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Research Paper

Material and energy flows in rotary kiln-electric furnace smelting of ferronickel alloy with energy saving

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HIGHLIGHTS

- Establish the synergy relationship of material and energy in key RKEF processes.
- Develop an analysis model to study energy saving with internal cycling of energy.
- Analyze material and energy flow parameters and assess its associated synergy effect.
- A methodology to evaluate the synergy and design indices of RKEF processes.

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ABSTRACT

An energy saving strategy with two energy saving measures has been proposed for reducing energy loss in the rotary kiln-electric furnace (RKEF) for the smelting of ferronickel alloy. One of the measures is to recover the waste heat of exhaust gas from the rotary kiln for preheating and dehydrating the wet laterite ores in the rotary dryer. Another measure is to recycle the furnace gas from the electric furnace into the rotary kiln as fuel. Based on the mass conservation and energy conservation laws, an analysis model of material and energy flows has been developed to understand the potential energy saving with the internal cycling of material and energy in the RKEF process. The analysis model not only considers the energy efficiency but also assess the synergy degree of system. Furthermore, the model also predicts the ratio of raw materials and the energy flow distribution to investigate residual heat and energy and analyze the effects of nickel content on energy flow. Finally, the evaluation methodology of synergy and the technic indices are also presented. Through the investigation of the synergy effect, the performance of the RKEF process can be evaluated and quantified for performance optimization in future.

1. Introduction

With the increasing demand for the ferronickel alloy, the technology of ferronickel smelting with high Ni grade has attracted reasonable attention in the past decades. Currently, the current methodology to alter the original mineralogy of laterite ores is to apply some chemical processes (e.g. pyrometallurgical or hydrometallurgical) that include pressure acid leaching [1–3], Caron process [4,5], atmospheric leaching [6,7], and rotary kiln-electric furnace (RKEF) process [8,9]. Among these methods, the rotary kiln-electric furnace (RKEF) process has the advantages of yielding high nickel/iron grade from crude ferronickel products, less harmful elements, raw materials with strong adaptability, high production efficiency and mature process. Nonetheless, the RKEF process also suffers from the high energy consumption and a large amount of by-product (e.g. slag and off-gas). Reducing the energy consumption while achieving the same product quality has become a pressing need for the current ferronickel smelting industry. In theory, considering the overall energy consumption, the supply energy can be categorized into three main components. The main portion of the supply energy is utilized to drive the ferronickel smelting process which is normally referred as available energy. The other portion is the unavoidable and irreversible energy loss due to the limitations of existing smelting technology. For example, the electricity loss and heat dissipation loss to the cooling water and walls are unavoidable in the RKEF process. The rest of supply energy is the avoidable energy loss which is discharged with the waste gas or heat throughout the whole process. In order to improve the energy efficiency, minimizing the avoidable energy loss or recover such waste energy could be a promising approach.

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Nomenclature

a	air factor
C'	continuation degree of process
c_p	specific heat (kJ/(kg °C))
DR	mismatching degree
E	energy (GJ/h)
e	order parameter
EC	efficacy coefficient
G	the group
g_{d}^{-}	dissipation quantity of energy flow (GJ/h)
g_{k}^{-}	output flow of energy (GJ/h)
K	number of output flow of energy
k	variable
L	number of the order parameter index
l	variable
L_0	theoretical air requirement (kg)
L_{n}	actual amount of air supply (kg)
M	mass flows (t/h)
N	number of the order parameter
OD	order degree
q	energy consumption per unit (kJ/kg)
R	recovery ratio
S^{en}	entropy (kJ/K)
SA	coordination ability
SD	synergy degree
T	temperature (K)
t	time (s)
w	weighting
V	volume (m^3)

Greek letters

ρ	density (kg/m^3)
η_{e}	energy efficiency (%)
η_{ep}	discharge rate of energy flow (%)
η_{sy}	recycling rate of residual heat and energy
η_{bp}	recycling rate of by-product energy
η_{ws}	recycling rate of waste solid
η_{w}	recirculation rate of waste
γ	fill rate
ψ	void fraction
θ	normalized data

Subscripts

A	available
a	anthracite
Avo	avoidable
bc	bituminous coal (bitumite)
bcc	bituminous coal combustion
ca	combustion air
D	rotary dryer
d	dust
dl	dust heat loss
dr	dissociation reaction
E	electric furnace
e	evaporation
el	electric loss
F	fuel
Fa	ferronickel alloy
Fg	furnace gas
fg	flue gas
Fgc	furnace gas combustion
Fgl	furnace gas heat loss
fge	flue gas entered into electric furnace
fgl	flue gas heat loss
fm	free moisture
fml	free moisture heat loss
hl	heat loss
ht	haulage time
in	input flow (s)/inlet
J	Joule heat
L	limestone
lhm	latent heat of melting
m	number of groups
mt	maintenance time
n	number of order parameter components
oc	laterite ores calcined
ocl	laterite ores calcined heat loss
out	output flow (s)/outlet
ppt	processing-time
R	rotary kiln
rr	reduction reaction
S	sensible heat
sl	slag
so	semi-dry laterite ores
sol	laterite ores heat loss
sr	slagging reaction
Un	unavailable
Unavo	unavoidable
w	waste
wc	water-cooling
whl	waste heat loss
wo	wet laterite ores
ws	waste solid
wt	waiting time

Superscripts

ca	combustion air
Fg	furnace gas
fg	flue gas
ll	lower limit
ul	upper limit

Several promising energy saving strategies have been proposed for other smelting fields, including ironmaking, steel making and limekilns industries. Lee and Sohn [10] adopted the strategy of recycling the exhaust gas and the slag for preheating the scrap and granulation. Besides, using the wasted heat of the exhaust gas, the CO_2 gas is also recycled to produce CO gases as fuel or reducing agent. Belt [11] used the furnace benchmark tests to measure and analyze the melt loss and melt rate, and the energy distribution or heat losses of the system. Nevertheless, a comprehensive energy saving strategy for the RKEF systems remains outstanding in the literature. In order to improve the energy efficiency of the RKEF, a complete mathematical model to describe the underlying material and energy flows within the system is very crucial. Previously, mathematical models for other applications have been proposed. Sohn and Oliver-Martinez [12] presented a mathematical model based on the material and energy flows of ironmaking process to analyze the chemical reaction heat and energy requirement of the system. Sagastume [13] adopted the energy and exergy analysis methods to determine the mass, energy and exergy balance and identify the dominant factors affecting the thermal efficiency of lime kiln. Several researchers adopted the synergetic theory to analyze the cooperativity between material and energy flows,