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Research Paper

Multi-objective optimization design of air distribution of grate cooler by entropy generation minimization and genetic algorithm

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HIGHLIGHTS

- A multi-objective optimization model of air distribution of grate cooler by genetic algorithm is proposed.
- Pareto Front is obtained and validated by comparing with operating data.
- Optimal schemes are compared and selected by engineering background.
- Total power consumption after optimization decreases 61.10%.
- Thickness of clinker on three grate plates is thinner.

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ABSTRACT

The cooling air distributions of grate cooler exercise a great influence on the clinker cooling efficiency and power consumption of cooling fans. A multi-objective optimization model of air distributions of grate cooler with cross-flow heat exchanger analogy is proposed in this paper. Firstly, thermodynamic and flow models of clinker cooling process is carried out. Then based on entropy generation minimization analysis, modified entropy generation numbers caused by heat transfer and pressure drop are chosen as objective functions respectively which optimized by genetic algorithm. The design variables are superficial velocities of air chambers and thicknesses of clinker layers on different grate plates. A set of Pareto optimal solutions which two objectives are optimized simultaneously is achieved. Scattered distributions of design variables resulting in the conflict between two objectives are brought out. The final optimal air distribution and thicknesses of clinker layers are selected from the Pareto optimal solutions based on power consumption of cooling fans minimization and validated by measurements. Compared with actual operating scheme, the total air volumes of optimized schemes decrease 2.4%, total power consumption of cooling fans decreases 61.1% and the outlet temperature of clinker decreases 122.9 °C which shows a remarkable energy-saving effect on energy consumption.

1. Introduction

Grate cooler plays a very important role in cement production line whose main functions are quenching high temperature clinker and redistributing the exhaust hot air as shown in Fig. 1(a). Increasing clinker cooling efficiency has great effects on decreasing power consumption of cooling fans and improving quality of clinker. Moving packed bed is usually used which includes fixed grate plates and moving grate plates. Cooling air flows through the horizontal moving clinker vertically from the plates below as shown in Fig. 1(b). The more the air volume is, the better clinker cooling effect is in theory. But larger air volume leads to higher pressure drop in clinker layer which results in more power consumption of cooling fans. So it has important engineering significance to discuss optimal air distributions that cooling effect is best but power consumption is minimization. Multi-objective optimization is usually used in handling conflicting objectives. It has certified that the multi-objective optimization technique have more preference than the traditional single variable-single objective [1,2]. Specific heating load, coefficient of performance and thermos-economic criterion are usually considered as objective functions simultaneously to be maximized in heat pump cycle optimization [3–5]. Sadatsakkak et al. considers the power output, ecological functions and thermos-economic criterion as objective functions to be maximized at the same time in a closed Brayton cycle optimization [6]. Ahmadi et al. considers coefficient of performance, ecological functions and thermos-economic criterion as objective functions to be

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Nomenclature

A	efficient heat transfer area [m^2]
C	heat capacity rates [W/K]
C_p	heat capacity [J/(kg·K)]
D_p	average diameter of clinker particle [m]
H	thickness of clinker [m]
h	convection heat transfer coefficient [W/(m^2·K)]
K	volume of clinker [m^3]
k	integrated heat transfer coefficient [W/(m^2·K)]
L	length of chamber [m]
m	mass flow rate [kg/s]
Ns	entropy generation number
Nu	the Nusselt number
P	pressure [Pa]
Q	heat transfer rate [W]
Re	the Reynolds number
R_g	air gas constant = 287 [J/(kg·K)]
r	particle heating depth [m]
S_{gen}	entropy rate [W/K]
t	temperature [°C]
V	superficial velocity of cooling air [m/s]
W	power consumption of cooling fans [W]
Y	width of grate cooler [m]
ε	porosity of clinker
η	efficiency of fan
λ	thermal conductivity [W/(m·K)]
μ	kinematic viscosity of air [kg/(m·s)]
ρ	density [kg/m^3]
v_g	dynamic viscosity of air [m^2/s]
φ	particle shape correction factor

Subscripts

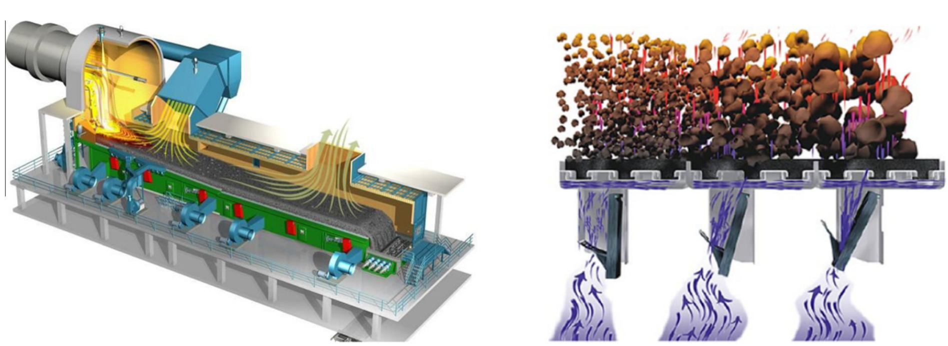
a	air
i	chamber number
in	inlet
j	grate plate number
out	outlet
ΔP	pressure change
s	clinker
ΔT	temperature change
0	environment

maximized in absorption refrigeration optimization [7]. Multi-objective optimization is also very common in energy system analysis and aims to improve exergetic efficiency [8–11]. Shell and tube exchanger is widely used in many industrial plants and multi-objective optimization is important way to maximize heat transfer effectiveness and minimalize exchanger weight and pressure loss [12,13]. Liu [14] analyzes the effects of raw preheating decomposition, clinker calcination and clinker cooling on heat efficiency of cement production by building energy flowing model and concludes that clinker cooling process is the second influence factor. Caputo [15,16] proposes clinker cooling model and optimizes heat recovery structure and operating parameters from the view of unsteady condition. Caputo [17] proposes optimal design of moving packed bed of grate cooler based on total investment minimum and annual cost of optimal structure reduced about 10–25%. Touil [18] analyzes the exergy balance of grate cooler, builds clinker cooling model, analyzes the entropy generation of cooling process and discuss the effect of cooling air temperature and chamber quantity on entropy generation. Madllol [19] summarizes the cement production process from the view of exergy balance and exergy efficiency and indicates that increasing system efficiency is an important way to reduce energy consumption. Most researches are focusing on cooling process and heat recovery currently. There is little research on air distribution of grate cooler but air distribution plays a very important role on reducing the power consumption of cooling fans.

The paper proposes a clinker cooling multi-objective optimization model of air distributions of grate cooler with cross-flow heat exchanger analogy. Based on entropy generation minimization analysis, modified entropy generation numbers caused by heat transfer and pressure drop are treated as objective functions respectively which optimized by genetic algorithm simultaneously. The design variables are superficial velocities of air chambers and thicknesses of clinker layer on three grate plates. A set of Pareto optimal solutions is achieved with some proper constraints. The optimal air distributions that meet the design requirements and constraint are selected from Pareto optimal solutions and validated by operating data. We also discuss the advantage of optimal air distributions comparing with operating scheme.

2. Entropy analysis of clinker cooling process

All the natural process is irreversible as indicated by the Second Law of Thermodynamics. As heat-exchanger equipment, the clinker cooling process in grate cooler is irreversible obviously. So reducing irreversible loss of cooling process is an important way



(a) (b)

Fig. 1. Principle of grate cooler (a) and clinker cooling (b).