Applied Thermal Engineering 128 (2018) 393–401

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A study case of energy efficiency, energy profile, and technological gap of combustion systems in the Colombian lime industry

Vianny Alcántara [a], Yonatan Cadavid [a], Mauricio Sánchez [b], Camilo Uribe [a], Camilo Echeverri-Uribe [a], Juan Morales [a], Julián Obando [a], Andrés Amell [a,*]

[a] *Grupo de Ciencia y Tecnología del Gas y Uso Racional de la Energía, Universidad de Antioquia, Calle 67 No. 53 108 (bloque 19 - 000), Medellín, Colombia*
[b] *Departamento de Ingeniería Química, Facultad de Ingeniería, Universidad de Antioquia, Calle 67 No. 53 108, Medellín, Colombia*

HIGHLIGHTS

- Energy audits were performed in two Colombian Lime factories.
- Limekiln thermal efficiencies of 54–59% were calculated.
- Energy intensities were found to be between 5.45 and 5.85 GJ/t.
- The main heat losses were determined to be in flue gases (0.93–1.07 GJ/t).
- Performance indicators were below those of state-of-the-art technology.

ARTICLE INFO

Article history:
Received 26 January 2017
Revised 28 August 2017
Accepted 3 September 2017
Available online 6 September 2017

Keywords:
Lime production
Energy intensity
Energy efficiency
Colombia

ABSTRACT

In this work, the energy audits and evaluation of the kilns used in the calcination stage of the calcium oxide production process of two Colombian factories are shown. The energy intensity and usage distribution were evaluated, as well as the technological state of the presently used heating equipment as compared with the most advanced technology available for the calcination process. For the energy audits, key process data - such as fuel consumption, flue gas temperature and composition, material flows, wall temperature, and furnace configuration - was gathered in-field during visits to production plants. The energy efficiency of the vertical kilns was calculated according to the ISO – 13579 Standard.

Substantial heat losses were found especially through the flue gases and kiln walls. The kiln thermal efficiencies calculated were in the range of 54–59%, with combustion efficiencies of 74–78%. The energy performance indicators of the vertical kilns were significantly below those of the most advanced technology available for the calcination stage. Potential energy savings through the introduction of the state-of-the-art kiln technology in the Colombian lime industry is discussed.

1. Introduction

China is the world's leader in calcium oxide (AKA lime or quicklime) production and consumption, at about 70% of total world production [1], an estimated 350 megatonnes in 2015 [2]. The most commonly used technology in China for the calcination stage of the lime production process is the twin shaft regenerative (TSR) kiln, representing 51% of installed furnaces, this kiln being preferred for its high efficiency. In spite of this, there are many unknown types of limekilns used (16%) due to many locally constructed kilns, as well as the rapid expansion of the lime industry in the country [3].

Lime is used in mortar, cement, water treatment, air pollution control, glass manufacture, the whitewashing of acid soils, and as a flux in foundry activities and an absorbent in many chemical processes [4]. Internationally, new uses of lime in the pharmaceutical industry are being researched, using CaO nanoparticles as an antimicrobial agent for the development of new drugs [5].

The calcium oxide industry in Colombia produces about 2,470,956 tonnes per year [6]. There is significant potential for energy savings due to the inefficiency of the presently used technology, as well as opportunity for the reduction of the environmental impact associated with fossil fuel use. In 2001, Law 697 was implemented addressing the rational use of energy, considering

---

* Corresponding author.
E-mail address: andres.amell@udea.edu.co (A. Amell).

http://dx.doi.org/10.1016/j.applthermaleng.2017.09.018
1359-4311/

Nomenclature

β	calcining reaction efficiency
$\dot{m}_L$	mass flow of limestone entering the kiln [kg/s]
$\dot{m}_{Prod}$	mass flow of produced lime [kg/s]
$\dot{m}_{UL}$	mass flow of uncalcined limestone [kg/s]
$\dot{m}_{CO2}$	mass flow of produced carbon dioxide [kg/s]
Q_L	total heat associated with the raw material entering the kiln [kW]
Cp_L	limestone specific heat [kJ/kg K]
T_e	temperature of the raw material entering the kiln [K]
T_{ref}	reference temperature (298.15 K)
P_T	thermal energy provided by the fuel [kW]
$\dot{m}_f$	fuel mass flow entering the control volume [kg/s]
HHV_M	fuel higher heating value [kJ/kg]
Q_{Prod}	sensible heat of the product exiting the reactor [kW]
Cp_{Prod}	specific heat of the product [kJ/kg K]
T_f	product final temperature [K]
Q_{rxn}	heat consumed by the calcination reaction [kW]
ΔH_{rxn}	specific enthalpy of the reaction [kJ/kg]
Q_{conv}	convection heat losses from kiln walls [kW]
Q_{rad}	radiation heat emission from kiln walls [kW]
$\dot{m}_i$	mass flow of the *i* component in the flue gases [kg/s]
Cp_i	specific heat of the *i* component [kJ/kg K]
Q_{H_2O}	heat of the water vapor exiting the kiln [kW]
$\dot{m}_{H_2O}$	mass flow of water vapor that exits the kiln [kg/s]
ΔH_{vap}	specific vaporization enthalpy of water [kJ/kg]
Q_{un}	total heat of unburned fuel [kW]
$\dot{m}_{CO}$	mass flow of carbon monoxide coming out in flue gas [kg/s]
HHV_{CO}	higher heating value of carbon monoxide [kJ/kg]
$\dot{m}_{H_2}$	mass flow of hydrogen coming out in flue gas [kg/s]
HHV_{H_2}	higher heating value capacity of hydrogen [kJ/kg]
P_U	useful power output (energy effectively applied to the process) [kW]
P_T	thermal power input provided by the combustion of the fuel [kW]

the guarantee of sufficient energy supply as a national issue of public interest [7]. Locally, energy saving guides have been published for several industrial activities, such as paper, cement, glass, ceramic, oil, and ammonia production. Energy saving potentials have been identified for the textile, pulp and paper, ceramic, glass, as well as the ferrous and nonferrous metals industries [8].

In this paper, we evaluated the performances of two limekilns in the Colombian lime industry. Specific consumption is calculated and compared with the best available kiln technology, aiming to establish a benchmark for improvements in energy efficiency. The energy saving potential of the introduction of new kiln technologies in Colombia is also discussed.

2. Lime production in Colombia

The lime production process begins with the extraction of limestone, the raw material of lime. In Colombia, the biggest limestone mines are located in the Colombian Andes and the Atlantic region [9]. In 2013, national limestone extraction totaled 13,954,059 tonnes [10].

First, limestone is crushed and ground to obtain smaller rocks. Raw material is then classified and sent to the calcination stage, where the calcium carbonate is exposed directly to fire in a kiln, reaching temperatures of between 900 °C and 1000 °C. This process transforms the limestone into carbon dioxide and lime, described by chemical reaction Eq. (1) [11], where α is the amount of CO_2 moles produced per mole of calcined limestone. The decomposition temperature at the center of a lump of limestone will be above 900 °C, as the partial pressure of carbon dioxide needs to be high enough to force the gas to exit the lump and enter the gaseous flow. Therefore, the actual calcination processes requires the rock to reach between 1200 °C and 1300 °C [12]. Generally, not all the raw material is calcined, creating production waste. Recently, lime production waste has been tested as a component of cement [13] and as a binder in composite materials [14].

$$CaCO_{3(s)} + Heat \rightleftharpoons CaO_{(s)} + \alpha CO_{2(g)} \quad Heat = 3.18\,\frac{GJ}{t} \tag{1}$$

In a real-world calcination process, the limestone conversion is not ideal, due to variable process conditions. This leads to uncalcined limestone in the products, as shown in Eq. (2)

$$CaCO_{3(s)} \rightleftharpoons \beta(CaO_{(s)} + \alpha CO_{2(g)}) + (1-\beta)CaCO_{3(s)} \tag{2}$$

where β is the calcining reaction efficiency (the ratio of calcined limestone to the total amount of limestone entering the kiln).

The calcined product pass through a grinding process in order to obtain the required granulometry, and is separated from the lime that will be used in the hydration process for the production of calcium hydroxide (AKA slaked lime). In Fig. 1 is showed a block diagram of the lime production process, along with the type of energy required at every stage,

2.1. Emissions of pollutants

The lime production process is the second most significant source of CO_2 among industrial processes, following only cement production. In 2012, China, the world's largest producer of lime, emitted 142 million tonnes of CO_2 associated with lime production [15].

Pollutant emissions related to the production process are considered direct emissions, whereas emissions related to combustion and electricity are counted as emissions caused by energy use [16]. This differentiation is useful for understanding the different estimates of CO_2 emissions. It has been reported that the calcination stage accounts for about 99% of greenhouse gas emissions of lime production [17].

Taking Europe's production as a reference, Fig. 2 shows the average share of CO_2 emissions from the manufacture of lime. Table 1 shows European CO_2 emissions depending on the lime product.

Additionally, the International Finance Corporation reports the reference pollutant levels for lime manufacturing; SO_2 less than 400 mg/N m, NO_x less than 500 mg/N m and dust less than 50 mg/N m [18]. Normal conditions are calculated as daily values corrected for 273 K, 101.3 kPa, and 10% O_2 dry gas.

2.2. Types of kilns

Kilns used in lime production can be grouped into two categories: Vertical and Horizontal. Vertical limekilns, such as parallel-flow regenerative shaft kilns, are highly efficient. On the other hand, horizontal limekilns, in spite of preheating combustion