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# REGULATORY CONTROL OF A PILOT ROTARY KILN FOR ACTIVATED CARBON PRODUCTION

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Abstract: The design of a regulatory control strategy for a pilot rotary kiln to produce activated carbon is presented. A complex dynamic behavior with high non-linearity and an important dead time characterizes the rotary kiln operation. The main control objective of the process is to maintain the solid temperature profile inside of a narrow limit in order to produce an activated carbon with acceptable adsorbent properties. The manipulated variables are the temperature and the mass flow rate of the heating gas. The control scheme proposed consists of a conventional PID controller with Smith predictor in order to compensate the time delay. The control scheme is tested by means of simulation with a dynamic model previously developed in Matlab. The results are satisfactory and constitute a reference point to develop other advanced control strategies. 

Keywords: Chemical Industry; Process control; Time delay; Conventional control

## 1. INTRODUCTION

The rotary kiln is the main process equipment in the activated carbon production by means of physical activation of charcoal with water vapor. In the last time, a complete study about the operation of a pilot rotary kiln for such process has been performed in our laboratory (Ortiz et al., 2003a, b; Ortiz et al., 2005). The activation process in the rotary kiln is inherently difficult to operate efficiently because of complex dynamics and multi-variable process with non-linear reaction kinetics, and long time delays. During its operation many interconnected variables must be considered and control actions must be designed to meet multiple and sometimes conflicting objectives, and changing operating conditions. Some measurements are unreliable, and the kiln characteristics may change during a long run. The operation may also be upset by disturbances such as changes in the mass flow rate and properties of the charcoal fed. In this context, the solid temperature inside the kiln must be maintained within predefined constraints in order to assure an acceptable product quality from its adsorbent properties point of view.
The control of rotary kilns, particularly in the field of the calcination and incineration processes, has been studied since the early 70`s and, very different schemes have been proposed. Such schemes varies since conventional controller based on phenomenological and empirical models to diverse approximations using artificial intelligence tools such as rule based expert systems, fuzzy logic and neural networks. Also, some applications based on model predictive control have been reported.

Despite the advent of many complicated control theories and techniques, more than 95% of the control loops based on proportional-Integral-Derivative (PID) controllers are still being used in the industrial processes. This is because PID controllers have a well and robust performance for a wide class of processes and for a wide range of operating conditions. Furthermore, engineers have expertise in PID tuning running in stand alone, in PLC or in SCADA systems (Astrom, 1995; Kaya, 2003). Other important advantage of PID controllers is its good performance in different configurations such as cascade PID control scheme, feedforward PID, Predictive Smith loops and antiwindup feedback loops (Kaya, 1998). In addition, the most controllers used really in the industry are of PID family type.

This work presents the design of a regulatory control for the operation of a pilot rotary kiln used in the charcoal activation process. The main control objective is to maintain the solid temperature profile inside of pre-specified constrains manipulating the temperature and mass flow rate of the heating gas. Due to the PID controllers have a variety of advantages; such as easiness to tuning, extensive use and familiarity in the industry, they have been adopted as a first approach to develop an adequate control scheme for the process. For the process identification, the Strejc method have been used and, taking account that the process presents a considerable time delay (Ortiz et al., 2005), the Smith predictor has been considered. For this proposes, a SISO controller is proposed. The design procedure must be made taking into account all the constraints imposed for the whole temperature profile. The performance of the control scheme proposed has been tested by means of simulation with the Matlab/Simulink tool.

## 2. PROCESS DYNAMIC MODEL

A pilot rotary kiln is a cylinder that rotates around its longitudinal axis and operates essentially as a heat exchanger. The cylinder is lightly inclined (i.e., slope about 2–6%) to facilitate the axial displacement of the solid bed, which moves towards the discharge end as the hot gases circulate countercurrent mode. The solid feed is a carbonized matter obtained from a variety of raw materials (e.g., eucalyptus wood). The hot gases originated by the combustion of natural gas arise from a central burner; supply the necessary energy for the activation reaction. Water vapor is injected as the activation agent in cocurrent mode.

The dynamic mathematical model developed includes the heat and mass balance equations for the three phases within the rotary kiln: freeboard gas, solid bed and wall. In order to model the transfer phenomena for the three phases the differential mass and energy balances, which include the chemical reaction is posed in cylindrical coordinates. Because of the main operating variables such as temperature and mass flow rate change along the axial axis, a distributed parameter system (DPS) is obtained. Therefore, the dynamic model is constituted by a set of algebraic and partial differential equations with boundary conditions. More details about the rotary kiln scheme with input and output streams, the model and its solution may be found in Ortiz et al., (2005). In that work a complete dynamic study is presented for three different operation modes; start up, shut down and normal operation with disturbances. Finally, is important to point out that the solid temperature profile inside the kiln must be maintained within narrow bounds in order to produce a high quality product.

### *2.1 Process identification*

The required model type and its precision, as well as the identification method to use depend on which objective it is needed to complete.

In this case, the process dynamic is knows by means of simulation, hence, an identification method that takes into account the system characteristics has been selected (Strejc, 1960). The used method is that of graphic identification of non-periodic systems of high order (Aguado, 2000), which is based on the graphic construction of a reaction curve of a high order system. In this one, a non-periodic system with n different time constants may be approximate adequately by means of a transfer function that represents n identical time constant, as the following:

$$G(s) = \frac{K}{(T_1 s+1)(T_2 s+1)\ldots(T_n s+1)} \cong \frac{K}{(\tau \cdot s+1)^n} \qquad (1)$$

where K represents the gain in steady state. Generally, the industrial processes are non-linear, though is possible approximate it through linear mathematical models plus a time delay (Ogata, 1998). For these one, it is possible to develop one or more control methods, where the determined performance specifications for the system suggest the class of method to use and, in addition the type of wanted system response.

## 3. PROPOSED CONTROL SCHEME

### *3.1 Controller design for systems with time delay*

Among the main troubles in classical controllers as PID, it can be mentioned its bad performance in plants with a considerable time delay. In these cases, it is necessary to consider a Smith predictor in order to compensate the time delay. Basically, the main idea is based on to previous knowledge of time delay in order to compensate its effect. In other words, it is based on the prediction of the future process behaviour (Smith, 1959). Based on such idea the proposed control scheme for the studied rotary kiln is shown in figure 1, where the regulation is obtained adjusting the process loop without delay.

## 4. SYSTEM IMPLEMENTATION

### *4.1 Plant model*

From the system reaction curve an incremental linear model has been determined, see figure 2. Thus, from the reaction curve for the output temperature that corresponds to a change of 10 % in the input temperature in open loop and in accordance with the identification method (Strejc, 1960), the following model is obtained (the time constants are in [min]):

$$G_p(s) = \frac{0{,}6038}{(5{,}53 \cdot s+1)^4} \qquad (2)$$

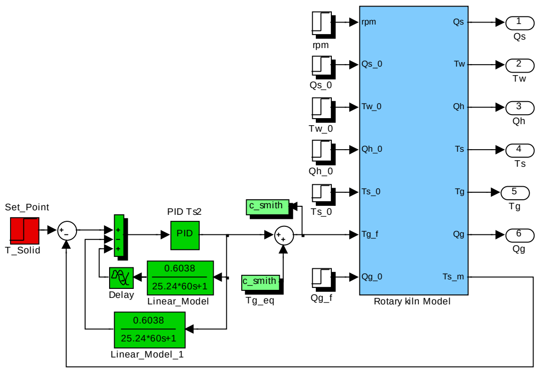


Fig. 1. Smith configuration for the rotary kiln control

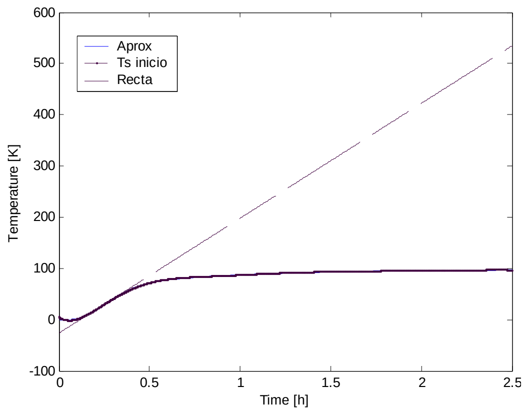


Fig. 2. Plant reaction and approximation curves (overlapped) and the straight line that cross the inflexion point

*4.2 Controller tuning*

For the tuning of the solid temperature controller an open loop is utilized. In this sense, a first order model with delay of the process is required. Using an approximation from the model in Eq. (2), the following model is derived:

$$G_p(s) = \frac{0{,}6038}{25{,}83 \cdot s + 1} \cdot e^{-7{,}24 \cdot s} \tag{3}$$

The controller parameters are obtained from the Cohen Coon tuning, corresponding to: $K_c = 8.29$, $t_r = 16$ [min] and $t_d = 2.51$ [min].

As the time delay is big in comparison with the time constant, the feedback control with Smith predictor is used (Kaya, 1998). The model in Eq. (2) is utilized for tuning the PID controller parameters.

## 5. PERFORMANCE OF THE CONTROL SYSTEM

In order to test the proposed control strategy the dynamic simulator implemented by Ortiz et al., (2005) has been used as actual plant. First, the performance of the feedback control to change in the set point and in presence of disturbances is presented. Second, the performance of the feedback control with Smith predictor to similar changes is analyzed and compared with the first scheme.

### *5.1 Performance of feedback control system to change in the set point*

In this section, the behaviour of the feedback system tuning a PID controller is analyzed. Firstly, the regulatory system is tested in the face of a set point change. Therefore, the desired solid temperature is changed as a step signal equal to 1100 ± 55 [K] (± 5% of steady state operation value) in a time of 16.67 [min]. Three points to register the temperature inside the kiln are considered, which correspond to three zones within the kiln: inlet zone ($z$ = 0.05$L$), middle zone ($z$ = 0.5$L$) and outlet zone ($z$ = 0.95$L$). L represents the axial length of the kiln.

Figure 3a depicts the wall temperature behaviour, where it is appreciated that the maximum time to reach the steady state is approximately 2.5 [h] and, shows an overshoot of 25 %. On the other hand, the wall temperature in the inlet zone presents a delay of 0.2 [h], 20 % of overshoot and it require 2 [h] to reach the steady state. The responses to changes in the reference signal, increment or decrement, are symmetric.

Figure 3b shows the behaviour of solid temperature. Particularly, the curve denominated as “z input” corresponds to the temperature controlled by the system. It is appreciated that the new steady state is reached after to 2.5 [hs]. Also, a delay and an overshoot of 20 % can be appreciated. However, at the outlet zone “z output curve”, the solid temperature presents a great overshoot of 25 % approximately. It must emphasize that exists a small asymmetry due to the non-linearity of the process.
Figure 3c shows the gas temperature behaviour, which presents the same tendency that the wall and solid temperature. The gas temperature at the outlet zone, “z output curve”, indirectly represents the system control action.

The solid mass flow rate, non-controlled process variable, presents an increment of 39 % respect of the nominal value at the outlet zone. In consequence, a decrement in the temperature reference value produces an apparent increment in the production yield. Such circumstance cause a diminution in the “burn off “ and hence a loss in the product quality. An increment in the temperature reference value causes the opposite effect. The necessary time to reach the new steady state is around 2.2 [h] (fig. 4a). As it was expected, see fig. 4b, the gas flow rate which is a controlled process variable not shows any variation at the outlet zone, “z output curve”, to a step change in the solid temperature reference value. Such behaviour shows clearly the efficiency of the gas flow rate controller.

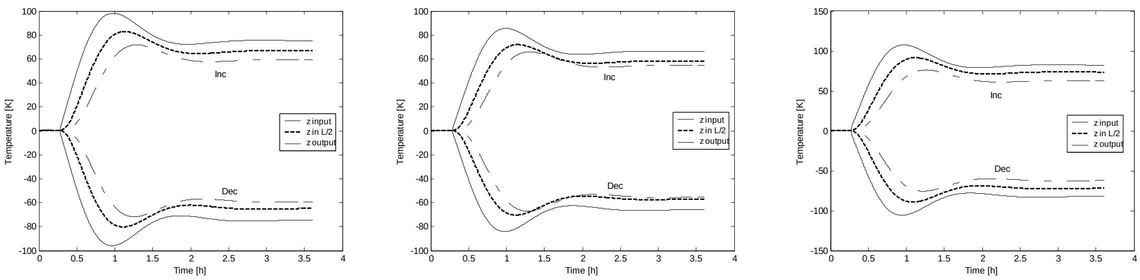


Fig. 3. Temperatures behaviour (a) wall, (b) solid y (c) gas.

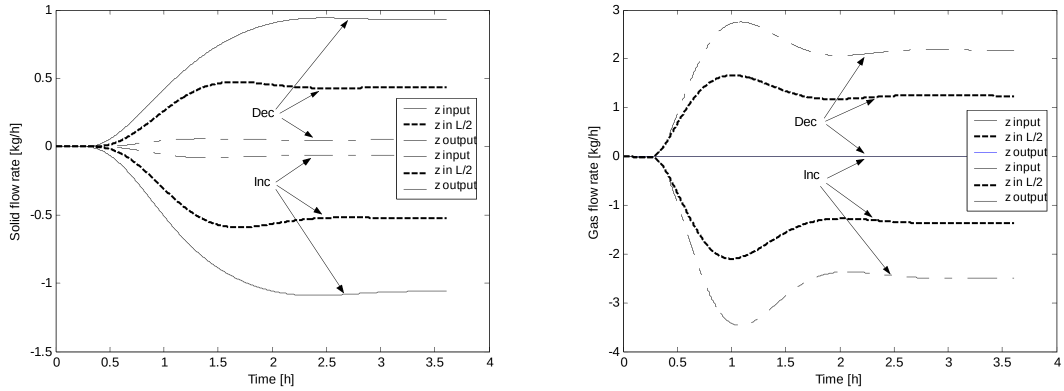


Fig. 4. Flow rate behaviour (a) solid y (b) gas.

### *5.2 Performance of feedback control system in presence of disturbances*

*Change in the rotary kiln speed.* Figures 5, and 6 show the operation variables response to a step change in rotary kiln speed of 2.0±0.5 [rpm]. An asymmetry in the curves of fig. 5 after an increment or decrement in the rotation speed can be observed. Particularly the solid temperature response, which is a controlled variable, presents an inverse performance. However, a tendency to reach its nominal value can be appreciated. Such behaviour may be explained by the sudden change in the rotary speed, which causes a sliding effect between the solid bed and the rotary kiln wall and, in consequence a decrease in the heat transfer by conduction between the solid and the wall. In addition, the before mentioned change mainly alter the regenerative effect that occur between the solid bed and the wall.

In fig. 6a, an appreciable difference in the variables behaviour may be observed when the rotary speed it is increased o decreased. Therefore, after a diminution in the rotary speed, a greatest control effort must be done. Such difference may be attributed to high non-linearity of the system. The same effect in the behaviour of gas mass flow rate in fig. 6b is appreciated.

*Change in the solid fed.* Figure 7 shows the response of the operation variables to a step change (±10%) in the reference point of the mass flow rate of solid fed. As can be seen from fig. 7b the controlled variable, solid temperature, presents a maximum variation of 5 [K] (0.5 % on set point). Also, the high non-linearity of the system may be appreciated.

### *5.3 Performance of feedback control system with Smith predictor*

In this section, the performance of the Smith predictor system tuning a PID controller is analyzed. Also, as in paragraph 5.1, the system is tested to a change in the set point.
In fig. 8a, the wall temperature shows a settling time of 1 [h] approximately with an overshoot smaller than that the obtained in paragraph 5.1. The controlled solid temperature, "z input", reaches the desired value faster that without Smith predictor and, the asymmetry for the increment and decrement is also less important (fig. 8b). On the other hand, the curve "z output" in fig. 8c, which indirectly represents the control action, shows that to achieve an improvement in the controlled system a smaller energy is required.

The asymmetry shown by the curves of mass flows rate (not showed due space reason) represent the high non-linearity of the system. In addition, an increment in the product mass flow rate may be appreciated when the set point temperature is diminished. This behaviour corresponds to an apparent growth in the production yield, because it occurs at the expense of the product quality.

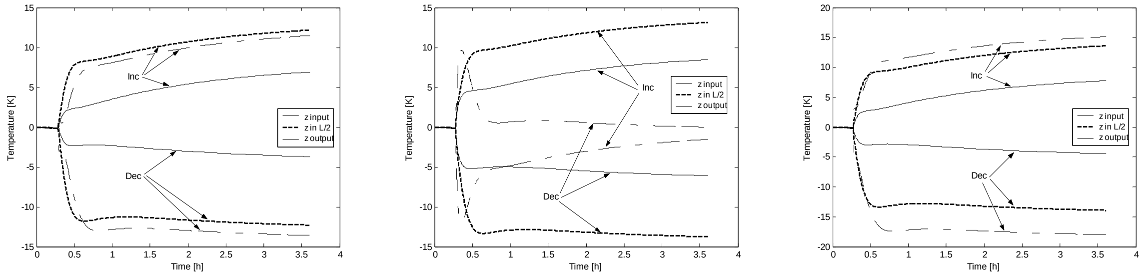


Fig. 5. Temperatures behaviour (a) wall, (b) solid bed (c) gas.

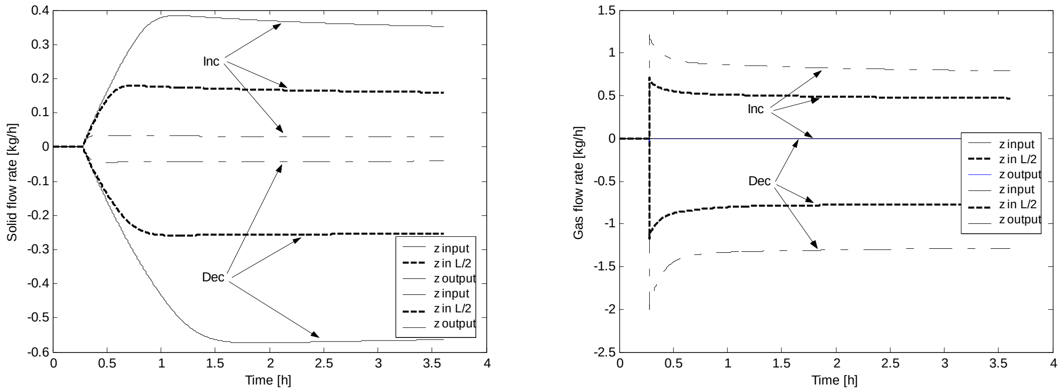


Fig. 6. Mass flows rate performance (a) solid (b) gas.

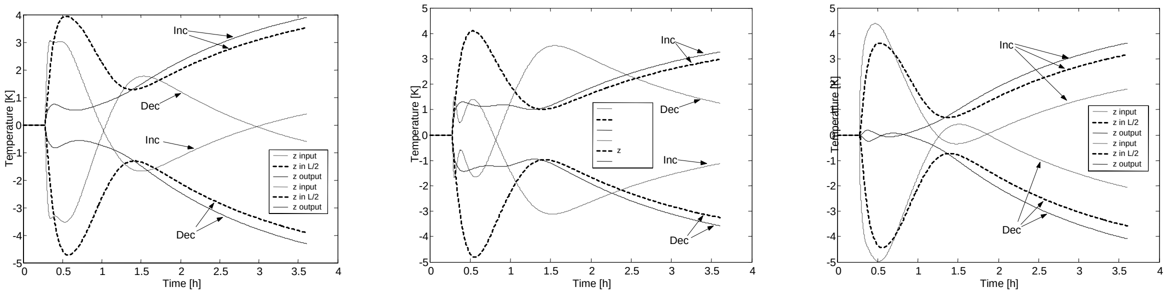


Fig. 7 Temperatures response to a step change in the solid mass flow rate fed (a) wall, (b) solid, (c) gas.

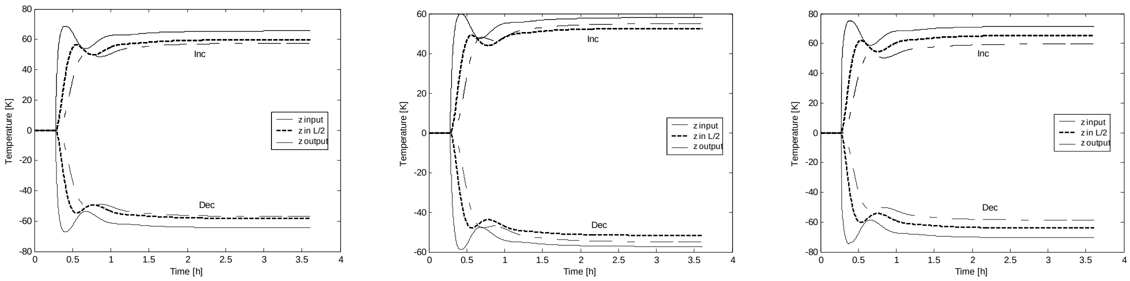


Fig. 8 Temperatures behaviour (a) wall, (b) solid (c) gas.

### *5.4 Performance of the control system with Smith Predictor in presence of disturbances*

*Change in the rotary kiln speed.* Figure 9 shows the response of the control system to variations in rotary kiln speed, which is considered as one of the more frequent disturbance during the steady state operation.

Figure 9a shows that the controlled variable, corresponding to the “z input” curve, attain the new set point equivalent to the step change when the steady state is reached. Such behaviour is observed for an increment or a decrement in rotary kiln speed. As can be observed the system with the Smith predictor have a more faster response that with the traditional PID. In addition, fig. 9b shows that the settling time is lower, 43.4 [min] approximately. Also, the non-linear characteristic of the system may be appreciated in the curve corresponding to solid mass flow rate vs. time (not showed), where the response to an increase and decrease do not show symmetry around the set point. For a change in the solid mass flow rate fed, the control system exhibits a notable improvement in its performance regarding the conventional PID.

## 6. CONCLUSIONS

The control of the solid temperature profile inside of a pilot rotary kiln for activated carbon production has been studied and a control scheme constituted by a conventional PID controller with Smith predictor was satisfactory tested. Taking into account that the studied system have special constraints such as: high non-linearity, variation of its main operation variables along the axial direction (distributed parameters system) and, an inherent time delay; we can assert that the control strategy proposed has been satisfactory. On the other hand, due to the conventional PID controller may be easily tuned, the same has been considered as a reference point for any other control strategy that it can be proposed.

The use of a control scheme such as a PID controller with a Smith predictor has allowed us to obtain a better system response, because that configuration permit to compensate the time delay in the process and, at the same time increase the speed of the closed-loop retaining its robustness. In addition, its performance in the presence of disturbances in rotary kiln speed and solid mass flow rate fed is excellent, because shows a stabilizing effect on the closed-loop response of the process. It can be affirm that the overshoots, settling times and frequency of oscillation are within acceptable limits.

The proposed control scheme constitutes the first approach to control the operation of the pilot rotary kiln in the activation process. Although the first results are promissory, an extensive work must be carried out. Though the dynamic model has been tested with experimental data is necessary to implement the control system in the actual plant in order to check its performance. Not always the phenomenological or empirical model have been adequate for control purpose (Barreto, 1997). In addition, different advanced control alternatives must be explored, especially those based on artificial intelligence tools such as rule-based expert systems, neural networks and fuzzy logic; which had have very acceptable performance in rotary kilns for calcinations and incineration processes. Finally, the model predictive control approach, widely used in other fields of the industry, also must be considered.

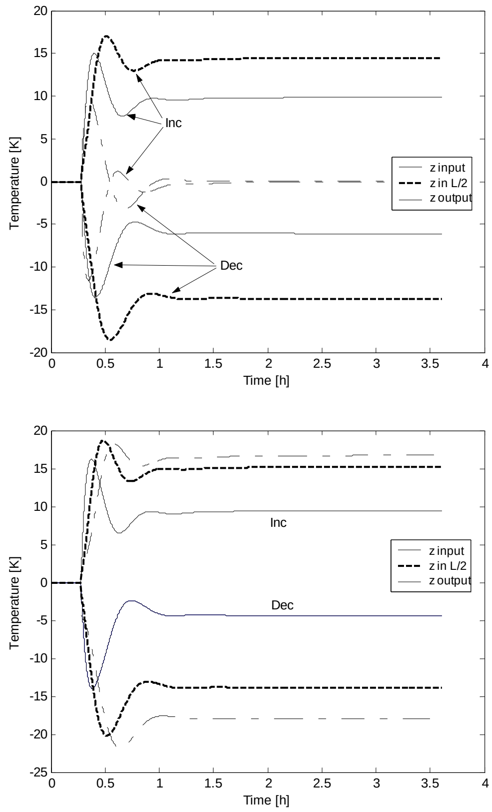

Fig. 9 Temperatures response to step change in rotary kiln speed (a) solid, (b) gas.

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