Assessment of energy and exergy efficiencies of a grate clinker cooling system through the optimization of its operational parameters


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A B S T R A C T

Grate coolers are widely used in cement industries to recover heat from hot clinker, coming out from the rotary kiln. This study focuses on improving the energy, exergy and recovery efficiencies of a grate cooling system through the optimization of its operational parameters such as masses of cooling air and clinker, cooling air temperature, and grate speed. It has been found that the energy and recovery energy efficiencies of a cooling system can be increased by 1.1% and 1.9%, respectively, with every 5% mass increases of cooling air. Similarly, it has been estimated that energy and recovery energy efficiencies can be increased by 2.0% and 0.4% with every 5% increase of cooling temperature. The exergy and its recovery efficiencies found to be increased by 3.6% and 2.2%, respectively, for the same condition. Energy efficiency and energy recovery efficiencies are increased by 3.5% and 1.4% with every 9.1% increase of grate speed. Using heat recovery from the exhaust air, energy and exergy recovery efficiencies of the cooling system found to be increased by 21.5% and 9.4%, respectively. It has been found that about 38.10% and 30.86% energy cost can be saved by changing mass flow rate of clinker and mass flow rate of cooling air, respectively.

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1. Introduction

The cement production is one of the most energy intensive industries and accounts for about 30–40% of the production cost. Nearly 5% of the total global industrial energy is used by the cement industries [1,2]. Therefore, various energy saving techniques can be applied to reduce energy used by this type of industry [3–5].

A grate clinker system is used in cement production and clinker burning system consists of a clinker cooler, the rotary kiln, and the suspension pre-heater [6]. A clinker cooler reduce the temperature of the clinker, and grind and recover energy from the sensible heat of the hot clinker by heating the cooled air. Four different types of clinker coolers (i.e. grate, planetary, shaft, and rotary coolers) are used to cool the hot clinker. A grate cooler has been proven to recover more heat than the other types of coolers. For large capacity plants, a great cooler is preferred one [7]. Fig. 1 presents the schematic of a typical grate clinker cooler.

In a grate cooler, the clinker comes out of the rotary kiln at a temperature of 1380 °C and it is cooled by fresh incoming air at a temperature of 65 °C through a cross-flow heat exchanger. After passing over the layer of clinker, hot air from the recuperation zone is used as a main burning air (secondary air) and as a pre-calciner fuel (tertiary air). The remaining air is sent to the stack through multi-clones or electrostatic precipitators (ESP). Once clinker leaves the kiln, it must be cooled quickly to ensure maximum yield of the compound that contributes to the hardening properties of cement [8].

This situation provides an opportunity to reduce energy use in a grate clinker cooling system by optimizing operational parameters. Numerous energetic and exergetic studies have already been performed on the individual components (i.e. raw mill, rotary kiln, and, etc.) of the cement production process. These analyses were also carried out for the whole process of cement production as well. Worrell et al. [9] identified cost-effective energy efficiency measures and potentials in the US cement industries. Thirty energy-efficient technologies and measures had been identified. Authors estimated amount of energy saved and cost of investment for energy saving measures for this study [6]. Despite the numerous studies on the thermal performance of a clinker cooling system, there has been lack of extensive studies on how operational parameters influence the energy and exergy performance of the system.

First law of thermodynamics (i.e. energy analysis) does not give any information on the degradation (quality) of energy that occurs in...
a process. Hence, exergy analysis is frequently used in addition to energy analysis when evaluating industrial processes [7,10]. The second law of thermodynamics (i.e. exergy analysis) provides both qualitative and quantitative aspects of energy using processes. Exergy is a measure of the maximum capacity of an energy system to perform a useful work as it proceeds to a specified final state in equilibrium with its surroundings [11,12]. Ari [13] did an energetic/exergetic analysis for a rotary kiln system recovering heat from preheater and clinker cooler exhaust gas. An increase of about 50% was reported for exergy efficiencies. A mathematical model was introduced by Sögüt et al. [14] for the heat recovery from a rotary kiln in a cement plant. Aside from emission reduction, the recovered heat was said to provide required thermal loads for about 680 homes. Some papers like that by Madlool et al. [15] have also reviewed the literature on exergy analysis done for various components of cement industries and in another article Madlool et al. [16] focused on energy use and energy saving methods in this industry.

To fill the identified gaps in the literature, this study investigated the effect of mass of the clinker, cooling air, grate speed and temperature of cooling air on energy and exergy efficiencies of a grate clinker cooling system. Study also investigated recovery efficiencies of the improved system using secondary and tertiary air as a heat recovery source.

### 2. Methodology

#### 2.1. Energy and exergy analyses

The energy analysis is a traditional approach, which uses energy balance to estimate energy use in various energy conversion processes. Energy and exergy are different in the sense that exergy is only conserved in a reversible process, but it is always consumed in an irreversible process [17]. An exergy analysis is a thermodynamic approach to identify the types, locations and magnitudes of thermal losses. Hence, exergy analysis will consequently allow the evaluation and improvement of the thermodynamic systems design [7]. Consequently, this analysis provides information on the maximum savings that could be achieved through the improved processes [18,19].

#### 2.2. Energy and exergy input data

Specific heat capacities, mass and temperature are the necessary input parameters to analyze the energy, exergy and recovery efficiencies of the grate clinker cooler. These are taken from studies performed by Rasul et al. [2], Kolip and Fevzi [3] and Mundhara and Sharma [20]. Table 1 shows the summary of the input and output.
data used for this analysis as input parameters. The reference temperature and pressure of the system considered to be 25 °C and 101.03 kPa, respectively.

In order to thermodynamically analyze the cooler system and simplify the analysis, the following assumptions were made:

i. Steady state working conditions.
ii. The change in ambient temperature is neglected.
iii. Cold air leakage into the system is neglected.
iv. Clinker compositions do not change.
v. Kinetic and potential energy changes of input and output materials are neglected.
vi. All gas streams are assumed to be ideal at the given temperatures.

To get a better picture of the system, flow schematic diagram is presented in Fig. 2. As it is shown, the system examined in this study paper has recovery processes in terms of secondary air, tertiary air and hot exhaust air which are recovered to kiln, preheater and raw meal, respectively, in order to improve the efficiency of clinker cooler system. Clinker and cooling air mass flow rates, grate speed and air cooling temperature are the parameters that are effective on the energy recovery efficiency by influencing the mass and the temperature of the secondary air, tertiary air and hot exhaust air.

2.3. Mathematical formulations for energy, exergy and their recovery efficiencies

2.3.1. Energy analysis

For a general steady state and steady-flow process, the mass and energy must be balanced. The energy balance equation can be written as [18]:

\[ \sum E_{\text{in}} = \sum E_{\text{out}} \]  

(1)

Based on Fig. 3, total input energy can be defined as:

\[ \sum E_{\text{in}} = \dot{Q}_{\text{ic}} + \dot{Q}_{\text{ca}} = m_{\text{ic}}C_{\text{ic}}(T_{\text{cl1}} - T_{\text{a}}) + m_{\text{a}}C_{\text{a}}(T_{\text{ac}} - T_{\text{a}}) \]  

(2)

Output heat from the cooler can be expressed as [2]:

\[ \sum E_{\text{out}} = \dot{Q}_{\text{as}} + \dot{Q}_{\text{at}} + \dot{Q}_{\text{oc}} + \dot{Q}_{\text{exh}} = m_{\text{as}}C_{\text{a}}(T_{\text{at}} - T_{\text{a}}) + m_{\text{at}}C_{\text{a}}(T_{\text{ac}} - T_{\text{a}}) + m_{\text{oc}}C_{\text{oc}}(T_{\text{oc}} - T_{\text{a}}) + m_{\text{exh}}C_{\text{exh}}(T_{\text{exh}} - T_{\text{a}}) \]  

(3)

To estimate the efficiency of the cooler and the amount of energy that can be recovered from the cooler, following equations are used. Energy efficiency is the ratio between the amount of energy output and input of the system and can be expressed as [18,21]:

\[ \eta_{f} = \frac{\sum \dot{E}_{\text{out}}}{\sum \dot{E}_{\text{in}}} \]  

(4)

The recovery energy efficiency of the secondary and tertiary air can be expressed as [2]:

\[ \eta_{\text{recovery, cooler}} = \frac{\dot{Q}_{r}}{\dot{Q}_{ic} + \dot{Q}_{ca}} \]  

(5)

2.3.2. Exergy analysis

The general exergy balance, using an exergy destruction concept for an ideal system, can be expressed as [6]:

\[ \sum \dot{E}_{x_{\text{in}}} - \sum \dot{E}_{x_{\text{out}}} = \dot{E}_{x_{d}} \]  

(6)

The steady state exergy balance, using exergy destruction for the open system of clinker cooling (Fig. 4), is thus stated as [17,22]:

\[ \dot{E}_{x_{d}} = (\dot{E}_{x_{ic}} + \dot{E}_{x_{ca}}) - (\dot{E}_{x_{oc}} + \dot{E}_{x_{as}} + \dot{E}_{x_{at}} + \dot{E}_{x_{exh}}) \]

\[ = \dot{m}_{\text{ic}}E_{x_{ic}} + \dot{m}_{\text{a}}E_{x_{a}} - (\dot{m}_{\text{as}}E_{x_{as}} + \dot{m}_{\text{at}}E_{x_{at}} + \dot{m}_{\text{exh}}E_{x_{exh}}) \]  

(7)
The exergy efficiency ($\eta_{II}$) defines all exergy input as the exergy consumed, and all exergy output as the exergy utilized and can be expressed as [18]:

$$\eta_{II} = \frac{\dot{E}_{out}}{\dot{E}_{in}}$$

$$\Rightarrow \eta_{II} = \frac{\dot{E}_{exch} + \dot{E}_{as} + \dot{E}_{at} + \dot{E}_{exch}}{\dot{E}_{ic} + \dot{E}_{ca}}$$

Exergy recovery efficiency is defined as the ratio of exergy recovered using the tertiary and secondary air to the exergy input. It can be mathematically defined as follows:

$$\eta_{II} = \frac{\dot{E}_{out} - \dot{E}_{waste}}{\dot{E}_{in}}$$

In this case, both the kinetic and potential exergies are neglected [17,22]. Realistically, there is a part of the output exergy, which remains unused, i.e. the exergy that is dissipated to the environment. In this case, exergy efficiency can be expressed as [9]:

$$\eta_{II} = \frac{\dot{E}_{exch} + \dot{E}_{as} + \dot{E}_{at}}{\dot{E}_{ic} + \dot{E}_{ca}}$$

2.4. Cost benefit analysis

2.4.1. Potential energy and cost savings

The change in cooler efficiency by optimizing its operational parameter, will result in potential energy saving. Energy savings through secondary air to the rotary kiln, tertiary air to the pre-calciner, and other channels (i.e. raw material and coal drier, cooling air preheater and primary air pre-heater) has been estimated here. The amount of cost savings through the associated with the recovered energy can be estimated using Eq. (10):

$$CS = ES \times EC$$

2.4.2. Cost of conserved energy (CCE)

The cost of conserved energy can be used to evaluate the cost effectiveness and the technical potential for energy efficiency improvement of this analysis. It shows the energy conservation potential as a function of the marginal cost of energy conserved. The cost of conserved energy (CCE) required for constructing the CSC (conservation supply curves), can be calculated as follows [23]:

$$CCE = \frac{(\text{Annualized capital cost + annual change in operations and maintenance costs})}{\text{Annual energy savings}}$$

Annualized capital cost can be expressed as:

$$ACC = \text{Capital cost} \times CRF$$

3. Results and discussion

3.1. Energy analysis of the base case clinker cooler

Using Eqs. (2)–(5) and data from Tables 1 and 2, energy analysis for the base case grate clinker cooler is performed and summary of results are presented in Table 3.

The value of energy efficiency of the clinker (81.3%) represents the overall performance of the grate clinker cooling system. However, heat energies contained in the exhaust gases and the cooled clinker are still considered to be recovered regardless of the end use. The energy recovery efficiency of the system found to be 51.3% which is quite low. This may be due to only the heat energy recovered and used at other processes of clinker production is taken into account. The energy recovery efficiency of the system plays a major role in the improvement of the clinker cooler, as the increase in its value translates to energy and cost saving.

3.2. 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 irreversible

### Table 2

<table>
<thead>
<tr>
<th>Sym.</th>
<th>Description</th>
<th>Formula used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{ic}$</td>
<td>Exergy of clinker</td>
<td>$m_{cl}(\overline{T}_{cl,\text{in}} - \overline{T}<em>0 - T_o(\overline{T}</em>{cl,\text{in}} - \overline{T}_0))$</td>
</tr>
<tr>
<td>$E_{ka}$</td>
<td>Exergy of cooling air</td>
<td>$m_{kl}(\overline{T}_{kl} - \overline{T}<em>0 - T_o(\overline{T}</em>{kl} - \overline{T}_0))$</td>
</tr>
<tr>
<td>$E_{as}$</td>
<td>Recovery exergy of kiln secondary air</td>
<td>$m_{at}(\overline{T}_{at} - \overline{T}<em>0 - T_o(\overline{T}</em>{at} - \overline{T}_0))$</td>
</tr>
<tr>
<td>$E_{at}$</td>
<td>Recovery exergy rate of tertiary air from cooler</td>
<td>$m_{at}(\overline{T}_{at} - \overline{T}<em>0 - T_o(\overline{T}</em>{at} - \overline{T}_0))$</td>
</tr>
<tr>
<td>$E_{oc}$</td>
<td>Exergy of clinker at cooler outlet</td>
<td>$m_{oc}(\overline{T}_{oc,\text{in}} - \overline{T}<em>0 - T_o(\overline{T}</em>{oc,\text{in}} - \overline{T}_0))$</td>
</tr>
<tr>
<td>$E_{exch}$</td>
<td>Exergy of cooler exhaust air</td>
<td>$m_{exch}(\overline{T}_{exch,\text{in}} - \overline{T}<em>0 - T_o(\overline{T}</em>{exch,\text{in}} - \overline{T}_0))$</td>
</tr>
</tbody>
</table>
process of clinker cooling produces entropy, which consequently leads to exergy destruction. The following subsection presents the sample calculations for the exergy balance, as well as the exergy and exergy recovery efficiencies of the grate clinker cooling system.

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

$$T_0 S_{\text{gen}} = \dot{E}_{\text{d}} = (\dot{E}_{\text{sc}} + \dot{E}_{\text{ca}}) - (\dot{E}_{\text{sc}} + \dot{E}_{\text{as}} + \dot{E}_{\text{at}} + \dot{E}_{\text{exh}})$$

(13)

Based on second law analysis, the exergy efficiency of this system is summarized in Table 4.

Similar to energy efficiency, the exergy efficiency (53.8%) represents the overall performance of the grate clinker cooling system. However, exergy contained in the exhaust gas and the cooled clinkers are still considered to be recovered regardless of the system. The exergy efficiency of the grate clinker cooling system is relatively low compared to its energy efficiency (81.3%). This confirms that at the given conditions of the system’s 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.

Söğüt et al. [14] also studied cement plant in Turkey and found that 51% of the initial energy was lost in their calculations. Authors found that thermal energy losses could be reduced using natural gas instead of coal.

The exergy recovery efficiency of the system is much lower (43.2%) than the energy recovery efficiency (51.3%). This is because, for exergy recovery efficiency, only the exergy recovered and used at other processes of clinker production, is taken into account. Similar to the energy recovery efficiency, the exergy recovery efficiency of the system also plays a significant role in the improvement of the clinker cooler. Exergy recovery efficiency represents the real room for improving the system.

3.3. Changing the operational parameters: mass flow rate of cooling air

3.3.1. Change in the first and second law efficiencies of the grate clinker cooling system

Variations in mass flow rate of cooling air will lead to a change in the outlet temperature of clinker, due to an increase or decrease in the rate of heat transfer between the two mediums. Theoretically, when the mass flow rate of cooling air is increased, it can recover more heat 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 temperatures) as well [20]. Hence the efficiency is also increased.

Mundhara and Sharma [20] showed that temperatures of the solid clinker and cooling are decreased along the length of the cooler at different mass flow rates of cooling air (when increasing the cooling air mass flow). The air temperature profile for the cooler is divided into three regions, i.e. the secondary air zone, the tertiary air zone and the exhaust air zone. When analyzed, with every 5% increase in the mass flow rate of cooling air, the estimated decrease of 0.2%, 1.2% and 2.1% occurs in secondary, tertiary and exhaust air temperatures, respectively. The temperature of the clinker outlet, on the other hand, is estimated to abate 1.9% for every 5% increase in the mass flow rate. By performing an ideal energy and exergy analyses on the clinker cooler, it is evident that the trend of first and second law efficiencies will be increasing with the increase of mass of cooling air. Fig. 5 presents the variation in the first and the second law efficiencies with the increment in mass flow rate of cooling air, respectively.

The trend in Fig. 5 shows that the energy efficiency, as well as the energy recovery efficiency of the grate clinker cooler increases with the increase in mass flow rate of the cooling air. Increasing of mass flow rate of cooling air up to 2.68 kg/kg (optimum clinker mass flow rate), clinker will cause low heat exchange between the clinker particle and the cooling air. This on the other hand will lead to increase in energy and recovery efficiencies. For every 5% increment in the mass flow rate, the clinker cooler experiences roughly 1.4% increase in energy efficiency and 2.32% in energy recovery efficiency. As the mass flow rate is augmented, the temperature of clinker solid at the outlet falls. More energy is absorbed by the increased air flow and returns 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 the 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. Fig. 5 also shows that the exergy efficiency, as well as the exergy recovery efficiency of the grate clinker cooler increases with the increasing mass flow rate. For every 5% increase in the mass flow rate, the clinker cooler experiences roughly 1.4% increase in energy efficiency and 2.32% in energy recovery efficiency.

Table 3

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material</th>
<th>Temperature, T, °C</th>
<th>Heat, Q, kJ/kg cl</th>
<th>% Of energy</th>
<th>Energy efficiency of cooler, $\eta_{\text{cool}}$ (%)</th>
<th>Recovery efficiency, $\eta_{\text{rec}, \text{cooler}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Hot clinker</td>
<td>1300.0</td>
<td>1351.5</td>
<td>96.3</td>
<td>81.3</td>
<td>51.3</td>
</tr>
<tr>
<td></td>
<td>Cooling air</td>
<td>45.0</td>
<td>51.5</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>Secondary air</td>
<td>850.0</td>
<td>423.2</td>
<td>30.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tertiary air</td>
<td>650.0</td>
<td>296.6</td>
<td>21.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cool clinker</td>
<td>115.0</td>
<td>82.8</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exhaust gas</td>
<td>220.0</td>
<td>337.4</td>
<td>24.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unaccountable losses</td>
<td>262.9</td>
<td>18.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material</th>
<th>Temperature, T, °C</th>
<th>Exergy, $E$, (kJ/kg cl)</th>
<th>Exergy efficiency, $\eta_{E}$ (%)</th>
<th>Recovery exergy efficiency, $\eta_{E,\text{rec}}$ (%)</th>
<th>Exergy losses (%)</th>
</tr>
</thead>
</table>
increases in mass

The additional fan electrical energy requirements for every 5% increase in mass represents the real room of improvement for the grate clinker.

It is apparent from Fig. 5 that the increase in second law efficiency (exergy) of the system is lower than the increase in first law efficiency (energy), in terms of the increase 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 specific final equilibrium state with its surroundings. Actually due to irreversibility, in the clinker cooling process, a large amount of exergy is always destroyed due to the difference in the energy sources and the environment. Compared to first law efficiency, second law efficiency are always lower for any system, because not all the energy sources can be converted into useful work. Exergy destruction during the process of clinker cooling is occurred 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 loss of the system.

3.3.2. Electrical energy required due to the increase in mass flow rate of cooling air

The increase in mass flow rate of cooling air is a result of an increase in air flow through the cooler fans. For variable and increased air flow, it is fairly necessary to install variable speed drives on the existing fans [24]. This technology allows controlling fan speed and hence mass flow rate of cooling air to be varied with respect to loads [25].

It can be estimated that the volumetric flow rate from a fan is directly proportional to the motor speed. On the other hand, power consumed by the fan is proportional to cube of the motor speed (i.e. a small change in motor speed results in a large change in power). Installation of VSD’s on a fan motor will allow the inlet guide fans or dampers to be left 100% open and regulate the motor speed to match load requirements [25]. 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 through fans.

Taking the plant output to be 3000 tons of clinker per day i.e. 187.5 tons per hour (daily operation of 16 h), it is easy to estimate the additional amount of electrical energy required for every 5% increase in mass flow rate of cooling air. The density of air is taken as 1.109 kg/m³ at 45 °C, 0.3149 kg/m³ at 850 °C, 0.3835 kg/m³ at 650 °C, and 0.7174 kg/m³ at 240 °C [11]. Therefore, additional amount of cooling air required for 5% increase is 0.1275 kg and considering 187,500 kg clinker production per hour, total additional cooling air is obtained by multiplying 187,500 kg with 0.1275. Then the result is multiplied by density, the additional amount of cooling air as is obtained and shown in Table 5. 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/(m³/h) [8]. Table 5 presents the additional fan electrical energy requirements for every 5% increase in mass flow rate of cooling air.

Table 5 shows that the total additional daily energy consumption goes up to 1296 kWh for every 5% increase in the mass flow rate.

3.4. Operational parameters: cooling air temperature

3.4.1. Change in the first and second law efficiencies of the grate clinker cooling system

Variation in cooling air temperatures 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 the two mediums. Despite the larger capacity to absorb heat, the lower temperature of cooling air also causes fall of air and clinker outlet temperatures, consequently leading to exergy losses [26]. The author showed that the entropy production and hence the exergy destruction increases with inlet temperature ratio for a clinker.

By performing an ideal energy and exergy analysis on the clinker cooler, one can find the trend of first and second law efficiencies change with the variation in cooling air temperature. Fig. 6 presents the variation in the first and second law efficiencies of the grate clinker cooler with the change in cooling air temperature, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>Original mass flow rate (kg/kg clinker)</th>
<th>Mass flow rate (kg/kg clinker) after 5% increment</th>
<th>Additional air mass flow rate (kg/kg clinker)</th>
<th>Additional air volume flow rate (m³/h)</th>
<th>Fan motor power (kW)</th>
<th>Energy requirement per day (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling air</td>
<td>2.55</td>
<td>2.68</td>
<td>0.13</td>
<td>21,563</td>
<td>27.6</td>
<td>442</td>
</tr>
<tr>
<td>Secondary air</td>
<td>0.45</td>
<td>0.48</td>
<td>0.02</td>
<td>11,912</td>
<td>15.2</td>
<td>244</td>
</tr>
<tr>
<td>Tertiary air</td>
<td>0.42</td>
<td>0.45</td>
<td>0.02</td>
<td>9781</td>
<td>12.5</td>
<td>200</td>
</tr>
<tr>
<td>Exhaust air</td>
<td>1.68</td>
<td>1.76</td>
<td>0.08</td>
<td>20,000</td>
<td>25.6</td>
<td>410</td>
</tr>
<tr>
<td>Total</td>
<td>6.68</td>
<td>6.99</td>
<td>0.34</td>
<td>67,456</td>
<td>81</td>
<td>1296</td>
</tr>
</tbody>
</table>
In the Fig. 6, any increase in the temperature of cooling air above 47.25°C (5% increase from cooling air temperature of 45°C) which is the optimum cooling air temperature, will reduce heat exchange between the hot clinker and cooling air according the first law of thermodynamics. Also it shows that the exergy efficiency, as well as the exergy recovery efficiency of the grate clinker cooler increases with increasing temperature of cooling air. There is 7.4% increase in exergy destruction that comes with every 5% decrease in cooling air temperature and is partially reflected through the trend of second law efficiency of the system. However, the exergy and exergy recovery efficiencies roughly dropped by 2.5% and 1.7%, respectively, with every 5% decrease in cooling air temperature.

Despite the increased amount of energy that the lower temperature cooling air is able to recover, this cooling does not restore the air to the initial hot clinker temperature. This fall of temperature consequently causes internal exergy losses. Theoretically, it is not desirable to cool clinker with the 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, which will contribute to the pre-heating of the cooling air and decreasing external exergy losses. 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 efficiency 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. Consequently, the first law efficiency of the system also increases slightly. Higher cooling air temperatures result in higher outlet air temperatures, which translate 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.

### 3.4.2. Heat energy requirement to increase the 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 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:

\[
\dot{Q}_{\text{cooling air}} = \dot{m}_{\text{avg}}(T_2 - T_1)
\]

\[
= \left( \frac{2.55}{\text{kg}} \right) \times \left( \frac{1.007}{\text{kJ}} \right) \times (334 \text{ K} - 318 \text{ K})
\]

\[
= 41.1 \text{ kJ/kg ck}
\]

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 found to be about 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 an average temperature of 52.5°C. This analysis was performed under the assumption that no heat was lost during the heat transfer.

### 3.5. Operational parameter: mass flow rate of clinker

#### 3.5.1. Change in the first and second law efficiencies of the grate clinker cooling system

Mass flow rate generally affects the heat transfer rate, i.e. the power consumed or generated for any given system. From the study by Mundhara and Sharma [20], it is known that decrease of the mass flow rate of clinker into the grate clinker cooling system will theoretically reduce the temperature of clinker outlet. The authors presented the temperature profiles of solid clinker along the length of cooler at different clinker flow rates. The clinker outlet is estimated to decrease 3.7% with every 5% decrease in clinker flow rate. And optimum value of clinker mass flow rate found to be about 0.8 kg which causes 20% decrement in outlet temperature. The decrement of mass flow rate of clinker will decrease the heat exchange between the clinker particles and cooling air at inlet of grate cooler. This on the other hand influences the energy, energy recovery, exergy, and exergy recovery efficiencies.

Fig. 7 shows that the energy and exergy efficiencies, as well as the recovery energy and exergy efficiencies of the grate clinker cooler increases with decreasing clinker flow rate. For every 5% decrease in mass flow rate of clinker, the clinker cooler experiences approximately 3.0% increase in energy efficiency and a 2.9% increase in energy recovery efficiency. As the mass flow rate of clinker decreases, 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

![Fig. 6. Variation in first and second law efficiencies of grate clinker cooler with change in temperature of cooling air.](image)

![Fig. 7. Variation in first law efficiencies of grate clinker cooler with decrement in mass flow rate of clinker.](image)
same amount of heat from the clinker and therefore the air temperature remains constant. But as the heat input is decreasing, the clinker temperature also decreases.

On the other hand, the increase in first law efficiency 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 has a maximum amount in the cooler at a reasonable plant output.

Fig. 7 also shows an improvement over second law efficiency of the system with a decrease of mass flow rate of the clinker. For every 5% decrease in mass flow rate of clinker, the clinker cooler experiences approximately 2.9% increase in exergy efficiency and exergy recovery efficiency each. In this case, the improvement in second law efficiency 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.

3.5.2. Energy requirement for decrement in the mass flow rate of clinker

It is proven from the analysis performed by Mundhara and Sharma [20] that decreasing the mass flow rate of clinker will result in the increase of the first and 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 noted that the reduction in mass flow rate of clinker is not similar to increase of the mass flow rates 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 decrease in mass flow rate of clinker would also affect the mass flow rates of the other processes in the cement production plant, as these processes are sequential. The main processes of interest are the calcination process and the burning process, because they are energy consumers and are directly related to the clinker cooling process. As such, the mass flow rates of clinker in those processes are not highly affected by the change in mass flow rate of clinker in the cooling process.

Taking the plant output of 3000 tons of clinker per day, and 187.5 tons of clinker per hour, the three processes, i.e. calcination, burning and cooling, would have to be run for an extended period of 0.84 h, or 50.5 min to reach the plant output rate mentioned. Table 6 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 h.

From Table 6, it is shown that the grate clinker cooler will consume a total of 3525 kWh of energy to run for an additional period of 50.5 min a day. It can be seen that the exhaust 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 air intake side, consequently causing the fans at the exhaust side to work harder to evacuate a given mass flow rate of air.

3.6. Operational parameter: grate speed

3.6.1. Change in the first and 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 temperature. As opposed to previous criteria, a change in grate speed does not result in the commonly predictable trends of outlet temperatures. Studies have proven that as grate speed is increased, at first the air outlet temperature increases and after achieving a certain value of grate speed, it starts to decrease. On the other hand, as the grate speed increases the solid bed height is decreased, therefore heat transfer is augmented. Consequently, heat transfer will be at a maximum certain grate frequency [20].

The variation in temperature of air outlets is observed from the study performed by Mundhara and Sharma [20]. 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. However, the change in grate speed is assumed to have no significant effect on the clinker outlet temperature [22].

By performing an ideal energy and exergy analyses on the clinker cooler, authors are able to find the trend of first and second law efficiencies changes with the variation in grate speed. Fig. 8 presents the variation in the first and second law efficiencies of grate clinker cooler at different grate speeds, respectively. The first and second law efficiencies increase in the beginning with increasing grate speed until it reaches a certain maximum value, i.e. after 18.2% increase in speed, and then drop with an increased grate speed. The highest energy efficiency and energy recovery efficiency for the system are 88.2% and 54.1% at this point, respectively. In 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 efficiency.

Air outlet temperatures will first increase with grate speed until they reach a certain maximum level, and 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.

Even though increasing grate speed results in generally air outlets with higher temperature, 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 a certain amount of heat losses to the surroundings through convection and radiation, starting to overcome the increased heat transfer efficiency between the two mediums in the cooler, which causes lower first law efficiencies of the system.

Similar to the trend in first law efficiencies, Fig. 8 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. However, on the other hand, the energy efficiency and the energy recovery efficiency increase 7.1% and 2.8%, 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 heats as well, 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 airs, respectively. It is noteworthy that when one is able to find the optimum speed at which the first and second law efficiencies of the system are at their maximums, higher grate speed does not only affect these efficiencies but also the cost incurred in supplying energy to move the grates.

3.6.2. Energy requirement with increment in grate speed

Similar to the variable speed drives that can be installed on the fans of the grate clinker cooling system, this technology can also be applied to the grate to regulate the speed in accordance with the load. The speed of the feed rate and the air flow regulate the cooling process in a clinker cooling system. The clinker bed thickness is often measured indirectly via temperature probes or back pressure of air flow. A rise in either temperature or back pressure is generally proportional to the clinker bed thickness, but it can also be affected by material size. The air flow and the air pressure measurements in the clinker cooler are made through differential pressure mounted on orifice plates and ceramic cell pressure transmitters, respectively.

The base case cooler grate motor power consumption has been calculated in Table 7.

The power consumption by each grate to produce the base case travelling speed found to be 66.8 kW. For a plant producing 3000 tons of clinker per day, it is fairly common for the plant 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 h daily.

**Table 7**

<table>
<thead>
<tr>
<th>Surface area, $G_s$ (m$^2$)</th>
<th>Sp. cooler drive force, $D_s$ (kN/m$^2$)</th>
<th>Number of strokes, N</th>
<th>Stroke length, $s$ (mm)</th>
<th>Cooler drive force, $f = G_s \times D_s$ (kN)</th>
<th>Torque, $T = (f \times s)/(2 \times 10^3)$ (kN m)</th>
<th>Shaft power, $P_s = 2\pi NT/60$ (kW)</th>
<th>Actual power, $P_a = 1.4 P_s$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>11.5</td>
<td>22</td>
<td>120</td>
<td>345</td>
<td>20.7</td>
<td>47.7</td>
<td>66.8</td>
</tr>
</tbody>
</table>

**Fig. 9.** Variation in first law recovery efficiencies of grate clinker cooler with varying parameters.

**Fig. 10.** Variation in second law recovery efficiencies of grate clinker cooler with varying parameters.
3.7. Heat recovery of exhaust air

3.7.1. Change in the first and 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 and latent 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 [2]. 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 second law analyses, all the other parameters of the grate clinker cooler remain the same as the results obtained previously. As such, only the recovery efficiencies of the cooler will be affected.

Fig. 9 presents the first law recovery efficiencies of the grate clinker cooler with varying parameters. The energy recovery efficiencies experience 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. The heat energy content in the exhaust air found to be about 24.1% (shown in Table 3). It may be noted that this exhaust energy can be utilized to increase the recovery energy efficiency. Energy recovery represents the best opportunity to improve the system’s efficiency, and consequently to reduce the cost incurred in supplying energy for the clinker production process. To have a greater picture of the room for improving the system, one can look at the exergy recovery efficiencies instead. The exergy recovery efficiencies also experience an improvement across the board similar to the energy recovery efficiencies (Fig. 10). The exergy recovery efficiencies for this case, experience an average 9.4% of improvement after the recovery of heat energy from exhaust air. It is also evident from Fig. 8; the mass flow rate of clinker plays the biggest role in exergy efficiency improvement. Exergy recovery efficiency for cooling air temperature shows a more accurate trend for this study, since its energy recovery efficiency is estimated from assumed plug-in temperatures of air outlets.

3.7.2. Use of exhaust air recovery to pre-heat the raw material

One of relatively more beneficial methods of utilizing heat energy contained within the exhaust air would be using it to preheat the raw material before the clinkering process. This is achieved by directing hot gas, i.e. exhaust air streams into the raw material just before the grinding mill. The drying process would lead to a more efficient grinding of the raw material, aside from increasing its temperature. The rise in raw material temperature would only be beneficial for cement production plants, which send this fresh material directly to the rotary kiln for the clinkering process without being stored in silos for a certain interval of time [27].

The main purpose of pre-heating the raw material in the mill is to make it dried, since it is heavily moist in nature. For this analysis, the moisture content of the raw material is taken as 6.8%, which indicates a water mass flow rate of 0.113 kg/kg-clinker coming into the mill. 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 240 °C to dry the moist raw material. From the analysis, it was found that 12.2% of the total heat is needed to perform the mentioned task. 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 material in the grinding mill. The majority of the useful energy must be used to heat the water from 15° to 100 °C, and to vaporize it at this temperature completely. In this analysis, the heat losses to the surroundings, i.e. via convection and radiation are ignored. Energy balance for the grinding mill will show the energy interactions within the system [14]:

\[ Q_{\text{hot air}} + Q_{\text{moist raw material}} = Q_{\text{water}} + Q_{\text{cooled air}} + Q_{\text{dry raw material}} \]  

(14)

Using the data available in the Fig. 11 and Eq. (14), the heat recovery by the cooled air is estimated to be 153.7 kW.

<table>
<thead>
<tr>
<th>Operating parameters</th>
<th>Average improvement</th>
<th>Cost-saved (USD/ton ck)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy recovery efficiency</td>
<td>Rotary kiln</td>
</tr>
<tr>
<td>Mass flow rate of cooling air</td>
<td>2.32</td>
<td>0.105</td>
</tr>
<tr>
<td>Cooling air temperature</td>
<td>0.14</td>
<td>0.062</td>
</tr>
<tr>
<td>Mass flow rate of clinker</td>
<td>2.88</td>
<td>0.112</td>
</tr>
<tr>
<td>Grate speed</td>
<td>0.77 (up to 18.2% optimization)</td>
<td>0.022</td>
</tr>
<tr>
<td>Total</td>
<td>0.301</td>
<td>0.213</td>
</tr>
</tbody>
</table>
3.7.3. Cost and energy savings

It is observed in the previous discussion that energy and energy recovery efficiencies vary along with the change in operating variables. Using the optimum values of the operational parameters, optimal energy and energy recovery efficiencies can be estimated (from Figs. 5–8 and Eqs. (8) and (9)). Based on the result from Figs. 6–8 and using Eqs. (11) and (12), energy savings and cost savings for the optimum conditions have been estimated and presented in Tables 8 and 9.

4. Conclusions

This study was performed primarily to determine how the operational parameters of the grate clinker cooling system and the recovery of heat from the hot exhaust air, affect the first and second law efficiencies. Energy and cost savings are calculated for the improvement as well. The outcomes of the analyses are summarized as follows:

a) The energy and exergy efficiencies of the base case clinker cooler found to be 81.2% and 53.7%, respectively. Whereas, the energy and exergy recovery efficiencies of system are 51.2% and 43.1%, respectively.

b) With 5% increase of mass flow rate of cooling air, the energy and the energy recovery efficiencies of the clinker cooling system increases 1.1% and 1.9%, respectively. For the same case, the average increase of exergy and exergy recovery efficiencies is 0.9% and 1.5%, respectively.

c) With 5% increase in temperature of cooling air, the energy and the energy recovery efficiencies of the clinker cooling system increase by 2.0% and 0.4%, respectively. In the similar case, the average rise of exergy and exergy recovery efficiencies is found to be 3.6% and 2.2%, respectively.

d) For every 5% decrease in clinker mass flow rate, the energy and the energy recovery efficiencies of the clinker cooling system augment by 2.7% and 2.5%, respectively. The average augmentation of exergy and exergy recovery efficiencies is found to be 2.4% and 2.2%, respectively.

e) With every 9.1% increase in grate speed, the energy efficiency and the energy recovery efficiency of the clinker cooling system averagely rise by 3.5% and 1.4%, respectively, up to 18.2% increase in grate speed. The average increase of exergy and exergy recovery efficiencies is 3.1% and 1.7%, respectively.

f) With the assistance of heat recovery from the exhaust air, typical grate clinker cooling system experiences 21.5% in energy recovery and 9.4% in exergy recovery efficiencies.

Material saving has been found that major cost savings can be achieved by changing mass flow rate of clinker (i.e. 38.10%) followed by mass flow rate of cooling air (30.86%).

According to the results, a number of viable ways are available to reduce energy use and energy loss in the cement industry. If other strategies are implemented on the investigated parameters more improvement may be achieved. Using nanotechnology including nanoparticles in the heat recovery process for instance might be one of the suggestions since more heat could be recovered from the exhaust air. One can obtain a significant reduction in energy use and losses by adding up the different effects of the parameters studied hereby.

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