

Energy and Exergy Analysis of Clinker Cooler in the Cement Industry

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Abstract. Grate coolers which represent one of the pyro-processing units are extensively used in cement industries. The essential function of grate coolers is a waste heat recovery from hot clinker which leaves the rotary kiln. This paper presents an analysis of energy and exergy based on the clinker temperature profile. It focuses on the distributions of temperature, energy and exergy for cooling air and hot clinker along the grate cooler in cement industries. Consequently, this distribution allows predicting the temperatures of secondary air, tertiary air, and exhaust air, which will lead to estimation of waste heat recovery from the clinker cooler system.

1. Introduction

The cement segment is considered one of the most intensive energy industries worldwide, so its technological, economic, energy and other aspects are widely studied [1-16]. The cost of energy consumed in cement industry accounts from 20% to 40% of the total cost of production. In addition, it is considered as a main source of greenhouse gases [17-19].

The consumption of energy for cement industry is appraised at approximately 2% and 5% of the global consumption of primary energy and the total global industrial energy respectively [20]. Specific consumption of energy in cement industry is a key pointer that measures the plant efficiency in its clinker production (in MJ/t clinker). Production process in cement industry needs electrical energy about 110kWh/t, 40% of this energy is directed to clinker grinding [21]. The consumption of the kiln process is more than 90 % of the cement manufacturing energy. The remaining consumption of 10 % is almost equally amounted by activities related to preparation of fuel and raw materials, clinker grinding and the materials blending for preparation of the finish cement product.

2. Description of a clinker cooling system

The system of clinker burning comprises three parts, namely, the suspension pre-heater, rotary kiln and the clinker cooler [22]. The essential functions of the clinker cooler system in cement plant are the reduction of the temperature of the hot clinker to an acceptable stage for additional transport and to grind. Also it serves for energy recovery from the hot clinker sensible heat by heating the cooling air. The modern type cooler is the grate cooler, and now it is used almost in all modern kilns. The large



grate cooler capacity accommodates large kilns when compared with other cooler types besides its ability to heat recovery efficiently. Figure 1 presents the scheme of typical pyro-processing units in the cement production line including grate clinker cooler.

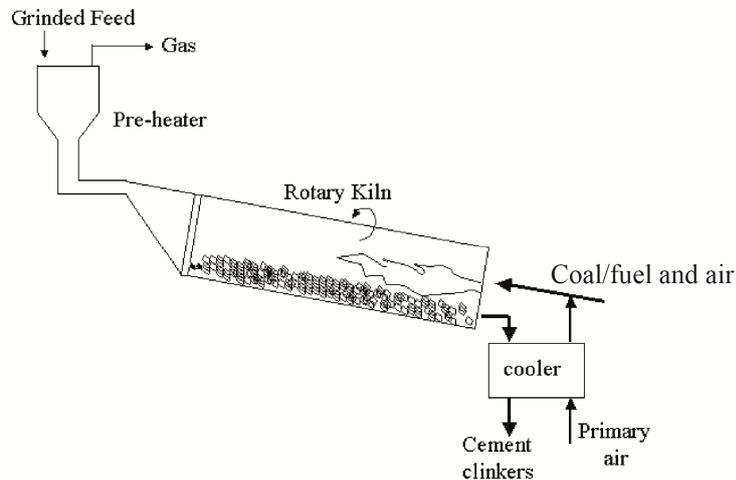


Figure 1. Scheme of pyro-processing units in the cement production line [23]

The grate system consists of three plates, the reciprocating frame and the supporting structures. Within the area of the recuperation zone, the grate cooler is operated with a high clinker bed while the clinker bed is somewhat lower in the secondary zone. The tertiary air pipes are connected to the kiln at the front end. The dust load of the secondary air is admitted to the kiln, and the tertiary air directed into the pre-heater is low. Because of its dimensions and connections, the kiln head is of stationary design.

The tertiary air pipes are fixed to the kiln head front, parallel to the kiln axis. The combustion air is withdrawn from the cooler and introduced into the preheater and the kiln.

3. Methodology

In this paper, we adopted two approaches for the analysis: the first approach considers the clinker flow as a packed bed, while the second approach considers the clinker cooler as a system. The performance of clinker cooler has been examined by calculating the efficiencies of energy, exergy and their recoveries.

3.1. Data collection

The data was collected from industry in Iraq.

Table 1. Properties of clinker and air

Characteristics	Clinker	Air
Density (kg/m^3)	1350	1.184
Heat capacity ($\text{J/kg}\cdot\text{K}$)	1080	1007.5
Viscosity ($\text{kg/m}\cdot\text{s}$)		$1.78\text{e-}05$
Thermal conductivity ($\text{W/m}\cdot\text{K}$)	0.2	$0.0042 + 0.00007 \times T$
Inlet temperature (K)	1573	300
Grate speed (m/s)	0.11	

3.2. Energetic and exergetic analysis for a clinker flow as a packed bed

In this analysis we will consider steady state conditions and neglect losses. It can further be assumed that the mass of heat transfer occurs through forced convection between the clinker and cooling air.

According to Newton's Law, the heat transfer rate therefore will be proportional to the temperature difference between the clinker temperature and air temperature (ambient temperature) at each stage [24]:

$$m_c C_p c dT_c = -K(T_c - T_o) dt \quad (1)$$

T_o can be neglected as its value is small comparing with T_c .

Equation (2) can be derived to get the clinker temperature at any distance within clinker cooler system, and by rearranging the eq. (1) as following:

$$m_c C_p c \frac{dT_c}{T_c} = -k dt \quad (2)$$

Integrating eq. (2) between limits T_{c_i} , the initial temperature of clinker, and T_{c_x} , its temperature after it has travelled a distance 'x' from the feed end during time of 't' seconds:

$$\int_{T_{c_i}}^{T_{c_x}} \frac{dT_c}{T_c} = -\frac{kt}{m_c C_p c} \quad (3)$$

$$\ln \frac{T_{c_x}}{T_{c_i}} = -\frac{kt}{m_c C_p c} \quad (4)$$

$$T_{c_x} = T_{c_i} e^{-\frac{kt}{m_c C_p c}} \quad (5)$$

From eq. (5) it is possible to calculate the clinker temperature at any point along the length of the grate cooler, as

$$t = \frac{x}{v} \quad (6)$$

The energy equation in general form can be expressed as

$$Q = m C_p (T - T_o) \quad (7)$$

By substituting eq. (5) in eq. (7), the clinker energy expression at any point along the grate in terms of T_{c_i} can be obtained:

$$Q_{c_x} = m_c C_p c (T_{c_i} e^{-\frac{kt}{m_c C_p c}} - T_o) \quad (8)$$

The air cooling energy is equal to the clinker energy at any point of the grate because of the lost heat from the hot clinker being equal to the gained heat for air cooling at the clinker bed. Thus, the air cooling energy expression can be written as follows:

$$Q = Q_a = Q_{c_x} = m_a C_p a (T_a - T_o) \quad (9)$$

From eq. (9) T_{a_x} can be calculated in term of T_{c_i} as follows:

$$T_{a_x} = \frac{m_c C_p c}{m_a C_p a} (T_{c_i} e^{-\frac{kt}{m_c C_p c}} - T_o) + T_o \quad (10)$$

Whereas the exergy in general form can be expressed as:

$$Ex = (H - H_o) - T_o (S - S_o) \quad (11)$$

For incompressible flow:

$$Ex = m C_p (T - T_o - T_o \ln \frac{T}{T_o}) \quad (12)$$

By substituting eq. (5) in eq. (12), the exergy of clinker expression at any point along the grate in term of T_{c_i} can be obtained:

$$Exc_x = m_c Cp_c (Tc_{in} e^{-\frac{kt}{m_c Cp_c}} - T_o - T_o \ln \frac{Tc_{in} e^{-\frac{kt}{m_c Cp_c}}}{T_o}) \quad (13)$$

The air cooling exergy expression at any point along the grate in terms of Tc_i is obtained by substituting eq. (10) in eq. (13). After simplification, we obtain:

$$Exa_x = m_c Cp_c Tc_{in} e^{-\frac{kt}{m_c Cp_c}} - m_a Cp_a T_o (1 - \ln \frac{m_c Cp_c (Tc_{in} e^{-\frac{kt}{m_c Cp_c}} - T_o)}{m_a Cp_a T_o}) \quad (14)$$

3.3. Energetic and exergetic analysis for a clinker cooler as a system

In this analysis, the following assumptions were made for the period of the data collection from the plant to simplify the analysis:

- Steady state plant operation.
- The boundary conditions around the pyro-processing units (kiln, preheater and cooler) were fixed.
- The clinker product flow rate was considered equal to the charged flow rate at any time.
- Changes of kinetic and potential energies are negligible for input and output materials.
- Energy losses which take place in the connections of pipeline among units are ignored.
- To compare with other work, grate work is negligible.

The specific heats of the input and output components for analyses are necessary to be known.

Table. 2. Specific properties of inlet and outlet clinker and air

	Mass flow rate (kg/s)	Specific heat (kJ/kg·K)	Temperature (K)
Hot clinker	1	1.08	1573
Cooling air	2.4	1.0075	300
Secondary air	0.2757	1.159	1123
Tertiary air	0.8944	1.136	973
Cooled clinker	1	0.795	393
Hot air	1.2744	1.0277	493

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (15)$$

The energy balance in general form is:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (16)$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \quad (17)$$

Where

$$\dot{Q} = \dot{Q}_{net,in} = \dot{Q}_{in} - \dot{Q}_{out} \quad (18)$$

And

$$\dot{W} = \dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in} \quad (19)$$

Assuming there is no change in potential energy, and kinetic energy in addition to no heat or work transfers, therefore eq. (17) can be simplified to get eq. (20) in terms of enthalpy flow only.

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \quad (20)$$

In order to estimate the cooler efficiency and the recovered energy quantity from the cooler, the clinker cooler is considered separate for energy balance [18].

Heat input into the cooler:

$$\dot{Q}_{in} = \dot{Q}_{ch} + \dot{Q}_{ca} \quad (21)$$

Heat output from the cooler:

$$\dot{Q}_{out} = \dot{Q}_{sa} + \dot{Q}_{ta} + \dot{Q}_{cc} + \dot{Q}_{ha} \quad (22)$$

And the recovery heat energy:

$$\dot{Q}_{rec} = \dot{Q}_{sa} + \dot{Q}_{ta} \quad (23)$$

Whereas, in the general and rate forms, the balance of exergy can be written as following:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \quad (24)$$

$$\text{Or } \sum \left(1 - \frac{T_o}{T_k}\right) \dot{Q}_k + \sum \dot{m}_{in} \psi_{in} - \dot{W} - \sum \dot{m}_{out} \psi_{out} = \dot{E}x_{dest}$$

Where

$$\psi = (h - h_o) - T_o(s - s_o) \quad (25)$$

For incompressible flow

$$\psi = \dot{m} C_p \left(T - T_o - T_o \ln \frac{T}{T_o} \right) \quad (26)$$

and

$$\dot{E}x_{dest} = \dot{I} = T_o \dot{S}_{gen} \quad (27)$$

3.4. Clinker cooler efficiencies

The efficiency of energy is the ratio of the output energy to the input energy of the system.

$$\eta_E = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (28)$$

The energy recovery efficiency can be expressed as following:

$$\eta_{E_{rec}} = \frac{\dot{Q}_{sa} + \dot{Q}_{ta}}{\dot{Q}_{in}} \quad (29)$$

The efficiency of exergy is the ratio of output exergy to input exergy of the system and it can be expressed as the following equation:

$$\eta_{Ex} = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in}} \quad (30)$$

Whereas the exergy recovery efficiency represents the ratio between the secondary and tertiary air exergy to the input exergy as the following expression:

$$\eta_{Ex_{rec}} = \frac{\dot{E}x_{sa} + \dot{E}x_{ta}}{\sum \dot{E}x_{in}} \quad (31)$$

4. Results and discussions

4.1. Behavior of clinker and cooling air along the grate cooler (clinker flow as a packed bed)

Figure 2 shows the temperature gradient, energy and exergy for both the clinker and the air along the grate cooler length for the actual operational data of the Al- Muthanna plant for cement production in the Iraq.

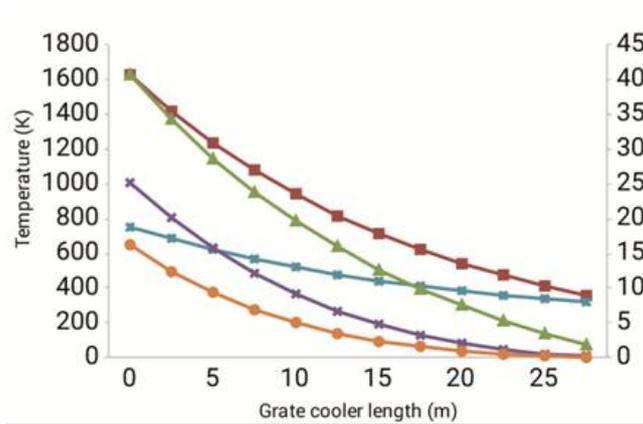


Figure 2. Behavior of temperature, energy and exergy of clinker and cooling air along the grate cooler length

4.2. Effect of mass clinker flow rate

As shown in Figure 3, the effect of variation of the clinker mass flow rate (at constant air mass flow rate) is evident in the cooler. Increasing and decreasing of clinker mass flow rate will cause more and less heat energy of clinker flow respectively. It was found that a 5% increase of the clinker mass flow rate resulted in an increase of 2.6% and 1.5% in the clinker and cooling air temperatures, respectively; a 8.26% rise in heat exchange between the clinker particles and the cooling air; it also increased the exergy for both clinker and cooling air by 8.22% and 8.04%, respectively) along the grate cooler length.

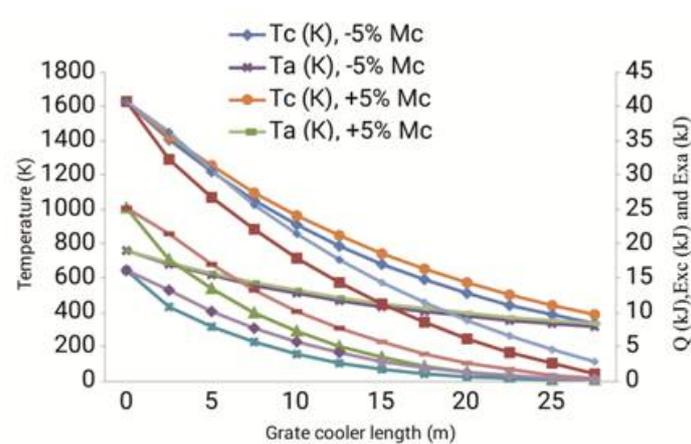


Figure 3. Temperature, energy and exergy gradients of clinker and cooling air at different increment of clinker mass flow rate

4.3. Effect of cooling air mass flow rate

Figure 4 shows the effect of changing the mass flow rate of the cooling air on the heat transfer phenomenon. It is shown that a 5% decrease in the mass flow rate of the air increased the clinker temperature by 4.1% and the cooling air temperature by 2.5% due to the coefficient of heat transfer of the air-clinker system. The same effect was observed on the air temperature as the air mass flow rate decreased the equilibrium air temperature, which increased with the increase in the clinker temperature.

Additionally, a 13.5%, 13.8% and 13.6% increase of heat exchange was noticed between the clinker and cooling air, clinker exergy and cooling air exergy respectively with every 5% decrease of mass flow rate of cooling air.

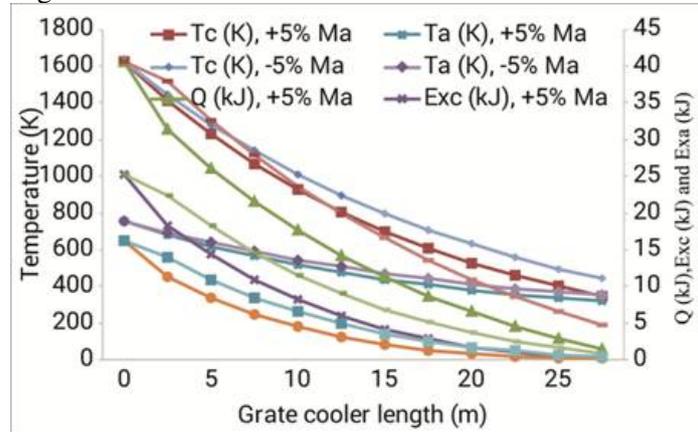


Figure 4. Gradients of temperature, energy and exergy of clinker and cooling air at different increment air mass flow rate

4.4. Effect of residual time and grate speed

The heat transfer between the clinker and the air is directly proportional to the time. With every 5% increase of residual time, there were increases of 2.6% in the clinker temperature, 1.5% in the cooling air temperature, 4% in the heat exchange between the particles of clinker and cooling air, 4.2% in the clinker exergy and 4.1% in the cooling air exergy. With every 5% decrease of grate speed, there was an increase of 2.5%, 1.5%, 3.8%, 4.2% and 4.19% of clinker and cooling temperatures, heat exchange between them and the clinker and cooling air exergies, respectively.

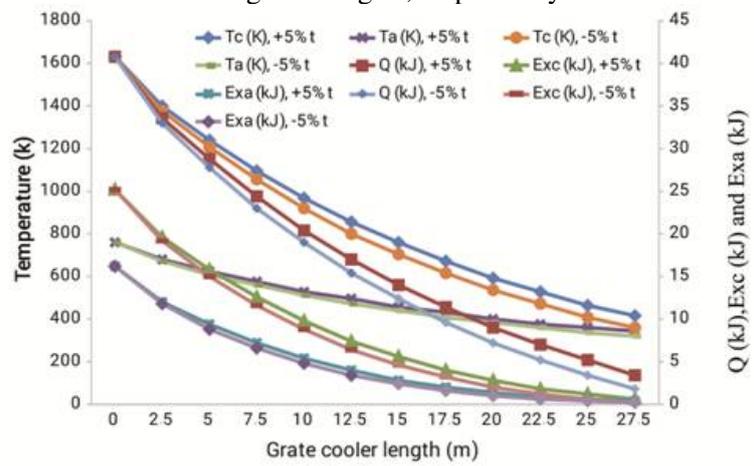


Figure 5. Effect of different increment of residual time on gradients of temperature, energy and exergy of clinker and cooling air

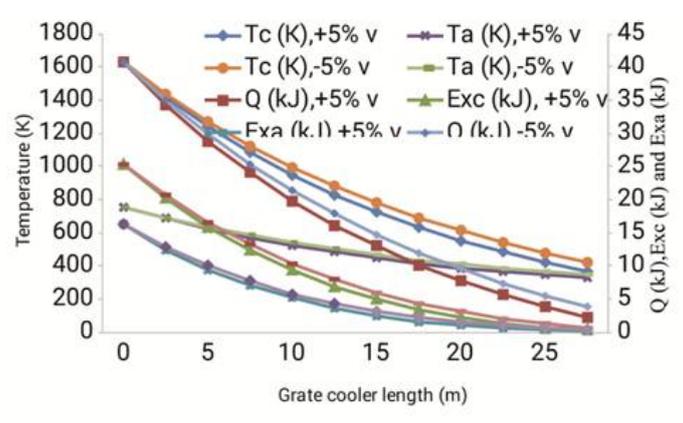


Figure 6. Behavior of temperature, energy and exergy of clinker and cooling air at different increment of grate speed

4.5. Energy and exergy balances (clinker cooler as a system)

The total energy output of this system at a value of 1433.47 kJ/kg clinker is equal to the total energy input, taking into account the unaccountable system losses. These losses are primarily due to heat losses via convection and radiation heat transfers as tabulated in Table 3 which presents the energy balance for the grate clinker cooler.

Table 3. Energy and exergy balance for clinker cooler of Al Muthanna Cement plant

	Energy		Exergy	
	kJ/kg	%	kJ/kg clinker	%
Hot clinker	1377	96	841.57	99.73
Cooling air	56.47	4	2.24	0.27
Secondary air	247.64	17.2	125.65	14.90
Tertiary air	530.70	37	253.46	30.03
Cooled clinker	75.52	5.2	9.96	1.18
Hot air	255.39	17.8	58.91	6.98
Unaccounted losses	324.21	22.6		
Energy efficiency %	77.4			
Energy recovery efficiency %	54.3			
Destruction			395.82	46.90
Exergy efficiency %			53.1	
Exergy recovery efficiency %			44.92	

5. Conclusions

This analysis was implemented to study the temperature distribution and consequently, to predict the temperatures of secondary air, tertiary air, and exhaust air. The prediction of these temperatures will lead to estimation of waste heat recovery from the clinker cooler system.

Many approaches were built to estimate the waste heat recovery from the clinker cooler system. These approaches could be improved to be economically applied in a real situational system. After accomplishment of the analysis of grate cooler system, the conclusions can be summarized and classified according to each study as follows:

Energy and exergy analysis of clinker flow as a packed bed

- Increased the clinker mass flow rate or residual time, increased the temperature of the clinker and the heat exchange between the clinker and cooling air and consequently on the exergy.

- The results indicate that the temperature profiles of the clinker bed always have an exponential type all over the axial direction (along the cooler).
- Increasing the mass flow rate of the air may improve the rapid cooling which can assist in the grinding process, in addition to decreasing the temperature of the outlet clinker.
- The temperature of the clinker at the bottom of the bed is always less than the temperature of the clinker at the top, because the air enters the compartment from the bottom at atmospheric temperature.

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