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Research Article

Comparative Energy and Exergy Analysis for the Utilization of Alternative Fuels in the Cement Kiln

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Abstract

The cement industry is one of the most energy and carbon-intensive industries. The energy and carbon reduction is an important issue in this industry. The present work considers the use of alternative fuels in the cement kilns. The amounts of excess air, the location of fuel and air entrance, as well as the amount of produced gas stacks, are the main design and operational variables in the kilns. Comparative assessments of alternative fuels (AF) are performed by the mass, energy, and exergy analysis of different regions in the kilns. The obtained results show that using alternative fuels reduces the amounts of excess air and the exit temperature becomes closer to the ambient temperature. The alternative fuels demonstrate lower energy and exergy loss inside the cement kiln by supplying the required energy for the clinker production. Their utilization in the current kiln reduces CO_2 emissions. The results of the present work may be used for the optimal design and operation of cement kilns. This work provides an in-depth analysis of the material efficiency, main energy losses and the exergy destruction of the process.

Keywords: Energy, Exergy efficiency, Cement industry, CO_2 emissions, Exergy destruction.

Introduction

One of the most important problems for industries is the reduction of energy consumption. Cement industry is an energy intensive industry with a great amount of Green House Gases (GHG) emissions. Using alternative fuels is an interesting way to save energy and reduce emissions during the whole life cycle. In 2016, around 85.9 million tons of cement was produced in the United States, and 4,200 million tons of cement produced in the world (www.statista.com). Energy demand is about 3.2-6.3 GJ per ton of clinker production. They also reviewed the use of several alternative fuel types and their effects on the implementation in the cement factories for different cement groups (Rahman et al. 2013). The production of 1 ton of cement emits about 0.65-0.95 ton of CO_2 (Kara, 2013). Mokrzycki and Uliasz-Bochénczyk studied different types of alternative fuels including RDF (Mokrzycki and Uliasz-Bochénczyk, 2003). They examined factors such as high combustion temperature and length of kiln which can approve advantages of using these kinds of fuels. Kääntee et al. used ASPEN PLUS to model a four-stage preheater kiln system using pet coke to select the suitable alternative fuels (Kääntee et al. 2004). Their aim was to optimize the process control and also

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fuel consumption while product quality was constant. They estimated the energy demand for different fuel mixes. Pipilikak et al. replaced 6% of a cement kiln fuel by the Tired Drived Fuels (TDF) and the characteristics are tested using X-ray diffraction (XRD) and X-ray fluorescence (XRF) (Pipilikaki et al. 2005). Engin and Ari studied the energy analysis of the dry cement kiln in Turkey (Engin and Ari, 2005). Their results showed that about 40% of input energy was lost during the manufacturing process. They estimated that about 15.6% of input energy may be recovered. According to Genon and Brizio, using the RDF instead of the coal or coke in the cement kilns has environmental advantages especially in terms of greenhouse gases (Genon and Brizio, 2008). This is mainly due to the lower flame temperature and the reduction of the amount of the excess air. Their study considered economic, technological, and environmental aspects. Kara investigated the feasibility of using the RDF and its environmental effects in an industrial plant in Istanbul (Kara, 2013). Vermeulen et al. investigated the Automotive Shredder Residue (ASR) and meat and bone meal (MBM) alternative fuels in cement industry (Vermeulen et al. 2012).

In addition to the energy aspect (Vahidi et al. 2017), exergy concept is an effective method to analyze the studied system. Exergy is one of the concepts which is used in various systems analyses and can provide more comprehensive and accurate results than the energy analysis in terms of real operating conditions of the system (Jafarinejad et al. 2019; Mehrpanahi et al. 2019; Nikbakht-Naserabad et al. 2019). Much research has been done in this area, some of which are related to the study of the system under study.

Madlool et al. reviewed different researches studying the exergy analysis in cement industry (Madlool et al. 2012). The exergy efficiency in cement manufacturing was obtained about 18-49% and kiln irreversibility caused the highest exergy loss. Kaddatz et al. compared the results of three different types of fuels (Spent Carbon Lining, used industrial lubricant and used tires) to find the most effective fuel sources (Kaddatz et al. 2013). They found that the used industrial lubricant and the Spent Carbon Lining (SCL) were the best and worst fuel among them, respectively. Reza et al. investigated the techno-economic feasibility and environmental impacts of the Refused Derived Fuel (RDF) production from Municipal Solid Waste (MSW) in Metro Vancouver as an alternative fuel for the cement kilns (Reza et al. 2013). Their results showed that the RDF usage is environmentally and economically suitable for their case. Aranda Usón et al. reviewed different methods to evaluate environmental, energetic and economic benefits of alternative fuels in cement industry (Aranda Usón et al. 2013). Chen described a mathematical model for clinker production using compressed carbon combustion (Chen, 2014). It was shown that numerical simulations may be a useful tool for new process ideas and process design recovery. Elatter et al. used the computational fluid dynamics in order to investigate the non-mixed flames in rotary kilns (Elattar et al. 2014). In another research, Rahman et al. studied the recent developments in the usage of alternative fuels and their environmental effects (Rahman et al. 2015) They found that utilization of a mixture fuel with 40% of meat and bone (MBM) was the best option for countries like Australia. Gao et al. tried to improve material efficiency and manage the resources in cement production (Gao et al. 2015). The material efficiency of three stages of the cement production and also waste recycle rates were calculated for an existing plant in China. Results showed that approximately 2.48 t, 4.69 t, and 3.41 t of materials were required to produce a ton of cement in raw material preparation, clinker production, and cement grinding stages and the waste rates in these stages were 63.31%, 74.12% and 78.89%, respectively. Ngako et al. presented a model for a rotary cement kiln in steady state in order to simulate small particle structure (Ngako et al. 2015). This formulation decreased the residence time.

Although some studies have been carried out on the fuel substitution in the kiln industry (Rahman et al, 2015), energy and exergy analyses of various regions in the kiln considering all the losses hasn't been investigated in details. In previous, the study of energy and exergy has been less commonly used for internal analysis of system components, and generally, the entire furnace is considered as the control volume. Also, the analysis of fuel consumption and energy and exergy losses when using alternative fuels in combination with fossil fuels was not considered. Using such an analysis considered to the studied objective functions will result in an optimal state for fuel, air, and their ratio. Also, due to the importance of CO_2 emissions, the amount of these gases in the furnace outlet due to combustion conditions has also been investigated.

The process design of the cement kiln is the crucial issue in case of maximizing the material, energy, and exergy efficiency. Here, a detailed mathematical model is used for four different regions in cement klins to study the material, energy, and exergy flow. In depth analysis of these regions will provide the guideline for the optimum design and operational consideration including type and location of alternative fuels, the amount of excess air and alternative fuels, as well as reduction of the energy and exergy losses. Three different fuels such as pure coal, mixture of coal and RDF and mixture of coal and TDF are considered. The aim of this study is to consider the thermodynamic and environmental behavior of the kiln. The temperature of leaving gases, the mass flow, and the exergy destruction in inner sections, total loss and destruction are compared by using a combination of coal and different alternative fuels (TDF and RDF). Section 2 describes the modeling of a typical cement rotary kiln, its chemical reactions and specifications of fuels for combustion as well as the mass, energy, and exergy equations. Section 3 describes the assumptions and the main findings. Section 4 concludes the paper outcome briefly.

Model Descriptions

Cement rotary kiln is a cylinder with a steel shell which its rotational speed is usually between 1 and 2 rpm with a slope of 3-4°. Its length depends on the process. For dry processes (which are the most typical today), the length is 90-120 m (Boateng, 2016).

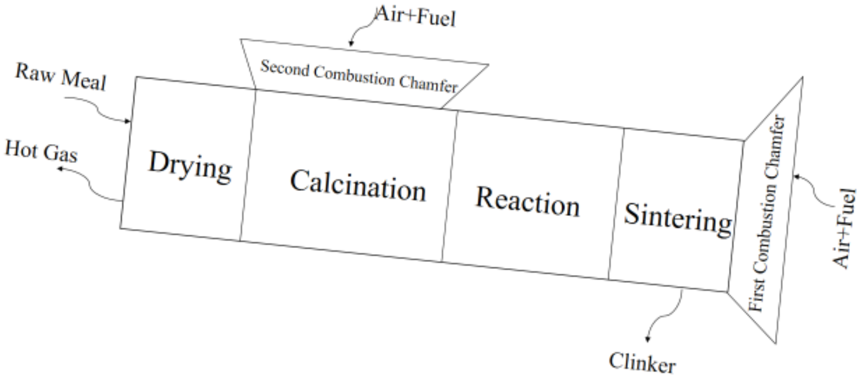


Figure 1. schematic of a cement rotary kiln (Atmaca and Yumrutas, 2014)

There are many chemical reactions inside the kiln. In this study, most important ones are considered (Hökfors, 2014). Schematic of a rotary cement kiln is shown in Fig 1. Clay, limestone, and other additives enter the top end, while fuel and air enter the combustion chambers. The short description of each region is as follows:

a. Drying (preheating): In this section, total moisture of solids and limestone evaporate and at the end of this section, soils are completely dried. Temperature range is between 25 - 200°.

$$H_2O(l) \rightarrow H_2O(g) \quad (1)$$

b. Calcination: Soils and limestone decompose to their constituents and the CO_2 emission is also released. Temperature range is between 200 to 900°C. The chemical reactions are described in Eqns. 2-6.

$$AS_4H \rightarrow \alpha - Al_2O_3 + 4SiO_2 + H_2O(g) \quad (2)$$

$$AS_2H_2 \rightarrow \alpha - Al_2O_3 + 2SiO_2 + 2H_2O(g) \quad (3)$$

$$CaCO_3 \rightarrow CaO + CO_2(g) \quad (4)$$

$$MgCO_3 \rightarrow MgO + CO_2(g) \quad (5)$$

$$2FeO(OH) \rightarrow \alpha - Fe_2O_3 + H_2O(g) \quad (6)$$

c. Reaction: Main reactions of cement phases occur in this section and compounds such as belite (C_2S) and C_4AF are made (Eqns. 7-11). The temperature range is between 900 - 1300°C.

$$2CaO + SiO_2 \rightarrow \beta - C_2S \quad (7)$$

$$3CaO + \alpha - Al_2O_3 \rightarrow C_3A \quad (8)$$

$$6CaO + 2\alpha - Al_2O_3 + \alpha - Fe_2O_3 \rightarrow C_6A_2F \quad (9)$$

$$4CaO + \alpha - Al_2O_3 + \alpha - Fe_2O_3 \rightarrow C_4AF \quad (10)$$

$$3CaO + SiO_2 \rightarrow C_3S \quad (11)$$

d. Sintering: This section is located at the bottom end of the kiln where the temperature of phases composed in previous regions increases and clinker, which is the main component of cement, is produced. The temperature range is between 1300 - 1500°C.

e. Combustion chambers: There are two combustion chambers in our modeling system as shown in Fig. 1. In both of them, the fuel and air enter and mix. After combustion, hot gases enter the kiln and transfer the heat to solid materials. Two types of alternative fuels are utilized and compared in combination with coal which is used as a fossil fuel.

The RDF is the combustible part of MSW and its heating value is usually higher than fossil fuels such as coal. The Tire-Derived Fuel (TDF) contains scrap tires of cars that can be burned in high temperature kiln such as cement kilns. The Eqns. (12) and (13) indicate the combustion of coal and typical alternative fuel in combustion chambers, respectively.

$$C(s) + O_2(g) \rightarrow CO_2(g) \quad (12)$$

$$C_nH_mO_qS_pN_r + (n + m/4 + 3p/2 - q/2) \rightarrow (n)CO_2 + (m/2)H_2O + (p)SO_3 + (r/2)N_2 \quad (13)$$

The aim of this study is to consider the thermodynamic and environmental behavior of the kiln. The temperature of leaving gases, the mass flows, the exergy loss and destruction in inner sections, total loss and destruction are compared by using a combination of coal and different alternative fuels (TDF and RDF).

$$\dot{m}_{coal} HHV_{coal} = \dot{m}_{AF} HHV_{AF} \tag{14}$$

Table 1 shows the compositions of RDF and TDF. As can be seen, TDF has a upper amount of carbon which can be reacted in combustion and generate more CO_2.

Table 1. Composition of alternative fuels used in this study (Kookos et al. 2011)

Element	% RDF	% TDF
C	60	70
H	10	7
O	25	10
S	1	1.5
N	0.1	0.5

Eq.14 shows the way used for calculating of mass flow rate of alternative fuel. As can be seen, here, heating values are assumed to be the same.

Mass Balance

The mass balance for an open system which acts under steady state condition is:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{15}$$

Where $\dot{m}$ is the mass flow rate [kg/s] of kiln and indices in and out indicate entering and leaving quantities of any variable in all cases, respectively.

Ideal equations for formation of cement phases are based on Bogue equations (Peray, 1979), as shown below:

$$C_3S = 4.0710CaO - 7.6024SiO_2 - 1.4297Fe_2O_3 - 6.7187Al_2O_3 \tag{16}$$

$$C_2S = 8.6024SiO_2 + 1.0785Fe_2O_3 + 5.0683Al_2O_3 - 3.0710CaO \tag{17}$$

$$C_3A = 2.6504Al_2O_3 - 1.692Fe_2O_3 \tag{18}$$

$$C_4AF = 3.0432Fe_2O_3 \tag{19}$$

For a typical example (Gao, 2015), the above equations are solved to obtain the amounts of CaO, SiO_2, Fe_2O_3 and Al_2O_3 and the results showed great agreement with Portland cement type I (Mamlouk and Zaniewski, 1999).

Energy Balance

The general form of energy balance equation is as follows:

$$\dot{Q}_{net,in} - \dot{W}_{net,out} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{20}$$

Where $\dot{Q}$, $\dot{W}$, $\dot{m}$ and h are the heat transfer rate [kW], the rate of work [kW], the mass flow rate [kg/s] and enthalpy [kJ/kg], respectively. In this analysis, the amount of work done in the kiln is assumed negligible. In details, the following energy equations are applied [20]:

$$\dot{Q} = \dot{m}C_{p,ave}\Delta T \tag{21}$$

Where $C_{p,ave}$ and ΔT are the average constant pressure specific heat [kJ/kgK] and the temperature difference between gas or solid with respect to ISO ambient temperature [K] as follows:

$$\Delta T = T - 298 \tag{22}$$

C_p could be presented as a function of temperature as bellow (Webbook.nist.gov/cgi/cbook, 2011):

$$C_{p,ave} = \frac{1}{T-298}\int_{298}^{T} C_P(T)dT \tag{23}$$

Where:

$$C_p = A + Bt + Ct^2 + Dt^3 + E/t^2 \tag{24}$$

Higher heating values of RDF and TDF are calculated by (Reza et al. 2013).

$$HHV(MJ/Kg) = 0.336C + 1.419H + 0.94S - 0.145O \tag{25}$$

Where C, H, S and O are percentages of carbon, hydrogen, sulfur, and oxygen in fuel, respectively. Higher heating value of coal is assumed 31 MJ/kg (Atmaca and Yumrutas, 2014).

Heat loss from the kiln surface is assumed 10% of input energy which is dispersed base on the lengths of sections. Energy balance is calculated for each section of the kiln. For different regions, the input and output energy are shown by $\dot{E}_{in}$ and $\dot{E}_{out}$ in eqns. 26 and 27, respectively. Also, the reaction heat is considered in Eqns. 28 and 29.

$$\dot{E}_{in} = \dot{\mathrm{m}}_{\mathrm{in}}\, C_{p,ave}\Delta T_{in} \tag{26}$$

$$\dot{E}_{out} = \dot{\mathrm{m}}_{out}\, C_{p,ave}\Delta T_{out} \tag{27}$$

$$\dot{E}_{gen} = \dot{\mathrm{m}}_{\mathrm{reactant}}\, \Delta\mathrm{H}_{\mathrm{reaction}} \tag{28}$$

$$\dot{E}_{con} = \dot{\mathrm{m}}_{\mathrm{reactant}}\, \Delta\mathrm{H}_{\mathrm{reaction}} \tag{29}$$

The energy equation of the combustion is:

$$HHV(MJ/Kg) = 0.336C + 1.419H + 0.94S - 0.145O \tag{30}$$

Where ΔT is temperature difference between combustion temperature of coal and alternative fuel (both are assumed 920K) respect to ISO ambient temperature (298K). In any case, coal and a percent of alternative fuel (from 0 to 100%) mix and enter the combustion chamber.

Exergy Balance

The general exergy equation is:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} + \sum \dot{E}x_{loss} \quad (31)$$

where:

$$\dot{E}x_{loss} = \dot{Q}_{loss}(1 - \frac{T_0}{T_{surf}}) \quad (32)$$

While $\dot{Q}_{loss}$ is the heat loss from surface in each control volume [kW] and T_{surf} is the kiln surface temperature [K] in that section (Atmaca and Yumrutas, 2014). The exergy is also calculated in inlet and outlet of each section.

The chemical exergy is due to the combustion in sintering and calcination sections ($\dot{m}_{Fuel} HHV_{Fuel}$) and also chemical reactions in internal regions of kiln and is added to the mixing exergy. The mixing exergy is defined as (Renó et al. 2013):

$$\bar{a}_f^{ch} = e_x^0 y_i + R_u T_0 y_i Lny_i \quad (33)$$

Where e_x^0 is the molar exergy, y_i is the mole fraction (mol/s) of specified material in the compound in inlet or outlet of control volume, R_u is the universal gas constant [kJ/kg.K] and T_0 is the ISO ambient temperature (298K). Dividing molar exergy and gas universal constant to molar mass of every component results in the change of the unit of $\bar{a}_f^{ch}$ from kJ/mol to kJ/kg. Physical exergy is due to the temperature difference respect to the ambient temperature which is calculated by (Atmaca and Yumrutas, 2014):

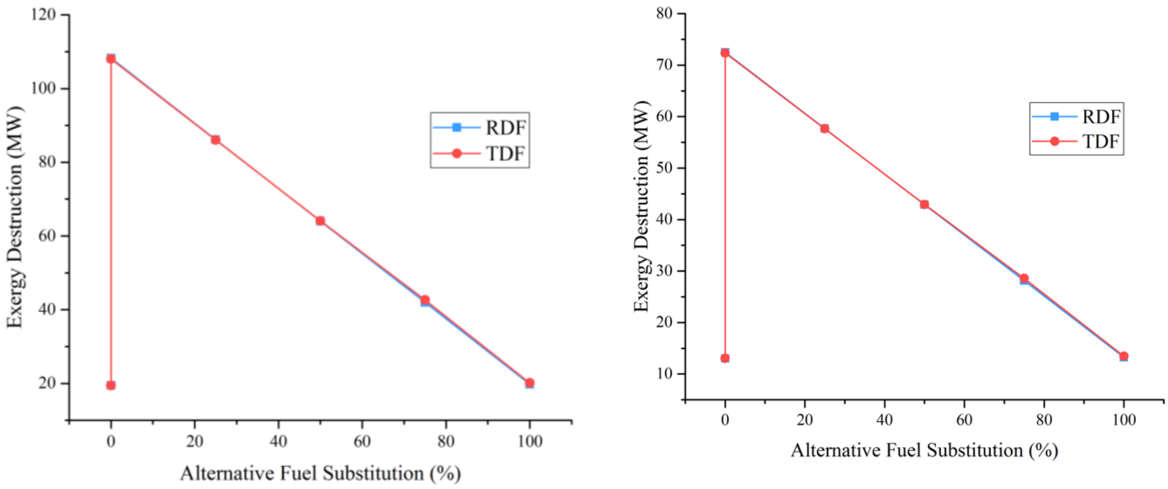
$$\bar{a}_f^{ch} = e_x^0 y_i + R_u T_0 y_i Lny_i \quad (34)$$

Where ΔS is the entropy difference [kJ/kg.K] between component temperature [K] and ambient temperature (298K) and is calculated by (Atmaca and Yumrutas, 2014):

Results and Discussion

This study has used a new method of investigation of energy and exergy and focused on internal sections of the cement kiln. So, there are no studies for using as a reference for validation. Our equations and calculation method have the advantage that could be applied to real data and be validated. The computations are validated against published data in (Atmaca and Yumrutas, 2014). There is a slight difference between some variables like stack gas temperature and mass flow rate of pollutants due to different assumptions considered in the present study such as considered combustion condition. Then, the model is applied for the analysis. The results included the exergy loss and destruction in inner regions of the kiln and combustion chambers, leaving gas temperatures, and mass flow rate of pollutants. All the results are obtained under the condition of using both alternative fuels and fossil fuels in different proportions in the cement kiln. The achieved results are shown for 20% excess air, 30% primary air and 70% secondary air.

Figure 2 shows the exergy destruction for the first and second combustion chambers using both alternative fuels. As it is illustrated in Fig. 2, adding alternative fuel causes a significant increase in exergy destruction of combustion chambers. As the rate of substitution increases, mass flow rate of fuel and air decrease and the exergy loss and destruction decreases as well.

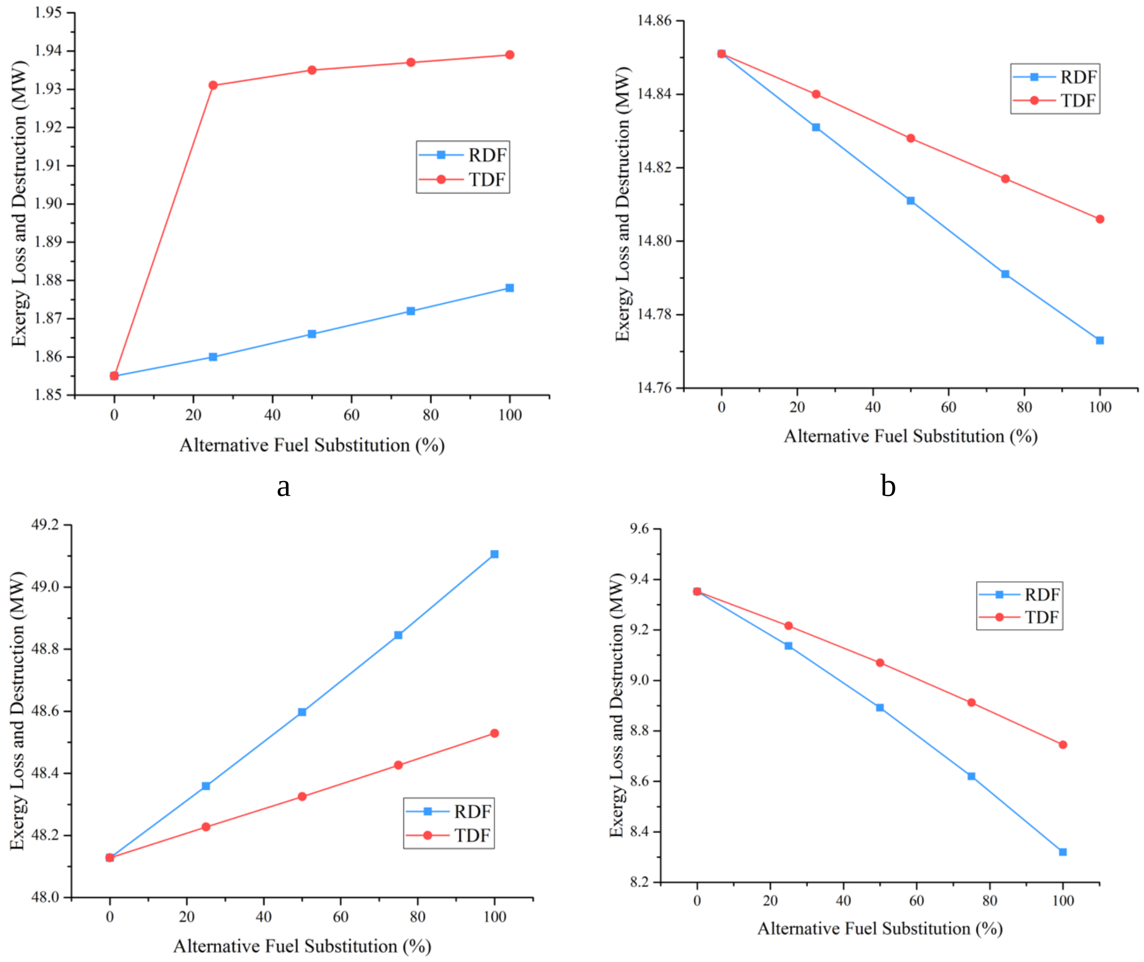


a b

Figure 2. Exergy destruction for (a) first combustion chamber and (b)second combustion chamber

Figures. 3a and 3b show the total exergy loss and destruction of both alternative fuels inside the kiln in four regions (drying, calcination, reaction and sintering). As seen in Fig.3a, exergy loss and destruction increases by increasing the amounts of alternative fuels. The mass flow rate of combustion gases decreases such that the gas temperature in inlet and outlet of sintering region increase. Fig.3b shows that the exergy loss and destruction in reaction region decrease as the rate of fuel substitution increases. In this region, the temperature difference between the inlet and outlet gases is almost equal. As the rate of fuel substitution increases, the amount of energy loss from the kiln surface decreases. As a result of this, the exergy loss slightly reduces in the kiln. So, the exergy difference between the inlet and outlet wall declines as well. Fig.3c. shows the exergy loss and destruction in the calcination region. Substituting alternative fuels increase the exergy loss and destruction. Since the main preliminary endothermic reaction of cement production occurs in this section (decomposition of limestone), the intensive temperature reduction is observed in this region. As the rate of substitution increases, the temperature difference increases and the summation of exergy loss and destruction increases. Due to the constant mass flow rate of solids inside the kiln, heat transfer rate for solid reactions is a constant value. This increase the total amounts of exergy difference. While the rate of fuel substitution increases, the exergy loss and destruction in drying region decreases (Fig 3d). Since mass flow of gases decrease as fuel substitution increases, chemical exergy decrease in inlet and outlet of the region and exergy loss and destruction decrease.

Figure 4 shows the leaving gas temperature for both alternative fuels. Since the amount of input energy to the kiln is almost constant, increasing alternative fuel reduces the combustion gases and increases its temperature. Increasing the fuel substitution rate results in the decrease in the mass flow rate of combustion stack gases and increase in the temperature difference between kiln inlet and outlet. The above reason elaborates why the temperature of leaving gas decreases in the kiln. Fig.5. shows the amounts of CO_2 emission for both alternative fuels. By substitution of alternative fuels, lower mass flow rate of these kind of fuels are needed and so, the CO_2 emission decreases. However, the combustion of alternative fuel produces fine values of some other pollutants such as SO_3 (Vermeulen et al. 2012).



c d

Figure 3. Exergy loss and destruction for (a) sintering (b) reaction (c) calcination (d) drying

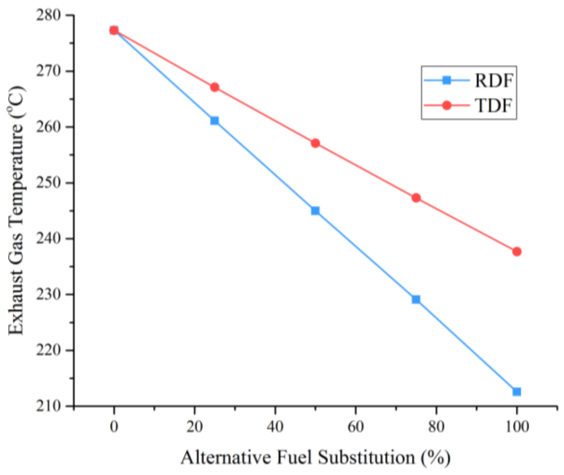


Figure 4. Leaving gases temperature

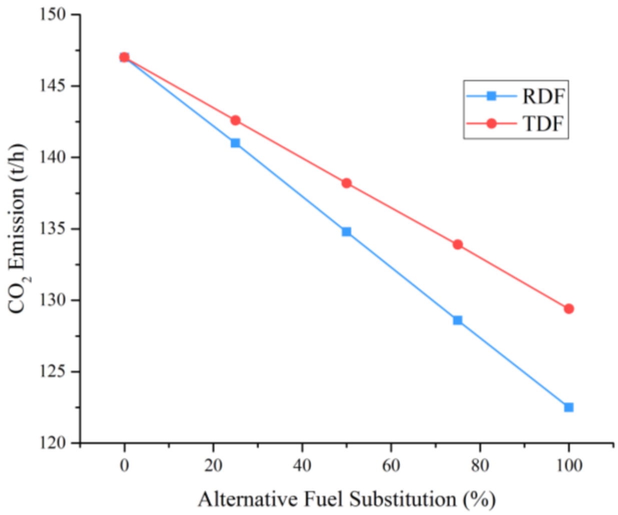


Figure 5. CO_2 emitted for combinations of coal and alternative fuels

Conclusion

In this study, the effects of using alternative fuels in combination with fossil fuels are investigated in a rotary cement kiln for a constant produced clinker. The novelty of this work lies in understanding of energy and exergy changes inside the kiln and inner sections. In depth analysis of energy and exergy analysis for different sections of the kiln are performed. A constant heating value was assumed in ambient temperature and mass flow rates of alternative fuel are determined on the basis of percentages of substituted energy content.

This investigation advances the current knowledge in this field by indicating the interaction between using the alternative fuels and greenhouse gas emission or CO_2 emissions.

The main parameters such as the temperature of combustion products, the exergy loss and destruction in various section of the kiln are studied. Here, a review of most important results is listed:

1. Replacing the fossil fuels by alternative fuels decreases CO_2 emission from kiln. Life cycle analysis may prove more benefits such as landfill demand decreasing, decreasing greenhouse gases, and economics of fossil fuels saving.
2. Less heat loss is occurred using alternative fuels.
3. Using alternative fuels decrease total exergy loss and destruction inside the kiln.

RDF contains lower amounts of carbon and so, generates lower CO_2 and is better than TDF environmentally. Also using RDF leads to lower temperature for stack gases. But it doesn't mean that it is the best option from the economical point of view.

Despite the fact that the substitution fuel can reduce the exergy loss and CO_2 emissions, the cost associated with supplying the kiln with this fuel requires further analysis and can be considered the future work in the area. This implies that the next topic in this field can be the optimization of the process using multi-objective optimization aiming for reducing the exergy destruction and cost.

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