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Constructal design of a blast furnace iron-making process based on multi-objective optimization

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ABSTRACT

For the fixed total raw material cost and based on constructal theory and finite time thermodynamics, a BFIM (blast furnace iron-making) process is optimized by taking a complex function as optimization objective. The complex function is integrated with HM (hot metal) yield and useful energy of the BF (blast furnace). The optimal cost distribution of raw materials (namely "generalized optimal construct") is obtained. The effects of some parameters, such as oxygen enrichment, blast temperature and pulverized coal dosage, on the optimization results are analyzed. The results show that the HM yield, useful energy and complex function are, respectively, increased by 3.13%, 2.66% and 2.90% after generalized constructal optimization. The utilization efficiencies of the BFG (blast furnace gas) and slag are 41.3% and 57.1%, respectively, which means that the utilization potentials of the BFG and slag can be further exploited. Increasing pulverized coal dosage and decreasing the agglomerate ratio can increase the complex function. The performance the BFIM process can be improved by adjusting the oxygen enrichment, blast temperature, blast dosage, pressure ratio of the Brayton cycle's air compressor and relative pressure drop of the air compressor inlet to their optimal values, respectively, which are new findings of this paper.

1. Introduction

The BF (blast furnace) iron-making process plays an important role in the iron and steel production process. The energy consumption of the BFIM (blast furnace iron-making) process accounts for above 50% of the energy consumption in the iron and steel enterprises, and the cost, residual energy and heat produced by the BFIM process are huge [1–9]. Hence, how to decrease the cost and enhance the utilization efficiency of the residual energy and heat is an important issue to be studied.

Some researchers have studied the problem on how to enhance the utilization of the residual energy and heat produced by the BFIM process [10–16]. Qin et al. [10] proposed a way to recovery the sensible heat of BF slag granulated by generating combustible gas from printed circuit boards. Meng et al. [11] put forward a technical solution recycling sensible heat of the BF slag flushing water based on thermoelectric power generation, and established a physical and numerical model. Based on Ref. [11], Xiong et al. [12] performed numerical calculation for a two-stage thermoelectric energy recovering system driven by the waste heat of BF slag flushing water, and analyzed the effects of the main parameters on the performance of the thermoelectric power generation. Duan et al. [13] performed the thermodynamic analyses of a BF slag waste heat recovering system based on the water and coal gasification reaction, and the results showed that the exergy efficiency and thermal recycling efficiency were much higher than those of the traditional BF slag waste heat recovery system based on the physical recycling method. Zhang et al. [14] proposed an air Brayton cycle for recovering waste heat of BF slag, and analyzed its waste heat recovery performance. van der Stel et al. [15] discussed the trial of iron-making with the top gas recycling BF, and proved that the top gas recycling was feasible and could be scaled up to industrial size. Chen et al. [16] analyzed the feasibility of H_2 production from blast furnace gas (BFG), and proposed the key operation conditions.

Some researchers have studied the performances of the BF and the BFIM process [17–23]. Liu et al. [17] established an optimization

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Nomenclature

A	area
C_m	specific heat capacity, kJ/(m^3 K)
C_0	total raw material cost, yuan
D	dosage, kg
Q_{elc}	electric energy generation, kJ
k	weight coefficient, adiabatic index
L_S	sulfur load, kg/t-hm
m	mass, kg
P	pressure, MPa; power, W
p	price, yuan
Q	heat, kJ
Q_u	useful energy, kJ
q	mass flow rate, kg/h
R	slag basicity
R_g	gas constant, J/(kg K)
r_{agg}	agglomerate ratio
T	temperature, °C
t	time, h
V	volume, m^3
v	velocity, m/s
X_{bg}	bosh gas index, m/min
Y	yield, kg

Greek symbols

γ	specific heat ratio
η	distribution rate, utilization ratio, efficiency, utilization coefficient
τ	temperature ratio
π	pressure ratio
ρ	density, kg/m^3
ω	fraction
ψ	relative pressure drop
ζ	pressure loss coefficient

Subscripts

Al_2O_3	aluminum oxide
ac	air compressor
acs	isentropic compression process for air
cb	combustion chamber
gcs	isentropic compression process for gas
t	turbine
ts	isentropic working process for turbine
air	air
b	blast air
bfg	blast furnace gas
bg	burnt gas
C	carbon
coke	coke
coal	coal
cog	coke oven gas
elc	electricity
env	environment
Fe	iron
fw	flushing water
gas	gas
gc	gas compressor
H_2	hydrogen
HBSs	hot blast stoves
he	heat exchanger
hm	hot metal
i	inner
in	input; inlet
lump	lump ore
Mn	manganese
MgO	magnesium oxide
m	mechanical
max	maximum
mm	twice maximum
oo	twice optimal
opt	optimal
out	output, outlet
pellet	pellet ore
S	sulfur
Si	silicon
sinter	sinter ore
TRT	top gas pressure recovery turbine unit
Ti	titanium
user	user
w	working medium

model of a BF by taking the minimum carbon emission as objective, respectively, and analyzed the effects of the major operating parameters on the optimization results. Liu et al. [18] further established an optimization model of a BF by using nonlinear programming method and taking the exergy loss minimization as objective, and analyzed the effects of the main parameters on the optimization results. Helle et al. [19] established a nonlinear optimization model of an iron-making system including BFIM process, and the results showed that the top gas recycling with CO_2-stripped could dramatically reduce the emissions of the system. Mitra et al. [20] established a multi-objective optimization model of an iron-making system including the BFIM process, and four different heating methods for blast and recycled top gas were analyzed. Spirin et al. [21] developed an information-modeling system to optimize the charge materials in the blast-furnace smelting, and the system could help for the evaluation of technical-economic indices of the smelting operation. Mitra and Saxén [22] simulated the burden distribution and charging of a BF through small-scale experiments, and the simulation results showed that the coke-push could redistribute the burden. Zhang et al. [23] established an optimization model of a BFIM process by taking the minimum energy consumption as objective, and analyzed the effects of some main operating parameters on the optimization results. The results showed that increasing the coal ratio, blast temperature, and furnace top pressure as well as decreasing coke ratio could decrease the energy consumption of the BFIM process.

Some researchers have studied the performances of open Brayton cycles [14,24–30] based on FTT (finite time thermodynamics) [31–35]. Radcenco et al. [24] established a FTTM (finite time thermodynamic model) of an open simple Brayton cycle, and analyzed the effects of compressor inlet pressure drop on the performance of the cycle. Chen et al. [25] performed power optimization of an open regenerative Brayton cycle by establishing a FTTM. Wang et al. [26] established a FTTM of an open intercooled Brayton cycle with pressure drop irreversibility. Chen et al. [27] and Zhang et al. [28] established a FTTM of an open cycle gas turbine power plant with a refrigeration cycle for compressor inlet air cooling. Chen et al. [29] established a FTTM of an open combined