ECONOMIC DESIGN CRITERIA FOR COOLING SOLID BEDS

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Abstract

Moving beds are widely employed in cooling particulate solids for process requirements. In this work a moving cooling bed design optimization approach is developed based on total cost minimization, considering either capital investment (bed structure, trolleys and fans) and operating expenses (for blowers and trolleys motion). Resorting to a previously developed heat exchange simulation model, to an optimization algorithm and to properly developed cost functions the optimal set of design variables, namely width, length, thickness, advancement speed and cooling air flow rate, are chosen on the basis of the given set of input data, including solid inlet flow rate, temperature and physical characteristics, in order to respect the required solid exit temperature and other constraints at the minimum total cost. After outlining the adopted solution method some optimized results are shown to highlight the capabilities of the proposed approach. A sinter cooling bed of ILVA steel works in Italy is assumed as reference case study.

Keywords: Moving bed cooler, heat recovery, optimization.

1. INTRODUCTION

Several process industries adopt moving beds for cooling particulate solids. Typical applications are in the cement and iron industry. A cooling bed is usually composed by grate panels or by a train of grate bottomed trolleys conveying the solids and moving along a linear or circular path, while a stream of ambient air is blown underneath the bed. Often, due to the relevant amount of waste heat involved, hoods are employed to perform heat recovery enabling also collection of the particles-laden air stream for dedusting.

In previous works (Caputo, A.C. et al., 1996, 1997a, 1997b, 1999, 2000) the problem of optimizing a hoods-based *heat recovery system* was analyzed considering existing beds working under defined operating parameters as happens in retrofit applications. In these cases, however, the obtained solution is not representative of a global optimum as many of the influencing design parameters are fixed input data instead of being decision variables. In this work, instead, the optimal design of the *cooling bed* is analyzed as a total cost minimization problem, considering either capital investment (bed structure, trolleys and fans) and operating expenses (for blowers and trolleys drive).

In the paper, after a definition of proper cost functions, the previously developed heat exchange simulation model is employed in conjunction with a minimization algorithm to define the optimal bed dimensions and operating parameters. In order to characterize the operating scenario specific reference is made to an iron ore sintering plant cooling bed at the ILVA steel works in Taranto, Italy. Results are presented by comparison with the actual bed and by analyzing the effects of operating and economic parameters on design arrangements.

2. PROBLEM STATEMENT

The typical structure of a cooling bed, as utilized in the ironmaking industry, is shown in figure 1. A series of bottom grate trolleys moves along a circular track above a concrete channell where cooling air is blown which eventually permeates through the bed bottom and the granular material carrying out solids cooling. Trolleys discharge is performed by opening their bottom grate enabling materials to fall onto a hopper equipped with a vibrating extractor. Trolleys motion is accomplished through DC electric motor driven chains. Five major parameters characterize cooling bed design and operation: width (W), length (L), thickness (H), advancement speed (V) and cooling air flow rate (F_{AI}). The design procedure requires either the assumption of a set of input data, including solid inlet flow rate (F_{SI}), temperature (T_{SI}) and physical characteristics (pellets size, specific heat, conductivity), and the definition of the process specifications, i.e. the required solid exit temperature (T_{SOUT}) and other constraints such as maximum pressure drop through the bed. The five design variables have thus to be set in order to respect the design specification and guarenteeing in the same time the minimization of the total system cost. However, only three of the five variables may be set independently as two constitutive laws apply, namely the solid flow continuity requirement, and the heat transfer energy balance. Continuity law may be simply written as

$$F_{SI} = \rho_S\ V\ W\ H \qquad (1)$$

where ρ_S is the solid bulk density. Complex heat exchange phenomena characterize instead the bed behaviour, requiring the overall heat balance among solid and gas streams to be represented resorting to previously developed computer models. These simulate the bed as an array of cross-flow heat exchangers in case of steady-state operation (Caputo et al., 1996).

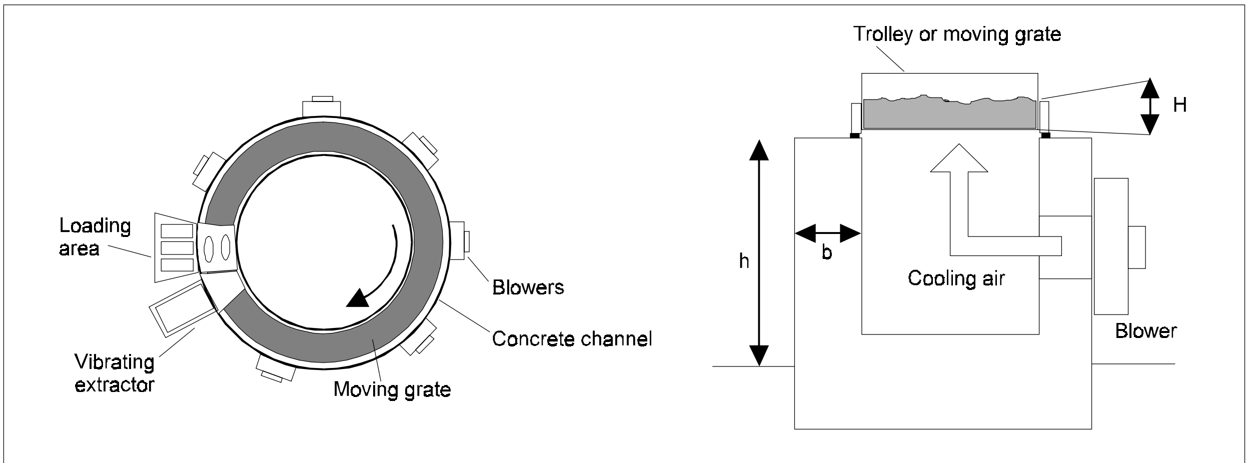

Figure 1. Scheme of a cooling bed

In case of a dynamic simulation, instead, the bed is schematized as a series of packed bed heat storage units undergoing cooling in single-blow mode of operation (Caputo et al., 1999). By fixing the values of the above cited design variables the models are able to evaluate the entire bed and cooling air stream temperature distribution, while assigning the values of all but one of the variables the models are able to evaluate the correct value of the missing variable consistent with the boundary conditions specified by the operator (i.e. by specifying bed dimensions it is possible to evaluate the cooling air flow rate required to attain a desired solid exit temperature and vice versa). However, bed design variables present counteracting effects on total system economics as capital investment is dictated by bed size while operating costs mainly by energy requirements in terms of blower operation and trolley movement. A reduction of bed size generally increases operating costs and lowers the required investment. In fact, a smaller bed length reduces capital investment but a greater cooling air flow rate is required increasing energy costs for blower operation. A lower advancement speed may compensate for shorter beds but at the expense of a greater bed width or thickness which, in turn, may increase capital investment. On the other side, an increase of bed height leads to an increase of the surface per unit area of bed normal to air flow and an increase of heat removed by unit air flow rate, even if heat exchange efficiency decreases due to the higher average air temperature.

In overall an increment of bed thickness decreases the total air flow rate requirement and also the pressure drop due to the prevailing effect of the reduced air flow rate over the increased length of the porous medium. Given a bed length and width, the bed may be also slower. Overall air flow rate is obviously reduced also by increasing bed length or width when other dimensions are fixed, leading to a much reduced pressure drop.

As a consequence, given a set of operating conditions, usually in terms of solid inlet temperature and flow rate plus the target exit temperature, an optimal set of bed dimensions and cooling air flow rate may be sought using a cost minimization approach.

3. COST MODEL

The plant Total Annual Cost (*TAC*, \$/year) has been assumed as the objective function to be minimized with respect to the main design parameters: bed width W, length L, thickness H, trolleys advancement speed V and cooling air flow rate F_{AI}. TAC is computed on the basis of Total Capital Investment (*TCI*, \$) and Annual Costs (*AC*, \$/year):

$$\mathrm{TAC} = \mathrm{AC} + (\mathrm{TCI})\,\tau \tag{2}$$

τ being the capital recovery factor,

$$\tau = \frac{i\,(1+i)^N}{(1+i)^N - 1} \tag{3}$$

with i the interest rate (%/year) and N (years) the plant life.

Considering the annual cost, the following operating cost items may be pointed out:

a) Maintenance and labor expenses ($AC_{M\&L}$);
b) Energy cost for blower operation (AC_{BL});
c) Energy cost for trolleys operation (AC_T);

resulting in

$$AC = AC_{M\&L} + AC_{BL} + AC_T \qquad (4)$$

Total capital investment is given by:

$$TCI = CI_B + CI_{BL} + CI_T \qquad (5)$$

Cost items take into account of:

a) Civil works and bed structure (CI_B);
b) Blowers cost (CI_{BL});
c) Trolleys cost (CI_T);

Bed structure cost is schematically made up of foundation cost C_F ($), concrete channel cost C_C ($), and channel insulation cost C_I ($), which can be expressed in terms of the dimensions indicated in figure 1 as follows:

$$CI_B = C_F + C_C + C_I \qquad (6)$$

$$C_F = C_{FOND}\, W\, L \qquad (7)$$

$$C_C = C_{CEM}\, (2\, L\, b\, h + L\, W\, b) \qquad (8)$$

$$C_I = C_{RIV}\, (2\, L\, (h-b) + L\, W) \qquad (9)$$

where C_{FOND} ($\$/m^2$) is the specific foundation cost, C_{CEM} ($\$/m^3$) is the reinforced concrete cost and C_{RIV} ($\$/m^2$) is the insulation material cost.

Due to the large air flow rate F_{AI} required, usually a number of blowers is utilized, uniformly distributed along bed length. In this work it is assumed that 6 blowers are employed, enabling the computation of each blower's capacity (Q_{FAN}, m^3/s) on the basis of the F_{AI} value computed by the simulation model. Resorting to literature correlations for blowers cost (Turton, et al., 1998), the total gas moving equipment installed cost ($) may be considered as

$$CI_{BL} = 6\, [(Q_{FAN}^{-0.96018})*879.353] \qquad (10)$$

Trolleys cost has been estimated as a function of their width W from vendor quotations assuming a trolley height of 1.6 m and a lenght L_T = 2 m. Trolley, or bed, width has been limited to the 2 - 6 m range due to practical technical constraints. Total trolleys installed cost is therefore:

$$CI_T = (L/L_T)\, (K_1 + K_2\, W) \qquad (11)$$

As a consequence, TCI is a function of the following decision variables: L, W, F_{AI}.

Annual maintenance and labor cost is simply assumed as a fraction of capital investment:

$$AC_{M\&L} = \alpha CI_B + \beta(CI_{BL} + CI_T) \qquad (12)$$

Annual energy cost for blower operation is instead given by

$$AC_{BL} = [(1/\eta)\ \Delta P_B\ (F_{AI}/\rho_{AI})\ OH\ C_{SE}] \tag{13}$$

where η is fan efficiency, OH the number of annual operating hours, C_{SE} the electricity cost and ρ_{AI} the density of inlet air.

Bed pressure drop ΔP_B (Pa) may be estimated resorting to Ergun equation (Ergun, 1952):

$$\Delta P_B = H\left[\frac{150\,\mu\,\nu\,(1-\varepsilon)^2}{d^2\,\varepsilon^3} + \frac{1.75\,\rho_A\,\nu^2\,(1-\varepsilon)}{d\,\varepsilon^3}\right] \tag{14}$$

being μ the air dynamic viscosity, ε the bed void fraction, v the air permeation velocity, ρ_A the average air density and d the particles diameter.

Energy cost for trolley motion is a function of loaded trolley weight and advancement speed. Trolley weight is the sum of empty trolley weight (depending on its width) ($K_3 + K_4\ W$), plus sinter load ($\rho_S\ L_T\ W\ H$).

$$AC_{TM} = \frac{[(K_3 + K_4\,W) + (\rho_S\,L_T\,W\,H)]\,f\ \ V\ C_{SE}\,OH\ \ L}{\eta_M\ L_T} \tag{15}$$

where f is the rail-wheel friction coefficient, and η_M the powertrain efficiency.

Annual cost therefore depends on all of the five decision variables W, H, V, L and F_{AI}. Table 1 reports the numerical values assumed in the computations for all the parameters which are not considered to be decision variables in the optimization process, unless otherwise indicated, including process data for the reference bed. In Table 1 sizing parameters values have been assumed with reference to similar existing plants or from common engineering practice, while cost parameters have been obtained from vendors quotations. Assumed bed physical characteristics include: pellets equivalent diameter d = 0.1 m, particles and bulk density ρ = 2700 and 1600 kg/m^3 respectively, thermal conductivity 1.14 W/m K, specific heat 920 J/kg K, void fraction ε = 0.4.

Table 1. Assumed parameters values

b (m)	0.6	F_{SI} (kg/s)	155	K_4 (kg/m)	750	T_{SOUT} (°C)	70
C_{CEM} (\$/m^3)	210	h (m)	3	L_T (m)	2	α	0.005
C_{FOND} (\$/m^2)	45	*i* (%/year)	0.07	N (years)	20	β	0.04
C_{RIV} (\$/m^2)	35	K_1 (\$)	10000	OH (hr/year)	7500	η	0.7
C_{SE} (\$/kWhr)	0.085	K_2 (\$/m)	3750	T_{AI} (°C)	20	η_M	0.7
f	0.175	K_3 (kg)	4500	T_{SI} (°C)	550		

4. OPTIMIZATION APPROACH AND SIMULATION RESULTS

Minimization of the objective function has been carried out resorting to Matlab numerical computation environment adopting Powell's sequential quadratic programming optimization algorithm. The bed simulation model has been also implemented in Matlab language. After initializing the process parameters, the physical properties data and the economic variables values, a first set of three decision variables values is input to the program. The simulation model is called to determine the corresponding values of the other two dependent design variables enabling the numerical evaluation of the objective function. The result is given in input to the optimization algorithm which supplies a new set of values for the three independent variables. The simulation model solves the energy and mass balances determining the two dependent variables values. As a consequence a new feasible solution is obtained and the updated value of the objective function is computed. This is compared to the previous one in order to determine a new set of independent variables. The entire sequence is repeated until a minimum of the objective function is obtained.

Before attempting any optimization, some parametrical simulations of the cooling bed behaviour where carried in order to evaluate the TAC and F_{AI} variations corresponding to different choices of bed length, height and width.

As shown in figures 2 and 3 an optimal bed length occurs which gives a minimum TAC. At bed lengths lower than the optimal one an extremely steep increase of TAC is observed mainly due to the rapid rise in operating costs caused by pressure drop and the large theoretical air flow rate required to cool an excessively short bed. However, at very short beds also an increase of TCI is observed deriving from the higher cost of the greater capacity gas moving equipment, which further contributes to the TAC increase. In fact, due to the thermal inertia and solid conductivity effects the heat removed from solid is not proportional to gas flow rate and increasingly high air flow rates are required to obtain the cooling velocity imposed by very short beds. At bed lengths greater than the optimal one, instead, the main cost factor is the capital investment, showing a moderate increase with bed length. However, at high lengths the TAC tends to become similar irrespective of the other design values.

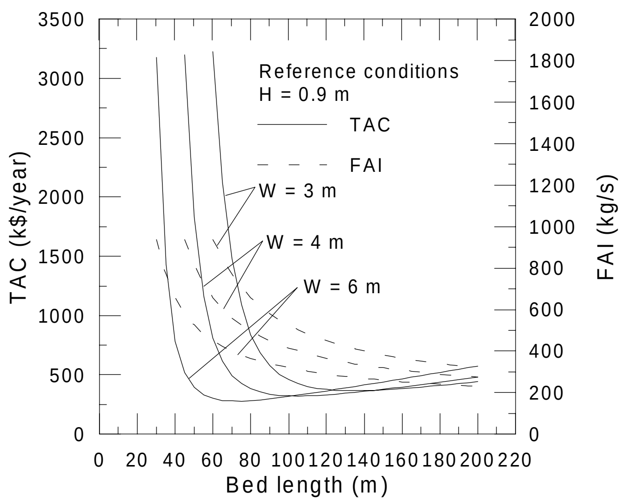

Figure 2. Effect of bed width

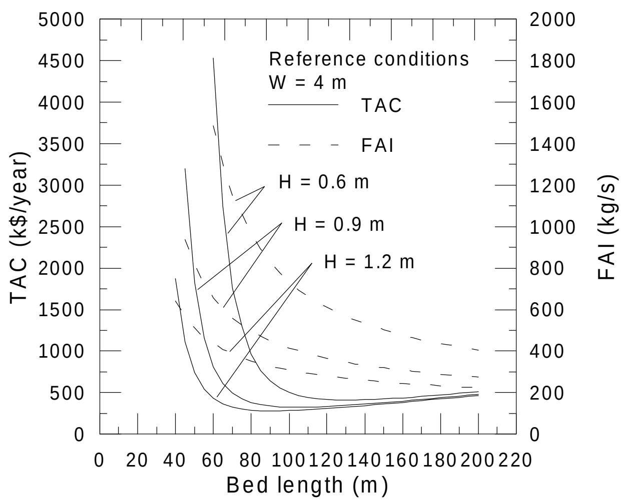

Figure 3. Effect of bed heigth

Either TAC and optimal bed length appear to be very sensitive to the values of cooling air flow rate, bed width and thickness, justifying the resort to an optimization model. In particular, when a set of design parameters has been given, the TAC curve is relatively flat around the minimum making the choice of the exact length less stringent as a fairly wide error margin may be tolerated without significant TAC penalties. While at fixed heigth an increase in bed width reduces AC due to a lower air flow rate, this effect is much more pronounced when increasing H. Bed heigth appears therefore to be the most sensitive parameter as it can significantly reduce TAC. An increase of H may surely lead to an increase of pressure drop, and electricity costs, but it enables a much more effective heat exchange thanks to the higher exchange area interested by the unit gas flow rate, resulting in a strong reduction of the overall flow rate. However, this advantage is progressively reduced as the bed thickness increases. From figure 3 it is evident that passing from H = 0.6 to 0.9 m nearly halves the required air flow rate, while this benefit is not maintained with a similar increment from 0.9 to 1.2 m.

As far as economic parameters are concerned figure 4 shows the effect of variables affecting the plant depreciation (namely *i* and *N*). A single AC curve is shown as it is not dependent from such values, while the amortization curves are computed as TCI times the capital recovery factor τ.

As already observed AC rises steeply as the bed shortens due to gas moving costs, but it also grows, although in a much weaker way, as the bed length increases due to the greater incidence of maintenance and trolley movement cost. Therefore, AC too shows a minimum, even if it is fairly apart from the optimal length. Although variations in *i* and *N* cause strong differences of actual TAC values it can be seen that the optimal bed length is only affected in a negligible manner. Therefore, an accurate estimate of *i* and *N* is not necessary when evaluating the optimal bed length which, instead, is much more sensitive to operating costs, i.e. to F_{AI} values, to pressure drop and other parameters affecting the heat exchange mechanism (pellet equivalent diameter, shape, conductivity, specific heat and bed porosity) plus, obviously, to electricity cost. This means that greater importance should be paid to correctly estimating operating costs rather than capital investment and the economic variables influencing such costs.

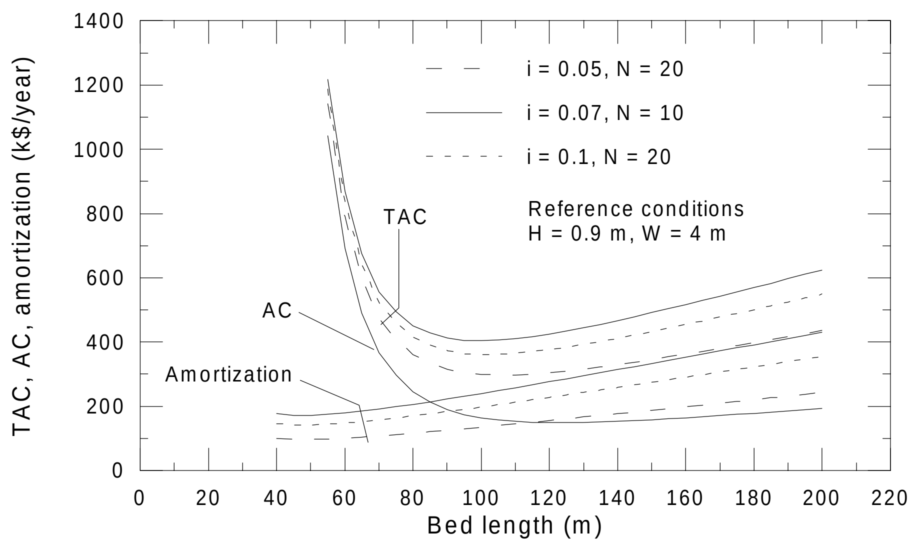

Figure 4. Effect of interest rate and plant life

Table 2. Optimized design values for reference bed case

T_{SOUT} (°C)	30	50	70	
	Calculated optimal value			Actual bed
L (m)	105	75	65	110
H (m)	1.2	1.2	1.2	0.8
W (m)	6	6	6	4
F_{AI} (kg/s)	495	380	313	500
AC (k$/year)	176	137	113	-
TAC (k$/year)	357	267	225	-

Table 3. Optimized design values for different operating conditions

F_{SI} (kg/s)	T_{SI} (°C)	L (m)	F_{AI} (kg/s)	TAC (k$/year)
110	500	49.1	196	195
110	550	52.9	202	203
110	600	55.2	209	208
180	500	79.5	321	300
180	550	81.7	333	310
180	600	85.5	342	322

When directly applying the optimization procedure to the reference bed (i.e. F_{SI} = 155 kg/s, T_{SI} = 550 °C), instead, the results shown in Table 2 were obtained. Apart from the actual cost figures, which depend from the assumed economic parameters values, it appears that the bed has been strongly oversized, maybe in consideration of future increments in sinter production (i.e. the trolleys height is 1.6 m while the adopted thickness of the bed is only 0.8 m) or because lower T_{SOUT} had been initially specified. However, in light of such results a modification of operation parameters (bed advancement speed and blowers flowrate) could be attempted in order to reduce operating costs, maintaining at the same time the solid cooling level currently achieved.

As a further analysis, Table 3 shows instead the optimal arrangement corresponding to different values of F_{SI} and T_{SI}, demonstrating how process conditions heavily affect optimal design parameters. Moreover significant cost savings may be obtained by proper design choices, solid flow rate rather than temperature being the leading process parameter.

5. CONCLUSIONS

An optimization approach has been presented to solve the moving solid bed coolers design problem. The procedure enables the optimal selection of the bed design variables: width, length, thickness, advancement speed and cooling air flow rate, on the basis of the given set of input data, including solid inlet flow rate, temperature and physical characteristics, in order to respect the required solid exit temperature and other constraints at the minimum total cost. Referring to an actual sinter cooler at the ILVA steel works in Italy, some computed results are presented to show how design variables may affect the total cost and how the optimal bed design parameters are affected by a change in the solid stream characteristics, highlighting the usefulness of the proposed cost minimization approach. As a concluding remark the optimal length is affected by all design values but especially by bed length and air flow rate, being much more sensitive to annual costs than to the capital investment. In proximity of the optimal length the TAC does not show significant variations highlighting the robustness of this approach. From the cost point of view it is preferable to exceed in bed length than to risk an excessively short bed. As a future work, by introducing some further design variables (temperature and flow rate of collected air, hoods arrangement and length) the proposed approach shall be then extended to the optimal design of the heat recovery system which may be coupled to the cooling bed to pursue the best compromise in heat recovery plant at the minimum total cost.

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