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Cost Benefits Analysis for Waste Heat Utilization in Sinter Cooling Bed

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Based on numerical simulation work in sinter cooling bed of our previous work, *AEG* (annual energy gain) is obtained on energy and exergy analysis under *WHCU* (waste heat cascade utilization). In the present paper, a method that integrates economics and energy analysis of a sinter cooling bed is proposed. Firstly, the symbolic regression is employed to find an accurate correlation between operational parameters and *AEG*. In order to improve the performance of GPLAB (genetic programming toolbox) of MATLAB environment, the symbolic regression is modified by adding new function modules into GPLAB. Then, the cost model is established to evaluate effects of operational parameters on *EAOC* (equivalent annual operational cost). Finally, the *CBR* (cost benefits ratio) is calculated to assess the comprehensive performance of the sinter cooling bed. Furthermore, for the purpose of optimising *CBR*, the method of Genetic Algorithm (GA) is adopted. The studied cases show that, it is an effective way to obtain optimal sets of operational parameters in a sinter cooling bed within the range of operating conditions. The optimisation results show that, the *CBR* based on the first law and second law of thermodynamics could be reduced by 18.4 % and 29.8 % when the optimal sets of parameters are employed.

1. Introduction

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 (Guo and Fu, 2010). According to Caputo et al. (1996), the sinter cooling bed is widely employed in sintering process and pelletizing process for cooling high temperature sinters and pellets. A sinter cooling bed of Anshan Steel including trollys and hoods could be seen in Figure 1.

Several related studies have been prevailed on heat transfer and *WHU* (waste heat utilization) in the sinter cooling bed. Zhang et al. (2013) investigated the influence of multi-layer feeding on *WHU* by optimising parameters with the mixed orthogonal experimental method. Liu et al. (2013a) 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. Economic analyses of process industry have also been studied and some meaningful conclusions have been drawn. Caputo and Pelagagge (2001) established a mathematical model based on total cost minimization of the sinter cooling bed. The results showed when an optimised design is adopted, the expected savings could range 10 % to 25 % of total cost. Ahamed et al. (2012) focused on improvement of the energy, exergy and recovery efficiencies of a grate cooling system through the optimisation of its operational parameters such as masses of cooling air and clinker, cooling air temperature, and grate speed. Nakano (2011) developed a differential equation that described sintering cost from basic relationships between relevant operational variables/parameters and to discuss the cost-minimum state and the direction for cost-minimum operation by applying the equation.

In order to study effects of different operating parameters on *WHCU* in the sinter cooling bed, we numerically examined *WHCU* based on the first and second law of thermodynamics (Liu et al., 2013b). In the study, a two-dimensional unsteady mathematical model was established to describe three-dimensional steady transport process and *WHU* in a sinter cooling bed. The Brinkman-Forchheimer extended Darcy

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model and the LTNE (local thermal non-equilibrium) model were employed to describe flow and heat transfer in the sinter cooling

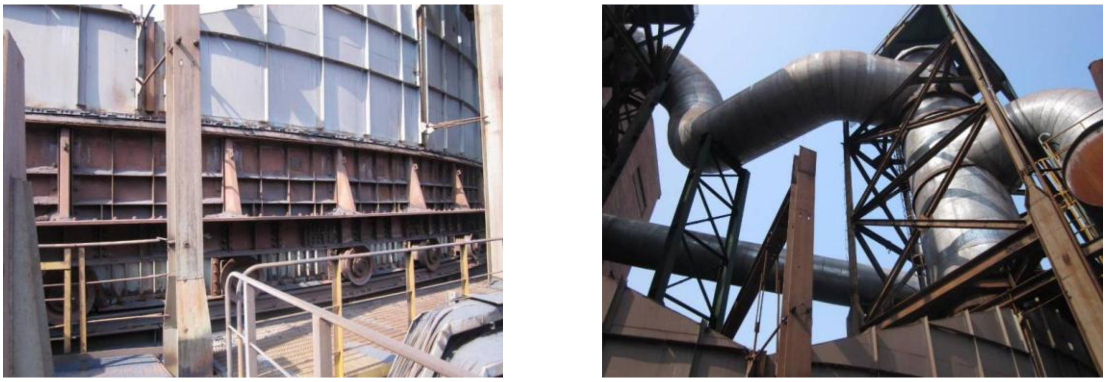

Figure 1: A sinter cooling bed of Anshan Steel (a) Trolly, (b) Hoods

bed. Based on above discussion, cost (economics analysis) and benefits (energy analysis) of the process industry have been studied independently. According to authors' knowledge, few researches have been conducted on the combining of the cost and benefits of the sinter cooling process. Therefore, in the present work, following the study of Liu et al. (2013b), a method that integrates economics and energy analysis of a sinter cooling bed is proposed. Firstly, the symbolic regression is employed to find an accurate correlation between operational parameters and *AEG*. Then, the cost model is established to evaluate effects of operational parameters on *EAOC* (equivalent annual operational cost). Finally, the *CBR* (cost benefits ratio) is calculated to assess the comprehensive performance in the sinter cooling bed. Furthermore, for the purpose of optimising *CBR*, the method of Genetic Algorithm (GA) is also adopted.

2. Construction of the cost benefits model

2.1 Energy model of the sinter cooling bed

The sinter cooling process has been examined in our previous work (Liu et al., 2013b). Temperature of cooling air, quantity and quality of waste heat have been obtained. *AEG* in each sector of the sinter cooling bed could be expressed as follows:

$$AEG_{\mathrm{egy}}^{\mathrm{Sector}\,m} = \sum Q_{\mathrm{f}}^{\mathrm{Sector}\,m} \cdot t_{\mathrm{op}} \tag{1}$$

$$AEG_{\mathrm{exy}}^{\mathrm{Sector}\,m} = \sum E_{\mathrm{x}}^{\mathrm{Sector}\,m} \cdot t_{\mathrm{op}} \tag{2}$$

where $Q_{\mathrm{f}}^{\mathrm{Sector}\,m}$ is quantity of waste heat per unit time of sector *m*; $AEG_{\mathrm{egy}}^{\mathrm{Sector}\,m}$ is *AEG* based on the first law of thermodynamics in sector *m*; $E_{\mathrm{x}}^{\mathrm{Sector}\,m}$ is quality of waste heat per unit time of sector *m*; $AEG_{\mathrm{exy}}^{\mathrm{Sector}\,m}$ is *AEG* based on the second law of thermodynamics in sector *m*. t_{op} is operational time of sinter cooling bed per year. *AEG* of the sinter cooling bed could be expressed as follows:

$$AEG_{\mathrm{egy}} = \sum_{m=1}^{4} AEG_{\mathrm{egy}}^{\mathrm{Sector}\,m} \tag{3}$$

$$AEG_{\mathrm{exy}} = \sum_{m=1}^{4} AEG_{\mathrm{exy}}^{\mathrm{Sector}\,m} \tag{4}$$

where AEG_{egy} is *AEG* based on the first law of thermodynamics; AEG_{exy} is *AEG* based on the second law of thermodynamics.

2.2 Cost model of the sinter cooling bed

A typical sinter cooling process including top view and cross-sectional view could be seen in Figure 2. Construction of the Cost model is mainly based on Figure 2(b). According to Fudholi et al. (2013), *EAOC* (equivalent annual operating cost) of the sinter cooling bed could be determined by *FCI* (fixed capital investment) and *AC* (annual cost) which could be expressed as follows:

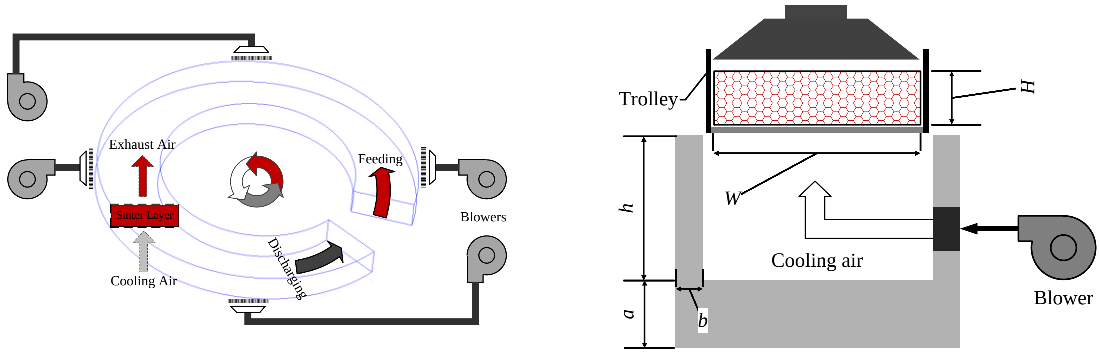

Figure 2: A typical sinter cooling process (a) Top view, (b) Cross-sectional view

$$EAOC = CRF \cdot FCI + AC \tag{5}$$

where *CRF* is capital recovery factor. According to Turton et al. (2009), the definition of the *CRF* could be expressed as follows:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

where *i* is lending rates and *N* is lifetime of the sinter cooling bed. According to different application, the sinter cooling bed could be divided into several parts containing trollys, moving bed, blowers, hoods, feeding and discharging devices (Caputo and Pelagagge, 2001). Based on the division, *FCI* could be expressed as follows:

$$FCI = FCI_{\mathrm{b}} + FCI_{\mathrm{bl}} + FCI_{\mathrm{t}} + FCI_{\mathrm{h}} + FCI_{\mathrm{f\,\&\,d}} \tag{7}$$

where FCI_b is *FCI* of sinter cooling bed; FCI_{bl} is *FCI* of blowers; FCI_t is *FCI* of trollys; FCI_h is *FCI* of hoods; $FCI_{f\&d}$ is *FCI* of feeding and discharging devices. *AC* could be expressed as follows (Caputo and Pelagagge, 2001):

$$AC = AC_{\mathrm{m\&l}} + AC_{\mathrm{bl}} + AC_{\mathrm{t}} + AC_{\mathrm{f\,\&\,d}} \tag{8}$$

where $AC_{m\&l}$ is *AC* of maintenance and labor; AC_{bl} is *AC* of blowers; AC_t is *AC* of trollys; $AC_{f\&d}$ is *AC* of feeding and discharging devices.

2.3 Cost benefits model of the sinter cooling bed

Based on the construction of energy model and cost model of the sinter cooling bed, we can obtain *AEG* and *EAOC* independently. For the purpose of comprehensive consideration of energy and economics aspect, the conception of *CBR* (cost benefits ratio) is proposed in the sinter cooling bed. *CBR* based on the first law and second law of thermodynamic could be expressed as follows:

$$CBR_{\mathrm{egy}} = \frac{EAOC}{AEG_{\mathrm{egy}}} \tag{9}$$

$$CBR_{\mathrm{exy}} = \frac{EAOC}{AEG_{\mathrm{exy}}} \tag{10}$$

where the unit of *CBR* is $/GJ.

3. Results and Discussion

3.1 *WHU* of the sinter cooling bed

Based on the principle of *WHCU*, the sinter cooling bed is divided into power recovery zone and heat recovery zone. Waste heat from power recovery zone could be used to generate electricity and waste heat from heat recovery zone could be adopted to preheat the sintering feed. In the present work, we mainly concern about

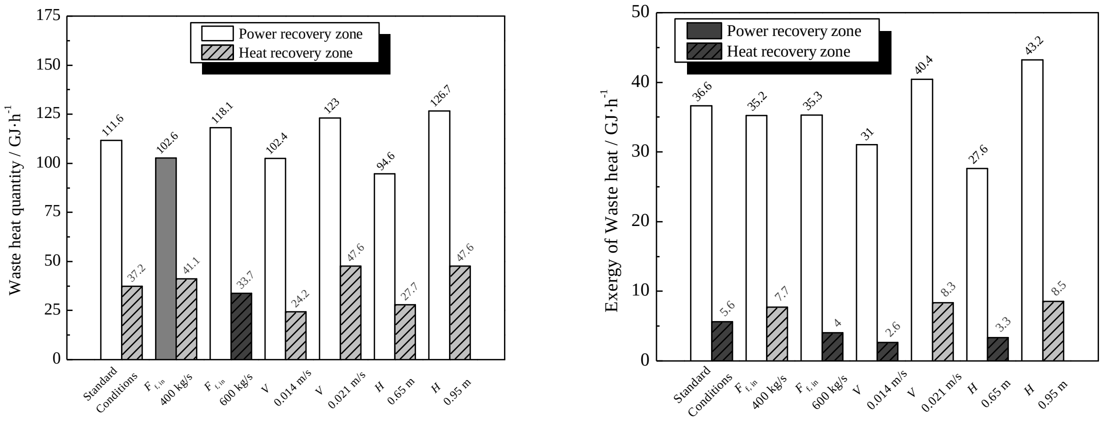

Figure 3: WHU of the sinter cooling bed (a) Based on the first law of thermodynamics, (b) Based on the second law of thermodynamics

WHU in power recovery zone. Figure 3 illustrates *WHU* of the sinter cooling bed based on the first and second law of thermodynamics. As shown in Figure 3(a), *WHU* based on the first law of thermodynamics in power recovery zone increases with $F_{f,\,in}$, V and H. We can see from Figure 3(b) that *WHU* based on the second law of thermodynamics in power recovery zone increases with V and H. However, both increase and decrease of $F_{f,\,in}$ lead to decrease of *WHU* based on the second law of thermodynamics. In short, influence of mass flow rate of cooling air should be examined further. For other operational parameters, increase of V and H could be adopted to increase *WHU*.

For the purpose of the optimising of *CBR*, the correlation between operational parameters and *AEG* should be obtained. In present work, The symbolic regression method based on MATLAB environment is employed to find an accurate correlation between operational parameters and *AEG*. However, when the undetermined function contains constant term, symbolic regression results usually have complicated structure and it is difficult to use them for practical applications adopting the original genetic programming toolbox. In order to improve the performance of genetic programming toolbox GPLAB of MATLAB environment, four new function modules were added into GPLAB by Xu et al. (2012), including structure simplification module, constants optimisation module, expansion rate reduction module with “self-swap” genetic operator, small term search intensity enhancement module with “intro-new” genetic operator. It is proved that, the correlations based on the modified symbolic regression have higher predictive accuracy and are less sensitive to the disturbance variation of the arguments (Xu et al., 2012). In order to expand the sample capacity of experimental data, a orthogonal table is designed and more sample are added. Correlation obtained between *AEG* and operational parameters based on the modified genetic programming toolbox is as follows:

$$AEG_{\mathrm{egy}} = 8.44 \cdot t_{\mathrm{op}} \cdot H \cdot F_{\mathrm{f,\,in}}{}^{7.1V} \tag{11}$$

$$AEG_{\mathrm{exy}} = t_{\mathrm{op}} \cdot (3700 \cdot V \cdot H - 1.29 \cdot F_{\mathrm{f,\,in}} \cdot V) \tag{12}$$

The average deviation rate and the maximum deviation rate of Eq(11) are 1.04 % and 4.15 %. The average deviation rate and the maximum deviation rate of Eq(12) are 1.69 % and 5.92 %. The small deviations indicate that Eq(11) and Eq(12) have high precision for the description of *AEG*.

3.2 Cost of the sinter cooling bed

We investigate the effect of operational parameters and economic parameters on the cost of the sinter cooling bed. It can be seen from Figure 4(a), (b) and (c) that *EAOC* increases with the three operational parameters under the same bed length. For a certain operational condition, there is an optimal bed length for the minimum of *EAOC*. For very short beds the *EAOC* could be very large, which shouldn’t be adopted in industrial production. When the bed length is shorter than the optimal one, *EAOC* decreases as the bed length increases. When the bed length is greater than the optimal one, *EAOC* increases with the bed length. Figure 4(d) illustrates that *EAOC* decreases with N (lifetime of the sinter cooling bed). According to common sense of economics, i (lending rates) and N are corresponding with each other. Generally, a larger N corresponding to a small i. In this perspective, continuous use of sinter cooling bed should be adopted. In other words, planning

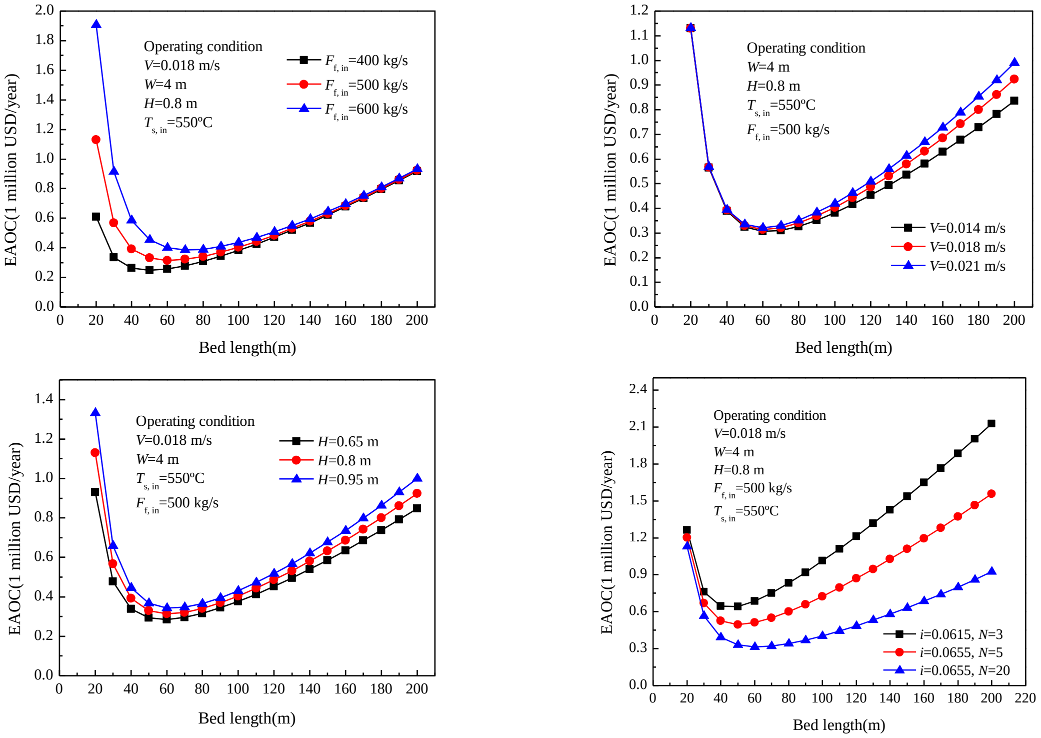

Figure 4: Cost of the sinter cooling bed (a) Effects of $F_{f,in}$, (b) Effects of V, (c) Effects of H, (d) Effects of i and N

and program demonstration are indeed important for reducing *EAOC*. Figure 4 illustrates that economic parameters have larger effects than operational parameters on the cost of sinter cooling bed.

3.3 Parameter optimisation based on *CBR*

Before parameter optimisation, effects of operational parameters on *CBR* are investigated. *CBR* based on the first law and the second law of thermodynamics could be seen in Figure 5. From Figure 5 we can know that decrease of $F_{f,\ in}$, increase of V and H could be adopted to reduce *CBR*.

In order to assess the comprehensive performance of *WHU* and economics in the sinter cooling bed, We employ the method of Genetic Algorithm (GA) based on MATLAB environment to optimise *CBR*. The objective function is *CBR* since we pursuit the minimum *CBR*. In the optimisation process, $F_{f,\ in}$, V and H range from 400 kg/s, 0.014 m/s and 0.65 m to 600 kg/s, 0.021 m/s and 0.95 m. According to Caputo et al. (1996), under the standard conditions, $F_{f,\ in}$, V and H are set to 500 kg/s, 0.018 m/s and 0.8 m. The optimisation results show that based on the first law of thermodynamics, the CBR_{egy} could be reduced to 0.323 \$/GJ when the parameters set of 412.9 kg/s, 0.021 m/s and 0.95 m is adopted for $F_{f,\ in}$, V and H, while CBR_{egy} under the standard conditions is 0.396 \$/GJ. The CBR_{egy} could be reduced by 18.4 % when the optimal set of parameters is employed. Based on the second law of thermodynamics, the CBR_{exy} could be reduced to 1.006 \$/GJ when the parameters are set to be 400 kg/s, 0.021 m/s and 0.95 m for $F_{f,\ in}$, V and H, while CBR_{exy} under the standard conditions is 1.434 \$/GJ. The CBR_{exy} could be reduced by 29.8 % when the optimal set of parameters is employed.

4. Conclusions

In the present paper, energy model and cost model of the sinter cooling bed are constructed independently, a method that integrates energy and economics analysis of the sinter cooling bed is put forward. Based on carefully analyses of *CBR*, the optimal operational parameters of the sinter cooling bed are obtained. The major findings are as follows:

1. Based on previous parametric study of *WHCU* of the sinter cooling bed (Liu et al., 2013b), we obtain correlations between *AEG* and operational parameters based on the modified GPLAB method. The correlations have simple structure and high predictive accuracy which would meet the requirements of engineering applications.

2. We examine effects of operational parameters and economics parameters on *EAOC* of the sinter cooling bed. For operational parameters aspect, the results shows that there are optimal bed length for different

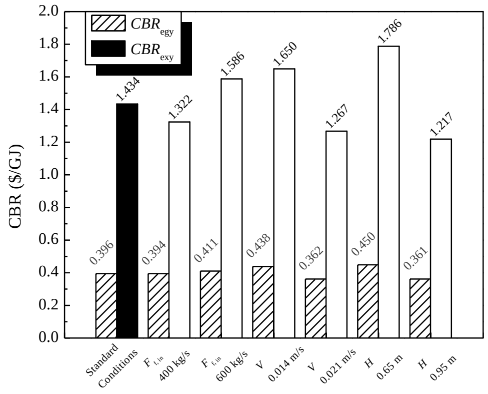

Figure 5: CBR of the sinter cooling bed

operational conditions and *EAOC* increases with the three operational parameters under the same bed length. For economics parameters aspect, planning and program demonstration are indeed important for reducing *EAOC*.

3. We employ the method of Genetic Algorithm (GA) to optimise *CBR*, which is proposed to assess the comprehensive performance of the sinter cooling bed. The results shows that it is an effective way to obtain optimal sets of operational parameters in a sinter cooling bed within the range of operational conditions. It is also shown that, the CBR_{egy} and CBR_{exy} could be reduced by 18.4 % and 29.8 % when an optimising sets of parameters are adopted.

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