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Prediction, parametric analysis and bi-objective optimization of waste heat utilization in sinter cooling bed using evolutionary algorithm[☆]

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ABSTRACT

Based on our previous work, the *AEGs* (annual energy gains) could be obtained on energy and exergy analysis for a sinter cooling bed. In the present study, a method synthesizing both economic cost and energy benefit aspects of the sinter cooling bed is proposed. Firstly, the GP (genetic programming) is employed to derive accurate correlations between the *AEGs* and operational parameters. Then, the economic cost model is established to evaluate effects of operational and economic parameters on the *EAOC* (equivalent annual operational cost). Finally, bi-objective optimization of the sinter cooling bed is performed to achieve the optimal operational conditions from both waste heat utilization and economic cost aspects using NSGA-II (non-dominated sorting genetic algorithm-II). In order to maximize the *AEGs* and minimize the *EAOC*, the *EAOC* and the *AEGs* based on the first and second laws of thermodynamics are selected as two objective functions. A Pareto frontier obtained shows that an increase in the *AEGs* can increase the *EAOC* of the sinter cooling bed. Under the given operational conditions, the optimum solutions with their corresponding decision variables are obtained. After considering both two Pareto frontiers curves, a set of suggested operational parameters for the decision-makers is also obtained.

1. Introduction

In recent years, the iron and steel industry has been one of the most energy-intensive industries, which accounts for 4–5% of global energy consumption [1]. Iron and steel industry in China is a major one of the industries with high consumption of energy. The annual growth rate of crude steel production in China was averaged about 18.5% from 2000 to 2009 [2], and represented 44.3% of the global steel production in 2010 [3]. In 2013, China's production of crude steel has amounted to 717 million tones, which continued to remain first in rank [4]. Sintering plants which occupy about 18% of the total energy consumed in iron and steel industry, generally consist of two moving beds: the sintering bed and the sinter cooling bed. Waste heat of sinter cooling process is about 19–35% of the total sintering energy consumption [5].

The sinter cooling bed is mainly employed in sintering process and pelletizing process for cooling high temperature sinters and pellets. Several related investigations have been conducted regarding the sinter cooling bed over heat transfer and waste heat utilization aspects. Caputo et al. [6] established a heat transfer model and performed analysis of waste heat utilization of the sinter cooling bed and subsequently, Pelagagge et al. [7] proposed different heat recovery schemes, Pelagagge et al. [8] obtained optimization criteria of heat recovery and Caputo et al. [9] conducted transient modeling of waste heat utilization at different operational conditions. With the mixed orthogonal experimental method, Zhang et al. [10] and Tian et al. [11] investigated the influence of multi-layer feeding and designed parameters on waste heat utilization by optimizing parameters. Under the assumption of the LTE (local thermal equilibrium), Leong et al. [12] and Liu et al. [13] numerically examined the gas flow field and sinter temperature field for different distributions of sinter porosity which was highly dependent on the arrangement and orientation of sinter within the sinter cooling bed.

The studies mentioned above mainly focused on the waste heat utilization of the sinter cooling bed, and the economic aspect of sintering and sinter cooling process should also be taken into account. So, several related work based on cost optimization of the sintering and sinter cooling process have been carried out. Caputo and Pelagagge [14] established a mathematical model based on total cost minimization of the sinter cooling bed. The results

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Nomenclature

AC	annual cost, USD year^{-1}
AEG	annual energy gain, GJ year^{-1}
b	thickness of channel wall, m
c_F	Forchheimer coefficient
c_p	specific heat, J kg^{-1} K^{-1}
CRF	capital recovery factor
d_p	equivalent particle diameter of sinters, m
E_x	exergy, GJ h^{-1}
$EAOC$	updated equivalent annual operating cost, USD year^{-1}
$EAOC^0$	basic equivalent annual operating cost, USD year^{-1}
f	rail-wheel friction coefficient; objective function
F	mass flow rate, kg s^{-1}; vector of objective function
F_s	additional factor
FCI	fixed capital investment, USD
g	inequality constraint
h	height of channel wall, m; equality constraint
H	height of sinter cooling bed, m
i	lending rate
k	thermal conductivity, W m^{-1} K^{-1}
K	permeability, m^2; constant
L	length of sinter cooling bed, m
m	sector index; number
n	number
N	lifetime of the sinter cooling bed, years
P_e	price of electricity, USD kW^{-1} h^{-1}
Q	waste heat utilization quantity, GJ h^{-1}
t_{op}	operating time, h year^{-1}
T	temperature, °C
v	velocity of cooling air, m s^{-1}
V	moving speed of trolleys, m s^{-1}
W	width of trolleys, m
X	vector of design variables

Greek letters

α, β, γ	coefficient
ΔP	pressure drop, Pa
η	efficiency
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ϕ	porosity

Subscripts

1, 2, 3, 4	index of constants
b	bed; bulk
bl	blower
c	concrete
ch	channel
egy	based on the first law of thermodynamics
exy	based on the second law of thermodynamics
f	cooling air; foundation
i	index of inequality constraint
in	inlet
ins	insulation
j	index of equality constraint
m&l	maintenance and labor
max	maximum
min	minimum
p	powertrain
s	sinters
sp	specific
t	trolley

Superscripts

0	unit value

Abbreviations

GP	genetic programming
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
NSGA-II	non-dominated sorting genetic algorithm-II

showed when an optimized design is adopted, the expected savings could range 10 %–25 % of total cost. Nakano [15] developed a differential equation that described sintering cost from basic relationships between relevant operational variables/parameters and discussed the cost-minimum state and the direction for cost-minimum operation by applying the equation. Zhang et al. [16] optimized blending ratios according to ore prices and properties to reduce production cost and found that, the cost of sintering process could be further reduced only by ratio adjustment of present ores. Recently, economic evaluation has become prevalent in other related field such as biomass power production [17], thermoelectric power generation [18] and organic Rankine cycle [19]. However, investigations mentioned above focused only on economic factor and didn't take waste heat utilization into consideration.

In order to investigate the thermal behavior in sinter cooling process and effects of different operational parameters on waste heat utilization, energy and exergy analysis for waste heat cascade utilization in sinter cooling bed were conducted in our recent study, as reported by Liu et al. [20]. In the study, a two-dimensional unsteady mathematical model was established to describe three-dimensional steady transport process and waste heat utilization in the sinter cooling bed. The Brinkman–Forchheimer extended Darcy model and the LTNE (local thermal non-equilibrium) model were employed to describe flow and heat transfer in the sinter cooling bed. The waste heat grade and quantity were taken into comprehensive consideration in energy and exergy analysis. In waste heat utilization of sinter cooling process, blowers blow the cooling air to their passages, and then the cooling air flows through the grate into high temperature sinters, heat is moved away from high temperature sinters to cooling air, lastly the cooling air is collected by the hoods on top of sinter cooling bed to be recycled. According to the rules of cascade utilization of waste heat, the whole sinter cooling zone is divided into four sectors in Ref. [20]. According to Liu et al. [20], high-temperature waste heat is employed to generate steam or electricity. While the low grade waste heat is employed for direct thermal utilization, such as drying and preheating of sinter mixture, combustion-supporting for ignition, hot-air sintering and so on. However, in the study of [20], only waste heat utilization was investigated without considering economic factor of the sinter cooling bed. In order to have a comprehensive understanding of waste heat utilization in the sinter cooling bed, waste heat utilization (energy benefits analysis) and economic cost (economic analysis) of the sinter cooling process cannot be investigated separately.

According to authors' knowledge, few researches have been conducted on the combining of the energy benefits and economic cost of the sinter cooling process. Therefore, in the present work,