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Research Paper

Multi-objective optimization of cooling air distributions of grate cooler with different clinker particles diameters and air chambers by genetic algorithm

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HIGHLIGHTS

- A multi-objective optimization model of air distributions of grate cooler by genetic algorithm is proposed.
- Optimal air distributions of different conditions are obtained and validated by measurements.
- The most economic average diameters of clinker particles is 0.02 m.
- The most economic amount of air chambers is 9.

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ABSTRACT

The paper proposes a multi-objective optimization model of cooling air distributions of grate cooler in cement plant based on convective heat transfer principle and entropy generation minimization analysis. The heat transfer and flow models of clinker cooling process are brought out at first. Then the modified entropy generation numbers caused by heat transfer and viscous dissipation are considered as objective functions respectively which are optimized by genetic algorithm simultaneously. The design variables are superficial velocities of air chambers and thicknesses of clinker layer on different grate plates. The model is verified by a set of Pareto optimal solutions and scattered distributions of design variables. Sensitive analysis of average diameters of clinker particles and amount of air chambers are carried out based on the optimization model. The optimal cooling air distributions are compared by heat recovered, energy consumption of cooling fans and heat efficiency of grate cooler. And all of them are selected from the Pareto optimal solutions based on energy consumption of cooling fans minimization. The results show that the most effective and economic average diameter of clinker particles is 0.02 m and the amount of air chambers is 9.

0. Introduction

The cement industry is one of the energy intensive industries. China's cement industry is the second largest energy consumer and CO_2 emitter (after the iron and steel industry), accounting for 7% of total Chinese energy use and 15% total CO_2 emissions [1]. According to relevant researches, cement industry still has large researching potential on energy conservation despite several efforts have been made in recent two decades in China [2], Ethiopia [3], US [4], Nigeria [5] and EU [6]. Grate cooler is an important equipment in cement production and its main functions are quenching clinker and redistributing exhaust air. The grate cooler of the third generation is the most common one in cement plants. It is equipped with resistance grate and aeration beam and usually includes several air chambers. The cooling air flows through the moving clinker vertically as shown in Fig. 1. Energy consumption of fans accounts for 16% of total motors energy consumption of cement production [7]. And the performance of cooling air system affects the energy consumption of cooling fans and heat efficiency of grate cooler greatly.

There have been many grate cooler researches focusing on energy flowing analysis and heat recovery. Usually, there are two main directions on theoretical research of grate cooler. One side is the exergy or entropy analysis: Madllol et al. [8] reviewed the cement production process from the view of exergy balance and exergy efficiency; Karellas et al. [9] and Touil et al. [10] analyze the energy and exergy balance in grate cooler. Ahamed et al. [11]

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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	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)]
S_{gen}	entropy generation rate [W/K]
t	temperature [°C]
U	volume of clinker [m^3]
V	superficial velocity of cooling air [m/s]
W	power consumption of cooling fans [W]
x	particle heating depth [m]
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

analyzes the energy, exergy and recovery efficiencies of the grate cooler and improves them via optimizing its operating parameters. Liu et al. [12] analyzes the effects of clinker cooling on heat efficiency of cement production by building energy flowing balance model. The other side is proposing mathematical model of clinker cooling process. Caputo [13,14] proposes clinker cooling mathematical model from the view of unsteady condition and optimized the annual total investment. Feng [15] conducted the grate cooler mathematical model by using energy conservation principle. The theoretical foundation of mathematical model includes convective heat transfer principle [16,17] and porous media theory [18]. To our knowledge, there are no researches on cooling air distribution which is related to energy consumption of grate cooler directly. Therefore it has engineering significance to optimize the cooling air system so as to decrease the energy consumption of cement production.

A multi-objective optimization model of cooling air distributions of grate cooler in cement plant based on entropy generation minimization analysis is proposed in the paper. The modified entropy generation numbers caused by heat transfer and viscous dissipation are considered as objective functions, and are optimized by a genetic algorithm simultaneously. Sensitive analysis of average diameters of clinker particles and air chambers are carried out. The final optimal air distribution is selected based on minimum energy consumption of cooling fans. Furthermore, the optimal cooling air distribution is discussed by heat recovered and energy consumption of cooling fans.

1. Entropy generation model description and assumptions

1.1. Entropy generation analysis

All the natural process is irreversible as the second law of thermodynamics indicates. Therefore entropy generation analysis is the most fundamental approach for thermodynamic optimization. As a heat exchanger equipment, heat transfer process inside the grate cooler is irreversible obviously. Furthermore, cooling air crosses the moving clinker layer vertically which can approximate to cross-flow heat exchanger. Therefore, the irreversible loss in grate cooler can be divided into those caused by heat transfer and viscous dissipation. The description of entropy generation rate for two fluid (fluid 1 and 2) heat exchanger is given by [19]:

$$S_{gen} = (mC_p)_1 \ln\left(\frac{t_{1,out}}{t_{1,in}}\right) + (mC_p)_2 \ln\left(\frac{t_{2,out}}{t_{2,in}}\right) - (mR)_1 \ln\left(\frac{P_{1,out}}{P_{1,in}}\right) - (mR)_2 \ln\left(\frac{P_{2,out}}{P_{2,in}}\right) \quad (1)$$

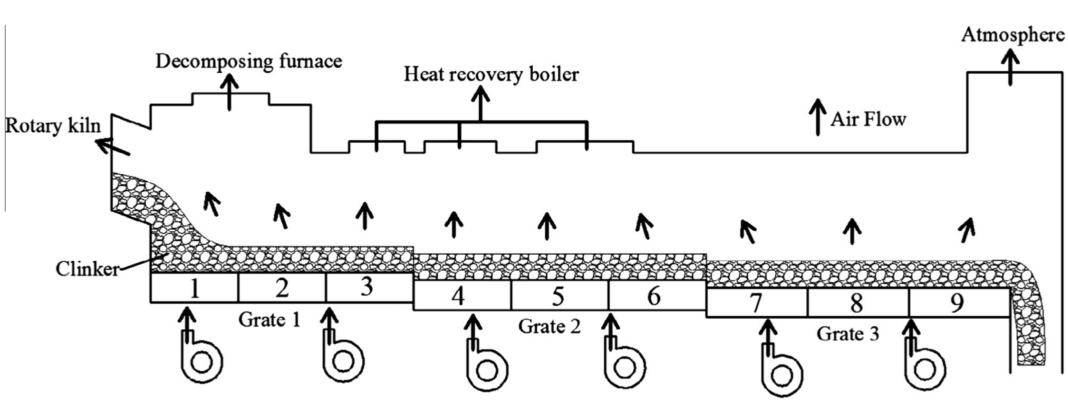

Fig. 1. Principle of grate cooler.