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Energy and exergy analysis of a rotary kiln used for plaster production

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HIGHLIGHTS

- Exergy destruction rate is 66% of the total exergy input.
- Energy and exergy loss values are 2597.65 kW and 755.347 kW, respectively.
- The energy and exergy efficiencies are found as 69% and 16%, respectively.

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ABSTRACT

This paper presents, the energy and exergy analysis of a rotary kiln used for plaster production was performed. Some parameters, such as losses, irreversibility and design were used for determining the energy and exergy efficiencies. Capacity of the rotary kiln is 22 ton/h and the power of it is 7.8 MW. Based on the calculations from the measured values of the rotary kiln, the energy and exergy efficiencies are calculated as 69% and 16%, respectively. The exergy analysis showed that the exergy destruction rate is determined to be 2969.97 kW which corresponds to 66% of the total exergy input. Also, considering governing parameters, some suggestions and discussions are carried out to get better working conditions and increasing the energy and exergy efficiencies of the rotary kiln.

1. Introduction

The rotary kilns are used in many engineering applications such as drying, cement production, melting, cooling, recycling of waste and destroying of hazardous substances. Performance analysis of industrial sector with high-energy consumption, about 30–70% of total energy use of the countries, is taken into consideration recently [1]. There are many studies on energy and exergy efficiency, environmental effects and exergoeconomy due to consume of intensive energy in these kinds of systems [1–3,11,12]. These studies have been conducted on energy analysis of different industries and during the last decades exergy analysis applied to offer more realistic suggestions for optimization and improvement of the industrial sector [1]. Some of these studies was discussed in the below.

BoroumandJazi et al. [1] presented a review on exergy analysis of industrial sector. They reviewed the existing studies on exergy analysis of industrial sector and determined the irreversibility and losses of industrial processes. Cement production has been one of the most energy intensive industries in the world. The rotary kilns are widely used in the cement plants to produce raw materials preparation, clinker. Studies on the rotary kilns are generally rising of energy efficiency value and energy saving from the system. Madlool et al. [2] made a critical review on energy use and savings in the cement industries. They categorized as four key processes for cement manufacturing and these key processes are dry, semi-dry, semi-wet and wet processes. Another study of Madlool et al. [3] is an overview of exergy analysis for cement industries. Their paper reviewed exergy analysis, exergy balance, and exergetic efficiencies for cement industry. It was found that the exergy efficiency for cement production units ranges from 18% to 49% as well as the exergy losses due to the irreversibilities. Peinado et al. [4] presented energy and exergy analyses of a rotary dryer employed in a Hot Mix Asphalt (HMA) plant for heating and drying of the aggregates in the mixture. In their analysis, the exergy method was employed to identify and evaluate the thermodynamic losses. Utlu et al. [5] performed energy and exergy analysis of a raw mill (RM) and raw materials preparation unit in a cement plant in Turkey using the actual operational data. Gutiérrez et al. [6] indicated that the vertical shaft kilns are widely used in the lime industry. The main objective of their work is to analyze the energy and exergy consumption of the calcination process in vertical shaft kilns to identify

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Nomenclature

C_p	specific heat capacity (kJ/kg K)
$\dot{E}x$	exergy rate (kW)
$\dot{E}$	energy rate (kW)
e_{ex}	specific exergy (kJ/kg)
$\overline{g}_i$	Gibbs functions (kJ/kmol)
h	enthalpy (kJ/kg)
LHV	low heating value (kJ/kg)
M	molar mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
$\dot{n}$	molar flow rate (kmol/s)
$\dot{Q}$	heat flow rate (kW)
$\overline{R}$	universal gas constant (kJ/kmol K)
s	entropy (kJ/kg K)
T	temperature (K)
t	time (s)
$\dot{W}$	work rate (kW)
x	mole fraction

Greek letters

λ	fuel-air ratio
η	energy efficiency
η_{ex}	exergy efficiency
$\overline{\varepsilon}^0$	standard chemical exergy (kJ/kmol)

Subscripts

a	air
cv	control volume
d	destruction
e	exit
f	fuel
fg	flue gas
fgr	flue gas recirculation
g	gypsum
i	inlet
k	k-th content
l	liquid
m	moisture
Ng	natural gas
p	plaster
s	surface
∞	reference environment

Superscripts

ch	chemical
ph	physical
0	standard environmental state

the factors affecting fuel consumption. Söğüt et al. [7] examined the heat recovery process from the rotary kiln for a cement plant in Turkey. Firstly, they carried out an exergy analysis on the operational data of the plant. Their results showed that the presence of 217.31 GJ of waste heat, which is 51% of the overall heat of the process. Then, the authors developed a mathematical model for a new heat recovery exchanger for the plant and determined that 5% of the waste heat can be utilized with the heat recovery exchanger. Yılmazoglu et al. [8] analyzed a solar assisted rotary coal dryer in terms of exergy, economy and environment (3E). In the analysis, they utilized two different heat sources. Karamarkovic et al. [9] used the energy balance of a rotary kiln for calcination of dolomite in a magnesium production company identified the kiln shell (26.35% of the input energy) and exhaust gases (18.95%) as the major sources of heat losses. A heat exchanger is designed to reduce heat transfer. It forms an annular duct over the calcination zone of the kiln to preheat combustion air. The exchanger decreases the fuel consumption of the kiln for 12%, and increases its energy and exergy efficiency as 7.35% and 3.81%, respectively. Çamdali et al. [10] studied on energy and exergy analysis in a rotary burner with pre-calcinations in cement production. They examined the applications of energy and exergy analyses for a dry system rotary burner (RB) with pre-calcinations in a cement plant of an important cement producer in Turkey. Kol and Chaube [11] studied a review based on exergy analysis which is focused on cement plant application only. Their paper review exergy analysis, exergy balance, and exergy efficiency for the cement plant. Their study shows that coal contribute major share of fuel use in cement plant but along with conventional fuels and industries are moving towards the use of alternative fuels to reduce environmental pollution. Their study reported that the cement industries are moving from wet process to dry process as it consume less energy compared to wet process. Atmaca and Yumrutaş [12] studied the energy, exergy and exergoeconomic analysis of a cement factory within two parts. The first part of their study included the thermodynamic and exergoeconomic methodology and formulations developed for such a comprehensive and detailed analysis. The second part of their study was about the application of the developed formulation which considers an actual cement plant located in Gaziantep, Turkey [13]. Renó et al. [14] presented an exergy analysis of clinker production, a powerful tool which has been used in the performance evaluation of energy-related systems. The results obtained by authors indicated that the main irreversibility source in the cement industry is the rotary kiln and calciner process where the clinkerization process occurs. Ashrafizadeh et al. [15] presented 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, they was simulated the burning system of the cement production (kiln & preheater) process in four thermal areas. The authors investigated three lines of cement production with 2,000, 2300 and 2600 ton/day. They studied fuel injection ratio into the secondary burner, from 10 to 40 percent for each line. The results obtained by them show that, for cyclone preheaters, fuel injection into the secondary burner up to a proportion resulting in the minimum temperature required for alite formation (2200 °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, their study show that the secondary burner application can reduce the exergy losses about 25 percent, which leads to a reduction of the greenhouse gases of about 35,000 cubic meters per year for each ton per day of clinker production.

In this study, exergy analysis of the rotary kiln, which is used for plaster powder production, was carried out on the operational data of the plaster plant. The main objective of this study is to examine the energy and exergy analyses of the rotary kiln by applying the First and Second Law of Thermodynamics. The obtained results can be used to propose better working conditions and low energy consumption of the thermal system. Before description of the system is presented, making a brief definition of the plaster production will be useful for understanding of physical phenomena that occur in rotary kiln.

The gypsum, which contains two molecules of water, is a naturally occurring Calcium Sulphate ($CaSO_4.2H_2O$) mineral. These water molecules constitute 20% of the total mass and the plaster