Rice Husk as a Substitute Fuel in Cement Kiln Plant

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***Abstract*-A simple mathematical model of heat balance was applied to a cement kiln plant with a precalciner to estimate the effect of using rice husk as a substitute fuel for natural gas on specific heat consumption. Effects of the husk ash on the characteristics of the raw mix and clinker of ordinary Portland cement were also evaluated. Referring to Egyptian kiln plants data, it was found that the weight of rice husk required to supply fuel heat in the precalciner represented about 11-13% of the raw mix weight and about 90% of the total fuel weight (natural gas + husk). Specific heat consumption increased by about 3.7%, and the amount of combustion flue gases increased by about 20% when natural gas was completely substituted by rice husk. The use of rice husk as a substitute fuel in a cement kiln plant was accompanied by a marked decrease of lime saturation factor of the raw mix, a drastic decrease of tricalcium silicate and an increase of dicalcium silicate in the clinker. This data can provide the basis for the formation of a new type of cement such as high belite cement. The raw mix design was adjusted using pyrite as a correcting factor to keep the characteristics of the raw mix and the clinker similar to the factory data.**

Keywords- Alternative Fuel; Rice Husk; Natural Gas; Raw Mix Design; Clinker Mineral Composition; Raw Mix Parameters; Specific Heat Consumption

Nomenclature

m_{s1} = mass of the inlet raw mix to the preheater (kg)

h_{s1} = specific enthalpy of the inlet raw mix to the preheater (kJ/kg)

m_f = mass of the fuel (kg)

h_f = low calorific value of the fuel (kJ/kg)

h_u = specific enthalpy of the fuel (kJ/kg)

m_{A3} = mass of tertiary air from the cooler to the calciner (kg)

h_{A3} = specific enthalpy of tertiary air from the cooler to the calciner (kJ/kg)

m_{A5} = mass of secondary air from the precooling zone in the kiln (kg)

h_{A5} = specific enthalpy of secondary air from the precooling zone (kJ/kg)

m_{A6} = mass of secondary air from the cooler to the kiln (kg)

h_{A6} = specific enthalpy of secondary air from the cooler to the kiln (kJ/kg)

m_{G1} = mass of outlet flue gas from the preheater (kg)

h_{G1} = specific enthalpy of outlet flue gas from the preheater (kJ/kg)

m_{s6} = mass of clinker leaving the firing zone to the cooler (kg)

h_{s6} = specific enthalpy of clinker leaving the firing zone (kJ/kg)

$\Delta H_{R.c}$, $\Delta H_{R.K}$ = heat of reactions in the calciner and the kiln, respectively (kJ)

$Q_{w.p.c}$, $Q_{w.k}$, $Q_{w.c.}$ = wall heat losses from the preheater- calciner, kiln, and cooler, respectively (kJ)

V_{af} = theoretical amount of fuel combustion air (Nm^3/kg fuel)

V_{gf} = theoretical amount of fuel combustion gases (Nm^3/kg fuel)

λ = excess air factor for fuel combustion

M_{CO2} = mass of evolved CO2 from calcination

Cp_g, Cp_a = specific heat of flue gases and air, respectively ($kJ/Nm^3\,^oC$)

T_g, T_a = temperature of flue gas and combustion air, respectively (^oC)

h.f.o. = heavy fuel oil

cli. = clinker

LSF = lime saturation factor

SIM = silica modulus

AM = alumina modulus

C_3S = tricalcium silicate

C_2S = dicalcium silicate

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C_3A = tricalcium aluminate

C_4AF = tetracalcium aluminate ferrite

Borders of the heat balance zones, as shown in Fig. 2:

[1] - [2] = preheating zone

[2] - [3] = precalciner zone

[3] - [4] = bottom stage cyclone

[4] - [5] = heating zone of the rotary kiln

[5] - [6] = precooling zone

[6] - [7] = cooler

I. INTRODUCTION

Cement manufacture is an energy-intensive industry in which energy is mainly consumed in the pyro process of the kiln plant for producing cement clinker. The heat requirements of a cement kiln plant depends, to a major extent, on the technology used. In the modern dry process with a suspension preheater and precalciner, the specific heat consumption ranges from 2,926 to 4,180 kJ/kg clinker depending on the various operational and technical parameters of the process [1]. Cement manufacture is also considered an industry of intense carbon dioxide emissions evolving from fuel combustion and decomposition of calcium carbonates, which usually constitutes the majority (about 80%) of the raw mix of ordinary Portland cement. Some estimates put the cement industry as high as 5% of the total global and anthropogenic CO2 emissions [2].

Today, the business environment for cement producers is becoming more challenging. Rising production costs, the depletion of conventional energy sources, and more stringent environmental regulations are the main limiting factors. Therefore, the cement industry is looking for ways to adjust production processes correspondingly. One proven solution is the utilization of alternative fuels, which has been realized, to various degrees, in different parts of the world [3, 4]. Compared to other energy-intensive industries, the cement clinker burning process allows for a relatively high potential to use secondary fuels [5]. This is due to the robustness of the clinker burning process and in its principal layout as a counter-current process. The manufacturing process of a cement clinker is characterized such that solid combustion residues are mixed directly into the product mass flows and the exhaust gases are brought into contact with the counter-currently flowing raw meal.

A. Dry Process Cement Kiln Plant with Suspension Preheater and Precalciner [1]

The dry process with precalcination is the most up-to-date technique for clinker manufacture. It is characterized by high productivity and a relatively low specific heat consumption [1]. Fig. 1 shows a schematic representation of a dry process kiln plant. The operational data shown in Fig. 1 corresponds to the industrial process of an Egyptian cement kiln plant [6].

As shown in the figure, the kiln plant consists of a multi stage cyclone preheater, calciner, rotary kiln, and cooler. Raw meal is fed into the cyclone preheater and heated by the rising hot gases. The preheated raw meal is then partially calcined in the calciner with supplied energy from fuel and hot gas flowing from the kiln to the calciner. The solid material then slides to the rotary kiln, where it flows counter-currently to the kiln fuel combustion gases. It is completely calcined in the kiln and heated to the clinkering temperature, promoting the formation of clinker phases. Clinker is then cooled in the cooler to its exit temperature by induced cooling air. There are three main types of clinker coolers: rotary, planetary, and grate. A portion of the hot air from the cooler is withdrawn to the kiln (secondary air) and a portion goes to the calciner (tertiary air) to act as fuel combustion air. ln cases where the raw materials and fuel are relatively rich of secondary constituents, such as alkalis, chlorides, and sulfates, an intense circulation occurs between the preheater-calciner and kiln. It is then necessary to expel a fraction of the kiln gas, in an amount determined by the intensity of the cycle, through a kiln gas bypass in order to break up the formed cycle and avoid operational and clinker quality complications [7-9].

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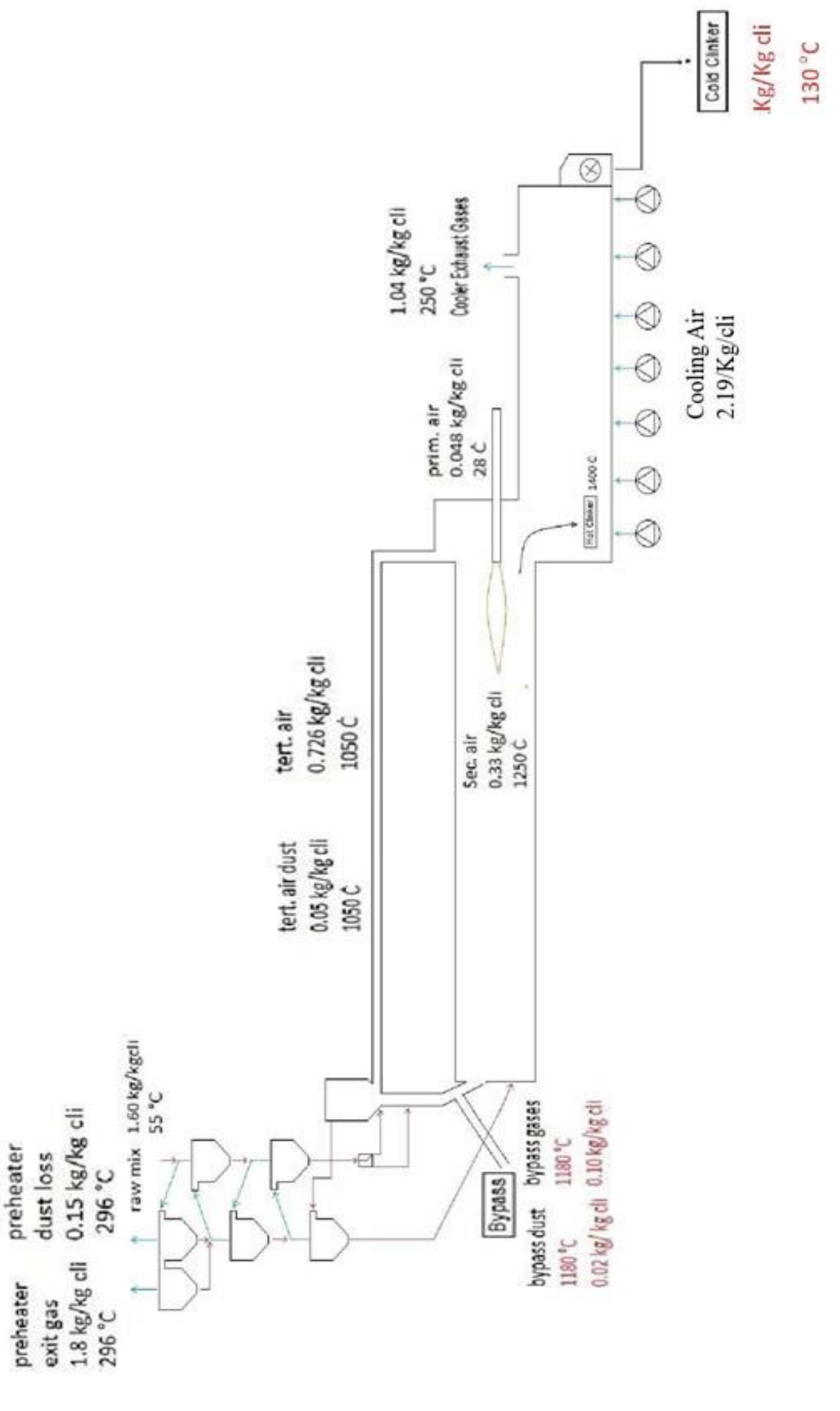

Fig. 1 Schematic diagram of kiln system

B. Rice Husk as Alternative Fuel in Cement Kiln Plant

Rice husk is an agricultural byproduct produced by hulling paddy. It is the outer shell of the rice grain representing about one fifth of the weight of the paddy, and is part organic and part inorganic. It has a moderate calorific value of ≈12,540 kJ/kg. The inorganic portion of the hull is represented by the remaining ash after hull combustion; it represents about 20% of the husk

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weight, comprised of 90-95% silica and other mineral oxides as oxides of Mg, Mn, K, Na [10, 11].

Egypt produces approximately one million tons of rice husk byproduct annually. This agricultural renewable residue has been of no use in Egypt until now. Rice husk as alternative fuel in cement kiln plants act as an energy source that is liberated by the husk combustion, and as a source of raw material represented by the remaining ash after combustion. However, the amount and composition of the ash should be taken into consideration in the design of the clinker raw mix.

The utilization of rice husk as an alternative fuel in cement kiln plants represents a great benefit regarding the conservation of conventional fuel and environmental control. The use of biomass, such as rice husk, as a non-conventional fuel is environmentally friendly because of the fact that the CO_2 created during combustion of the biomass is removed from the atmosphere by that species during its plant growth phase. Because the growth of the biomass and its usage as a fuel occurs in a short time scale, the entire cycle is believed to have zero net impact on atmospheric carbon emissions [12, 13]. The use of biomass residues has the added benefit of reducing the cement's nitrogen oxide (NOx) emissions [14]. Empirical evidence suggests that the reduction in NOx is due to the fact that most of the nitrogen in the biomass is released as ammonia (NH3), which acts as a reducing agent for NOx to form N2.

A biomass, such as rice husk, can be used in cement plants through direct combustion in the preheaters, the precalciner, and in the kiln by partially replacing the fossile fuel used. This can happen in two ways [15]: first, by mixing crushed and pulverized biomass with coal or petcoke; and secondly, by the direct-feeding of biomass in solid lump form (such as pellets or briquettes) into the rotary kiln and/or the preheater/precalciner combustion chamber. The biomass can also be transformed into a producer gas (also known as synthesis gas or syngas) and co-firing it in the kilns using a gas burner [15]. A well-established technology allows the rotary kiln of any cement plant to be fired with low-volatile fuels, such as petcoke, low-volatile bituminous coal, and anthracite, without complications [16]. On the other hand, highly volatile low-calorific alternative fuels have limited use in kiln primary firing systems due to their relatively low combustion temperatures. They are utilized more in the precalciner firing than in the kiln unless their calorific value exceeds 16.8 MJ/kg [4, 17]. Experience has shown that it is difficult to obtain complete combustion of low-volatile fuels in a precaliner [16, 18]. It is suggested that a non-conventional fuel, such as rice husk, be mostly utilized in precalciners [4].

It is necessary to adapt the combustion process of the alternative fuel (AF), e.g. rice husk, in a cement kiln plant in order to achieve its complete combustion. In the case of incomplete combustion of the fuel, unburned carbon particles accumulate in the clinker, which has a detrimental effect on the clinker and cement properties [19, 20]. Additionally, an increase of water demand would arise due to the extra water adsorption on the surface of the carbon particles. Unburned carbon particles have more surface area and porosity, resulting in more water being absorbed. Increased water demand increases the water-cement ratio of mortar or results in concrete with decreased ultimate strength.

In general, high substitution rates of fossil fuel by an AF can only be achieved if the process and the machine technology is tuned and adapted to the requirements that arise through the use of the AF.

Optimization criteria to consider for the combustion of an AF are:

Favourable ignition and burn-out conditions for the mostly lumpy material.

Avoidance of wall contacts of the ignited fuel particles, which become sticky.

Creation of sufficient residence time of the fuel to complete burn-out before immersion in the material bed or before quenching of the combustion by the meal.

Creation of favourable gas composition and temperatures for low pollutant generation or emission.

The challenges arising from the implementation of these targets are briefly described below for the two most frequently used feed locations, the main burner in the kiln and in the calciner [5, 21].

Feed Point: Main Burner

A process should be designed in the main burner to guide the secondary fuel quickly through a zone of high temperature and high O2 content. Falling the fuel prematurely and unburnt into the bed of material is to be expected. The development of a modern low-NOx three-channel burner can be employed in this case as a kiln burner or a calciner burner [21].

Calciner Solutions:

Calciner design has a strong influence on both emissions and the ability to effectively burn an alternative fuel that is difficult to burn. A combined theoretical and practical approach has helped to develop new calciner designs and produced a strong platform for predicting emission levels under different conditions. Depending on the application, the low-NOx inline calciner, separate–line calciner with downdraft, pre-combustion chamber, and disc reactor for firing of lumpy solid waste fuel present optimal choices to maximize the utilization of available difficult-to-burn fuels, while still maintaining environmental compliance with maximum kiln availability [21].

The present article provides a theoretical evaluation of the effect of utilizing rice husk as an alternative fuel to natural gas in

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an Egyptian dry process cement kiln plant with a precalciner on both the specific heat consumption and operational data of the process, as well as its effect on the parameters of the OPC raw mix and the mineral composition of the clinker. A simple mathematical model of heat balance [22] with a slight modification was applied to the kiln plant to estimate the effects of the type of fuel used (e.g., natural gas or rice husk) on some operational conditions of the plant such as the specific heat consumption and amount of flowing hot gases. The raw mix design was re-adjusted, taking into consideration the effect of the husk residual ash, in order to keep the same characteristics of the raw mix and the clinker as the factory data. The present study was based on actual operational data of Egyptian cement kiln plants [22, 6].

II. COMBUSTION CHARACTERISTICS OF RICE HUSK AND NATURAL GAS

Table 1 shows the micro analysis of an available sample of rice husk [11].

TABLE 1 MICRO ANALYSIS OF ONE OF THE AVAILABLE SAMPLES OF RICE HUSK

Wt%	Carbon	Hydrogen	Nitrogen	Oxygen	Ash
Dry basis	37.69	5.23	0.5	36.58	20
Green basis	33.92	4.70	0.45	32.92	18

Moisture content of rice husk is about 10% of its green weight, and its total volatile matter attains about 60% of its dry weight. Table 2 shows the chemical composition of the residual husk ash.

TABLE 2 CHEMICAL COMPOSITION OF THE RESIDUAL HUSK ASH

Oxide	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
Wt %	94.3	1.7	0.2	0.09	0.74	0.78	0.48	1.68

The combustion heat of the rice husk was determined using the empirical Dulong-Berthelot correlation [23]:

For dry husk ≈ 12479.8 kJ/kg

For green hulls (considering the heat required for evaporation of its water content) = 10982.95 kJ/kg

The chemical composition of natural gas, wt %:

74.72 % C, 24.54 % H2, 0.09 % N2

LCV (low calorific value) = 48784.78 kJ/kg gas

By applying thermochemical equations of combustion [20], the combustion data of natural gas and rice hull were calculated and summarized in Table 3.

TABLE 3 COMPARATIVE COMBUSTION DATA OF NATURAL GAS AND RICE HUSK

Data	Natural gas	Rice husk (green basis)
Low calorific value ,kJ/kg	48784.78	10982.95
Fuel weight ,kg/4180 kJ	0.086	0.38
Theoretical combustion air: Nm^3/kg Nm^3/ 4180 kJ	 15.67 1.34	 3.47 1.16
Theoretical combustion gases: Nm^3/kg fuel Nm^3/ 4180 kJ	 16.53 1.42	 4.55 1.73
Composition of combustion co gases, Mole %: CO_2 H_2O N_2	 7.9 16.69 75.4	 14.26 21.88 63.77
Amount of evolved gases, Nm^3/4180 kJ CO_2 H_2O N_2	 0.11 0.24 1.07	 0.25 0.39 1.10
Amount of residual ash, kg /4180 kJ	 --------	 0.07

As is clear from Table 3, rice husk is characterized by relatively low calorific value, expressing itself in larger weights of the husk, needing about 4 times the weight of natural gas to give the same amount of heat. Theoretical amount of combustion gases to produce 4,180 kJ (1000 kcal) of combustion heat is larger for rice hulls than for natural gas with a higher concentration of CO_2. However, the amount of combustion air for 4,180 kJ (1,000 kcal) evolved heat is somewhat smaller for rice hulls than for natural gas. (This refers to the husk content of O_2.)

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III. AVERAGE OPERATIONAL DATA OF EGYPTIAN CEMENT KILN PLANTS

Table 4 shows average operational data of six Egyptian dry process cement kiln plants with precalciners. It also shows the estimated weight of rice husk required to substitute conventional fuel in the calciner.

As is clear from Table 4, fuel used in Egyptian kiln plants is mostly conventional fuel, natural gas, or heavy fuel oil. Productivity ranges from 2,000 to 6,000 T/d (2-3.7 T/ d .m3 kiln volume). Percentage of fuel heat in the calciners range from 57-66% of the total fuel heat; it ranges from 2,000-2,600 kJ/kg clinker. To obtain such heat demand via combustion of rice husk, 0.18-0.23 kg hulls are needed per kg clinker, corresponding to 0.11- 0.13 kg hulls per kg raw mix.

It is noteworthy to mention that the operational data of the process listed in column 6 (the most thermally-efficient process) was used as the basis for calculations in applying the mathematical model of heat balance, as is shown in the next part [6].

TABLE 4 AVERAGE OPERATIONAL DATA OF SIX EGYPTIAN CEMENT KILN PLANTS

Process/data	1	2	3	4	5	6
Kiln dimensions,m	4.2*85	3.9*73.1	4.6*75	4.6*75	4.75*58.8	5*80
Productivity -T/day -T/d.m3kiln vol.	4399 3.735	3159 3.617	3472 2.786	3360 2.696	2150 2.063	6300 4.01
Fuel Type -Calciner -kiln	h.f.oil " "	h.f.oil natural gas	h.f.oil " "	h.f.oil " "	h.f.oil " "	natural gas " "
Specific heat consumption -kJ/kg cli. -kg fuel/kg cli	4202 0.103	3507 0.086	3754 0.092	3998 0.098	3957 0.097	3151.7 0.065
Net thermal efficiency	41.2%	50.04%	46%	43.6%	44.25%	55%
% Fuel heat in calciner	57.3	62	60.9	59.2	64.9	66
Fuel heat in calciner, kJ	2407	2170	2285	2366	2470	2080
Rice husk in calciner, kg	0.219	0.198	0.208	0.215	0.225	0.189
Raw mix factor,kg/kg cli.	1.9	1.76	1.76	1.8	1.79	1.6
Calciner rice husk, kg kg/kg raw mix	0.115	0.113	0.118	0.119	0.125	0.118

Table 5 shows the chemical compositions of the raw mix, limestone, and clay derived from the Egyptian cement factory [6] and were used as the basis for the calculation of the effects of husk ash on both the raw mix and the chemical and mineral composition of the clinker.

TABLE 5 CHEMICAL COMPOSITION OF THE RAW MIX, LIMESTONE, AND CLAY

Raw Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Cl	L.O.I
Raw mix	14.02	2.97	1.92	42.08	1.04	1.38	0.36	0.365	35.86
Clay	61.38	13.77	9.09	2.65	1.89	1.52	1.24	1.05	7.42
Limestone	2.58	0.37	0.19	51.60	0.90	1.35	0.05	0.20	42.76

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IV. SIMPLE MATHEMATICAL MODEL OF HEAT BALANCE AROUND THE HEATING ZONE OF CEMENT KILN PLANT [19]

A simple mathematical model of mass and heat balances around the heating zone of a cement kiln plant with a precalciner and tertiary air from the cooler to the calciner [19] was applied to estimate the effect of replacing a part of a conventional fuel, e.g., natural gas, with rice husk on the specific heat consumption and some operational data of the process. Fig. 2 shows various items of mass and heat balances around the kiln plant.

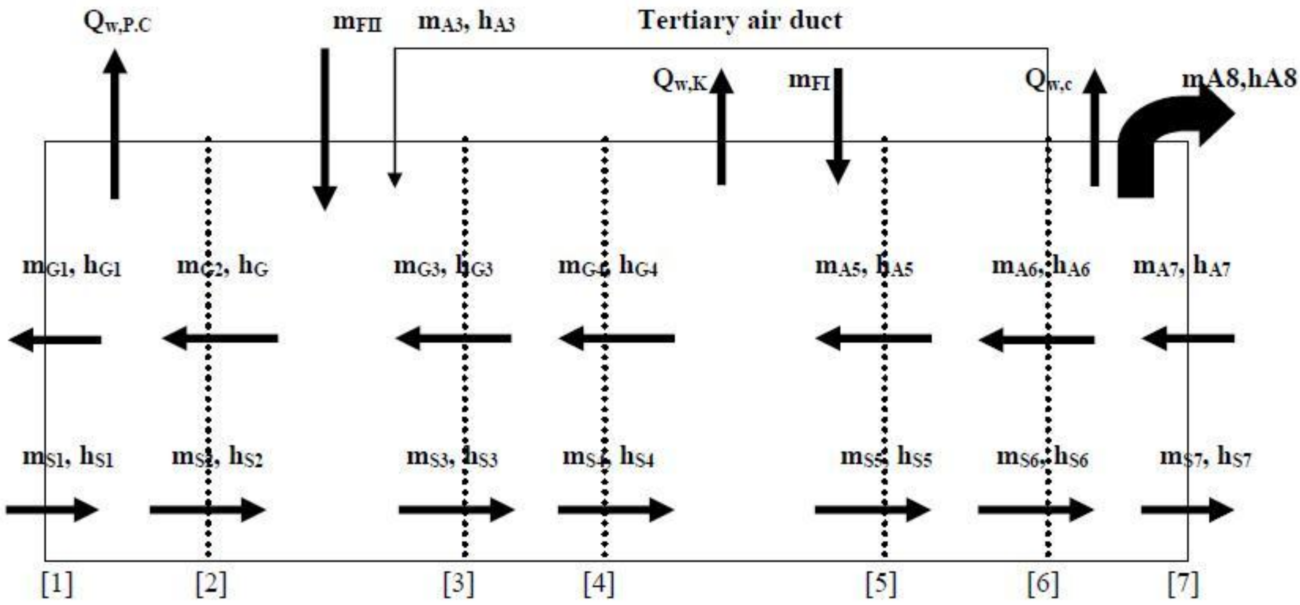

Fig. 2 Mass and heat balance items around cement kiln plant with tertiary air duct

A. *Simplifying Assumptions in Establishing the Model*

- Induced false air and primary air for fuel combustion have been neglected.

- Dust loads of gases in the kiln system have been neglected.

- The process is operated without kiln gas bypass.

- The specific enthalpies of secondary air to the kiln and tertiary air to the calciner are equal. In other words, they have the same temperature.

- Heat changes due to circulated compounds between the rotary kiln and preheater precalciner have been neglected.

B. *Heat Balance around the Kiln System*

1) *Heat Balance around the Heating System*

The equation of heat balance around the heating system of the kiln plant (cyclone preheater-precalciner-kiln), considering the same type of fuel in the calciner and kiln, can be expressed as follows:

Sum of heat inputs = sum of heat outputs,

$$m_{s1}.h_{s1} + m_f(h_f+h_u) + m_{A3}h_{A3} + m_{A6}h_{A6}= m_{G1}h_{G1} + m_{s6}\, h_{s6} + \Delta H_{R\cdot c} + \Delta H_{R\cdot K} + Q_{w.p.c} + Qw.k \quad (1)$$

where mf sum of fuel weights in calciner and kiln.

From Eq. (1), the required fuel weight mf can be estimated according to the following equation:

$$m_f = (m_{s6}\, h_{s6} – m_{s1}h_{s1} + \Delta H_{R.c} + \Delta H_{R.K} + Q_{w.p.c} + Q_{w.k} - m_{CO2}Cp_gT_g) / (h_f + \lambda V_{af}Cp_aT_{af}-(V_{gf} + (\lambda - 1)\, V_{af})\, Cp_gT_g)) \quad (2)$$

In Eq. (2), the numerator expresses the sum of different heat consuming items irrespective of the fuel used; it can be put as ∑Q, whereas the denominator expresses various characterizing data of the fuel used, e.g., calorific value, theoretical combustion air, theoretical combustion gases, and excess air factor for combustion.

Considering the use of two different types of fuel, natural gas (ng) and rice husk (rh), and assuming the weight fraction of natural gas in the total fuel is 'r' and that of rice husk is '(1-r)', the following is true:

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$$mf = [r\ mf](\text{kg natural gas}) + [(1\text{-}r)mf]\ (\text{kg rice hulls}) \quad (3)$$

The total fuel weight, i.e. the sum of weights of natural gas and rice husk, mf, can be calculated from Eq. (2) by expressing the sum of fuel characterizing data of natural gas and rice husk in the denominator as follows:

$$m_f = \sum Q / [r\ \{h_f + \lambda V_{af}\ Cp_a T_{af} - (V_{gf} + (\lambda -1)\ V_{af})\ Cp_g T_g\}ng + (1\text{-}r)\ \{h_f + \lambda V_{af} Cp_a T_{af} - (V_{gf} + (\lambda - 1)\ V_{af})\ Cp_g T_g\}\ rh] \quad (4)$$

For simplicity, Eq. (4) can be rewritten as:

$$mf = \sum Q / (r\ (A) + (1\text{-}r)\ B) \quad (5)$$

where A expresses the combustion characteristics of the natural gas:

$A = \{h_f + \lambda V_{af}\ Cp_a T_{af} - (\ V_{gf} + (\ \lambda -1)\ V_{af}\ )\ Cp_g T_g\}ng;$

and B expresses combustion characteristics of rice hulls:

$B = \{h_f + \lambda V_{af} Cp_a T_{af} - (V_{gf} + (\lambda -1)V_{af}\ )\ Cp_g T_g\}\ rh$

2) Heat Balance and Thermal Efficiency of the Cooler

The heat balance equation around the cooler can be expressed as follows:

$$m_{s6}\ h_{s6} + m_{A7} h_{A7} = m_{s7} h_{s7} + m_{A6} h_{A6} + m_{A3} h_{A3} + Q_{w.c} + m_{A8} h_{A8} \quad (6)$$

The thermal efficiency of the cooler, η_c, can be expressed as a function of the amounts and specific enthalpies of secondary air and tertiary air from the cooler, as follows:

$$\eta_C = (m_{A6}\ h_{A6} + m_{A3}\ h_{A3}) / (m_{s6}\ h_{s6}) \quad (7)$$

By applying Eqs. (4) and (7), specific consumption weights of natural gas and rice husk and the thermal efficiency of the cooler were calculated for different substitution degrees of the gas by the hulls, i.e., for various values of r ranging from r = 1 corresponding to 100% natural gas and r = zero corresponding to 100% husk.

The mathematical model was applied considering average operational data of column 6 in Table 4 [6].

$\sum Q$ was estimated from operational data of the process as the sum of the following heat items:

$m_{s6}\ h_{s6} = 1(1.1)\ (1400) = 1{,}544.9$ kJ

$m_{s1}\ h_{s1} = 1.6(0.88)\ (55) = 77.7$ kJ

$M_{CO2}\ (h_{CO2}) = 0.27\ (1.46)\ (296) = 117.04$ kJ

$\Delta H_{RC} = 1{,}923.6$ kJ

$\Delta H_{rk} = -144.6$ kJ

$Q_{w.p.c} = 229.9$ kJ

$Q_{wk} = 130.8$ kJ

$\sum Q = 3{,}723.96$ kJ/kg clinker

Considering both fuels:

$\lambda = 1.1;\ T_a = 1{,}050\ ^oC;\ T_g = 296\ ^oC$

The values of A and B were calculated as follows:

A = 65,912.7 kJ/kg fuel; B = 14,390.78 kJ/kg fuel

V. RESULTS

A. Results of Applying the Simple Mathematical Model of Heat Balance

Table 6 shows the estimated operational data of the cement kiln plant for substitution fractions of natural gas with rice husk varying from zero to 1, i.e., from 100% natural gas to 100% rice husk. The estimated operational data were specific heat consumption, specific weights of natural gas and rice husk, liberated heat of each fuel, specific amounts of combustion air, and combustion gases.

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TABLE 6 ESTIMATED OPERATIONAL DATA OF CEMENT KILN PLANT (BASIS 1 KG CLINKER)

r	H_f kJ	Natural gas		Rice husk		V_{fa} Nm^3	V_{fg} Nm^3
		Amount kg	Heat kJ	Amount kg	Heat kJ		
1	2731.6	0.056	2731.6	0	0	0.96	1.28
0.8	2732.5	0.053	2585.8	0.013	142.5	0.98	1.3
0.6	2742.1	0.049	2386.7	0.032	351.3	0.96	1.32
0.4	2747.5	0.042	2048.2	0.064	702.6	0.96	1.34
0.2	2781.3	0.03	1463.4	0.12	1317.5	0.97	1.4
0.1	2804.8	0.019	926.7	0.171	1876.8	0.98	1.45
0	2833.6	0	0	0.258	2833.6	0.98	1.53

As is clear from Table 6, with the increase of weight fraction of the rice husk in the fuel used, the following was noticed:

- The overall specific heat consumption increased by about 3.7% when changed from 100% gas to 100% rice husk. For the husk to supply fuel heat required in the calciner (1,672 – 2,090 kJ/kg clinker, as shown in Table 4), its required weight would be ≈0.9 of the total weight of the needed fuel (gas + hulls). At complete substitution of natural gas with rice husk, the weight of husk needed was about 5 times that of gas. This is attributed to the relatively low calorific value of rice husk compared to that of natural gas.

- The specific amount of flue gases increased with the increase of husk fraction in the used fuel; it increased by about 20% in complete substitution of the gas with the husk, whereas the amount of combustion air was almost constant.

- The thermal efficiency of the cooler was found to vary between 0.9 and 0.92. This meant that about 90-92% of the clinker heat was recovered in the cooler via preheating combustion air for the precalciner and kiln fuel. The cooler thermal efficiency remained nearly constant when the natural gas was substituted with rice husk.

B. Effects of Rice Husk Ash on The Characteristics of OPC Raw Mix and Clinker

Expressing the amount of rice husk used as wt% of the clinker raw mix, Table 7 shows the change of both the chemical composition and the parameters of the OPC raw mix (LSF, SM, AM) with the increase of rice husk until it formed about 10 wt% of the raw mix. As is clear from Table 7, with the increase of rice husk percentage, the SiO_2 in the raw mix increased, whereas percentages of all the other oxides (Al_2O_3, Fe_2O_3, CaO, SO_3 …) decreased. On the other hand, LSF of the raw mix decreased remarkably, whereas SM and AM increased only slightly with the husk percentage increase.

TABLE 7 CHARACTERISTIC DATA OF OPC RAW MIX WITH HUSK ADDITIONS

% of added rice husk in raw mix	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	Cl	LSF	SM	AM
0	14.02	2.97	1.92	42.08	1.04	1.38	0.37	0	0	0.365	95.62	2.86	1.548
2	14.11	2.92	1.88	41.24	1.02	1.35	0.292	0.002	0	0.358	93.32	2.94	1.551
4	14.21	2.87	1.85	40.40	1.00	1.33	0.287	0.004	0.001	0.35	91.05	3.01	1.554
6	14.31	2.82	1.81	39.56	0.99	1.30	0.28	0.006	0.001	0.343	88.79	3.09	1.57
8	14.41	2.76	1.77	38.73	0.97	1.27	0.275	0.008	0.001	0.336	86.54	3.18	1.56
10	14.50	2.71	1.73	37.89	0.95	1.24	0.27	0.010	0.002	0.329	84.32	3.26	1.564

Table 8 shows the estimated change of both the chemical composition and the potential mineral composition of OPC clinker with the increase of husk additions. As is clear from Table 8, with the increase of such additions, weight percentages of all oxides in the clinker, except SiO_2, decreased. The potential mineral composition of the clinker changed remarkably with the husk addition: C_3S decreased, C_2S increased, whereas C_3A and C_4AF decreased only slightly.

The data in Table 8 are shown graphically in Fig. 3. As is clear from Fig. 3, with the husk additions till forming about 10 wt% of the raw mix, the potential mineral composition of the clinker changed remarkably; both C_3S decreased and C_2S increased remarkably, whereas C_3A, C_4AF, and the liquid phase decreased only slightly. C_3S decreased from 65.5 wt% to 39 wt% and C_2S increased from 13 wt% to 40 wt% when rice husk increased from zero to 10 wt% of the raw mix. At about 9% husk addition, % C_3S and % C_2S in the clinker were nearly equal.

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TABLE 8 CHANGE OF CHEMICAL AND MINERAL COMPOSITION POTENTIAL OF OPC CLINKER WITH RICE HUSK ADDITIONS

% of added rice husk in raw mix	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	Cl	C_3S	C_2S	C_3A	C_4AF
0	21.876	4.64	3	65.60	1.62	2.16	0.47	0	0	0.57	65.49	13.25	7.22	9.11
2	22.336	4.62	2.98	6.266	1.616	2.15	0.462	0.003	0.001	0.566	60.56	18.35	7.21	9.07
4	22.81	4.61	2.96	64.85	1.611	2.13	0.46	0.006	0.001	0.562	55.41	23.60	7.19	9.016
6	23.298	4.59	2.94	64.42	1.606	2.12	0.457	0.009	0.002	0.559	50.12	28.99	7.17	8.96
8	23.80	4.57	2.92	63.98	1.600	2.10	0.455	0.013	0.002	0.555	44.676	34.4	7.15	8.90
10	24.317	4.54	2.91	63.53	1.59	2.09	0.452	0.016	0.003	0.551	39.06	40.25	7.13	8.84

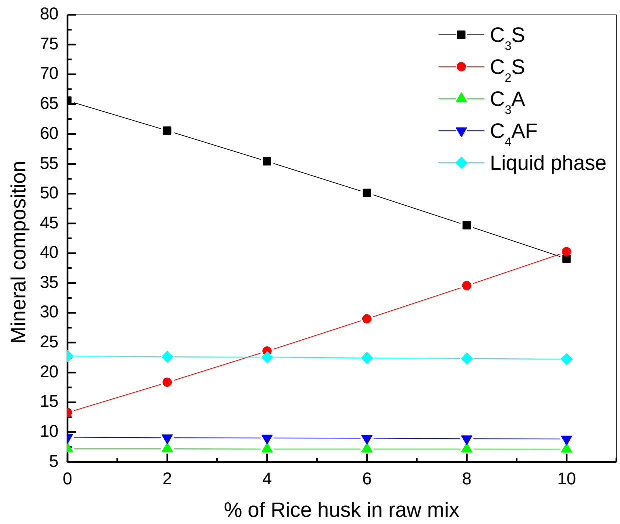

Fig. 3 Effects of rice husk additions on the mineral composition potential of OPC clinker

As shown above, the use of rice husk as a substitute fuel in a cement kiln plant was accompanied by marked changes in the parameters of the mix and the produced clinker. That referred to the enrichment of the husk ash with silica, which led to an increase of silica content of the raw mix on the expense of other oxides such as Al_2O_3, Fe_2O_3, CaO, MgO. In fact, this can form a basis for the production of other types of clinkers such as a high belite clinker.

If it is required to maintain the raw mix parameters and the clinker mineral potential composition in the same range of factory data (the same C_3S% and C_2S%), it will be necessary to re-adjust the raw mix design to achieve that purpose. In the present work, the raw mix was adjusted while keeping LSF and SM nearly constant through the use of pyrite as a correction factor. The calculations were based on equations for raw mix with three components, modified clay (clay + husk), limestone, and pyrite [24].

Tables 9 and 10 show the characteristics of the adjusted raw mix and clinker, respectively. As shown in Table 9, with husk addition, percentages of all oxides in the mix decreased except Fe_2O_3; LSF and SM of the mix remained constant, whereas AM decreased. As is clear from Table 10, with husk additions, C_3S and C_2S in the clinker were nearly constant, C_3A decreased, C_4AF increased, and the liquid phase decreased slightly.

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TABLE 9 CHARACTERISTIC DATA OF THE CALCULATED OPC RAW MIX (WT., %)

% of Rice husk in the clay	Raw mix composition =100%				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	Cl	LSF	SM	AM
	Lime stone %	Clay %	Rice husk **%**	Pyrite %													
0	80.54	19.45	0	0.008	14.02	2.97	1.93	42.07	1.09	1.38	0.28	0	0	0.365	95	2.86	1.54
10	79.20	18.51	2.06	0.223	13.81	2.85	1.98	41.36	1.07	1.35	0.27	0.002	0	0.354	95	2.86	1.44
20	77.69	17.47	4.37	0.465	13.58	2.71	2.03	40.56	1.04	1.32	0.27	0.004	0.001	0.341	95	2.86	1.33
30	75.99	16.29	6.98	0.738	13.33	2.55	2.10	39.66	1.01	1.29	0.26	0.007	0.001	0.327	95	2.86	1.22
40	74.04	14.95	9.96	1.049	13.03	2.38	2.17	38.62	0.97	1.25	0.26	0.010	0.002	0.311	95	2.86	1.1
50	71.8	13.40	13.40	1.408	12.69	2.17	2.26	37.44	0.93	1.21	0.25	0.013	0.003	0.292	95	2.86	1

TABLE 10 CHEMICAL COMPOSITION AND MINERAL COMPOSITION POTENTIAL OF THE CLINKER

%of Rice husk in the clay	% of Rice husk in the raw mix	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	Cl	C_3S	C_2S	C_3A	C_4AF	Liquid phase
0	0	21.86	4.64	3.00	65.62	1.70	2.16	0.44	0	0	0.57	65.48	13.28	7.21	9.14	22.82
10	2.06	21.89	4.52	3.14	65.6	1.69	2.15	0.44	0.003	0.001	0.561	65.70	13.22	6.678	9.54	22.75
20	4.37	21.95	4.39	3.29	65.55	1.68	2.14	0.44	0.007	0.001	0.552	65.81	13.28	6.062	10.01	22.68
30	6.98	22.00	4.23	3.47	65.50	1.66	2.14	0.440	0.012	0.002	0.540	65.975	13.340	5.3350	10.55	22.59
40	9.96	22.07	4.04	3.68	65.44	1.64	2.13	0.440	0.017	0.003	0.527	66.182	13.383	4.4658	11.21	22.49
50	13.40	22.16	3.80	3.95	65.37	1.62	2.119	0.44	0.023	0.005	0.510	66.448	13.422	3.4059	12.01	22.37

VI. CONCLUSION

Rice husk can be used as an alternative fuel to supply the heat required in calciners of modern cement dry processes. Calciner operation conditions and its relatively low operational temperature are suitable for rice husk combustion as a highly volatile low-calorific fuel in contrast to a rotary kiln, which needs fuel that is low-volatile and highly calorific to attain the high temperature needed. It was estimated, according to Egyptian cement kiln plant data, that the weight of rice husk needed to supply heat in a calciner would attain about 10% of the raw mix weight and be several times higher than that of a conventional fuel, such as natural gas, because of the much higher calorific value of the latter. In general, retrofitting of a kiln plant is necessary to accomplish complete combustion of a low-calorific, difficult-to-burn fuel such as rice husk.

By applying a simple mathematical model of heat balance to a kiln plant, it was found that using rice husk as a substitute fuel for natural gas in the calciner was accompanied by an increase of the specific heat consumption and an increase of the specific amount of flowing hot combustion gases through the process. Rice husk ash remarkably affected the raw mix parameters and the potential of the clinker mineral composition; LSF decreased dramatically and SM increased, whereas AM increased only slightly. The change of raw mix parameters was reflected in a decrease of C_3S and an increase of C_2S percentages of the clinker. In order to maintain nearly the same mineral composition of the clinker, the latter was adjusted through the use of pyrite as a correction factor to keep the same LSF and SM of the raw mix. With husk additions, the mineral potential of the clinker was characterized by nearly constant percentages of C_3S and C_2S, a slight decrease of C_3A, and an increase of C_4AF with a slight decrease of the liquid phase.

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