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Full Length Research Paper

Energy and exergy analyses of a parallel flow, four-stage cyclone precalciner type cement plant

Ahmet Kolip[1*] **and Ahmet Fevzi Savas**[2]

[1]University of Sakarya, Technical Education Faculty 54187, Esentepe, Sakarya, Turkey.
[2]University of Bilecik, Osmaneli Vocational School 11500, Osmaneli, Bilecik, Turkey.

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It is well known that cement production is one of the most energy consuming industries in the world and comes after steel industry (19.7%). For this reason, energy saving and efficiency efforts target these industries in the first place. The method developed for cement industry, in which the ratio of energy costs with respect to total costs is very high (55%) that provides the optimum working ranges according to energy costs and efficiency for the units. Additionally, in the case of a problem occurring in the system, whether the source is a parameter or not on a unit is detected easily. In this paper, a mathematical model related to energy and exergy balance for four-stage cyclone precalciner type cement plant is developed. The energy and exergy balances for the whole system and each unit are calculated and presented. The results showed that the first and second law efficiencies were 51 and 28%, respectively. Total exergy loss of the system was found to be about 72%.

Key words: Parallel flow, precalciner, cement, energy and exergy analysis, mathematical model.

INTRODUCTION

The cement production of the world since 2006 has reached 2.3 billion ton by a rise of 24%, Turkish cement production has reached 50.7 million ton by a rise of 44% [UTCP, 2008]. The world's biggest producers have been listed as: China (43%), India (6%), USA (5%) and Japan (3%). While Turkey has been in first ten large producers by a ratio of 2% in cement production and consumption in the world, Turkey is in a competition for the first row with Spain and Italy in Europe. Besides, Turkey has been on the top of the list who export cement most in Europe and among the three in the world (Doğan, 2007). The construction movements in the far East countries, in Iraq after the war and in the near neighboring countries have raised the demand to the cement enormously. The geographical closeness of Turkey to these countries offers a potential advantage for the national cement industry.

Cement sector is the third sector with a 19.7% ratio in the industrial consumption among the sectors using the energy most. Electricity and fuel energy have a portion of approximately 55% among all the costs. This sector which has dense energy consumption should profit at the greatest point in minimizing of energy use, or in the methods and techniques of saving off the energy and especially fuel energy in order to compete against related sectors of the foreign countries (TUBITAK report, 1997).

Since the cement production is an energy intensive process, the energy economics is particularly of interest in this industry. Therefore, this subject has been of much interest in the last few decades. Recently, Engin et al. (2005) studied the energy audit and recovery for a dry type cement rotary kiln system with a capacity of 600 ton-clinker per day. They showed that 15.6% of the total input energy could be recovered. Karbassi et al. (2010) aimed at the investigation the role of Iranian cement industries and their contribution of greenhouse gases contribution. The strength, weakness, opportunity and threat technique analysis showed that the best strategy to combat greenhouse gases from Iranian cement factory is to implement energy efficiency measures. Further, strategic position and action evaluation matrix analysis indicates that Iranian cement industries fall within invasive category. The results show that replacement of ball mills with vertical roller mill can reduce the electricity consumption from 44.6 to 28 kWh/ton. Borsukiewicz- Gozdur and

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*Corresponding author. E-mail: akolip@sakarya.edu.tr. Tel: +90 264 295 65 17.

Nowak (2009) studied the waste energy heat utilisation from the process of burning the cement clinker in the power station with supercritical organic cycle. They showed that the waste heat available from cooler stack could be recovered by converting it into electiricity. Hepbasli and Utlu (2007) reviewed energy and exergy utilization efficiencies in the Turkish industrial sector (TIS) over the period from 1990 to 2003. They performed energy and exergy analyses for eight industrial modes, namely iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry, other industry, while in the analysis the actual data were used. They concluded that the methodology used in their study was practical and useful for analyzing sectoral and subsectoral energy and exergy utilization to determine how efficient energy and exergy were used in the sector studied. It was also pointed out that their study would be helpful in developing highly applicable and productive planning for energy policies.

Mujumdara et al. (2007) presented an integrated reaction engineering based mathematical model for clinker formation in cement industry. They developed separate models for pre-heater, calciner, rotary kiln and cooler. Calciner was modelled in their study by considering simultaneous combustion of coal particles and calcinations of raw meal. Complex heat transfer and reactions (solid–solid, gas–solid and homogeneous reactions in gas phase) in rotary kiln were modelled using three sub-models coupled to each other. Their model predictions were shown to be agreeing well with the observations and experience from cement industry. The model was then used to gain better understanding of influence of operating conditions on energy consumption in cement plant. They also proposed several ways for reducing energy consumption. Worrell et al. (2000) reported on an in-depth analysis of the US cement industry, identifying cost-effective energy efficiency measures and potentials. They examined 30 energy-efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. They also constructed an energy conservation supply curve for the US cement industry which found a total cost-effective energy saving of 11% of 1994 energy use for cement making and a saving of 5% of total 1994 carbon dioxide emissions.

Khurana et al. (2002) presented an energy balance and cogeneration for a cement plant. They found that about 35% of the input energy was being lost with the waste heat streams. The steam cycle was selected to recover the heat from the streams using a waste heat recovery steam generator and it was estimated that about 4.4 MW of electricity could be generated.

Kabir et al. (2010) introduced an energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant. To enhance the energy performance of the unit, they considered heat losses conservation systems that could be potentially used to recover waste heat, such as waste heat recovery steam generator (WHRSG) and secondary kiln shell.

In additon to the first law, second law of thermodynamics offers an invaluable tool to describe the equilibrium conditions to get the maximum performance for the thermal systems (Bejan, 1998; Moran, 1982; Çengel, 2008). Usability or exergy is a measure to determine the maximum usable work load when the system is absolutely thermodynamically in equilibrium with the environment (thermal, mechanical and chemical). The energy and exergy analyses in the thermal systems are crucially important in the determination of the irreversibility resources formed in the system and in whether the system is worked productively or not. Therefore the thermal systems can be optimized with the help of the outcomes made by energy and especially exergy analyses. The energy and exergy analysis in cement plants have received significant attention in the last decades. Leimen et al. (1992) studied the saving methods for heating and electricity energy use in German cement industry. Koroneos et al. (2005) investigated on the recycled waste heating sources which can be used to minimize the energy costs by applying the exergy analysis. Sögüt et al. (2009) investigated the effect of varying dead-state temperatures on energy and exergy efficiencies of a raw mill process in a cement plant. The exergy efficiency values ranged from 44.5 to 18.4% at varying dead-state temperature values between -18 and 41°C. Their results indicated that varying dead-state temperatures had an effect on the exergy efficiency. Wang et al. (2009) carried out an exergy analyses and parametric optimizations for different cogeneration power plants in cement industry. Their results showed that the exergy losses in turbine, condenser and heat recovery steam generator were relatively large and reducing the exergy losses of these components could improve the performance of the cogeneration system. Compared with other systems, the Kalina cycle was shown in their study to achieve the best performance in cement plant. Camdali et al. (2004) made energy and exergy analyses in a rotary burner with pre-calcinations in cement production.

They examined the applications of energy and exergy analyses for a dry system rotary burner (RB) with pre-calcinations in a cement plant of an important cement producer in Turkey. Söğüt and Oktay (2008) performed energy and exergy analyses in a thermal process of a production line for a cement factory and applications. Efficiencies (energy/exergetic) of the processes for the raw mill, the rotary kiln, the trass mill and the coal mill on the production line were found in their study as 84/25, 61/49, 74/13 and 74/18%, respectively.

This study focuses on the energy and exergy analysis of the four cyclone parallel flow cement production system. The energy and exergy balances for the whole system and each unit are calculated and presented.

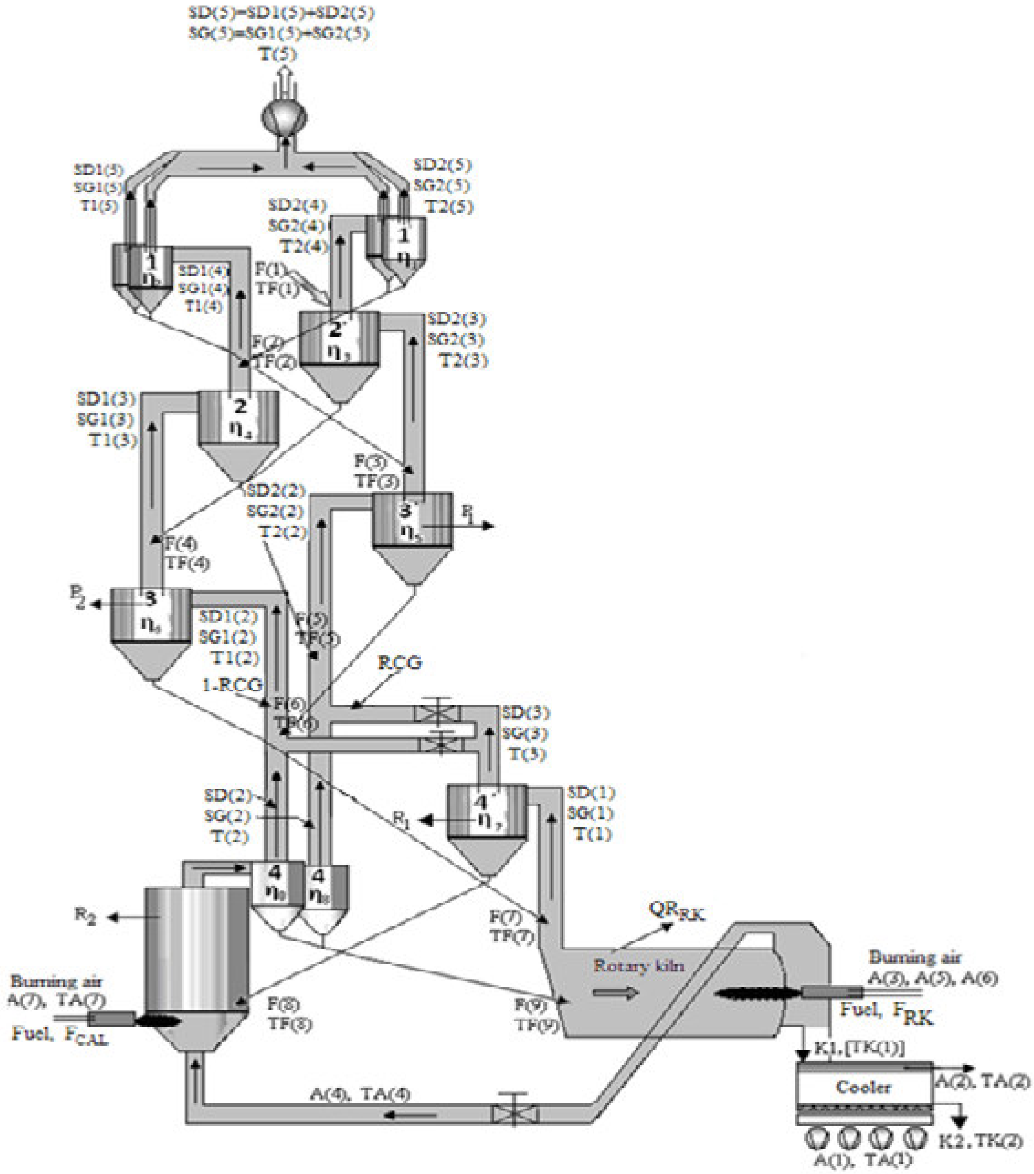

Figure 1. The schematic view of the gas and solid flows with the factory enterprise parameters of the parallel flow four stage preheater cyclone calciner type cement factory.

PROCESS DESCRIPTION

The cement which is one of the most crucial items in construction sector has been produced in three methods as: wet, semi-wet and dry system. Wet and semi-wet system is almost not used since the energy consumption is too high. Dry system cement production is done with much serial multi-stage and parallel flow (as four, five and six, generally four stages) preheater cyclone and precalciner methods.

The study presented here is based on dry system, parallel flow four preheater cyclone stages pre-calcinated cement production technique. In a four stage cyclone parallel flow pre-calcinated cement production systems, the circulation of the solid and gas flows take place simultaneously. The stack gases coming from the rotary kiln directly go into the bottom cyclone. Since a second burning has occurred in precalciner while the stack gases coming from the bottom cyclone and calciner being equally divided and distributed to up, all of the raw material is fed to the cyclone group from the first cyclone (Number 1 cyclone in Figure 1).

All the raw material passes through the cyclones connected to each other in parallel. The main feature of this system is that the raw material passes in a relatively very short time through both parallel cyclone groups' gas flow. That is, only half of the gas amount is in touch with all of the raw material. In the first cyclone of the preheater cyclone group (1st cyclone and 1'st cyclone) the raw material is both heated and dried.

The raw material which touches the hot stack gas and stack dust are heated in the upper second and third cyclones of the preheater cyclone group (2nd and 3rd cyclone and 2nd and 3rd cyclone).

Also, in the third cyclones on the top (3rd cyclone and 3rd cyclone) the P1 and P2 portions of the CaO dragged by means of raw material dust in the stack gas is decarbonised. Namely, in these cyclone groups, decarbonisation reaction also occurs in addition to the heating of the raw material.

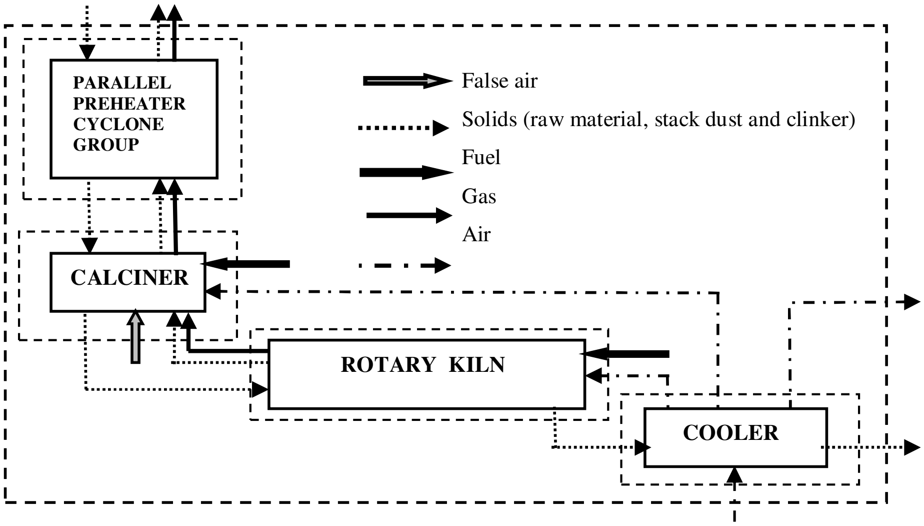

Figure 2. The schematic view of the systems and the subsystems based on the energy and exergy analyses in parallel flow multistage preheater cyclone calciner type cement factory.

In the fourth cyclone of the top fourth cyclone group (4'th cyclone), the calcination of R1 portion occurs besides the heating of the raw material. In the calciner which is at the base of the parallel cyclone group (4th cyclone), the raw material becomes highly (approximately 90 - 95%) calcinated. The rest of the calcinations process of the raw material from the calciner occurs in the rotary kiln. Besides, the raw material turns out to the clinker which is the raw material of the cement and which goes through the cooking process in the rotary kiln.

The distribution of the stack gases which come out of the bottom cyclone and calciner is made possible with the help of dampers. Hot stack gas and stack dusts are usually equally distributed to the parallel cyclone groups.

The position of the damper system is set by the two gas analyser which shows the CO and O2 emissions of the two gases flows. This gas analyser after the bottom cyclones normally displays 2% O2 in bottom cyclone gases, and 1% O2 in heating gases. The amount of CO is often assumed to be negligible from a practical point of view (Locher, 2002a; 2002b).

ENERGY AND EXERGY ANALYSIS

Systems and sub-systems are defined in order to make exergy and energy analysis in the four stage cyclone parallel flow precalciner cement factory under consideration. The system consists of a clinker cooling unit, rotary kiln, calciner and preheating cyclone group and sub-systems of preheating cyclone group. The schematic view of the systems and the subsystems is shown schematically in Figure 2.

Reaction energies in various units

In a cement plant, the calcination process of the CaCO3 found in the raw material take place in the calciner and bottom cyclone, the re-carbonation process of the CaO found in the stack dust takes place in cyclone right above of the bottom cyclone and the calcination process of the remaining raw material takes place in the rotary kiln and clinkering process. The re-carbonation enthalpy in the cyclone stage, the calcination enthalpy in a rotary kiln and precalciner as well as the clinker formation enthalpy can be calculated in various ways. In this study the related reaction enthalpies are calculated with the method of multiplication and addition of the chemical analyses of the raw material with the factors given by H. Zur Strassen [Peray, 1979]. P1 part of the CaO and MgO in the raw material and in the stack dust are re-carbonated in the 3'rd cyclone right above the bottom cyclone, and P2 part is re-carbonated in the 3rd cyclone. The re-carbonation reactions are exothermic (rejecting heat) and the calculation of the reaction enthalpy is done as follows:

$$\mathrm{RCE(1)} = 3200\,.\,\mathrm{CaO(1)}_{re\text{-}c} + 2175\,.\,\mathrm{MgO(1)}_{re\text{-}c} \tag{1}$$

$$\mathrm{RCE(2)} = 3200\,.\,\mathrm{CaO(2)}_{re\text{-}c} + 2175\,.\,\mathrm{MgO(2)}_{re\text{-}c} \tag{2}$$

Some part of the CaCO3 found in the raw material and whole amount of MgCO3 are calcinated in the bottom cyclone. The reaction energy related to the calcination process of CaCO3 and MgCO3 in the raw material is calculated as below.

$$\mathrm{QC}_1 = 3200\,.\,\mathrm{CaO(3)} + 2175\,.\,\mathrm{MgO} \tag{3}$$

Raw material is mostly (90 - 95%) calcinated in the calciner. This reaction is endothermic (heat receiving) and calculated with the terms below.

$$\mathrm{QC}_2 = 3200\,.\,\mathrm{CaO(2)} \tag{4}$$

In the rotary kiln unit, the remaining part of calcination of the raw material and clinker formation process take place. Reaction energy in the rotary kiln is determined from,

$$\mathrm{QRRK} - 3200.[\mathrm{CAO(1)} + \mathrm{CAOF}] + 1721.\mathrm{AL2O3,K} + 2715.\mathrm{MGOF} - 2142.\mathrm{SiO2,K} - 247.\mathrm{Fe2O3,K} \tag{5}$$

Clinker formation enthalpy (per kg clinker) is calculated from,

$$\mathrm{HK} = 100.\{3200.\%\mathrm{CaOK} + 2715.\%\mathrm{MgOK} + 1721.\%\mathrm{Al2O3,K}\text{-}[247.\%\mathrm{Fe2O3,K} + 2142.\%\,\mathrm{SiO2,K}]\} \tag{6}$$

Exergy equations

Physical exergy also known as thermodynamic exergy is the maximum possible work that can be gained in a reversible process from an initial condition (T, P) to the environment states (T0, P0).

Specific physical exergy:

$$ex_{ph} = (h - h_0) - T_0 (s - s_0) \qquad (7)$$

The fixed specific heat in ideal gases:

$$ex_{ph} = c_p (T - T_0) - T_0 \left(\frac{c_p \ln T}{T_0} - R \ln \frac{P}{P_0} \right) \qquad (8)$$

The fixed specific heat in solid and liquid:

$$ex_{ph} = c \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] - v (P - P_0) \qquad (9)$$

where, v is the specific volume at the specified T0 temperature. Chemical exergy is the maximum possible work that can be acquired during a process that brings the system from environmental condition (T0, P0) to the dead state (T0, P0, µ0i). The specific chemical exergy (exch) of a substance in P0 states is calculated by equating the components with the reference environment. The reference environment (atmosphere) components which do not exist in the atmosphere may be acquired with the help of reference concentrations of their P00.

The specific molar chemical exergy of the reference species i having a partial pressure of P00 is evaluated from,

$$\frac{ex_{ch,0i} = R \ T_0 \ln P_0}{P_{00,i}} \qquad (10)$$

The chemical exergy of the ideal gas and liquid mixtures is computed from,

$$ex_{ch} = \sum_i x_i \ [ex_{ch,0i} + R \ T_0 \ ln(x_i)] \qquad (11)$$

where, xi is the molar ratio of the species i, and exch,0i is the standart chemical exergy (Sukuya et al., 2002).

Energy and exergy calculations are basically done in two parts, that is solid and gas flows. Gas flow consists of the combustion products formed from the burning (oxidation) in the calciner and rotary kiln, CO_2 which come out of the calcination of the carbonates in the raw material and the leakage air admitted into the system from the various parts of the rotary kiln. Solid flow, on the other hand, comes to existence from the raw material, stack dust and bulk product clinker leaving out of the rotary kiln.

The assumptions below are made before we start to calculate the chemical components of the solid flows which take place in cement plants:

For the raw material at the entrance of cyclone stages

MgO is present as $MgCO_3$ completely, the rest of the carbonate is present as $CaCO_3$, the rest of the CaO is present as $CaO.SiO_2$, Fe_2O_3 and Al_2O_3 are present as $Fe_2O_3.SiO_2$ $Al_2O_3.SiO_2$, the rest of the SiO2 is free oxide and additionally all of the CaO and MgO which come out of the calcination of $CaCO_3$ in calciner or bottom cyclone are free oxide.

For the stack dust flow in the exit of the rotary kiln and cyclone stages

MgO which drags the stack gases from the rotary kiln along and MgO coming out of the calciner and bottom cyclone is in totally free oxide state in the stack dust flows. The ratio of $CaO.SiO_2$ to the non-volatile oxides (n.v.o.) is equal to the ratio in the flow which goes into the rotary kiln from the bottom cyclone. In that case, the rest of the CaO is in oxide state. The assumption depicted for raw material also holds for stack dust load.

For clinker

MgO is totally in free oxide state, SO_3 is totally in $CaSO_4$ state, Fe_2O_3 is totally $4CaO.Al_2O_3.Fe_2O_3$ (C4AF) state, the remaining part of the Al2O3 is totally in 3CaO.Al2O3 (C3A) state, the remaining part of the CaO and all of the SiO2 is in 2CaO.SiO2 (C2S) and $3CaO.SiO_2$ (C3S) state.

Chemical exergy of the stack dust and raw material

$$Ex_{ch} = ex_{ch,CaCO_3}.m_{CaCO_3} + ex_{ch,MgCO_3}.m_{MgCO_3} + ex_{ch,CaO.SiO_2}.m_{CaO.SiO_2} + ex_{ch,Al_2O_3.SiO_2}.m_{Al_2O_3.SiO_2}$$
$$+ \ ex_{ch,Fe_2O_3.SiO_2}.m_{Fe_2O_3.SiO_2} + ex_{ch,SiO_2}.m_{SiO_2} \qquad (12)$$

Chemical exergy of the clinker

$$Ex_{Clin_{ch}} = ex_{ch,C_2S} \cdot m_{C_2S} + ex_{ch,C_3S} \cdot m_{C_3S}$$
$$+ \ ex_{ch,C_3A} \cdot m_{C_3A} + ex_{ch,C_4AF} \cdot m_{C_4AF}$$
$$+ \ ex_{ch,Mgo} \cdot m_{Mgo} + ex_{ch,CaSO_4} \cdot m_{CaSO_4} \qquad (13)$$

The reference atmosphere definition in the calculation of the chemical exergy of solid and gas flows are taken from the reference (Moran 1982, Table 1), the standard chemical exergy values were taken from (Morris et al., 1986, Table 2).

Clinker cooler

The hot clinker (~1300 - 1450°C) left the rotary kiln comes into the clinker cooler, where it cools down to ~50 - 250°C. Some portion of the air used to cool the hot clinker [A(3)] is provided as the secondary burning air. Another portion of this cooling air [A(4)] is given to the calciner as tertiary burning air. The schematic view of the solid and gas flows' exergy and energy equation in this unit is given in Figure 3. For the clinker cooler the following relations hold:

Energy in:

$$e_{in,cool} = eK(1) + eA(1) \qquad (14)$$

Energy out:

$$e_{out,cool} = eK(2) + eA(2) + eA(3) + eA(4) + QWcool \qquad (15)$$

Exergy in:

$$ex_{in,cool} = exK(1) + exA(1) \qquad (16)$$

Exergy out:

$$ex_{out,cool} = exK(2) + exA(2) + exA(3) + exA(4) \qquad (17)$$

Table 1. Environment considered in exergy analysis (Moran, 1982) (T_0 = 298. 15K, P_0 = 1.01325 bar).

Gas reference species	Mole fraction
N_2	0.75700
O_2	0.20120
H_2O	0.02170
CO_2	0.00033
Others	0.01977

Table 2. Standard chemical exergy values of the gas and solid flows in cement plant (Morris et al., 1986).

Species	Chemical exergy (kJ / kmol)	Species	Chemical exergy (kJ / kmol)
Al_2O_3 (s,α)	200400	$CaSO_4$(s, α)	8200
$Al_2O_3.SiO_2$ (s)	15400	Fe_2O_3 (s)	16500
CO (g)	275100	H_2 (g)	236100
CO_2 (g)	19870	H_2O (1)	900
$CaCO_3$ (s)	1000	H_2O (g)	9490
$CaCO_3.MgCO_3$ (s)	15100	K_2O (s)	413100
CaO (s)	110200	MgO (s)	66800
$CaO.Al_2O_3$ (s)	275400	$MgCO_3$ (s)	37900
$2CaO.Al_2O_3$ (s)	460400	N_2 (g)	690
$3CaO.Al_2O_3$ (s)	500600	O_2 (g)	3970
$CaO.SiO_2$ (s)	23600	Na_2O (s)	296200
$2CaO.SiO_2$ (s, β)	95700	SO_2 (g)	313400
$3CaO.SiO_2$ (s)	219800	SiO_2 (s)	1900
CaS	844600	$Fe_2O_3.SiO_2$	18400
$4CaO.Al_2O_3.Fe_2O_3$	667000		

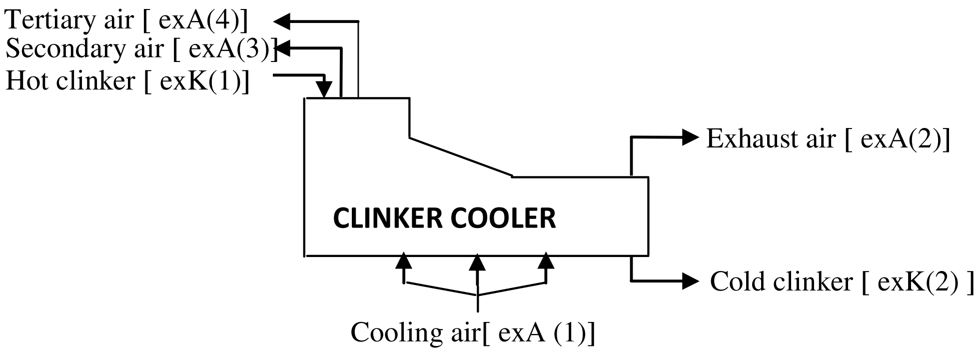

Figure 3. Energy and exergy flows in clinker cooling unit.

Irreversibility:

$$I_{cool} = ex_{in,cool} - ex_{out,cool} \qquad (18)$$

Rotary kiln

The calcinations and cooking process of the remaining raw material which is substantially calcinated in the calciner occurs within this unit. Solid and gas flows based on the energy and exergy analysis are shown schematically in Figure 4.

Energy in:

$$e_{in,RK} = eF_{RK} + eF(n) + eA(3) + eA(5) + eA(6) \qquad (19)$$

Energy out:

$$e_{out,RK} = eK(1) + eSG(1) + eSD(1) + QR_{RK} + QW_{RK} \qquad (20)$$

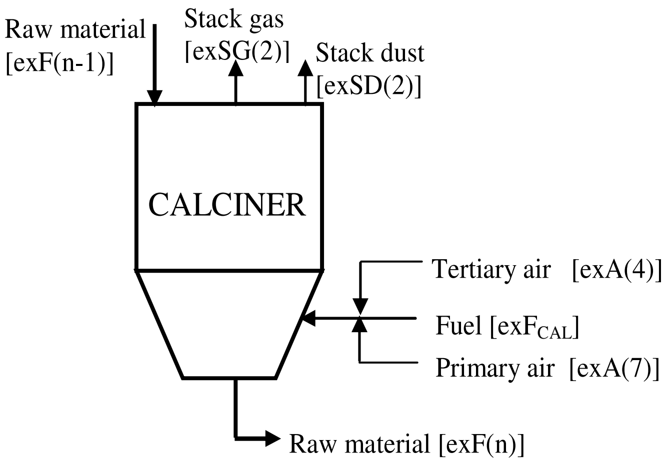

Figure 4. The schematic view of the solid and gas flows used for the energy and exergy equation in the rotary kiln unit.

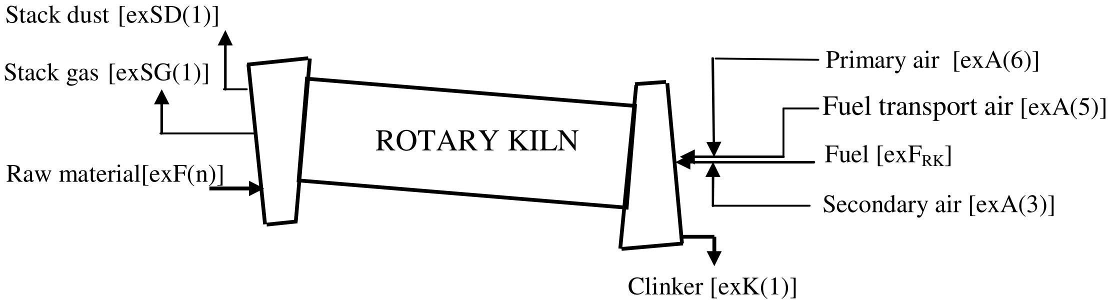

Figure 5. Schematic view of the solid and gas flows used for the energy and exergy in calciner unit.

Exergy in:

$$ex_{in,RK} = exF_{RK} + exF(n) + exA(3) + exA(5) + exA(6) \quad (21)$$

Exergy out:

$$ex_{out,RK} = exK(1) + exSG(1) + exSD(1) \quad (22)$$

Irreversibility:

$$I_{RK} = ex_{in,RK} - ex_{out,RK} \quad (23)$$

Calciner

In this unit, a secondary combustion takes place. In addition, the 90-95% calcination process of the raw material occurs in this unit. Solid and gas flows based on the energy and exergy analysis is given schematically in Figure 5.

Energy in:

$$e_{in,CAL} = eF_{CAL} + eF(n-1) + eA(4) + eA(7) \quad (24)$$

Energy out:

$$e_{out,CAL} = eF(n) + eSG(2) + eSD(2) + QR_2 + QW_{CAL} \quad (25)$$

Exergy in:

$$ex_{in,CAL} = exF_{CAL} + exF(n-1) + exA(4) + exA(7) \quad (26)$$

Exergy out:

$$ex_{out,CAL} = exF(n) + exSG(2) + exSD(2) \quad (27)$$

Irreversibility:

$$ICAL = ex_{in,CAL} - ex_{out,CAL} \quad (28)$$

Preheater cyclone

The heating, drying and also partly the calcination process of the raw material take place in the preheater cyclone connected in serial and parallel types. In the first cyclone, the moisture of the raw material is also evaporated, and the raw material is pre-heated. The raw material is partly subject to calcination in the bottom cyclone. The raw material is only heated mid cyclones. Solid and gas flows based on the energy and exergy calculations in the pre-heater

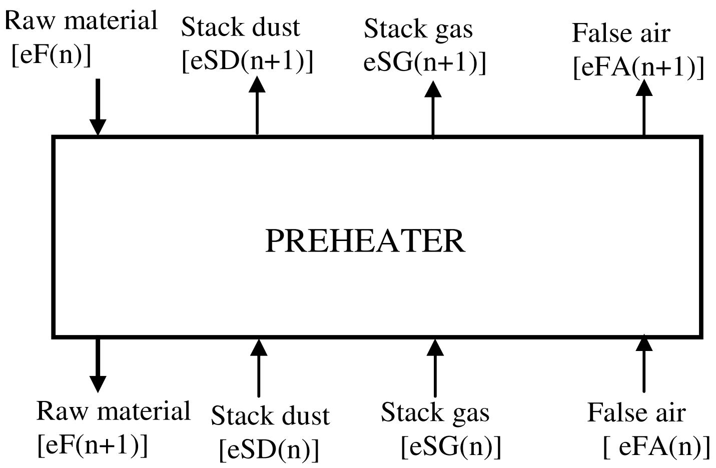

Figure 6. Schematic view of the solid and gas flows used for the energy and exergy in preheater cyclone group.

cyclone group is given in Figure 6.

Energy in:

$$e_{in,PRH} = eF(n) + eSG(n) + eSD(n) + eFA(n) + RCE(1) + RCE(2) \qquad (29)$$

Energy out:

$$e_{out,PRH} = eF(n+1) + eSG(n+1) + eSD(n+1) + eFA(n+1) + QR_1 + QW_{PRH} \qquad (30)$$

Exergy in:

$$ex_{in,PRH} = exF(n) + exSG(n) + exSD(n) + exFA(n) \qquad (31)$$

Exergy out:

$$ex_{out,PRH} = exF(n+1) + exSG(n+1) + exSD(n+1) + exFA(n+1) \qquad (32)$$

Irreversibility:

$$I_{PRH} = ex_{in,PRH} - ex_{out,PRH} \qquad (33)$$

Energy inputs for whole system:

$$e_{in,SYS} = eF_{RK} + eF_{CAL} + eF(1) + eA(1) \qquad (34)$$

Energy outputs for whole system:

$$e_{out,SYS} = eK(2) + eSG(n+1) + eSD(n+1) + eA(2) + H_K + Total \text{ Losses} \qquad (35)$$

Exergy inputs for whole system:

$$ex_{in,SYS} = exF_{RK} + exF_{CAL} + exF(1) + exA(1) \qquad (36)$$

Exergy outputs for whole system:

$$ex_{out,SYS} = exK(2) + exSG(n+1) + exSD(n+1) + exA(2) \qquad (37)$$

Irreversibility for whole system:

$$I_{SYS} = ex_{in,SYS} - ex_{out,SYS} \qquad (38)$$

or

$$I_{SYS} = I_{cool} + I_{RK} + I_{CAL} + I_{PRH} \qquad (39)$$

First law efficiency for the system is defined as follows

$$\eta_I = \frac{\text{Clinker formation energy}}{\text{Input energy}} = 1 - \left(\frac{\text{Output energy}}{\text{Input energy}}\right) \qquad (40)$$

Second law for the system is defined as follows

$$\eta_{II} = \frac{\text{Clinker formation exergy}}{\text{Input exergy}} = 1 - \left(\frac{\text{Output exergy} + \text{Irreversibility}}{\text{Input exergy}}\right) \qquad (41)$$

The ratio of the loss exergy defined as energy and expressed as follows:

$$\varphi = \frac{ex_{out,sys} + I_{sys}}{ex_{in,sys}} \qquad (42)$$

RESULTS AND DISCUSSION

Energy and exergy analyses have been performed using plant parameters given in Tables 3 - 5. The mass flow rates of solid and gas flows were calculated with the help of (Kolip et al., 2008). In order to make energy and exergy analyses related computations, a computer code was developed in GW-BASIC language (Figure 7). The

Table 3. Fuel properties.

Hu (kJ/kg)	C (%)	H (%)	O (%)	S (%)	N (%)	Ash (%)	Humidity (%)
30250	78.0	5.0	6.0	1.0	1.5	8.5	0.0

Table 4. Chemical compositions of raw material, clinker and fuel ash.

	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	H_2O (%)	SO_3 (%)	Non-volatile oxides (%)
Raw material (farine)	43.1	13.37	3.47	2.60	1.18	2.0	0.36	63.72
Clinker	66.0	20.14	5.72	3.80	1.54	0.0	0.81	97.2
Fuel ash	10.94	48.80	14.25	21.0	0.63	0.0	0.55	95.62

Table 5. Parameters used in energy mass equilibrium in parallel flow four stage preheater cyclone calciner type cement plant.

Standard Parameter (per kg of clinker)	Symbol	Value
Stack dust leaving the rotary kiln (kg)	SD (1)	0.15
False air (m^3)	FA	0.00
The inlet air to cooler (m^3)	A(1)	2.50
Specific humidity of the ambient air (kg H_2O / kg dry air)	Xs	0.0128
Excess air ratio	λ	1.15
The ratio of rotary kiln gases to the cyclone groups (%)	RCG	50.0
Calcination ratio in calciner [%]	R2	90.00
Fuel temperature (℃)	TF	25.00
Clinker outlet temperature from rotary kiln (℃)	TK (1)	1300.00
Clinker inlet temperature to cooler (℃)	TK (1)	1300.00
Clinker outlet temperature to cooler (℃)	TK(2)	140.00
Raw material temperature entering first cyclone (℃)	TF (1)	55.00
Raw material temperature entering rotary kiln (℃)	TF (n)	860.00
Stack gas temperature leaving the rotary kiln (℃)	T(1)	1100.00
Environment air temperature to cooler (℃)	TA(1)	25.00
Outlet air (waste) temperature from cooler (℃)	TA(2)	240.00
Primary air temperature to rotary kiln (℃)	TA(6)	90.00

calculations can be grouped into three categories discussed below.

Temperature calculations of various points in cement plant

The cold raw material in cement plants comes in touch with hot stack dust and hot stack gas while passing through the cyclone stages and there is heat transfer among two mediums. As a result of this interaction, the raw material is heated. Raw material which comes to the calciner at approximately 700 - 800℃ is calcinated 90 - 95% in this unit. Since the stack dusts move with the stack gases, their temperature in the related flow is assumed to be the same with the stack gases. All the units are thought to be like a two-phase heat exchanger which works according to counter-flow principle. The temperatures calculated for the solid instances and the cyclone group of the stack gas and stack dust, the calciner and rotary kiln output points are given in Table 6. The amount of leakage air in energy and exergy calculations was disregarded. However, it was considered for each individual unit. In the clincer cooler, wall heat losses were estimated to be 495 [kJ/kg.clinker].

Energy and exergy balances for whole system

The energy and exergy equations were solved for the whole system with the aid of the developed computer code, and the results are summarized in Table 7. In addition to the first law efficiency, 2nd law efficiency was

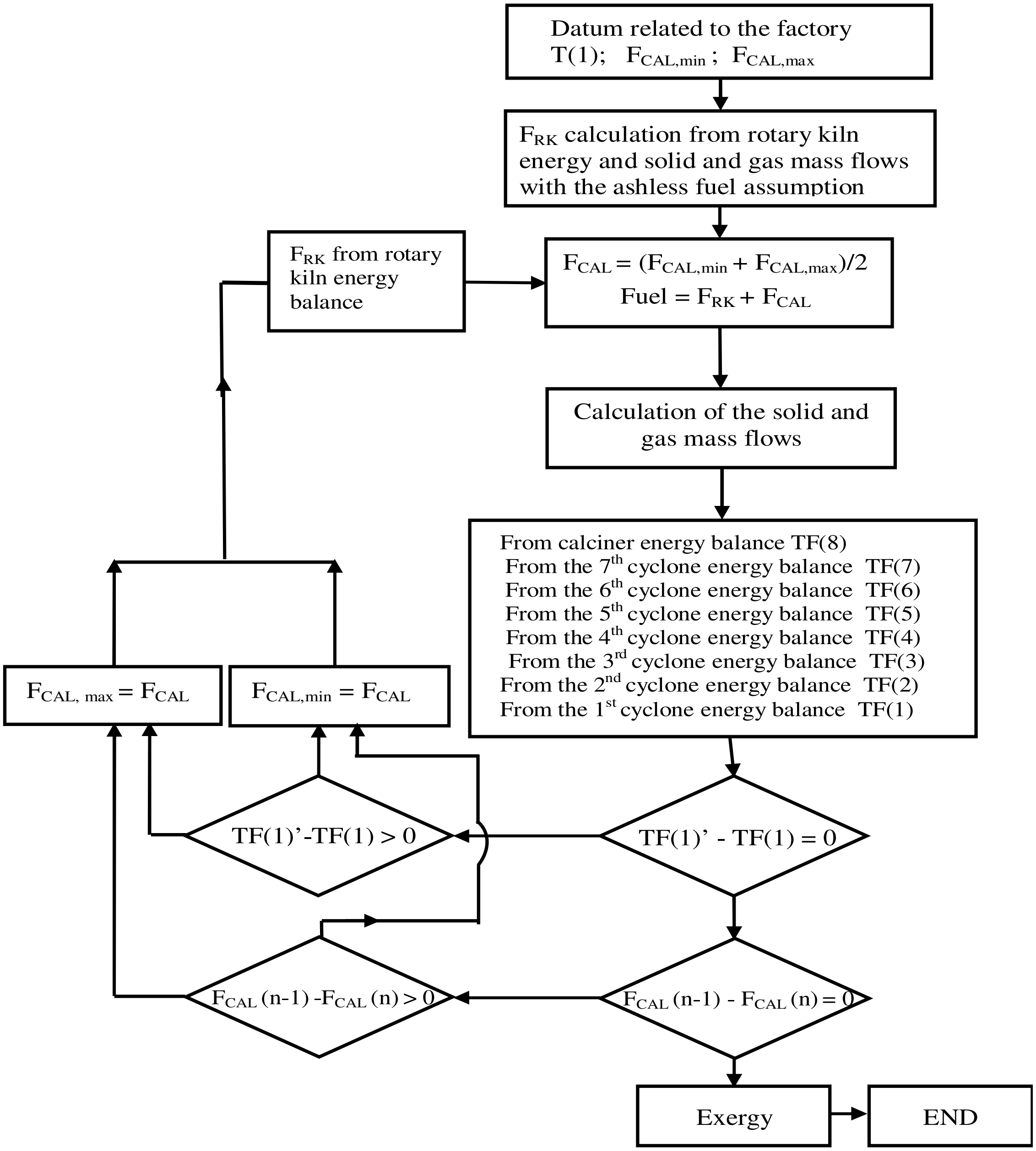

Figure 7. The scheme of computer programme in GW-BASIC language which is developed to be used in energy and exergy balance for parallel flow four stages preheater cyclone calciner type cement plant.

also provided in this table. Based on the collected data, energy and exergy balances are applied to the whole system. It is clear from Table 7 that the total energy used in the process is 3442 kJ/kg-clinker and the main heat source is the fuel, giving a total heat of 3395 kJ/kg-clinker. Table 7 reveals that the major heat losses are primarily due to cooler air exhaust (207 kJ/kg-clinker), stack gas stream (706 kJ/kg-clinker) and combined heat transfer from hot surfaces (350 kJ/kg-clinker). These findings exhibits generally well agreements with the literature and there are several opportunities to recover these losses in the system (Engin et al., 2005). Also, the energy balance given in Table 7 indicates relatively good consistency between the total heat input and total heat output. Since most of the heat loss sources have been considered, there is only about 2 kJ/kg-clinker of energy difference from the input heat. This difference is nearly 0.06% of the total input energy and can be attributed to the assumptions and nature of data. The distribution of heat losses to the individual components exhibits reasonably good agreement with some other key plants (Engin et al., 2005). In terms of exergy balance, on the

Table 6. Temperature calculated with the aid of computer software of various points in parallel flow four stage preheater cyclone calciner type cement plant.

The points in which the temperature is calculated	(°C)
1st Raw material input temperature which goes into the cyclone [TF(1)]	52.78
The stack gas mixture temperature which goes out from the top cyclone group [T(5)]	348.02
1'st The stack gas and raw material exit temperature from the cyclone unit [T2(5)]	245.56
1st The stack gas and raw material exit temperature from the cyclone unit [T1(5)]	426.28
2'nd The stack gas and raw material exit temperature from the cyclone unit[T2(4)]	566.85
2nd The stack gas and raw material exit temperature from the cyclone unit [T1(4)]	660.94
3'rd The stack gas and raw material exit temperature from the cyclone unit[T2(3)]	741.83
3rd. The stack gas and raw material exit temperature from the cyclone unit [T1(3)]	790.60
The stack gas and raw material exit temperature from the bottom cyclone unit[T(3)]	844.53
The stack gas and raw material exit temperature from the calciner unit (data) [T(2)]	860.00
The stack gas exit temperature from the rotary kiln unit. (data) [T(1)]	1100.00

Table 7. Energy and exergy balance calculated with the aid of computer programme in parallel flow four stage preheater cyclone calciner type cement plant

		Energy (kJ/kg.clinker)	Exergy (kJ/kg.clinker)
Input	Fuel	3394.78	3394.78
	Raw material	38.68	45.67
	Fuel transport air	8.97	1.50
	Energy input	3442.44	-
	Exergy input		3441.95
Output	Cool clinker	90.27	14.02
	Coolant outlet air	404.73	115.14
	Stack gas	706.48	597.39
	Stack dust	25.24	10.79
	Water evaporation	110.48	86.49
	Heat transfer	350.81	-
	Energy losses	1688.01	-
	Exergy losses	-	823.83
	Exergy destruction (irreversibility)	-	1645.88
	Reaction energy to from clinker	1756.28	
	Reaction exergy to from clinker	-	972.23
	Total output	3444.29	3441.94
	Energy efficiency	51 %	-
	Exergy efficiency	-	28 %
	Anergy	-	72 %

other hand, there is no detectable difference between input exergy and output exergy as is seen from Table 7.

The energy and exergy equations were also solved for each unit composing the cement plant under consideration. The results are summarized in Tables 8a-d. In Table 8a the energy and exergy balances for the clinker cooler are shown. The energy and exergy balances given in Table 8a indicate very good consistency between the total heat input and total heat output, indicating the accuracy of the analysis. Similar analyses have been done for other units, that is, rotary kiln, calciner, bottom cyclone (Table 8b) and other cyclone groups (Table 8 c - d). Especially, by analyzing irreversibility ratings, some decision may be taken about the units that need

Table 8a. Energy and exergy equation in clinker cooling unit calculated with the aid of computer software in parallel flow four stage preheater cyclone calciner type cement plant.

			Energy (kJ/kg.clinker)	Exergy (kJ/kg.clinker)
Clinker cooling unit	Input	Hot clinker	1497.44	1938.84
		Cooling air	0.00	0.00
		Energy input	1497.44	-
		Exergy input	-	1938.84
	Output	Cold clinker	90.27	986.25
		Air thrown out from the cooler	404.73	115.14
		Rotary kiln secondary air	190.41	101.26
		Calciner tertiary air	812.03	473.18
		Output energy	1497.44	-
		Output exergy	-	1675.84
		Loss exergy (Irreversibility)	-	263.00
		Total output energy	-	1938.84
Rotary kiln unit	Input	Rotary kiln fuel	1394.13	1394.13
		Raw material	1025.78	1690.62
		Rotary kiln secondary air	190.41	101.26
		Fuel dispatch air	8.97	1.50
		Input energy	2619.29	-
		Input exergy	-	3187.50
	Output	Hot clinker	1497.44	1938.84
		Stack gas	964.05	736.80
		Stack dust	168.47	161.33
		Reaction in rotary kiln	-114.87	-
		Water evaporation	3.38	0.83
		Rotary kiln wall heat losses	100.81	-
		Output energy	2619.29	-
		Output exergy	-	2837.80
		Loss exergy (irreversibility)	-	349.71
		Total output exergy	-	3187.50

Table 8b. Energy and exergy equation in bottom cyclone, calciner and rotary kiln calculated with the aid of computer software in parallel flow precalciner with four stage cyclone cement plant.

Calciner unit	Input	Calciner fuel	2000.65	2000.65
		With raw material	1625.85	1115.58
		With calciner tertiary air	812.03	473.18
		Input energy	4438.54	-
		Input exergy	-	3589.41
	Output	Raw material	1025.78	1690.62
		Stack gas	1345.28	993.99
		Stack dust	297.81	490.82
		Reaction in calciner	1720.17	-
		Water evaporation	4.86	1.15

Table 8b. Contd.

		Calciner wall heat losses	45.00	-
		Output energy	4438.89	-
		Output exergy	-	3176.58
		Loss exergy (irreversibility)	-	412.83
		Total output exergy	-	3589.41
Bottom cyclone unit	Input	Raw material	1704.10	1053.07
		Stack gas	964.05	736.80
		Stack dust	168.47	161.33
		Input energy	2836.62	-
		Input exergy	-	1951.20
	Output	Raw material	1625.85	1115.58
		Stack gas	725.89	392.50
		Stack dust	286.92	196.87
		Reaction in the cyclone	173.41	-
		Cyclone wall heat losses	25.00	-
		Output energy	2837.07	-
		Output exergy	-	1704.94
		Loss exergy (irreversibility)	-	246.26
		Total output exergy	-	1951.20

Table 8c. Energy and exergy equation in 3rd and 3’rd and 2nd cyclone unit calculated with the aid of computer programme in parallel flow four stage preheater cyclone calciner type cement plant.

3. Cyclone unit	Input	Raw material	1504.03	956.76
		Stack gas	1035.58	739.91
		Stack dust	292.36	345.06
		Re-carbonation	24.96	-
		Input energy	2856.93	-
		Input exergy	-	2041.73
	Output	Raw material	1704.10	1053.07
		Stack gas	938.32	669.15
		Stack dust	189.35	117.01
		Cyclone wall heat losses	25.00	-
		Output energy	2856.77	-
		Output exergy	-	1839.23
		Loss exergy (Irreversibilty)	-	202.50
		Total output exergy	-	2041.73
3’. Cyclone unit	Input	Raw material	1241.58	658.84
		Stack gas	1035.58	739.91
		Stack dust	292.36	344.65
		Re-carbonation	0.53	-
		Input energy	2570.06	-
		Input exergy	-	1743.40

Table 8c. Contd.

	output	Raw material	1504.03	956.76
		Stack gas	873.33	622.70
		Stack dust	167.11	106.31
		Cyclone wall heat losses	25.00	-
		Output energy	2569.47	-
		Output exergy	-	1685.76
		Loss exergy (Irreversibilty)	-	57.64
		Total output exergy	-	1743.40
2. Cyclone unit	input	Raw material	968.29	483.09
		Stack gas	938.32	669.15
		Stack dust	189.35	117.01
		Input energy	2095.95	-
		Input exergy	-	1269.25
	Output	Raw material	1241.58	658.84
		Stack gas	763.11	544.84
		Stack dust	65.35	34.68
		Cyclone wall heat losses	25.00	-
		Output energy	2095.04	-
		Output exergy	-	1238.35
		Loss exergy (Irreversibilty)	-	30.90
		Total output exergy	-	1269.25

Table 8d. Energy and exergy equation in 2'nd and 1st and 1'st cyclone unit calculated with the aid of computer software in parallel flow four stage preheater cyclone calciner type cement plant.

2'. Cyclone unit	Input	Raw material	649.57	290.05
		Stack gas	873.33	622.70
		Stack dust	167.11	106.31
		Input energy	1690.01	-
		Input exergy	-	1019.05
	Output	Raw material	968.29	483.09
		Stack gas	640.76	463.23
		Stack dust	50.96	25.43
		Cyclone wall heat losses	30.00	-
		Output energy	1690.01	-
		Output exergy	-	971.75
		Loss exergy (irreversibility)	-	47.30
		Total output exergy	-	1019.05
1. Outlet cyclone	Input	Raw material	334.67	130.88
		Stack gas	763.11	544.84
		Stack dust	65.35	34.68
		Input energy	1163.13	-
		Input exergy	-	710.40

Table 8d. Contd.

	output	Raw material	649.57	290.05
		Stack gas	461.43	351.71
		Stack dust	16.66	7.44
		Cyclone wall heat losses	35.00	-
		Output energy	1162.65	-
		Output exergy	-	649.20
		Loss exergy (irreversibility)	-	61.20
		Total output exergy	-	710.40
1'. Cycl$one unit	input	Raw material	38.68	45.67
		Stack gas	640.76	463.23
		Stack dust	50.96	25.43
		Input energy	730.40	-
		Input exergy	-	534.33
	Output	Raw material	334.67	130.88
		Stack gas	245.05	245.68
		Stack dust	8.58	3.36
		Water evaporation	102.24	84.51
		Cyclone wall heat losses	40.00	-
		Output energy	730.54	-
		Output exergy	-	464.43
		Loss exergy (irreversibility)	-	69.90
		Total output exergy	-	534.33

betterment. It is useful to remind that most of irreversibility is derived from burning and chemical reaction and such irreversibility are inescapable. In most of the new factories or overhauled ones, temperature of raw material and gas flow are checked with the aid of computer systems. Nevertheless, via such a mathematical model and computer software, more convenient decisions can be taken during the process. Comparing the ratings of worsening units may suggest a course of action on which parameter is wrong. It may also help whether it is time for maintenance of the units and machines are near or not, whether solid and gas flows are under right conditions or not and whether administration parameters at different points are acceptable or not.

In Figure 8, energy (Sankey) diagram and in Figure 9, exergy (Grassmann) diagram are also drawn. In addition, the first and the second law efficiency and irreversibility are included. While the first law efficiency is 51%, the second one is figured out as 28% and anergy rate as 72%. Anergy rate is a little high and the first and second law efficiencies are a little low. In these rates, the raw material and clinker composition and basically the effect of quality of fuel are important.

Once the quality of fuel is improved much more, the energy rate would reduce and thus, the first and the second law efficiency would increase. When the irreversibility is taken into account in terms of units, 412 kJ calciner for each kilogram, rotary kiln with 350 kJ, clinker cooler with 263 kJ and bottom cyclone unit with 246 kJ draw attention. In the processes of rotary kiln and calciner, burning process is included in addition to chemical reaction. There is partly chemical reaction and there are thermal interaction and mixture among stack dust and solid raw material and burning gases in the calciner and rotary kiln.

CONCLUSION

Cement industry is the second industry that uses energy densely (19.7%) coming after iron-steel industry; because of that, it is one of the few industries on which energy saving and usage of energy has taken much interest over the past decades. In this paper, a detailed energy and exergy analyses, which can be directly applied to any dry type cement plant have been made for a specific key cement plant. In order to perform the energy and exergy computations, a computer code was developed in GW-BASIC language.

The distribution of the input heat energy and exergy to the system components showed good agreement between the total input and output energy and gave

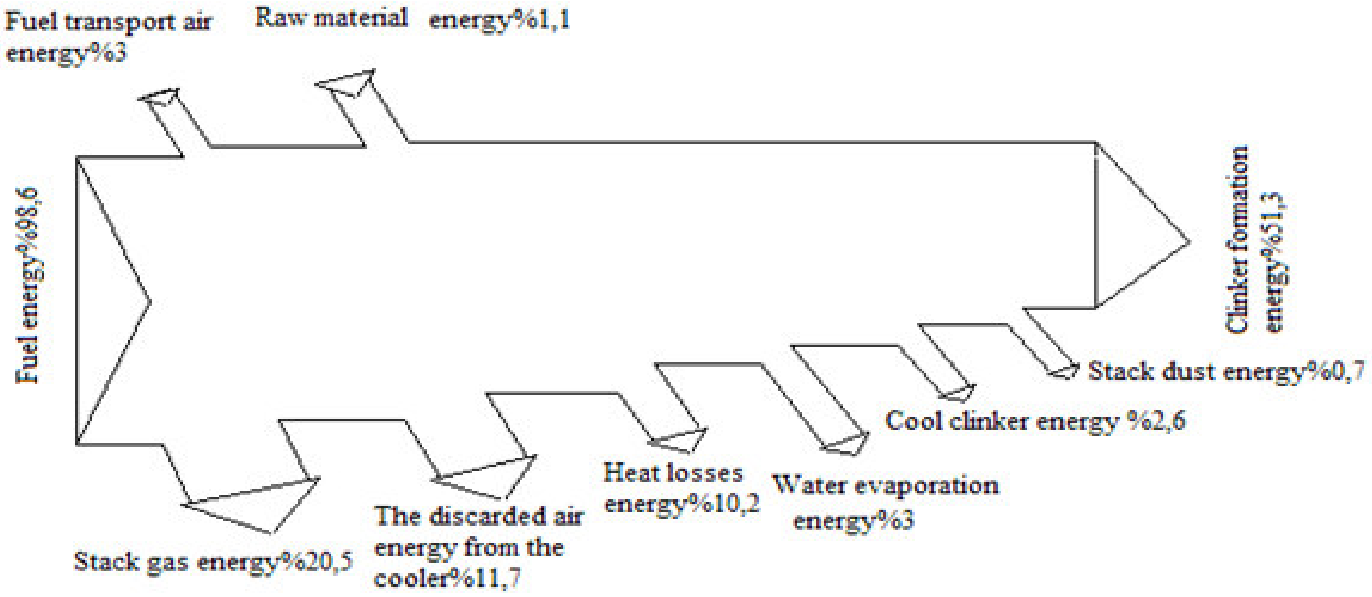

Figure 8. Sankey (energy) diagram of the values calculated with the aid of computer programme in parallel flow four stages preheater cyclone calciner type cement plant.

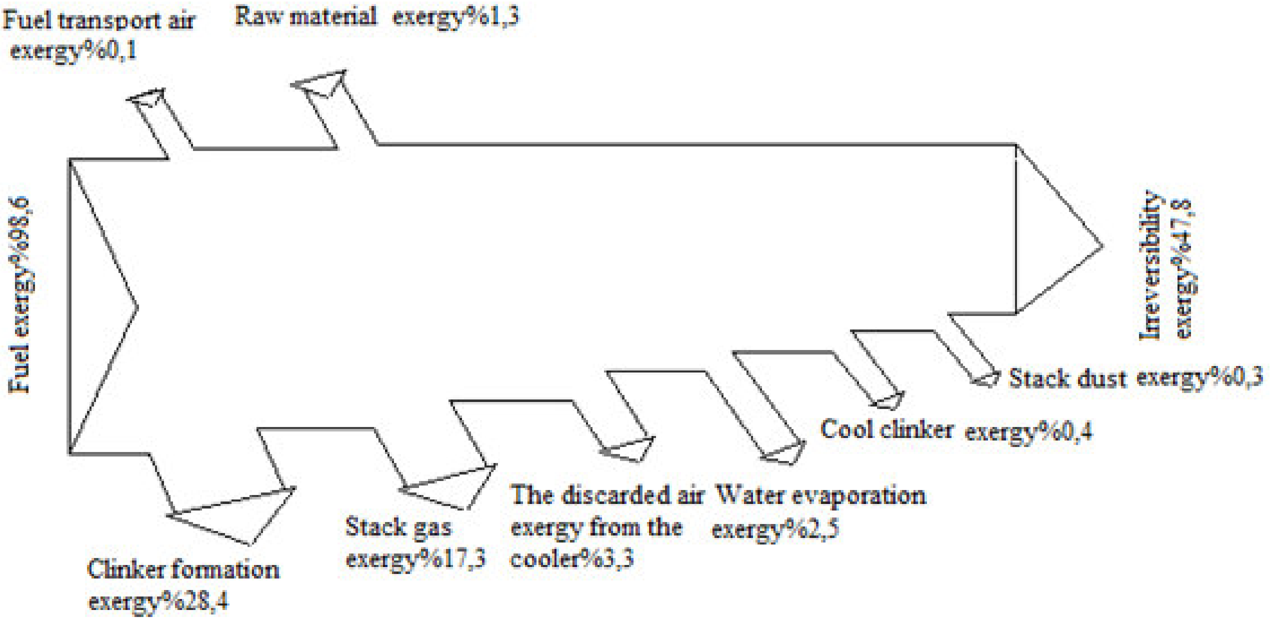

Figure 9. Grasmann (exergy) diagram of the values calculated with the aid of computer programme in parallel flow four stages preheater cyclone calciner type cement plant

significant insights about the reasons for the low overall system efficiency. According to the results obtained, the first and second law efficiencies of the system were estimated to be 51 and 28%, respectively. The thermodynamics-based model presented here is particularly developed for cement industry of which the portion of energy (fuel and electricity) expenses are high in the context of total cost (55%) and enables to determine optimum apertures in terms of energy costs and efficient usage of the units.

With the model developed the fuels of different qualities and effects of other parameters on energy and exergy balance can be observed both in the context of system and in each unity.

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