23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

COMPARISON OF GAS RESIDENCE TIME IN DIFFERENT CEMENT PRODUCTION SYSTEMS FOR THE CO-PROCESSING OF MUNICIPAL SOLID WASTE

Josué de Almeida Meystre
Rogério José da Silva
Instituto de Engenharia Mecânica (IEM), Universidade Federal de Itajuba (UNIFEI), Av. BPS, 1303, Bairro Pinheirinho, Itajubá-MG, CEP 37500-000, Brazil
josue@unifei.edu.br
rogeriojs@unifei.edu.br

Abstract. Portland cement manufacturing is characterized by high emission of pollutants gases during the clinker production process, due to a large amounts of raw materials and fuel entering the system that operates at high temperature, reaching 1450 °C for the solid phase and up to 2000 °C for the flame temperature. The introduction of the co-processing technique by cement industry has expanded the range of pollutants that can be generated during the production of clinker. In the co-processing when traditional or alternative fuels are burned, incomplete combustion may generate besides carbon monoxide (CO), nitrogen oxides (NO_x) and sulfur oxides (SO_x), also forming a number of other pollutants, such as hydrochloric acid (HCl), hydrofluoric acid (HF), volatile organic compounds (VOCs), heavy metals, dioxins and furans (PCDD/F), ammonia and chlorine. This study demonstrates the generation of different volumes of gases produced by the calcination of raw materials and the burning of differents fuels, coke of petroleum and materials constituents of Municipal Solid Waste (MSW), considering its chemical characteristics to be co-processed, into two kinds of systems to produce clinker, In Line Calciner (ILC) and Separate Line Calciner (SLC), aiming at maintaining an oxidizing atmosphere into the rotary kiln and precalcinator. Based on the type, design and dimensional characteristics of the kiln system. It was analyzed the variation of the Gas Residence Time (GRT) and temperatures, necessary to ensure the efficient destruction of Refuse Derived Fuel (RDF) from MSW.

Keywords: *Co-processing, Municipal Solid Waste, Gas Residence Time, Cement Rotary Kiln, Refuse Derived Fuel*

1. INTRODUCTION

The increasing amounts of Municipal Solid Waste (MSW) in developing countries, especially in urban areas, is because of population growth, the consequence of urban territorial expansion and production and consumption system that, did not consider the necessity of suitable sites to make the proper disposal and treatment of waste materials, as these are currently the very big problem for society (Meystre and Silva, 2012).

The main negative environmental impacts caused by the irregular disposal of MSW are the potential risk of groundwater, surface water and soil contamination by leaching, the proliferation of vector-borne diseases transmission and air pollution that increasing Greenhouse Gas (GHG) emissions. This situation shows the severity in the manner of the urban waste is disposal, and point to the importance of establishing mechanisms that include its management (Meystre and Silva, 2013).

MSW should be managed under Integrated Solid Waste Management (ISWM) hierarchy and shall be landfilled only if there is no financially and ecologically better way of avoidance, recycling or recovery energy from the waste(GTZ and Holcim, 2006). According to the Article 4 of the Waste Framework Directive 2008/98/EC (WFD2008), "waste hierarchy" was described through five measures: prevention, preparing for reuse, recycling, other recovery (e.g. energy recovery) and disposal (EC, 2008). This hierarchization lays down a priority order of what constitutes the best overall environmental option in waste legislation and policy (EC, 2012).

Unfortunately, for energy recovery from MSW is necessary to know its origins and proceed with pretreatments that consisting of, according to Velis, *et al.*, (2010), waste preparation techniques (e.g. hammer mill, shredder, rotating drum, ball mill) and waste separation techniques (e.g. trommels, screens, manual separation, magnetic separation, eddy current separation, wet separation, air classification ballistic separation, optical separation), to ensure minimum quality (heat value and chemical composition) before the use as an alternative fuel (CEMBUREAU, 2009). Another issue is that the composition of MSW varies significantly from region to region, due to cultural differences, level of industrialization, level of source separation (recycling) and each way of waste processing in different countries.

Thus, fractions from urban, commercial and some industrial wastes with high heat value and same characteristics are being more and more used as alternative fuels for power generation and also to replace other types of fuels in industrial processes. These fractions, named as Refuse Derived Fuel (RDF) has a series of advantages when used for co-combustion in industrial processes.

The main benefits of using RDF for co-combustion are the following: 1) can be milled into particles of uniform size or densified briquettes to facilitate the handling, storage, transportation and combustion; 2) can be burned together with other combustible in different physical states; 3) low production costs, which can reduce the cost of generation of heat or electricity; 4) low concentration of heavy metals; 5) uniform composition which ends up helping in the control of the combustion process; 6) saving non-renewable resources, with the substitution of fossil fuels in processes with high energy demand (Kara, 2011; GTZ and Holcim, 2006; Velis *et al.*, 2010). The chemical composition of the feedstocks used in RDF composition together with their respective higher and lower heat values is presented in Tab.1.

Table 1. Chemical composition of the feedstocks used in the RDF composition and their calorific values.

Samples	Ultimate Analysis (wt. %, dry basis)						HHV (MJ/kg)	LHV* (MJ/kg)	Authors
	C	H	O	N	S	Cl			
Newspaper	52.10	5.90	41.86	0.11	0.03	0	19.300	17.973	Sørum *et al.*, 2001
Cardboard	39.93	5.40	38.64	0	0.03	0	15.700	14.485	Wang *et al.*, 2012
Magazine paper	35.50	4.60	35.96	0.45	0	0	12.340	11.305	Grammelis *et al.*, 2009
Wood	48.10	5.99	45.74	0.08	0	0	19.916	18.569	Parikh *et al.*, 2005
Tetra pack	48.00	6.30	39.04	0.08	0	0	18.520	17.103	Grammelis *et al.*, 2009
PA	62.70	9.70	5.12	10.67	0	0	32.600	30.418	Grammelis *et al.*, 2009
PC	74.10	5.50	6.50	0.22	0	0	32.200	30.963	Grammelis *et al.*, 2009
LDPE	83.72	13.16	2.37	0	0	0	45.970	43.010	Wang *et al.*, 2012
HDPE	84.90	13.35	1.68	0	0	0	46.890	43.887	Wang *et al.*, 2012
PP	86.10	13.70	0.20	0	0	0	46.400	43.319	Sørum *et al.*, 2001
PS	92.70	7.90	0	0	0	0	42.100	40.323	Sørum *et al.*, 2001
PET	69.24	7.61	23.09	0	0.07	0	23.360	21.648	Wang *et al.*, 2012
PVC	44.62	5.81	3.27	0.04	0.17	46.10	23.860	22.553	Wang *et al.*, 2012
RDF (1)	38.40	5.60	37.30	1.30	0.10	0.10	14.226	12.966	Lin *et al.*, 1999
RDF (2)	56.30	4.70	20.21	1.65	0.13	0	22.350	21.293	Grammelis *et al.*, 2009

PA – Polyamide
PC – Polycarbonate
LDPE – Low Density Polyethylene
HDPE – High Density Polyethylene
PP – Polypropylene
PS – Polystyrene
PET – Polyethylene terephthalate
PVC – Polyvinyl chloride
RDF – Refuse Derived Fuel
HHV – Higher Heating Value
LHV – Lower Heating Value

Relation between heat values
$*LHV = HHV - (4{,}186 * 597 * (9H))$

2. CO-PROCESSING MSW IN CEMENT KILN SYSTEM

The thermic process in clinker production can be roughly split into four sequential steps: preheating, calcining, sintering (or burning, formation of clinker minerals) and cooling. Typically, these steps are called "kiln system". However, many different plant configurations with rotary kilns of different types, preheater cyclone configurations, with or without precalciner, with or without tertiary air duct, and others are known. Typically, the configuration depends strongly on the available feedstock, the available fuels and the plant evolution driven by the progress of the cement production technologies (Nielsen, 2012).

The manufacture of Portland cement is a process that requires a large consumption of thermal and electrical energy. Each cement production plant comprises, besides mining fronts, a transformation industry that has proven consuming large volumes of fuels and electric energy to grind, calcine and fuse the raw materials of interest to the process. The heat generated by the fuel constitutes 90% of total energy consumed in the process, remaining 10% attributed to electricity consumption. The most used technology in the clinker manufacturing process is a dry route with multi-stage cyclones in preheating and precalciner, with a specific consumption of thermal energy between 2.900 to 3.300 MJ/t of clinker produced (EIPPCB, 2013).

Technological advances in the replacement of fossil fuels and use of renewable raw materials for alternative inputs in the cement industry have always been boosted by the search for reduction of thermal and electrical energy consumption, and the rational use of non-renewable natural resources, especially due to the high economic appeal, linked to the cost of energy or the extension of the mine lifespan (Maringolo, 2001). In addition, the possibility of using waste as an alternative fuel makes co-processing more competitive and at the same time, helps solve society's problems with solid waste by establishing a huge opportunity to improve environmental and social image of the cement plants.

In general, researchers indicates that the co-processing offers many advantages, including: 1) Thermal disposal of hazardous waste and environmental liabilities; 2) Preservation of fossil fuel reserves by reducing the consumption of fuels derived from oil; 3) Recovery of the energy value of the materials used for co-processing; 4) Reduction of the manufacturing cost; 5) Reduction of waste disposal in sanitary landfills or incinerated; 6) Reduction of the overall greenhouse gases and 7) Optimization of technology in existing facilities. (EIPPCB, 2013; Karstensen, 2007; Greco *et al.*, 2004).

The co-processing condition of MSW occurs when physical and chemical characteristics of some materials, allow their use in kiln systems of cement plants for the energy recovery. The properties of equipment integrated at production line and the high technology involved in the cement manufacturing process, where the rotary kiln plays a fundamental role on the characteristics and control of combustion, causes thermal destruction of the materials. The material to be completely degraded must be heated to a temperature of destruction and maintained at that temperature for a time together with a sufficient amount of oxygen to oxidize and destroy it (Maringolo, 2001). Combustion temperature and Gas Residence Time (GRT), needed for totality destruction of MSW, cannot be readily calculated and are often determined empirically (Meystre and Silva, 2013). The standards temperatures, GRT and material residence time that normally occur into the rotary kiln, precalciner and preheater, during cement production, is shown in Fig. 1.

However, not all types of waste can be co-processed in cement industry and some factors such as the final chemical composition of cement and the environmental impact combined with the manufacturing process should be taken into account to decide the feasibility of its use. Between non-viable residues to co-processing are mainly: 1) Nuclear waste; 2) Contaminated waste from health service; 3) Battery and 4) MSW without previous treatment or separation (CEMBUREAU, 2009).

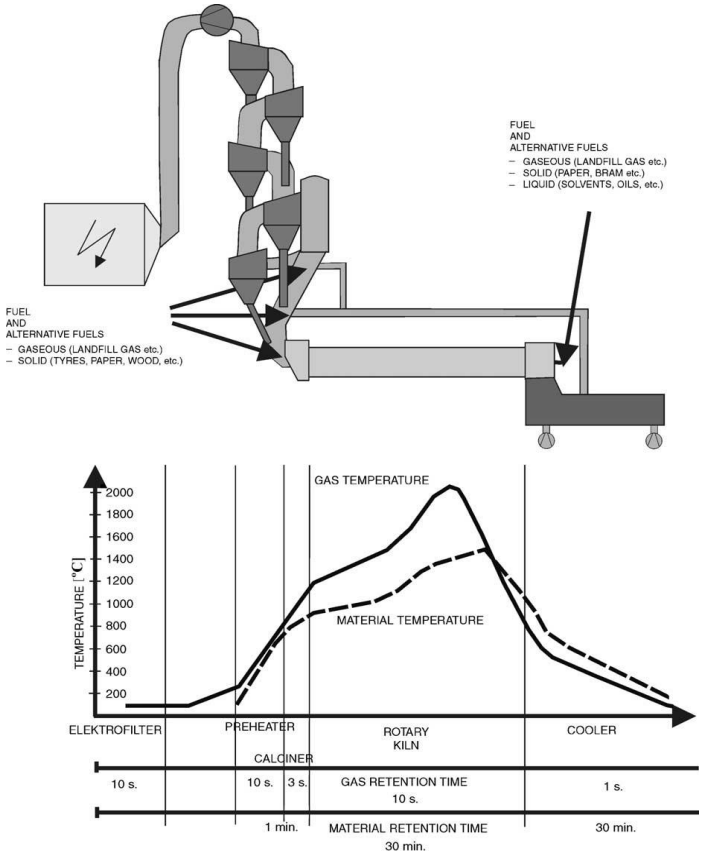

Figure 1. Diagram of the temperatures, retention time of gases and materials in a cement kiln
Source: Mokrzycki and Bocheńczyk (2003)

3. RSU FEEDING POINT IN THE KILN SYSTEM

To ensure gas temperature profile inside the rotary kiln (temperatures reaching 2000 ° C), only alternative fuels that have heat value higher than 20 MJ/kg can be fed to the main burner. The remaining fuels can be fed through the rear of the rotary kiln, in the feed zone of the precalciner, where the raw meal hardly exceeds the temperature of 1,100 °C, where calcination reaction is endothermic, being maintained with the fuel burning, and in that case it is possible the use of materials with low heating value (Santi, 2003).

There are basically four feed points at cement plants (Fig. 1): 1) In the main burner; 2) rotary kiln inlet (back end chamber); 3) Together with the raw meal; (4) In the secondary burner in precalciner (Minas Gerais, 2010; GTZ and Holcim, 2006). These feed points can be used to insert fuels and raw materials, in different physical states to the cement manufacturing process.

The manner of fuel introduction in the system has direct effects on emissions. Multi-channel burners are designed for the use of different types of fuels, including RDF. Waste fed through the main burner, in the rotary kiln, are decomposed into the primary burning zone at high temperatures up to 2000 ° C. Already waste fed through the secondary burner, in the precalciner, are burned at lower temperatures, which is not always sufficient to decompose halogenated organic substances or precursors of toxic substances.

Therefore, alternative fuel fed to the main burner which will pass through the highest temperature zone in the rotary kiln can be decomposed or linked in the clinker, while the alternative fuel fed into the secondary burner will have lower temperature and GRT, and dependent on the design and system operation to be destroyed (EIPPCB, 2013).

4. POLLUTION PRODUCED BY USE OF MSW

The RSU, in RDF condition, with appropriate heat values can replace other types of fossil fuels and alternative fuels. However, despite cement kilns system are technically capable of replacing a large portion of conventional fuels by alternative fuels, there are some practical limitations. These limitations are usually associated with the production process in which alternative fuels with significantly different properties from conventional fuels, either low heat value, high moisture content or high concentration of chlorine and other trace substances, must be carefully managed.

In clinker production process, the large temperatures and amounts of inputs, materials and energy that entering into the system, make production unit a generator of atmospheric pollutants. Typically, a fossil fuel has a combination of carbon and hydrogen which when burned efficiently form water (H_2O) and carbon dioxide (CO_2). But in practice, fossil fuel as well as alternative fuel, they contain other elements such as nitrogen, sulfur, chlorine, fluorine, heavy metals and others.

The major constituents of the cement plant exhaust gases are nitrogen (N_2) incorporated into the combustion air, carbon dioxide (CO_2) from combustion and calcination, water (H_2O) formed in the combustion and incorporated in the raw material and excess of oxygen (O_2) that was not used in the combustion. In the co-processing, when fuels are burned, whether traditional or alternative fuels, it incomplete combustion can lead to beyond the carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), also the formation of various other pollutants, such as hydrochloric acid (HCl), hydrofluoric acid (HF), volatile organic compounds (VOCs), heavy metals, dioxins and furans (PCDD/F), ammonia and chlorine (Karstensen, 2008; GTZ and Holcim, 2006; Santi, 2003; Araújo, 2002).

Despite the extensive formation of acid gases in the rotary kiln during the process of burning fuel, the addition of the raw meal, that appears to be highly alkaline, neutralizes the majority of them (USEPA, 2003). However, due to accumulative effect, certain elements, even if issued in very small quantities, are harmful to the health of populations which live near the emission sources, where small amounts continuously absorbed keep adding up until a level sufficient to cause harm is reached(Santi, 2003).

The main problem regarding the use of RDF by cement kilns system is chlorine presence. When the chlorine content is high, it weakens the concrete in terms of compression strength, where chlorine compounds and alkali-silica reactions create salts, which cause microcracks and the compression strength decrease. Also, chlorine creates the oxidation of iron in concrete or else can increase substantially the formation of polychorinated dibenzo-p-dioxins (PCCD) e polychlorinated dibenzofurans (PCCF) due to presence of organochlorine (Kara *et al.*, 2011).

5. TYPES OF CALCINERS

According Signoretti and Silva (2005), there are basically two kinds of kilns systems with precalciner outlined below.

In-Line Calciner (ILC): Is a precalciner system in which the tertiary air and rotary kiln exhaust gas pass through the combustion zone of the precalciner (Fig. 2). This type of precalciner is commonly used for normal fuels, such as coal, oil, gas, and wastes, with relatively high volatile bituminous coal serving as the main fuel. An ILC uses the hot recovered air from the cooler for fuel combustion. Since rotary kiln combustion gases (O_2 content of approximately 2%) are mixed with the air from the cooler, the oxygen content of the ILC is much less than 21%, and the temperature is normally below 900 °C. The low-oxygen content and temperature makes the ILC more compatible with fuels that have relatively high volatile content. Fuels with low volatile content, such as petroleum coke, are difficult to burn in the ILC system.

Separate Line Calciner (SLC): In these systems (Fig. 3), the rotary kiln exhaust gas bypasses the combustion zone of the precalciner. An SLC uses air containing 21% oxygen recovered from the cooler for combustion, and this air is not mixed with rotary kiln combustion gases. SLCs usually have longer GRT and higher temperatures, allowing these systems to use low-volatile fuels, such as petroleum coke and anthracite. Existing systems are easier to upgrade with SLCs because there are many configurations for this type of precalciner.

6. CASE STUDY

To perform the calculations of the GRT in different chambers of the kiln system, was utilized schematic drawings based on two different designs of plants of cement manufacturing that use such as technology dry process, composed with precalciner and five stages cyclones in preheating tower provided by FLSchmidt (Fig. 2 and Fig. 3).

As conventional fuel, petroleum coke was used with a specific energy consumption of 70%, and as alternative fuels, tire waste of 10% and different materials that constitute the RDF of 20%. Into the rotary kiln was used only petroleum coke and within the precalciner also with other alternative fuels. A typical characteristic of the waste that compose RDF is in Tab. 1 and the characteristics of the other fuels are observed in Tab. 2.

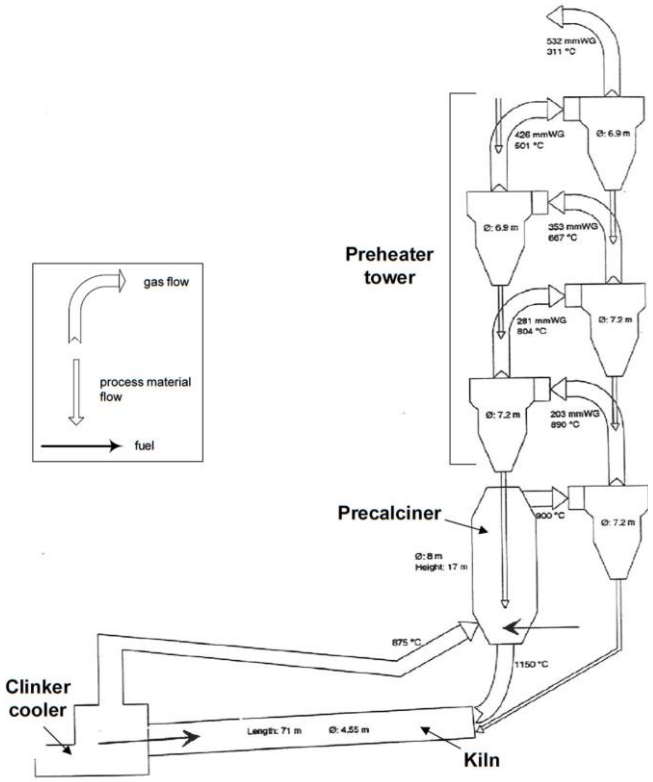

Figure 2. F.L. Schmidt ILC – In Line Calciner kiln system
Source: USEPA (2007)

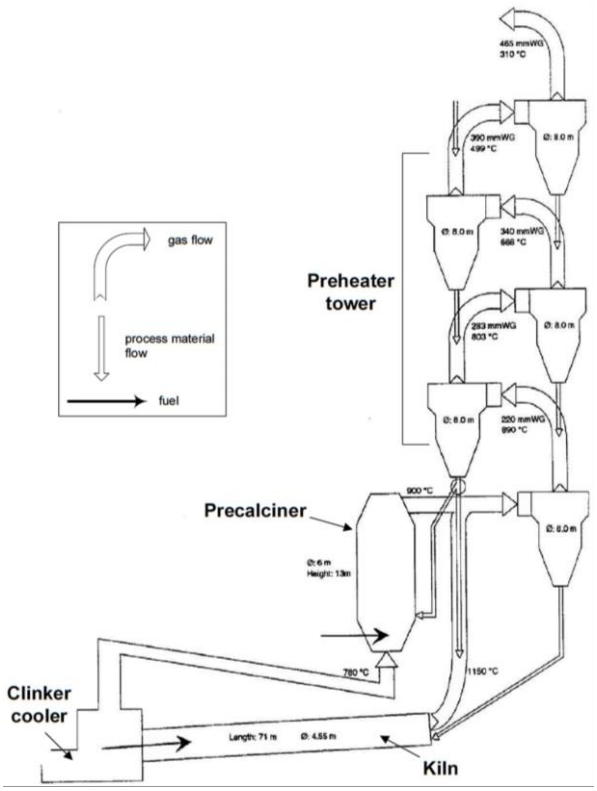

Figure 3. F.L. Schmidt SLC - Separate Line Calciner kiln system
Source: USEPA (2007)

Table 2. Chemical composition of the fuel and their heat value.

Samples	Ultimate Analysis (wt. %, dry basis)						HHV (MJ/kg)	Authors
	C	H	O	N	S	Cl		
Petroleum Coke	85.65	3.95	1.55	0.91	6.04	0	33.000	Olmeda *et al.*, 2013
Tire Unserviceable	74.30	7.20	15.89	0.90	1.71	0	30.500	Ucar *et al.*, 2005

The nominal production capacity adopted is 34.722 kg/s of clinker and the specific heat consumption in the system is around 3,129.0 kJ/kg of produced clinker. The energy required in the rotary kiln is 1,251.6 kJ/kg of produced clinker and into precalciner is 1,877.4 kJ/kg of produced clinker. Using transformation factor of 1.568 kg of raw meal per kg of clinker was admitted typical composition of the raw meal together with its molar and mass flow rate described in Tab. 3. The percentages adopted for calcining of $CaCO_3$ and $MgCO_3$ for purposes of calculating the quantity of the CO_2 from calcination in precalciner was 90% and in rotary kiln 10%. For the calculation of different stoichiometric combustion reactions was used excess air of 1.7% in the rotary kiln and 2.4% in the precalciner. For the balancing of SO_2 and HCl was assumed that 90% is absorbed and incorporated into the raw meal.

Table 3. Chemical composition, mass and molar flow rate of the raw material used in the clinker production

	Component	Molar Mass (kg/Kmol)	Composition of Raw meal	Molar Flow Rate (kmol/s)	Mass Flow Rate (kg/s)
CONSUMPTION OF RAW MEAL	$CaCO_3$	100.0869	75.21%	0.409240	40.959544
	SiO_2	60.0843	12.79%	0.115922	6.965094
	Al_2O_3	101.9612	3.44%	0.018373	1.873332
	Fe_2O_3	159.6882	1.86%	0.006343	1.012907
	$MgCO_3$	84.3139	3.57%	0.023058	1.944127
	SO_3	80.0632	0.92%	0.006258	0.501008
	Na_2O	61.9788	0.03%	0.000264	0.016337
	K_2O	94.1960	1.70%	0.009828	0.925775

For the gas flow calculations, it was adopted a thickness of 0.32 m for the existing refractory in the wall of the rotary kiln while the clinker outlet area, inside the rotary kiln, is 15% of the circular cross section.

The diameter of the tubing that connects the different stages of cyclones is 2.50 m. Already the length adopted in both systems (ILC and SLC) between the rotary kiln and precalciner, precalciner to the cyclone 5, cyclone 5 to the cyclone 4, cyclone 4 to the cyclone 3, cyclone 3 to the cyclone 2, cyclone 2 to the cyclone 1 were respectively 2.00, 6.00, 15.00, 15.00, 12.00 and 10.00 m.

Based on the specific heat consumption it is possible to calculate the mass flow rate of fuel in the system and consequently the molar flow rate of fuel chemical constituents necessary to produce clinker. The stoichiometric combustion and excess of air reactions, respectively addressed in Eq. (1) and Eq. (2), were calculated for combustion in the rotary kiln and precalciner.

$$(aC + bH_2 + cS + dCl + eO_2 + fN_2)_{Fuel} + (gO_2 + hN_2)_{Air} \rightarrow iCO_2 + jH_2O + lSO_2 + mN_2 \quad (1)$$

$$(aC + bH_2 + cS + dCl + eO_2 + fN_2)_{Fuel} + (g'O_2 + h'N_2)_{Air} \rightarrow iCO_2 + jH_2O + lSO_2 + nO_2 + m'N_2 \quad (2)$$

The O_{2Free} required to excess of air reaction was calculated using Eq. (3) and due to the process being in dry way, the water was not considered for O_{2Free} calculation.

$$\%\ de\ O_{2_{Free}} = \frac{nO_{2_{Free}}}{(n_T - n_{H_2O}) + O_{2_{Free}} + (3{,}76\ .\ O_{2_{Free}})} \quad (3)$$

Where: n_T is the total output of gases (kmol/s) and n_{H_2O} is the product of water (kmol/s)

After application of the equation for the combustion reaction with excess of air in the rotary kiln, that final product as a reagent entering in the combustion reaction equation in the precalciner and it being possible to calculate the molar flow rate of gases and final product of combustion in the rotary kiln and precalciner using different material of RDF.

Applying Eq. (4) it is possible to calculate the volumetric flow rate of gases ($\dot{V}$) that are emitted during the combustion process in each section of the rotary kiln, precalciner and at different stages of the cyclone tower (preheater), and consequently, knowing the sections areas, the velocity and the GRT.

$$\dot{V} = \frac{\dot{n}.R.T}{P_{atm}} \quad (4)$$

Where: $\dot{n}$ is the molar flow rate of the gases (kmol/s), R is the universal gas constant, T is the absolute temperature (K) and P_{atm} is atmospheric pressure (kPa).

7. RESULTS AND DISCUSSION

The results presented below were calculated for both of cement production systems described in the case study. The Tab. 4 describes the results of calculations of the input and output molar flows rate, using the average values of temperatures of the different processes involved in clinker production (kiln system) and the respective GRT. It is important to note that the values of the molar flow rate in the rotary kiln in ILC and SLC systems are the same because there is no difference in size and fuels used.

Table 4. Results of molar flows rate and GRTs in the different processes involved in clinker production

Fuel (70% Petroleum coke + 10% tire + 20% RDF)	**ILC/SLC**		**ILC**				**SLC**				
	Rotary Kiln		Precalciner		Preheater		Precalciner			Preheater	
	$\dot{n}$ (In) (kmol/s)	GRT (s)	$\dot{n}$ (In) (kmol/s)	GRT (s)	$\dot{n}$ (In) (kmol/s)	GRT (s)	$\dot{n}$ (In) (kmol/s)	GRT (s)	$\dot{n}$ (Out) (kmol/s)	$\dot{n}$ (In) (kmol/s)	GRT (s)
Newspaper	0.5655	9.27	0.6231	3.85	2.0058	8.60	0.7402	3.19	1.3628	1.9858	9.32
Cardboard	0.5655	9.27	0.6231	3.87	1.9972	8.64	0.7270	3.23	1.3542	1.9773	9.36
Magazine Paper	0.5655	9.27	0.6231	3.81	2.0314	8.49	0.7469	3.15	1.3884	2.0115	9.20
Wood	0.5655	9.27	0.6231	3.92	1.9700	876	0.7096	3.30	1.3270	1.9500	9.49
Tetra pack	0.5655	9.27	0.6231	3.84	2.0116	8.56	0.7436	3.18	1.3686	1.9917	9.29
PA	0.5655	9.27	0.6231	3.85	1.9865	8.68	0.7490	3.20	1.3435	1.9666	9.41
PC	0.5655	9.27	0.6231	3.88	1.9670	8.77	0.7411	3.24	1.3240	1.9471	9.50
LDPE	0.5655	9.27	0.6231	3.88	1.9712	8.75	0.7406	3.23	1.3281	1.9512	9.48
HDPE	0.5655	9.27	0.6231	3.88	1.9699	8.76	0.7399	3.24	1.3268	1.9500	9.49
PP	0.5655	9.27	0.6231	3.86	1.9801	8.71	0.7480	3.21	1.3371	1.9602	9.44
PS	0.5655	9.27	0.6231	3.88	1.9676	8.77	0.7436	3.23	1.3246	1.9476	9.50
PET	0.5655	9.27	0.6231	3.70	2.0792	8.30	0.8141	2.98	1.4361	2.0592	8.98
PVC	0.5655	9.27	0.6231	3.90	1.9583	8.81	0.7292	3.27	1.3127	1.9358	9.56
RDF (1)	0.5655	9.27	0.6231	3.81	2.0320	8.49	0.7496	3.14	1.3890	2.0120	9.20
RDF (2)	0.5655	9.27	0.6231	3.86	1.9854	8.69	0.7447	3.21	1.3423	1.9654	9.41

The molar flows and GRTs into the rotary kiln are identical as there was no variation in conventional fuel (only coke) and design, that has the same dimensions for both systems. For the different materials used with alternative fuels

(RDF) average GRT in the precalciner was 3.85 s and in the preheater 8.65 s for the ILC system. Already for the SLC system, average GRT in precalciner was 3.20 s and in the preheater 9.37 s. Significant variation in mass flow rates with the combustion of different materials that compose the alternative fuel (RDF) was not observed. The material co-processed that showed lower GRT was the PET.

Table 5 represents a comparison of the GRTs involved in the stages of the two different systems (ILC/SLC). Despite the variation between GRT values, mainly due to the constructive aspect, both systems (ILC/SLC) had overall GRT close to 22 s.

Table 5. Comparison between GRTs calculated in stages of the kiln system

Fuel (70% Petroleum coke + 10% tire + 20% RDF)	**Rotary Kiln**	**Precalciner**		**Preheater**									
				Cyclone 5		Cyclone 4		Cyclone 3		Cyclone 2		Cyclone 1	
	ILC/SLC GRT (s) Aver. Temp. (1745 K)	ILC GRT (s) Average Temp. (1292 K)	SLC GRT (s) Average Temp. (1083 K)	ILC GRT (s) Average Temp. (1173 K)	SLC GRT (s) Average Temp. (1192 K)	ILC GRT (s) Average Temp. (1166 K)	SLC GRT (s) Average Temp. (1185 K)	ILC GRT (s) Average Temp. (1099 K)	SLC GRT (s) Average Temp. (1098 K)	ILC GRT (s) Average Temp. (974 K)	SLC GRT (s) Average Temp. (973 K)	ILC GRT (s) Average Temp. (759 K)	SLC GRT (s) Average Temp. (813 K)
Newspaper	9.27	3.85	3.19	1.78	1,96	1.76	1.89	1.49	1,62	1.56	1,77	2.01	2.08
Cardboard	9.27	3.87	3.26	1.79	1.97	1.76	1.90	1.50	1.63	1.57	1.77	2.02	2.09
Magazine Paper	9.27	3.81	3.15	1.76	1.93	1.73	1.87	1.47	1.60	1.54	1.74	1.99	2.05
Wood	9.27	3.92	3.29	1.81	2.00	1.79	1.92	1.52	1.65	1.59	1.80	2.05	2.12
Tetra pack	9.27	3.84	3.18	1.77	1.95	1.75	1.88	1.49	1.62	1.56	1.76	2.01	2.08
PA	9.27	3.85	3.20	1.80	1.98	1.77	1.91	1.51	1.64	1.58	1.78	2.03	2.10
PC	9.27	3.88	3.24	1.81	2.00	1.79	1.93	1.52	1.66	1.59	1.80	2.05	2.12
LDPE	9.27	3.88	3.23	1.81	1.99	1.79	1.92	1.52	1.65	1.59	1.80	2.05	2.12
HDPE	9.27	3.88	3.24	1.81	2.00	1.79	1.92	1.52	1.65	1.59	1.80	2.05	2.12
PP	9.27	3.86	3.21	1.80	1.99	1.78	1.91	1.51	1.64	1.58	1.79	2.04	2.11
PS	9.27	3.88	3.23	1.81	2.00	1.79	1.93	1.52	1.66	1.59	1.80	2.05	2.12
PET	9.27	3.70	2.98	1.72	1.89	1.69	1.82	1.44	1.57	1.51	1.70	1.94	2.01
PVC	9.27	3.90	3.27	1.82	2.01	1.80	1.94	1.53	1.67	1.60	1.81	2.06	2.14
RDF (1)	9.27	3.81	3.14	1.76	1.93	1.73	1.87	1.47	1.60	1.54	1.74	1.99	2.05
RDF (2)	9.27	3.86	3.21	1.80	1.98	1.77	1.90	1.51	1.64	1.58	1.78	2.03	2.10

8. CONCLUSIONS

In this article it was possible to observe the relation of the variations of the molar flow rate when introducing different alternative fuels as RDF from MSW for the production of clinker. Furthermore, were compared the GRT, with the combustion of the alternative fuels, in two different clinker production systems (ILC/SLC).

Even with great difference in the chemical composition and heat value of the constituents of RDF material there was no significant variation in molar flow rates after the combustion of them in analyzed systems (ILC/SLC).

Applying the molar flow rates in the two different systems (ILC/SLC) it was possible to perform the calculation of GRT at different stages of each system and it was observed that there is a small variation of GRT between them, primarily due to the constructive design, but both showed almost the same value for total GRT, when partial values of GRT obtained in the different steps of the kiln system was added.

Temperature and GRT values calculated for the two clinker production systems (ILC/SLC) using RDF as alternative fuel are within the standards found in literature, allowing the destruction of the RDF during combustion in the kiln system. However, confirmation of this destruction shall be carried out using empirical calculations of chemical kinetics and equilibrium reactions.

Based on the GRT and real temperatures in the two different systems (ILC/SLC) it is possible to perform a comparison with empirical calculations in which can be estimated the complete destruction of the constituents present in RDF from MSW used as alternative fuel in the kiln system.

9. ACKNOWLEDGEMENTS

The authors would like to acknowledge FAPEMIG, CNPq and CAPES for the financial support that allow the performing of this study.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

11. REFERENCES

Araújo, S. 2002. *"Estudo da formação e festruição de dioxinas e duranos em fornos rotativos de produção de clínquer utilizados no co-processamento de resíduos".* Thesis (Master in Mechanical Engineering) – Universidade Federal de Itajubá (UNIFEI), Itajubá, Brazil, p. 116.

CEMBUREAU - The European Cement Association. *"Sustainable cement production: Co-processing of alternative fuels and raw materials in the european cement industry"*. Jan. 2009 <http://www.cembureau.be/sustainable-cement-production-co-processing-alternative-fuels-and-raw-materials-cement-industry>.

EC – European Comission, 2008. *"Directive 2008/98/EC of The European Parliament and of The Council on Waste and Repealing Certain Directives"*. Official Journal of the European Union, L312, Nov., p. 3–30.

EC – European Comission, 2012. "*Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste*". Directorate General of Environment, Jun., p.74.

EIPPCB - European Integrated Pollution Prevention and Control Bureau. 2013. *"Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide"*. Set. 2014 <http://eippcb.jrc.es/reference/cl.html>.

GTZ/Holcim - Deutsche Gesellschaft für Technische Zusammenarbeit/Holcim, 2006. *"Guidelines on co-processing waste materials in cement production"*. 01 Mar. 2015 <http://www.coprocem.org/>.

Grammelis, P., Basinas, P., Malliopoulou, A., Sakellaropoulos, G.2009. "Pyrolysis kinetics and combustion characteristics of waste recovered fuels". *Fuel*. v.88, p.198-205.

Greco, C., Picciotti, G., Greco, R. B., Ferreira, G. M. "Fuel selection and use". In: BHATTY, J. I., MILLER, F. M., HOSMATKA, S. H. *Innovations in Portland cement manufacturing*. Portland Cement Association, Skokie, p. 1404, 2004.

Kara, M., Günay, E., Tabak, Y., Durgut, U., Yildiz, S., Enç, V. 2011. "Development of refuse derived fuel for cement factories in turkey". *Combust. Sci. and Tech.*, n.183, p.203–219.

Karstensen, K. H. 2007 *"A literature review on co-processing of alternative fuels and raw materials and hazardous wastes in cement kilns"*. Jun. 2015 <http://www.aitec-ambiente.org/Portals/2/docs/pubblici/Documenti/Raccolta%20bibliografica/Coprocessing%20literature%20review%202007.pdf>

Karstensen, K.H. 2008. "Formation, release and control of dioxins in cement kilns – a review". *Chemosphere* n. 70, p. 543–560.

Lin, K.-S., Wang, H. P., Liu, S.-H., Chang, N.-B., Huang, Y.-J., Wang, H.-C. 1999. "Pyrolysis kinetics of refuse-derived fuel". *Fuel Processing Technology*. n.60, p.103-110.

Maringolo, W. 2001. *"Clínquer co-processado: produto de tecnologia integrada para sustentabilidade e competitividade da indústria de cimento"*. Tesis (PhD in Mineralogy and Petroleum), Universidade de São Paulo (USP), São Paulo, Brazil, p. 163.

Meystre, J. A. and Silva, R. J. 2012. "Coprocessamento de resíduos sólidos urbanos - RSU em fornos de clínquer para produção de cimento. Parâmetros e limites ambientais aplicáveis". In: *Proceedings of the 7 th Congresso Nacional de Engenharia Mecânica - CONEM 2012*. São Luiz do Maranhão, Brazil, p. 9.

Meystre, J. A. and Silva, R. J. 2013. "The possibility of coprocessing Municipal Solid Waste - MSW in clinker kilns to cement production". *Thermal Engineering*, v.12, n.2, p.34-39.

Minas Gerais. Fundação Estadual do Meio Ambiente (FEAM). 2010. *"Análise Técnica e Ambiental da Utilização de Resíduos Sólidos Urbanos na Produção de Cimento (coprocessamento)"*. FEAM-DPED-GEDIF-GEDIN-RT. Jun. 2015. http://www.feam.br/images/stories/arquivos/mudnacaclimatica/novos2012/coprocessamento.pdf.

Mokrzycki, E., Bocheńczyk, A. U. 2003. "Alternative fuels for the cement industry". *Applied Energy*, v.74, p. 95-100.

Nielsen, A. R., 2012. *Combustion of large solid fuels in cement kilns*. Thesis (Ph.D.) Technical University of Denmark, Lyngby, Denmark.

Olmeda, J., Sánchez de Rojas, M.I., Frías M., Donatello, S., Cheeseman, C.R. 2013. "Effect of petroleum (pet) coke addition on the density and thermal conductivity of cement pastes and mortars". *Fuel*, v. 107, p. 138-146.

Parik, J., Channiwala, S. A., Ghosal, G. K. 2005. "A correlation for calculating HHV from proximate analysis of solid fuels". *Fuel*, v.84, p.487-494.

Santi, A. M. M. 2003. *"Co-incineração e co-processamento de resíduos industriais perigosos em fornos de clínquer: Investigação no maior pólo produtor de cimento do país, região Metropolitana de Belo Horizonte, MG, sobre os riscos ambientais, e propostas para a segurança química"*. Tesis (PhD in Mechanical Engineering) – Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil, p. 227.

Signoretti, V. T. and Silva, R. J. 2005. " NOx formation in co-processing of useless tires in the cement industry clinker kilns". In: *Proceedings of the 18 th International Congress of Mechanical Engineering*. Ouro Preto, Brazil, p. 8.

Sørum, L., Grønli, M. G., Hustad, J. E., 2001. "Pyrolysis characteristics and kinetics of municipal solid wastes". *Fuel*, v.80, p.1217-1227.

Ucar, S., Karagoz, S., Ozkan, A. R., Yanik, J., 2005 "Evaluation of two different scrap tires as hydrocarbon source by pyrolysis". *Fuel*, v.84, p.1884-1892.

USEPA – United States Environmental Protection Agency, 2007. "*Alternative control techniques document update - NOx emissions from new cement kilns*". USEPA, EPA-453/R-07-006, Washington, USA.

Velis, C. A., Longhurst, P. J., Drew, G. H., Smith, R., Pollard, S. J.T. 2010. "Production and quality assurance of solid recovered fuels using mechanical biological treatment (MBT) of waste: a comprehensive assessment". *Critical Reviews in Environmental Science and Technology*, v.40, n.12, p. 979-1105.

Wang, J., Liu, Y., Yan, R., Dong, Z., Tay, J.-H. 2012. "Pyrolysis characteristics and kinetics of municipal solid wastes in Singapore". In: *3rd International Conference on industrial and Hazardous Waste Management*. Chania, Grece.