MATHEMATICAL MODELLING OF CLINKER PRODUCTION WITH SERIAL FLOW PREHEATER CYCLONES AND PRECALCINER

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ABSTRACT

A simple mathematical model is presented for clinker production via a pyroprocessing unit consisting of serial flow preheater cyclone stages, a precalciner, a rotary kiln and a clinker cooler. The model equations are based on steady state material and energy balances for solid and gas phases around each piece of equipment. The contribution of fuel ash to raw meal, recarbonation reactions in the preheater section and temperature dependence of specific heats are included in this model. A computer program has been developed to solve the model equations via an iterative procedure, yielding raw meal, stack gas, stack dust and temperature profiles and specific fuel consumption for a given set of input variables, thus enabling the user to investigate the impact of any design or process variable on the system performance. In this study the effects of fuel type and number of preheater stages on specific fuel consumption are investigated. The results indicate that in certain cases, by changing the fuel type, and by adjusting the degree of calcination in the precalciner when there is a fuel mix, energy savings equivalent to addition of an extra preheater stage may be possible.

KEYWORDS

Serial flow, Preheater cyclone, Precalciner cement plant, Mass balance, Energy balance, Mathematical modelling

INTRODUCTION

Production of cement from basic raw materials, namely limestone, clay, sand and iron bearing materials, consists of the following basic steps: (1) Grinding of raw materials and preparation of a *raw meal* containing predetermined amounts of calcium and magnesium carbonate, alumina, silica and iron oxide (2) pyro-processing of the raw meal to produce *clinker* particles (3) cooling of clinker (4) final grinding of clinker particles and addition of various *agents* to obtain the final cement product with the desired properties. The first and the last steps consume large amounts of electrical energy to generate motive power whereas pyro-processing requires high temperature heat.

During pyro-processing the following phenomena take place with increasing temperature:
- Evaporation of free water in the raw meal (endothermic, 100°C)
- Evolution of combined water from clay (endothermic, above 500°C)
- Evolution of carbon dioxide during the calcination of carbonates (endothermic, 850°C and above)
- Formation of clinker compounds (exothermic, 900°C-1200°C and above)

- The energy necessary for the endothermic phenomena to take place is supplied by burning a fuel, mostly coal since fly ash also contributes to the raw meal.

To produce one ton of cement, a state of the art plant consumes about 3.6 GJ of thermal energy and 120 kWh of electrical energy [1]. Thermal and electrical energy costs together account for 30% to 60% of the total production costs [2, 3]. Since it is one of the most energy intensive manufacturing processes, research on energy utilization and measures to conserve energy in the cement sector has been abundant. Methodology and scope of available literature is also highly variable: Some researchers used actual plant data [2, 4-16] while others employed data generated by mathematical models [17-33]. Most of these models are based on material and energy balances and exhibit substantial variation in degree of complexity [4, 5, 19, 21, 22, 23, 24, 26-31]. Models based on reaction engineering, transport phenomena and computational fluid dynamics [33-37] are also available. Although the analysis of results is inevitably based on the first law of thermodynamics there is an increasing number of research where a combination of the first and the second laws is preferred [7, 8, 13, 16, 38-41]. As for the scope, some work is focused on a specific process unit [5, 7, 8, 9, 10, 18, 36, 37, 38, 42] while others focus on an entire plant [11, 13, 39] or the entire sector [6, 43].

This study is focused on thermal energy, therefore the clinker manufacturing process rather than the entire cement production process is considered, excluding the initial and final grinding steps. The raw meal sequentially flows through a preheater consisting of several cyclone stages, a precalciner, a rotary kiln and a cooler. In the preheater, temperature of the raw meal is increased to the required calcination temperature as it flows countercurrent to the hot gases leaving the precalciner. In the precalciner, partial calcination takes place as the necessary heat is supplied by the hot gases leaving the rotary kiln and by the combustion of the fuel injected. Calcination is completed and clinker compounds such as dicalcium silicate (C_2S), tricalcium silicate (C_3S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) are formed in the rotary kiln where the required high temperatures are maintained by combustion of a fuel which may be of a different kind than the fuel employed in the precalciner. The hot clinker particles leaving the kiln are cooled in the clinker cooler by exchanging heat with air. Heated air leaving the cooler is sent to the kiln (*secondary air*) and the precalciner (*tertiary air*) to provide the necessary oxygen for combustion. The exhaust gases leaving the rotary kiln are laden with entrained solid particles. This so-called *dust* is partially recovered in the cyclone stages. The remainder is recovered with electrostatic precipitators and recycled back to the pyro-processing unit to minimize raw material losses.

The purpose of the present study is to develop a simple mathematical model of the clinker manufacturing process based on steady state material and energy balances which can be utilized to provide rapid yet accurate estimates of the effects of system configuration (number of cyclone stages) and fuel type on over-all performance.

MATERIAL BALANCES

Material streams in the clinker manufacturing process can be classified as (i) solid (raw meal and clinker), (ii) solid entrained by gas (dust) and (iii) gas (air and combustion gas) streams. Flow rates and compositions of each of these streams can be calculated by writing the appropriate material balances for each process unit as described below. These material balances were developed using the following assumptions [25, 26]:

a. Ash of rotary kiln and precalciner fuels is completely absorbed by clinker.
b. Chemical composition of entrained solids (dust) leaving the rotary kiln with combustion gases is identical with the chemical composition of the clinker product.

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c. Each cyclone stage is completely back mixed. Therefore, the outlet streams (solid, dust and gas) from each cyclone are at the same temperature and the chemical composition of dust is identical with that of the solids.

d. The last cyclone stage (4th, 5th or 6th stage) serves as the precalciner.

e. All MgO in the raw meal is in the form of $MgCO_3$.

f. $MgCO_3$ in the raw meal is completely calcined in the precalciner whereas calcination of $CaCO_3$ is not complete.

g. Recarbonation of CaO and MgO takes place in the cyclone stage above the precalciner.

h. All of MgO and a certain fraction (*P*) of CaO entering the cyclone are converted.

i. All of CaO and MgO produced in the precalciner leave the unit as free oxides.

j. Calcination of remaining $CaCO_3$ and all of the clinkerization reactions take place in the rotary kiln.

k. Dust leaving the first cyclone is completely recovered and recycled.

l. Evaporation of chemically bound water in the raw meal is neglected.

Solid streams

Total amount of a solid phase (raw meal, dust or clinker) is simply the sum of the amounts of its components. The major components are $CaCO_3$, CaO, $MgCO_3$, MgO, SiO_2, Fe_2O_3 and Al_2O_3 and other nonvolatile oxides such as K_2O, Na_2O, TiO_2, Mn_2O_3 may also be present in very small amounts. Using the symbols shown in Figure 1 for the relevant process variables, the following equations can be written for the amounts (kg) of solid components.

For CaCO₃ (X) and CaO (Y)

$$X_1 - [(1 - \eta_1)X_2] = X_0 \tag{1}$$

$$(\eta_{i-1}X_i) - [(1 - \eta_i)X_{i+1}] = X_0 \qquad \text{for } i = 2,3, \dots, N-1 \tag{2}$$

$$(\eta_{N-1}X_N) - [(1 - \eta_N)X_{N+1}] = X_0 + \left| P\ \{(\eta_{N-2}Y_{N-1}) + [(1 - \eta_N)Y_{N+1}]\}\left(\frac{MW_X}{MW_Y}\right)\right| \tag{3}$$

$$(\eta_N X_{N+1}) - (DL.X_{CL}) + R_{true}[(\eta_{N-1}X_N) + (DL.X_{CL}) + X_{PC}] = X_0 + X_{PC} + \left| P.\{(\eta_{N-2}Y_{N-1}) + [(1 - \eta_N)Y_{N+1}]\}\left(\frac{MW_X}{MW_Y}\right)\right| \tag{4}$$

$$Y_1 - [(1 - \eta_1).Y_2] = Y_0 \tag{5}$$

$$[\eta_{(i-1)}.Y_i] - [(1 - \eta_i).Y_{i+1}] = Y_0 \qquad \text{for } i=2, 3, \dots, N-1 \tag{6}$$

$$\eta_{(N-1)}.Y_N - (1 - \eta_N).Y_{N+1} = Y_0 + P.[\eta_{N-2}.Y_{N-1} + (1 - \eta_N).Y_{N+1}] \tag{7}$$

$$\eta_N.Y_{N+1} - [(DL).Y_{CL}] + \left| R_{true}.\{(\eta_{N-1}X_N) + [(DL).X_{CL}] + X_{PC}\}.\left(\frac{MW_Y}{MW_X}\right)\right| = Y_0 + Y_{PC} + P.\{(\eta_{N-2}Y_{N-1}) + [(1 - \eta_N).Y_{N+1}]\} \tag{8}$$

$$Y_{CL} = \left[(X_0 + X_{PC} + X_{RK} - X_{CL}).\left(\frac{MW_Y}{MW_X}\right)\right] + Y_0 + Y_{PC} + Y_{RK} \tag{9}$$

where N is the number of cyclone stages including the precalciner, η_i is the collection efficiency of the ith cyclone stage, DL is the amount of entrained solids leaving the kiln per unit amount of clinker product and R_{true} is the fraction of $CaCO_3$ entering the precalciner which is converted to CaO and P is the fraction of CaO converted to $CaCO_3$.

$$R_{true} = \frac{[Y_{N+1} - (\eta_{N-1}Y_N) - (DL).Y_{CL}]}{\left(\frac{MW_Y}{MW_X}\right).[(\eta_{N-1}X_N) - (DL).X_{CL} - X_{PC}]} \tag{10}$$

Assuming the raw meal does not contain any CaO ($Y_0 = 0$), the preceding 2N+3 equations can be solved to determine 2N+3 unknowns (X_0, X_1, ..., X_{N+1}, Y_1,........, Y_{N+1}) when DL, R_{true}, P and the amounts of $CaCO_3$ and CaO in the clinker product (X_{CL} and Y_{CL}) and the fuel ash (X_{PC}, X_{RK}, Y_{PC} and Y_{RK}) are known.

For MgCO3 (V) and MgO (W)

Equations similar to $CaCO_3$ and CaO can be written with R_{true} and P equal to unity. Since recarbonation and calcination are assumed to be complete, $W_N = V_{N+1} = 0$. Therefore, assuming the raw meal does not contain any MgO ($W_0 = 0$) the 2N+1 equations for V and W can be solved to determine 2N+1 unknowns when DL and the amounts of $MgCO_3$ and MgO in the clinker product (V_{CL} and W_{CL}) and the fuel ash (V_{PC}, V_{RK}, W_{PC} and W_{RK}) are known.
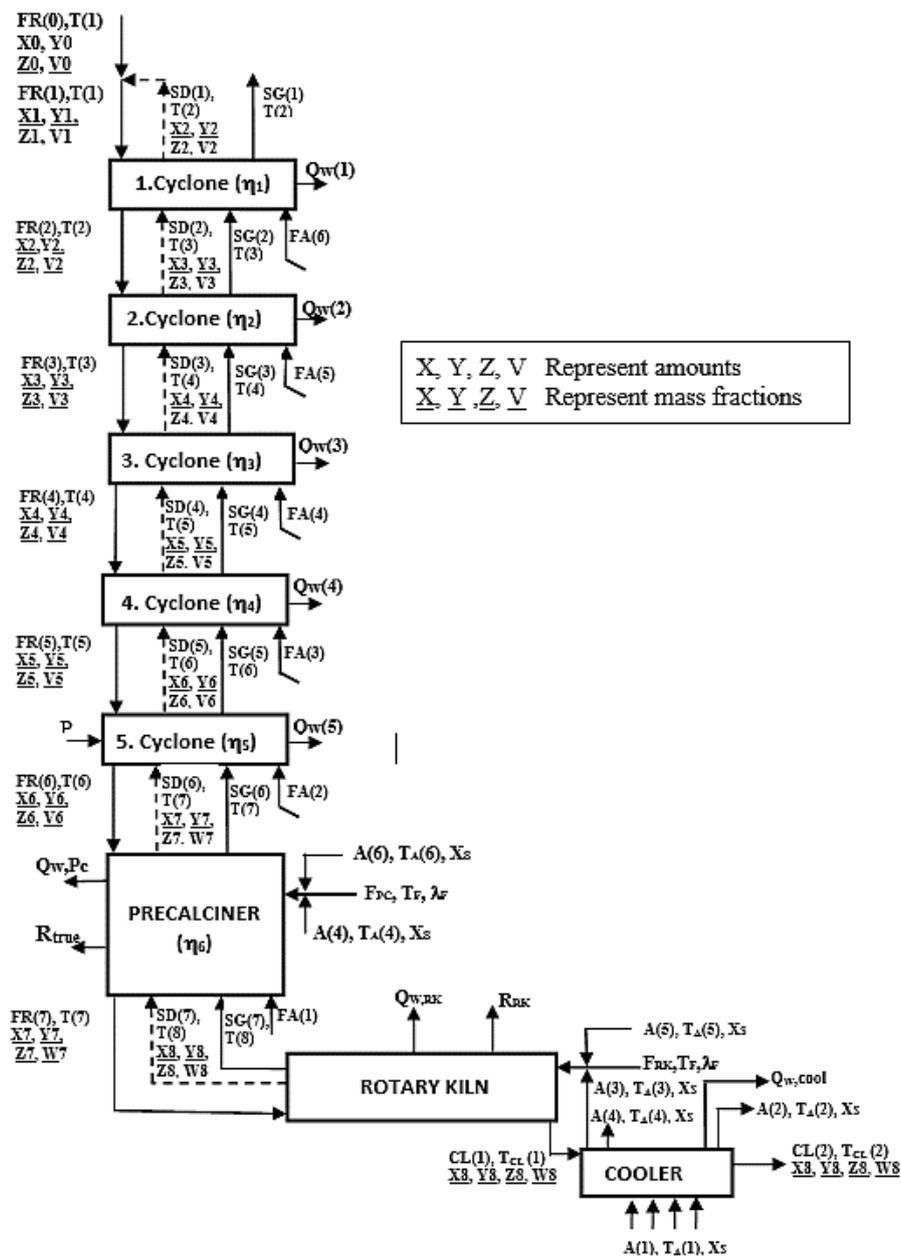

Fig. 1 - Schematic presentation of process variables

For a non-volatile oxide (Z)

Again we have similar equations with R_{true} and P both equal to zero. For each non-volatile oxide, N+2 equations can be solved to determine N+2 unknowns (Z_0, Z_1, ...,Z_{N+1}) when DL and the amounts of Z in the clinker product (Z_{CL}) and the fuel ash (Z_{PC}, Z_{RK}) are known.

The total amounts of raw meal (FR), clinker (CL) and dust (SD) streams can be calculated as the sum of the amounts of their constituents.

$$FR(0) = X_0 + Y_0 + V_0 + \sum Z^M \qquad \text{for} \quad M = SiO_2, Al_2O_3, Fe_2O_3,\ldots.. \qquad (11)$$

$$FR(\dot{I}) = \eta_i \left[X_i + Y_i + V_i + W_i + Z_i^{SiO_2} + Z_i^{Al_2O_3} + Z_i^{Fe_2O_3} + \cdots.. \right] \quad \text{for} \quad i = 1,2,3,\ldots,N+1 \qquad (12)$$

$$CL(1) = CL(2) = X_{CL} + Y_{CL} + V_{CL} + W_{CL} + Z_{CL}^{SiO_2} + Z_{CL}^{Al_2O_3} + Z_{CL}^{Fe_2O_3} + \cdots \qquad (13)$$

$$SD(\dot{I}) = (1 - \eta_i) \cdot \left[X_i + Y_i + V_i + W_i + Z_i^{SiO_2} + Z_i^{Al_2O_3} + Z_i^{Fe_2O_3} + \cdots \right] \quad \text{for} \quad i = 1,2,3,\ldots,N+1 \quad (14)$$

Gas streams

Products of the combustion reactions in the rotary kiln and the precalciner and carbondioxide released during calcination are the constituents of the gas streams. The amount of combustion air and the amounts of combustion products (in kmol) are calculated with well-known combustion formulae which will not be repeated here. Moisture present in the fuel and the combustion air should also be added to find the total water vapor amount in the combustion products:

$$F_{w,l} = F \cdot H_2O_F / 18 \qquad (15)$$

$$A_w = A \cdot x_s \cdot 28,97/18 \qquad (16)$$

$$\sum H_2O = H_2O_{F,WV} + F_{W,l} + A_w \qquad (17)$$

Carbon dioxide production during calcination

Carbon dioxide is released during calcination of $CaCO_3$ (in the precalciner and the rotary kiln) and $MgCO_3$ (only in the precalciner). The amount of carbon dioxide (kmol) released in the rotary kiln is given by:

$$CO_2(RK) = \frac{\eta_N X_{N+1}}{MW_x} \qquad (18)$$

Similarly, the amount of carbon dioxide released in the precalciner:

$$CO_2(PC) = \frac{R_{true} [\eta_{N-1}X_N + (DL) \cdot X_{CL} + X_{PC}]}{MW_V} + \frac{\eta_{N-1}V_N + (DL) \cdot V_{CL} + V_{PC}}{MW_V} \qquad (19)$$

Carbon dioxide retention during recarbonation

The amount of carbon dioxide (kmol) removed from the gas phase during recarbonation of $CaCO_3$ and $MgCO_3$ can be calculated as:

$$CO_2(RET) = \frac{P \cdot [\eta_{N-2}Y_{N-1} + (1-\eta_N) \cdot Y_{N+1}]}{MW_Y} + \frac{\eta_{N-2}W_{N-1} + (1-\eta_N) \cdot W_{N+1}}{MW_Y} \qquad (20)$$

The total amounts of gas streams (SG) can be calculated as the sum of the amounts of their constituents:

$$SG(N + 1) = CP_{RK} + CO_2(RK) \tag{21}$$
$$SG(N) = SG(N + 1) + CP_{PC} + CO_2(PC) \tag{22}$$
$$SG(N - 1) = SG(N) - CO_2(RET) \tag{23}$$
$$SG(I) = SG(I + 1) \qquad \text{for I = N–2,……….., 2} \tag{24}$$
$$SG(1) = SG(2) + (FR_w/18) \tag{25}$$

where CP represents total combustion products:

$$CP = CO_2 + CO + SO_2 + \sum H_2O + O_2 + N_2 \tag{26}$$

and FR_w is the moisture content of dust free raw meal:

$$FR_w = [FR(0) . W_F]/(100.0 - W_F) \tag{27}$$

ENERGY BALANCES

Energy balances for each process unit were developed using the following assumptions:
a. Forms of energy other than enthalpy and heat are negligible.
b. Specific heat of a solid stream (raw meal, dust or clinker) is independent of composition.
c. Specific heat of dust leaving the kiln is the same as that of clinker, specific heats of all other dust streams are the same as those of raw meal.
d. Energy consumed during formation of melt phases is completely released back in the precooling zone of the kiln.

Enthalpies of solid and gas streams

Total enthalpy of a solid phase is simply the product of its amount and its specific enthalpy. Specific enthalpy at any desired temperature T is calculated by:

$$\Delta h = \int_{T_0}^{T} (c_p)_s . dT \tag{28}$$

where $(c_P)_s$ is the specific heat of the solid stream and T_0 is the reference temperature. Specific heats of raw meal, dust and clinker as a function of temperature are taken from references [4,18].

Total enthalpy of a gas stream is calculated as the sum of the enthalpies of its constituents. Specific heats of these constituents (CO_2, CO, O_2, N_2, SO_2 and H_2O) as a function of temperature are taken from references [44] and [45]. In the case of water vapor originating from moisture in the fuel(s) burned in the precalciner and rotary kiln, enthalpy of vaporization at T_0 must be added to the specific enthalpy.

Reaction enthalpies

Heat effects associated with recarbonation, calcination and clinkerization reactions must be accounted for in the energy balances by including proper reaction enthalpies. For the highly exothermic calcination reaction, the reaction enthalpy (in kJ) can be expressed as [4, 18, 46]:

$$\Delta H_{rxn} = 3200 (CaO) + 2715 (MgO) \tag{29}$$

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where CaO and MgO are the amounts of oxides produced from their carbonates. Same equation also applies to the recarbonation reaction with a sign change.

Although production of clinker from raw materials takes place at several stages at different temperatures and involves numerous reactions and phase transitions, a theoretical reaction enthalpy can be calculated using standard heats of formation of compounds in the raw meal and the clinker product. Using this approach, several equations relating the reaction enthalpy to the amount of each oxide in the clinker have been developed. In this study, the following expression developed by zur Strassen is adopted [4, 18, 46]:

$$\Delta H_{zS} = 3200\,(CaO) + 2715\,(MgO) + 1721(Al_2O_3) - [247(Fe_2O_3) + 2142(SiO_2)] \tag{30}$$

Model equations

Energy balances for each process unit include terms representing enthalpies of solid streams (FRE and SDE), enthalpies of gas streams (SGE), enthalpies of air streams (HE), heat losses from the surface (Q_W) and, if applicable, enthalpies of reaction (ΔH_{rxn}) and enthalpies of water evaporation (WE). Using the symbols shown in Figure 1 for the relevant process variables, each of these terms are calculated as follows:

$$FRE(i) = FR(i) \int_{T_0}^{T(i)} (Cp)_s\, dT \qquad \text{for i= 1,.....,N+1} \tag{31}$$

$$SDE(i) = SD(i) \int_{T_0}^{T(i)} (Cp)_s\, dT \qquad \text{for i= 1,.....,N+1} \tag{32}$$

$$SGE(i) = SG(i) \int_{T_0}^{T(i)} (Cp)_M\, dT \qquad \text{for i= 2,.....,N+2} \tag{33}$$

$$HE(i) = A(i) \int_{T_0}^{TA(i)} (Cp)_M\, dT \tag{34}$$

$$(Cp)_M = \sum y_j (Cp)_j \tag{35}$$

where y_j is the mole fraction of component j.

The enthalpies of reaction are calculated as follows:

$$\Delta H_{rxn}(i) = 0 \qquad \text{for } i = 1,.....N–2 \tag{36}$$

For the recarbonation reaction taking place in the cyclone stage above the precalciner:

$$\Delta H(N-1) = 3200\,.\,P\,.\,[\eta_{N-2}.Y_{N-1} + (1-\eta_N).Y_{N+1}] + 2715\,.\,[\eta_{N-2}.W_{N-1} + (1-\eta_N).W_{N+1}] \tag{37}$$

For the calcination reaction taking place in the precalciner:

$$\Delta H_{PC} = \frac{3200.R_{true}\,\{[\eta_{N-1}.X_N + (DL).X_{CL}] + X_{PC}\}}{\left(\frac{MW_Y}{MW_X}\right)} + \frac{2715\,[\eta_{N-1}.V_N + (DL).V_{CL} + V_{PC}]}{\frac{MW_W}{MW_V}} \tag{38}$$

In the rotary kiln, calcination of $CaCO_3$ will be completed in addition to all other clinkerization reactions (formation of clinker compounds, melt formation and resolidification). However, for an over-all energy balance on the rotary kiln, these details are not significant since melt formation energy is recovered during resolidification and reaction enthalpy is simply equal to:

$$\Delta H_{RK} = 3200 \cdot [\eta_N . X_{N+1}] . \left(\frac{MW_Y}{MW_X}\right) + 1721 \cdot \left(Z_{CL}^{Al_2O_3}\right) - \left[247 . \left(Z_{CL}^{Fe_2O_3}\right) + 2142 . \left(Z_{CL}^{SiO_2}\right)\right] \qquad (39)$$

Finally, heat requirements for evaporation of moisture in the first cyclone stage, the precalciner and the rotary kiln are as follows:

$$WE(1) = FR_W . \Delta H_{vap} \qquad (40)$$
$$WE_{PC} = (F . H_2O_F)_{PC} . \Delta H_{vap} \qquad (41)$$
$$WE_{RK} = (F . H_2O_F)_{RK} . \Delta H_{vap} \qquad (42)$$

where ΔH_{vap} is the enthalpy of vaporization of water (in kJ/kg) at the reference temperature.

COMPUTATIONAL METHODOLOGY

The model equations developed in the preceding sections are linear (material balances) and non-linear (energy balances) algebraic equations with mass flows and temperatures as the unknown variables. If the contribution of fuel ash to raw meal is ignored, material and energy balances can be solved consecutively: First, material balances are solved to determine the amount and composition of raw meal (X_0, Y_0, V_0, W_0, …) and mass flows (X_i, Y_i, ...) to produce a product of known composition (X_{CL}, Y_{CL}, …) and then this information is used to solve the energy balances. However, the contribution of fuel ash to raw meal cannot be ignored, especially when low quality coal with high ash content is to be utilized. When this is the case, material and energy balances must be solved simultaneously by an iterative procedure:

1. Material balances are solved ignoring the contribution from fuel ash.
2. Energy balance for the rotary kiln is solved to determine the required amount of fuel.
3. The amount of fuel in the precalciner is assumed.
4. Material balances are solved to obtain new mass profiles.
5. Energy balances are solved with new mass profiles to find raw meal inlet temperature.
6. If the calculated temperature is not within a specified tolerance of the known value of raw meal inlet temperature, assumed value for the precalciner fuel is changed and steps 2 through 6 are repeated until convergence is obtained.

A computer program has been developed based on this algorithm. The required inputs to this program are (i) the chemical composition of clinker, (ii) properties of fuels entering the precalciner and rotary kiln, (iii) chemical composition of fuel ash and (iv) several operating parameters such as degree of calcination, collection efficiency of a cyclone, dust load of gas leaving the kiln, etc. The complete list of input variables and their numerical values adopted in this study are shown in Tables 1-5.

Tab. 1 - Chemical compositions of clinker and fuel ash

	CaO (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	Fe$_2$O$_3$ (%)	MgO (%)	H$_2$O (%)	SO$_3$ (%)	nvo (%)
Clinker	66.0	20.14	5.72	3.80	1.54	0.0	0.81	97.2
Fuel ash	17.05	43.81	25.52	5.26	2.19	0.0	5.20	93.8

Tab. 2 - Fuel properties

Fuel type	LHV (kJ/kg)	C$_F$ (%)	H$_F$ (%)	O$_F$ (%)	S$_F$ (%)	N$_F$ (%)	H$_2$O$_{F,I}$ (%)	A$_F$ (%)
Coal_1	20600	57.0	4.3	5.86	4.19	1.5	2.0	25.15
Coal_2	30265	78.0	5.0	6.0	1.0	1.5	0.0	8.50
Fuel-oil	43534	85.9	11.9	1.0	0.1	1.0	0.0	0.1

Tab. 3 - Other process variables required as input

Process variable	Symbol	Value
Humidity of ambient air (kg water/kg dry air)	x_S	0.0128
Degree of recarbonation(%)	P	15
Amount of clinker entering and leaving the cooler (kg)	CL(1)=CL(2)	1.00
Dust entrained in gas leaving the kiln (kg/kg clinker)	DL	0.15
Excess air (%)	λ_{PR}, λ_{RK}	15
Combustion efficiency	KK	0.98
Air entering the cooler for coal-1 (m^3/kg clinker)	A(1)	2.45
Air entering the cooler for coal-2 (m^3/kg clinker)	A(1)	2.40
Air entering the cooler for fuel-oil (m^3/kg clinker)	A(1)	2.30
True degree of calcination in the precalciner (%)	R_{true}	80.0
Raw meal inlet temperature (°C)	T(1)	60.00
Dust free raw meal moisture content (%)	W_F	0.74
Fuel inlet temperature (°C)	T_F	25.00
Raw meal temperature entering rotary kiln (°C)	T(N+1)	865.00
Clinker temperature leaving rotary kiln (°C)	$T_{CL}(1)$	1350.00
Clinker temperature leaving cooler (°C)	$T_{CL}(2)$	100.0
Gas temperature leaving rotary kiln (°C)	T(N+2)	1100.00
Ambient air temperature (°C)	$T_A(1)$	25.00
Air temperature leaving cooler (°C)	$T_A(2)$	220.00
Secondary air temperature for coal-1 (°C)	$T_A(3)$	900.00
Secondary air temperature for coal-2 (°C)	$T_A(3)$	1000.00
Secondary air temperature for fuel-oil (°C)	$T_A(3)$	1050.00
Rotary kiln primary air temperature (°C)	$T_A(5)$	25.00
Precalciner primary air temperature (°C)	$T_A(6)$	25.00
Secondary/tertiary air ratio for four stage [A(3)/A(4)] (%)	STR	0.40
Secondary/tertiary air ratio for five stage [A(3)/A(4)] (%)	STR	0.45
Secondary/tertiary air ratio for six stage [A(3)/A(4)] (%)	STR	0.45

Tab.4 - Heat losses in various stages (kJ/kg.clinker)

Preheater Cyclone Stage	4 Stage	5 Stage	6 Stage
1st	45.0	40.0	40.0
2nd	30.0	25.0	25.0
3rd	40.0	35.0	30.0
4th	-	40.0	35.0
5th	-	-	40.0
Total cyclones heat loss	115.0	140.0	170.0
Precalciner	50.0	50.0	50.0
Rotary kiln	200.0	200.0	200.0
Clinker cooler	30.0	30.0	30.0
Cooler heat loss (total) CLE(2)+HE(2)+Q$_{W;COOL}$	500.0	500.0	500.0

Tab. 5 - Preheater cyclone dust collection efficiency (%)

	4 Stage	5 Stage	6 Stage
1st stage preheater cyclone	95	95	95
2nd stage preheater cyclone	90	90	90
3rd stage preheater cyclone	85	85	85
4th stage preheater cyclone	-	85	85
5th stage preheater cyclone	-	-	80
Precalciner	75	75	75

Numerical values listed in Tables 4 and 5 were adopted after a careful review of numerous studies available in literature [4, 18, 19, 20, 47, 48, 49, 50, 51, 52].

RESULTS

The model equations and the computational algorithm presented in the previous sections were implemented via a computer program to understand the effects of cyclone preheater configuration (4, 5 or 6 stages), fuel type and degree of calcination in the precalciner on overall system performance. In order to isolate the effect of the parameters under investigation, all other process variables have been kept constant except wall heat loss of preheater cyclone group. The results are summarized in Figure 2 and Tables 6-8.
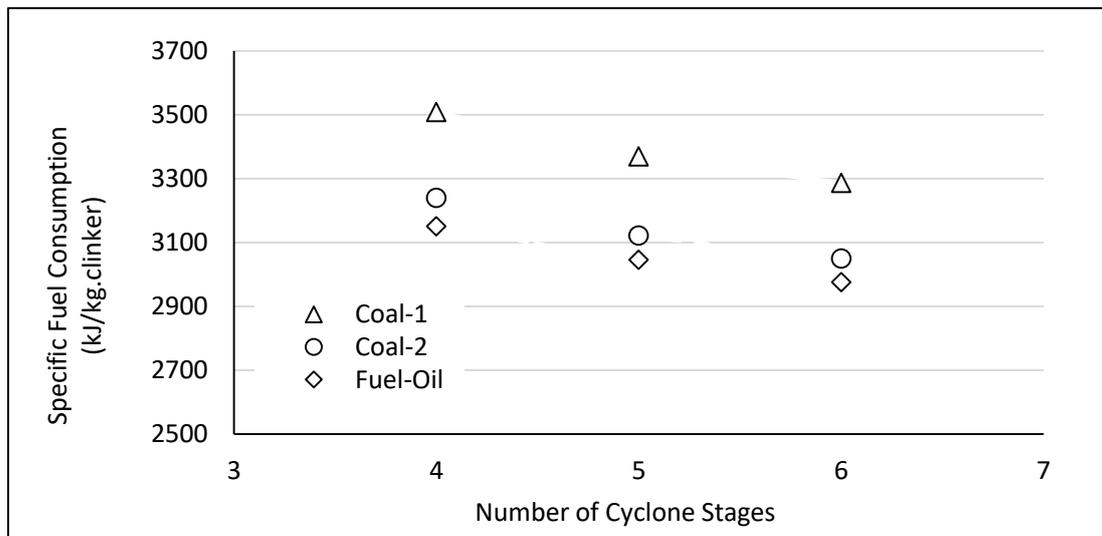

Fig. 2- Variation of specific energy consumption with fuel type and number of preheater stages.

When the figure and tables below are analyzed, it is observed that for a given fuel type, specific energy consumption decreases as expected with increasing number of preheater cyclone stages. The decrease in energy consumption is 5.7% for Coal-1, 5.5% for Coal-2 and 5.1% for Fuel- oil as the number of preheater stages increase from 4 to 6 (Figure 2). This decrease should be attributed to the better heat exchange between stack gas and raw meal in the preheater stages. Indeed, the stack gas temperature leaving the first cyclone decreases and the raw meal temperature entering the precalciner increases as the the number of preheater stages increase for each fuel (Table 8). It should be also noted that the incremental increase in energy saving is significantly reduced with increasing number of preheater stages.

Tab. 6 - Stack gas profiles

Stack gas (kmol/kg clinker)	Coal-1			Coal-2			Fuel oil		
	4 stage	5 stage	6 stage	4 stage	5 stage	6 stage	4 stage	5 stage	6 stage
Leaving the 1st cyclone	0.0705	0.0682	0.0668	0.0602	0.0585	0.0574	0.0563	0.0548	0.0539
Leaving the 2nd cyclone	0.0699	0.0676	0.0662	0.0596	0.0579	0.0568	0.0556	0.0542	0.0532
Leaving the 3rd cyclone	0.0699	0.0676	0.0662	0.0596	0.0579	0.0568	0.0556	0.0542	0.0532
Leaving the 4th cyclone	--	0.0676	0.0662	--	0.0579	0.0568	--	0.0542	0.0532
Leaving the 5th cyclone	--	--	0.0662	--	--	0.0568	--	--	0.0532
Leaving the precalciner	0.0707	0.0685	0.0671	0.0605	0.0587	0.0577	0.0565	0.0551	0.0541
Leaving the rotary kiln	0.0285	0.0272	0.0272	0.0193	0.0184	0.0185	0.0176	0.0168	0.0169

Tab. 7 - Temperature profiles

Raw meal, stack gas and stack dust temperature (^{0}C)	Coal-1			Coal-2			Fuel oil		
	4 stage	5 stage	6 stage	4 stage	5 stage	6 stage	4 stage	5 stage	6 stage
Leaving the 1st cyclone	384.1	327.9	296.5	327.9	262.8	226.9	303.2	238.1	202.1
Leaving the 2nd cyclone	609.8	529.0	472.8	551.4	451.5	383.0	525.6	418.9	348.1
Leaving the 3rd cyclone	772.7	676.1	605.3	737.8	610.9	518.8	722.1	581.7	482.9
Leaving the 4th cyclone	--	798.5	716.5	--	762.5	649.1	--	745.7	619.9
Leaving the 5th cyclone	--	--	816.5	--	--	779.4	--	--	762.5
Leaving the precalciner	865.0	865.0	865.0	865.0	865.0	865.0	865.0	865.0	865.0
Leaving the rotary kiln	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0	1100.0

Tab. 8 - Effect of calcination degree on fuel consumption (4 preheater stages).

Precalciner fuel	Rotary kiln fuel	R_{true}	Total fuel LHV(kJ)
Coal-1	Fuel oil	0.80	3342.55
Coal-1	Fuel oil	0.95	3403.56
Fuel oil	Coal-1	0.80	3287.23
Fuel oil	Coal-1	0.95	3220.50

When the above figure and tables are analyzed, it is observed that for a given fuel type, specific energy consumption decreases as expected with increasing number of preheater cyclone stages. The decrease in energy consumption is 5.7% for Coal-1, 5.5% for Coal-2 and 5.1% for Fuel- oil as the number of preheater stages increase from 4 to 6 (Figure 2). This decrease should be attributed to the better heat exchange between stack gas and raw meal in the preheater stages. Indeed, the stack gas temperature leaving the first cyclone decreases and the raw meal temperature entering the precalciner increases as the the number of preheater stages increase for each fuel (Table 8). It should be also noted that the incremental increase in energy saving is significantly reduced with increasing number of preheater stages.

The decrease in specific energy consumption with increasing number of preheater stages is approximately equal to the decrease in the enthalpy content of stack gas leaving the first stage minus the increase in wall heat loss of the preheater group excluding the calciner. Hence reducing the enthalpy content of stack gas is a key factor for saving energy and not only the temperature but also the amount of stack gas is significant. For a given number of preheater stages the flow rate of stack gas decreases with fuel type in the following order: Coal-1, Coal-2 and Fuel oil (Table 6). Energy consumption also decreases in the same order. In fact, sometimes consumption changes with fuel type (Coal-1 → Coal-2) can be more pronounced (above 7%) than consumption changes due to preheater configuration. This is due to the fact that the flow rate of stack gas is lower when the stoichiometrically required amount of combustion air is lower which in turn leads to a more effective performance of the preheaters as a heat exchanger, culminating in lower stack gas

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discharge temperatures. Since both its flow rate and temperature are reduced, the enthalpy of stack gas is synergistically reduced to a significant extent.

The preceding discussion suggests that fuels which stoichiometrically require lower amounts of combustion air are preferable from an energy saving standpoint. Of course there are other important factors influencing fuel selection, for instance high rank bituminous coal is preferred over natural gas for kiln firing because it produces a more luminous flame. Clinker production also offers a viable option for environment friendly utilization of low quality fuels. Alternative fuels including hazardous wastes can also be utilized because of the high temperatures in the rotary kiln. The best solution would be employment of different fuels in the precalciner and the rotary kiln. Reducing the excess air coefficient whenever possible will further improve the specific energy consumption.

When different fuels are used in the precalciner and the rotary kiln, the degree of calcination in the precalciner affects the specific energy consumption as can be seen from Table 8. In this case, to save energy the degree of calcination should be adjusted such that the fuel with the lower air/fuel ratio assumes as big a share as possible in the total energy consumption.

Modern clinker technology with six preheater stages preceding the precalciner has reduced the specific energy consumption below 3000 kJ/kg [53]. However, managers of existing older plants may be unwilling to retrofit additional preheater stages considering the increase in stack gas fan power and other necessary adjustments. The results of the present study indicate that changing the fuel and/or adjusting calcination degree in the precalciner when there is a fuel mix may be alternate options for saving energy.

Nomenclature

A	: Combustion air (kmol),
A_{min}	: Stoichiometrically required amount of combustion air (kmol)
A_W	: Moisture in air (kmol).
A_F	: Ash content of fuel (%).
C_F	: Carbon content of fuel (%).
CL	: Clinker (kg)
CO_F	: Carbon monoxide in the combustion products (kmol).
CO_{2F}	: Carbon dioxide in the combustion products (kmol).
CP	: Total combustion products (kmol).
Cp	: Specific heat (kJ/kg-K or kJ/kmol-K)
DL	: Entrained solids leaving the kiln per kg of clinker (kg)
F	: Amount of fuel (kg).
FA	: Amount of false air (kmol).
FR(n)	: Amorun of rab meal entering stage n (kg).
Fr	: Moisture content in dust free raw meal (kg).
ΔH_{rxn}	: Calcination enthalpy (kJ)
ΔH_{zS}	: Clinker formation enthalpy (kJ)
H	: Enthalpy (kJ/kg, kJ/kmol)
H_F	: Hydrogen content of fuel (%).
H_2O_F	: Moisture content of fuel (%).
H_2O_{FWV}	: Water vapor in the combustion products (kmol).
KK	: Combustion efficiency (%).
MW	: Molecular weight (kg/kmol)
Nvo	: Non-volatile oxide content (%).
N_F	: Nitrogen content of fuel (%).
N_{2F}	: Nitrogen in the combustion products (kmol).

O_F	: Oxygen content of fuel (%).
O_{2F}	: Oxygen in the combustion products (kmol).
P	: Fraction of CaO converted to $CaCO_3$.
PC	: Precalciner
Q_w	: Wall heat loss (kJ)
R	: Fraction of $CaCO_3$ converted to CaO.
RK	: Rotary kiln
SD(n)	: Dust entrained by gas leaving stage n (kg)
SG(n)	: Gas stream leaving stage n (kmol)
S_F	: Sulfur content of fuel (%).
SO_{2F}	: Sulfur dioxide in the combustion products (kmol).
T(n)	: Temperature of raw meal entering stage n (^oC, K)
T(n+1)	: Temperature of gas, dust and raw meal streams leaving stage n (^oC, K)
T_A	: Air temperature (^oC, K)
V(n+1)	: Amount of $MgCO_3$ leaving stage n (kg).
W(n+1)	: Amount of MgO leaving stage n (kg)
W_F	: Moisture content of dust free raw meal (%)
X(n+1)	: Amount of $CaCO_3$ leaving stage n (kg)
Xs	: Moisture content of air (kg water vapor/kg dry air)
Y(n+1)	: Amount of CaO leaving stage n (kg).
Z(n+1)	: Amount of a non-volatile oxide leaving stage n (kg).
$\eta(n)$	: Efficiency of nth cyclone stage (%).
λ	: Excess air coefficient (%)

Subscripts

CL	: Clinker
L	: Liquid
PC	: Precalciner
RK	: Rotary kiln
W	: Magnesium oxide or water
W, l	: Liquid water
WV	: Water vapor

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