Applied Thermal Engineering 119 (2017) 629–638

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Energy and exergy analysis of an annular shaft kiln with opposite burners

Wenjie Rong[a], Baokuan Li[a,*], Fengsheng Qi[a], Sherman C.P. Cheung[b]

[a] School of Metallurgy, Northeastern University, Shenyang 110819, China
[b] School of Engineering, RMIT University, Victoria 3083, Australia

HIGHLIGHTS

- An OBASK is investigated for the energy and exergy performance.
- The energy and exergy efficiency of the OBASK is of 63.6% and 35.7%, respectively.
- The exergy destruction accounts for 44.5% of the total exergy input.

ARTICLE INFO

Article history:
Received 20 December 2016
Revised 28 February 2017
Accepted 19 March 2017

Keywords:
Annular shaft kiln with opposite burners
Energy analysis
Exergy analysis
Efficiency

ABSTRACT

Annular shaft kilns with opposite burners (OBASK) has been widely adopted due to the advantages of cost saving and easy controlling. Nonetheless, compared with the traditional annular shaft kiln, the OBASK is not favorable in terms of thermal performance and energy efficiency. Aiming to improve the thermal performance, a comprehensive energy and exergy analysis of an OBASK has been conducted based on the actual operational data obtained from on-site measurements. For making a thorough thermal analysis of the OBASK, special attentions have been focused in considering magnesium decomposition reaction and moisture in limestone in the methodology. The energy and exergy efficiencies are determined to be 63.6% and 35.7%, respectively. The exergy destruction is 44.0% of total exergy input of which fuel combustion causes 56.6% of the exergy destruction. Furthermore, the effects of CaO and moisture contents in limestone on energy and exergy efficiencies are analyzed. The results have demonstrated the potential energy saving of the OBASK and identified three proposed energy conservation measures. Improvement and effect of the three proposed measures on the thermal performance are verified via further analysis.

1. Introduction

Lime kiln is one of the essential equipment for producing lime material for iron and steel enterprises, calcium carbide factories, alumina industry, refractories and other industries. With the rapid growing of the related industries in China, the market records a scouring demand on lime material which certainly drives an increasing investment on the lime kiln equipment. In current industry practice, there are several types of kilns commonly used for lime burning; including the rotary kiln, the normal shaft kiln, the Maerz kiln and the annular shaft kiln. Among all these kilns, the annular shaft kiln has been widely adopted with the advantage of being able to produce lime with various reactivities [1,2]. Aiming to reduce the construction cost of the traditional annular shaft kiln, an annular shaft kiln with opposite burners (OBASK) was proposed and built recently. Based on the traditional design, the OBASK has a simplified and improved combustion chamber structure which could be fabricated on site with less refractory materials; leading to a significantly reduction of construction cost. The total construction cost worth approximately 70% of the traditional annular shaft kiln and only 50% of the Maerz kiln with the same capacity. Although the construction cost could be reduced substantially, compared to the traditional annular shaft kiln, the OBASK is not favorable in terms of thermal performance and energy efficiency. Thus, there is a pressing need for the industry to enhance the thermal performance of the OBASK; reducing the energy cost to cope with ever increasing energy price.

Several previous studies have been carried out to improve the thermal efficiency of a few different type of limekilns [3–5]. Senegačnik et al. [3] proposed a kiln gas recirculation measure to enhance the performance of an annular shaft kiln. The measure

---

[*] Corresponding author.
E-mail address: libk@smm.neu.edu.cn (B. Li).

http://dx.doi.org/10.1016/j.applthermaleng.2017.03.090
1359-4311/

Nomenclature

A	percentage of CaO in quicklime (%)
B	percentage of $CaCO_3$ in limestone (%)
c	volume fraction of gas in air (%)
c_p	specific heat (kJ/(kg·K))
D	conversion degree (%)
En	energy rate (kW)
Ex	exergy rate (kW)
ex	specific exergy (kW/kg)
f	volume fraction of gas in air (%)
H	enthalpy (kW)
heat	decomposition heat (kJ/kg)
LHV	low heating value (kJ/kg)
m	mass rate (kg/h)
P	pressure (Pa)
Q	heat (kW)
R	universal gas constant (kJ/kmol·K)
r	latent heat of vaporization (kJ/kg)
S	entropy (kJ/kg·K)
T	temperature (K)
V	volume (m^3)
v	volume fraction of gas in flue gas

Greek letters

η	efficiency (%)
φ	relation between chemical exergy and LHV
ω	mass fraction of chemical species in limestone
ς	mass fraction of chemical species in lime

Subscripts

a	combustion air
ca	cooling air
ch	chemical
com	combustion
comg	combustion gas
D	destruction
d	dust
de	decomposition
en	energy
ex	exergy
f	fuel
fg	flue gas
gen	generation
hl	heat loss
in	input
k	the number of components
la	leaking air
ls	limestone
out	output
ph	physical
prod	product
re	reaction
reac	reactant
ql	quicklime
w	water
0	ambient

collected exhaust kiln gas at the recuperator outlet and used it for cooling the flame in the combustion chambers instead of using secondary air in the conventional system. They reported that the kiln gas recirculation achieved a substantial fuel saving of 4.6% compared to normal operation. On the other hand, Deng et al. [4] presented a supervisory-level simulated mathematical model and a holographic monitoring system for providing assessment and support for decision-making for the process management based on the history of operation conditions through the real-time display. Similarly, Ochoa et al. [5] proposed an operational control method for the calcination stage in a small kiln aiming for improving the fuel and limestone utilization and reducing waste production.

Recently, with the advancement of theory and technology, exergy analysis has become one of widely adopted methodology for advanced thermodynamics performance assessment [6]. Previous works have been carried out to estimate the energy saving potential for various industrial applications based on energy and exergy balance [7–17]. For the cement production plant, Rasul et al. [7] presented a thermal assessment model and concluded that the conversion of the chemical energy of the fuel to thermal energy is the major significant cause of irreversibility. Afterwards, Rasul et al. [8] also developed another assessment model for the blast furnace. Based on their assessment, the first and second law efficiencies of the blast furnace were found to be of 77.3% and 39.13% respectively. Utlu et al. [9] also performed an energy and exergy analysis on the raw mill and raw materials preparation unit of a cement plant with comprehensive considerations on the moisture embedded in the limestone and leaking air of the plant. Furthermore, aiming to investigate the induration of iron ore pellet in the grate-kiln-cooler, Zhang et al. [10] presented a combined energy and exergy analyses for the particular balling process of pellet through the modelling of the exergy of iron oxide pellets instead of the conventional ideal mixture exergy. For the iron and steel industrial sector, based on the second law analysis, Camdali et al. [13] investigated the actual and reversible work, irreversibility and exergy efficiency of a ladle furnace. Similarly, Camdali et al. [15] also performed an energy and conservation analysis on the production of steel process in the electric arc furnace. Their study revealed that the second law efficiency of the system can be improved by recovering the heat from the stack gas through a preheating system.

Although considerably substantial amount of research works have been carried out, to the best of our knowledge, exergy assessments and possible energy saving measures for lime kilns are not yet to be comprehensively performed in literature. Lately, Gutiérrez et al. [16,17] presented two individual exergy assessments for two different shaft lime kilns. In their first article, they analyzed the energy and exergy consumption of the calcination process in two vertical shaft kilns where liquid fuel and solid fuel were used in the process respectively [16]. They concluded that the fuel combustion as well as the internal heat and momentum transfer have the maximum influence on the exergy destruction. In another separate work, they proposed two exergy-based indicators for evaluating the energy performance of a lime shaft kiln [17]. The two exergy indicators clearly identify the distinction between avoidable and unavoidable exergy destruction; leading towards a better presentation of the fuel saving potential. With no doubt, their research work has laid a firm foundation for a detail exergy analysis of shaft lime kiln. Nonetheless, the moisture and magnesium carbonate content in limestone are not considered in their work, which brings calculation error and has an impact on the accurate judge of energy saving potential. Therefore, the present work aims to incorporate the considerations of the moisture and magnesium carbonate content in the limestone to develop a more comprehensive energy and exergy analysis model for assessing the thermal performance of the OBASK. The assessment also attempts to iden-