A control relevant dynamic model of grate sintering

Frode Martinsen, Bjarne A. Foss and Tor Arne Johansen
Norwegian University of Science and Technology
Department of Engineering Cybernetics
N-7491 Trondheim, NORWAY
fax: + 47-73594399 email: frodem@itk.ntnu.no
www.itk.ntnu.no/groups/process_control/

Keywords: Sintering, dynamic model, multi-model, simulation.

Abstract

In this paper a control relevant nonlinear dynamic model of grate sintering is presented. The model is designed for control purposes for use in future model predictive control (MPC) strategies. A multi-model approach is utilized where the model is presented as a convex combination of locally affine models. The model performance is compared to global models listed in the literature by simulations and by comparison to industrial plant data.

1 Introduction

The metallurgical process of sintering prepares the (iron) ore to form suitable feed for the blast furnace. Granulated ore and coke are mixed, moistened with water and micro-pelletized to form the charge. The charge is loaded onto a grate and leveled to form a bed which is ignited by a gas-fueled ignition hood. A heat wave and coke combustion zone travels down through the bed under the influence of a suction pressure. Hot gas from the combustion zone passes through moist charge deeper in the bed where water evaporates. The process can be divided in five subsequent zones; heat exchange, fusion, combustion, drying and over-moist charge. This is illustrated in figure 2 a). The main purpose of sintering is to convert weakly-bounded granules into a partially fused porous sinter cake suitable for feeding to the blast furnace. Sintering is a complex process involving flow of gas through a packed bed, heat and mass transfer between gas and solids, heterogeneous chemical reactions and melting of solids.

Several models of the sintering process is presented in the literature [1], [2], [3], [4], [5], [6], [7], [8]. These models are presented as nonlinear PDE's, and mainly focus on reproducing important process quantities. There are few reported results on model based control of the sintering process. Kwon et al. [9] uses a linear MPC scheme with an identified input/output model to control the burn-through point of traveling grate sintering. The reported real-time experiments and simulations demonstrates that the chosen MPC algorithm performs well. In the present work, the problem of controlling production rate and quality is directly addressed by identifying a model from designed experiments. As argued below there is an economic criteria restricted by constraints involved, and investigating MPC as a means to control grate sintering is motivated. We seek to exploit the underlying structure of the sintering process to develop a structured model which later on can be utilized to develop a robust control strategy for the sintering process. In the present approach the global nonlinear PDE model is approximated by a convex combination of locally linear or affine models. The local (zone) models are interconnected by both boundary values and propagation of zone positions as sintering proceeds. The interconnection of the zones are handled by the multi-modeling techniques of Johansen and Foss [10]. This method gives smooth interpolation of zones and is chosen since exact zone boundaries are uncertain and overlap.

Early attempts to model the sintering process divided the process into zones [1]. This approach was later abandoned [2]. The present approach re-investigates this approach, but the motivation for this differs from earlier works. The model in this paper aims at a *control relevant* model, not a detailed first principles model. In a control relevant model reproducing the internal states is not as important as reproducing the outputs. This becomes important in a state space oriented MPC strategy due to the need for either measuring or estimating the next internal state value x_{k+1}. If x_{k+1} cannot be measured and estimation is hard, it is likely that the MPC algorithm performs poorly. In such a case an input/output oriented MPC strategy might perform better, despite the model being less accurate in reproducing the internal states.

The present paper will emphasize the development of the control relevant model, and the control algorithm itself is to be investigated in a later paper.

2 Model

A model can be derived either from physical knowledge, identified from data or as a combination of these. A control relevant model is tailored to the selected control strategy, i.e. the control strategy influence on what information the model should produce. For the sintering process the overall goal is to produce sinter at prescribed quality and rate at the lowest possible cost. Manipulated inputs are coke, water, ignition energy and air flow, while the feed is regarded as a disturbance. The process dependent outputs are quality in terms of mechanical strength and reducibility [11], and production rate. The amplitude and shape of the heat wave determines the quality: Increased coke content increases the maximum sintering temperature, $T_{s,max}$ [8], but to achieve high reducibility $T_{s,max}$ should not be too high [12]. In addition proper ignition is necessary to establish the initial conditions for sintering [2]. The process variable influencing on production rate is mainly the permeability of the bed which in turn is influenced mainly by water content. There is an optimal water content yielding the highest bed permeability, i.e. there is an optimum in both coke [12] and water content [13] which can be formulated in a MPC criterion. Bounds on $T_{s,max}$ and minimum ignition energy are formulated as constraints in the MPC formulation. Due to the large (hot) recycle and time delays present the process is considered difficult to control, with quality and production rates being hard to predict [5].

The recycle stream is an important process variable serving as an on-line measure of mechanical sinter quality: Poor mechanical quality will give increased recycle rate, which in turn reduces the production rate. Reducibility can be quantified from the temperature profile in the fusion zone [12]. Since modeling the sinter quality is difficult, it is identified from experimental data not modeled explicitly at this stage. The stationary equations of the Voice permeability P in the laminar and turbulent flow regimes are respectively:

$$P_l = v\left(\frac{L}{\Delta p}\right)^{1.0} = \frac{1}{150\mu}\cdot\frac{\varepsilon^3}{(1-\varepsilon)^2}\cdot d_p^2$$

$$P_t = v\left(\frac{L}{\Delta p}\right)^{0.5} = \sqrt{\frac{1}{1.75\rho}}\cdot\left(\frac{\varepsilon^3}{1-\varepsilon}\right)^{0.5}\cdot d_p^{0.5}$$

The productivity relation thus becomes:

$$G = \frac{v}{G_s} = \frac{P}{G_s}\cdot\left(\frac{\Delta p}{L}\right)^n \qquad (1)$$

where $n = 0.5$ for turbulent flow and $n = 1$ for laminar flow. The mass air flow G serves as an on-line measure of production rate. Note that when significant melting occurs d_p becomes a conceptual parameter.

The discussion above on in- and outputs is represented graphically in figure 1.

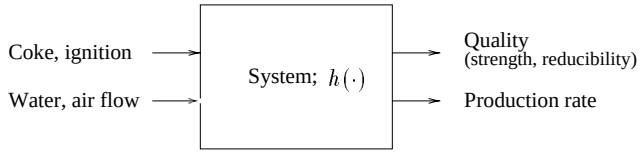

Figure 1: *System description.* The sinter quality is influenced mainly by coke content and ignition temperature, i.e. $h_q = h_q(x_C, T_{ign})$, while production rate is influenced mainly by water content and air flow, i.e. $h_p = h_p(x_{H_2O(l)}, G)$. Reduced mechanical quality increases recycle, which in turn decreases the production rate, i.e. the system is not decoupled.

A mechanistic model based on models reported in literature is presented in section 2.1, and a state-space multimodel is suggested in section 2.2. The models considered in this paper does not incorporate radial distributions, and the industrial process considered is batch-wise sintering of manganese ore in Greenawalt pans.

2.1 Mechanistic model

The general PDE model is stated in appendix A. Parameter uncertainties are present in the global models, since essential parameters typically are determined from empirical formulas valid only under idealized conditions. In industrial sintering processes the formation of cracks and channels leads to areas where air passes through without interacting with the mass in the sinter bed. In particular, the mass, h_m, and heat, h_c, transfer coefficients are calculated from the Nusselt and Sherwood numbers. These number are again calculated from the empirical relations [14]:

$$Nu = \frac{h_c d_p}{k} = \frac{1}{\varepsilon}\left(2 + 1.1Pr^{1/3}Re^{0.6}\right) \qquad (2)$$

$$Sh = \frac{h_m d_p}{D_{ON}} = \frac{1}{\varepsilon}\left(2 + 1.1Sc^{1/3}Re^{0.6}\right) \qquad (3)$$

valid for an idealized bed with homogeneous packing. In an industrial bed the gas flowing through channels and large cracks are not interacting with the solid, and the values estimated from the empirical relations for an idealized bed will deviate from the actual values. Various heuristics are utilized to overcome this in the literature, i.e. altering the constants of the empirical relations [2], [3], [7], and introducing a scaling factor [5], [6].

The kinetic parameters of coke combustion, fusion and solidification of solids and condensation are also not known in detail. The kinetic model of coke combustion is discussed in [1] assuming the reaction $C + O_2 \rightarrow CO_2$. The kinetics of fusion of solids is described by empirical schemes based on slag diagrams [6] or linear schemes based on process experience [5]. The kinetics of condensation of water is derived from laboratory tests [15] or

by heuristics and experience [2]. In addition the heat capacity of the solid and the void fraction will change in a complicated way as sintering proceeds. The average particle diameter, d_p, will not have a physical interpretation once melting in the fusion zone has occurred. Still all cited models utilize some equivalent particle diameter when melting has occurred.

Assuming infinite fast gas dynamics a mechanistic energy balance yields the pressure drop as the isothermal Ergun's relation:

$$\frac{\partial p}{\partial z} = 150\frac{\mu v(1-\varepsilon)^2}{d_p^2\varepsilon^3} + 1.75\frac{\rho v^2(1-\varepsilon)}{d_p\varepsilon^3} \qquad (4)$$

The pressure profile $\frac{\partial p}{\partial z}$ is highly nonlinear in ε and d_p, and estimating them by use of the Ergun relation will lead to uncertain values. Consequently the models available in literature uses heuristic estimates of the profiles $\frac{\partial \varepsilon}{\partial z}$ and $\frac{\partial d_p}{\partial z}$. All these phenomena gives rise to a model with many uncertain parameters, which must be accounted for when applying model based control to the sintering process.

2.2 State-space multi-model

The bed is divided in a fixed number n_z of vertical layers named elements Δz_i. Each element is allocated a model type $M_{z,i}$, $i \in 1, \cdots, 5$. These zone models are models of the natural zone partitioning depicted in figure 2 a). The allocation is based on process knowledge, i.e. as the state of the element as a function of either T_s and/or x_C, $x_{H_2O(l)}$. Once the model in an element has changed from $M_{z,i}$ to $M_{z,i-1}$, it can never change back to $M_{z,i}$.

As an example the transition from $M_{z,4}$ to $M_{z,3}$ is controlled by the ignition temperature of coke $T_{C,ign} \approx 900-1050^oC$, i.e. in an element Δz_i with solid temperature in this range, both $M_{z,4}$ and $M_{z,3}$ is calculated, and the resulting states become a weighted sum of the two models. Similar heuristics controls the transition between other zone models. The void fraction profile $\frac{\partial \varepsilon}{\partial z}$ is estimated by combining the weighting functions, the measured pressure and the Ergun relation in equation (4). A graphical illustration of the modeling concept and weighting functions is presented in figure 2 b). Note that a transition spans more than one element in general. In addition the same technique can be applied independent of the model type, linear vs. nonlinear etc., allocated to the individual elements. However, if the structure of the zone models differs explicit handling of initial conditions must be done to prevent inconsistencies. In the present model the model structure inside each zone is identical (linear or affine), and such initialization problems does not occur.

Viewed as a discretization of a system of PDE's, the described multi-modeling technique is related to the finite element method (FEM)[1]. Extensions to FEM is that in the present approach interpolation is done in the state-space as well as in time and the spatial domain.

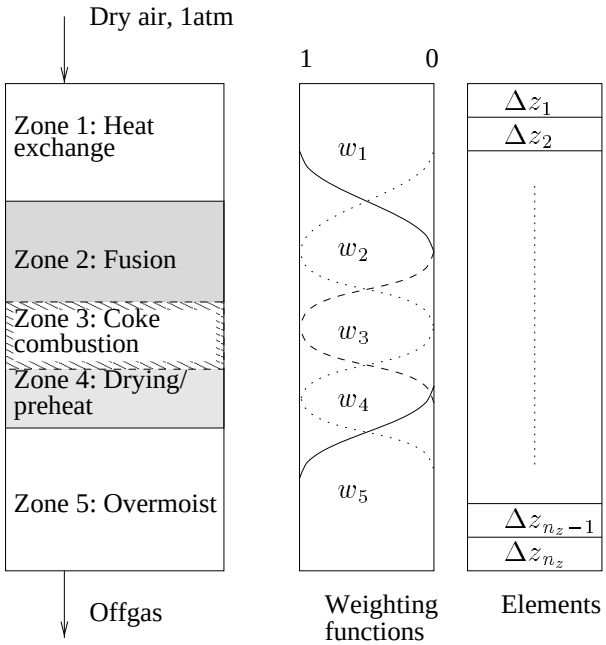

Figure 2: *Sintering zones.* **a)** The sinter bed is composed of five zones modeled separately. The zone widths and positions vary during the batch. The figure shows a typical situation at a time instance midway through the batch. The width and temperature of the fusion zone determines the sinter quality. **b)** Zone interconnection is handled by multi-modeling techniques. The elements Δz_i to the right have stationary vertical positions throughout the batch, but are allocated different models $M_{z,i}$ depending on the value of the weighting functions w_i which are moving as the batch proceeds. In transition regions the new model state in the element is computed as a weighted sum of the neighboring model types.

3 Simulations

Simulations of the global and multi-model approaches are compared to measurements taken on an industrial plant. The plant data and simulations are shown in figure 3.

The temperature dependent aggregated parameters of the mechanistic model were manually tuned against the plant data. Similarly, the parameters associated with each of the five multi-models were tuned against the

[1] FEM is applied in [6].

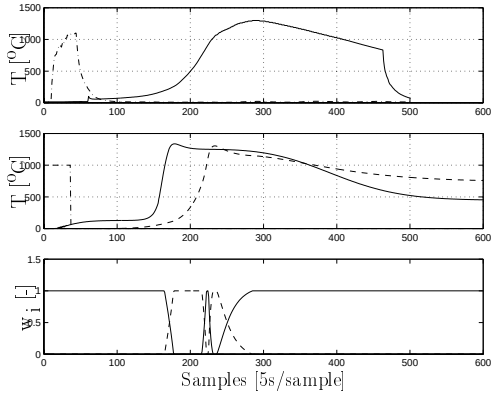

Figure 3: *Process data, simulations and weighting functions.* The upper part shows measured ignition temperature (dashed) and solid temperature measured at 15cm depth. The measured value has its peak value $1300^{o}C$ at sample 285. The sudden fall at sample 463 is caused by removing the S-element from the sintering pan. The middle part shows simulated temperatures at 15 cm depth, together with the applied ignition temperature (dashed, samples 1-36). The mechanistic model (solid line) has its peak value $1337^{o}C$ at sample 179, while the multi-model (dashed line) has its peak value $1305^{o}C$ at sample 233. The lower part shows the values of the weighting functions w_5 to w_1 from left to right. Note the resemblance to figure 2 and the simulated multi-model temperature.

plant data. Since the multi-models are valid in different operating ranges as defined by the weighting functions, tuning the multi-models was easier than tuning the mechanistic model. The interpolation functions are linear (non-smooth), with support and localization selected by process knowledge.

4 Discussion

Noting that simplified kinetics of fusion and water evaporation/condensation have been utilized, some improvements of the mechanistic model are expected upon introducing the results of Patisson et al. [6], [15]. The model does not incorporate radial spatial inhomogeneities, which are known to appear regularly in industrial applications in form of channels, cracks and inhomogeneous filling and mixing. Such inhomogeneities causes radial temperature and concentration gradients, in addition to the axial gradients modeled herein. Future work on mechanistic modeling should incorporate radial gradients, possibly with additional simplifying assumptions.

Manual tuning of parameters in a non-linear, coupled distributed system is non-optimal, and a suitable identification scheme should be implemented. Manual tuning of the parameters of the (affine) multi-models is again non-optimal, and work is in progress to implement augmented Kalman filtering in each operating regime. The observability of the (distributed) system is yet to be investigated. Tuning has only been performed for one set-point $x_{c,0}, x_{w,0}$ and is not expected to be robust to set-point variations. The affine multi-model uncertainty problem can be adressed by the method of Slupphaug and Foss [16].

The mechanistic model was simulated by applying Newton iterations to an implicit finite difference scheme giving unconditional stability. The stability of the multi-model simulation scheme has not been analyzed. The linear weighting functions can be replaced by smooth functions, and the elements Δz_i of the multi-model can be decoupled from the spatial discretization resolution of the implicit difference scheme. The relation between FEM and the proposed state-space multi-model algorithm should be pursued further. A multi-model uncertainty class should be defined and identified. The control algorithm itself is to be investigated in a later paper.

The simulations showed that the performance of the simpler model gave satisfactory results as compared to the mechanistic model. However, an improved mechanistic model can give better simulation performance. The proposed multi-model algorithm reveals an interesting relation between multi-modeling techniques and finite-element methods which suggests a direction for future research. This also suggests that stability issues of the proposed multi-model algorithm can be analyzed with methods previously applied to FEM. Finally, multi-models have so far been extensively investigated for data driven models, while the present case is motivated by acknowledging that models published in the literature have important parameter uncertainties.

A Mechanistic model

The following states are included in the model $x = \left[T_s, T_g, x_c, x_w, x_{O_2}, x_{N_2}, x_{CO_2}, x_{H_2O(v)}\right]$; i.e. temperature of solids and gas, coke concentration in solid, liquid water content[2] and gas composition including water vapor. Void fraction and particle size are estimated from

[2] Liquid and solids are lumped in one phase.

measured values, the pressure profile and (4).

$$\frac{\partial T_s}{\partial t} + k_1 (T_s - T_g) = g(T_s)$$
$$\frac{\partial T_g}{\partial t} + v\kappa_g \frac{\partial T_g}{\partial z} + k_2 (T_g - T_s) = 0$$
$$\frac{\partial x_c}{\partial t} = -M_C R_r(T_s)$$
$$\frac{\partial x_w}{\partial t} = -M_{H_2O} r_4$$
$$\frac{\partial x_j}{\partial t} + v\frac{\partial x_j}{\partial z} = r_j$$

where k_1, k_2 and k_3 are aggregated temperature dependent parameters and

$$g(T_s) = [k_3 R_r(T_s)\Delta H_r - k_3 R_f(T_s)\Delta H_f - k_3 r_{H_2O}\Delta H_v(T_s)]$$
$$r_1(T_s) = -R_r(T_s)$$
$$r_2(T_s) = 0$$
$$r_3(T_s) = R_r(T_s)$$
$$r_4(T_s) = r_{H_2O(v)}$$

Relations for $R_r(T_s)$ are given by [1], $R_f(T_s)\Delta H_f$ and r_{H_2O} by [7]. Kinetic parameters is only considered for coke combustion, fusion and drying in the model. Shrinkage and slump is not included. The heat of coke combustion is released to the solid phase, see discussion in [5]. Limestone is not utilised in the industrial plant, and is not included in the model.

B Notation

Parameters:

ε - void fraction

d_p - average particle diameter

h_m - mass transfer coefficient

h_c - heat transfer coefficient

k - thermal conductivity of gas

v - gas velocity

μ - viscosity

ρ - density

D_{ON} - axial gas dispersion coefficient (O_2-N_2)

G - mass flow rate of gas

G_s - gas volume per sinter mass

L - height of bed

p - pressure

κ_g - adiabatic constant

ΔH - heat of reaction

c_p - specific heat capacity

Dimensionsless numbers:

Re - Reynolds number: $Re = \frac{d_p G}{\mu}$

Sh - Sherwood number: $Sh = \frac{h_m d_p}{D_{ON}}$

Sc - Schmid number: $Sc = \frac{\mu}{\rho D_{ON}}$

Nu - Nusselt number: $Nu = \frac{h_c d_p}{k}$

Pr - Prandtl number: $Pr = \frac{c_p \mu}{k}$

References

[1] I. Muchi and J. Higuchi, "Theoretical Analysis of Sintering Operation," *Trans. Iron Steel Inst. Jpn.*, vol. 12, pp. 54–63, 1972.

[2] I. Dash and E. Rose, "An Analytical Study of Processes Occurring in an Iron Ore Sinter Bed," in *Automation in Mining, Mineral and Metal Processing* (F. Lancaster, ed.), IFAC Proc., pp. 649–659, 1977.

[3] F. Hoislbauer and C. Jaquemar, "Mathematical Modelling of Heat and Mass Transfer in Iron Ore Packed Bed Industrial Processes," in *Num. Met. Heat Transf.* (R. Lewis, K. Morgan, and B. Schrefler, eds.), vol. II, ch. 19, pp. 485–510, Wiley, 1983.

[4] E. Kasai, J. Yagi, and Y. Omori, "A mathematical model of sintering process considering melt-formation and solidification phenomena," in *Proc. Ironmak. Conf.*, vol. 43, pp. 241–249, AIME, 1984.

[5] M. Cumming and J. Thurlby, "Developments in Modelling and Simulation of Iron Ore Sintering," *Ironmak. Steelmak.*, vol. 17, no. 4, pp. 245–254, 1990.

[6] F. Patisson, J. Bellot, D. Ablitzer, E. Marlière, C. Dulcy, and J. Steiler, "Mathematical Modelling of Iron Ore Sintering Process," *Ironmak. Steelmak.*, vol. 18, no. 2, pp. 89–95, 1991.

[7] N. Nath, A. Da Silva, and N. Chakraborti, "Dynamic Process Modelling of Iron Ore Sintering," *Steel Research*, vol. 68, no. 7, pp. 285–292, 1997.

[8] R. Venkataramana, S. Gupta, P. Kapur, and N. Ramachandran, "Mathematical Modelling and Simulation of the Iron Ore Sintering Process," *Tata Search*, pp. 25–30, 1998.

[9] W. Kwon, Y. Kim, S. Lee, and K.-N. Paek, "Event-based modeling and control for the burnthrough point in sintering processes," *IEEE Trans. Contr. Sys. Tech.*, vol. 7, no. 1, pp. 31–41, 1999.

[10] T. A. Johansen and B. A. Foss, "Operating regime based process modelling and identification," *Computers and Chemical Engineering*, vol. 21, pp. 159–176, 1997.

[11] P. Dawson, "Part 2 Research Studies on Sintering and Sinter Quality," *Ironmak. Steelmak.*, vol. 20, no. 2, pp. 137–143, 1993.

[12] H. Toda, T. Senzaki, S. Isozaki, and K. Kato, "Relationship Between Heat Pattern in Sintering Bed and Sinter Properties," *Trans. Iron Steel Inst. Jpn.*, vol. 24, pp. 187–196, 1984.

[13] J. Hinkley, A. Waters, D. O'Dea, and J. Litster, "Voidage of Ferrous Sinter Beds: New Measurement Technique and Dependence on Feed Characteristics," *Int.J.Miner.Proc.*, vol. 41, no. 1-2, pp. 53–69, 1994.

[14] N. Wakao and S. Kaguei, *Heat and Mass Transfer in Packed Beds*, vol. 1 of *Topics in Chemical Engineering*. Gordon and Breach Science Publishers, 1982.

[15] F. Patisson, J. Bellot, and D. Ablitzer, "Study of Moisture Transfer During the Strand Sintering Process," *Metall. Trans.*, vol. 21B, pp. 37–47, 1990.

[16] O. Slupphaug and B. A. Foss, "Quadratic Stabilization of Discrete-Time Uncertain Nonlinear Multi-Model Systems using Piecewise Affine State-Feedback," *Int. J. of Control*, 1999. To appear.