Review

Comparative evaluation of different kinetic models for batch cooking: A review

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Abstract

The purpose of this study was to review some of the existing models for delignification in kraft cooking. Data and results from earlier studies were utilized to evaluate the performance of the models of Gustafson (M_G), Purdue (M_P), Andersson (M_A) and Bogren’s method “continuous distribution of reactivity” (M_Bcdr) in terms of their ability to give a realistic description for delignification of softwood and hardwood. The M_G, M_P and M_Bcdr were tested on lignin data obtained from cooks of Eucalyptus globulus. In this case, M_P seemed to perform best, whereas the M_Bcdr failed in the range of low residual lignins. M_A considers the lignin subunits with various reaction speeds, and this feature improves the performance in the case of low residual lignins and helps to reflect sudden changes in cooking conditions, but the difference to the ordinary M_P is moderate.

Keywords: Andersson model; delignification; Gustafson model; kinetic model; kraft cooking; lignin subcomponents with various reactivity; model of continuous distribution of reactivity; Purdue model.

Introduction

Wood cell wall is a natural composite of the biopolymers cellulose, hemicelluloses, and lignins. In chemical pulping processes, wood chips are cooked in a digester together with the chemicals to produce a fibrous mass (pulp). Sulphite or sulphate-type pulps are the most common. The sulphite process works in aqueous solutions of hydrogen sulphite and sulphur dioxide, and the cations can be magnesium, sodium, ammonium or calcium. The digestion occurs in sulphate (or kraft) process in sodium hydroxide and sodium sulphide. At present, the kraft process is the dominant one for several reasons. Traditionally, the alkaline cook is divided into three parts, each with kinetic characteristics of its own (Teder 2007). During the initial part, delignification is fast, but also a substantial amount of carbohydrates is degraded. During the slow bulk delignification, most of the lignin is removed due to the long reaction time. Here, the selectivity is higher than in the initial phase, i.e., more lignin is removed than carbohydrates. In the residual delignification, all reactions are slowed down – also those for carbohydrate elimination – and the selectivity is worsened. Thus, from the point of view of maximizing the carbohydrate yield, it is favourable to stop the cooking before reaching the residual delignification. The chemical reactions during delignification are highly complex and are still not understood in all details (Potthast 2008).

A realistic mathematical model of the batch pulping process must contain the equations describing several different physical and chemical phenomena, such as flows of liquid and heat in the reactor, diffusion of chemicals into the chips as well as the chemical reactions related to delignification and carbohydrate degradation. The present work is dealing with modelling of the reaction kinetics of delignification. The purpose is to answer the question: Which kinetic models give a reliable description of the experimental delignification? In the best case, the model could support a simulation program of the cooking process. Computational aspects have also to be taken into consideration: a too complex model would slow down the simulation.

Review of the kinetic models

An array of different kinetic models of delignification has been suggested since the first half of the 20th century. The Vroom’s H-factor model belongs to the first ones (Vroom 1957). In this, the temperature and cooking time are combined through integration to a single variable, the H-factor, expressing the extent of cooking. The degree of delignification is then given as an empirical function of the H-factor and the initial concentration of alkali. The function contains parameters that have to be updated with changing cooking conditions. Though the H-factor model is widely accepted, it describes the reaction kinetics insufficiently (Rantanen 2006). More complex models consider various phases of the degradation of the various wood components with different reaction kinetics. Kleinert (1966) attributed different reaction rates to the bulk and the residual phases of delignification. The reactions involved were assumed to be of first order and depending on temperature and alkali level. Wilde and Daleski (1965) adopted the Arrhenius equation to describe the temperature dependence of the reaction kinetics. LéMon and Teder (1973) confirmed that the delignification rate was of first order in lignin content. They also modelled the effect of alkali and sulphide concentrations. In the following, four of the descendants of these early models will be revisited. The models in discussion are listed in Table 1.
Model 1: Gustafson model (M_G)

In the Gustafson model (M_G), the cooking time is divided into the initial, bulk and residual stages, according to the amount of remaining lignin in the pulp (Gustafson et al. 1983). The lignin level that marks the transition from the initial to the bulk stage is set at 22.5% of lignin in softwood and the transition level from the bulk stage to residual stage at 2.2%. In all three stages, the rate of carbohydrate degradation is proportional to the delignification.

Initial stage, lignin content >22.5%:

\[
\frac{dL}{dt} = -k_1 \sqrt{T} L \\
\frac{dCH}{dt} = c_1 [OH]^{1.1} \frac{dL}{dt}.
\]  (1)

Bulk stage, lignin content between 22.5% and 2.5%:

\[
\frac{dL}{dt} = -(k_{2a}[OH] + k_{2b}[OH]^{1.3}[HS]^{1.4}) L \\
\frac{dCH}{dt} = c_2 \frac{dL}{dt}.
\]  (2)

Residual stage, lignin content <2.5%:

\[
\frac{dL}{dt} = -k_3 [OH]^{\frac{3}{2}} L \\
\frac{dCH}{dt} = c_3 L.
\]  (3)

In the above equations, \(L\) is for lignin and \(CH\) is for carbohydrate contents, \([OH]\) is the hydroxyl concentration, \([HS]\) the sulphide concentration and \(T\) is the absolute temperature. The coefficients \(k_1, k_{2a}, k_{2b}\) and \(k_3\) are Arrhenius expressions

\[
k = Ae^{-E_a/RT},
\]  (4)

where \(E_a\) is the activation energy of the corresponding reaction and \(R\) is the gas constant.

Pu et al. (1991) modified the Gustafson model by differentiating between cellulose and hemicelluloses concerning the CH moiety. The authors also assumed that parts of the CH are nonreactive. Further, the number of stages of the CH kinetics was reduced to an initial stage and a bulk stage. As for the other kinetic models, the M_G was mostly applied to softwoods. Teder and Olm (1980) and Olm et al. (1988) found that in the case of eucalyptus, only young wood could be modelled with three consecutive phases of the traditional model, whereas for old eucalyptus wood, a preliminary phase, characterized by a very rapid delignification, should be added before the initial phase.

Model 2: Purdue model (M_P)

The kinetic part was only one aspect of the original M_p formulated by Smith and Williams (1974), which was developed for the simulation and control of a Kamyr digester by approximating the entire digester by a series of continuously stirred-tank reactors, modelling also the flows of liquor and heat at the reactor level.

In the M_P, the same kinetic equations are valid throughout the cook, but the different wood components are assumed to consist of fast- and slow-reacting subcomponents. Some authors refer to the subcomponents as “species” with various reactivities (Andersson et al. 2001). In its original version, only the lignin was considered to consist of two subcomponents with different reaction speeds, whereas each of the other wood components – cellulose, glucomannan and xylan – were thought to be uniform with regard to reactivity. Subsequently, the model was developed by adding non-reactive subcomponents for each main wood component. The rate of degradation was then expressed as:

\[
\frac{dW}{dt} = -(h[OH]+k[OH][HS][Na]) (W-W_0)
\]  (5)

where \(W\) is the wood component, \(h\) and \(k\) are rate constants and \(W_0\) is the unreactive portion of the wood. Lindgren and Lindström (1996) and Lindgren (1997) modelled delignification based on three lignin reactions: a fast, an intermediate and a slow one, each associated to its own subcomponent of the lignin. Andersson et al. (2001) extended the three-reaction type concept to the other wood components. The concentration of sodium ions is also thought to have some effect on the degradation processes and was included into a M_P type by Bogren (2008).

The M_P with four wood components, each consisting of three subcomponents having different reaction speeds:

\[
W = W_i + W_2 + W_3 \\
\frac{dW_i}{dt} = -k_i[OH]^{1.5}[HS]^{1.5}[Na]^{1.5} W_i, \quad i=1,2,3
\]  (6)

Table 1 Delignification models investigated in this work.

<table>
<thead>
<tr>
<th>Model no., Lit., a Abbreviation</th>
<th>Principal author</th>
<th>Reaction types</th>
<th>Lignin subcomponents b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, M_G</td>
<td>Gustafson</td>
<td>Consecutive</td>
<td>1</td>
</tr>
<tr>
<td>2, M_P</td>
<td>Purdue</td>
<td>Parallel</td>
<td>2–3</td>
</tr>
<tr>
<td>3, M_A</td>
<td>Andersson</td>
<td>Parallel</td>
<td>3</td>
</tr>
<tr>
<td>4, M_Bcdr</td>
<td>Bogren</td>
<td>(Parallel), “continuous distribution reactivity”</td>
<td>(Infinite)</td>
</tr>
</tbody>
</table>

a 1: Gustafson et al. (1983); 2: Smith et al. (1974); 3: Andersson et al. (2003); 4: Bogren et al. (2008).

b According to the reaction speed during delignification.
Here, the $W$ is any of the wood components, lignin, cellulose, glucomannan or xylan, $W_1$, $W_2$ and $W_3$ are the subcomponents with fast-, intermediate- and slow-reaction types. The $k$ coefficients are Arrhenius expressions, and the powers of the concentrations $a$, $b$ and $c$ are constants that have to be determined experimentally. The differential equations in (6) imply a certain simplification of the original kinetic equations of the $M_p$ and they can be applied only for kraft cooking conditions, when $[\text{HS}^+] > 0$.

**Model 3: Andersson model ($M_A$)**

Andersson (2003) and Andersson et al. (2003) improved the $M_p$ by working with three types of reactivities for each component. The authors also considered the interchange between the intermediate- and the slow-reaction steps. Initially, the wood contains more of the lignin reacting with an intermediate speed than of the slowly reacting lignin. Because of the difference in reaction speed, at some stage, there will be equal amounts of these two lignin portions. The experimental observation was that the intersection level depends on the amounts of hydroxyl and sulphide groups as well as on the temperature in a regular way. The expression was derived for the intersection level $L^*$ by means of a multivariable curve fit:

$$L^* = 0.49 ([\text{OH}^-]+0.01)^{0.65} ([\text{HS}^-]+0.01)^{0.19} (1.83-2.91\times10^{-5} (T-273.15)^2)$$

(7)

It is then possible to calculate the time, at which the intersection level is reached by solving the nonlinear equation:

$$L - L_0 = L^* \left(e^{k_1[\text{OH}^-]} + e^{k_2[\text{HS}^-]}\right)$$

(8)

for $\Delta t$. In other words, changes in the cooking conditions can be taken into account by recalculating the amounts of lignin reacting with moderate and slow speed by means of equations (7) and (8). The main objective of including the lignin type “interchange” in the $M_A$ is to reflect more swiftly the changes in the cooking conditions. Similar expressions for intersection levels are also introduced for the other wood components.

**Model 4: Bogren’s “continuous distribution of reactivity” model ($M_{Bcd}$)**

The Kohlrausch relaxation function (KRF, or the stretched exponential function) is frequently the adequate empirical tool to model deviations from simple exponential behaviour in time in case of studying complex systems. KRF is a generalization of the exponential function with a stretching parameter $\gamma$.

$$L(t) = L_0 e^{-(\delta t)^\gamma}$$

(9)

The parameter $\tau_0$ has the dimension of time. In the context of delignification, the constant $L_0$ in equation (9) represents the original amount of lignin. When the values of $\gamma$ are between 0 and 1, the graph of the KRF appears as stretched in the horizontal direction compared to the exponential function. The KRF is the solution of the modified kinetic differential equation:

$$\frac{dL}{dt} = \frac{\gamma}{\tau_0} t^{\gamma-1} L$$

(10)

where $L$ can be the amount of lignin. Thus, delignification modelled by the KRF can be interpreted as having first-order kinetics with a time-dependent rate coefficient:

$$k(t) = \frac{\gamma}{\tau_0} t^{\gamma-1}$$

(11)

This form of rate coefficient was proposed by Kopelman (1988) to describe reaction kinetics in porous geometry, where the reactants are spatially constrained.

Another interpretation of the KRF is as a superposition of simple exponential functions:

$$e^{-(\delta t)^\gamma} = \int_0^\infty H(k)e^{-kt}dk$$

(12)

With this interpretation, the wood component in question is thought to consist of a continuous distribution of subcomponents with various reactivities, where $H(k)$ is the probability density distribution for the reaction rate $k$. The right-hand side in equation (12) is the Laplace transform of $H(k)$. Hence, the $H(k)$ can, at least in principle, be calculated by taking the inverse transform. Based on the Bromwich integral formula, it can be shown according to Pollard (1946) and Berberan-Santos et al. (2005) that:

$$H(k) = \frac{\tau_0}{\pi} \int_0^\infty e^{-k u - u^\gamma} \sin(\pi u) \frac{1}{\Gamma(1/\gamma)} d\gamma$$

(13)

The shape of the distributions can be obtained by numerically integrating equation (13). Because of rapid oscillations of the integrand, the integral is difficult to compute for small values of $k$. Berberan-Santos et al. (2005) provide a similar integral, better suited for the small values of $k$. In Figure 1, the $H$ distribution $H(k)$ is shown for different values of $\beta$.

The expression on the right-hand side of equation (9), when divided by $L_0$, to obtain the value 1 at $t = 0$, can be interpreted as the complementary cumulative distribution of lifetime. As it cannot be negative, the mean lifetime can be calculated by integrating the complementary cumulative distribution starting from zero:

$$\tau = \int_0^\infty e^{-\delta t/\tau_0} dt = \frac{\tau_0}{\gamma} \Gamma\left(\frac{1}{\gamma}\right)$$

(14)

where $\Gamma$ denotes the gamma function:

$$\Gamma (\gamma) = \int_0^\infty e^{-x} x^{\gamma-1} dx$$

(15)

It can be observed when $\gamma=1$, and when the KRF is restored to the familiar exponential function that the mean
Table 2  Wood species and experimental conditions considered in the quoted papers, which were also utilized in the present study.

<table>
<thead>
<tr>
<th>Lit.</th>
<th>Species</th>
<th>Type of raw material</th>
<th>Temp. (°C)</th>
<th>Concentration</th>
<th>Liquor to wood ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norway spruce</td>
<td>Screened industrial chips</td>
<td>150–180</td>
<td>0.1–0.9</td>
<td>0.6–2.6</td>
</tr>
<tr>
<td>2</td>
<td>Norway spruce</td>
<td>Screened industrial chips</td>
<td>150–167</td>
<td>0.1–0.9 Sulphidity const.</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Scots pine</td>
<td>Wood meal, sapwood</td>
<td>108–168</td>
<td>0.1–0.8</td>
<td>0.1–0.8</td>
</tr>
<tr>
<td>4</td>
<td>Eucalyptus&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Screened chips from Uruguay</td>
<td>140–170</td>
<td>0.1–0.2</td>
<td>0.1–0.6</td>
</tr>
</tbody>
</table>

<sup>a</sup>Lindgren and Lindström (1996); <sup>b</sup> Andersson (2003); <sup>c</sup>Bogren (2008); <sup>d</sup>Rutkowska (2009a).<sup>1</sup>E. globulus.
are presented in Figures 3A and 3B. The values of the parameters obtained for the different models are given in Tables 3–5. The \( M_p \) and \( M_A \) both provide reasonable fits, but the \( M_p \) describes delignification slightly better, in case of low residual lignin contents. The \( M_{BCa} \) seems unable to model delignification at low lignin levels of a hardwood cook. None of the tried models is fully satisfactory for the high levels of [OH\(-\)]. In a simulation program, both the \( M_c \) and the \( M_p \) are easier to implement than the \( M_{BCa} \) due to the higher mathematical complexity of the latter.

**Effect of the lignin interchange in \( M_A \)**

The \( M_p \) with three parallel lignin reactions was fitted to softwood data (Lit. 1 of Table 2), and the fits are presented in Figure 4a. Andersson et al. (2003) had also fitted \( M_A \) to the same data. This model provides a slightly better performance, especially, when it comes to the accurate modelling of the profile “lignin content vs. time” at low levels of lignin content. The interchange between the two lignin subgroups with slower reaction in the model means a dependence of lignin types of cooking conditions, whereas this parameter is independent of the cooking conditions for \( M_p \). In Table 6, it can be seen that the initial portion of slowly reacting lignin decreases with increasing hydroxide content in the cooking liquor. When the \( M_p \) is fitted to the same data, the initial levels of the subcomponents with intermediate and slow reaction speeds are 17.4% and 2.6%, respectively, notwithstanding the different [OH\(-\)] levels.

The \( M_p \) and \( M_A \) were both fitted to cooking data from Lit. 2, which had substantial step changes in the [OH\(-\)] level. As visible in Figure 4b, \( M_A \) performed better. Also, the *Eucalyptus* data from Lit. 4 contain cooking series with sudden (discontinuous) changes in cooking conditions. The fittings of \( M_p \) and \( M_A \) to this data (see Figure 4c) confirm the better performance of the latter.

For in-depth considerations, both \( M_p \) and \( M_A \) were applied for some hypothetical cases including a change in cooking conditions. The results are shown in Figures 5A and 5B. The differences in the predictions of the two models are not large. The susceptibility of \( M_p \) to abrupt changes is comparable to that of \( M_A \). In some cases (Figures 5A,b and 5B,c) of the deviation from the constant conditions, predictions are even slightly more elevated for \( M_p \) than for \( M_A \).

Andersson (1997) and Andersson et al. (1997) found better agreement between experimental data and modelling by \( M_A \) than by \( M_p \). But it should be remembered again, that the...
Figure 3A,B  Delignification models fitted to cooking data of *Eucalyptus globulus*. The solid curve represents the Gustafson model (M<sub>G</sub>, no. 1) with two consecutive periods, the dashed line, the Purdue model (M<sub>P</sub>, no. 2) with two lignin reactivities (subcomponents), and the dotted line, the Bogren model (M<sub>B</sub>cdr, no. 4). The points represent experimental data. The x axes are logarithmic.
Table 3 Parameters of the Purdue model (M_P) when fitted to the E. globulus data of Rutkowska (2009b). Lignin 1 is the lignin subcomponent with fast reaction speed, and Lignin 2 is that with slow reaction speed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Lignin 1</th>
<th>Lignin 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial content (%)</td>
<td>λ</td>
<td>17.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Activation energy (kJ mol(^{-1}))</td>
<td>E_a</td>
<td>130.6</td>
<td>129.7</td>
</tr>
<tr>
<td>Frequency factor (min(^{-1}))</td>
<td>A</td>
<td>1.1×10(^{15})</td>
<td>1.4×10(^{14})</td>
</tr>
<tr>
<td>Exponent [OH(^-)]</td>
<td>a</td>
<td>0.63</td>
<td>1.71</td>
</tr>
<tr>
<td>Exponent [HS(^-)]</td>
<td>b</td>
<td>0.33</td>
<td>0.53</td>
</tr>
<tr>
<td>Exponent [Na(^+)]</td>
<td>c</td>
<td>-0.58</td>
<td>-0.68</td>
</tr>
</tbody>
</table>

Table 4 Values of the parameters of the Gustafson model (M_G) when fitted to data of E. globulus according to Rutkowska (2009b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Bulk</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial content (%)</td>
<td>λ</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>Activation energy 1 (kJ mol(^{-1}))</td>
<td>E_a</td>
<td>66.7</td>
<td>171.3</td>
</tr>
<tr>
<td>Frequency factor 1 (min(^{-1}))</td>
<td>A_1</td>
<td>3.7×10(^{6})</td>
<td>4.2×10(^{19})</td>
</tr>
<tr>
<td>Activation energy 2 (kJ mol(^{-1}))</td>
<td>E_a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency factor 2 (min(^{-1}))</td>
<td>A_2</td>
<td>3.87×10(^{15})</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Values of the parameters of the M_Bcdr when fitted to the data of E. globulus according to Rutkowska (2009b).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_0</td>
<td>5.0×10(^{14})</td>
<td>min(^{-1})</td>
</tr>
<tr>
<td>m</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>-1.60</td>
<td></td>
</tr>
<tr>
<td>o</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>-0.30</td>
<td></td>
</tr>
<tr>
<td>q</td>
<td>-0.82</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>-0.24</td>
<td></td>
</tr>
<tr>
<td>E_a</td>
<td>127</td>
<td>kJ mol(^{-1})</td>
</tr>
<tr>
<td>γ_1</td>
<td>-2.01</td>
<td></td>
</tr>
<tr>
<td>γ_2</td>
<td>7.1×10(^{-3})</td>
<td>K(^{-1})</td>
</tr>
</tbody>
</table>

quoted authors considered three lignin reactivities instead of two in M_P. The real importance of three lignin subgroups reacting with various speeds can only be judged by further empirical experiments.

Additional explanations to the modelling

Effective cooking time

In the heating up period of cooks, the delignification temperature is not constant. The relative length of this period cannot be neglected in the kinetic model. The problem has been handled by transforming the cooking time into “effective time”, i.e., the time at which the same amount of delignification would have occurred as at a theoretical constant temperature cook.

The relation between the real cooking time and the effective time is calculated assuming that the reaction rate is an Arrhenius expression:

\[ k = Ae^{E_a/RT} \]  

Table 6 Initial portions of lignin subcomponents for different [OH\(^-\)] concentrations.

<table>
<thead>
<tr>
<th>[OH(^-)] conc (M)</th>
<th>Lignin subcomponents with</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interm. reaction speed (%)</td>
</tr>
<tr>
<td>0.1</td>
<td>16.8</td>
</tr>
<tr>
<td>0.23</td>
<td>18.1</td>
</tr>
<tr>
<td>0.44</td>
<td>18.7</td>
</tr>
<tr>
<td>0.9</td>
<td>19.1</td>
</tr>
</tbody>
</table>
with constant activation energy $E_a$ and that the delignification with reasonable approximation can be described by the simple differential equation:

$$\frac{dL}{dt} = kL$$  \hspace{1cm} (24)$$

By switching the differentials into finite differences, the equation is:

$$\frac{\Delta L}{\Delta t} = kL \Rightarrow \Delta L = Ae^{E_a/RT} L \Delta t.$$  \hspace{1cm} (25)$$

Then, the time interval $\Delta t'$, at which the same amount of delignification is achieved at the temperature $T'$, can be calculated from:

$$Ae^{E_a/RT} L \Delta t = Ae^{E_a/RT} L \Delta t' \Rightarrow \Delta t' = e^{E_a/(R(T' - T))} \Delta t.$$  \hspace{1cm} (26)$$

The effective time of the cook is calculated by adding the converted time steps of the heating up time.

**Consistency of the different models**

Even though the various kinetic models give similar predictions for the lignin development and are in reasonable accordance with experimental data, it must be remembered that the underlying assumptions for the chemical mechanisms associated with the models are quite disparate and cannot all be valid at the same time. At present, the models can be accepted as phenomenological ones in simulation as long as extrapolation is avoided. In order to distinguish between the different kinetic models, more experiments are needed, as pointed out by Burazin (1986), under such cooking conditions where their predictions diverge.
Conclusions

1. For softwood, the Purdue model (M_p model 2) and the Bogren model (M_Bogren model 4) are both in reasonably good agreement with the cooking data. Prolonged softwood cooks at low temperatures could help in discriminating between the M_p and M_Bogren.

2. For hardwoods, the Gustafson model (M_G, model 1) and the M_p perform better than the M_Bogren especially in describing the low lignin contents after prolonged cooks. In this region of residual lignins, there is also a small advantage for M_p over the M_G.

3. The Andersson model (M_A, model 3) offers some improvements compared to M_p which are more visible for softwoods than for hardwoods.

4. The M_p is also able to reflect sudden changes in cooking conditions, i.e., changes occurring in discontinuous steps.

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