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Thermal energy analysis of a lime production process: Rotary kiln, preheater and cooler

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ABSTRACT

In this paper, thermal energy analysis of three zones of a lime production process, which are preheater, rotary kiln and cooler, is performed. In order to perform a proper quantitative estimation, the system was modeled using energy balance equations including coupled heat transfer and chemical reaction mechanisms. A mathematical model was developed, and consequently, the thermal and chemical behavior of limestone was investigated. The model was verified using empirical data. After model confirmation, the variation of Specific Fuel Consumption (SFC) versus production rate was predicted and the optimum condition was determined. Subsequently, fuel consumption was calculated regarding to altered residence time inside each zone of lime production process, for a constant output. Results indicate that increasing the residence time inside each zone of lime production process, will enhance thermal efficiency and saves fuel consumption. Relative enhancement will be the same for different sizes of limestone. It was found that a 10-min increase in material residence time inside the preheater or rotary kiln can reduce fuel consumption by around two percent. Whereas, a 5-min increase in material residence time inside the cooler would be enough to obtain a similar result. Finally, the ratio of air-to-fuel and production rate are changed in such a way that the same product is achieved. The model predicts that lowering excess air from 15% to 10% leads to a 2.5% reduction of Specific Fuel Consumption (SFC).

1. Introduction

Determining the more important parameters and their impact on energy efficiency can play a key role in thermal management and fuel consumption reduction of any heating process. Nowadays, mathematical modeling is a widespread method for studying the thermal behavior of industrial furnaces, and finding ways to reduce their energy consumption. Examples of related works with this approach could be found in Refs. [1–11].

A rotary kiln is a type of industrial furnace with applications in steel, cement, incineration and chemical industries. It is also the prevalent type of kiln in the lime production process. Numerous investigations have focused on the mathematical modeling of this type kiln; however, most of them have only modeled the rotary kiln section regardless of its up- and down-stream sections [12–23]. However, the effects of the cooler and preheater, which have been employed in more modern installations, have seldom been studied [23–26]. Engin and Ari investigated energy audit in a dry type cement rotary kiln using empirical data. They analyzed all three parts (rotary kiln, preheater and cooler) [24]. Mujumdar et al. presented the integrated model for cement rotary kiln, calciner, cooler and preheater, and developed a simulation software titled RoCKS [25]. However, they did not make any comparisons with experimental data. Söğüt et al. performed an exergy analysis on the cement production line [26]. In most recent work, Liu et al. presented the energy flow model for the cement clinker manufacturing process [27].

In this paper, a specific integrated model is developed for the lime production unit at Mobarakeh Steel Complex (MSC), Iran. For this process, the heat transfer and calcination reaction phenomena have been simulated using 1D thermochemical equations in rotary kiln, preheater and cooler. Integrated modeling helps us to consider the effects of upstream and downstream sections in the thermal efficiency of the process. Comparing calculated values from model and experimental measurements proves the suitable accuracy of the model. In the results section, first, the effect of limestone feed rate on SFC is studied. Next, the effects of material residence time inside preheater, rotary kiln and cooler on fuel consumption are investigated. Finally, the effect of air-to-fuel ratio on

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Nomenclature

A	area (m^2)
a	kiln inclination (deg)
c	specific heat (kJ/Nm^3 °C)
D	diameter (m)
F_f	feed rate of fuel (kg/s)
F_{ij}	view factor between i and j surfaces
f_a	form factor
G	volume of gas (Nm^3/kg)
h	heat transfer coefficient (W/m^2 K)
H_{CaCO_3}	enthalpy of reaction for calcination (kJ/kg)
k	thermal conductivity (W/m K)
L	kiln length (m)
M	mass of material (kg)
$N_{element}$	number of element
$N_{particle}$	number of particle
Nu	Nusselt number
Pr	Prandtl number
Q	heat flow (W)
Q_N	net calorific value (kJ/kg)
R	reaction rate (1/s)
Ra	Rayleigh number
Re	Reynolds number
r	radius (m)
SFC	Specific Fuel Consumption (Nm^3/ton)
t	time (s)
T	temperature (K)
u	axial velocity (m/s)
U	overall convection heat transfer coefficient (W/m^2 k)
v	solids fraction
w_{free}	superficial velocity above the solid
x	coordinate in the length direction
y	bed depth/kiln radius

Greek letters

α	fraction of original mass of $CaCO_3$ converted to CO_2
γ	angle of repose (deg)
ε	emissivity
η	thermal efficiency of lime production unit
κ_f	rate constant of flame combustion (1/m)
υ	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stephan–Boltzmann constant (W/m^2 K^4)
φ	mass fraction of $CaCO_3$ in particle
X	fraction of wall surface contacts with rotating solids
ω	rotational speed (rpm)

Subscripts

0	initial
a	ambient air
b	bed
c	calcination
cnv	convection heat transfer
cnt	contact heat transfer
eq	equivalent
eff	effective
f	flame
g	gas
in	inner
l	loss
out	outer
p	particle
r	reaction
res	residence time
rad	radiation heat transfer
s	solid
w	wall

Superscript

$*$	average of wall and solids

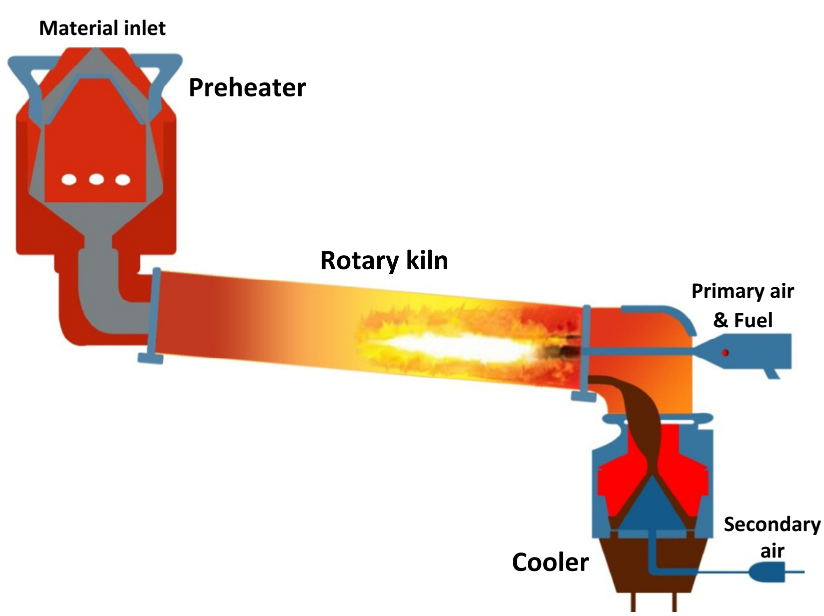

Fig. 1. Schematic view of the lime production process.