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Exergetic and environmental performance improvement in cement production process by driving force distribution

Seyed Ali Ashrafizadeh*, Majid Amidpour*,†, and Ali Allahverdi**

*Department of Environment and Energy, Science and Research Branch, Islamic Azad University, Tehran, Iran
**Cement Research Center, School of Chemical Engineering, Iran University of Science and Technology, Narmak 1684613114, Tehran, Iran
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Abstract−This paper presents an investigation of the effects of temperature gradient distribution by the aid of a secondary burner on exergetic and environmental functions of the cement production process. For this reason, the burning system of the cement production (kiln & preheater) process was simulated in four thermal areas. Three lines of cement production with 2,000, 2,300 and 2,600 ton/day were investigated. Fuel injection ratio into the secondary burner, from 10 to 40 percent was studied for each line. The obtained results show that, for cyclone preheaters, fuel injection into the secondary burner up to a proportion resulting in the minimum temperature required for alite formation (2,200 °C) in the kiln burning zone is suitable. For shaft preheaters, however, according to percent calcinations, there exists an optimum proportion for 15 to 20 percent injection fuel into secondary burner. Finally, it was shown that the secondary burner application can reduce the exergy losses about 25 percent, which leads to a reduction of the green house gases of about 35000 cubic meters per year for each ton per day of clinker production.

Key words: Exergy Analysis, Green House Gases, Secondary Burner, Cement Production, Driving Force

INTRODUCTION

Nowadays, due to energy and environmental considerations, it is crucial to apply suitable methods by which reductions in both energy carriers' consumption and green house effects would be possible. Among different energy consuming industries, the cement industry as a strategic one has a major role in energy carriers' consumption. In this industry, the burning system including preheater and rotary kiln is the core of the cement production process and the main consumer of the fuel.

On the other hand, the second law of thermodynamics provides the designers and engineers with a powerful and efficient tool known as exergy analysis. Reducing exergy losses leads to decreases in fuel consumption and green house gasses emission. Since exergy losses have direct relation with irreversibility factors in the system, and according to the relations between these factors with driving forces in the transfer phenomena, a logical relationship between them can be expected. Obviously, the distribution of driving forces, because of their effects in reducing potentials, can affect exergy losses.

The term "exergy" was first introduced by Rant [1]. Bonsjakovic [2] was one of the early leaders in applying the exergy analysis to processes and chemical industries in his fight against irreversibility. Later Szargut [3] and Kotas [4] developed and applied the concept of exergy analysis in various processes. Bjan [5,6] and Bejan and Tsatsaronis [7] linked the principles of heat transfer to the second law of thermodynamics and entropy generation.

Currently, the application of energy- exergy-environment analysis and thermal improvement has been developed in various industries, including cement production. Kaantee et al. [8], used a commercial modeling tool (ASPEN PLUSÒ) to model the four-stage pre-heater kiln system of a full-scale cement plant (clinker production ~2,900 tons/day), using petcock as fuel for select a suitable alternative fuel. Choate [9] found that opportunities exist both in the near-term and in the long-term for reducing energy usage and lowering emissions. Immediate and near-term improvements can be achieved by implementing demand-side energy management measures to improve energy efficiency and reduce electricity and fuel use. These improvements can come from utilizing free and low-cost options that include motor, compressed air and process heater optimization software tools. Other site-specific near-term energy and environmental improvements can be achieved with contracted formal energy audits. Changes in product formulation also offer significant near-term energy and environmental improvements. Longer-term improvements could come from advanced research and development programs. Koroneos et al. [10] examined cement production using the exergy analysis methodology. The analysis involves assessment of energy and exergy input at each stage of the cement production process. The chemical exergy of the reaction is also calculated and taken into consideration. It is found that 50% of the exergy is being lost even though a large amount of waste heat is being recovered. Kawaes [11] introduced the effective factors on energy carrier consumption in the cement production and the methods for energy management. Sogut and Oktay [12] proposed energy and exergy analyses in a thermal process of a production line for a cement factory. Zeman and Lackner [13], investigated the oxygen consumption and emission and CO_2 capture in the cement production. Worrell et al. [14] investigated the opportunities for energy efficiency improvement for the cement industry. Sogut et al. [15] investigated the heat recovery from a rotary kiln for a cement plant. An exergy analysis

†To whom correspondence should be addressed.
E-mail: amidpour@kntu.ac.ir

was performed on the operational data of the plant. A mathematical model was developed for a new heat recovery exchanger for the plant. The applied method leads to energy and green house effect improvements. Sogut et al. [16] investigated the effects of varying dead-state temperatures on the energy and exergy analyses of a raw mill in a cement plant. Some researchers focused on fly ash and dust effects on the environment due to cement production. Park and Kang [17], investigated the effects of different activator concentration, liquid/fly ash ratio, and curing temperature and time on the compressive strength of specimens prepared from low-calcium fly ash activated with sodium hydroxide without the use of Portland cement. They emphasized that fly ash should not only be disposed of safely to prevent environmental pollution but treated as a valuable resource. Dust is a main resource of air pollution in the cement industry. Ahn et al. [18] studied the physical, chemical and electrical characteristics of cement dust generated.

The cement industry is a well known industry with many related references providing the exact process data to users. For example, Kurt [19], Kohlhaas and Labahn [20], Duda [21], Boateng [22] and Alsop [23] are useful references in cement industry. They give much useful information about the operation and design parameters of cement production.

The combination of cement production and exergy can give some useful results. The main principle in this research is based on the process rate effect on entropy generation and exergy losses. These two factors can be reduced if the process operation conditions could be closer to a reversible situation. Using the secondary burner can result in a more suitable temperature gradient distribution, leading to decreased heat transfer rates and hence improvements in system operation.

The second burner is installed in some lines of cement production. But there are different ideas about its benefits because there is no comprehensive information about its effect. Fuel injection into the secondary burner has many complicated effects on the system. The originality of this paper is a new look at the second burner effect on the temperature profile and combustion factors of the system. Another innovation of this work is a new method for simulation of the burning system. Exergy and green house effects relations with the second burner installation are the final and main goal of this work which provide a new look at this burner effect.

CEMENT BURNING SYSTEM

The cement burning system has been widely developed in in the past fifty years. Fig. 1 shows a modern cement burning system.

As can be observed, the kiln feed, in the form of a dry powder, injected into the cyclone preheater initiates the heat transfer process with the hot gases during its downward movement. This heat transfer inside the preheater leads to physical and chemical changes including preheating, dewatering and partial precalcination. Before entering the kiln, the raw meal passes through precalciner which has burners for a better precalcination process. In fact, the basic difference between the old and the modern burning systems is the usage of precalciners. Many researchers, such as Ashrafizadeh [24], emphasize that the precalciner has significantly reduced the kiln duty, resulting in a lower thermal load in the burning zone, thereby inducing a more stable and smooth operation with considerably decreased operating costs. The major reason for these improvements is high efficiency heat transfer in precalciner (fluidized bed heat transfer). The emergence of the precalciner system has encouraged the owners of the *older* cement industry to use the same philosophy to explore simple and economical modifications. One such modification has been the installation of a secondary burner for some fuel injection into the preheater.

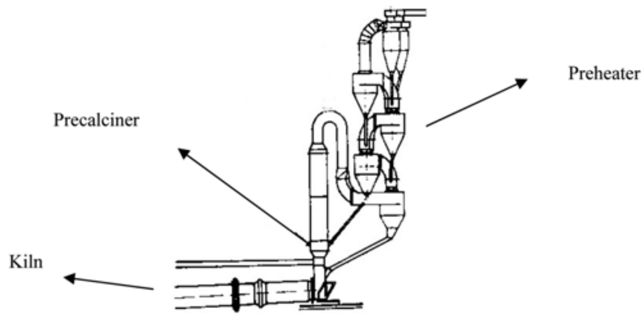

Fig. 1. Modern cement burning system.

The prevalent type of preheater that is widely used is the cyclone or suspension preheater shown in Fig. 1 This type of preheater has an additional duty of separating solid and gas phases besides its main duty of heat transfer. Another type of preheater from a relatively old technology is the shaft preheater (shown in Fig. 2). As the name shows, the preheater is simply composed of a vertical column providing conditions for heat transfer between countercurrent flows of hot gases and kiln feed.

BURNING SYSTEM EXERGY ANALYSIS

Considering both the kiln and the preheater as a single system, the inlet and outlet exergy factors can be shown in Fig. 3.

Exergy losses of this system can be obtained from Eq. (1):

$$EL = EX_{in} - EX_{out} \tag{1}$$

Where EL is the exergy loss; EX_{in} and EX_{out} are exergy input and output, respectively.

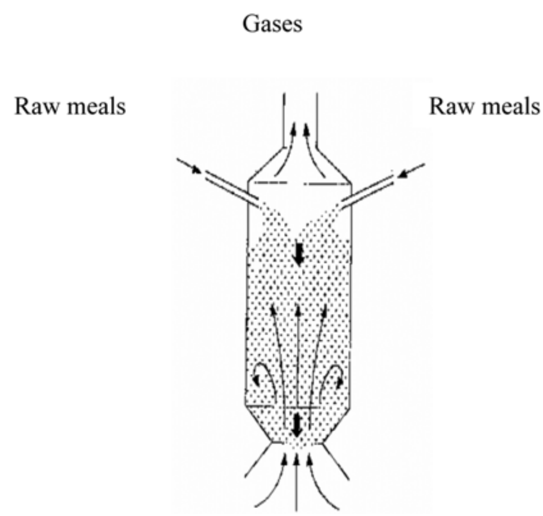

Fig. 2. Shaft preheater.

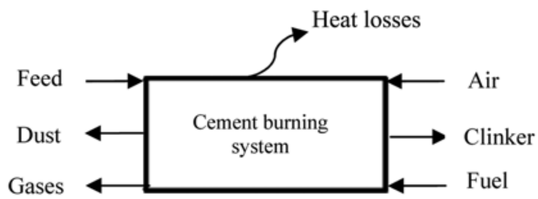

Fig. 3. Inlet and outlet exergy factors of the burning system.

According to Fig. 3, the exergy inlet and outlet factors are given by Eqs. (2) and (3):

$$EX_{in}=EX_{feed}+EX_{air}+Ex_{fuel} \tag{2}$$

$$EX_{out}=EX_{gases}+EX_{clinker}+EX_{dust}+EX_{losses} \tag{3}$$

The exergy of substances is arranged as consisting of physical and chemical parts. The chemical part of exergy is conventionally attributed to the chemical formation of the substances in the standard state from the exergy reference level substances in the environment, while the physical part of exergy is attributed to the changes in temperature, pressure and concentration (mixing) of the substance. The overall exergy (EX) is given by Sato [25], as the following relation:

$$EX=\sum_i n_i ex_i^0+RT_0\sum_i n_i Ln\frac{P_i}{P_0}+\sum_i n_i C_{P,i}^{mean}\left(T-T_0-T_0 Ln\frac{T}{T_0}\right)$$
$$+RT_0\sum_i n_i Ln\left(\frac{n_i}{\Sigma_i n_i}\right) \tag{4}$$

Where n_i is mole number of components, ex_i^0=molar exergy of components (j/mole), T and P are absolute temperature and pressure, respectively. Subscript 0 denotes the environmental condition, $C_{P,i}^{mean}$ is the average specific heat capacity ($J \cdot gmol^{-1} \cdot K^{-1}$) and R=ideal gas constant ($J \cdot gmol^{-1} \cdot K^{-1}$).

In Eq. (4), the first term on the right side is the chemical exergy, the second term is the pressure exergy for gaseous substances, the third term is the thermal exergy due to the change in temperature, and the fourth term is the mixing exergy due to the change in concentration of the substances. For liquid and solid phases, the pressure exergy may be approximated by $V_m(P-P_0)$, where V_m is the volume of the condensed phase at temperature T.

The pressure change compared to the other variables (composition, temperature and concentration) is negligible and the second term can be omitted. By rearranging the above equation, Eq. (5) can be obtained.

$$EX_{mix}=\sum_i n_i ex_i^0+\sum_i n_i C_{Pi}\Delta T_i\left(1-\frac{T_0}{T_{mix}}\right)+RT_0\sum_i n_i Ln(x_i) \tag{5}$$

Where $x_i=(n_i/\Sigma_i n_i)$ and T_{mix} is temperature of the mixture (K).

The right-hand side terms in Eq. (5) are the chemical, thermal, and mixing exergies, respectively. The first term of Eq. (2) and the two first terms of Eq. (3) include all the three mentioned kinds of exergies. The second term in Eq. (2) and the last term in Eq. (3) include only the thermal exergy (air is the thermodynamics reference.). Finally, the last term in Eq. (2) can be considered free of the thermal exergy (for the gas fuel). Typical average chemical compositions of raw meal, natural gas as fuel, and clinker [26] along with standard molar exergy of the components [3] are given in Tables 1, 2, and 3, respectively:

Table 1. The typical average chemical composition for cement raw meal

Component	Mass analysis (%)	Molar exergy kJ/mol
$CaCO_3$	75.5	1
SiO_2	14.4	1.9
Al_2O_3	3.6	200.4
Fe_2O_3	2.4	16.5
H_2O	0.5	0.9
$CaMg(CO_3)_2$	2.5	15.1
K_2O	0.5	413.1
SO_3	0.5	249.1

Table 2. The typical average chemical composition for natural gas as fuel

Component	Volume analysis (%)	Molar exergy kJ/mol
CH_4	77.73	831.63
C_2H_6	5.56	1495.84
C_3H_8	2.4	2154
C_4H_{10}	1.18	2805.8
C_5H_{12}	0.63	3450
CO_2	5.5	19.87
N_2	7	0.72

Table 3. The typical average chemical composition for Portland cement clinker

Component	Mass analysis (%)	Molar exergy kJ/mol
CaO	66	110.2
Al_2O_3	6	200.4
SiO_2	22	1.9
Fe_2O_3	4	16.5

Not only the standard exergy of each substance, but also the exergetic effects such as the mixing and temperature above the environment must also be considered. In general, it can be written as the following model.

MODELING

Fuel injection into the secondary burner has many different effects on the cement burning system, among which the most important ones are as follows:

1. Temperature profile change

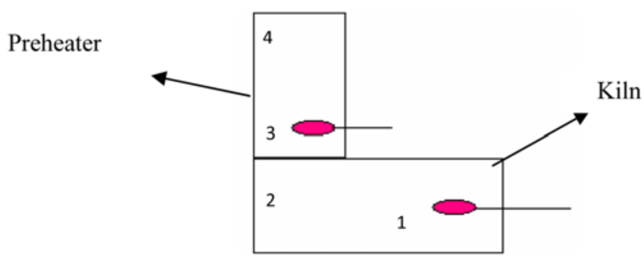

Fig. 4. Thermal areas of the system.

2. Gas velocity change
3. Change in the contact time between gasses and raw materials
4. Precalcination degree change
5. Mass and energy balance changes.

The above items are the functions of the four basic variables including:

- The combustion quality in the secondary burner
- The proportion of fuel injection into the secondary burner
- The excess air proportion in the combustion process
- The location of the secondary burner.

The best location for the secondary burner installation is the duct between the kiln and preheater to minimize the changes in the gas velocity profile and to eliminate any need for structural changes in preheater. Moreover, the contact time between the raw meals and

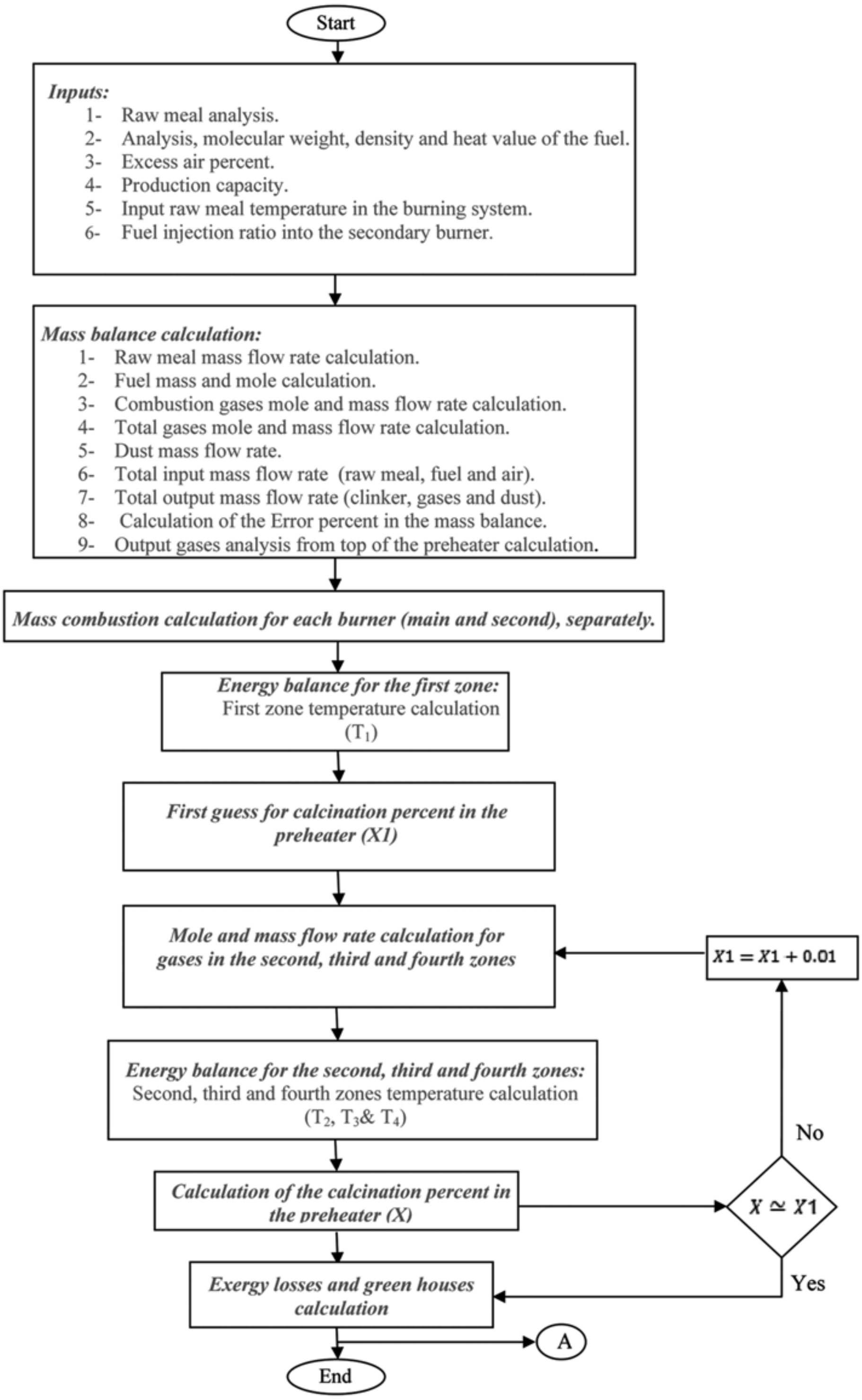

Fig. 5. The model algorithm.

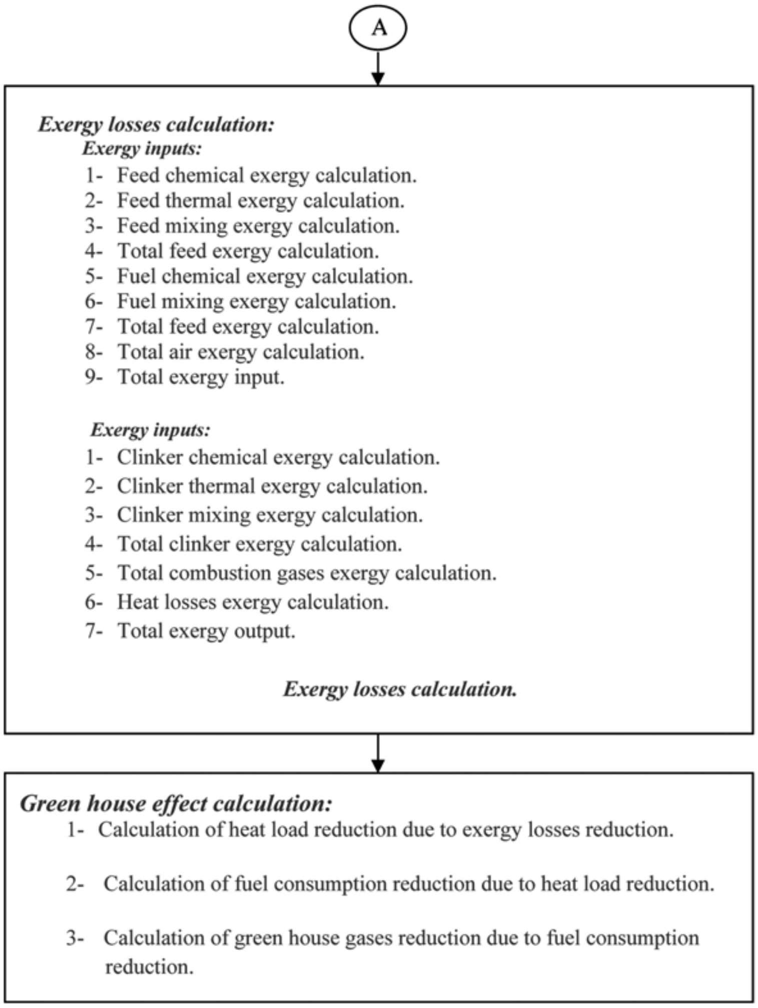

Fig. 5. Continued.

hot gasses will be maximum, resulting in a higher degree of calcinations in the preheater. Combustion quality is related to numerous operational conditions. The most important conditions include burner type, the mixing quality of the combustion air and fuel and the excess air proportion.

Atmospheric burners are more advantageous compared to the other types for which the required air is normally supplied through the kiln, resulting in a relatively low mixing efficiency in the secondary burner due to the high volume of gases. To determine the optimum proportion of fuel injection into the secondary burner, the following important points should be considered: The required thermal energy for sintering process in the kiln burning zone must be completely supplied, and the gas velocity should not exceed the acceptable limit at the kiln inlet for preventing excessive dust load.

Due to the close relations between all the above-mentioned parameters and also due to the complexity of the process, the considered thermodynamics system, i.e., the burning system including kiln and preheater, is divided into four thermal areas for more simplicity in the modeling. These thermal areas shown in Fig. 4 include:

1. First area from the main burner to the end of the kiln

2. Second area from the end of the kiln to the secondary burner location

3. Third area from the secondary burner to the calcinations zone inside preheater

4. Fourth area from the calcinations zone to the top of the preheater.

As the fuel injection into the secondary burner affects the precalcination degree, for any proportion of fuel injection into the secondary burner an initial guess has been considered for the precalcination degree. If all the other factors remain constant, then for any given proportion of fuel injection into the secondary burner, there exists a unique value for the degree of precalcination. This unique value, of course, is that making complete coincidence between kinetics and dynamics equations. Considering all the above mentioned points, the following algorithm has been considered for the model.

According to the Table 2, total exergy for the given fuel equal 835 kJ/mole and the heat value for this fuel equals to 778.49 kJ/mole. Then the heat value to exergy ratio for this fuel is equal 0.932. Therefore, any change in the exergy unit leads to 0.932 changes in the heat value unit consumption of the fuel. On the other hand, if the fuel is the source of the exergy in the system, then any reduction in the exergy losses leads to exergy source (fuel) consumption reduction. Thus, exergy losses reduction leads to green house gases reduction.

RESULTS AND DISCUSSION

Table 4 compares important model results with actual parameters of an existing cement plant.

As can be seen, the model has acceptable results in many parameters. In some parameters, as fuel flow rate and preheater gas outlet temperature, the error percent is about 10%. Obviously, the principal aim in this simulation is not to design the burning system as such, but merely to calculate the parameters needed for exergy evaluation and exergy losses rate changes due to second burner application. Therefore, this accuracy can be acceptable for this aim. There are complicated processes in the burning system. In addition, some important factors such as ambient condition, raw meal analysis, raw meal grinding, fuel analysis have some undesirable variations which affect the system and add to complications of the simulation.

Table 5 represents the results obtained for different proportions of fuel injection into the secondary burner (α) for both cyclone and shaft preheaters at three different production capacities and two different amounts of excess air.

The important results that can be deduced from the above table are:

- In all cases, the exergy losses decrease with the increasing the proportion of fuel injection into the secondary burner.

- At the same conditions, the amount of exergy losses and specific exergy losses (exergy losses per unit of volume fuel consumption) increases with production capacity.

- As seen in Fig. 6, the temperature of the first and the second areas declines with increase in the proportion of fuel injection into the secondary burner, whereas the temperatures of the third and the fourth thermal areas rise.

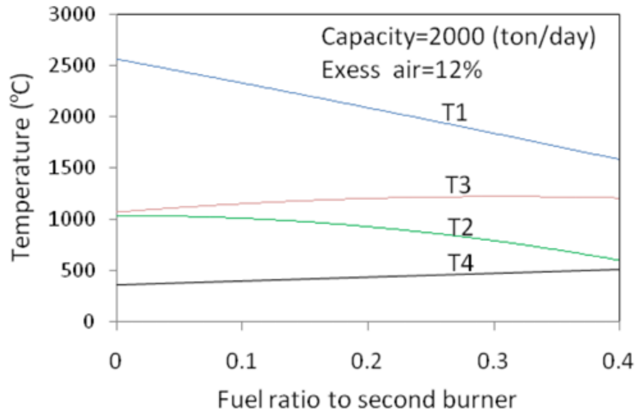

Fig. 6. Temperatures of the four thermal areas versus the ratio of the fuel injection into the secondary burner.

The maximum temperature of the kiln burning zone should not be lower than 2,200 °C. This can be considered as the limiting factor for the amount of fuel injection into the secondary burner. As seen in Fig. 7, in shaft preheaters for any production capacity there is a maximum point for precalcination degree as the ratio of fuel injection into the secondary burner increases.

The situation in cyclone preheaters, however, is different. Fig. 8 shows that the precalcination degree continually increases with in-

Table 4. Model and real data comparison (capacity=1,700 ton/day; excess air=10%)

Parameter	Feed (ton/day)	Fuel (m^3/hr)	Air (m^3/hr)	Kiln gas outlet temp. (°C)	Preheater gas outlet temp. (°C)
Real	2880	7600	73000	1100	400
Model	2871	6817.5	71162.5	1006	358
|Error| (%)	0.31	10.3	2.5	8.5	10.5

Table 5. Effects of the ratio of the fuel injection into the secondary burner on burning system parameters*

		8% Excess air							12% Excess air						
	α	T_1	T_2	T_3	T_4	X_{cy}	X_{sh}	EL	T_1	T_2	T_3	T_4	X_{cy}	X_{sh}	EL
2000 Ton/day	0	2640	945	945	390	13	24	128	2560	1036	1062	376	22	25.3	129
	0.1	2400	939	1038	394	23	26.3	120	2330	1013	1152	387	30	26.6	121
	0.2	2152	859	1082	414	29	26.15	112	2085	925	1196	420	35	25.9	113
	0.3	1890	720	1100	451	33	24.1	103.4	1835	794	1214	467	39	23.6	103
	0.4	1620	534	1105	497	36	20.5	94.5	1580	599	1203	517	41	20.2	96
2300 Ton/day	0	2645	960	960	409	11	22.8	149	2565	1062	1062	397	21	25.4	150
	0.1	2405	950	1058	417	23	26.5	139	2327	1044	1152	407	32	26.2	140
	0.2	2155	894	1114	433	30	26.1	129	2085	990	1196	444	38	24.7	130
	0.3	1900	771	1144	474	35	23.8	119	1836	860	1214	495	42	22.3	119
	0.4	1635	600	1161	528	39	20	101	1580	665	1203	548	44	19.2	109
2600 Ton/day	0	2650	965	965	424	11	23.4	169	2570	1151	1151	411	22	25.6	170
	0.1	2410	1086	1086	433	24	26.7	160	2330	1074	1236	424	37	23.9	159
	0.2	2155	1169	1169	453	33	25.3	148	2086	1064	1281	469	43	21.5	147
	0.3	1905	1213	1213	503	39	22.3	136	1837	956	1298	527	47	18.9	136
	0.4	1670	1215	1215	556	41	18.9	124	1584	745	1300	581	48	17.2	123

*T_i: temperature of areas (°C), X_{cy}: cyclone preheater calcination (%), X_{sh}: shaft preheater calcination (%)

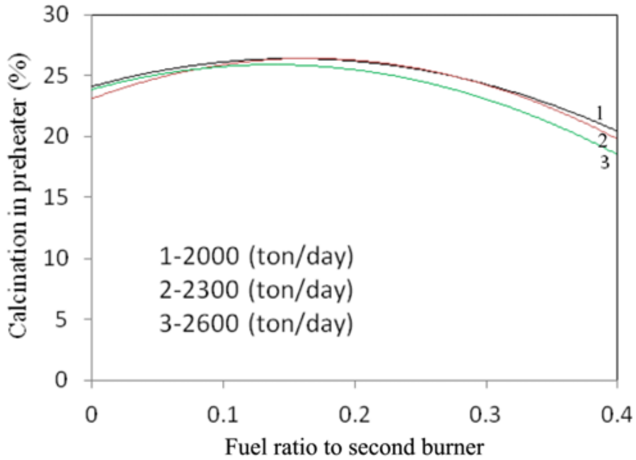

Fig. 7. Precalcination degree versus the ratio of the fuel injection into the secondary burner in shaft preheaters.

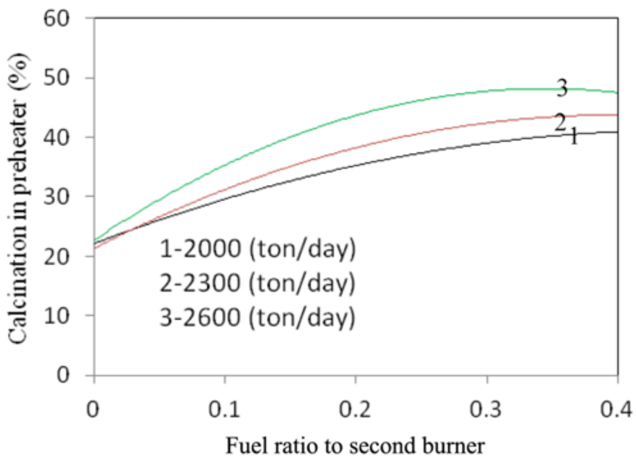

Fig. 8. Precalcination degree versus the ratio of the fuel injection into the secondary burner in cyclone preheaters.

crease in the ratio of the fuel injection into the secondary burner.

Such a difference between the two types of preheaters is due to their structural differences. According to the obtained results, in shaft preheaters the temperature effect on gas residence time is more announced than cyclone preheaters.

Decrease in exergy losses due to fuel injection into the secondary burner normally leads to decreasing fuel consumption and green house gases generation. Table 6 shows the decreasing amounts of exergy losses and green house gases generation for natural gas fuel with 12% excess air.

Fig. 9 shows the annual reductions in green house gases for three different capacities. As seen, the amount of green house gases emission decreases considerably with increasing the ratio of the fuel injection into the secondary burner. The higher the production capacity, the higher the amount of decrease in green house gases emission. In other words, the use of a secondary burner is more advantageous for kilns of higher production capacities.

CONCLUSIONS

Temperature gradient distribution by installation of a secondary burner has positive effects on both exergetic and environmental functions of cement production process. The higher the production capacity of the kiln, the higher the decreases in both exergy losses and green house gas emissions. Structural differences between shaft and cyclone preheaters result in different behavior in variations of precalcination degree with the ratio of the fuel injection into the secondary burner. As the ratio of the fuel injection into the secondary burner increases, in shaft preheaters the precalcination degree passes through a maximum, whereas in cyclone preheaters it increases continually.

Table 6. Decrease in exergy losses and green house generation with the ratio of the fuel injection into the secondary burner (fuel: N.G., excess air=12%)

	Decrease in exergy losses (J/Sec)	Decrease in CO_2 generation (mole/s)	Decrease in H_2O generation (mole/s)
Capacity: 2000 ton/day			
0.1	8	9.9	18.8
0.2	17	20.9	39.7
0.3	26	32.03	60.7
0.4	33	40.7	77.03
Capacity: 2200 ton/day			
0.1	10	12.3	23.31
0.2	20	24.6	46.7
0.3	31	38.2	72.4
0.4	41	50.6	95.8
Capacity: 2600 ton/day			
0.1	11	13.6	13.6
0.2	23	28.3	28.3
0.3	34	41.9	41.9
0.4	48	59.2	59.2

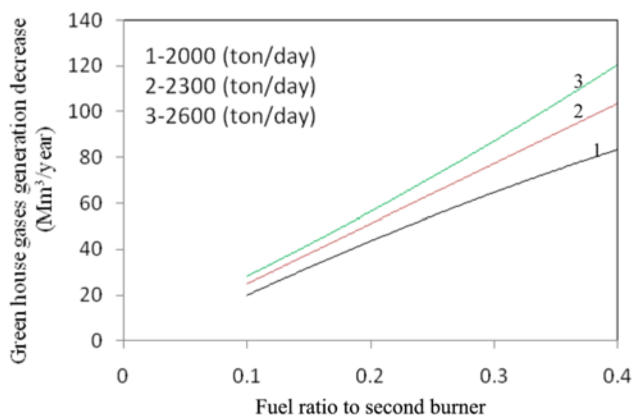

Fig. 9. Annual decrease in green house gases emission versus the ratio of the fuel injection into the secondary burner.

NOMENCLATURE

Symbols

c : specific heat capacity [J/kg·K]

ex : specific exergy [J/gmol]
EL : exergy losses [J]
EX : exergy [J]
n : mole number [gmol]
P : pressure [Pa]
R : ideal gas constant [J/mole K]
T : temperature [K]
X : percent of calcination in the preheater [%]

Greek Symbols

α : fuel ratio into the secondary burner
Δ : change or difference

Subscript

0 : reference state
i : iteration
in : input
mix : mixture
out : output

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