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Optimization design and economic analyses of heat recovery exchangers on rotary kilns

Qian Yin, Wen-Jing Du, Xing-Lin Ji, Lin Cheng *

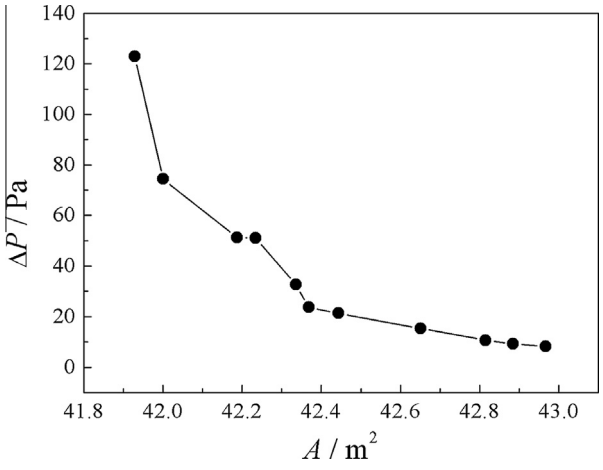
Institute of Thermal Science and Technology, Shandong University, Jinan 250061, Shandong Province, China

HIGHLIGHTS

- A novel heat recovery exchanger is proposed to absorb heat loss from the kiln shell.
- A multi-objective optimization model between heat transfer rates and design parameters is derived.
- The optimal design parameters of the novel heat recovery exchanger is obtained.
- The economic analyses of a practical heat recovery system are proposed.

GRAPHICAL ABSTRACT

The variation of ΔP and A in the Pareto optimal solutions of the water tubes.



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ABSTRACT

Heat loss from the kiln shell accounts for a certain proportion of total energy input in a rotary kiln. To reduce the heat loss, a novel heat recovery exchanger installed on the kiln shell is proposed to preheat water in this paper. Numerical simulations and experimental measurements are carried out to investigate the flow and heat transfer characteristics of the heat recovery exchanger. Then, multi-objective optimization models are proposed with the heat transfer area, the pressure drop and the modified entropy generation number set as objective functions. The mathematic models describe the relation between heat transfer rates and the design parameters of the heat recovery exchanger, i.e. the tube length, the tube numbers and the tube diameter. With the aid of the Matlab genetic algorithm toolbox, the optimized design parameters are obtained. Finally, economic analyses of a practical heat recovery system with nine heat recovery exchangers are proposed to estimate the saving of the fuel consumption. The optimization results show that the Pareto solutions are the trade-off between the two conflicting objective functions and give some final decisions considering specific requirements for the designers. Besides, the optimized results of heat transfer areas and pressure drop of the heat recovery exchanger are decreased by at least 18% and 11%, respectively. As the modified entropy generation number due to heat transfer and fluid friction decrease, the corresponding heat transfer area and pressure drop decrease, respectively. The economic analyses indicate that the heat recovery system is profitable and the revenue comes from the fuel savings.

* Corresponding author.
E-mail address: cheng@sdu.edu.cn (L. Cheng).

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Nomenclature

A	heat transfer area (m^2)
C	cost (€)
C_E	unit price of electrical energy (€/kW h)
C_o	*Stefan Boltzmann* constant ($W/(m^2 K^4)$)
c_p	constant pressure specific heat (J/(kg K))
d	diameter (m)
F	log-mean temperature difference correction factor
f	Moody friction factor
G	revenue (€)
h	tube-side or shell side of the heat transfer coefficient ($W/(m^2 K)$)
i	year
K	minor loss coefficients
k	heat transfer coefficient of heat recovery exchangers ($W/(m^2 K)$)
l	tube length (m)
M, m	mass flow rate (kg/s)
N	number of structural details
N_{pass}	number of tube passes
N_s	entropy generation number
N_{s1}	modified entropy generation number
n	number of tubes
n_y	maximum value of year
P	temperature effectiveness
Pr	Prandtl number
Q	heat transfer rate (W)
$q_{net,ar}$	net calorific value of fuel (J/kg)
R	heat capacity ratio
Re	Reynolds number
r	radius (m)
S_{gen}	entropy generation (W/K)
T	temperature (°C)
t	thickness (m)
U	the price of coal (€)
V	air velocity (m/s)
v	fluid velocity (m/s)
w	tube weight per unit length (kg/m)

Subscripts

a	air
ac	annual current cost
ad	air duct
$atot$	annual total
c	cold
co	coal
cs	shell of the coiled pipes
$EHRE$	equivalent capital investment of heat recovery exchanger
fu	fuel consumption
HRE	heat recovery exchanger
h	hot
i	inlet, inner side
ins	insulation
o	outlet, outer side
op	operating
rs	required shell
rhl	required heat loss
s	shell
t	tube bundles
tot	total
$uins$	specific insulation cost
us	specific cost of shell material
ut	specific cost of the structural material
w	water side
wl	wall surface
ws	shell of the water tubes
1	water tubes
2	coiled pipes

Greek symbols

β	capital recovery factor
γ	annual interest rate
ΔP	pressure drop (Pa)
ΔT	logarithmic mean temperature difference (°C)
ε	radiative emissivity of heat exchangers
η	pump efficiency
λ	thermal conductivity (W/(m K))
μ	viscosity at the fluid temperature (Pa s)
Π	annual profit
ρ	fluid density (kg/m^3)
τ	hours of operation per year (h/year)
υ	dynamic viscosity (m^2/s)
φ	view factor between kiln shell and water tubes

Abbreviation

SOO	single objective optimization
MOO	multi-objective optimization

1. Introduction

Cement production is an important ingredient of national economic components and is also one of the highly energy-consuming industries [1–3]. Some plants with well-equipped facilities still consume 3–4 GJ of energy to produce only one ton of cement [4,5], where 26% of the energy input is lost by dust, clinker cooling, pre-heaters and heat loss from kiln shell [2]. Therefore, to improve the energy utilizing efficiency is of great significant in cement industry.

In order to reduce energy consumption in the cement production, some methods have been developed, e.g. exhaust gas for power generation [6,7], waste heat to preheat raw meal [8–10] and efficiency improvement of raw mills [11–13]. Besides, some researchers investigated energy consumption of each component in cement plants using energy and exergy analyses [2,6,14,15]. The results indicated that the rotary kiln, the preheater and the clinker cooler had larger energy loss compared with other components [7,16,17]. Atmaca et al. [16,18] found that the highest energy loss occurred in the rotary kiln of an actual plant. Therefore, to improve the energy efficiency of rotary kilns is a profound method for saving energy consumption. The heat loss from kiln shell accounted for a certain proportion of energy consumption [19,20]. Some researches [6,16,21,22] suggested that this loss were about 6–15% of the total heat input. Therefore, heat recovery from kiln shell surfaces is a potential way for energy conservation in cement industry.

Some scientists have invented different types of heat recovery exchangers to recover heat from kiln shell. Karamarković et al. [22] designed a heat recovery device to absorb heat loss from shell surfaces for preheating air. The heat recovery exchanger was covered along the external kiln surface, which formed a secondary shell. The air flew into the passage between the secondary shell and external kiln surface and absorbed heat for fuel combustion.