. These points represent the points of average temperatures for every zone in the cooler. In this analysis, the secondary air temperature is estimated to decrease 0.2% with every 5% increase in mass flow rate of cooling air, the tertiary air temperature is estimated to decrease 1.2% with every 5% increase in mass flow rate of cooling air, and the exhaust air temperature is estimated to decrease 2.1% with every 5% increase in mass flow rate of cooling air. The temperature of the clinker outlet, on the other hand, is estimated to decrease 1.9% for every 5% increase in mass flow rate of cooling air (Mundhara and Sharma, 2005).

Referring to the air temperature profile, the temperature of air varies along the length of the cooler. 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 it reaches a temperature equal to the solid temperature and after a certain bed height, no more heat transfer can take place. The temperature of the top layer of air will be at a maximum. Moving along the length of the cooler, the heat transfer increases at the top layers of air and decreases at the bottom layers of air. After a certain length, the bottom layers of solids reach a temperature equal to the inlet temperature of air, and no more 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.

The air temperature profile of the air is also affected by the height of the cooler. At the initial height, 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 a temperature very close to the air temperature. No more heat transfer can take place at this place. Moving 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, reaching a temperature very close to the air temperature and ceasing any heat transfer. After a certain height the temperature of the cooler entrance air has reached a temperature equal to the inlet temperature of solid where no more heat transfer can take place. The maximum heat transfer will take place in the region where the high temperature solid goes to the cooler exit layers.

By performing an ideal energy and exergy analyses on the clinker cooler, we are able to find the trend of the first and the second law efficiencies increment with the increase of cooling air mass flow rate. Figure 4.3.1 (c) and Figure 4.3.1 (d) present the variation in the first and the second law efficiencies with increment in mass flow rate of cooling air, respectively.

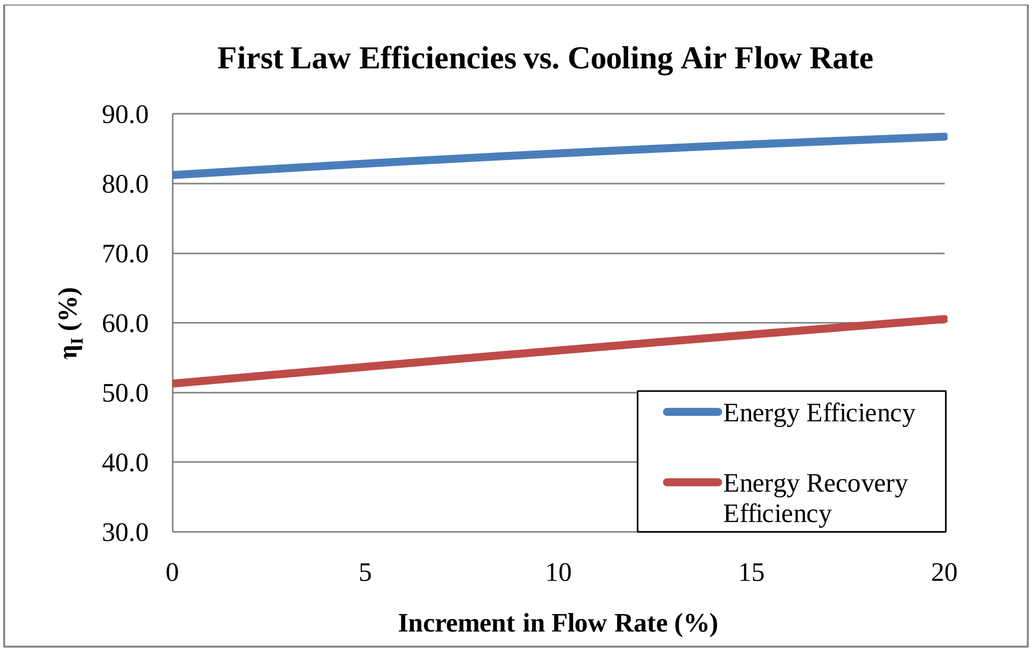

Figure 4.3.1 (c)
Variation in first law efficiencies of the grate clinker cooler with increment in mass flow rate of cooling air

The overall performance of the system can be represented by the general first law or energy efficiency. For this study however, the energy recovery efficiency plays a bigger role as it represents the major opportunity in energy and thus, cost saving. The trend in Figure 4.3.1 (c) shows that the energy efficiency, as well as the energy recovery efficiency of the grate clinker cooler increase with increasing mass flow rate of cooling air. For every 5% increment in mass flow rate of cooling air, the clinker cooler experiences roughly 1.4% hike in energy efficiency and 2.3% hike in energy recovery efficiency.

As the mass flow rate of cooling air is increased, the temperature of clinker solid at the outlet decreases. More energy is able to be absorbed by the increased air flow and returned to the rotary burner and the pre-calciner as secondary and tertiary air, respectively. Even though the increase in cooling air mass flow rate causes a drop in air outlet temperatures, the main sources of energy recovery of the system, i.e. energy from the secondary and tertiary air, are not significantly affected due to the low temperature drops of these two parameters. In average, air temperatures near the end of the cooler are more significantly affected compared to the ones near the beginning, where secondary and tertiary air are returned to the rotary kiln and pre-calciner respectively. 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 can be determined with further variation of the parameter studied.

The unaccountable losses of the cooler, which are mainly convection and radiation heat losses, reduce with increasing mass flow rate of cooling air. Consequently, the first law efficiencies of the system also increase. These losses are related primarily to the cooler surface and the surrounding temperatures. Introducing larger mass flow rate of cooling air into the system improves the heat transfer rates within the clinker cooler. As interpreted above, the air temperatures within the cooler will drop with increasing mass flow rate of cooling air, as more air is available to absorb and recover the same amount of heat energy from a specific amount of clinker. This drop in temperature consequently leads to a lower average temperature in the cooler, which causes the cooler wall temperature to drop as well. Since convection and radiation are both dependent upon the magnitude of temperature difference between the wall and the surroundings, a drop in wall temperature will decrease the amount of heat loss to the surroundings.

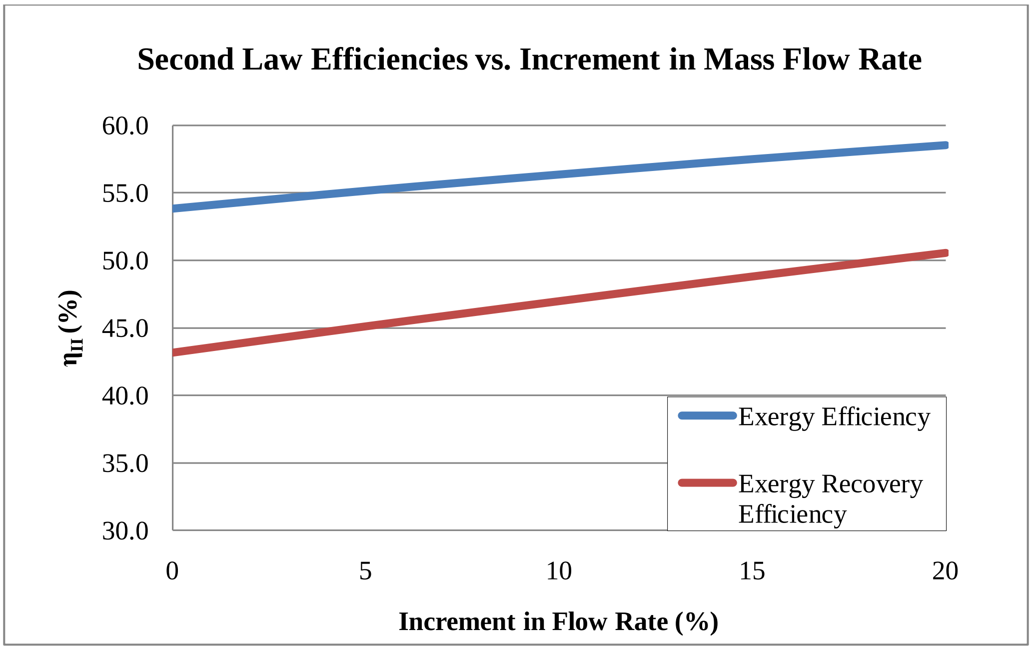

Figure 4.3.1 (d)

Variation in second law efficiencies of the grate clinker cooler with increment in mass flow rate of cooling air

The trend in Figure 4.3.1 (d) shows that the exergy efficiency, as well as the exergy recovery efficiency of the grate clinker cooler increase with increasing mass flow rate of cooling air. For every 5% increment in mass flow rate of cooling air, the clinker cooler experiences roughly 1.2% hike in energy efficiency and 1.9% hike in energy recovery efficiency. As stated previously, the first law efficiencies of a system only represent its general performance. It does not give any information on the degradation of energy that occurs in the clinker cooling process. The second law efficiencies on the other hand, represent the real room of improvement for the grate clinker cooler. Similar to the energy recovery efficiency, the exergy recovery efficiency plays a bigger role compared to exergy efficiency of the system alone.

It is apparent from Figure 4.3.1 (c) and Figure 4.3.1 (d) that the increase in second law efficiencies of the system is lower than the increase in first law efficiencies, with increment in cooling air mass flow rate. Actual processes occur in the direction of decreasing quality of energy, and exergy represents the maximum capacity of a system to perform useful work as it proceeds to a specified final equilibrium state with its surroundings. In actual and irreversible processes such as the clinker cooling process, a big amount of exergy is always destroyed due to the difference in conditions between the energy sources and the environment. Compared to first law efficiencies, second law efficiencies are always lower for any system, because not all the energy sources can be converted to useful work.

The exergy content of a material depends on its temperature, its specific heat, and its reference environment. The exergy contents of ideal gases also depend on their pressures, but for this analysis they are assumed to be equal to that of the environment. Exergy destruction during the process of clinker cooling is mainly due to the change in the materials' temperatures and the specific heat capacities associated with them. Convection and radiation heat losses to the surroundings also contribute to the external exergy losses of the system.

4.3.2 Electrical Energy Requirement with Increment in Mass Flow Rate of Cooling Air

It is evident from the previous analysis that the increase in mass flow rate of cooling air would bring about the improvement in the first and the second law efficiencies of the grate clinker cooler. The increment in mass flow rate of cooling air is a result of an increase in air flow from the cooler fans. To have an increment in air flow, it is fairly typical for a cement plant to install Variable Speed Drives on the existing fans. This technology allows fan speed and hence mass flow rate of cooling air to be varied with respect to loads (Energy Efficiency Guide for Industry in Asia, 2005).

It can be estimated that the volumetric flow rate from a fan is directly proportional to the motor speed, making the most efficient method to control the fan output through fan speed control. On the other hand, power consumed by the fan motor is proportional to the motor speed cubed, i.e. a small change in motor speed results in a large change in power. (Energy Efficiency Guide for Industry in Asia, 2005).

Assuming the grate clinker cooler is originally equipped with fans at four different sections, i.e. secondary air fans, tertiary air fans, exhaust air fans and cooling air fans, the upgrade to cooling air fans would also have to be complemented by the upgrades to these other fans. The additional electrical energy requirements after the installation of VSD's would be dependent on the fraction of air flow rate that these fans have to accommodate.

Taking the plant output to be 3000 tonnes of clinker per day, and 187.5 tonnes of clinker per hour, i.e. 16 hours of operation per day, we can estimate the additional amount of electrical energy required from every 5% optimization of the mass flow rate of cooling air. The density of air is taken as 1.109 kg/m^3 at 45˚C, 0.3149 kg/m^3 at 850˚C, 0.3835 kg/m^3 at 650˚C, and 0.7174 kg/m^3 at 220˚C (Cengel, 2006). The motor power consumption is estimated from the amount of additional air flow rate and typically used fan sizes. The additional power consumptions of the fan motors are based on the assumptions that the average fan motor power consumption per unit volume air flow rate is 0.00128 kW/cmh (Energy Efficiency Guide for Industry in Asia, 2005). Table 4.3.2 presents the additional fan electrical energy requirements for every 5% increase in mass flow rate of cooling air.

Table 4.3.2
Additional fan electrical energy requirements for every 5% increase in mass flow rate of cooling air

Material	Original Mass Flow Rate (kg/kg clinker)	Mass Flow Rate (kg/kg clinker) after 5% Increment	Additional Air Mass Flow Rate (kg/kg ck)	Additional Air Volume Flow Rate (m^3/h)	Fan Motor Power (kW)	Energy Requirement per day (kWh)
Cooling air	2.55	2.68	0.13	21563	27.6	442
Secondary air	0.45	0.48	0.02	11912	15.2	244
Tertiary air	0.42	0.45	0.02	9781	12.5	200
Exhaust air	1.68	1.76	0.08	20000	25.6	410
TOTAL					**81**	**1296**

(Energy Efficiency Guide for Industry in Asia, 2005)

Table 4.3.2 shows that the largest power consuming fans that have to be added into the clinker cooling system are the cooling air fans, with a total motor power of 27.6 kW, resulting in 442 kWh of energy consumption per day. This is followed by the exhaust air fans at 410 kWh of energy consumption per day, the secondary air fans at 244 kWh of energy consumption per day and the tertiary air fans at 200 kWh of energy consumption per day. The total additional daily energy consumption goes up to 1296 kWh per day for every 5% increase in mass flow rate of cooling air. Accurate fan and motor sizing requires the balancing between the volume flow rate of air that the fans have to accommodate and their corresponding static pressures. Intuitively, bigger volume of air to be handled will require a fan motor with higher power input, given the same impeller size and fan speed.

It is generally known that costs would be involved in increasing the mass flow rate of cooling air. These costs include the costs of materials, i.e. the new Variable Speed Drive, the costs of commissioning of these new materials, and the additional operating costs. The economic standpoint for these upgrades can be viewed more clearly in the cost benefit analyses, when the costs incurred are economically analyzed.

4.4 Operational Parameter: Temperature of Cooling Air

4.4.1 Change in First & Second Law Efficiencies of the Grate Clinker Cooling System

Variation in cooling air temperature will theoretically affect the heat transfer rate between the cooling air and the hot clinker, as heat transfer is driven by the temperature difference between these two mediums. The magnitude of heat transfer is dependent upon the magnitude of the abovementioned temperature difference. Despite the larger capacity to absorb heat, the lower temperature cooling air also causes fall of air outlet and clinker outlet temperatures, consequently leading to exergy losses (Touil et al., 2005)

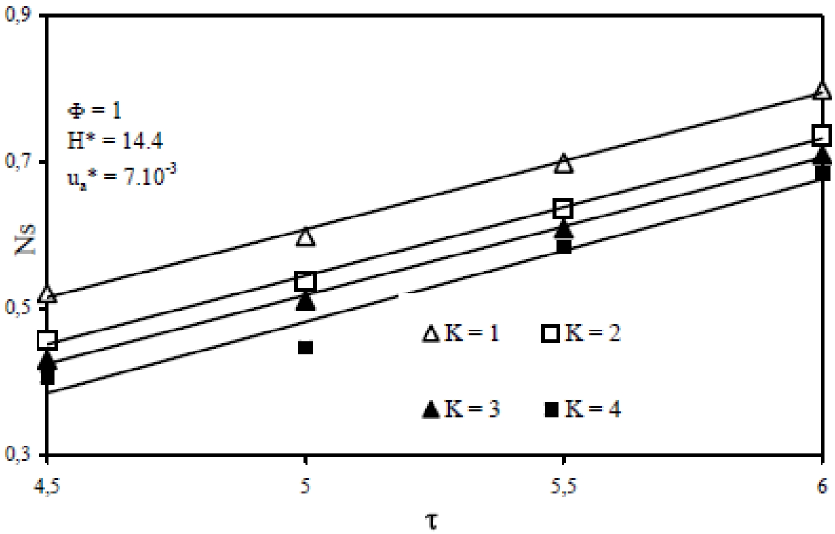

Figure 4.4.1 (a)
Effect of inlet temperature ratio on entropy production in the grate clinker cooler
Source: Touil et al., 2005

Figure 4.4.1 (a) presents the effect of inlet temperature ratio, i.e. ratio of the temperature of cooling air to the temperature of hot clinker, on entropy production in a grate clinker cooler. The results were obtained from a previous analysis done by Touil et al. (2005), showing that the entropy production and hence the exergy destruction increase with inlet temperature ratio. The results had suggested that for every 5%

decrease in cooling air temperature, the exergy destruction increases 7.4%. Similar to the case with increasing the mass flow rate of cooling air, reducing its temperature will also cause a decrease in the outlet temperatures of air, as well as the outlet temperature of clinker. For this analysis, in order to estimate the first law efficiencies of the clinker cooler, the clinker outlet temperature, the secondary and the tertiary air temperatures, and the exhaust air temperature are assumed to vary an average of 2.31% with every 5% variation in temperature of cooling air (Touil et al., 2005).

By performing ideal energy and exergy analyses on the clinker cooler, we are able to find the trend of the first and the second law efficiencies with variation in cooling air temperature. Figure 4.4.1 (b) and Figure 4.4.1 (c) present the variation in the first and the second law efficiencies of the grate clinker cooler with change in temperature of cooling air, respectively.

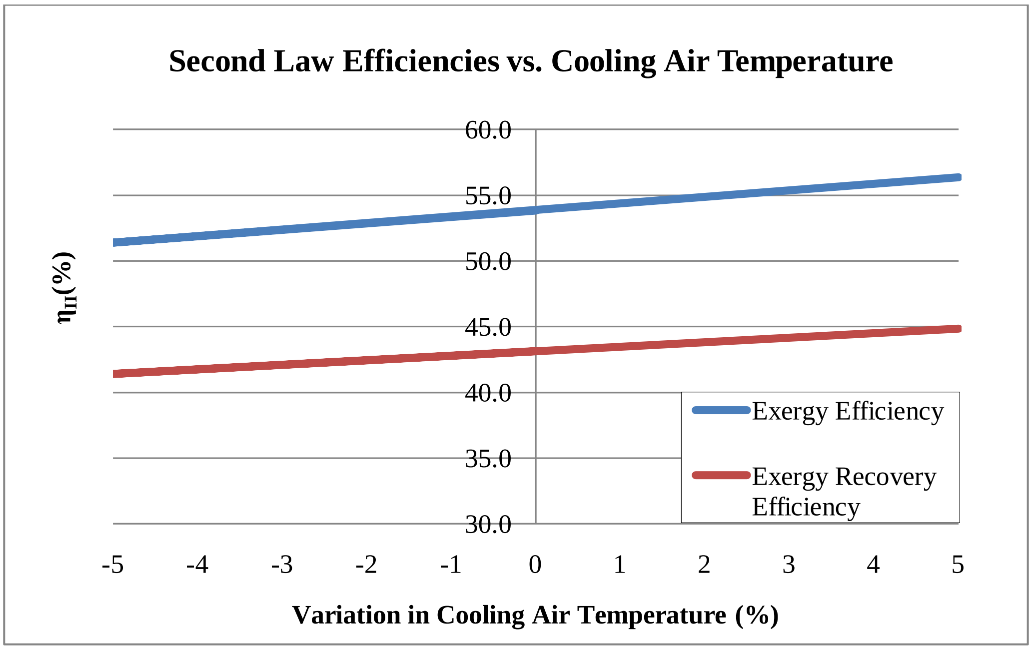

Figure 4.4.1 (b)
Variation in second law efficiencies of the grate clinker cooler with change in temperature of cooling air

The trend in Figure 4.4.1 (b) shows that the exergy efficiency, as well as the exergy recovery efficiency of the grate clinker cooler increase with increasing temperature of cooling air. The 7.4% increase in exergy destruction that comes with every 5% decrease in cooling air temperature is partially reflected through the trend of second law efficiencies of the system, where the exergy efficiency and the exergy recovery efficiency roughly decrease 2.5% and 1.7% respectively, with every 5% decrease in cooling air temperature.

Despite of the increased amount of energy that the lower temperature cooling air is able to recover, this cooling does not restore to the air the initial hot clinker temperature. This fall of temperature consequently causes internal exergy losses. Theoretically, it is not desirable to cool clinker with air at low temperature, but at an optimal high temperature corresponding to the minimum exergy loss. Heat recovery of the exhaust air is a means that will contribute to the pre-heating of the cooling air and decreasing external exergy losses.

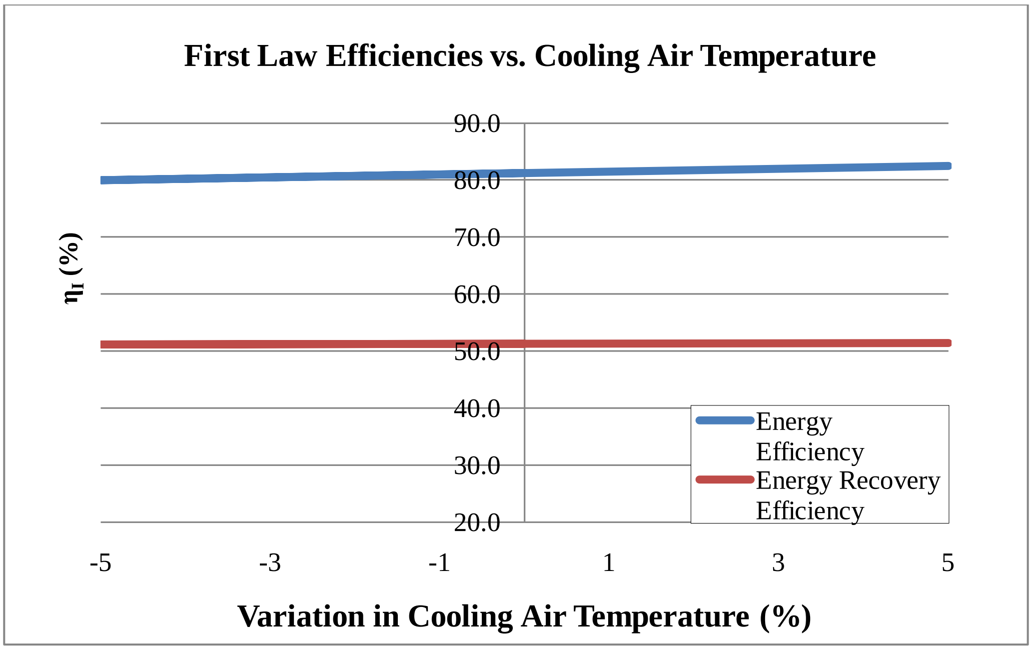

Figure 4.4.1 (c)
Variation in first law efficiencies of the grate clinker cooler with change in temperature of cooling air

With the given magnitude of increment in exergy destruction for every 5% decrease in cooling air temperature, we are able to come up with an estimate of the trend of the first law efficiencies of the clinker cooling system. Assuming a balance variation in air outlet temperatures, i.e. 2.31% decrease with every 5% decrease in cooling air temperature, the energy efficiency and the energy recovery efficiency of the system drop roughly 1.2% and 0.1% respectively, with every 5% decrease in cooling air temperature.

The unaccountable losses of the cooler, which are mainly convection and radiation heat losses, reduce with increasing cooling air temperature up to a certain extent. Consequently, the first law efficiencies of the system also increase slightly. Higher cooling air temperatures result in higher outlet air temperatures, which translates to higher amount of heat recovered to rotary kiln and pre-calciner. This effect slightly overcomes the increased amount of heat loss through radiation and convection to the surroundings, which also rises with increasing average temperature in the cooler.

4.4.2 Heat Energy Requirement with Increment in Temperature of Cooling Air

It has been proven that increasing the temperature of the cooling air to a certain degree will result in the increment of the first and the second law efficiencies of the grate clinker cooler. In order to increase the temperature of the cooling air, heat from the exhaust air needs to be transferred to the cooling air via pipelines. Typically clinker coolers will utilize a fraction of the exhaust air to perform this job.

Considering heat transfer efficiency of 100% between the exhaust air and the cooling air, the amount of sensible heat required to increase the temperature of cooling air by 5% is as follows:

$$\dot{Q}_{\text{cooling air}} = \dot{m}c_{\text{ave}}(T_2 - T_1)$$

$$= \left(2.55\,\frac{\text{kg}}{\text{kg. ck}}\right) \text{x} \left(1.007\,\frac{\text{kJ}}{\text{kg}}.\text{K}\right) \text{x}\ (334\text{K} - 318\text{K})$$

$$= 41.1\,\frac{\text{kJ}}{\text{kg.ck}}$$

Taking the total sensible heat contained within the exhaust air for the base case clinker cooler to be 337.2 kJ/kg.ck, the fraction of heat that is returned to heat the cooling air is:

$$\%\ \text{Heat} = \frac{\dot{Q}_{\text{cooling air}}}{\dot{Q}_{\text{exh}}}\ \text{x}\ 100\%$$

$$= \frac{41.1\ \frac{\text{kJ}}{\text{kg. ck}}}{337.4\ \frac{\text{kJ}}{\text{kg. ck}}}\ \text{x}\ 100\% = 12.2\%$$

From the analysis, it is apparent that 12.2% of the sensible heat contained within the exhaust air is used to preheat the incoming cooling air from 45˚C to approximately 60˚C. The specific heat of the air is taken at the average temperature of 52.5˚C. This analysis was performed under the assumption that no heat was lost during the heat transfer. In reality, most of the heat is loss through convection and radiation heat transfers from the improperly insulated pipelines to the surroundings. Out of the 337.4 kJ/kg clinker of sensible heat contained within the exhaust air, it can be said that 97.8% is dedicated to dry the coal and raw materials.

4.5 Operational Parameter: Mass Flow Rate of Clinker

4.5.1 Change in First & Second Law Efficiencies of the Grate Clinker Cooling System

Mass flow rate generally affects the rate of heat transfer, i.e. the power consumed or generated for any given system. From the previous study done by Mundhara and Sharma (2005), we know that reducing the mass flow rate of clinker into the grate clinker cooling system while maintaining the mass flow rate of cooling air will theoretically reduce the temperature of clinker outlet. It has also been proven that the temperatures of the outlet air are not significantly affected by the change in mass flow rate of clinker (Mundhara and Sharma, 2005).

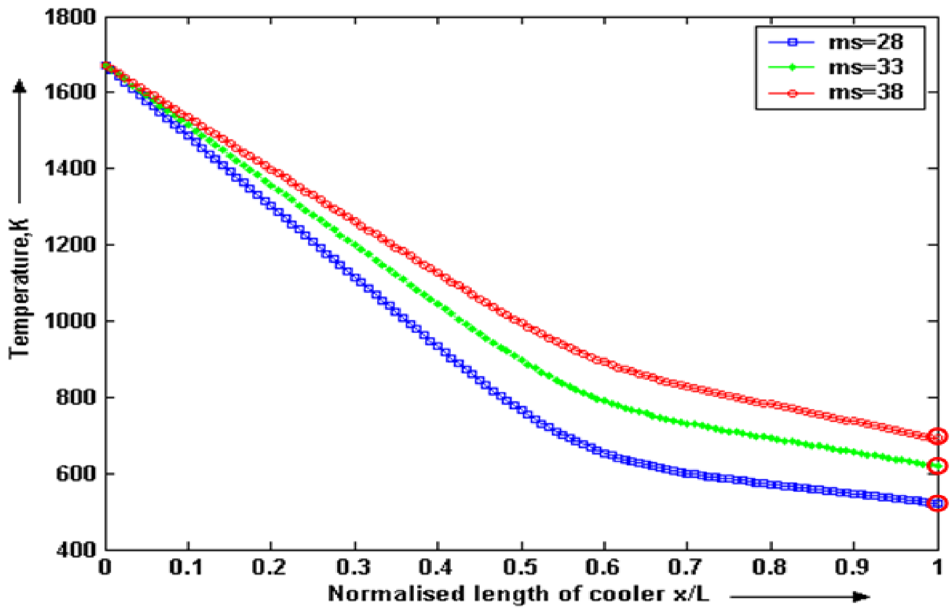

Fig. 4.5.1 (a)
Variation of clinker temperature along the length of cooler at different mass flow rate of clinker
Source: Mundhara and Sharma, 2005

Figure 4.5.1 (a) presents the temperature profiles of solid clinker along the length of cooler at different mass flow rate of clinker. The temperature variation of clinker is estimated from the corresponding variation in the figure borrowed from the computational results obtained in the study performed by Mundhara and Sharma (2005). The clinker outlet is estimated to decrease 3.7% with every 5% decrease in mass flow rate of clinker (Mundhara and Sharma, 2005).

Referring to the clinker temperature profile, the temperature of clinker varies along the length of the cooler. At the initial length, the heat transfer is more at the bottom layers of clinker bed compared to the upper layers of clinker bed. When 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. Hence, the temperature of the top layer of solids will be at a 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 reaches a temperature equal to the inlet temperature of the air. No more heat transfer can take place at these layers. The maximum heat transfer will take place in the upper part of the bed.

By performing ideal energy and exergy analyses on the clinker cooler, we are able to find the trend of the first and the second law efficiencies with decrement in clinker mass flow rate. Figure 4.5.1 (b) presents the variation in the first and second law efficiencies of grate clinker cooler with decrement in mass flow rate of clinker, respectively.

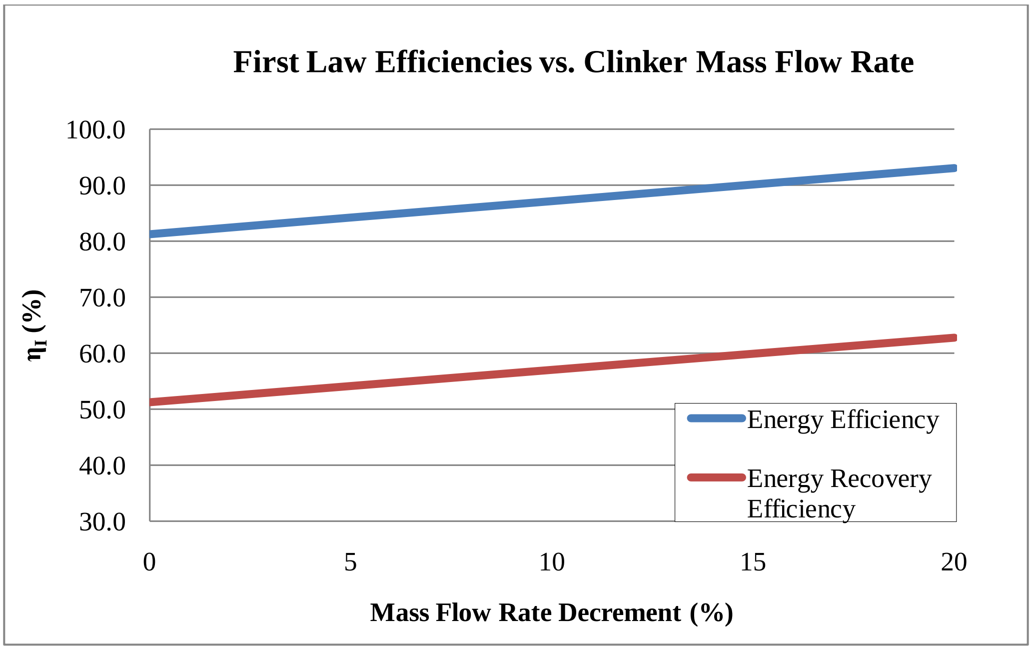

Fig. 4.5.1 (b)
Variation in first law efficiencies of the grate clinker cooler with decrement in mass flow rate of clinker

The trend in Figure 4.5.1 (b) shows that the energy efficiency, as well as the energy recovery efficiency of the grate clinker cooler increase with decreasing mass flow rate of clinker. For every 5% decrement in mass flow rate of clinker, the clinker cooler experiences approximately 3.0% hike in energy efficiency and 2.9% hike in energy recovery efficiency. As the mass flow rate of clinker is decreased, the clinker outlet temperature experiences a decrement but the air outlet temperatures do not significantly experience any change. Also, as the mass flow rate of clinker is decreased, the heat input decreases but there is no decrement in heat transfer between solid and air. Therefore the air still gets the same amount of heat from the clinker and hence the air temperature remains constant. But as the heat input is decreasing the clinker temperature also decreases.

The increment in the first law efficiencies actually represents the increased ratio of cooling air to clinker at an instant, as well as the increase in time for the heat transfer process to take place. More cooling air with a given amount of clinker to cool and time for the heat transfer process to take place correspond to better heat transfer and recovery rates. An optimum value of mass flow rate of clinker is required so that the recovery of energy is at a maximum in the cooler at a reasonable plant output.

As mentioned above, it takes the same amount of cooling air to absorb a given amount of heat from clinker, hence there would not be a change in temperature of air outlets nor the average temperature of the cooler. With an increase in heat transfer efficiency between the hot clinker and the cooling air, and the same amount of heat loss through convection and radiation to the surroundings, the total unaccountable losses of the system decreases significantly with decreasing mass flow rate of clinker.

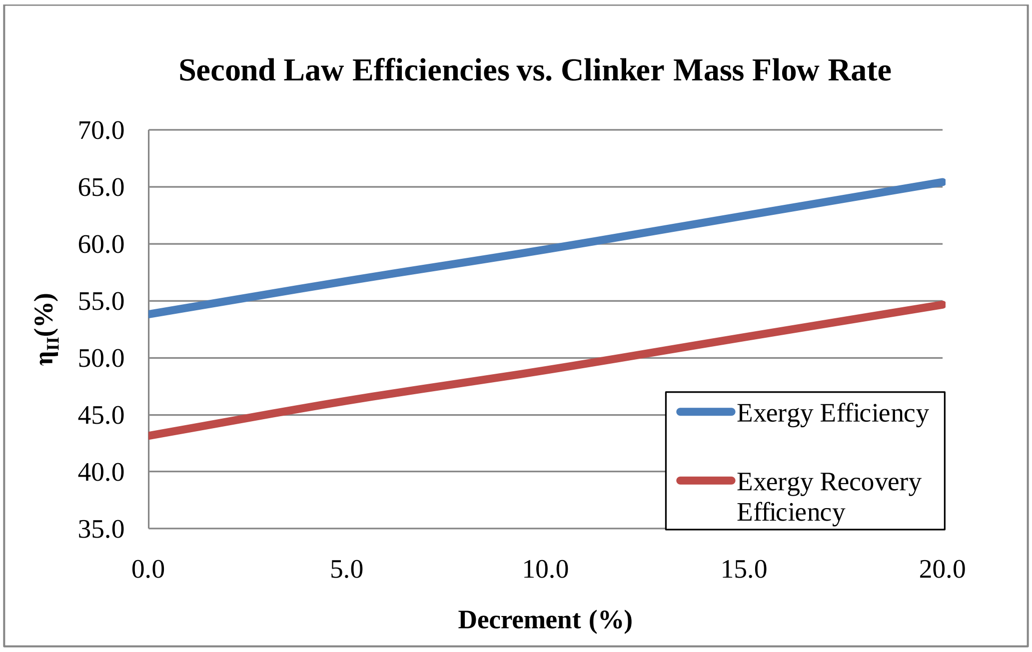

Figure 4.5.1 (c)
Variation in second law efficiencies of the grate clinker cooler with decrement in mass flow rate of clinker

The trend in Figure 4.5.1 (c) also shows an improvement over the second law efficiencies of the system with decrement in mass flow rate of clinker. For every 5% decrement in mass flow rate of clinker, the clinker cooler experiences approximately 2.9% hike in exergy efficiency and exergy recovery efficiency each. In this case, the improvement in second law efficiencies of the system is comparable to its first law counterparts. As previously discussed, the increase in these efficiencies represents the improvement in the rates of heat transfer and heat recovery, due to the increased amount of cooling air per unit clinker and to the prolonged amount of time for the heat transfer process to occur. The main task of cooler is to cool down the hot clinker to the lowest possible temperature and at the same time the cooling air should be preheated to a temperature level such that we need the lowest energy input for the burning process in rotary kiln. Decreasing the mass flow rate of clinker will improve the system's first and second law efficiencies, but at the expense of clinker output of the plant.

4.5.2 Energy Requirement with Decrement in Mass Flow Rate of Clinker

It was proven from the analysis performed that decreasing the mass flow rate of clinker will result in the increment of the first and the second law efficiencies of the clinker cooling system. Evidently decreasing the mass flow rate of clinker would also translate to a decrease in plant output per unit time. It is to be noted that the reduction in mass flow rate of clinker is not similar to increasing the mass flow rate of cooling air, secondary air, tertiary air and exhaust air by the same percentage. This is because heat transfer rate is also affected by the amount of time that the clinker spends inside the cooler, and not only by the relative mass flow rates of the air to the clinker.

The decrement in mass flow rate of clinker would also affect the mass flow rate of the other phases in the cement production process, as these phases are sequential. The main phases of interest would be the calcination phase and the burning phase, because they are energy consumers and are directly related to the clinker cooling phase. Phases such as milling, mixing and grinding are isolated from the abovementioned phases, as the materials are commonly stored in silos beforehand. As such, the mass flow rates of clinker in those phases are not highly affected by the change in mass flow rate of clinker in the cooling phase.

To come up with the same amount of output rate per day of the plant, the three phases would have to be run at an extended period of time. Even so, it can be assumed that no additional thermal energy is required to run the calcination phase and the burning phase, since the thermal energy consumption rates are based on the rate of material input into these phases. However, the electrical energy consumption rates, i.e. by the conveyor motors in the pre-calciner and the rotary kiln that move the clinker, are affected by the extension of running period. The conveyor motors' energy consumption are assumed to be equal that of the energy consumption of the cooler grate, each.

Taking the plant output of 3000 tonnes of clinker per day, and 187.5 tonnes of clinker per hour, the three phases, i.e. calcination, burning and cooling, would have to be run for an extended period of 0.84 hour, or 50.5 minutes to reach the plant output rate mentioned. Table 4.5.2 presents the additional amount of energy consumed for the clinker cooling system for every 5% decrease in mass flow rate of clinker, i.e. to run at an extended period of 0.84 hour.

Table 4.5.2
Additional energy requirement for the grate clinker cooler for every 5% decrease in mass flow rate of clinker

Power Consumer	**Power Consumption (kW)**	**Additional Energy Requirement per day (kWh)**
Cooling Air Fans	1153	969
Secondary Air Fans	717	602
Tertiary Air Fans	549	461
Exhaust Air Fans	1174	987
Grate	200	168
Conveyors	400	336
TOTAL	**3794**	**3523**

From Table 4.5.2, it is shown that the grate clinker cooler will consume a total of 3187 kWh of energy to run for an additional period of 50.5 minutes a day. The highest energy consumers from the grate clinker cooling system are the exhaust air fans, with 987 kWh. This is followed by the cooling air fans at 969 kWh, the secondary air fans at 602 kWh, the tertiary air fans at 461 kWh, the conveyors at 336 kWh, and lastly the grate at 168 kWh. It can be seen that the exhaust air fans require more energy compared to the cooling air fans, as well as the secondary and tertiary air fans. Fan power consumption is based on volumetric flow rate, and not only on the mass flow rate of air. Hotter air on the exhaust side has lower density compared to the cooler air on the intake side, consequently causing the fans at the exhaust side to work harder to evacuate a given mass flow rate of air.

4.6 Operational Parameter: Grate Speed

4.6.1 Change in First & Second Law Efficiencies of the Grate Clinker Cooling System

Variation in grate speed will result in change of clinker outlet temperature, as well as the air outlet temperatures. As opposed to previous parameters, change in grate speed does not result in the commonly predictable trends of outlet temperatures. Studies have proven that as grate speed is increased, first the air temperature increases with grate speed and after a certain value of grate speed it starts to decrease. On the other hand as the grate speed increases the solid bed height will decrease, therefore increasing heat transfer. Consequently, heat transfer will be at a maximum at a certain grate speed (Mundhara and Sharma, 2005).

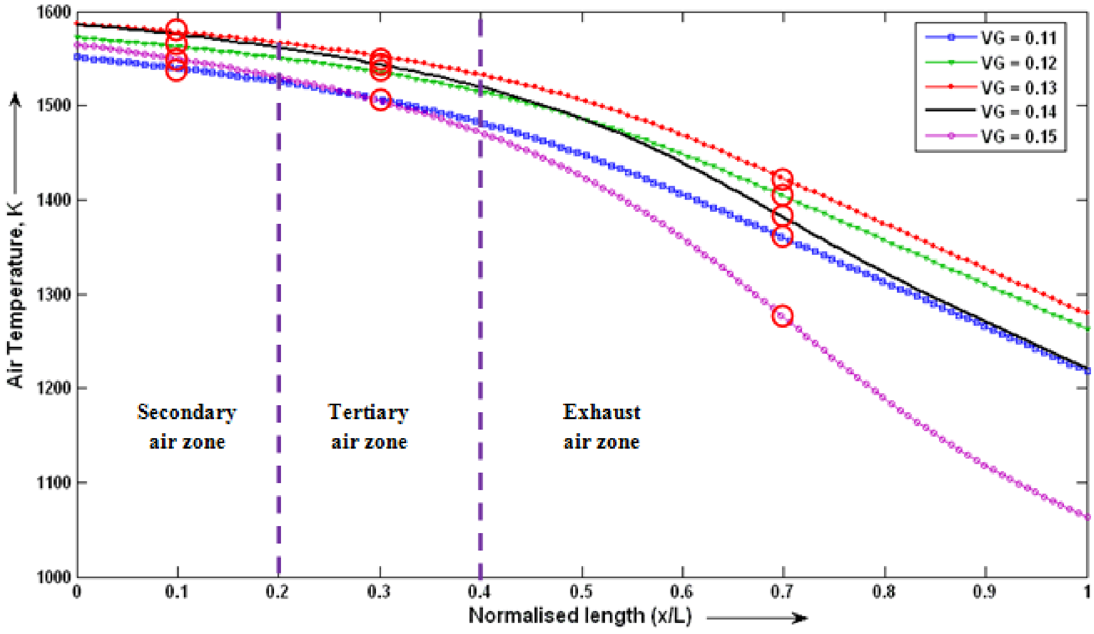

Figure 4.6.1 (a)
Variation of air temperature along the length of cooler at different grate speeds
Source: Mundhara and Sharma, 2005

Figure 4.6.1 (a) presents the temperature profile of cooling air along the length of cooler at different grate speeds. The temperature variation of air is estimated from the corresponding variations in the figures borrowed from the computational results obtained in the study performed by Mundhara and Sharma (2005). Similar to the previous case, the cooler is divided into three regions, i.e. the secondary air zone, the tertiary air zone and the exhaust air zone. The secondary and the tertiary air temperatures, as well as the exhaust air temperature are assumed to vary accordingly. However, the change in grate speed is assumed to have no significant effect on the clinker outlet temperature (Mundhara and Sharma, 2005).

By performing ideal energy and exergy analyses on the clinker cooler, we are able to find the trend of the first and the second law efficiencies with variation in grate speed. Figure 4.6.1 (b) and Figure 4.6.1 (c) present the variation in the first and the second law efficiencies of grate clinker cooler at different grate speeds, respectively.

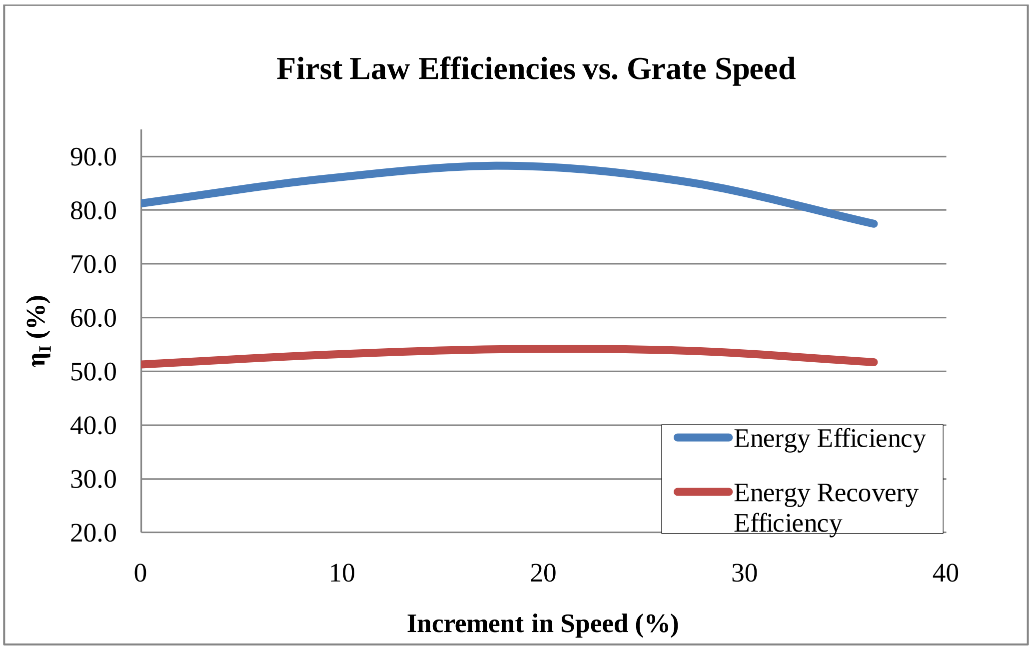

Figure 4.6.1 (b)
Variation in first law efficiencies of the grate clinker cooler at different grate speeds

The trend in Figure 4.6.1 (c) shows that the first law efficiencies first increase with increasing grate speed until it reaches a certain maximum, i.e. after 18.2% increment in speed, and they will then drop with further increasing grate speed. The highest energy efficiency and energy recovery efficiency for the system are 88.2% and 54.1% at this point, respectively. For this case, the air outlet temperatures play an important role as they affect the amount of heat recovery of the system, and hence, the first law efficiencies.

Air temperature will first increase with grate speed until it reaches a certain maximum, and then drop thereafter. The reason behind this is that as the grate speed is increased, the residence time of clinker will decrease, giving less time for the given amount of cooling air to absorb the heat from the hot clinker. This consequently leads to lower heat transfer between the two mediums. However, as grate speed is increased, the clinker bed height will decrease, leaving more surface area of the hot clinker exposed to the cooling air, which consequently leads to higher rate of heat transfer. This opposing effect causes the first law efficiencies of the system to be at a maximum at a certain speed, and for this case, it corresponds to the grate speed after 18.2% speed increment from the base case.

As discussed previously, higher heat transfer efficiency between the two mediums automatically means less heat energy is loss in the process. Even though increasing grate speed results in generally higher temperature air outlets, the amount of energy that is able to be recovered through secondary and tertiary air supersedes the amount of heat losses to the surroundings via convection and radiation. This is generally true up to about 27.3% of grate speed increment. Further increment in grate speeds results in the amount of heat loss to the surroundings through convection and radiation overcoming the increased heat transfer efficiency between the two mediums in the cooler, causing lower first law efficiencies of the system.

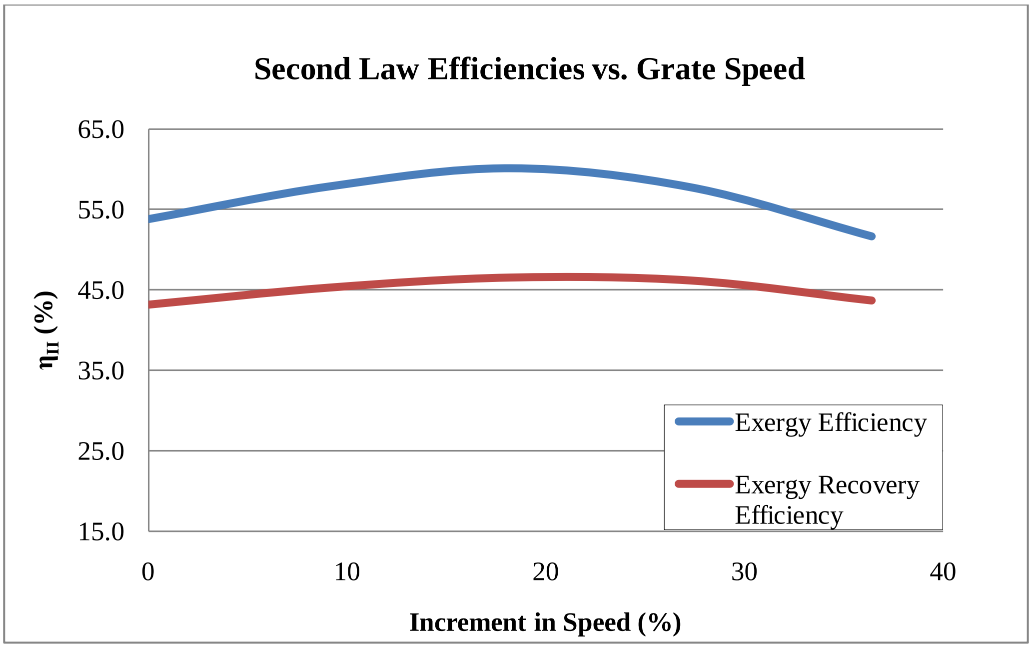

Figure 4.6.1 (c)
Variation in second law efficiencies of the grate clinker cooler at different grate speeds

Similar to the trend in first law efficiencies, Figure 4.6.1 (c) also signifies maximum second law efficiencies after 18.2% increment in grate speed. The exergy efficiency and the exergy recovery efficiency of the system have values of 60.1% and 46.5% respectively at this very speed. While the energy efficiency and the energy recovery efficiency increase 7.1% and 2.8% respectively, its second law efficiency counterparts managed to climb at a comparable magnitude of 6.4% and 3.3% respectively when the grate speed is increased 18.2%. The exergy efficiency and the exergy recovery efficiency are at their lowest values of 51.7% and 43.7% after 36.4% of grate speed increment, respectively.

Higher exergy recovery efficiency improvement compared to energy recovery efficiency improvement at the optimum speed signifies that the internal exergy destruction during the process is minimized more than the external exergy destruction. The second law efficiencies are at a certain extent affected by the temperatures of the air outlets, clinker and their specific heat, which may also cause the greater improvement in exergy recovery efficiency over energy recovery efficiency. As we already know, the biggest contributors to heat recovery are the hot air returning to the rotary burner and pre-calciner as secondary and tertiary air, respectively.

The important note that should be taken when one is able to control the grate speed is to find the optimum speed at which the first and the second law efficiencies of the system are at their maximums, as higher grate speed does not only affect these efficiencies but also the cost incurred in supplying energy to move the grates.

4.6.2 Energy Requirement with Increment in Grate Speed

Up to a certain value of grate speed, its increment will bring about the improvement in the first and the second law efficiencies of the clinker cooling system. Unfortunately the increment of grate speed would also mean the increment in power input to move the grate faster. Similar to the VSD's that can be installed on the fans of the grate clinker cooling system, this technology can also be applied to the grates to regulate the speed in accordance to the load.

The base case cooler grate motor power consumption can be calculated by first finding the cooler grate drive force, $\mathrm{F} = \mathrm{G_a} \text{ x } \mathrm{D_f}$ where $\mathrm{G_a}$ is the grate area in m^2, and $\mathrm{D_f}$ is the specific cooler drive force in kN/m^2. Taking each cooler grate to have a surface area of 30 m^2 and the specific cooler drive force as 11.5 kN/m^2 (MathCement 2000):

$$\mathrm{F} = 30\mathrm{m}^2 \text{ x } 11.5\,\frac{\mathrm{kN}}{\mathrm{m}^2}$$

$$= 345.0 \text{ kN}$$

The torque at eccentric shaft is $T = F \text{ x } \frac{S}{2 \text{ x } 1000}$, where F is the total drvie force in kN and S is the stroke length in mm (MathCement 2000).

$$T = 345.0 \text{ kN x } \frac{120\text{mm}}{2 \text{ x } 1000}$$

$$= 20.7 \text{ kN.m}$$

This torque has to be transmitted via chain wheel with a maximum driven sprocket or strokes per minute of N. The shaft power is then (MathCement 2000):

$$P_s = \frac{2\pi NT}{60}$$

$$= \frac{2\pi \text{ x } 22 \text{ strokes/ min x } 20.7 \text{ kN.m}}{60}$$

$$= 47.7\text{kW}$$

Taking into account power losses through the gears and etc., the motor power required to run each grate is as follows (MathCement 2000):

$$P_m = 1.4P_s$$

$$= 1.4 \text{ x } 47.7\text{kW}$$

$$= 66.8 \text{ kW}$$

The power consumption by each grate to produce the base case travelling speed is 66.8kW. For a plant producing 3000 tonnes of clinker per day, it is fairly common for the phase to have three travelling grates. Hence, the total power consumption to produce the base case travelling speed would be 200.4 kW. Assuming that the increment in power input to the grate is proportional to the grate speed, the clinker cooling system would require an additional power of 18.2 kW for every 9.1% increment in grate speed. This would result in a total of 291.8 kWh per day, assuming that the plant operates 16 hours daily.

Costs that have to be incurred in having the capability to manipulate the grate speed include the costs of materials, i.e. the new VSD's, the cost of commissioning of the new materials, and the additional operating costs for having a higher grate speed. The cost benefit analyses shall present the economic standpoint for these investments in a clearer manner, when the costs are economically analyzed using various methods such as payback period, present value and cost of energy conserved.

4.7 Heat Recovery of Exhaust Air

4.7.1 Change in First & Second Law Efficiencies of the Grate Clinker Cooling System

Generally, all output flows from the cooler system have potential for waste heat recovery. One of the main sources of energy conservation is the sensible heat of exhaust air from the clinker cooler. Considerable amount of heat is lost in the excess cooler exhaust, which can be used to preheat primary air to the kiln system, as well as the cooling air into the clinker cooler (Rasul et al., 2005). The effect of exhaust air recovery is studied under varying mass flow rate of cooling air, temperature of cooling air, mass flow rate of clinker, and grate speed. For the first and the second law analyses, all the other parameters of the grate clinker cooler remain the same as with the results obtained previously. As such, only the recovery efficiency of the cooler will be affected.

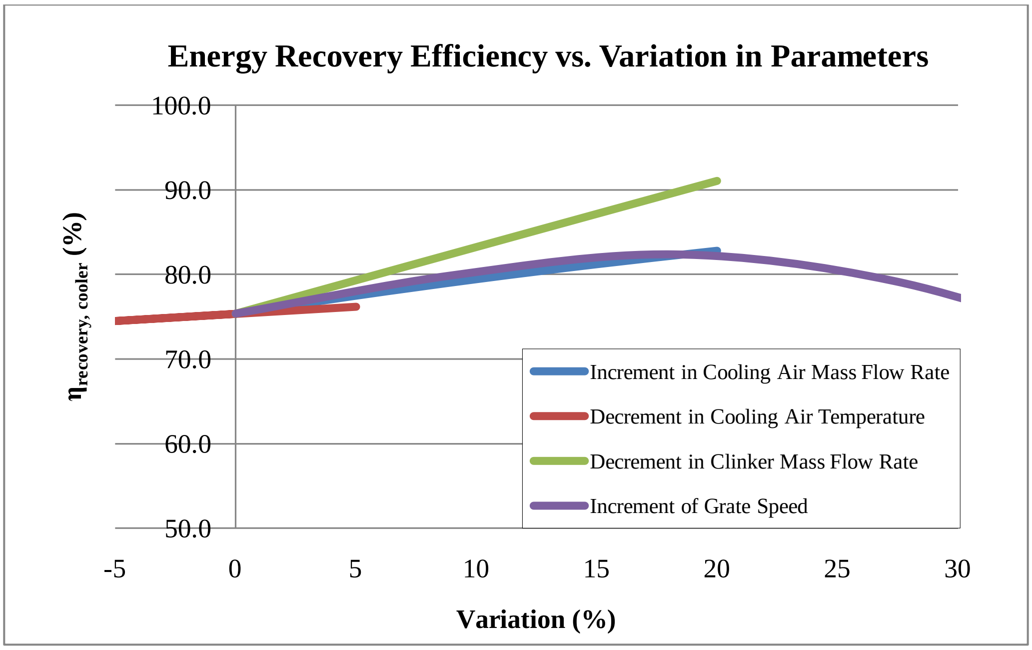

Figure 4.7.1 (a)
Variation in energy recovery efficiency of the grate clinker cooler with varying operational parameters

Figure 4.7.1 (a) presents the energy recovery efficiency of the grate clinker cooler with varying parameters. The energy recovery efficiency experiences an improvement across the board as the system now utilizes heat energy from the exhaust air, which was previously meant to be rejected to the surroundings. For this analysis, the energy recovery efficiency experiences an average of 24.1% of improvement after the recovery of heat energy from exhaust air. From Fig. 4.7.1 (a) it is apparent that the parameter that plays the biggest role in increasing the energy recovery of the system is the mass flow rate of clinker, followed by grate speed, mass flow rate of cooling air and lastly temperature of cooling air. Energy recovery represents the best opportunity to improve the system's efficiencies, and consequently to reduce the cost incurred in supplying energy for the clinker production process. To have a greater picture of the room of improvement for the system, one can look at the exergy recovery efficiencies instead.

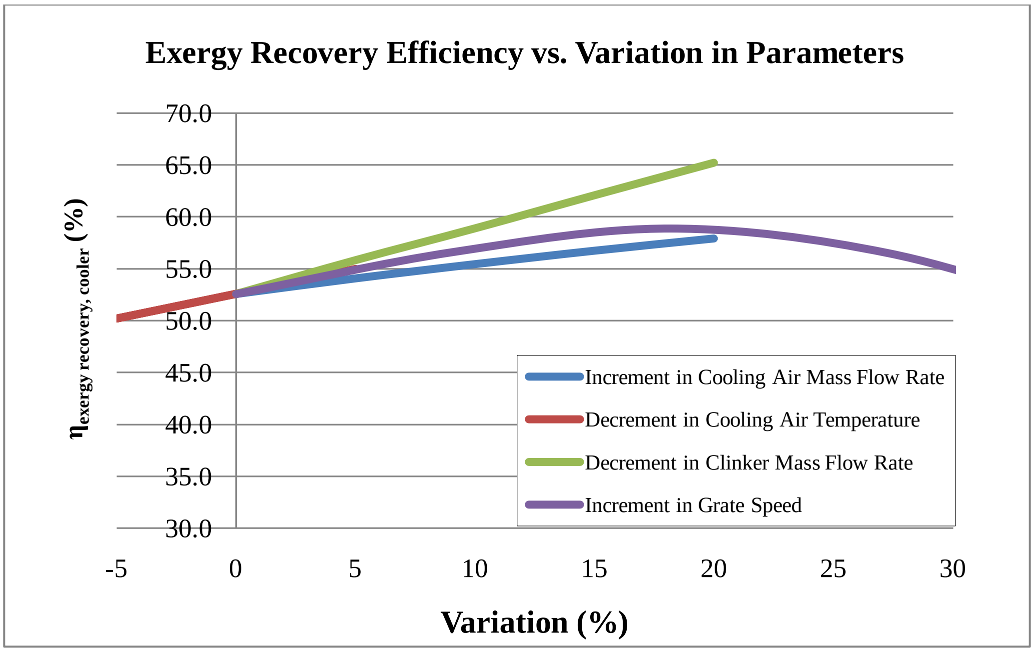

Figure 4.7.1 (b)
Variation in exergy recovery efficiency of the grate clinker cooler with varying operational parameters

Figure 4.7.1 (b) presents the exergy recovery efficiency of the grate clinker cooler under the same variation of parameters as in the case above. The exergy recovery efficiency also experiences an improvement across the board similar to the energy recovery efficiency. The exergy recovery efficiency for this case, experiences an average of 9.4% of improvement after the recovery of heat energy from the exhaust air. It is also evident from Figure 4.7.1 (b) that the mass flow rate of clinker plays the biggest role in exergy efficiency improvement. However, the parameter of cooling air temperature has now not the smallest role. Exergy recovery efficiency with variation in cooling air temperature is more accurate for this study, since the energy recovery efficiency was estimated from assumed plug-in temperatures of air outlets.

The hot air exiting from the clinker cooler as exhaust air has not a very high temperature, for which it cannot be used as secondary air for combustion in the rotary kiln or as tertiary air going to the pre-calciner for the upcoming calcination process. Despite that disadvantage, the heat carried by this exhaust air can still be used to preheat the primary air to the rotary kiln, to dry raw material and coal, as well as to preheat the cooling air to an optimum temperature. The use of this heat energy is as a substitute to the heat energy that is supplied by combusting fossil fuel in these phases of the clinker production process.

4.7.2 Use of Exhaust Air Recovery to Pre-heat the Raw Material

One of the more beneficial methods of utilizing heat energy contained within the exhaust air would be to use it to preheat the raw materials before the clinkering process. This is achieved by directing hot gas, i.e. exhaust air streams towards the raw material just before the grinding mill. The drying process would lead to a more efficient grinding of the raw materials, aside from increasing their temperature. The rise in raw material temperature would only be beneficial for cement production plants that direct these fresh materials straight to the rotary kiln for the clinkering process without it being stored in silos for a certain interval of time (Engin and Ari, 2005).

The main purpose of pre-heating the raw materials in the mill is to dry them, since they are heavily moist in nature. For this analysis, the moisture content of the the raw materials is taken as 6.8%, which indicates a mass flow rate of water of 0. 113 kg/kg-clinker coming into the mill (Engin and Ari, 2005). The heat energy contained within the exhaust air can be partially used for this task, where the hot exhaust air recovered will be returned as hot air stream at approximately 220˚C to dry the moist raw materials. From the analysis performed earlier on the amount of heat energy in the exhaust air used to preheat the incoming cooling air for the clinker cooler, it was found that 12.2% of the total heat is needed to perform the mentioned task. For this analysis, it can be assumed that the remaining heat energy contained in the exhaust air, i.e. 97.8% of the heat, is used to dry the raw materials in the grinding mill.

The majority of the useful energy must be used to heat the water from 15˚ C to 100˚C, and to vaporize it at this temperature completely. For this analysis, the heat losses to the surroundings, i.e. via convection and radiation are ignored. Energy balance for the grinding mill will shows the energy interactions within the system (Engin and Ari, 2005):

$$\dot{Q}_{\text{hot air}} + \dot{Q}_{\text{moist raw material}} = \dot{Q}_{\text{water}} + \dot{Q}_{\text{cooled air}} + \dot{Q}_{\text{dry raw material}} \tag{5.1}$$

$$\dot{Q}_{\text{cooled air}} = 6.944 \text{ x } (1.48 \text{ x } 300 + 1.78 \text{ x } 12) - 0.7845 \text{ x } (419 - 63 + 2257) - 6.994 \text{ x } 1.67 \text{ x } 88$$

$$= 153.7 \text{ kW}$$

The related enthalpies are shown more clearly in Figure 4.7.2.

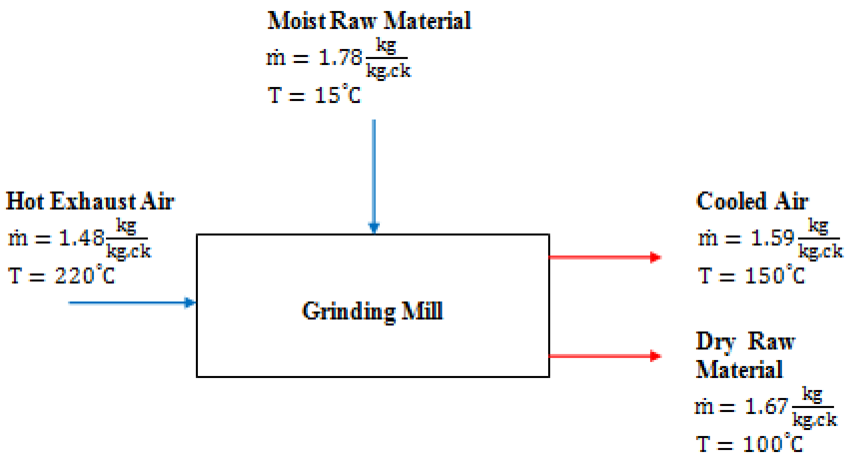

Figure 4.7.2
Energy balance of the grinding mill for the drying process of raw materials (Engin and Ari, 2005)

4.8 Potential Energy & Cost Savings

An improvement in energy recovery efficiency of the clinker cooling system translates to energy savings, as the energy recovered serves as a substitute to the energy supplied through combustion of fossil fuel throughout the whole process of clinker production. For this analysis we will focus the attention to the improvement in energy recovery efficiency of the clinker cooler as it represents the theoretical opportunity for cost saving. Table 4.8 (a) presents the energy saving summary for every 5% optimization of the parameters analyzed, while Figure 4.8 (a) presents the energy saving contribution for each operational parameter.

Table 4.8 (a)
Energy saving summary for every 5% optimization of operational parameters

Operating Parameters	Average Improvement in Energy Recovery Efficiency (%)	Energy Saved (kJ/kg.ck)		
		Rotary Kiln	Pre-Calciner	TOTAL
Mass Flow Rate of Cooling Air	2.32	22.54	11.48	34.01
Cooling Air Temperature	0.14	13.31	10.12	23.43
Mass Flow Rate of Clinker	2.88	23.98	18.01	41.99
Grate Speed	0.77 (up to 18.2% optimization)	4.75	6.02	10.77
TOTAL		**64.58**	**45.63**	**110.21**

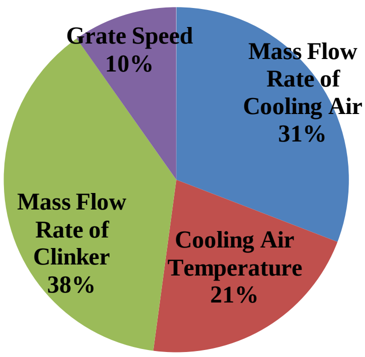

Figure 4.8
Energy saving contribution of operational parameters

The manipulation of operational parameters of the grate clinker cooler will result in direct energy saving, and improvements over these parameters contribute directly to heat recovery via secondary and tertiary air to the rotary kiln and the pre-calciner, respectively. From Figure 4.8, out of the four operational parameters analyzed, mass flow rate of clinker plays the largest role in contributing to heat recovery, and hence energy saving. It contributes 38% of the total energy savings from the four operational parameters analyzed. This score is followed closely by mass flow rate of cooling air with 31%, cooling air temperature with 21%, and lastly grate speed with 10%.

Considering the average fuel price of USD 4.664/GJ, Table 4.8 (b) presents the summary of theoretical cost per tonne clinker that can be saved as a result from every 5% optimization of the operational parameters of the grate clinker cooler (Price et al., 2009). It is to be noted that the cost saving only represents the amount of money saved from the improvement of the grate clinker cooler's operational parameters, not taking into account the increment in cost incurred as a result of the respective upgrades.

Table 4.8 (b)
Cost saving summary for every 5% optimization of the operational parameters

Operating Parameters	**Average Improvement in Energy Recovery Efficiency (%)**	**Cost Saving (USD/tonne.ck)**		
		Rotary Kiln	**Pre-Calciner**	**TOTAL**
Mass Flow Rate of Cooling Air	2.32	0.105	0.054	0.159
Cooling Air Temperature	0.14	0.062	0.047	0.109
Mass Flow Rate of Clinker	2.88	0.112	0.084	0.196
Grate Speed	0.77 (up to 18.2% optimization)	0.022	0.028	0.050
TOTAL		**0.301**	**0.213**	**0.514**

(Price et al., 2009)

From Table 4.8 (b), it is apparent that for every tonne of clinker produced, 5% of mass flow rate of clinker optimization will result in theoretically USD 0.196 of cost saving. The trend follows with USD 0.159 for the optimization of mass flow rate of cooling air, USD 0.109 for the optimization of cooling air temperature, and lastly USD 0.050 for the optimization of grate speed. A total cost saving of USD 0.514 per tonne of clinker is generated for having optimized operational parameters, i.e. an energy efficient clinker cooling system. For this analysis, the average unit price of fuel paid by the cement plants, i.e. USD 4.664/GJ does not take into account the price of diesel fuel. This is due to the fact that only a small amount of diesel is used in most plants, and is negligible compared to coal consumption (Price et al., 2009).

Almost all modern cement production plants will utilize heat energy from the exhaust air to save cost. The sensible heat of exhaust air from the clinker cooler that are recovered serves as substitutes for purchased energy at other phases of cement production, consequently resulting in a more efficient plant. This study also aims at emphasizing on the significance of exhaust air heat recovery as a means of saving energy and cost. Table 4.8 (c) shows the energy and cost saving comparison between operational parameters of the grate clinker cooler and the exhaust air heat recovery.

Table 4.8 (c)
Energy and cost saving comparison between the operational parameters of clinker cooler and the exhaust air heat recovery

Contributors	**Energy Saved (kJ/kg.ck)**	**Cost Saving (USD/tonne.ck)**	**Contribution (%)**
Operational Parameters	110.2	0.51	24.62
Exhaust Heat Recovery	337.4	1.24	75.38
TOTAL	447.6	1.75	100.00

From Table 4.8 (c), it is evident that the recovery of heat from exhaust air overshadows all the operational parameters in terms of energy and cost savings. It represents roughly 75% of the amount heat recovery itself, as compared to 25% for the operational parameters. Even though 75% of heat recovery takes place during the clinker cooling process via heat recovery of exhaust air, not all of the heat acts as a substitute to heat energy generated from the combustion of fossil fuel or to electrical energy consumed. For example, heat that is returned to preheat the incoming cooling air for the clinker cooler to an optimum temperature cannot be counted as a substitute to energy consumed. This is because in the original configuration, no heat energy is purchased to heat up the incoming cooling air. For the heat recovery of exhaust air, 12.2% of the recovered heat energy is assumed to be dedicated to pre-heat the cooling air for the cooler, and the remaining to dry the raw material and the coal.

The focus of this study however, would be on how the improvements in the grate clinker cooler's operational parameters alone can generate cost saving. For a cement plant that produces about 3000 tonnes of clinker per day, and operates 300 days a year, the theoretical total cost saving from optimizing the four operational parameters analyzed goes up to USD 462,600.00 annually. The mass flow rate of clinker brings forth the most saving out of the four operational parameters analyzed, but it is also a compromise between energy efficiency and clinker output rate of the plant. Mass flow rate of cooling air and grate speed on the other hand, are a compromise between energy efficiency and the amount of electrical energy supplied to the blower and the grate, respectively. The temperature of the cooling air however, has no trade-off for its improvement, except for the amount of heat energy recovered that one decides to supply to the air instead of other phases of the production process the drying of raw material.

4.9 Payback Period

The payback period method of appraisal for this analysis is the period of time over which the energy savings of a project equal the amount of cost incurred at project inception. This generally tells how much time it takes for the cash inflow will overcome the amount of cost incurred, taking into account the energy purchased and saved. Before proceeding with the payback period, the study will first present the estimated amount of initial investment and the incremental operations costs for the optimization of each operational parameters of the grate clinker cooler analyzed. Table 4.9 presents the summary of the initial investment and incremental operations costs according to the operational parameters analyzed.

Table 4.9
Summary of the costs incurred to optimize the operational parameters of the grate clinker cooler

Costs	Operational Parameters			
	Mass Flow Rate of Cooling Air	**Temperature of Cooling Air**	**Mass Flow Rate of Clinker**	**Grate Speed**
Initial Investment Cost (USD)	512,400.00	20,000.00	120,000.00	59,800.00
Incremental Operations Costs (USD/year)	30,900.00	8,175.00	38,700.00	3,825.60

For the operational parameters mass flow rate of cooling air and grate speed, the initial investment costs would be the cost to retrofit the Variable Speed Drive (VSD) on the existing fans and grate motors respectively. The cost of retrofitting VSD's is taken as USD 200.00 per fan or grate motor horsepower respectively (Koski, 2003). For the operational parameter temperature of cooling air, the initial investment cost would be the cost to construct piping to redirect the exhaust air which contains useful sensible heat to the fresh incoming cooling air in order to pre-heat it before it performs its intended function, and the cost to insulate the incoming cooling air for better heat reclaiming. This cost is estimated to be within the range of USD 20,000.00. For the operational parameter mass flow rate of clinker, the initial investment cost would be the cost to reprogram the feed rate of clinker into the pre-calciner, rotary kiln and the cooler, as well as equipping VSD's to the feeder motors.

The optimization of each operational parameter analyzed would result in an increase in energy input required. The incremental operations cost accounts for such investments. Figure 4.9 presents the payback period of the investment made for every 5% optimization of the operational parameters of the grate clinker cooler.

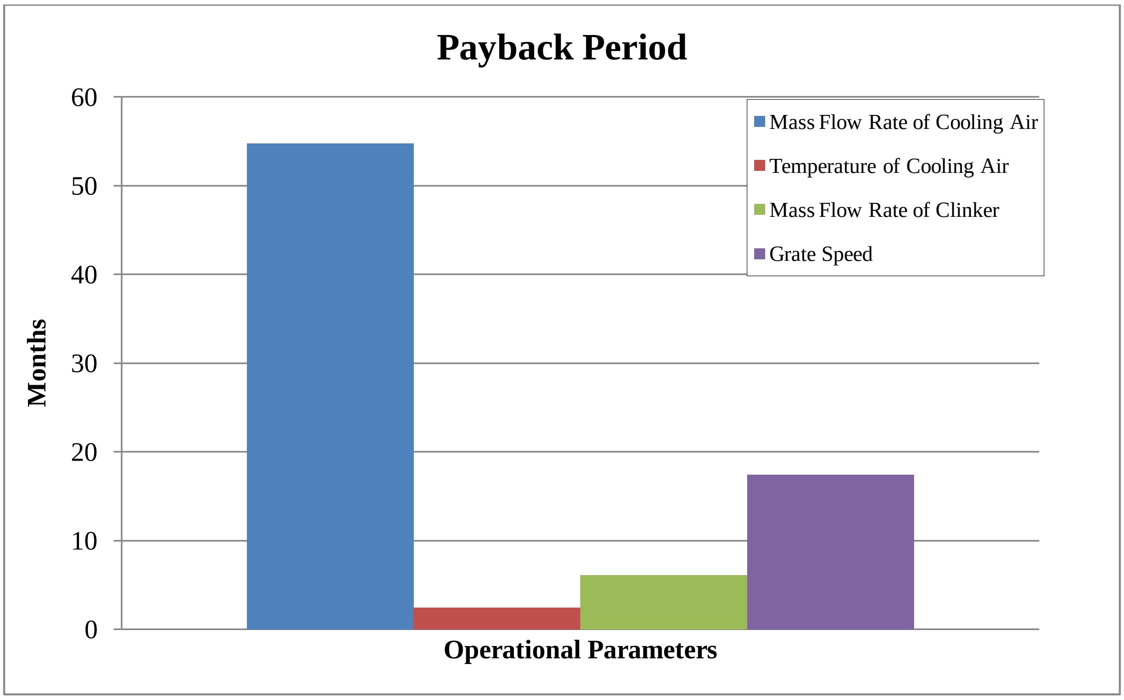

Figure 4.9
Payback period of the investment made for every 5% optimization of the operational parameters of the grate clinker cooler

The payback period is a means of determining the relative worth of the modifications made to the clinker cooling system by calculating the time they will take to pay back what they cost. From Figure 4.9, it is apparent that the shortest payback period is for the modification made to optimize the temperature of cooling air, with 1.2 months. This is followed by the modification to optimize the mass flow rate of clinker with 6.1 months, the modification to optimize the grate speed of the cooler with 17.4 months, and lastly the modification to optimize the mass flow rate of cooling air with

54.8 months. Unlike the potential energy and cost saving analyses performed earlier, payback period also takes into account the amount of additional energy that has to be spent on in order to raise the efficiencies of the clinker cooling system. For example, the optimization of mass flow rate of cooling air and grate speed would also mean that additional electrical energy needs to be bought to accommodate the change in the blower and grate motor power requirement, respectively.

If one makes an investment decision solely on the basis of payback period, the modification with the shortest payback period should be favoured as opposed to the ones with longer payback periods. The outcome of insisting that each proposed investment has a short payback period is that the investors of such modification can assure themselves of being restored to their initial positions within a short span of time (Park, 2007). Consequently they can take advantage of the benefits that will come after these investment costs are recovered.

The simple payback period method of appraisal may sometimes eliminate some alternatives, thus eliminating such time spent to analyze. However, the serious drawbacks of this method would be its inability to measure profitability, and its failure to recognize the differences in the timing of cash flows, i.e. time value of money (Park, 2007). For instance, even though the period it takes to recover the cost incurred in modifying the clinker cooler to optimize the mass flow rate of cooling air is far lengthier than the period it takes to cover the cost incurred to optimize the grate speed, the method does not tell how much the invested money is contributing towards the cost expense. On top of that, even when two different modifications have the same period of payback, a front-loaded investment is actually more beneficial because money available today is worth more than that to be gained later. Payback period method of appraisal also ignores all proceeds after the payback period, it does not allow for the possible advantages of an investment with longer life span (Park, 2007).

4.10 Present Value

The present value method of appraisal is a method that uses the discounted cash flow technique, which takes into account the time value of money. Under the net present value criterion, the present value of all cash inflows is compared against the present value of all cash outflows associated with the energy efficiency measure. The difference between the present values of these cash flows determines whether the investment is feasible. Figure 4.10 presents the present values of the investment made for every 5% optimization of the operational parameters of the grate clinker cooler.

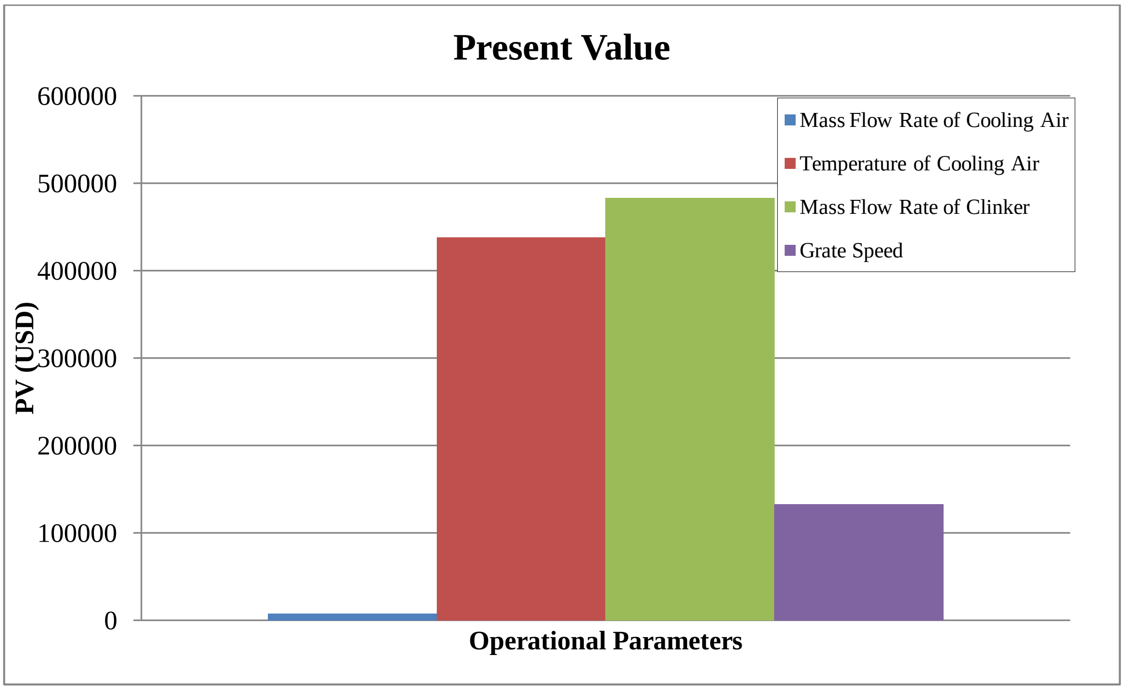

Figure 4.10
Present values of the investment made for every 5% optimization of the operational parameters of the grate clinker cooler

From Figure 4.10, the results show that the investment with the highest present value is the modification made to optimize the mass flow rate of clinker. The present value of this investment is estimated at USD 483,141.00, considering 15 years of service life for the upgrades and 20% discount rate. This is followed by the modification made to optimize the temperature of cooling air with an investment present value of USD 437,860.00, the modification made to optimize the grate speed at a value of USD 132,775.00, and lastly the modification made to optimize the mass flow rate of cooling air at a value of USD 7,742.00.

Since all the energy efficiency investments show a positive present values, they are all practically feasible options. However, the most feasible option that should be considered from this analysis is the investment to optimize the mass flow rate of clinker. Unlike the conventional payback period, the present value method of appraisal takes into account the time value of money. It can be clearly seen that each investment has different annual cash flows from the other. Since we are considering a simple constant annual cash flow for each energy efficiency measure, the investment with the lower initial cost and the bigger annual cash flow will have better present value.

When dealing with large amounts of money, long periods of time, or high interest rates, the change in the value of a sum of money over time becomes extremely significant. The operation of interest and the time value of money must be taken into consideration in order to make valid comparisons of different amounts of cash flows at various times when deciding between the presented energy efficiency investments.

4.11 Capital Recovery Factor

Capital recovery factor indicates the correlation between the real discount rate and the lifespan of the energy efficient clinker cooling system. It comes in the form of a ratio, i.e. ratio of a constant annuity to the present value of receiving that annuity for a given length of time.

Taking the life span of the upgrades as 15 years, the capital recovery factor for the grate clinker cooler for this study is as follows:

$$\mathrm{CRF} = \frac{20\%}{(1-(1+20\%)^{-15})}$$

$$= 0.2139$$

The real discount rate is taken as 20% for this study to reflect the barriers to energy-efficiency investment in the cement industry. According to Worrell et al. (2008), these barriers include perceived risk, management concerns about production and other issues, lack of information, opportunity cost, capital constraints and preference for short payback periods and high internal rates of return.

A real discount rate of 20% is comparatively high for the financial calculation of the energy efficiency studies in the cement industry, when compared to other industrial sector analyses. This high discount rate is used for calculating cost of conserved energy while accounting for the aforementioned barriers to energy-efficiency improvement. This would avoid overestimation of cost-effective energy-saving potential (Price et al., 2007).

The choice of the real discount rate is also dependent upon the purpose of the analysis and the approach used, i.e. prescriptive versus descriptive. A prescriptive approach uses lower discount rates, typically 4% to 8%, especially for long-term studies like climate change or public sector analyses. Using low discount rates, one will have the advantage of treating future generations equally to current generations, but the comparatively low rates may also cause relatively certain, near-term effects to be ignored in favour of more uncertain, long-term effects (Price et al., 2007). A descriptive approach on the other hand, uses comparatively higher discount rates, typically from 10% to 30% to reflect the existence of barriers to energy efficiency investments (Worrell et al., 2008).

4.12 Cost of Conserved Energy

The cost effectiveness and the technical potential for the investments made towards energy efficiency measures are typically evaluated through the cost of energy conserved. In the cost of energy conserved, an energy price line, i.e. fuel energy price line is determined to reflect the current cost of energy. All measures that fall below the energy price line are can be considered cost effective. Figure 4.12 presents the cost of conserved energy for each of the operational parameters of the grate clinker cooler analyzed for optimization.

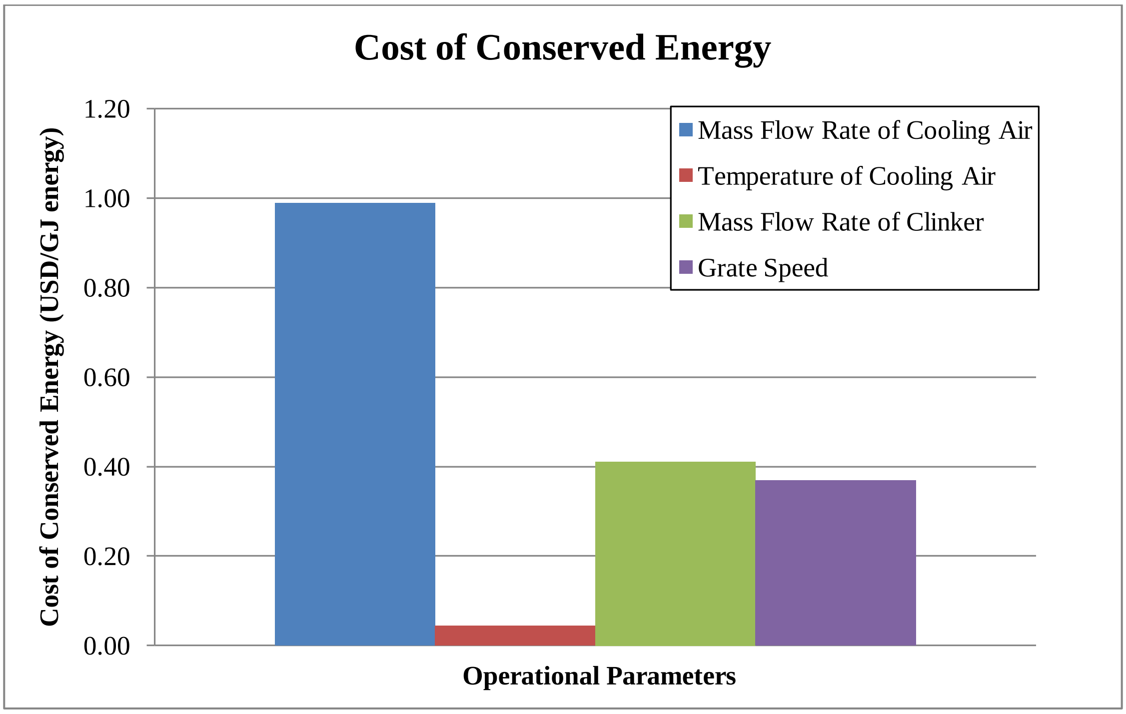

Figure 4.12
Cost of conserved energy for every 5% optimization of the operational parameters of the grate clinker cooler

Figure 4.12 shows that the modification made to optimize the temperature of cooling air has the lowest cost of conserved energy with USD 0.04/GJ energy saved. This is followed by the modification made to optimize the grate speed with USD 0.37/GJ energy saved, the modification made to optimize the mass flow rate of clinker with USD 0.41/GJ energy saved and lastly the modification made to optimize the mass flow rate of cooling air with USD 0.99/GJ energy saved. It is apparent that all four energy-efficiency measures fall under the average unit price of coal, i.e. USD 4.644/GJ. This is to say that the cost of conserved energy is less than the average unit price of coal, i.e. the cost of investing in these for energy-efficiency measures to save one GJ of energy is less than purchasing one GJ of coal at the given price.

The cost of energy conserved takes into account the initial investment incurred for each modification made to optimize the operational parameters of the clinker cooler. These investments however are weighed by the capital recovery factor calculated earlier, to reflect the barriers to energy-efficiency investments in the cement industry. From Equation 3.21, it can be noted that the annual increase in operations and maintenance costs are also taken into consideration. For this analysis, the annual increment in maintenance costs is neglected. However, to increase the efficiencies of the operational parameters of the grate clinker cooler, the significant increment in annual operations costs have to be considered. For example, to optimize the mass flow rate of cooling air and grate speed, the rise in electrical energy consumption for the fan and grate motors will highly affect the cost of energy conserved.

It should be highlighted that the cost of conserved energy is a good screening tool to present energy-efficiency measures and capture the potentials for improvement. In reality however, the energy-saving potential and cost of each energy-efficiency measure and technology may vary. They are highly dependent on various conditions such as raw materials, the technology provider, the production capacity, the size of the kiln, the fineness of the final product and byproducts, and the time of the analysis (Price et al., 2007).

4.13 Summary of the Cost Benefit Analyses

Table 4.13
Summary of cost benefit analyses

Operational Parameters	Adjusted Cost Saving (USD/month)	Payback Period (months)	Present Value (USD)	Cost of Conserved Energy (USD)
Mass Flow Rate of Cooling Air	9,350.00	54.8	7742	0.99
Temperature of Cooling Air	8,175.00	2.4	437860	0.04
Mass Flow Rate of Clinker	10,825.00	11.1	483141	0.41
Grate Speed	3,431.00	17.4	132775	0.37

Table 4.13 presents the summary of the cost benefit analyses performed. It can be clearly seen that in terms of adjusted cost saving and present value of investment, the modification made to optimize the clinker mass flow rate ranks the highest among the energy efficiency measures considered. Although the optimization of cooling air temperature seems like the more feasible option considering the low initial cost, payback period, and the cost of energy conserved, the adjusted cost saving does not take into account the thermal energy that is sacrificed for other functions, i.e. to be returned to dry the raw materials. In a pure sense of energy efficiency improvement, optimizing the cooling air temperature plays a big role, but it does not tell how much of actual cost can be saved. It is also wise to note that transferring heat to the cooling air via piping does involve losses in reality. Optimization of the mass flow rate of clinker however, evidently increases the efficiencies of the system as well as results in cost saving. Even though the initial investment cost to be incurred in manipulating such parameter are of a significant amount, the adjusted cost saving signifies a good cash inflow, making the energy efficient measure a promising investment.

Putting aside the optimization of cooling air temperature, the modification made to optimize the grate speed is a fairly feasible alternative. Compared to the optimization of mass flow rate of clinker, this energy efficiency measure does not require as much initial investment cost. Even though the annual cost saving is smaller compared to the former, this measure has a higher investment present value for its intended 15 years of service period, thus making it a highly recommended option. The investment cost of the latter is not as significant as the former, due to the number of motors that need to be equipped with VSD's in order to vary the motor speed and the load as intended. It is to be noted that VSD retrofitting cost is highly dependent on motor size. Considering a 15 year service life for both options, the energy efficiency measure to optimize the grate speed presents a better opportunity since it has a higher investment present value and lower cost of energy conserved.

The cost of energy conserved is a useful measure of how much cost can be saved via these energy efficiency measures. However, considering the volatile price of energy in the present and the coming future, one cannot be fully dependent on such estimations. It can be said though, that the optimization of grate speed is as competent as the optimization of mass flow rate of clinker, as an alternative.

4.14 Emission Reduction

The cumulative amount of emission reduction of NO_x, CO and PM, as well as the greenhouse gas CO_2, can be estimated directly from the amount of energy saving resulting from the optimization of the operational parameters of the clinker cooler. Table 4.14 presents the amount of emission reduction for every 5% optimization of the operational parameters analyzed.

Table 4.14
Average emission reduction for every 5% optimization of the grate clinker cooling system's operational parameters

Operating Parameters	Energy Recovery (kJ/tonne clinker)	Average Emission Reduction (kg/tonne clinker)			
		NO_x	CO	PM (Dust)	CO_2
Mass Flow Rate of Cooling Air	34013	0.030	0.024	0.002	3.477
Cooling Air Temperature	23427	0.021	0.016	0.001	2.395
Mass Flow Rate of Clinker	41992	0.037	0.029	0.002	4.293
Grate Speed	19607	0.017	0.014	0.001	2.004

(Integrated Pollution Prevention and Control (IPPC), 2001)

The clinker burning phase is the most significant phase in terms of cement manufacturing environmental issues, as it contributes to the major part of energy use and emissions to the environment. The key environmental emissions are nitrogen oxides (NO_x) and dust. For this study, the average emission of oxides of Nitrogen (NO_x) is taken as 3.2 kg/tonne clinker, carbon monoxide (CO) as 2.5 kg/tonne clinker, particulate matter (PM) or dust as 0.21 kg/tonne clinker and carbon dioxide (CO_2) as 368 kg/tonne clinker (Integrated Pollution Prevention and Control (IPPC), 2001). The average fuel energy consumed by the kiln and the pre-calciner is taken as 3600MJ/tonne clinker. Figure 4.14 presents the average emission reduction for every 5% optimization of the grate clinker cooler's operational parameters.

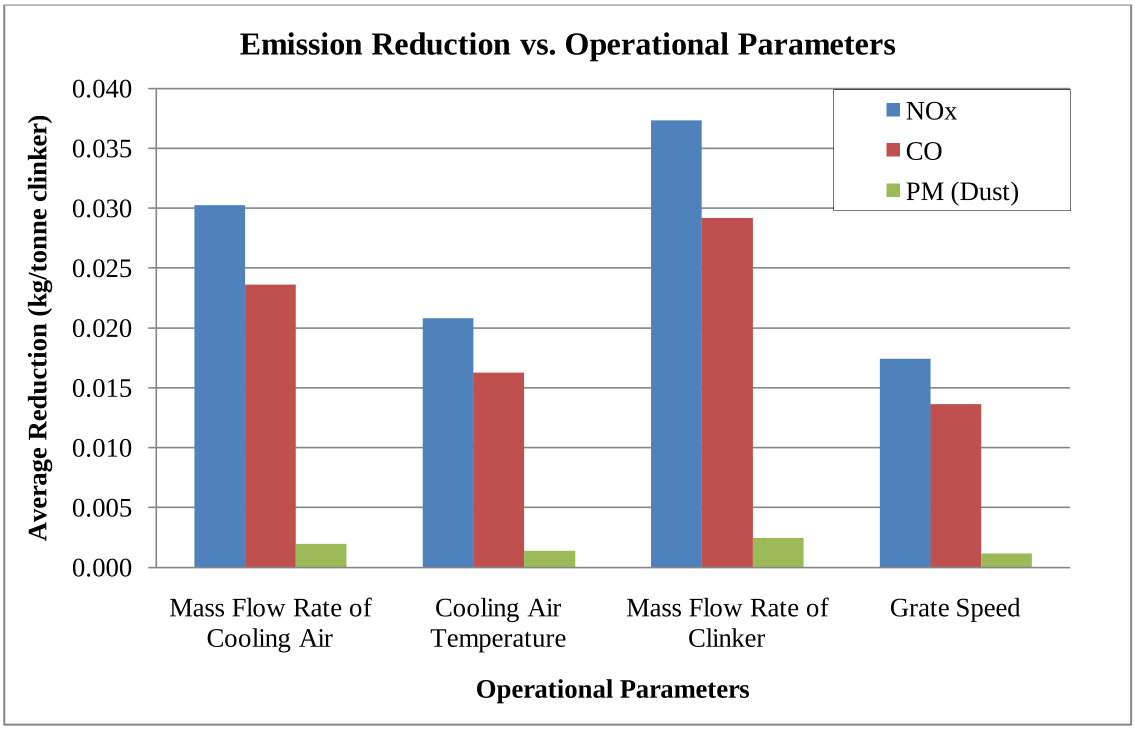

Figure 4.14 (a)
Average emission reduction for every 5% optimization of the grate clinker cooler's operational parameters

From Figure 4.14 (a), it can be seen that among the operational parameters of grate clinker cooler analyzed, the optimization of mass flow rate of clinker will result in the most reduction of emission of NO_x, CO, and PM. This score is followed by mass flow rate of cooling air, cooling air temperature and lastly grate speed. The reduction of emission is calculated based on the amount of energy recovered and returned to the rotary kiln and the pre-calciner via secondary and tertiary air respectively. This is the amount of energy assumed to be of substitute to fuel energy, consequently resulting in emission reduction.

Nitrogen oxides (NO_x) are of major significance with respect to air pollution from cement manufacturing plants. The dominant nitrogen oxides in cement kiln exhaust gases are the NO and NO_2, with NO being over 90% of the nitrogen oxides. Thermal NO_x and fuel NO_x are the two main sources for the production of NO_x. Thermal NO_x occur when part of the nitrogen in the combustion air reacts with oxygen to form various oxides of nitrogen, while fuel NO_x occur when nitrogen containing compounds chemically bound in the fuel react with oxygen in the air to form various oxides of nitrogen (Integrated Pollution Prevention and Control (IPPC), 2001).

The major contributor to the emission of CO is the content of organic matter in the raw materials. CO emission is also a result from poor combustion from sub-optimal control of the solid fuel feed. Sub-stoichiometric combustion may lead to short term peaks of greater than 0.5% CO. Dust emission from kiln stacks has been the main environmental concern in the cement production industry. Dusts are byproducts of the processes that take place in kilns, raw mills, clinker coolers and cement mills. Large volumes of gases are flowing through dusty materials in all these processes (Integrated Pollution Prevention and Control (IPPC), 2001).

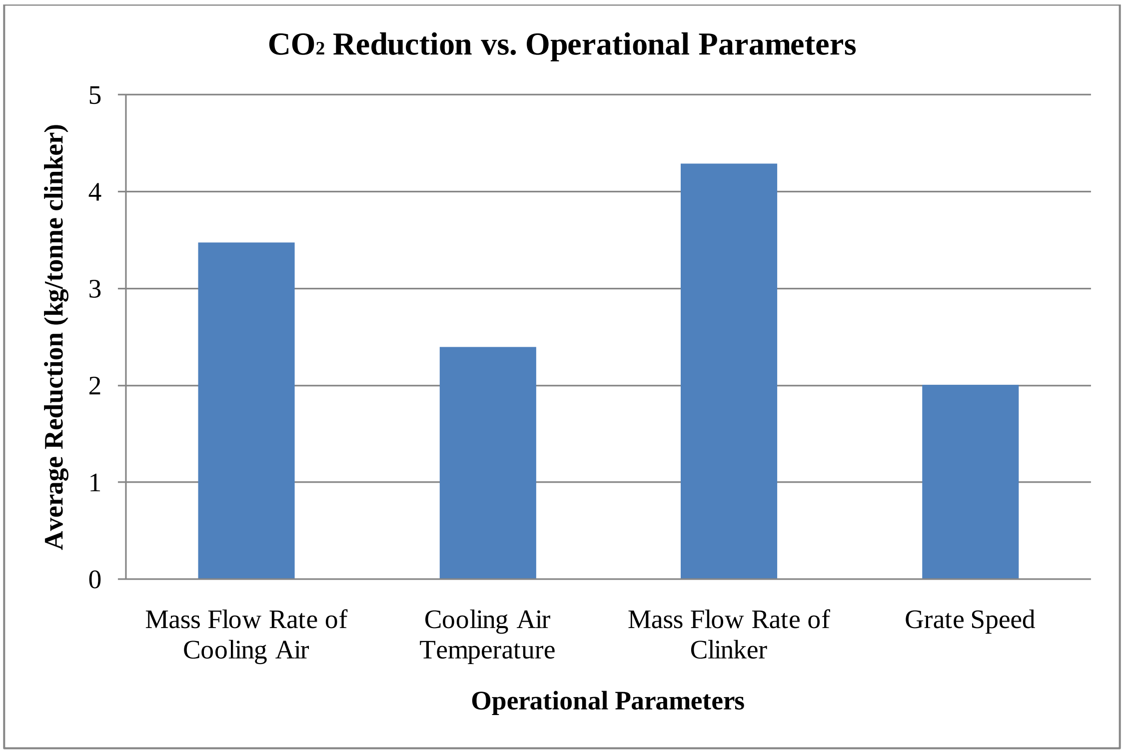

Figure 4.14 (b)
Average CO_2 emission reduction for every 5% optimization of the grate clinker cooler's operational parameters

Similar to the trend in Figure 4.14 (a), Figure 4.14 (b) shows that the optimization of mass flow rate of clinker will result in the most reduction of emission of CO_2. This is followed by the mass flow rate of cooling air, the cooling air temperature and lastly the grate speed. The emissions of CO_2 resulting from the combustion of the carbon content of the fuel is directly proportional to the ratio of carbon content to the calorific value of the fuel, as well as the specific heat demand (Integrated Pollution Prevention and Control (IPPC), 2001).