Energy 67 (2014) 370–380

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy and exergy analysis for waste heat cascade utilization in sinter cooling bed

Yan Liu, Jian Yang, Jin Wang, Zhi-long Cheng, Qiu-wang Wang*

Key Laboratory of Thermal-Fluid Science and Engineering, Ministry of Education, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

ARTICLE INFO

Article history:
Received 25 August 2013
Received in revised form
27 November 2013
Accepted 30 November 2013
Available online 11 January 2014

Keywords:
Sinter cooling bed
Porous media
Local thermal non-equilibrium
Cascade utilization
Energy and exergy analysis

ABSTRACT

In the present paper, a numerical study is presented to investigate the cascade utilization of waste heat in sinter cooling bed. With the aid of CFD (computational fluid dynamics), a two-dimensional unsteady mathematical model, which would significantly reduce the computational time, is established to describe three-dimensional steady flow and heat transfer in sinter cooling bed. The Brinkman–Forchheimer extended Darcy model and the LTNE (local thermal non-equilibrium) model are employed to describe flow and heat transfer in sinter cooling bed. And the reliability of this mathematical model is validated with both related simulation and experimental work. And then, numerical simulations are conducted to examine the effects of different operating parameters on the cooling air temperature and waste heat utilization quantity. Furthermore, the waste heat grade and quantity are taken into comprehensive consideration in energy and exergy analysis. The results indicate that, both the quantity and quality of waste heat utilization would be improved by increasing sinter cooling bed height, trolly's moving speed and sinter heat flux. Meanwhile, it is also found that, with different assignments of cooling air flow rate, the quantity and quality of waste heat in sinter cooling bed would not be improved at the same time.

1. Introduction

With the thread of increasingly serious global climate change, more and more attention is paid on energy conservation in iron steel industry all over the world. Relevant reports indicate that the iron and steel industry in China is a major one of the industries with high consumption of energy, accounting for about 15.2% of the national total energy in 2006 [1]. The iron and steel industry in China has made much progress in reducing use of energy, starting from energy conservation on individual equipment energy saving in 1980s to systematic energy saving via process optimization in 1990s [2]. Sintering plant which generally consists of two moving beds: the sintering bed and the sinter cooling bed occupy about 18% of the total energy consumed in iron and steel industry. Waste heat of sinter cooling process is about 19–35% of the total sintering energy consumption. Meanwhile, irrational waste heat utilization is not only a waste of heat resources but also a threat to the environment [3].

In engineering applications, temperature of sinter should be cooled below 150 °C at the tail of cooler considering the sinter quality and the convenience of transportation. As reported by Dong et al. [4], the temperature of cooling air becomes lower and lower in the direction of sinter cooling bed's moving. Generally, the temperature of cooling air is within the range 500 °C–150 °C. According to the rules of grade recovery and cascade utilization, the whole cooling zone is divided into several sectors. The waste heat is recovered in grades according to the quality firstly, and then different quantities of waste heat recovered are utilized in cascades. Generally, high-temperature segment waste heat is used for generating steam or electricity. While the low grade waste heat is used for direct thermal utilization, such as drying and preheating of sinter mixture, combustion-supporting for ignition, hot-air sintering and so on. Therefore, it is necessary to obtain grades and quantities of waste heat utilization in each sector for the subsequent reutilization.

It is difficult to understand the flow and heat transfer in sinter cooling bed comprehensively due to its complexity of geometry and instability of operations. In order to have a better understanding of sinter cooling process in sinter cooling bed, several related numerical simulation studies have been prevailed and some useful conclusions have been drawn. Caputo et al. [5] made a first contribution towards the optimization of heat recovery from moving beds by adopting a one-dimensional unsteady mathematical model. Gas–solid bed behavior of different operating

---

* Corresponding author. Tel./fax: +86 29 82665539.
E-mail address: wangqw@mail.xjtu.edu.cn (Q.-w. Wang).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.11.086

Nomenclature

A	cross sectional area, m^2
Bi	Biot number
c	specific heat, J kg^{-1} K^{-1}
c_F	Forchheimer coefficient
$c_{\varepsilon 1}$, $c_{\varepsilon 2}$	model constants in turbulent kinetic energy equation
c_μ	model constant in turbulent viscosity correlation
d_p	equivalent particle diameter, m
E_x	exergy, GJ h^{-1}
F	mass flow rate, kg s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_e	effective heat transfer coefficient, W m^{-2} K^{-1}
h_v	volumetric heat transfer coefficient, W m^{-3} K^{-1}
K	permeability, m^2
k	turbulent kinetic energy, m^2 s^{-2}
$\langle k \rangle^i$	intrinsic average for k, m^2 s^{-2}
k_f	thermal conductivity of cooling air, W m^{-1} K^{-1}
k_s	thermal conductivity of sinter, W m^{-1} K^{-1}
L_h	height of sinter cooling bed, m
L_l	location away from the sinter inlet, m
L_w	trolly width, m
Nu	Nusselt number
p	pressure, Pa
$\overline{p}$	ensemble average for pressure, Pa
$\langle p \rangle^i$	intrinsic average for pressure, Pa
Pr	Prandtl number
Q	waste heat utilization quantity, GJ h^{-1}
Re	Reynolds number
T	temperature, °C
$\overline{T}$	ensemble average for temperature, °C
$\langle T \rangle^i$	intrinsic average for temperature, °C
T_0	atmosphere temperature, °C
$\overline{\mathbf{u}}_D$	Darcy velocity vector, m s^{-1}
V_H	heat capacity ratio
$V_{f,\ in}$	cooling air inlet velocity, m s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
x, y, z	coordinate directions, m

Greek letters

β	thermal capacity ratio
ε	turbulence dissipation rate, m^2 s^{-3}
$\langle \varepsilon \rangle^i$	intrinsic average for ε, m^2 s^{-3}
μ_t	turbulent viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ_k	Prandtl number in turbulent kinetic energy equation
σ_ε	Prandtl number in turbulence dissipation rate equation
τ	cooling time, s
ϕ	porosity
ϕ_s	shape factor
Ω	energy level

Subscripts

b	green balls
f	cooling air
g	preheating gas
in	inlet
out	outlet
s	sinter

parameters and design choice were presented. Wen et al. [3] established a one-dimensional unsteady mathematical model to clarify the high temperature sinter cooling air flow rate, waste hot air flow rate and the temperature variation with time. On the basis of parametric studies, some reasonable proposals were put forward for optimizing operations of the sinter cooler. Jang et al. [6] employed both CFD (computational fluid dynamics) and experimental method to investigate the thermal and flow field in a three-dimensional sinter bed which was simplified as a 4-row packed bed of spheres during a cooling process. The conjugated convective heat transfer in the flow field and heat conduction in the spheres was considered. Leong et al. [7] numerically investigated 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. In the study, assumption of the LTE (local thermal equilibrium) was made which means temperatures of sinter and the cooling air are the same at the same point. However, it is far away from actual condition and there is room to improve.

Waste heat utilization in sinter cooling process on the basis of first law of thermodynamics has been studied and some meaningful conclusions have been drawn. Pelagagge et al. [8,9] and Caputo et al. [10] developed a dynamic simulation approach and optimized waste heat recovery at different inlet air flow rate and temperature, as well as different sinter thermal flow. In a subsequent study, an analysis of transients due to start-up phase and operating condition variations were investigated. Zhang et al. [11] investigated the influence of multi-layer feeding on waste heat utilization by optimizing parameters with the mixed orthogonal experimental method. Most of the above research was carried on directed towards waste heat utilization in sinter cooling bed based on the first law of thermodynamics. Waste heat utilization in process industries have been investigated based on engineering practice. Ahamed et al. [12] examined how the operating parameters of the grate clinker cooling system and heat recovery from the cooling air, influence the first and second law efficiencies. Karellas et al. [13] energetically and exergetically studied two different waste heat recovery methods: a water-steam Rankine cycle, and an Organic Rankine Cycle. Mert et al. [14] performed the exergoeconomic analysis of the cogeneration plant with a 39.5 MW electricity and 80 ton/h steam production capacity in iron and steel factory. Refer to these investigations, it is pressing to examine the sinter cooling process not only from the perspective of quantity of waste heat utilization but also quality.

In order to have a comprehensive understanding of the sinter cooling process in a sinter cooler, the thermal performance and non-uniform distribution of sinter temperature field in a sinter cooling bed were also numerically investigated in our recent study as reported by Liu et al. [15]. In this study, the effects of inlet velocity, layer height, porosity and sinter layer distribution on the pressure, velocity and temperature fields in the sinter cooling bed were carefully analyzed, and several reasonable recommendations of corresponding operational parameters were proposed. However, in this study [15], the LTE (local thermal equilibrium) model was used, which would not give a reasonable description of heat transfer between cooling air and sinters comprehensively. Furthermore, both the quantity and quality of the waste heat in the sinter cooling bed were also not analyzed. In order to have a further understanding of the utilization of waste heat in the sinter cooling bed, more suitable heat transfer model should be constructed and more informative energy analysis should also be performed. According to authors' knowledge, few researches have been devoted