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Exergetic assessment and pollutants emission of a rotary kiln in a tunisian cement manufacturing plant

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Abstract: The cement industry is one of the most energy consuming sectors in the world. Rotary kiln is the most energy intensive section that consumes the highest portion of the total energy. This energy is degaged in the form of dust and atmospheric pollutants. It is therefore very necessary to perform energy, exergy and environmental analyzes to determine possible energy saving options. Thus a thermodynamic evaluation of the rotary kiln unit of a cement plant is carried out. For the analysis, the mass, energy and exergy budgets of the rotary kiln are constituted and the actual performance of the installation makes it possible to identify the performance of the rotary kiln. The energy and exergy efficiency of the unit is 64% and 59% respectively.

The atmospheric emissions method was used to calculate the annual emissions of the cement kiln. Carbon dioxide CO_2 accounts for about 99% of total air pollutant emissions. At the end of the study, the available heat recovery and optimization options are examined.

Keys words: Rotary kiln, Mass balance, emission factor, exergetic efficiency, energetic efficiency.

I.Introduction

The cement industry is a large energy-consuming sector and a source of greenhouse gases (CO_2, NOx...), from heat energy needs for cooking clinker, calcination and power consumption. Reducing greenhouse gas emissions in this sector must focus on controlling energy through actions to increase energy efficiency.

The thermodynamic analysis of the processes, by the exergy approach, is essential for the energy optimization of the processes ([1], [2]). If all the results of the exergy analysis, applied to the cement industry cited in the literature ([3],[4],[5],[6],[7]) tends to identify the clinker cooking process (consisting of the cyclone preheater, the rotary kiln and the grate cooler) as the most degrading energy, understanding and identifying mechanisms and causes that preside over their thermodynamic imperfection remain unknown.

This lost energy is manifested in the form of heat and atmospheric emissions (gas and dust). The main objectives of this study which applied energy, exergy and atmospheric emissions analysis to a rotary kiln in the clinker production process were to evaluate energy and exergy efficiencies.

In the United States of America and for 27 years (1970-1997) Worrell et al. [8] attributed the energy survey in industry. For the preheating process, the CO_2 emission intensity per 1000 kg of cement is 5.4 kg of CO_2.

An investigation is presented by Engin and Ari [9] on a rotary kiln in a cement plant in Turkey. They said that 4 MW of energy could be recovered.

Kabir and El-Nafaty [10] used a blanket surrounding the surface of the kiln. This method saves 42.9 MWh / year.

Atmaca and. al [11] studied cyclone insulation that affects a total heat loss of 22.7 MW to 17.3 MW.

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In this study, using the actual operating data of a Tunisian cement plant, a rotating kiln in operation was analyzed with the evaluation of balance equations (energy, exergy and mass) and the first and second thermodynamic law.

II.Methodology

A. Process description

The raw materials used in the manufacture of cement are extracted from quarries (open pit) from limestone and clay. They are then transported by dumper to the crushing hall. In this first stage, the rock is continuously sampled at each stage of transformation of the material to determine the quantity of various additions required (iron oxide, alumina, silica, etc).The previously crushed raw materials (in elements of 80 mm maximum) are pre-homogenized, dried and then ground mechanically. Other minerals are usually added to correct the chemical composition of the mixture. This first grinding produces a fine powder; it is the "raw cement" or farine. After having been homogenized and crushed a first time, the raw material is filtered and then heated to high temperature in a two-part cooking system [12].

The raw material is poured into a heat exchanger in which the hot gases escaping from the oven circulate in the opposite direction. The material progresses to the entrance of the latter where the temperature is around 800°C. Thus, this preheating makes it possible to start the decarbonation process. The raw material then enters a rotary calcination furnace which is generally fed with petroleum coke or ground coal. This method of cooking allows the material to be progressively conveyed against the current of the hot gases thanks to a slow rotation of 1 at 3 rpm .The travel time of the material can vary between 20 minutes and 1 hour, depending on the production techniques used. The interior of the furnaces is generally covered with refractory bricks, which makes it possible to reach a temperature of 1450°C and to trigger a physic chemical phenomenon called clinkerisation.

As soon as you leave the oven, the incandescent granules must be cooled rapidly. Solid grains (clinker) are then obtained which are transported to huge storage silos. Thus, several types of cement can be created according to the added products, called "adjuvants". In general, a small amount of plaster (3 to 5%) and gypsum are added to the clinker to regulate the setting characteristics of the cement. Although clinker is generally the basic element of the finished product, especially for Portland cements, it can nevertheless be mixed and milled with other industrial or natural minerals. These substitute constituents make it possible to limit CO_2emissions and create cements with varied properties.

B. Energy and Exergy analysis

Some hypotheses are formulated in this study. The process occurs in steady state and the flue gases are supposed to be ideal gases. The kinetic and potential energy variations are supposed insignificant. It is assumed that the system temperature is constant and the energy variations are constant.

The mass balance equation is expressed as follows:

$$\sum_i \dot{m}_{in} = \sum_i \dot{m}_{out} \quad (1)$$

Where $\dot{m}$ is the mass flow rate, the subscript out for outlet and in stands for inlet. It is generally more practical to define the mass/energy data per kg of clinker produced per unit of time. The mass balance of the clinker cooking system (preheater, kiln, cooler) is summarized in Figure1. Used data are obtained from the studied cement plant and the others are found by material balance from the balance equations.

	Inputs: kg/kg-clinker		**Outputs: kg/kg-clinker**	
1.56	farine	Rotary kiln	clinker	1
1.35	Secondary air		Hot gases	2.1
0.29	Primary air		dust	0.22
0.112	coke			

Fig.1 Mass balance of the rotary kiln

The energy balance is given by:

$$\dot{Q}_{net,in} - \dot{W}_{net,out} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \quad (2)$$

Where W is the rate of work, Q is the heat transfer rate and h is the enthalpy.

Energy efficiency is defined as the ratio of the output energy amount and the input energy [13].

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$$\eta_I = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (3)$$

The exergy of a material stream flow is the summation of its chemical exergy (Ex^{ch}) and the physical exergy (Ex^{ph}) [11]. It's given by:

$$\mathrm{Ex} = \mathrm{Ex}^{\mathrm{ph}} + \mathrm{Ex}^{\mathrm{ch}} \quad (4)$$

$$Ex^{ph} = \dot{m}\,[(h - h_0) - T_0(S - S_0)] \quad (5)$$

Where T_0 is the reference temperature (K), $\dot{m}$ is the mass flow rate (kg/h), $(S - S_0)$ is the entropy change from reference point (kJ/kgK) and $(h - h_0)$ is the enthalpy change from reference point (kJ/kg). From the first law of thermodynamics, the enthalpy change is given as:

$$(h - h_0) = C_p(T - T_0) \quad (6)$$

The entropy change is obtained by combining the first and second laws of thermodynamics. It's given by Equation (4), for ideal gases and by Equation (8) for solids and liquids.

$$(S - S_0) = \left[C_p \log\left(\frac{T}{T_0}\right) - R \log\left(\frac{P}{P_0}\right)\right] \quad \text{For ideal gases} \quad (7)$$

$$(S - S_0) = \left[C_p \log\left(\frac{T}{T_0}\right) - V(P - P_0)\right] \quad \text{For solid and liquid} \quad (8)$$

Where T_0 is the reference temperature (K),$(S - S_0)$is the entropy change from reference point (kJ/kgk),V is the specific volume (m^3/kg) and $(P - P_0)$is the pressure change from reference point. The dead state properties are denoted by the subscript (*0*).

The chemical exergy is determined using the following equation [14]:

$$Ex^{chi} = D[\sum X_i \xi_{io} + RT_0 \sum_i X_i (\log X_i)] \quad (9)$$

D is the molar flow of material flow (kmol/s).

X_i is the molar fraction of component (i).

ξ_{io}Is the standard chemical exergy of component (i) (KJ/Kmol).

exergy efficiency η is calculated using:

$$\eta = \frac{\sum \mathrm{Ex_{out}}}{\sum \mathrm{Ex_{in}}} \quad (10)$$

C.Inventory of atmospheric emissions

According to the literature review, there are several methods to make an inventory of emissions. In our case we chose the product-oriented method.

Process Emission Factors

The estimation of the emissions of the process is carried out with reference to European emission factors according to the following formula [15].

$$E_1 = E_S = P_r * FE_s \quad (11)$$

Pr: annual production in tones (Ton/year).

The estimation of emissions related to the fuel is carried out by referring to French emission factors according to the following formula:

$$E_2 = E_s = \sum Q_f\, PCI_f FE_{s,f} \quad (12)$$

In the Equation (11):

E_sIs the emission of the substance (s) (ton / year).

Q_fIs the amount of fuel consumed (ton/year).

PCI_fIs thelower calorific value of the fuel (f) (MJ/Kg).

$FE_{s,f}$Is theemission factor of the substance (s) for the fuel f (g/GJ).

Estimation of atmospheric emissions

The estimate of the atmospheric emissions (*E*) of a given industrial sector is equal to the sum of the emissions related to the process (E_1) and the emissions related to the fuel (E_2):

$$E = E_1 + E_2 \quad (13)$$

III.Results and discussions

A. Energy and Exergy analysis

The total energy output (Ėout) involves the energy of constituents and hot gases leaving the furnace, as well as the heat loss of the outer surface of the rotary kiln. The energy input of the incoming materials and the energy resulting from the combustion process is the total energy input (in).

It is found that 25% of the input energy is lost during the formation of the clinker and in the form of heat on the surface of the rotary kiln. The total amount of energy entering and leaving the system was calculated at 85.33 MW and 55.417 MW, respectively. The energy efficiency of the oven is 64%. The physical and chemical exergy is 109.623 MW. Total exergy for production is the sum of physical and chemical exergy, heat transfer and clinker formation in the kiln.

The main input energy is provided by the combustion process. The combustion process has the greatest influence on the energy and exergy of the system.

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Table1. Energy and Exergy values of rotary kiln

Input material	Content	$\dot{m}$ (kg/h)	cp (kJ/kgK)	T_0 (K)	T_{in} (K)	Δh (kJ/kg)	Δs (kJ/kgK)	$\Sigma \dot{m} h$ (kW)	$\Sigma \dot{m} \psi$ (kW)	Ex_{ch} (kW)	Ex_{ph}(kW)
Farine	CaO	52457,58	0,6	298	1073	465	0,768672	6775,771	3337,822	5206,958	3437,949
	SiO_2	15663,06	0,689	298	1073	533,975	0,882692	2323,245	1144,457	1449,672	1178,788
	Al_2O_3	4443,075	2	298	1073	1550	2,562241	1912,991	942,361	242,8597	970,6296
	Fe_2O_3	2617,02	4,15	298	1073	3216,25	5,316649	2338,053	1151,752	91,62029	1186,301
	MgO	1474,515	0,37	298	1073	286,75	0,474014	117,4492	57,85682	204,7075	59,59239
	K_2O	1396,395	4,3	298	1073	3332,5	5,508817	1292,635	636,7668	253,7088	655,8683
	CO_2	17869,95	1,24	298	1073	961	1,588589	4770,284	2349,896	3246,763	2420,388
	Na_2O	166,005	4,36	298	1073	3379	5,585684	155,8141	76,75582	30,16119	79,05832
	SO_3	1562,4	0,62	298	1073	480,5	0,794295	208,537	102,7277	283,87	105,8093
Total	-	97650						19894,78	9800,395	11010,32	10094,38
Coke kiln	C_2	5692,4	0,03	298	330	0,96	0,00306	1,517973	1,441873	806,0868	0,0761
	Ash	32,2	1,3	298	330	41,6	0,132599	0,372089	0,353435	0	0,018654
	O_2	31,5	0,92	298	330	29,44	0,093839	0,2576	0,244686	4,460638	0,012914
	H_2	200,9	14,32	298	330	458,24	1,460628	25,57234	24,29033	28,44896	1,282012
	H2O	560	4,18	298	330	133,76	0,426357	20,80711	19,76399	79,30023	1,043118
	N_2	61,6	1,04	298	330	33,28	0,106079	0,569458	0,540909	8,723025	0,028548
	S_2	421,4	5,64	298	330	180,48	0,575275	21,12619	20,06707	59,67342	1,059114
Total	-	7000.00						70,22276	66,7023	986,6931	3,52046
Combustion	-	7000		298	1300	33000	0	64166,67	0		64166,67
Primary Air kiln	N_2	*14430,8*	1,039	298	298	0	0	0	0	2873,528	0
	O_2	*3866,03*	0,918	298	298	0	0	0	0	673,6252	0
	Ar	*222,612*	4,97	298	298	0	0	0	0	31,03221	0
	CO_2	*7,32765*	0,846	298	298	0	0	0	0	0,928618	0
	H2O	*5,6395*	4,18	298	298	0	0	0	0	1,746999	0
	Other	*16,733*	1,007	298	298	0	0	0	0	3,220845	0
Total	-	18551						0	0	3584,082	0
Secondary air	N_2	65829,79	1,046	298	420	127,612	0,358947	2333,52	1955,988	12251,87	377,532
	O_2	17635,85	0,95	298	420	115,9	0,326003	567,7764	475,9178	2872,137	91,85856
	Ar	1015,5	4,97	298	420	606,34	1,705511	171,0384	143,3667	132,3121	27,67171
	CO_2	33,42688	0,952	298	420	116,144	0,326689	1,078425	0,903951	3,959349	0,174475
	H2O	25,726	1,97	298	420	240,34	0,676028	1,717496	1,439629	7,448683	0,277868
	Other	76,33175	1,17	298	420	142,74	0,401499	3,026554	2,536898	13,73273	0,489656
Total	-	84625						3078,157	2580,153	15281,46	498,0043

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Table2. Continued Energy and Exergy values of rotary kiln

Input Material	Content	ṁ (kg/h)	cp (kJ/kgK)	T_0 (K)	Tin (K)	Δh (kJ/kg)	Δs (kJ/kgK)	Σ ṁ h (kW)	Σ ṁ ψ (kW)	EX_{ch} (KW)	EX_{ph} (KW)
clinker chaud	4CaO	1875	0,62	298	1550	776,24	1,022328	404,2917	158,6739	63,8369	245,6178
	Al_2O_3	1375	2,17	298	1550	2716,84	3,578149	1037,682	407,263	102,8066	630,419
	Fe_2O_3	2812,5	4,43	298	1550	5546,36	7,304701	4333,094	1700,626	134,9006	2632,468
	2CaO	7231,3	0,6	298,0	1550	776,24	1,022328	1559,218	611,9523	492,3953	947,2659
	SiO2	7500	0,74	298	1550	926,48	1,220198	1930,167	757,5398	953,2977	1172,627
	3CaO	3125	0,62	298	1550	776,24	1,022328	673,8194	264,4565	141,8598	409,363
	Al_2O3	3250	2,17	298	1550	2716,84	3,578149	2452,703	962,6216	242,9974	1490,081
	3CaO	22500	0,62	298	1550	776,24	1,022328	4851,5	1904,087	1021,39	2947,413
	SiO_2	10625	0,74	298	1550	926,48	1,220198	2734,403	1073,181	1350,505	1661,221
	K2O	287,5	4,78	298	1550	5984,56	7,881822	477,9336	187,5764	23,32537	290,3572
	SO_3	1168,75	0,89	298	1550	1114,28	1,467536	361,7541	141,979	111,4167	219,7751
	MgO	706,25	0,39	298	1550	488,28	0,643078	95,79104	37,59547	134,6533	58,19557
	Na_2O	43,75	4,71	298	1550	5896,92	7,766398	71,66396	28,12623	5,381519	43,53773
Total		62500	-	-	-			12462,64	4891,259	4778,767	7571,379
Hot gases	N_2	12638,76	1,081	298	1120	888,582	1,431234	3119,603	1497,368	2282,559	13643,13
	CO_2	105222,2	1,092	298	1120	897,624	1,445798	26236,11	12592,99	12092,9	1794,03
	H2O	7370,418	2,05	298	1120	1685,1	2,71418	3449,97	1655,94	2070,596	474,2429
	O_2	3954,538	1,01	298	1120	830,22	1,33723	911,9824	437,7395	624,9158	713,2752
	CO	1208,696	4,97	298	1120	4085,34	6,580233	1371,648	658,3731	218,2905	83,30176
	SO_2	985,35	0,712	298	1120	585,264	0,942681	160,1916	76,88987	77,85496	18330,21
Total		131380		-	-			35249,51	16919,3	17367,12	35038,18
Dust Kiln	4CaO	502,056	0,7	298	585	200,9	0,4753	28,01751	19,75303	12,45209	8,264483
	Al_2O_3	195,244	0,92	298	585	743,33	1,75861	40,31409	28,42242	10,63446	11,89167
	Fe_2O_3	334,704	0,7	298	585	1518,23	3,59191	141,1549	99,51765	11,69504	41,63725
	2CaO	1854,818	0,92	298	585	200,9	0,4753	103,5091	72,97647	92,00709	30,53267
	SiO_2	1004,112	0,7	298	585	264,04	0,62468	73,64604	51,92225	92,97559	21,72378
	3CaO	794,922	2,59	298	585	200,9	0,4753	44,36106	31,27563	26,28774	13,08543
	Al_2O_3	474,164	0,7	298	585	743,33	1,75861	97,90565	69,02587	25,82655	28,87978
	3CaO	4685,856	2,59	298	585	200,9	0,4753	261,4968	184,3616	154,9593	77,13518
	SiO_2	1673,52	5,29	298	585	264,04	0,62468	122,7434	86,53709	154,9593	36,20631
	Ash	2426,604	1.3	298	585	373,1	0,8827	251,4905	177,307	0	74,18358
Total		13946	-	-	-	-	-	1164,639	821,099	581,7972	343,5401

Summarizing these tables, we can extract the following table, especially the energetic and exergetic efficiency of the kiln.

Table3. Energy and exergy efficiency of kiln.

	Input energy (MW)	Output energy(MW)	Energetic efficiency	Input exergy (MW)	Output exergy(MW)	Exergetic efficiency
kiln	85.33	55.417	0.64	109.623	65.679	0.59

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B.Emissions from the cement industry

The flue gases and most of the particles are emitted by the large chimney. The other filters only remove dust.

Energy emissions are the atmospheric emissions associated with the combustion of the fuel used by the rotary kiln.For an annual consumption of 61320 tonnes / year of petroleum coke and 191135 tonnes / year of natural gas, the calculation of energy emissions resulting from combustion is carried out according to the emission method (12). For annual clinker production in the order of 814164.8 tonnes / year, with a known process emission factor, the calculation of process emissions is calculated according to equation (11).

The fuel and process emissions are summarized in the following table.

Table4. Cement Industry Contribution to Air Pollution

	E SO2	E NOx	E CO	E CO2	ECOV	ETSP
natural gas	**0**	**635.18**	**180.12**	**54037.68**	**37.92**	**0**
pet coke	**2569.2**	**323.4**	**26.94**	**172480.89**	**5.38**	**0**
process	**0**	**0**	**0**	**427436.52**	**0**	**73.27**
Total emis	**2569.2**	**985.32**	**207.06**	**653955.09**	**43.3**	**73.27**

It was noted that CO_2 is the main pollutant compared to other pollutants. The calcination process and the fuel combustion process are responsible for emissions of particulates and gases (nitrogen oxides (NOx), carbon monoxide (CO), sulfur, carbon dioxide (SO_2)) and other pollutants. CO_2 accounts for about 99% of all major air pollutants. Dry cement [15] revealed that about 0.59 tonnes of CO_2 is emitted per tonne of cement. However, the estimated value obtained for this study is about 0.90 tonnes of CO2 / tonne of clinker produced. This represents approximately 1.53 multiples of the value obtained by the study. In recent years, several studies have been conducted to reduce CO_2 emissions, considered as the greenhouse gas. Proposed approaches to regulation in recent decades include the use of fuels and alternative sources of energy. Substitution of raw materials, use of energy efficient equipment and replacement of old facilities are ways to improve the energy efficiency of processes. Better furnace insulation and optimization of clinker cooling are part of the process upgrade [16]. Using the best available technology can help to increase energy efficiency and to reduce pollutant emissions. Increasing energy consumption increases pollutant emissions.

IV.Conclusion

This simulation of rotary kiln cement has made it possible to evaluate exergy, energy efficiency and pollutant emissions from this equipment in a large Tunisian cement factory. The exergetic and energetic efficiency of the rotary kiln are respectively 0.59 and 0.64. Degraded exergy in the furnace was 43.9 MW. CO_2 emissions accounted for more than 99%. Approximately 0.900 tonnes of CO_2 were emitted per ton of clinker produced. This waste heat can be recovered in other uses such as electricity generation.

The thermodynamic parameters must be optimized to improve its exergetic efficiency. Carbon mitigation and capture strategies need to be used to reduce CO_2 emissions in the cement industry.

Researchers are still working on optimizing the cement kiln and finding solutions to reduce degraded energy.

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