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Optimization design of heat recovery systems on rotary kilns using genetic algorithms

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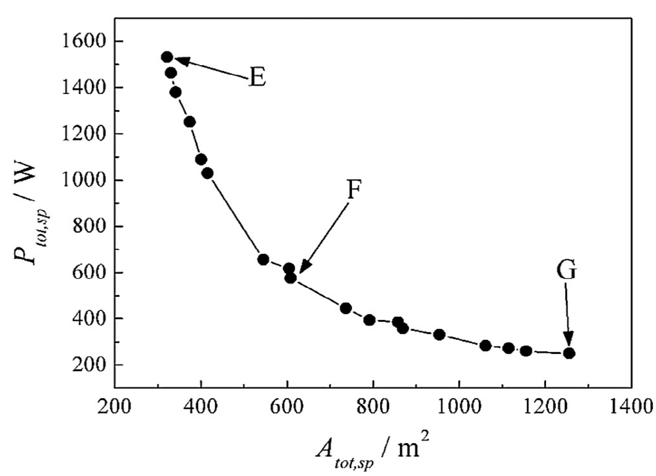
HIGHLIGHTS

- Two forms of heat recovery systems are proposed to absorb heat loss.
- The multi-objective optimization models of the heat recovery systems are derived.
- The optimal design parameters of the heat recovery systems are obtained.
- The optimization results of the systems are compared with the original values.

GRAPHICAL ABSTRACT

The variation of $A_{tot,sp}$ and $P_{tot,sp}$ in the Pareto solutions in the MOO case III.



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ABSTRACT

Heat loss from rotary kilns accounts for certain amounts of the total energy consumption in chemical and metallurgical industries. To reduce the heat loss, a parallel and a series-parallel heat recovery systems with nine heat recovery exchangers are proposed to preheat the cold water in this paper. Experimental measurements are carried out to determine the heat transfer coefficient equations of each heat recovery exchanger. Then, the heat recovery systems are analyzed to deduce the mathematic relation between the design parameters and the system requirements, i.e. the temperatures and heat transfer rates of the nine heat recovery exchangers. The total heat transfer area, the total power consumption and the entropy generation due to heat transfer and fluid flow are set as the objective functions in four multi-objective optimization (MOO) cases. With the aid of the genetic algorithm in the Matlab 2015, the optimized operational and structural parameters are obtained. Finally, the MOO results are compared with that of the single objective optimization (SOO) method and the original values. The optimization results show that the MOO method are more suitable for the operational parameters design of the heat recovery systems compared with the SOO method. The required total heat transfer area and the total power consumption are decreased by at least 12.1% and 13.7%, respectively. Besides, as the entropy generation due to heat transfer and fluid flow decrease in the MOO cases, the corresponding heat transfer area and power consumption of the heat recovery system decrease, respectively.

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Nomenclature

A	heat transfer area (m^2)
C_0, k_0	undetermined coefficient
c_p	constant pressure specific heat (J/(kg K))
D	pipe diameter (m)
f	Darcy friction-factor
g	acceleration of gravity (m/s^2)
H	head loss (m)
h	heat transfer coefficient of shell-side or tube-side ($W/(m^2 K)$) or the installation height of the pipelines (m)
K	minor loss coefficient
k	the total heat transfer coefficient ($W/(m^2 K)$)
L	characteristic length (m)
l	pipeline length (m)
m	mass flow rate (kg/s)
Nu	Nusselt number
P	power consumption (W)
Q	heat transfer rate (W)
Re	Reynolds number
S	the cross-sectional area of the pipelines (m^2)
S_{gen}	entropy generation (W/K)
T	temperature (°C)
u	cold fluid velocity of the water tubes (m/s)
V	volume flow rate (m^3/h)
v	fluid velocity in the pipelines (m/s)

Subscripts

c	the cross-section area of the water tubes or the cold fluid
d	dynamic head
i	the ith branch or the tube side
in	inlet
$i1$	the 1st heat recovery exchanger in the ith branch of the series-parallel system
$i2$	the 2nd heat recovery exchanger in the ith branch of the series-parallel system
$i3$	the 3rd heat recovery exchanger in the ith branch of the series-parallel system
o	outlet or the shell-side
$outi$	outlet of the ith branch
p	parallel
s	static head
sp	series-parallel
tot	total
w	water

Greek symbols

α	undetermined exponent
ΔP	pressure drop (Pa)
ΔT	logarithmic mean temperature difference (°C)
λ	fluid thermal conductivity (W/(m K))
μ	fluid viscosity (Pa s)
ρ	fluid density (kg/m^3)
φ	pump efficiency

1. Introduction

Cement production is an important part in the constructional sectors and is also one of the most energy-intensive industries [1–3]. In China, the cement production had accounted for about 40–60% of total production around the world in the past three years [4]. In order to produce the large amount of cement, some well-equipped facilities were put into use in plants. However, some researchers pointed out that the plants with these well-equipped facilities still consume about 3–5 GJ to produce one ton of cement [3,5,6]. The energy consumption occurred mainly in rotary kilns [7], grate clinker coolers [5] and pyroprocessing towers [8], which about 36% of the total energy input is lost through dust, exhaust gas and radiation from the kiln shell [5,7]. Therefore, to improve the efficiency of the energy utilization is of great significant in the cement industry.

Many scientists have developed some methods for reducing the heat loss of the cement plants. Khurana et al. [9] proposed a power generation for recovering the waste heat from the exhaust flue gas. Rasul et al. [10] made an assessment of the energy conservation opportunities and recovered the heat loss from the grate cooler exhaust to preheat raw meal. Schneider et al. [11–13] improved the energy utilizing efficiency of the raw mills to reduce the energy consumption in cement plants. Besides, some other researchers studied the energy utilization and analyzed the exergy consumption of the key components in cement industry [5,8,14,15]. The findings showed that the energy and exergy loss of the preheaters, the clinker coolers and the rotary kilns are higher than that of other components. Atmaca et al. [7,14] used the thermodynamic and exergoeconomic analyses in a practical plant and found that the rotary kiln had larger energy and exergy loss compared with other production components. These studies illustrate that improving the energy utilizing efficiency of rotary kilns is an effective way for energy savings in the cement industry. The heat loss from the kiln surfaces was about 11.3–15% of the total heat input [5,16], which accounted for a certain proportion of the energy consumption in plants. Chakrabarti [17,18] investigated a plant with the dead burning of magnesite and found this loss could reach 24.8% of the total heat consumption. Therefore, heat recovery from the kiln surfaces could be a potential method for energy conservation in cement plants.

In order to absorb the heat loss from the kiln shell, many researchers invented different kinds of heat exchange devices. Karamarković et al. [19] proposed a heat recovery device called recuperator to absorb the heat loss from the kiln shell to preheat the ambient air for fuel combustion. The recuperation system with the heat recovery device reduced the fuel consumption and had a payback period of less than 6 months. Besides, the heat recovery exchangers were also widely used to preheat water. Caputo et al. [20] designed the heat recovery exchangers with two different tubes arrangement and established a mathematic model to analyze the performance as a function of the structural parameters. The results indicated that the heat transfer rates would be improved as the length of the tube bundles was increased. Söğüt et al. [21] developed a heat transfer model for a heat recovery exchanger and obtained a certain amount of financial savings in a practical plant. These heat recovery exchangers were covered along the entire rotary kilns. Besides, the tube bundles were distributed uniformly while the heat loss from the kiln shell were not uniform along the rotary kilns. Therefore, the aforementioned heat recovery devices could not meet the requirements of the temperatures and heat loss in different reaction sections along the kiln shell [18,22]. In view of the limitations, Cheng et al. [18] proposed several novel heat recovery exchangers which were installed on different sections of the rotary kiln. Furthermore, the novel heat recovery exchangers were formed into a heat recovery system to obtain