



## **New Method of Materials Flow Calculation for Double-String SLCI Type Cement Plant (Part 1: The Whole Clinker Plant)**

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### **Highlights:**

- New approach in calculating detail materials and heat flows in a double strings separate and in-line calciners (SLC-I) type cement plant, presenting in two parts (part-1 and part-2).
- Using least square method, based on the measurement of kiln feed and gas temperatures, for solving the overdetermined system equations proposed.
- With this method the detailed flow of materials and heat as well as the separating efficiency of each cyclone that cannot be measured directly in the plant during operation can be approached with the error of heat balance is less than 1%.
- The obtained results can be used for operational control need, new equipment design and analysis, numerical study of suspension pre-heater, and even modification of equipment.
- This part 1 focuses on the heat and materials flows of the whole clinker plant main equipment including their impact on the operational practices.

**Abstract.** Materials flow values are instrumental in many industries for controlling and simulating processes, designing new equipment as well as modifying existing plants. They are sometimes impossible to determine by direct measurement in an operating plant due to the very high temperatures. This study attempted to overcome the difficulties associated with this measurement by proposing a new method to calculate materials flow of a double-string suspension preheater type of cement plant with separate line and in-line calciners (SLC-I), with heat balance error less than 1%. This study was divided into two sequential parts, with the first part presented in this paper. The methodology of the first part was to solve the conservation law of the main clinker plant equipment, supported by Bogue's equation, the heat of calcination, and the thermodynamic properties of the related materials. The least-square method was employed for solving the overdetermined system equations obtained in the second part. The results of the first part were: the ratio of heat formation to specific heat consumption was 52.13% (> 50%), and the gas exhausted from the plant yielded more than 117 MW heat equivalent, which can potentially be recovered for electricity production.

**Keywords:** *calciner; electricity production; heat ratio; materials flow; overdetermined system.*

## 1 Introduction

Generally, a modern cement plant consists of a suspension preheater (SP), calciners, a kiln, and a clinker cooler. Although modern cement plants currently often utilize renewable energy as the energy source, the specific heat consumption, both thermal and electric, in cement plants is still high. In order to improve energy consumption in cement plants it is essential to conduct a precise heat consumption analysis in order to be able to optimize heat conservation and efficiency, as proposed by Rivendra, *et al.* [1]. As stated by Anantharaman [2], investigating actual heat consumption and ways to conserve heat must always be carried out in cement industries to be more efficient. Therefore, energy auditing at a cement plant is always conducted to identify opportunities to reduce heat consumption, improve productivity, and plan conservation efforts that should be conducted, as well as determine the action plan related to environmental issues, as mentioned by Avami & Sattari [3] and Parinya & Unchalee [4]. Based on audit results, Aly [5] proposed several methods to improve heat conservation in cement plants, such as improving the quality of the kiln feed, utilization of waste materials, modifying the cyclone, enhancing the control system, utilizing waste heat, and improving the combustion process in the kiln.

Several works on waste materials utilization have been reported, such as industrial waste by Nørskov *et al.* [6], biomass by Mikulčić, *et al.* [7] and Chao, *et al.* [8], and tires in the VDZ Activity Report [9]. Another important issue is the utilization of alternative materials as clinker substitute both to increase cement production by reduction of the clinker to cement ratio and to reduce the production cost, e.g. steelmaking slag reported by Kourounis [10], fly ash by Varma & Gadling [11], pozzolanic material by Ghassan, *et al.* [12], limestone and micro-silica by Allahverdi & Salem [13], and lime-based mortar by Mydin [14].

Several works on heat waste conservation have been reported, such as the utilization of waste heat from the preheater and cooler for producing electric power reported by Ayu, *et al.* [15] and Hendi & Sigit [16]. More than 30 units of waste heat recovery power generation (WHRPG) were established by Kawasaki Plant System Ltd. [17] around the world by utilizing heat recovered from preheater and grate cooler exhaust gases with a ratio of generated electricity (kWe) to cement production (tons) in the range of 0.5 up to 1.66 kWe/ton. A review on the possibility of using four standard power generation cycles, i.e. the steam Rankine cycle, organic Rankine cycle, Kalina cycle, and supercritical CO<sub>2</sub> cycle, in cement plant heat recovery has been reported by Ali & Mohammad [18].

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The results showed that the Kalina cycle has significantly higher efficiency than the steam cycle and the ORC. Moreover, as the critical point of CO<sub>2</sub> is very low compared with other fluids, these cycles can run within relatively lower temperature ranges and are more green than other cycles.

Heat and exergy analysis methods have been studied in some kilns by Parmar, *et al.* [19], preheater and calciners by Anthony, *et al.* [20]. Using thermodynamic analysis of processes in a raw mill was reported by Ahmet & Ahmet [21], and heat transfer analysis of exiting preheater hot gas for heat conservation goals by Sasanka & Srinivasa [22], who found that there are many opportunities left unexplored. Another recently proposed method for thermal waste utilization is the integration with renewable heat systems to produce other products and electricity. For example, waste heat from the produced clinker by a cement plant can be used to supply the required heat for the NH<sub>3</sub> decomposition reaction. As proposed by Firman & Mohammad [23] and Firman, *et al.* [24], the product of this decomposition, H<sub>2</sub>, can partially substitute the main fuel required by the cement plant to reduce the utilization of carbon-based fuel and CO<sub>2</sub> emissions as well. NH<sub>3</sub> can be sourced from the proposed integrated N<sub>2</sub> production/NH<sub>3</sub> synthesis system, and a power generation process was proposed to produce NH<sub>3</sub> efficiently. With this integrated system, part of the electricity demand of the clinker plant, which is normally supplied by a fossil fuel power plant, can also be substituted.

All of the abovementioned reports require an understanding of the materials flow in the plant of each case study. However, this is sometimes impossible to gather from direct measurement due to the high temperatures and other conditions in the operating plant. It was the aim of this study to overcome the difficulties associated with this measurement. Thus, the main objective of this research was to develop a new method for detailed plant materials flow evaluation of SLC-I type cement clinker plants, with heat balance error less than 1%, without performing direct mass flow rate measurements on the related equipment. The study was divided into two sequential parts, with the first part presented in this paper. The methodology used in the first part was solving the conservation law of the main clinker plant equipment, supported by Bogue's equation, the heat of calcination as well as the thermodynamic properties of the related materials. The least-square method was employed for solving the overdetermined system equations obtained in the second part. Through this proposed method, the detailed value of the mass flow rate can be calculated for each main piece of equipment. Finally, the mass flow rate in each cyclone can be approximated using these calculated parameters. Through this study, we also expected to contribute to providing more detailed data required for system equipment design, modification, control of plant operation, process simulation, and detailed heat auditing. In the first part of this presentation, the discussion is limited to the evaluation of the materials flow in

the whole clinker plant as a large system consisting of SP and calciners, kiln, and clinker cooler.

## 2 Methods

### 2.1 Methodology

In general, a cement clinker plant is equipped with measuring devices and instrumentation to monitor operating parameters such as temperature and pressure. A weighing feeder is applied for measuring the mass flow rate of the kiln feed and the coal. An oxygen content monitoring system is placed in the kiln inlet and SP gas outlets. An obstruction meter for measuring airflow is generally available at the control system of the plant. In addition, the flow of return dust from the unseparated kiln feed leaving the top cyclone of each string is also measured. This allows estimation of the separation efficiency of the top cyclone. The methodology used in this paper was the implementation of the abovementioned measurement results of the main process parameters to the conservation of mass and heat in each of the main pieces of equipment and the relevant supporting empirical equations, such as Bogue's equation of heat formation, as mentioned in Duda [25]; Chatterjee [26], Philip, *et al.* [27], Cement Manufacturing Services [28], the heat of calcination proposed by Fidaros [29], and the empirical equation of heat loss as well as thermodynamic properties related to the clinker burning process materials proposed by FLSmidth [30]. These equations are interdependent and can be formed into linear algebraic equations and solved simultaneously.

### 2.2 Conservation Equations for the Whole Clinker Plant

A schematic diagram of the studied cement clinker plant is presented in Figure 1. It consists of three main pieces of equipment, i.e. a suspension preheater (SP), calciners, a kiln, and a clinker cooler. The SP and calciners are of the two-string type, where each string has four series of cyclone separators and one calciner. Based on this figure, the flow of materials entering into the plant consists of kiln feed through top cyclones of strings A and B ( $m_{kf}$ ), cooling air supplied to the clinker cooler ( $m_{cool-air}$ ), and fine coal as main fuel, including its transporting air ( $m_{coal}$  and  $m_{tr-air}$ ). The flow of materials exiting from the plant consists of clinker product ( $m_{cli}$ ), evaporated water content of the kiln feed ( $m_{H2O-kf}$ ), unseparated dust of the kiln feed from the top cyclones ( $m_{unsep-kf.1}$ ), the mass of coal combustion process gas or flue gas ( $m_{hg}$ ), the mass of gas resulted from the kiln feed calcination process ( $m_{gas-kf}$ ), and excess cooling air from the clinker cooler ( $m_{exc-air}$ ). From Fig. 1, with the assumption that the plant condition is stable and considering the chemical composition of the kiln feed and fuel (fine coal)

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presented in Tables 1 and 2, if all ash contained in the fuel forms clinker, the mass flow balance of the plant can be written in Eq. (1):

$$m_{kf} + m_{coal} + m_{tr-air} + m_{cool-air} = m_{cli} + m_{H_2O-k} + m_{unsep-kf-} + m_{hg} + m_{gas-kf} + m_{exc-a} \quad (1)$$

The production of clinker ( $m_{cli}$ ) can be evaluated by Eqs. (2) to (10b):

$$m_{kf} = m_{kf-A} + m_{kf-B} \quad (2)$$

$$m_{coal} = m_{coal-k} + m_{coal-ILC} + m_{coal-SLC} \quad (3)$$

$$m_{tr-air} = m_{tr-air-k} + m_{tr-air-ILC} + m_{tr-air-SLC} \quad (4)$$

$$m_{cli} = m_{sep-kfc-A} + m_{sep-kfc-B} + m_{ash} \quad (5)$$

$$m_{sep-kfc-A} = (1 - LOI_{kf}) * m_{sep-kf-A} \quad (5a)$$

$$m_{sep-kfc-B} = (1 - LOI_{kf}) * m_{sep-kf-B} \quad (5b)$$

$$m_{sep-kf-A} = \eta_{1A} * m_{kf-A} \quad (5c)$$

$$m_{sep-kf-B} = \eta_{1B} * m_{kf-B} \quad (5d)$$

$$m_{ash} = ash_{coal} * m_{coal} \quad (6)$$

$$m_{H_2O-kf} = H_2O_{kf} * (m_{sep-kf-A} + m_{sep-kf-B}) \quad (7)$$

$$m_{unsep-kf-1A} = (1 - \eta_{1A}) * m_{kf-} \quad (8a)$$

$$m_{unsep-kf-1} = (1 - \eta_{1B}) * m_{kf-} \quad (8b)$$

$$m_{hg} = (m_{hg-A} + m_{hg-B}) = (1 - ash_{coal}) * m_{coal} + m_{tr-a} + m_{cool-air} - m_{exc-air} \quad (9)$$

$$m_{gas} = m_{gas-kf-A} + m_{gas-kf-B} \quad (10)$$

$$m_{gas-kf-A} = (LOI_{kf} - H_2O_{kf}) * m_{sep-kf-A} \quad (10a)$$

$$m_{gas-kf-B} = (LOI_{kf} - H_2O_{kf}) * m_{sep-kf-B} \quad (10b)$$

The clinker plant heat balance can be written as:

$$En_{kf} + En_{coal} + En_{air} + En_{coal-com} = En_{cli} + En_{hg} + En_{vapor-kf} + En_{unsep-kf} + En_{gas} + En_{form} + En_{evap} + En_{exc-air} + Q_{loss} \quad (11)$$

The flow of heat entering the plant consists of:

1. Heat flow of kiln feed entering to the SP through the A and B strings:

$$En_{kf} = (m_{kf-A} + m_{kf-B}) * h_{kf}(T_{kf}) \quad (12)$$

2. Heat flow of coal entering the kiln:

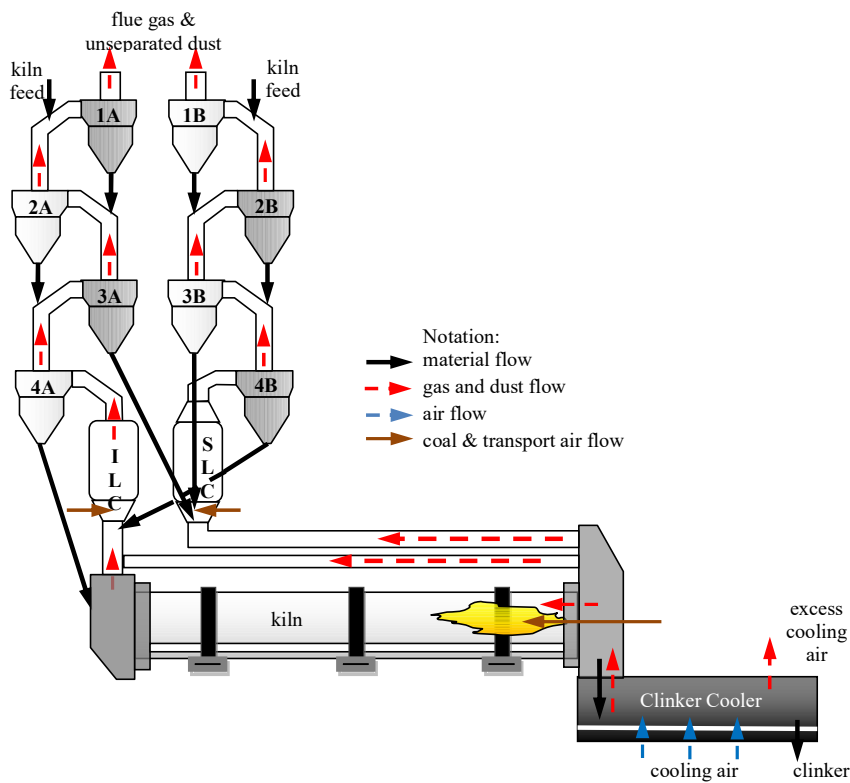
$$En_{coal} = (m_{coal-} + m_{coal-ILC} + m_{coal-SLC}) * h_{coal}(T_{coal}) \quad (13)$$

3. Heat of air entering the plant through cooler and kiln, ILC and SLC burners:

$$En_{air} = (m_{cool-air} + m_{tr-air-k} + m_{tr-air-ILC} + m_{tr-air-SLC}) * h_{air}(T_{air}) \quad (14)$$

4. Heat flow resulted by the coal combustion process:

$$En_{coal-comb} = (m_{coal-} + m_{coal-ILC} + m_{coal-SLC}) * NHV_{coal} \quad (15)$$



**Figure 1** Schematic of clinker plant mass flow.

The flow of heat exiting the plant's main equipment, with the assumption that the temperature of the dust and gas exiting from the SP is equal  $T_{hg-1A}$  and  $T_{hg-1B}$ , consisting of:

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1. Heat flow of the clinker product at temperature  $T_{cli}$ :

$$En_{cli} = m_{cli} * h_{cli}(T_{cli}) \quad (16)$$

2. Heat flow of coal combustion process gas from the top cyclone of the SP, Eqs. (17a) and (17b):

$$En_{hg} = En_{hg-A} + En_{hg-B} \quad (17)$$

$$En_{hg-A} = ((1 - ash_{coal}) * (m_{coal-k} + m_{coal-ILC}) + (m_{tr-air-k} + m_{tr-air-IL}) + (m_{comb-air-k} + m_{comb-air-ILC})) * h_{hg}(T_{hg-1A}) \quad (17a)$$

$$En_{hg-B} = ((1 - ash_{coal}) * (m_{coal-SLC}) + m_{tr-air-SLC} + m_{comb-air-ILC}) * h_{hg}(T_{hg-1B}) \quad (17b)$$

3. Heat of vapor resulted from the evaporation of water content in the kiln feed:

$$En_{vapor-kf} = En_{vapor-kf-A} + En_{vapor-kf-B} \quad (18)$$

$$En_{vapor-kf-A} = H_2O_{kf} * m_{sep-kf-A} * h_{vapor}(T_{hg-1A}) \quad (18a)$$

$$En_{vapor-kf-B} = H_2O_{kf} * m_{sep-kf-B} * h_{vapor}(T_{hg-1B}) \quad (18b)$$

It is noted that the mass of vapor resulted from the coal combustion process is included in the flue gas,  $m_{hg}$ .

1. Heat flow of the unseparated kiln feed from the top cyclone of the SP:

$$En_{unsep-kf} = En_{unsep-kf-1} + En_{unsep-kf-1B} \quad (19)$$

$$En_{unsep-kf-1} = m_{unsep-kf-1} * h_{kf}(T_{hg-1A}) \quad (19a)$$

$$En_{unsep-kf-1} = m_{unsep-kf-1B} * h_{kf}(T_{hg-1B}) \quad (19a)$$

2. Heat of the kiln feed gas resulted from the calcination process, which is dominated by CO<sub>2</sub> exiting from the SP:

$$En_{gas-kf} = m_{gas-kf-A} * h_{CO2}(T_{hg-1A}) + m_{gas-kf-B} * h_{CO2}(T_{hg-1B}) \quad (20)$$

3. Heat from clinker formation, where the value can be approached by Bogue's equation multiplied by the rate of clinker production, as written in Duda [25], Chatterjee [26], Philip *et al.* [27], Cement Manufacturing Services [28]:

$$En_{form} = m_{cli} * \{7.646 * (CaCO_3)_{kf} + 6.48 * (MgCO_3)_{kf} + 4.11 * Al_2O_3)_{kf} - 5.176 * (SiO_2)_{kf} - 0.59 * (Fe_2O_3)_{kf}\} \quad (21)$$

where  $(CaCO_3)_{kf}$ ,  $(MgCO_3)_{kf}$ ,  $(Al_2O_3)_{kf}$ ,  $(SiO_2)_{kf}$ , and  $(Fe_2O_3)_{kf}$  are the mass basis percentages of each substance contained in the kiln feed respectively. It should be noted that for each kilogram of produced clinker, the heat from clinker formation consists of calcination heat ( $En_{calc}$ ), which is endothermic, and the heat of sintering ( $En_{clink}$ ), which is exothermic. Hence, the heat from

clinker formation is the difference between the calcination and the sintering heat.

Calcination is the decomposition of  $\text{CaCO}_3$  to form  $\text{CaO}$  and  $\text{CO}_2$ , while sintering is the reaction of oxides forming in the clinker. Sintering occurs in a temperature range from 1250 to 1450 °C, thus it occurs in the kiln only. Fidaros *et al.* [29] proposed that the heat of the calcination reaction, which can occur in the SP, calciners, and kiln, is considered constant at 425 kcal/kg of  $\text{CaCO}_3$ . Using this value, the sintering heat per kg of produced clinker can be calculated.

1. The evaporation heat of the water content in the kiln feed and coal exiting from the SP:

$$En_{evap} = (m_{H_2O-k} + m_{H_2O-coal}) * h_{fg} \quad (22)$$

where  $h_{fg}$  is the enthalpy of the water evaporation process and  $m_{H_2O-coal} = H_2O_{coal} * m_{coal}$  is the coal water content, where  $H_2O_{coal}$  is the percentage by mass of water in the fine coal used in the clinker plant.

2. The heat flow from the excess cooling air, where its temperature is  $T_{exc-air}$ :

$$En_{exc-a} = m_{exc-air} * h_{air}(T_{ex} \quad ) \quad (23)$$

3. The heat loss by radiation and convection ( $Q_{loss}$ ) through the overall surface area of the main equipment  $A_{tot}$ , which can be approached by FLSmidth's formula proposed in [30]:

$$Q_{loss} = A_{tot} * [4 \cdot 10^{-8} (T_{surf}^4 - T_{amb}^4) + 80.33 * \left( \frac{T_{surf} - T_{amb}}{2} \right)^{-0.724} (T_{surf} - T_{amb})^{1.333}] \quad (24)$$

The enthalpy of the substances can be calculated if their temperature is known, based on design data or by measurement, and using Eq. (25):

$$h(T) = \int_{T_1}^{T_2} C_p dT = A + B \cdot T^2 \cdot 10^{-6} + C \cdot T^3 \cdot 10^{-9} \quad (25)$$

where  $C_p$  is the specific heat of substance and  $T_1$  is the reference temperature. The value of constants  $A$ ,  $B$ , and  $C$  for limited substances and gas refer to FLSmidth [30]. Calculating the flows of mass and heat in the SP, calciners, kiln, and clinker cooler is very useful for plant operation monitoring and parametric design as well as equipment modification. Their formulations are derived one by one in Appendix 1.

### 2.3 Materials

The fuel used was fine coal, which was introduced into the plant through ILC, SLC, and kiln burners. Table 1 shows the average chemical composition of the kiln feed and the fine coal used in the studied cement plant.



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**Table 1** Chemical composition of kiln-feed and fine coal.

Kiln feed composition	% of mass	Coal composition	% of mass
CaO	43.96	H <sub>2</sub>	4.24
MgO	0.65	C	73.06
SiO <sub>2</sub>	13.09	N <sub>2</sub>	4.56
Al <sub>2</sub> O <sub>3</sub>	3.22	O <sub>2</sub>	8.15
Fe <sub>2</sub> O <sub>3</sub>	2.24	S	0.51
H <sub>2</sub> O	1.0	H <sub>2</sub> O	4.50
LOI (CO <sub>2</sub> , Na <sub>2</sub> O, K <sub>2</sub> O&SO <sub>3</sub> )	35.84	Ash+dust	5.49

### 3 Results and Discussion

#### 3.1 Operation Data Parameters

A cement factory plant in Indonesia, Padang Plant 5, was used as a case study. Daily average data at normal operation capacity was used for the current analysis. The data were taken from the control room and some direct field measurements. The data for the input values can be classified into a number of groups (i.e. kiln feed, fine coal, SP and calciners, kiln, and grate cooler). The chemical composition of the kiln feed and fine coal used were presented in Table 1. The kiln feed supplied to strings A and B was 270 and 254 tons per hour (TPH), respectively. The total fine coal consumption was 49.16 TPH with 5,000 kcal/kg of net heating value (NHV) and distributed 22.33, 9.13, and 17.7 TPH to the SLC, ILC, and kiln burners respectively with related transporting air of 6,304; 1,410; and 5,611 Nm<sup>3</sup>/h each. Based on the return dust flow measurement, the separation efficiency of the top cyclones of ±93.5% was used as the first estimation value and was iterated during the plant mass and heat balance calculation.

The remaining oxygen percentage in the kiln and the top cyclones of the A and B string outlets were measured at 1.5%, 2.5%, and 2%, respectively, and were used to estimate the kiln excess air and SP false air as proposed by FLSmidth [30]. The average value of the ambient temperature was 33 °C. Based on these main operation data, the production of clinker, flue gas, and kiln feed gas was evaluated using Eqs. (2) to (10). Meanwhile, the operation data of kiln, grate cooler, and SP (cyclones and calciners) were gathered by direct measurement and the general assumption parameter values used in cement plant operations are given in Tables 2, 3, and 4. Other parameters that cannot be measured directly in the plant are the mass flow rates of re-circulated dust from the cooler to the kiln, ILC, and SLC. In this study, their values were assumed at 5%, 1% and 2.3% of produced clinker, respectively.

**Table 2** Input data for kiln and cooler.

Parameter	Unit	Kiln	Grate Cooler
Average kiln surface temperature	(°C)	317.7	-
Kiln diameter	(m)	5.6	-
Length of kiln	(m)	85	-
ILC tertiary air duct surface temperature	(°C)	117.1	-
SLC tertiary air duct surface temperature	(°C)	127.0	-
Grate cooler surface area	(m <sup>2</sup> )	-	1007.84
Clinker product temperature	(°C)	-	120
Clinker cooling air supplied	(m <sup>3</sup> /min)	-	382.53
Average cooler surface temperature	(°C)	-	106.1

**Table 3** Input data for each cyclone (C) of string A of SP and ILC.

Parameters	Unit	C1A	C2A	C3A	C4A	ILC
Average surface temperature	(°C)	83.8	194.2	84.0	86	116.0
Total surface area	(m <sup>2</sup> )	445.8	499.9	504.9	500.0	413.39
Hot gas inlet temperature	(°C)	602	742	861	862	1000
Hot gas exit temperature	(°C)	385	602	742	861	862
Fine coal feed to ILC	(kg/s)	-	-	-	-	2.536
Coal transporting air flow rate	(m <sup>3</sup> /s)	-	-	-	-	0.392
Separated kiln feed temperature	(°C)	377	593	738	860	-
Estimated return dust from kiln	(%)	-	-	-	-	20
Estimated calcined kiln feed exit SP	(%)	-	-	1.11	85.30	85.01

**Table 4** Input data for each cyclone of string B of SP and SLC.

Parameters	Unit	C1B	C2B	C3B	C4B	SLC
Average surface temperature	(°C)	75.9	80.3	198.8	226	116
Total surface area	(m <sup>2</sup> )	455.8	499.9	376.5	455.3	533.30
Hot gas inlet temperature	(°C)	594	736	867	840	880
Hot gas exit temperature	(°C)	390	594	694	833	840
Fine coal feed to SLC	(kg/s)	-	-	-	-	6.203
Coal transporting air flow rate	(m <sup>3</sup> /s)	-	-	-	-	1.751
Separated kiln feed temperature	(°C)	386	592	735	830	-
Estimated calcined kiln feed exit SP	(%)	-	-	0.10	56.3	54.95

In general, a cement clinker plant is equipped with measuring devices and instrumentation to monitor operating parameters such as temperature and pressure. Feeder weighing is applied for measuring the mass flow rate of the kiln feed and the coal. An oxygen content monitoring system is placed in the kiln inlet and SP gas outlets. An obstruction meter for measuring air flow is generally available at the control system of the plant. In addition, the flow of dust returning from the unseparated kiln feed leaving the top cyclone of each string was also measured. This allows estimation of the separation efficiency of the top cyclone by using Eq. (8a) and (8b). With the measurement results of these instrumentation devices, and using Eqs. (1) to (10), the materials flow of the whole clinker plant can be determined.

### 3.2 Plant Materials and Heat Flows

Based on the available input data, the mass and heat balances for the whole case-study plant was evaluated using Eqs. (11) to (25). The results of materials flow calculation are presented per kg of produced clinker. With a total kiln feed mass of 524 TPH for the studied plant and an estimated top cyclone separation efficiency of around 93.5%, the clinker production was approximately 7,549 tons per day (TPD), or 314.54 TPH. All materials and heat flows in the clinker plant per unit mass of produced clinker are given in Table 5.

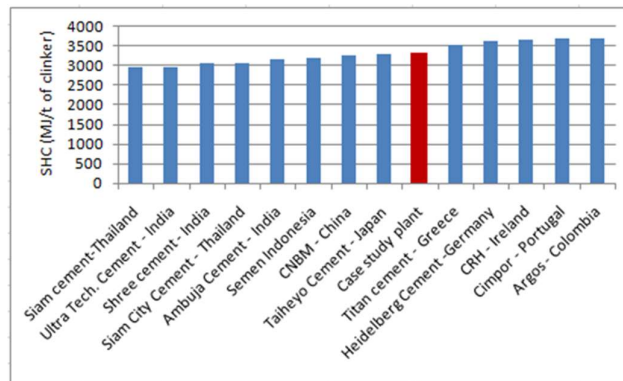
**Table 5** Materials and heat flows per kg of produced clinker for the whole clinker plant.

Parameter	Inlet		Outlet	
	mass(kg)	heat(kcal)	mass(kg)	heat(kcal)
Kiln feed supplied to the plant	1.6656	22.775	-	-
Fine coal consumption	0.1563	790.717	-	-
Cooling air and coal transport air	3.1486	26.880	-	-
Clinker production	-	-	1.0000	23.098
Combustion gas including excess air	-	-	1.8399	181.343
Kiln feed gas	-	-	0.5492	50.094
Return dust	-	-	0.1073	9.950
Clinker heat formation	-	-	-	412.200
Convection & radiation loss	-	-	-	57.190
Water evaporation process	-	-	-	14.160
Excess cooling air from cooler	-	-	1.4741	91.982
Total of materials and heat flows	4.9705	840.372	4.9705	840.017

Since the calculation results are expressed per kilogram of produced clinker, for precision purposes, the mass rate is given in four significant digits, while for the heat flow rate three significant digits are sufficient. From the evaluation results, it appears that the difference between the rate of outgoing and incoming heat flows of the whole cement plant can be neglected. Hence, it can be considered an acceptable result from an engineering point of view. From Table 5, the specific heat consumption (SHC) in the plant was close to 790.717 kcal/kg of produced clinker, or equal to 3307 MJ/t of clinker. This value is reasonable for the recent operation of cement plants in Indonesia, as reported by Alfi, *et al.* [31]. It was slightly higher than the result found by Parinya & Unchalee [4] in a cement plant in Thailand due to different operational parameters. Further comparison with the average audit results of several cement factories in the world, presented in Figure 2, indicates that this case study plant was relatively efficient, but of course there are still opportunities for additional energy conservation.

Generally, cement plants with a higher capacity have lower heat consumption. Summarizing from the results, the heat formation per kilogram of clinker was around 412.2 kcal in the case study. The heat of this clinker formation generally

consisted of calcination heat from  $\text{CaCO}_3$  and sintering heat to form clinker-contained oxides. The calcination process is endothermic, while the sintering process is exothermic. Because both processes occur in a high-temperature range (600-1450 °C), additional heat is needed to maintain this temperature of the kiln, SP, and calciners. This is the reason why the plant's heat consumption is far above its clinker heat formation. However, if the efficiency of the heat utilization of the kiln system is defined as the ratio between heat formation and specific heat consumption, then for this case study a value of 52.13% ( $> 50\%$ ) is obtained so that the system is still efficient, as reported by Kabir, *et al.* [32] and Engin & Ari [33]. Part of this excess heat is finally carried away by the flue gas,  $\text{CO}_2$ , other SP's gases and clinker product. This exhausted gas exiting the plant brings more than  $\pm 320$  kcal/kg of produced clinker or close to 117 MW heat equivalent, which can potentially be recovered for material drying and electricity production. The clinker heat could be recovered in the cooler to increase the combustion air temperature and reduce coal consumption.

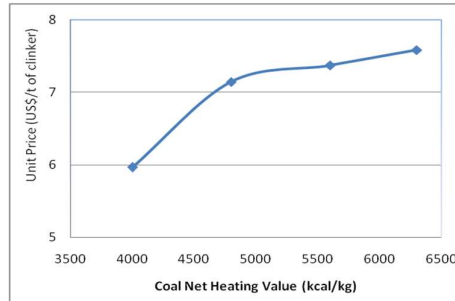


**Figure 2** SHC comparison of some clinker plants worldwide [31].

In order to reduce production costs and supporting environmental sustainability, part of the fuel used recently is low-rank coal and other alternative fuels. However, by shifting to lower rank coal with high water content, added with the use of alternative fuels, specific heat consumption could increase to  $\pm 830$  kcal/kg or  $\pm 3475$  MJ/ton of produced clinker due to the higher evaporating heat required by the fuel and the decrease of production capacity, as mentioned in the report of Alfi *et al.* [31]. Furthermore, the use of low rank coal can save costs because the price of raw coal is not proportional to its calorific value, as shown in Figure 3. In general, several factories in Indonesia have started to use coal with a heating value between 4000 to 4500 kcal/kg by mixing several types of coal. Based on the unit price mentioned in Figure 3, the utilization of 4500

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kcal/kg of coal NHV can reduce fuel costs by about 8.5% compared to 5000 kcal/kg used in the present study.



**Figure 3** The influence of the calorific value of fuel on its unit price per ton clinker produced.

### 3.3 Cooler and Kiln Materials and Heat Flows

The calculation results for materials and heat flows of the cooler and kiln are given in Tables 6 and 7 respectively. The difference between the incoming and outgoing heat of the cooler was less than 1%.

**Table 6** Materials and heat flows per kg of produced clinker in the clinker cooler.

Parameters	Inlet		Outlet	
	mass(kg)	heat(kcal)	mass(kg)	heat(kcal)
Clinker from kiln	1.0500	436.541	-	-
Cooling air	3.0942	24.273	-	-
Clinker product	-	-	1.0000	23.098
Return clinker dust to kiln and SP	-	-	0.0510	9.186
Combustion and raw mix drying air	-	-	1.6191	346.472
Excess cooling air exhausted	-	-	1.4741	76.510
Convection & radiation loss	-	-	-	6.544
Total of materials and heat flows	4.1442	460.814	4.1442	461.810

From Table 6 it can be seen that the recovery heat efficiency of the clinker cooler was 79.36%. This high heat recovery resulted in a high combustion air temperature (600 °C up to 900 °C), which is in the range of the measurement values reported by Alfi, *et al.* [31]. The other potential waste heat is the heat of excess cooling air (76.5 kcal/kg from the clinker product, or 28 MW of heat equivalent), which could be further utilized, e.g. for producing additional electricity using a heat recovery boiler and turbine, as proposed and studied by Tao, *et al.* [32], Chen & Shi [33], and Huang, *et al.* [34]. From Table 7 it can be seen that the materials and heat flows per kilogram of produced clinker in the kiln

are clearly presented. The difference between the rate of heat entering and exiting the kiln is insignificant, with an approximate value of 0.42%. This calculation was obtained by assuming that 20% clinker from the kiln returns back to the SP and calciners. By limiting the difference of  $\leq 1\%$  between the heat flows in and out of the kiln, we can estimate the percentage of the kiln feed that was decarbonized in the preheater, calciners and kiln. The calculation results of this heat balance show that about 85% of the kiln feed was decarbonized in the SP and calciners, while the remaining 15% occurred in the kiln. In addition, using this evaluation result, the calculated sintering heat in the kiln was about 91.95 kcal/kg of produced clinker. It can also be seen that the heat carried by clinkers to the cooler and the combustion gas as well as the calcination gas out from the kiln to the SP are very large. In the cooler, the heat carried by the clinker is mostly recovered by combustion air (79.36%). In the SP it is used for heating and the initial calcination process of the kiln feed. It also appears that heat loss to the environment (i.e. 31.98 kcal/kg of produced clinker) was also significant. Since the study object was a large cement plant, the value obtained was lower than the 50 kcal/kg of produced clinker reported by Aly [5]. In general, the specific heat loss decreases with increasing plant capacity.

**Table 7** Rotary kiln's materials and heat flows per kg of produced clinker.

Parameters	Inlet		Outlet	
	mass(kg)	heat(kcal)	mass(kg)	heat(kcal)
Kiln feed from SP	1.3110	299.324	-	-
Coal and combustion heat	0.0560	284.697	-	-
Combustion air	0.5810	115.018	-	-
Return clinker dust from cooler	0.0172	3.160	-	-
Produced clinker	-	-	1.0500	436.541
Recirculating clinker dust to SP	-	-	0.2000	48.000
Flue gas to SP	-	-	0.6343	174.496
Kiln feed gas	-	-	0.0809	21.873
Net of calcination and sintering heat	-	9.308	-	-
Evaporating of coal moisture content	-	-	-	1.514
Convection & radiation loss	-	-	-	31.980
Total of materilas and heat flows	1.9652	711.507	1.9652	714.404

#### 4 Conclusion

Equations and solutions for a new proposed method for calculating detailed materials flow in a double-string suspension preheater with separate line and in-line calciners (SLC-I) type cement plant were presented in this paper. The advantage of the proposed method is that it can calculate detailed materials flow and estimate the separation efficiency in each cyclone without directly measuring the flow rate, which is impossible in the field when the plant is operating. As a case study, operational data from the Padang 5 cement plant were used for detailed calculations. The materials flow analysis provided in this paper is the

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first part of an integrated two-part study. From this first part of the study, some conclusions that can be drawn are:

1. The ratio between the heat formation and specific heat consumption was 52.13%, which shows that the case study plant is efficient.
2. The exhausted gas out from the plant brings around more than 320 kcal/kg of produced clinker or close to 117 MW heat equivalent, which provides potential opportunities to be recovered for material drying and electricity production.
3. The other waste heat potential is excess cooling air heat (76.5 kcal/kg of produced clinker, or 28 MW of heat equivalent), which can be further utilized.
4. The heat carried by the clinker is mostly recovered by the combustion air (79.36%) in the cooler.
5. Based on the recent unit price of coal in the Indonesian market, the utilization of 4500 kcal/kg of coal NHV can potentially reduce fuel costs by about 8.5% compared to 5000 kcal/kg in the present study.

### Acknowledgment

The authors would like to express their gratitude and highest appreciation for the collaboration between PT Semen Padang and the Indonesian Cement and Concrete Institute in providing data on field observations for the case study in this paper.

### Nomenclature

Symbol	Description	Symbol	Description
$A$	surface area (m <sup>2</sup> )	$h_{fg}$	enthalpy of evaporation (kcal/kg)
ash	mass percentage of ash in coal (%)	$(CaCO_3)_{kf}$	mass percentage of CaCO <sub>3</sub> (%)
$En$	heat flow rate (kcal/s) or (kW)	$(MgCO_3)_{kf}$	mass percentage of MgCO <sub>3</sub> (%)
$\Delta E_{Cyclone}$	difference in heat flow between outlet and inlet cyclone in (%) $= \Delta E_{Cyclone} = \left[ \frac{(En_{out} - En_{in})}{En_{out}} \right]_{Cyclone} * 100\%$		
$M$	mass flow rate (kg/s)	$(SiO_2)_{kf}$	mass percentage of SiO <sub>2</sub> (%)
$\Delta m_{Cyclone}$	mass flow difference between exiting and entering cyclone (kg/s) $\Delta m_{Cyclone} = (m_{outlet} - m_{inlet})$		
$NHV$	net heating value (kcal/kg) or (kJ/s)	$(Al_2O_3)_{kf}$	mass percentage of Al <sub>2</sub> O <sub>3</sub> (%)
$\eta$	separation efficiency of the cyclone (%)	$(Fe_2O_3)_{kf}$	mass percentage of Fe <sub>2</sub> O <sub>3</sub> (%)
$LOI$	loss of ignition (%)	$T$	temperature (°C)
$H_2O$	mass flow rate of vapor (kg/s)	$Q_{loss}$	radiation and convection heat loss (kcal/s) or (kW)
$h_x(T_x)$	enthalpy of substance x at temperature $T_x$ (kcal/kg)	$\%Calc_i$	percentage of calcined kiln feed in equipment i (%)

Subscript	Description	Subscript	Description
<i>amb</i>	ambient	<i>gas-kf</i>	kiln feed gas
<i>ash</i>	ash in coal	<i>hg</i>	hot gas
<i>c</i>	clinker cooler	<i>hgi</i>	hot gas exit from cyclone <i>i</i>
<i>calc</i>	calcination process	<i>H2O-kf</i>	kiln feed evaporated water
<i>C</i>	cyclone separator	<i>k</i>	kiln
<i>C1</i>	cyclone 1 (top)	<i>kf</i>	kiln feed
<i>C2</i>	cyclone 2	<i>kfi</i>	separated kiln feed from cyclone <i>i</i>
<i>C3</i>	cyclone 3	<i>SP</i>	suspension preheater
<i>C4</i>	cyclone 4 (lowest)	<i>sec-air-c</i>	combustion air from cooler to kiln
<i>A</i>	A-string	<i>sep-kf</i>	separated kiln feed
<i>B</i>	B-string	<i>sep-kfc</i>	separated kiln feed to form clinker
<i>cli</i>	clinker	<i>sep-kfi</i>	separated kiln feed by cyclone <i>i</i> ( <i>i</i> = 1A and 1B, 2, 3 and 4)
<i>clid-to-k</i>	clinker dust return to kiln	<i>surf</i>	surface area
<i>coal</i>	coal	<i>tr-air</i>	transporting air
<i>coal-comb</i>	coal combustion process	<i>tot</i>	whole plant
<i>cool-air</i>	clinker cooling air	<i>unsep-kf-i</i>	unseparated kiln-feed by cyclone <i>i</i> ( <i>i</i> = 1A and 1B, 2, 3 and 4)
<i>cool-air-k</i>	cooling air to kiln	<i>vapor</i>	water vapor
<i>evap</i>	evaporation process	<i>vapor-kf</i>	vapor from kiln feed
<i>form</i>	clinker formation process		

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## Appendix 1

### Materials Flow Conservation Equations of Clinker Cooler and Kiln

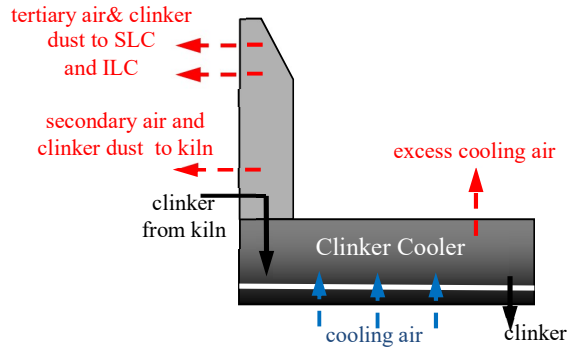
#### A.1 Mass and Heat Balances of Clinker Cooler

A schematic diagram of mass flow entering and leaving a grate type clinker cooler is presented in Figure A1. With the assumption of no false air entering the cooler, the mass balance equation can be written as Eq. (A1):

$$m_{cli-k} + m_{cool-air} = m_{cli} + m_{comb-air-k} + m_{comb-air-ILC} + m_{comb-air-SL} + m_{clid-c-k} + m_{clid-c-ILC} + m_{clid-c-SLC} + m_{exc-a} \quad (A1)$$

where  $m_{cli-k}$ ,  $m_{cool-air}$ ,  $m_{cli}$ ,  $m_{comb-air-k}$ ,  $m_{comb-air-ILC}$ ,  $m_{comb-air-SLC}$ ,  $m_{clid-c-k}$ ,  $m_{clid-c-ILC}$ ,  $m_{clid-c-SLC}$ , and  $m_{exc-air}$  are respectively the mass flow rate from the clinker entering the cooler, cooling air entering the cooler, clinker product, cooling air entering the kiln, ILC and SLC as combustion air, return clinker dust entering the kiln, ILC, and SLC, and excess air exhausted into the ambience. With the assumption that there is no leakage in the cooler, the mass flow rate of the cooling air is equal to combustion air minus transporting air.

The rate of clinker mass from the kiln entering the cooler must be equal to the sum of clinker production and return clinker dust entering the kiln. This clinker dust is carried by the combustion air back from the cooler to the kiln. The percentage of clinker dust returning to clinker production will be assumed in the calculation of the mass balance in the cooler due to the difficulty of direct measurement. The heat balance calculation errors in the cooler and kiln are limited, not more than 1%. With the determined accuracy limit of the measurement data in the plant, calculation of the mass and heat balances in the cooler can be executed. The heat balance equation for the grate type clinker cooler is written in Eq. (A2):



**Figure A1** Materials flow in the grate cooler.

$$En_{cli-k} + En_{cool-air} = En_{cli} + En_{comb-air-k} + En_{comb-air-IL} + En_{comb-air-SLC} + En_{clid-c-k} + En_{clid-c-IL} + En_{clid-c-SLC} + En_{ex} + Q_{loss} \quad (A2)$$

The flow of heat entering the grate clinker cooler consists of:

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- a. Heat flow of the clinker from the kiln at temperature  $T_{cli-k}$ :

$$En_{cli-k} = m_{cli-k} * h_{cli}(T_{cli-k}) \quad (A3)$$

- b. Heat of cooling air:

$$En_{cool-air} = m_{cool-air} * h_{air}(T_{air}) \quad (A4)$$

Meanwhile, the flow of heat leaving for the cooler under the assumption that the temperature of return dust entering the kiln and gas exiting from the cooler is equal to  $T_{hg-i}$ , consisting of:

- a. Heat flow of clinker product  $En_{cli}$  at temperature  $T_{cli}$  as mentioned in Eq. (16).

- b. Heat of combustion air entering the kiln  $En_{comb-air-k}$  at temperature  $T_{hg-k}$ :

$$En_{comb-air-k} = m_{comb-air-k} * h_{hg-k}(T_{hg-k}) \quad (A5)$$

- c. Heat of combustion air entering the ILC  $En_{comb-air-ILC}$  at temperature  $T_{hg-ILC}$ :

$$En_{comb-air-ILC} = m_{comb-air-ILC} * h_{hg-ILC}(T_{hg-ILC}) \quad (A6)$$

- d. Heat of combustion air entering the SLC  $En_{comb-air-SLC}$  at temperature  $T_{hg-SLC}$ :

$$En_{comb-air-SLC} = m_{comb-air-SLC} * h_{hg-SLC}(T_{hg-SLC}) \quad (A7)$$

- e. Heat flow of return clinker dust entering the kiln  $En_{clid-c-k}$  at temperature  $T_{hg-k}$ :

$$En_{clid-c-k} = m_{clid-c-k} * h_{cli}(T_{hg-k}) \quad (A8)$$

- f. Heat flow of return clinker dust entering the ILC  $En_{clid-c-ILC}$  at temperature  $T_{hg-ILC}$ :

$$En_{clid-c-ILC} = m_{clid-c-ILC} * h_{cli}(T_{hg-ILC}) \quad (A9)$$

- g. Heat flow of return clinker dust entering the SLC  $En_{clid-c-SLC}$  at temperature  $T_{hg-SLC}$ :

$$En_{clid-c-SLC} = m_{clid-c-SLC} * h_{cli}(T_{hg-SLC}) \quad (A10)$$

Heat loss by radiation and convection  $Q_{loss-c}$  through the surface area of the clinker cooler ( $A_{cooler}$ ) can be approached by Eq. (25) and replacing  $A_{tot}$  with  $A_{cooler}$ . In Eqs. (A1) and (A2), the value of the mass flow rate of return dust to the kiln ( $m_{clid-c-k}$ ) and combustion air temperature cannot be measured directly at the plant. However, mass and heat balance in the kiln can be evaluated with the minimum acquisition limit between the heat entering and exiting the kiln. Using this condition, Eqs. (A3) to (A10) can be solved by completing the heat balance of the cooler.

### A.2 Mass and Heat Balances of the Kiln

For the kiln system, mass flow in and from the kiln is described in Figure 3. The equation of mass balance is written in Eq. (A11):

$$m_{sep-kf-4A} + m_{clid-c-k} + m_{coal-k} + m_{comb-air-k} + m_{tr-air-k} = m_{cli-k} + m_{clid-k-ILC} + m_{hg-k-ILC} \quad (A11)$$

where

$m_{sep-kf-4A}$	= mass flow rate of kiln feed from A-string SP
$m_{coal-k}$	= mass flow rate of coal
$m_{comb-air-k}$	= mass flow rate of air combustion
$m_{tr-air-k}$	= mass flow rate of coal transporting air to kiln
$m_{clid-k-ILC}$	= mass flow rate of clinker dust entering to ILC
$m_{hg-k-ILC}$	= mass flow rate of hot gas from kiln to ILC

The hot gas entering to SP consists of flue gas resulted from the fuel combustion process in the kiln and  $CO_2$  and other gases from calcination and feed burning processes in the kiln, which can be evaluated using Eq. (4) multiplied by the percentage of kiln feed calcinated in the kiln ( $\%Calc_k$ ). Thus the value of  $m_{hg-k-ILC}$  can be described as Eq. (A12):

$$m_{hg-k-ILC} = (1 - ash_{coal}) * m_{coal-k} + m_{tr-air-k} + m_{comb-air-k} + (\%Calc_k * m_{gas-k}) \quad (A12)$$

The other notations were already mentioned in the mass balance of cooler. While the heat balance equation of the kiln is as follows:

$$\begin{aligned} En_{kf-4A-k} + En_{coal-k} + En_{coal-comb} + En_{tr-air-k} + En_{comb-air-k} \\ + En_{clid-c-k} + En_{clink} = \\ En_{cli-k} + En_{clid-k-ILC} + En_{calc-k} + En_{hg-k-ILC} \\ + En_{evap-H2O-coal-k} + Q_{loss} \end{aligned} \quad (A13)$$

The flow of heat entering the kiln consists of:

- a. Heat flow of the kiln feed from cyclone 4A at temperature  $T_{in-k}$ , Eq. (A14):

$$En_{kf-4A-k} = m_{sep-kf-4A} * h_{kf}(T_{in-k}) \quad (A14)$$

- b. Heat of coal entering the kiln is:

$$En_{coal} = m_{coal-k} * h_{coal}(T_{coal}) \quad (A15)$$

- c. Heat from the coal combustion process:

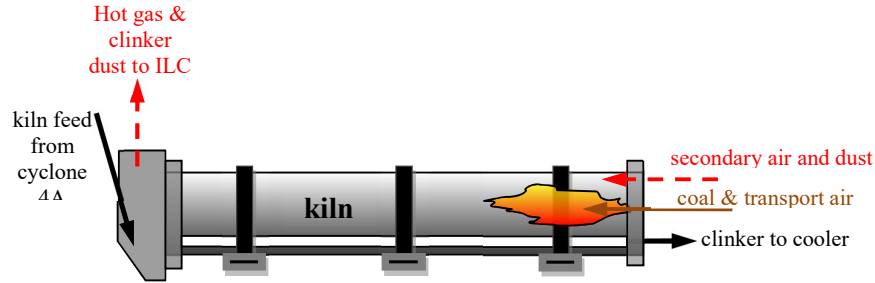
$$En_{coal-comb} = m_{coal-k} * NHV_{coal} \quad (A16)$$

- d. Heat flow of coal transporting air:

$$En_{tr-air-k} = m_{tr-air-k} * h_{air}(T_{air}) \quad (A17)$$

- e. Heat flow of air combustion  $En_{comb-air-k}$  as mentioned in Eq. (A5).

- f. Heat of return clinker dust from cooler  $En_{clid-c-k}$  as written in Eq. (A8).



**Figure A2** Materials flow in the kiln.

- g. Heat of clinkerization which is the reaction heat of oxides to form clinker. This heat is exothermic and equal to the difference from the calcination process heat with clinker formation heat Eq.(A18):

$$En_{clink} = (CaCO_3)_{kf} * m_{kf} * En_{calc} - En_{form} \quad (A18)$$

While the flows of heat leaving for the kiln consist of:

- a. Heat flow of clinker product  $En_{cli-k}$  to the cooler Eq. (A3).

- b. Heat flow of return clinker dust to ILC  $En_{clid-k-ILC}$  in which its temperature is assumed to equal to the temperature of hot gas leaving for kiln  $T_{in-k}$ :

$$En_{clid-k-ILC} = m_{clid-k-IL} * h_{cli}(T_{in-k}) \quad (A19)$$

- c. Heat of calcination process in the kiln  $En_{calc-k}$ :

$$En_{calc-k} = (\%Calc_k) * En_{calc} \quad (A20)$$

Here,  $\%Calc_k$  can be estimated indirectly when the evaluation of heat balance in the kiln is executed. The value of  $\%Calc_k = 1 - \%Calc_{SPC}$ , where  $\%Calc_{SPC}$  is the

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percentage of calcined kiln feed in the SP and calciners. In this study we assume that the calcination process in SP occurs at the cyclones 3A, 3B, 4A, 4B, ILC, and SLC with the percentage of calcination degree of  $\%Calc_{3A}$ ,  $\%Calc_{3B}$ ,  $\%Calc_{4A}$ ,  $\%Calc_{4B}$ ,  $\%Calc_{ILC}$  and  $\%Calc_{SLC}$  respectively.

- d. Heat flow of hot gas from the kiln to ILC where its temperature is  $T_{in-k}$ . The total mass of this hot gas, including the vaporized water content of coal and  $CO_2$  from the calcination process in the kiln, is mentioned in Eq. (A11). Therefore, the heat flow of hot gas can be calculated as follows Eq. (A21),

$$En_{hg-k-ILC} = m_{hg-k-ILC} * h_{hg}(T_{in-k}) \quad (A21)$$

- e. Evaporation heat of water content in coal supplied to the kiln:

$$En_{evap-H2O-coal-k} = H2O_{coal} * m_{coal} * h_{fg} \quad (A22)$$

Heat loss by radiation and convection  $Q_{loss-k}$  through the surface area of the kiln ( $A_{kiln}$ ) that can be approached by Eq. (24) by substituting  $A_{tot}$  with  $A_{kiln}$ .