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Design requirements and performance optimization of waste heat recovery systems for rotary kilns

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ABSTRACT

Heat loss from the shell of a rotary kiln accounts for a certain proportion of total energy consumption. In order to reduce heat loss, a practical heat recovery system with nine heat exchangers is proposed to preheat water in this paper. We first propose a mathematic model to analyze the shell temperatures and heat loss rates of several regions on rotary kilns. Integration of theoretical analyses and experimental measurements yields the temperatures and heat transfer rates of heat exchangers, i.e. the design requirements of the nine heat exchangers in the practical system. Secondly, an optimization model is formed to describe the relation between design parameters, i.e. heat transfer area and mass flow rate of each heat exchanger, and system requirements without introducing any intermediate temperatures. With the aid of the Lagrange multiplier method, the optimal design parameters are obtained. Finally, an optimization case of the practical system is studied. The results show that the heat recovery system should meet the requirements of chemical reactions in rotary kilns and mechanical characteristic of shell. The required total heat transfer area of the system after optimization is reduced by 15.6% compared to the value before optimization. As the total mass flow rate increase and inlet temperature decreases, the required heat transfer area decreases while the mass flow distribution ratios remains unchanged.

1. Introduction

Cement production is one of the most energy-intensive industrial processes [1,2], where some well-equipped plants still consume about 3 to 4 GJ to produce only one ton of cement [2–4]. The cement industry has consumed a larger proportion of energy compare to other industrial sectors [4,5]. Therefore, improving the energy efficiency has become one of the key issues in the cement industry.

In recent years, scientists have developed several methods to reduce energy consumption, such as sensible heat recovery from hot products [6] and exhaust gases for power generation [7,8]. Besides, some researchers use energy and exergy analysis method to find the potential ways to increase the energy efficiency [9–11]. The findings indicate that the rotary kiln, the preheater and the clinker cooler have larger energy loss and energy saving potential compare to other components of the plant [7,10,12]. Atmaca and Yumrutaş [5,9] studied an actual cement plant and found that the highest energy loss occurs in the rotary kiln. The rotary kilns consume a large amount of energy, which lose heat from the external surfaces [13,14]. Some discoveries [1,4,7,15] point that this loss accounts for 5–15% of the total heat consumption. Especially, Chakrabarti [16] investigated the dead burning of magnesite process and found a larger loss, 24.8% of the total heat consumption. Therefore, heat recovery from rotary kilns is an alternative promising method for energy conservation in cement industry.

Vladan [15] designed a device to recover heat from the kiln surface to preheat air, which was used for fuel combustion. Comparing to preheat air, the waste heat from external surface was widely used for heating water [1,17], which was for district heating or power generation [18]. In order to improve heat recovery performance, some scientists invented different tube arrangements for heat recovery exchangers, including bent tube arrangement [18] and axial tube arrangement [17]. On the other hand, Caputo et al. [1] developed a mathematic model for heat exchangers to analyze the economic performance as a function of equipment length. Söğüt et al. [17] obtained the amount of fuel saving in a heat recovery system and ensured that financial saving was achieved. These discussions focused on optimizing the structural and operating parameters of heat exchangers to absorb more heat from shell surfaces. However, heat loss from kiln shell should not be maximized or minimized. More specifically, excessive heat loss from rotary kilns will cause the clinker to be under burnt and reduce the

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Nomenclatures

A	heat transfer area (m^2)
c_p	constant pressure specific heat ($J/(kg \cdot K)$)
F	Lagrange function
k	heat transfer coefficient ($W/(m^2 \cdot K)$)
k_0	undetermined coefficient
l	length (m)
L	characteristic length (m)
m	mass flow rate (kg/s)
Nu	Nusselt number
Q	heat flow rate (W)
r	radius (m)
R	thermal resistance (K/W)
Re	Reynolds number
T	temperature (°C)
T_0	ambient air temperature (°C)
u	cold fluid velocity (m/s)
x	distribution ratio

Subscript

c	the cross-section area vertical to the flow
f	outer side of the refractory layer
g	flue gas
gs	heat transfer rate between glue gas and raw materials
gw	heat transfer rate between flue gas and inner wall
i	the ith branch
in	inlet
$outi$	outlet of the ith branch
rsi	required for the ith region of kiln shell
rwi	required for the ith region of kiln inner wall
s	raw materials
sh	kiln external shell
shi	kiln external surface of the ith region
t	total
w	inner wall
wi	inner wall of the ith region
ws	heat transfer rate between wall and raw materials
$w1$	kiln coating
$w2$	inner side of the refractory layer

Greek symbols

α	undetermined exponent
β	Lagrange multiplier
ρ	density of the fluid (kg/m^3)
Δt	logarithmic mean temperature difference (°C)
λ	thermal conductivity ($W/(m \cdot K)$)

property of cement, and on the other hand, insufficient heat loss will destroy the refractory layers and external shell [15,17]. Therefore, the heat loss from the kiln shell should maintain at a suitable value for equipment operation and clinker reaction. From this viewpoint, the function of heat exchangers installed on the kilns is to absorb a certain amount of heat from the shell, not to absorb more heat. Besides, the heat loss rates from the kiln surfaces are not uniform along the rotary kilns [19,20]. Therefore, the design of heat recovery system with several heat exchangers should meet the requirements of the temperatures and heat loss rates. Furthermore, it is necessary to save the investment of the heat recovery systems.

Based on aforementioned analyses, we propose a newly practical heat recovery system with several parallel connected heat recovery exchangers. The heat recovery exchangers are installed on external kiln surfaces of different temperatures and heat loss rates. In this paper, the required temperatures and heat transfer rates of heat recovery exchangers in the practical system are first calculated by theoretical analyses and experimental measurements. Based on the thermal resistance analysis and optimization method proposed by Chen and his colleagues [21,22], the heat recovery system is then analyzed to deduce several formulas to connect the design parameters, i.e. heat transfer area and mass flow rate of each heat exchanger, to the system requirements without introducing any intermediate parameter, which are the physical constraints for system optimization. An optimization case is studied by applying the Lagrange multiplier method and the conditional extremum principle. The optimization results directly gives the optimal design parameters with the minimum investments for several different system requirements. Finally, some factors that affect the optimization results are further discussed.

2. Analysis of the required temperature and heat loss along a rotary kiln

Fig. 1 shows all the physical and chemical processes in a rotary kiln, which involves heat transfer processes through particles, mass transfer processes and chemical reaction processes at raw particles [2,3,7,11,19,20,23,24]. Raw materials passes through the rotary kiln and absorbs heat from the counter-flow flue gas. Carbonate absorbs heat and breaks down into oxide at 800–900 °C in the decomposition reaction zone. Then, dicalcium silicate forms at 1000–1200 °C in the solid–solid reaction zone and prepares for clinkering. Finally, cement clinker forms at 1300–1450 °C in the clinkering reaction zone [11,19,20]. Meanwhile, coating also forms on kiln refractory during the cement production. All the chemical reactions require certain temperatures and sufficient heat. Therefore, chemical reaction processes are closely related to heat transfer processes in rotary kilns.

Fig. 2 shows a simplified heat transfer model in an arbitrary cross section of a rotary kiln [19,20,23]. The energy conservation equation of solid materials is

$$Q_s = Q_{gs} + Q_{ws}, \tag{1}$$

where Q_s is the heat absorbed by solid materials, Q_{gs} is heat transfer rate between gas and solid materials and Q_{ws} is heat transfer rate between kiln inner wall and solid material.

The energy equation of heat loss from the shell is

$$Q_{sh} = Q_{gw} - Q_{ws}, \tag{2}$$

where Q_{sh} and Q_{gw} are the heat loss from shell and the heat transfer rate between gas and kiln inner wall, respectively.

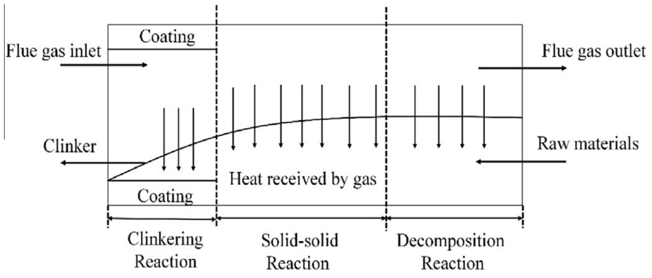

Fig. 1. The schematic diagram of all process in a rotary kiln.