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Energy and exergy assessments of a lime shaft kiln

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HIGHLIGHTS

► Is evaluated the energetic and exergetic performance of limestone calcination.
► Are described as the main factors affecting the thermal efficiency of calcination.
► Fuel combustion and heat & momentum transfer accounts for >40% of irreversibilities.

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ABSTRACT

Calcium oxide (CaO), commonly known as lime or quicklime, is an energy intensive product. In order to produce lime, vertical shaft kilns are widely used in the lime industry. The objective of this work is to analyze the energy and exergy consumption of the calcination process in vertical shaft kilns, in order to identify the factors affecting fuel consumption. Data on energy and exergy consumption and losses throughout the calcination process are given for two shaft kilns. In the process, the energy efficiency is found to be higher than the exergy efficiency, e.g. 71.6% and 40.8% for the energy and exergy efficiency of one of the kilns. Results also showed that the most irreversible processes taking place in the kiln are the exergy destruction due to fuel combustion and the exergy destruction due to internal heat and momentum transfer both accounting for about 40% of the efficiency loss. Moreover, the main exergy loss through the boundaries of the kiln is the exergy loss with the exhaust gases contributing with more than 10% of the efficiency loss. Improvements on both the energy and the exergy efficiencies can be achieved through a better control of the operational parameters of the kiln (ratio limestone/fuel supply, excess of combustion air, size and size distribution of the limestone fed to the kiln and exit temperature of quicklime flow). The present study proposes a tool for the analysis of energy and exergy utilization of the calcination process in limekilns, and also provides some energy conservation measures.

1. Introduction

Lime production is an energy intensive process characterized by high emissions of CO_2. The main energy consumption of lime production is located in the calcination process and accounts for more than 90% of the total energy consumption [1]. The fuel consumed during calcination represents ca. 50% of the production costs of lime [2]. The calcination stage also accounts for 99% of the impact of lime production on global warming [1].

The evaluation of the thermal efficiency of limekilns has been the subject of several studies [2–7]. The optimization of limekiln operation has also been discussed [2,8]. Ochoa et al. [2] carried out an experimental optimization by means of statistical methods, and achieved a reduction of the fuel consumption and the CO_2 emissions. Sheng-Xian et al. [8] proposed a diagnostic expert system based on holographic monitoring and real-time simulation, combining online measurements with simulation of the calcination processes. The implementation of the system increased the output of the industrial test kiln employed by 25%. The advantages of the energy and exergy analysis have been more extensively discussed in studies of the cement industry [9]. Several studies [10–18] discussed, on the basis of energy and exergy balances, the saving potentialities of different units in cement plants highlighting the sources of inefficiencies.

According to Sogut et al. [13] energy efficiency is an important, and often inexpensive, component in the environmental strategy of a company. The energy analysis approach is based on the first principle of thermodynamics; and according to [19], it has some inherent limitations. To overcome these limitations it is necessary to include in the analysis the second principle of thermodynamics. Exergy analysis combines both the first and second principles of thermodynamics.

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Nomenclature

A	Area (m^2)
A_{Ql}	Percentage of CaO in quicklime (%)
B	Percentage of $CaCO_3$ in the limestone (%)
c_p	Specific heat (kJ/kg·K)
e	Specific exergy (kW/kg)
E	Exergy (kW)
En	Energy (kW)
G	Gibbs free energy (kW)
h	Convective heat transfer coefficient (W/K·m^2)
H	Enthalpy (kJ)
LHV	Low heating value (kJ/kg)
m	Mass (kg)
$\dot{m}$	Mass flow (kg/s)
p	Pressure (Pa)
Q	Heat (kW)
R	Universal gas constant (kJ/kmol·K)
s	Specific entropy (kJ/kmol·K)
S	Entropy (kJ/K)
T	Temperature (K)
z	Coordinate (m)

Greek letters

η	Efficiency
χ	Molar fraction
φ	Relation between chemical exergy and LHV

Subscripts

a	air
Cal	Calcination
Ch	Chemical
Comb	Combustion
d	Dissociation
D	Destroyed
F	Fuel
g	Gases
gen	Generation
HMT	Heat and momentum transfer
in	Input flow(s)
loss	Loss
Ls	Limestone
MaT	Mass transfer
o	Ambient
out	Output flow(s)
Ph	Physical
PH	Preheating
Q	Heat
Ql	Quicklime
R	Dissociation reaction

This is a powerful method to identify and quantify the irreversibilities of a thermodynamic process [20]. The identification of the sources of exergy destruction shows the way to improve the operation of a system [16,21]; and its implementation in the production process is a very efficient way to enhance the energetic performance of a process [18]. Utlu et al. [12] point out that understanding the exergetic implications of a process provides a better understanding of efficiency and sustainability. Exergy analysis investigates the performance of devices and processes to evaluate the efficiency and exergy losses in order to locate the largest margins for improvements [22].

Although some efforts have been devoted to evaluate the thermal efficiency of limekilns [2–7], the influence of the exergy destruction in the fuel consumption of the calcination process have been not yet discussed. Consequently, not all of the saving potentialities of the process have been highlighted. Of the studies discussing the thermal efficiency of shaft kilns, only one paper [7] used the exergy approach. Moreover, even though reference [7] discusses some exergetic implications of the vertical limekiln operation, the main factors affecting the thermal efficiency of limekilns should be further clarified and the sources of exergy destruction should be discussed.

The objective of the present paper is to assess the performance of a vertical limekiln using energy and exergy analysis methods to identify the main factors affecting the thermal efficiency of a vertical shaft kilns for lime production and their influence on the fuel consumption.

2. Process description

In order to produce lime it is necessary to calcine limestone with a heat supply. The term calcination refers to the process of thermal decomposition of the $CaCO_3$ as shown by the reaction:

$$CaCO_3 + \text{Heat} = CaO + CO_2 \quad (1)$$

This is a highly endothermic reaction, with a heat requirement of 1784 kJ per kg of $CaCO_3$. In limekilns this reaction starts at 820 °C [23,24], but complete calcination occurs at 900 °C [24].

There are different designs of limekilns, the vertical shaft kiln being one of the most used designs, because of its thermal efficiency. A vertical shaft kiln (Fig. 1) is basically a moving bed reactor with the upward flow of hot combustion gases counter-current to the downward flow of limestone particles that undergo calcination at elevated temperatures usually above 900 °C. For a better understanding the kiln is divided in to three zones, namely the preheating, the calcination and the cooling zone. The preheating zone begins at the top of the kiln, where the limestone is supplied and the process gases exit. This zone ends when the limestone reaches the reaction temperature and calcination starts. Here begins the calcination zone which ends at the level of the burners where fuel is supplied. In the calcination zone both the calcination and the combustion reactions take place. The cooling zone begins at the end of the calcination zone and ends at the bottom of the kiln at

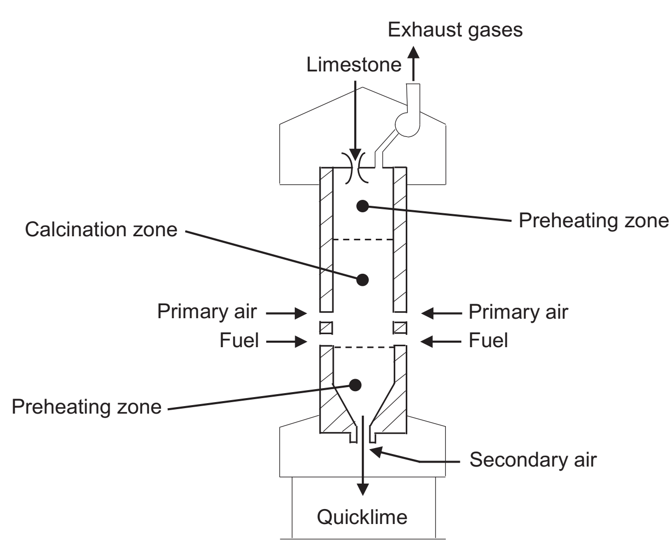

Fig. 1. Lime shaft kiln.