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Thermodynamics and Parametric Study of the Grate ClinkerCooler Using the Process Model

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Abstract

In cement industries, grate coolers are commonly used for heat recovery from hot clinker discharged from the rotary kiln. The study focuses on improving a grate cooling system's energy, exergy, and recovery efficiencies by optimizing its operating parameters such as cooling air and clinker mass flow rate. Aspen plus V10 process simulator was used to explore the impact of clinker mass, and ambient cooling airflow rate on the thermodynamics efficiencies of a cooling system for grate cooler. The energy and exergy efficiency of the grate clinker cooler gives estimates of 85.9% and 56.2 % respectively. Whereas the energy and exergy recovery of the grate clinker cooler was estimated as 75.9 % and 45.4 % respectively. It was found that a cooling system's energy and exergy efficiencies can be improved by 2.1 % and 2.2 %, respectively, for each 5 % rise in cooling air mass. Considering the utilization of the heat recovery efficiencies of the exhaust air cooling system, energy and exergy recovery have been found to increase by 8.5 % and 9.2 % respectively. It was discovered that significant emission reductions of 0.23 % can be achieved by raising both secondary air and tertiary temperature via optimization of the grate cooler parameter, resulting in a reduction of fuel for kiln operations. Nevertheless, these units provide opportunities in great potential for energy savings, therefore the method used can also aid informed decision-making to enhance process performance.

Keywords: grate clinker cooler, modeling, simulation, energy, exergy.

1. Introduction

Cement manufacturing is one of the highly energy-intensive sectors with an estimate of 30 to 40 % of production cost-share and uses approximately 5 % of the total global industrial energy [1, 2]. A typical cement plant that produces approximately 3000 tons of clinker per day needs around 2500–4000 kJ / kg clinker for energy input [3]. Consequently, different energy-saving strategies have been used by this sector with an only marginal decrease in both energy consumption and cost implication [1, 4, 5]. In the manufacture of cement, a grate clinker cooler is of great significance in the operation such as clinker cooling and energy recovery purpose. The cement production process units consist of the preheater with calciner, the rotary kiln, and the grate cooler [6]. Clinker cooling systems are of different types subject to the technology, and these are grate (most recent in technology), planetary cooler (attached to the long wet or dry kiln), shaft, and rotary coolers. It has been proven that a grate cooler recovers more heat than other forms of coolers and this makes energy savings achievable.

These circumstances offer a prospect of minimizing energy consumption through optimization of operating parameters in a grate clinker cooler operations. There have already been numerous energetic and exergetic studies on the individual subsystem such as raw mill, rotary kiln, rotary burner, and as well as the whole system of the cement production process. [7 – 10]

Cost-effective measures potential and thirty technology measures for energy efficiency in US cement industries were identified by Worrell et al., [11]. The estimated amount for the investment costs for the energy-saving measures was studied by the US EPA sector [12]. Despite several studies on the clinker cooling system to calculate thermal efficiency, there has been inadequate comprehensive analysis effect of operating parameters on thermodynamics efficiency using process simulator software.

The first law of thermodynamics gives little or no detail on the energy dissipation (quality) that arises during a process. Therefore, exergy analysis is frequently used to address the inadequacy of energy analysis for the industrial processes assessment [11, 13]. Hence, the second law of thermodynamics analysis expresses both qualitative and quantitative aspects of the energy in equilibrium with its environment [4, 14]. Ari [15] examined a rotary kiln with waste heat recovery from both the preheater, cooler using an energetic and exergetic analysis approach. The result posited an estimate of 50% of the exergy efficiency of the system. Sögüt et al., [16] developed a mathematical model for the recovery of heat of a pre-calcined kiln in a cement production process.

Several papers such as Madlool et al., [17], examined the literature on exergy analysis performed for different sections in the cement industry, and also, Madlool et al., [18], studied energy usage and saving techniques of the cement sector.

Ahamed et al., [14], investigated the clinker grate cooler and evaluated the unit's thermodynamics efficiencies on various operating conditions itself. The cooling system's energy and exergy recovery efficiencies were suggested to improve by 21.5 and 9.4 %, respectively. The study does not include the impacts of the evaluated operational parameters on the efficiency of the rotary kiln process. It is understood that the literature studies are often based separately on either grate clinker cooler or rotary kiln operations. The grate clinker cooler’s operational parameters, however, have significant impacts on the energy consumption of the rotary kiln system.

For this analysis, a cement plant's grate clinker cooler, first and second thermodynamics law efficiencies of the process are determined about the cooler's changing operating parameters. In comparison to previous papers, the impacts of the operational parameters on grate cooler and rotary kiln system specific energy consumption were studied using conventional methods. To close the established gaps in previous studies, this work used Aspen plus V10 process simulator to explore the impact of clinker mass, and ambient cooling airflow rate on the thermodynamics efficiencies of a cooling system for grate clinkers. The study also investigated improved clinker cooling recovery efficiencies with both secondary and tertiary mass flow of a cement plant located in South west, Nigeria, This paper will contribute to a deeper understanding of the use of

Aspen plus process modeling in varying some of these parameters, such as clinker mass flow rate, air mass flow rate cooling, and their relationship to the thermodynamics efficiency of the grate clinker.

1.1 Process Description of Grate Clinker Cooler (GCC)

In the cement industry, grate clinker cooler (GCCs) are widely used for heat recovery from the hot nodulized clinkers coming from the kilns. The heat transfer from the cooler influences the kiln's output indirectly, which is critical cement production. GCC minimizes clinker temperature through sensible heat which translates to energy recovery. Figure 1 represents a schematic material and energy flow of a typical grate clinker cooler system. The hot clinker exit the rotary kiln into a grate cooler at a temperature approximately 1400 ^{o}C and cooled to a temperature of 85 ^{o}C above ambient temperature.

The recuperated hot air from the cooler is used up as secondary air to aid the complete combustion of the fuel from the kiln burner. The remaining recovered heat is also used up as precalciner fuel (tertiary air). The waste heat is transferred to the environment through a cyclone or bag filter for de-dusting purposes. A quick quenching of the clinker must be achieved to facilitate a maximum yield of the compounds which support cement's hardening properties [19].

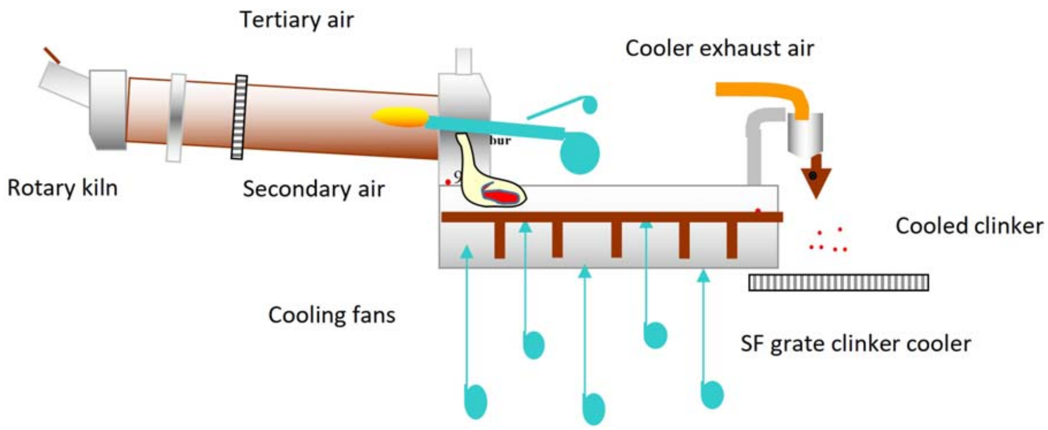

Figure 1: Schematic diagram of rotary kiln and Grate cooler

Four important roles of grate clinker cooler in the cement production process,

• The kiln cannot continue to function as a conveying system for clinker if grate cooler stop

• Cooling the clinker for safe handling afterward

• Preheating of secondary and tertiary air as combustion air

• Recovering of heat exchanged during hot clinker cooling.

The clinker can be cooled by various clinker coolers depending on the technology, namely grate, planetary, shaft, and rotary coolers. Worrell and Galitsky, [20] suggested that grate coolers have greater cooling and energy efficiency as opposed to planetary coolers. The clinker falls from the kiln into the cooler's reciprocating grates at approximately 1400 ° C and cooling air estimated at

30 ° C is sent through fans into compartments through the packed clinker bed. The clinker is cooled the cooler recovers the thermal energy and preheats combustion air as secondary and tertiary air. Cooler exhaust air is used up for raw material drying during raw mill operation. Clinker is quenched cooled to facilitate the compound's maximum yield which contributes to cement's hardening properties. The cooler's first grate is in inclination. The inclined first grate is quick to push the hot clinker with the aid of shock blaster or cannon, while others are moveable grates, moving at a reciprocating motion moderately to support good heat exchange within the cooler.

The general Grate clinker cooler specifications used in south west, Nigeria are summarized in Table 1. [6]

Specification	SF Crossbar grate cooler
Operation capacity (Kg/hr)	125,000
Cooler total length (m)	72
Operating Power (KW)	450
Cooling fans/Total airflow (kg/h)	5/252,500
Number of chamber or Compartments	5

For thermodynamic analysis of the cooler structure, the following assumptions were made:

• process is considered to be a continuous, steady-flow mechanism

• both temperature and pressure at ambient conditions

• ideal system for all gases within the process

• no heat is then transferred into the process

2. Thermodynamic Analysis

2.1 First Law of Thermodynamics performance of clinker cooler

The energy balance of the system, for which the sum of energy input of the system should be equal to the sum of the energy output of the process

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} \quad (1)$$

Regarding figure 2, the total sum of the input energy is defined as:

$$\sum \dot{E}_{in} = \dot{E}_{hot\ clinker\ feed\ in} + \dot{E}_{cooling\ air} \quad (2)$$

A total sum of the output energy is defined as:

$$\sum \dot{E}_{out} = \dot{E}_{clinker\ feed\ out} + \dot{E}_{Tertiary\ air} + \dot{E}_{Secondary\ air} + \dot{E}_{cooler\ exhaust} \quad (3)$$

The following calculations are used to estimate the performance of the cooler and the amount of energy that can be extracted from the cooler. Energy efficiency is the ratio of system energy output to input, which can be expressed as [16, 21]:

$$\eta_1 = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (4)$$

Secondary and tertiary air recovery energetic efficiency can be expressed as [2]:

$$\eta_{recovery,\,cooler} = \frac{\dot{E}_{Tertiary\ air} + \dot{E}_{Secondary\ air}}{\dot{E}_{hot\ clinker\ feed\ in}} \quad (5)$$

The cooling efficiency of a cooler can be expressed as:

$$\eta_{cooling\ efficiency} = \frac{\dot{E}_{Hot\ clinker\ in} - \dot{E}_{Hot\ clinker\ out}}{\dot{E}_{Hot\ clinker\ feed\ in}} \quad (6)$$

2.2 Second Law of Thermodynamics Analysis of clinker cooler

The total exergy of the material stream is calculated from equations (7 –9). The exergy efficiency of the energy stream is calculated from equation 9 for a typical clinker cooler system as shown in Figure 2.

The exergy analysis for the clinker cooler in the base case grate is almost identical to its counterpart in the energy analysis. 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 cooling the clinker generates entropy, resulting in loss of exergies.

$$\sum Ex_{in} = Ex_{clinker\ feed} + Ex_{cooling\ fan} \quad (7)$$

$$\sum Ex_{out} = Ex_{clinker\ out} + Ex_{Tertiary\ air} + Ex_{Secondary\ air} + Ex_{cooler\ exhaust} \quad (8)$$

$$\varphi = \frac{\sum Ex_{out}}{\sum Ex_{in}} \quad (9)$$

Secondary and tertiary air recovery exergetic efficiency can be expressed in equation 10 as [2]:

$$\eta_{xrecovery,\,cooler} = \frac{\dot{E}x_{Tertiary\ air} + \dot{E}x_{Secondary\ air}}{\dot{E}x_{hot\ clinker\ feed\ in}} \quad (10)$$

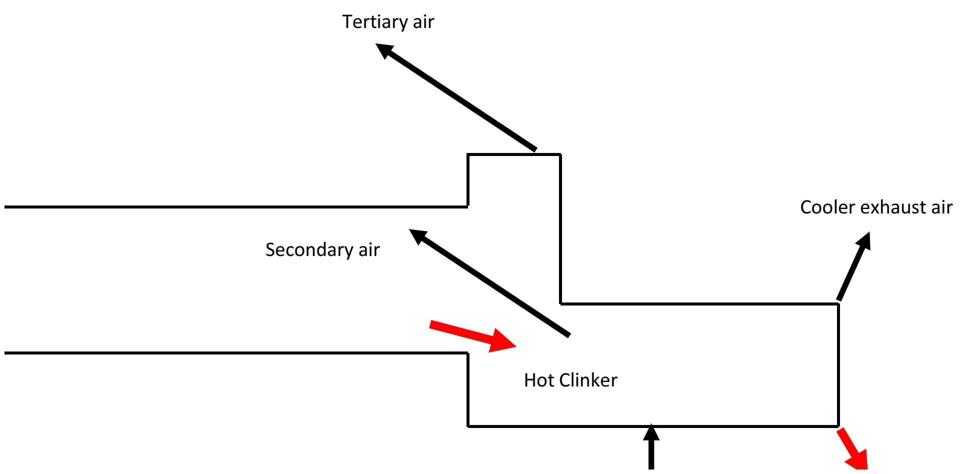

Figure 2: Schematic diagram of Grate clinker cooler

2.3 Modelling approach

Clinker cooler

The clinker cooler was simulated as a set of five heat exchangers. The first two heat exchangers represent secondary and tertiary air to 950 °C and 805 °C, respectively, while the last three heat-exchanger cool the clinker to 125 °C and the heat recuperated is used for the drying of raw meal in vertical roller mill. Before each heat exchanger, a part of the solid split out from the mainstream as recuperated hot gas rotary kiln operation while the noodle-like clinker; a combination of this four-component ($2CaO*SiO_2$, $3CaO*Al_2O_3$, $CaO*Al_2O_3*Fe$ and $3CaO*SiO_2$) as finished products.

Model Simulation.

ASPEN Plus version 10.0 was used as a process simulator in the study of grate clinker cooler content, energy, and exergy balance. The Aspen simulations provide the thermophysical properties of flux flows needed to analyze exergy and validate current mass and energy balance. The simulated model, Aspen Plus for the grate clinker cooler using data from a reference site. Several operating blocks of the simulation system used to build the whole section of the process as shown in figure 3. The concept for the method was designed for chemical compounds and the operating blocks with mass and energy balance. Table 2 summarizes the operating values comprising simulation data obtained from the reference plant [22].

Table 2: Plant and model data of grate clinker cooler

Parameters	Plant data (^oC)	Model data (^oC)
Clinker outlet temperature	125	127
Secondary air temperature	950	890
Tertiary air temperature	805	810
Exhaust air temperature	283	289

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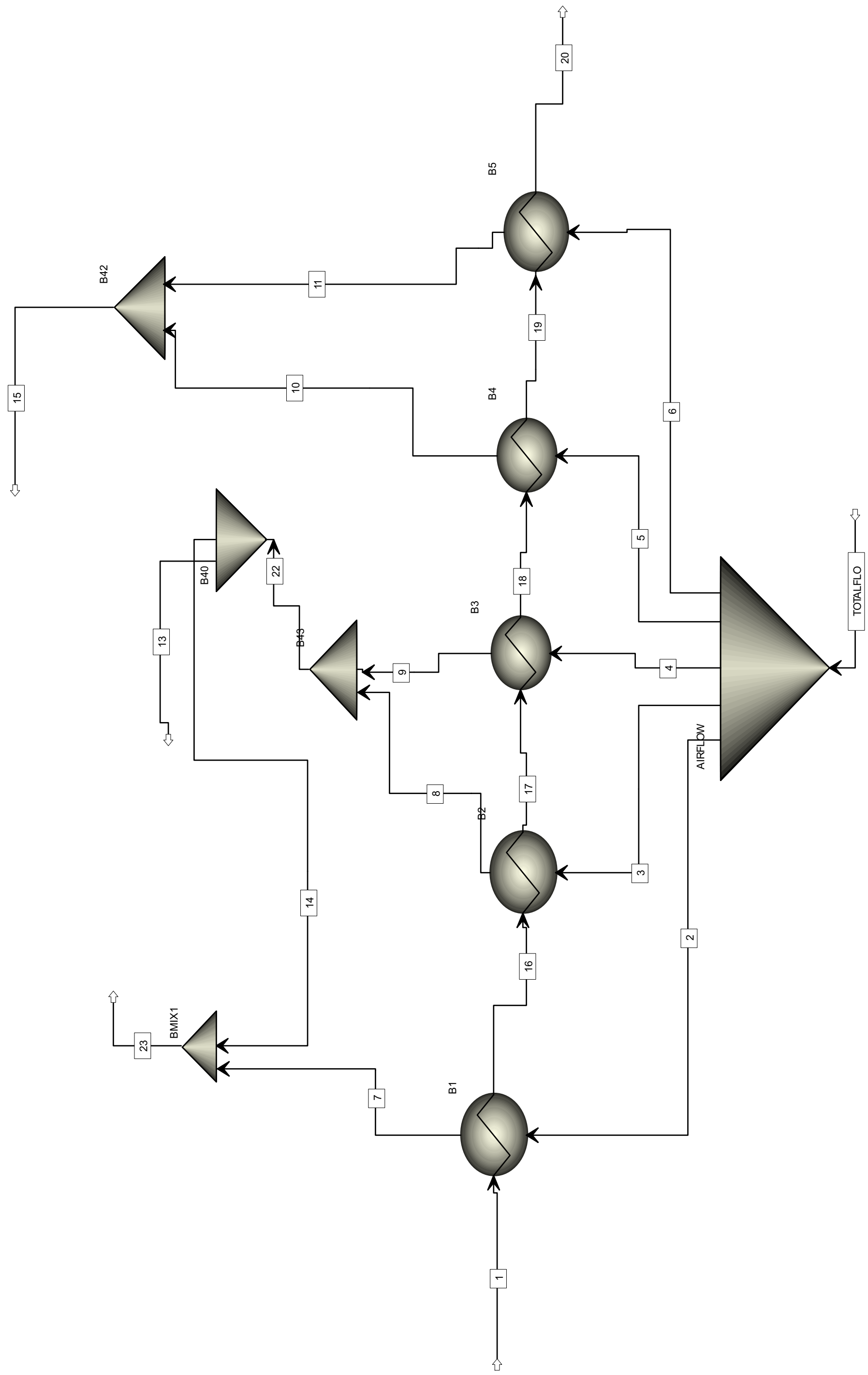

Figure 3: Grate clinker cooler flow sheet represented with Aspen Plus process model

3 Results and Discussions

3.1 First law Thermodynamic performance (Energy) of base case clinker cooler

The description for the reference case grate clinker cooler energy study using the plant data input and output in Table 3..Equation 4, which expresses the energy efficiency of the clinker cooler, and gives an estimate of 85.9% with a possibility of heat recovery from the cooler exhaust air. Equation 6 indicates that the system's energy recovery efficiency at 75.9 % is much lower. The recovered heat or energy used up for other purposes such as the clinkerization process will be considered as energy recovery efficiency. The system's energy recovery performance plays a bigger role in improving the clinker cooler, as its benefit boost converts into energy and cost savings.

Condition	Materials	Temperature, T, °C	Heat, Q kJ/kg cl	% Of energy	Energy efficiency of a cooler, Ƞ cooler, I (%)	Recovery efficiency, Ƞ recovery, cooler (%)
Input	Hot clinker	1398	1404.8	94.2	85.9	75.9
	Cooling air	25	86.2	5.8		
Output	Secondary air	898	598.9	46.8		
	Tertiary air	805	533.5	41.7		
	Cooled clinker	127	39.0	3.0		
	Cooler exhaust air	289	108.9	8.5		
	Unaccountable loss		210.8			

Table 3: Energy balance analysis over the Grate clinker cooler system. T_0 = 303.15 K

3.2 Second law Thermodynamic performance (Exergy) of base case clinker cooler

The summary of the thermodynamic performance of base case clinker cooler using theoretical input and output data in Table 3 and the results of the energy analysis. The clinker cooler's exergy efficiency is approximately 56.2 % from equation 10, which is similar to the system's energy output, this statistic reflects the overall performance for the system. The exergy calculated from both cooler exhaust air and as well as the cooled clinker is agreed to be recovered irrespective of end usage. The Grate clinker cooling system's exergy performance is comparatively poor compared to the energy efficiency of 85.9%. However, not all the energy stored inside the system is transformed into useful work in the given system environment. While in the state of equilibrium with the immediate environment, the clinker cooling exergy lost is considered as an irreversible process.

Equation 10 indicates that the system's exergy recovery performance is at 45.4 % much lower because the recovered exergy used at other phases of clinker production is only considered as recovery exergy efficiency. This also plays a similar role as energy recovery, giving the opportunity of improving the clinker cooler's performance.

Table 4: Exergy balance analysis over the Grate clinker cooler system. T_0 = 303.15 K.

Condition	Materials	Temperature, T, °C	Exergy, Ex (kJ/kg ck)	Exergy efficiency, Ƞ,1 (%)	Recovery exergy efficiency, Ƞ,2 (%)	Exergy losses (%)
Input	Hot clinker	1398	828.1	56.2	45.4	43.7
	Cooling air	25	-1.9			
Output	Secondary air	898	249.5			
	Tertiary air	805	126.2			
	Cooled clinker	127	11.6			
	Cooler exhaust air	289	76.2			
	Unaccountable loss		362.7			

3.3 Clinker cooler blowing density

Thus maximizing the air in the recovery zone also requires an increase at the first fans, to reduce power costs the overall cooling air should be reduced. Decide on a target temperature clinker necessary for the quality of cement but do not go below that temperature. With low total cooling air, an optimized cooler will achieve a low clinker temperature as shown in figure 4.

Typical figures: 1.8 to 2.2 Nm^3 / kg cl, old grate coolers up to 2.4 Nm^3 / kg cl without fixed inlet.

Clinker Bed Height

Maximize bed height for heat exchange rise. The typical limit is the average static pressure from the fan and the need to retain reserves to operate in the event of a kiln increase. New traditional coolers can hold 500-700 mm of bed. Monitor the height of the bed by measuring or setting marks from inspection windows for observation.

Higher airflow might be required to avoid static clinker areas that could lead to snowman formation. The purpose of a fixed inlet is to ensure that the clinker on the moving grate is well distributed. The following chambers would show a gradual decrease in the blowing rate.

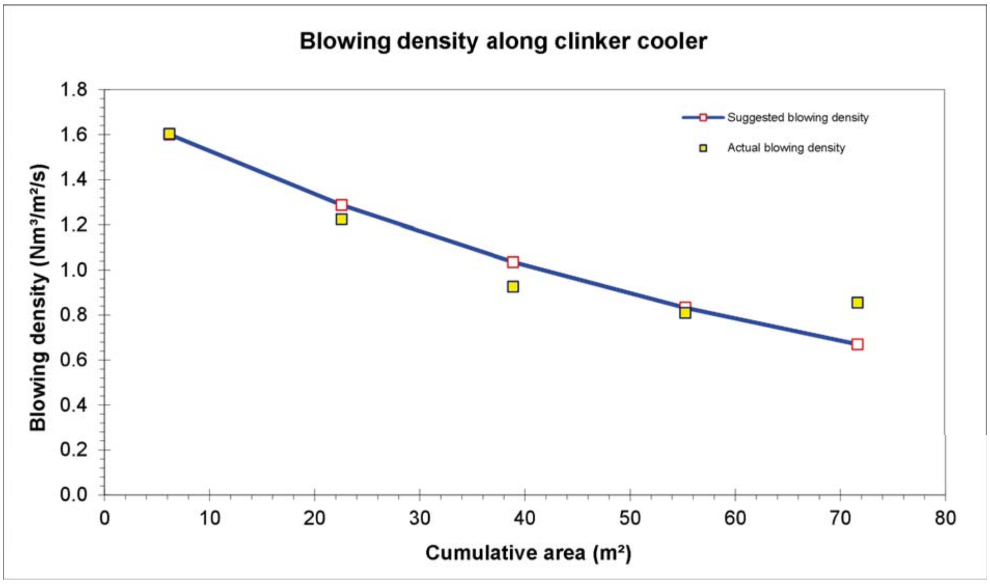

Figure 4: Grate clinker cooler blowing density.

3.4 Changing the operational parameters: mass flow rate of cooling air and clinker

3.4.1 Change in Clinker temperature and Cooler exhaust air temperature

The result of variability in the clinker mass flow rate and cooling air mass flow rate is obvious in the cooler as shown in Figure 5, Increasing and reducing the clinker mass flow rate respectively would produce a change in exit clinker temperature. A rise in 5 % in the clinker mass flow rate with constant maximum cooling airflow, will lead to an increase in 3.5 % and 2.5 % clinker exit temperature and cooler exhaust air temperature respectively. Although this may lead to a reduced fuel or energy used for the kiln but to the detriment of the clinker conveying system with a ripple effect in cement milling operations. While Increasing and decreasing the cooling air mass flow rate would produce a change in exit clinker temperature. A rise in 5 % in the cooling air mass flow rate with a constant clinker mass flow rate, leads to a decrease in 0.5 %, 2%, and 2.5 % clinker exit, tertiary and cooler exhaust air temperature respectively.

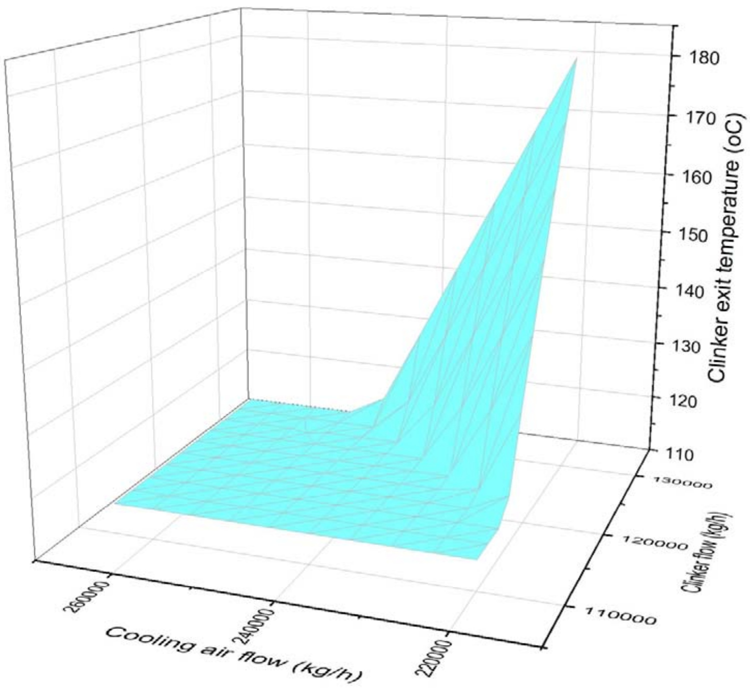

Figure 5: Effect of cooling airflow rate and clinker flow rate on clinker exit temperature

3.4.2 Change in Secondary air temperature

The effect of variability in the clinker mass flow rate and cooling air mass flow rate is pronounced in the grate cooler as shown in Figure 6, Increasing and decreasing the clinker mass flow rate respectively may lead to a change in secondary air temperature. A rise in 5 % in the clinker mass flow rate with constant maximum cooling airflow, would produce a rise in 4.5 % secondary air temperature. And it corresponds to a 1.5% reduction in fuel or energy used for the kiln operations but to the detriment of the clinker conveying system with a ripple effect in cement milling operations. While Increasing and decreasing the cooling air mass flow rate would produce a change in exit clinker temperature. A rise in 5 % in the cooling air mass flow rate with a constant clinker mass flow rate, leads to a decrease of 2.5 % and 1.5 % secondary and tertiary temperature respectively. This would, in turn, cause operation instability and a 2 % increase in fuel used by the rotary kiln.

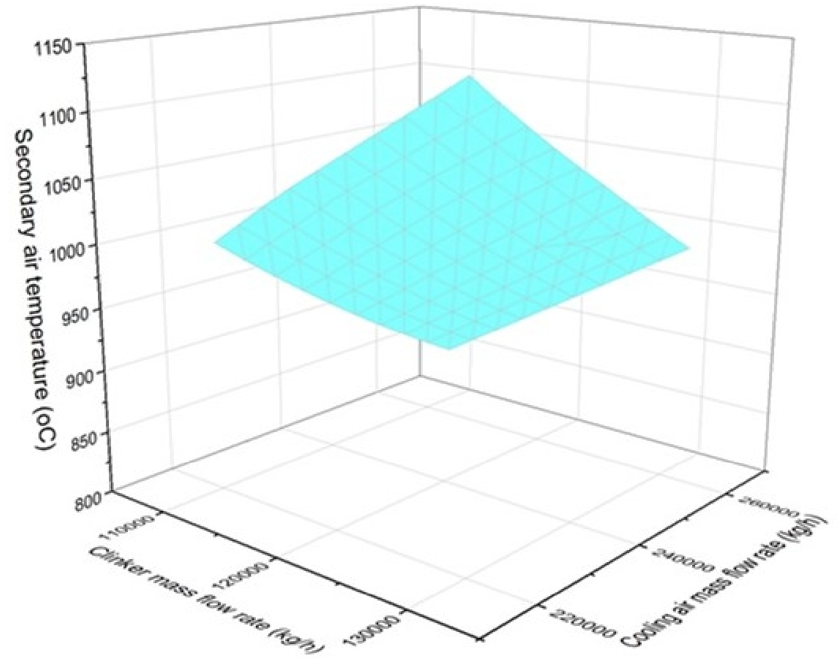

Figure 6: Effect of Clinker mass flow rate and cooling air mass flow rate on Secondary air temperature

3.4.3 Change in Exergy efficiency

The impact of variation in the clinker mass flow rate and cooling air mass flow rate is established in the clinker cooler as shown in Figure 7, Increasing and decreasing the clinker mass flow rate respectively would cause a change in exergy efficiency and energy recovery of the grate cooler system. A rise in 5 % in the clinker mass flow rate with constant maximum cooling airflow, would produce a rise in 2.2 % and 1.7 % exergy performance and energy recovered respectively. And it corresponds to a 1.5% reduction in fuel or energy used for the kiln operations. An increase in the recovered heat is a function of a cooling air and clinker heat exchange as energy utilization which corresponds to exergy efficiency. A rise in 5 % in the cooling air mass flow rate with a constant clinker mass flow rate, leads to a reduction of 2.5 % and 1.5 % exergy efficiency and energy recovery respectively. This would, in turn, cause operation instability and a 2 % increase in fuel used by the rotary kiln.

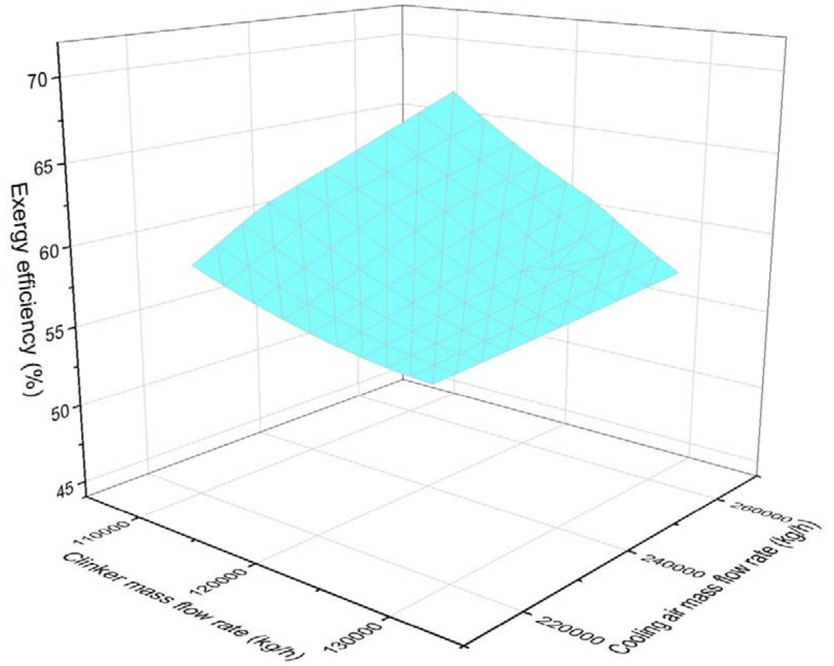

Figure 7: Effect of Clinker mass flow rate and cooling air mass flow rate on Exergy efficiency of grate cooler

4. Conclusions

The work was primarily conducted to determine the impact of clinker cooling process operating parameters with the effect of secondary air, tertiary air, and cooler exhaust air on thermodynamic (first and second law) efficiencies. Equally for the development, energy and CO_2 savings are measured. The findings of the study shall be summarized as follows:

I. The efficiency of both first and second law thermodynamics is calculated at 85.9 % and 56.2 % respectively. Whereas the grate cooler's energy and exergy recovery efficiencies stand respectively at 75.9 and 45.4 %.

II. When the clinker mass flow rate rises by 5 %, the clinker cooling process energy and energy recovery efficiencies increase by 2.1 % and 1.9 % respectively. The average increase in efficiencies for exergy performance and recovery for the same case is 2.2 % and 1.7 % respectively.

III. For both energy conservation and recovery, the grate clinker cooler process increases by 1.8 and 2 % for each 5 % decrease in the cooling mass flow rate. In the case at hand, exergy performance and recovery improved respectively by 1.9 and 1.5 %.

IV. The standard grate clinker cooling system achieves 8.5 % and 9.2 % of energy and exergy recovery efficiencies with the help of heat recovery from exhaust air.

V. It was discovered that significant emission reductions of 0.23 % can be achieved by raising both secondary air and tertiary temperature via optimization of the grate cooler parameter, resulting in a reduction of fuel for kiln operations.

According to the findings, the cement industry has a variety of feasible ways of reducing energy usage and exergy loss. It is possible to achieve a reduction in fuel consumption in the rotary kiln with carbon dioxide (CO_2) by reducing various losses in the grate clinker cooler. Improved combustion efficiency with the aid of good secondary and tertiary air temperature as the main parameters on the efficiency of the system according to the results. However, the cooling air ambient temperature variable should also be considered in subsequent work. Again, these systems provide tremendous potential for energy savings, and the approach used can also aid informed decision-making to enhance process efficiency.

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