

Optimum temperature operation mode for glucose isomerase reactor operating at constant glucose conversion

N.M. Faqir, I.M. Abu-Reesh

Abstract The optimum temperature operation mode required to achieve constant outlet glucose conversion is determined for immobilized glucose isomerase continuous packed bed reactor. The reactor design equation assumes reversible Michaelis-Menten kinetics with both enzyme deactivation and substrate protection. An increasing temperature profiles are determined for different operating periods, residence times and glucose conversions. The temperature increase with time is very small at low degree of glucose conversion and at relatively long residence time. The temperature rise with time increases at high degree of conversion and at relatively short residence time.

List of symbols

| | | |
|--------------------|--------------------|--|
| a | | residual enzyme activity |
| E | [mg/l] | concentration of active enzyme |
| E_0 | [mg/l] | initial concentration of active enzyme |
| k_d | [h ⁻¹] | first order thermal deactivation rate constant |
| k_e | | equilibrium constant |
| k_m | [mole/l] | apparent Michaelis constant |
| k_p | [mole/l] | Michaelis constant for product |
| k_s | [mole/l] | Michaelis constant for substrate |
| s' | [mole/l] | apparent substrate concentration |
| s_0 | [mole/l] | substrate concentration at reactor inlet |
| Pr | [mole fructose/lh] | time average reactor productivity |
| T | [k] | temperature |
| T^{Lower} | [k] | lower temperature bound |
| T^{Upper} | [k] | upper temperature bound |
| t | [h] | operating time |
| t_f | [h] | operating period |
| v_m | [mole/lh] | maximum apparent reaction rate |

| | | |
|-------|-----------|--|
| v_p | [mole/lh] | maximum reaction rate for product |
| v_s | [mole/lh] | maximum reaction rate for substrate |
| x | | substrate fractional conversion |
| x_0 | | specified substrate fractional conversion |
| x_e | | substrate fractional conversion at equilibrium |

Greek symbols

| | | |
|------------|-----|--|
| α | | real positive variable |
| β | | real positive variable |
| θ | | dimensionless operating time |
| θ_i | | dimensionless operating time at a given time i |
| τ | [h] | residence time |
| σ | | substrate protection factor |

Special symbols

| | | |
|---------|--|--|
| $[]_i$ | | the expression in parenthesis is a function of the dimensionless operating time θ_i . |
|---------|--|--|

1

Introduction

High fructose corn syrup (HFCS) production is considered the most important industrial enzymatic process in the industry. Glucose isomerization to fructose by the enzyme glucose isomerase (GI) is the last step in the manufacture of HFCS which is carried out traditionally in a packed bed reactor using immobilized GI.

Glucose isomerase reactor should be operated to obtain constant quality product and fructose content. Glucose conversion decreases with time due to enzyme deactivation. Different strategies have been suggested in the literature to obtain constant product quality and conversion for GI reactor:

1. Decreasing the feed flow rate to the reactor [1].
2. Using packed bed reactors in series with fresh enzyme addition to the last reactor [2].
3. A multistage fluidized-bed reactor with continuous refreshment of the catalyst [3].
4. Increasing the reactor temperature to compensate for loss of enzyme activity [4].

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In particular, to obtain high fructose content different operation modes exists for running the reactor. Reactor operation under constant outlet conversion and under variable conversion such as isothermal and varying temperature operations.

In a previous paper [1], the optimum temperature for glucose isomerase reactor is determined for the two modes of operation: constant flow rate (variable conversion) and variable flow rate (constant conversion). This is carried out at different operating conditions.

Hass et al. [5] have found that about 10% enzyme could be saved when varying temperature operation mode is used for glucose isomerization reaction as compared to constant optimal isothermal temperature operation mode. Park et al. [4] reported a linearly rising temperature control policy for maximizing the productivity of GI reactor for a relatively short operating period. Kim et al. [6] reported about 8% improvement in fructose productivity using preprogrammed variable temperature operation mode as compared to constant temperature operation mode. Sadana [7] derived a generalized optimum temperature operation criteria for the isomerization of glucose to fructose catalyzed by GI in an isothermal batch reactor system.

In this work, the optimal temperature mode required to achieve constant outlet glucose conversion is determined for GI reactor at different operating periods, residence times and substrate conversions. The effect of substrate protection on reactor performance is considered in this work.

2

Problem formulation

In order to achieve high fructose productivity, the immobilized enzyme packed bed reactor should be operated optimally. Temperature is one of the most important factors affecting the performance of glucose isomerase reactor. The problem is to select the temperature operation mode i.e. temperature profile to operate the reactor which gives the highest time average productivity over the whole operating period.

2.1

Mathematical model

The following design equation for glucose isomerase packed bed reactor is used [1]:

$$s_0 x(t) - k_m(T(t)) \ln \left[1 - \frac{x(t)}{x_e(T(t))} \right] = v_m(T(t)) \tau e^{-(1-\sigma)k_d(T(t))t} \quad (1)$$

where v_m , is the maximum apparent reaction rate; τ , is the residence time; k_m , is apparent Michaelis constant. Note that k_m is a function of temperature and initial substrate (glucose) concentration s_0 . Also, x and x_0 , are glucose conversion at any time and at equilibrium. The reactor design equation is valid under the following assumptions [1]:

1) The isomerization of glucose to fructose by immobilized GI is described by a reversible Michaelis-Menten kinetics.

2) Ideal plug flow reactor.

3) The enzyme deactivation follows a first order reaction mechanism with substrate protection.

4) Quasi-steady state approximation is assumed, and this is valid if the operating period is much longer than the mean residence time.

The residual enzyme activity, a , with substrate protection [8, 9] at any time t is given by:

$$a = \frac{E}{E_0} = e^{-(1-\sigma)k_d t} \quad (2)$$

where k_d is the first order thermal deactivation rate constant, and σ is the substrate protection factor.

The kinetic parameter expressions k_p , k_s , k_d , k_e , k_m , v_m , v_p , v_s , x_e and σ can be found in a previous publication [1].

The above algebraic design equation is used in determining the performance of the reactor by studying the temperature effects $T(t)$ on the reactor conversion $x(t)$ at any time t . The performance of the reactor is described by its time average productivity Pr, and it is defined over the operating period t_f as:

$$\text{Pr} = \left(\frac{s_0}{\tau} \right) \left[\frac{\int_0^{t_f} x(t) dt}{\int_0^{t_f} dt} \right] \quad (3)$$

2.2

Packed bed reactor simulation and optimization

For a given residence time τ and initial glucose (substrate) concentration s_0 , selection of the optimal temperature mode $T(t)$ which maximizes the time average productivity Pr over the operating period t_f , $t \in [0, t_f]$ is an optimization problem, which can be posed as:

$$\text{Maximize Pr} = \left(\frac{s_0}{\tau} \right) \left[\frac{\int_0^{t_f} x(t) dt}{\int_0^{t_f} dt} \right] \quad (4)$$

subject to:

$$s_0 x(t) - k_m(T(t)) \ln \left[1 - \frac{x(t)}{x_e(T(t))} \right] = v_m(T(t)) \tau a(t) \quad (5)$$

$$x_e(T(t)) = \frac{k_e}{1 + k_e} \quad (6)$$

$$a = e^{-(1-\sigma(x(t), T(t)))k_d T(t)t} \quad (7)$$

$$v_m(T(t)) = \left(\frac{v_s k_p}{k_p - k_s} \right) \left(1 + \frac{1}{k_e} \right) \quad (8)$$

$$k_m(T(t)) = \left(\frac{k_p k_s}{k_p - k_s} \right) \left[1 + \left(\frac{k_e}{k_p} + \frac{1}{k_s} \right) \left(\frac{s_0}{1 + k_e} \right) \right] \quad (9)$$

$$\sigma(x(t), T(t))$$

$$= \frac{0.5 \left[k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]}{\left[k_p k_s \left(\frac{1+k_e}{s_0} \right) + k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]} \quad (10)$$

$$s' = s_0 (x_e(T(t)) - x(t)) \quad (11)$$

$$T^{\text{Lower}} \leq T(t) \leq T^{\text{Upper}} \text{ for all } t \in [0, t_f] ,$$

$$0.0 \leq x(t) \leq x_e(T(t)) \text{ for all } t \in [0, t_f] .$$

Note that, in the above formulation, the variables $T(t)$ and $x(t)$ are functions of operating time t , which we do not know explicitly their functional forms.

2.3

Optimal temperature operation mode

For given residence time τ , initial glucose concentration s_0 , and operating period t_f , the temperature operation mode of the immobilized packed bed reactor operating at constant outlet conversion x is determined. The reactor performance operating at constant outlet conversion x_0 , if possible, till the end of the operating period t_f is studied. As a measure of reactor performance the time average productivity Pr is used.

Let θ be a dimensionless time, defined as $\theta = \frac{t}{t_f}$, where $\theta \in [0, 1]$. With this change of variables, the original optimization problem will be formulated as:

$$\text{Maximize Pr} = \left(\frac{s_0}{\tau} \right) \left[\int_0^1 x(\theta) d\theta \right] ,$$

subject to:

$$s_0 x(\theta) - k_m(T(\theta)) \ln \left[1 - \frac{x(\theta)}{x_e(T(\theta))} \right]$$

$$= v_m(T(\theta)) \tau e^{-(1-\sigma(x(\theta), T(\theta))) k_d(T(\theta)) t_f \theta}$$

$$k_p = 1.7539 * 10^9 * e^{-7360.939/T(\theta)} ,$$

$$k_s = 431.6294 * e^{-2138.035/T(\theta)} ,$$

$$v_s = 1.1696798 * 10^{10} * e^{-7163.882/T(\theta)} ,$$

$$v_p = 1.5503 * 10^{14} * e^{-10469.39/T(\theta)} ,$$

$$k_d = 6.2716819 * 10^{23} * e^{-20551.81/T(\theta)} ,$$

$$k_e = 385.7142 * e^{-1996.4/T(\theta)} ,$$

$$x_e(T(\theta)) = \frac{k_e}{1 + k_e} ,$$

$$v_m(T(\theta)) = \left(\frac{v_s k_p}{k_p - k_s} \right) \left(1 + \frac{1}{k_e} \right) ,$$

$$k_m(T(\theta)) = \left(\frac{k_p k_s}{k_p - k_s} \right) \left[1 + \left(\frac{k_e}{k_p} + \frac{1}{k_s} \right) \left(\frac{s_0}{1 + k_e} \right) \right] ,$$

$$\sigma(x(\theta), T(\theta))$$

$$= \frac{0.5 \left[k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]}{\left[k_p k_s \left(\frac{1+k_e}{s_0} \right) + k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]} ,$$

$$s' = s_0 (x_e(T(\theta)) - x(\theta)) ,$$

$$0.0 \leq x(\theta) \leq x_e(T(\theta)) \text{ for all } \theta \in [0, 1] ,$$

$$T^{\text{Lower}} \leq T(\theta) \leq T^{\text{Upper}} \text{ for all } \theta \in [0, 1] .$$

For a given time $\theta_i \in [0, 1]$ and a specified outlet conversion $x_0(\theta_i)$, we have a nonlinear system of equations to solve, which consists of $T(\theta_i)$, $k_p(T(\theta_i))$, $k_s(T(\theta_i))$,

$v_s(T(\theta_i))$, $v_p(T(\theta_i))$, $k_e(T(\theta_i))$, $x_e(T(\theta_i))$, $v_m(T(\theta_i))$, $k_m(T(\theta_i))$ and $\sigma(x_0(\theta_i), T(\theta_i))$ as variables and the following equations:

$$s_0 x_0(\theta_i) - k_m(T(\theta_i)) \ln \left[1 - \frac{x_0(\theta_i)}{x_e(T(\theta_i))} \right]$$

$$= v_m(T(\theta_i)) \tau e^{-(1-\sigma(x_0(\theta_i), T(\theta_i))) k_d(T(\theta_i)) t_f \theta_i} , \quad (4)$$

$$k_p(T(\theta_i)) = 1.7539 * 10^9 * e^{-7360.939/T(\theta_i)} , \quad (5)$$

$$k_s(T(\theta_i)) = 431.6294 * e^{-2138.035/T(\theta_i)} , \quad (6)$$

$$v_s(T(\theta_i)) = 1.1696798 * 10^{10} * e^{-7163.882/T(\theta_i)} , \quad (7)$$

$$v_p(T(\theta_i)) = 1.5503 * 10^{14} * e^{-10469.39/T(\theta_i)} , \quad (8)$$

$$k_d(T(\theta_i)) = 6.2716819 * 10^{23} * e^{-20551.81/T(\theta_i)} , \quad (9)$$

$$k_e(T(\theta_i)) = 385.7142 * e^{-1996.4/T(\theta_i)} , \quad (10)$$

$$x_e(T(\theta_i)) = \left[\frac{k_e}{1 + k_e} \right]_i , \quad (11)$$

$$v_m(T(\theta_i)) = \left[\left(\frac{v_s k_p}{k_p - k_s} \right) \left(1 + \frac{1}{k_e} \right) \right]_i , \quad (12)$$

$$k_m(T(\theta_i)) = \left[\left(\frac{k_p k_s}{k_p - k_s} \right) \left[1 + \left(\frac{k_e}{k_p} + \frac{1}{k_s} \right) \left(\frac{s_0}{1 + k_e} \right) \right] \right]_i , \quad (13)$$

$$\sigma(x_0(\theta_i), T(\theta_i))$$

$$= \left[\frac{0.5 \left[k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]}{\left[k_p k_s \left(\frac{1+k_e}{s_0} \right) + k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]} \right]_i , \quad (14)$$

$$s'(\theta_i) = s_0 (x_e(T(\theta_i)) - x_0(\theta_i)) . \quad (15)$$

In order for the above system of equations to have a feasible solution i.e. the variable temperature $T(\theta_i)$ to be bounded between T^{lower} and T^{upper} at the specified time θ_i and outlet conversion $x_0(\theta_i)$. The above system of nonlinear equations can be written as a minimization problem as follows:

Minimize α ,

subject to:

$$s_0 x_0(\theta_i) - k_m(T(\theta_i)) \ln \left[1 - \frac{x_0(\theta_i)}{x_e(T(\theta_i))} \right] + \alpha$$

$$= v_m(T(\theta_i)) \tau e^{-(1-\sigma(x_0(\theta_i), T(\theta_i))) k_d(T(\theta_i)) t_f \theta_i} ,$$

$$k_p(T(\theta_i)) + \alpha = 1.7539 * 10^9 * e^{-7360.939/T(\theta_i)} ,$$

$$k_s(T(\theta_i)) + \alpha = 431.6294 * e^{-2138.035/T(\theta_i)} ,$$

$$v_s(T(\theta_i)) + \alpha = 1.1696798 * 10^{10} * e^{-7163.882/T(\theta_i)} ,$$

$$v_p(T(\theta_i)) + \alpha = 1.5503 * 10^{14} * e^{-10469.39/T(\theta_i)} ,$$

$$k_d(T(\theta_i)) + \alpha = 6.2716819 * 10^{23} * e^{-20551.81/T(\theta_i)} ,$$

$$k_e(T(\theta_i)) + \alpha = 385.7142 * e^{-1996.4/T(\theta_i)} ,$$

$$x_e(T(\theta_i)) = \left[\frac{k_e}{1 + k_e} \right]_i ,$$

$$v_m(T(\theta_i)) + \alpha = \left[\left(\frac{v_s k_p}{k_p - k_s} \right) \left(1 + \frac{1}{k_e} \right) \right]_i ,$$

$$k_m(T(\theta_i)) + \alpha = \left[\left(\frac{k_p k_s}{k_p - k_s} \right) \left[1 + \left(\frac{k_e}{k_p} + \frac{1}{k_s} \right) \left(\frac{s_0}{1 + k_e} \right) \right] \right]_i ,$$

$$\sigma(x_0(\theta_i), T(\theta_i)) = \left[\frac{0.5 \left[k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]}{\left[k_p k_s \left(\frac{1+k_e}{s_0} \right) + k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]} \right]_i ,$$

$$s'(\theta_i) = s_0 (x_e(T(\theta_i)) - x_0(\theta_i)) .$$

$$T^{\text{lower}} \leq T(\theta_i) \leq T^{\text{upper}} \text{ for given } \theta_i ,$$

$$0.0 \leq \alpha < \infty ,$$

where α is a positive variable. If the minimum is zero i.e. $\alpha = 0.0$, then the original system of nonlinear equations is satisfied and hence a feasible solution is found. If at certain time $\theta_j \in [0, 1]$ the minimum is different from zero, $\alpha \neq 0.0$, then the original system of nonlinear equations has no solution. Which means that the reactor cannot be run at the specified outlet conversion $x_0(\theta_j)$ at the given time θ_j . In this case, the reactor at times $\theta > \theta_k$ is operated isothermally at temperature $T(\theta_k)$. Where θ_k is the maximum allowable time under which the reactor is run under the specified conversion x_0 i.e. constant conversion, and temperature $T(\theta_k)$. Thus, the reactor should be operated at different conversions $x < x_0$ i.e. falling conversion. For all times $\theta_j > \theta_k$, the conversion x under which the reactor is operated isothermally at $T(\theta_k)$ is determined by solving the following optimization problem:

Minimize β ,

subject to:

$$s_0 x(\theta_j) - k_m(T(\theta_k)) \ln \left[1 - \frac{x(\theta_j)}{x_e(T(\theta_k))} \right] + \beta = v_m(T(\theta_k)) \tau e^{-(1-\sigma(x(\theta_j), T(\theta_k))) k_d(T(\theta_k)) t_f \theta_j} ,$$

$$\sigma(x(\theta_j), T(\theta_k)) = \frac{0.5 \left[k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]}{\left[k_p k_s \left(\frac{1+k_e}{s_0} \right) + k_p \left(1 + \frac{s'(1+k_e)}{s_0} \right) + k_s k_e \left(1 - \frac{s'(1+k_e)}{k_e s_0} \right) \right]} + \beta ,$$

$$s'(\theta_j) = s_0 (x_e(T(\theta_k)) - x(\theta_j)) ,$$

$$0.0 \leq x(\theta_j) \leq x_e(T(\theta_k)) \text{ for all } \theta_j > \theta_k ,$$

$$0.0 \leq \beta < \infty .$$

Note that at the given temperature $T(\theta_k)$, the kinetic parameters $k_p(T(\theta_k))$, $k_s(T(\theta_k))$, $v_s(T(\theta_k))$, $v_p(T(\theta_k))$, $k_e(T(\theta_k))$, $x_e(T(\theta_k))$, $v_m(T(\theta_k))$, and $k_m(T(\theta_k))$ are specified. If the minimum is zero i.e. $\beta = 0.0$, then the conversion $x(\theta_j)$ at time θ_j and temperature $T(\theta_k)$ is

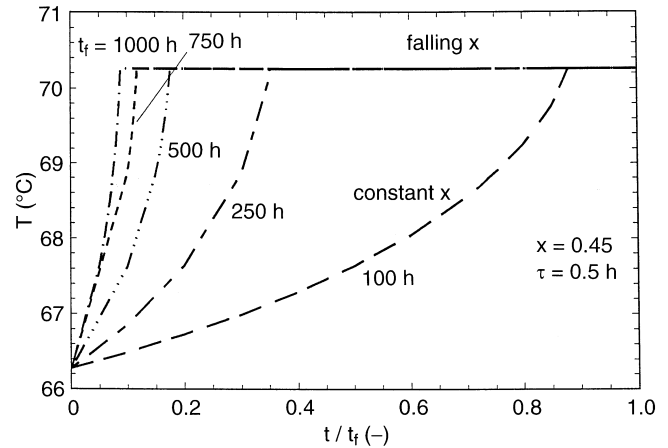


Fig. 1. Optimal temperature profiles of glucose isomerase reactor at different operating periods and residence time of 0.5 h

determined. The above minimization problems are solved using the GAMS software [10].

3 Numerical examples

The optimal temperature profiles required to achieve a certain glucose conversion are determined at different operating periods, residence times and glucose conversions.

The initial glucose concentration, s_0 of 2.8 mole/l is used in this work [11]. This value is a typical glucose concentration from the enzymatic liquifaction and saccharification of starch. Figure 1 shows an increasing temperature profile for operating periods of 100, 250, 500, 750 and 1000 h and residence time of 0.5 h. The required conversion here is 45% which corresponds approximately to 90% of the theoretical maximum conversion. As can be seen in the figure, constant conversion of 45% cannot always be achieved through out all of the operating periods. Figures 2 and 3 show the residual enzyme activity and glucose conversion respectively corresponding to the optimal temperature profiles in Fig. 1.

Figure 4 shows the temperature profiles for operating periods of 100, 250, 500, 750 and 1000 h for residence time

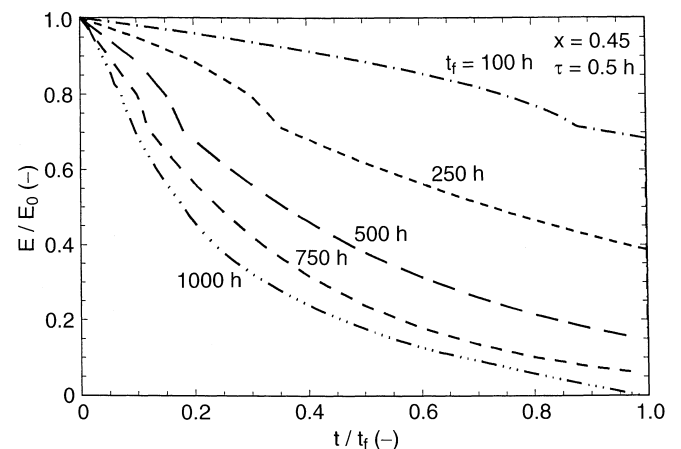


Fig. 2. Time course of GI deactivation corresponding to the temperature profiles in Fig. 1 and residence time of 0.5 h

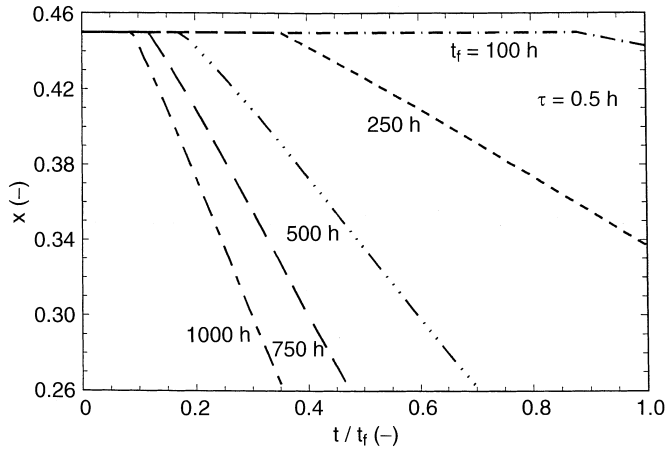


Fig. 3. Conversion profiles corresponding to the temperature profiles in Fig. 1 at different operating periods and residence time of 0.5 h

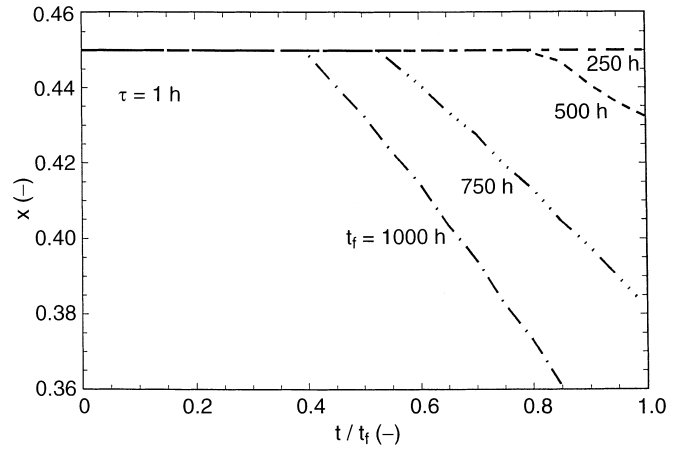


Fig. 6. Conversion profiles corresponding to the temperature profiles in Fig. 4 at different operating periods and residence time of 1 h

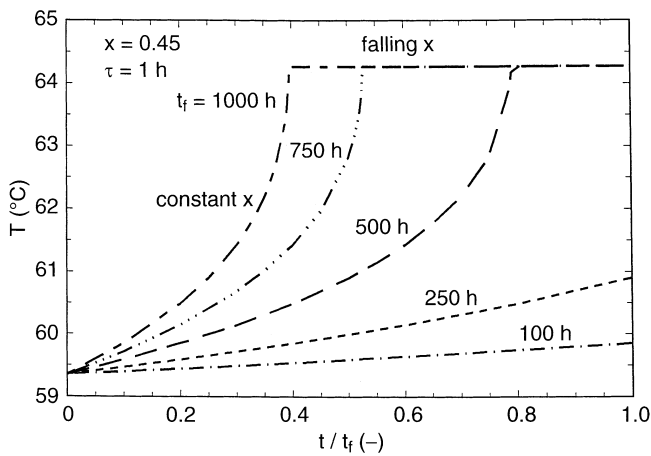


Fig. 4. Optimal temperature profiles of glucose isomerase reactor at different operating periods and residence time of 1 h

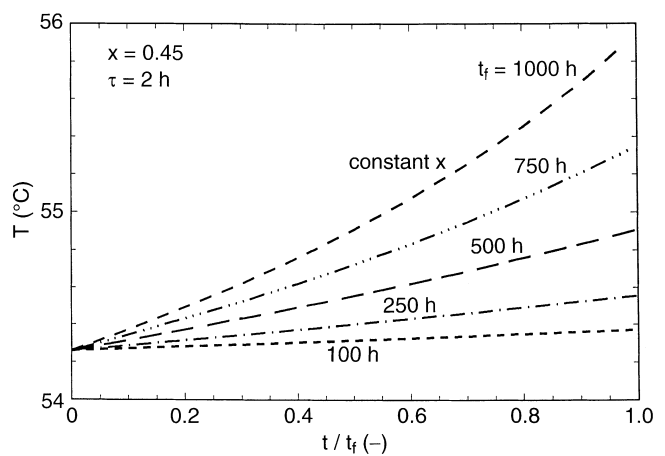


Fig. 7. Optimal temperature profiles of glucose isomerase reactor at different operating periods and residence time of 2 h

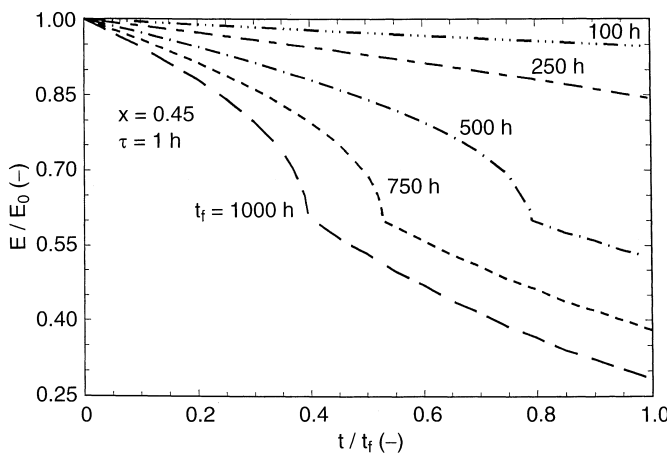


Fig. 5. Time course of GI deviation corresponding to the temperature profiles in Fig. 4 and residence time of 1 h

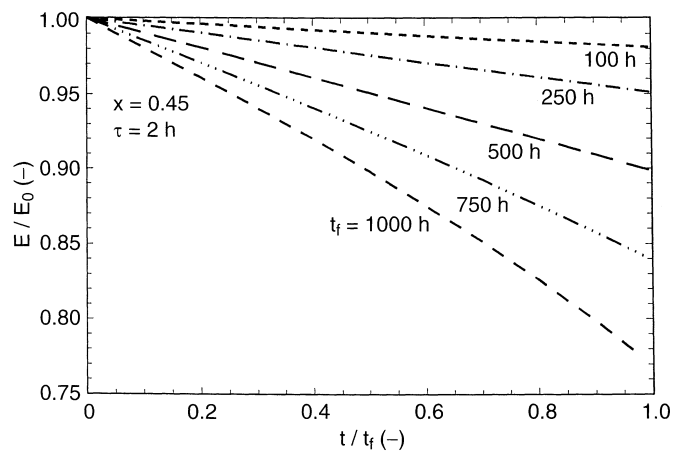


Fig. 8. Time course of GI deactivation corresponding to the temperature profiles in Fig. 7 and residence time of 2 h

of 1 h. Again, the required conversion here is 45%. Figures 5 and 6 show the residual enzyme activity and glucose conversion respectively corresponding to the optimal temperature profiles in Fig. 4.

Another optimal temperature profiles are determined for 2 h residence time (Fig. 7). The corresponding enzyme activity is shown in Fig. 8. It can be seen here that a constant glucose conversion of 45% is obtained

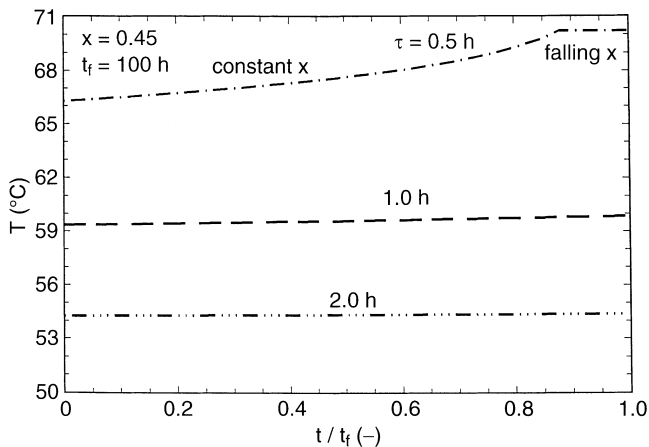


Fig. 9. Conversion profiles corresponding to the temperature profiles in Fig. 7 at different operating periods and residence time of 2 h

in all the operating periods studied using residence time of 2 h.

To show the effect of residence time on the optimal temperature profile; this temperature profile is plotted for operating period of 100 h and conversion 45% at residence times of 0.5, 1 and 2 h in Fig. 9.

To show the effect of the required reactor outlet glucose conversion on the optimal temperature profile, this temperature profile is plotted at different conversions for operating period of 100 h and residence times of 0.5 (Fig. 10) and 1 h (Fig. 11).

4 Discussion and conclusions

It is clear from Figs. 1, 4 and 7 that an increasing temperature profile is required to obtain a constant glucose conversion. This increase in temperature is used to compensate for loss of enzyme activity.

It is not always possible to obtain a constant conversion during the whole operating period. This depends on the residence time, length of the operating period and the required degree of conversion. Using residence time of 2 h, it is possible to obtain a 45% conversion in all the oper-

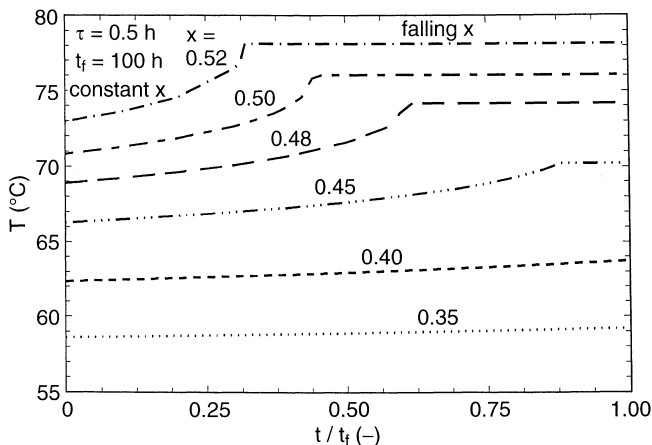


Fig. 10. Optimal temperature profiles of glucose isomerase reactor at different conversions and residence time of 0.5 h

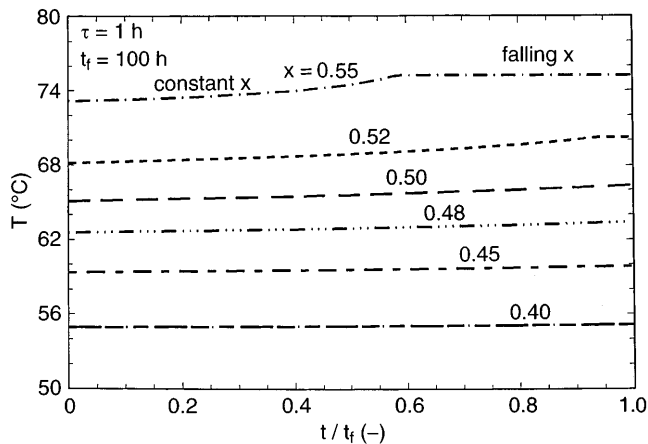


Fig. 11. Optimal temperature profiles of glucose isomerase reactor at different conversions and residence time of 1 h

ating periods studied, till the end of the period. While operating the reactor at 1 h residence time, a 45% conversion can be achieved only in operating time less than 396 h (i.e. 100, 250 h). Operating the reactor at constant temperature after this time results in almost linear decreasing conversion profile (less than 45%). For reactor operating at 1 h residence time, the maximum constant temperature is about 64 °C.

Operating the reactor at short residence time (0.5 h), it is not possible to obtain a 45% conversion after operating time of 88 h. The maximum temperature we can work with to get 45% conversion is 70.25 °C.

Inspecting the reduced enzyme activity profiles (Figs. 2, 5 and 8), it can be seen that curves can be divided into two distinct regions. The first one corresponds to the increasing temperature profile (45% conversion) followed by the constant temperature profile (falling conversion).

It is clear from Fig. 9 that the temperature increase is very small when operating the reactor at relatively long residence time such as 2 h (i.e. almost isothermal operation). The temperature rise increases when operating at relatively short residence time (0.5 h).

The effect of the degree of glucose conversion on the optimal temperature profiles shows that small degree of conversion can be achieved with a very small rise in temperature with time. The temperature rise increases at high degree of conversion. This is more obvious when operating the reactor at 0.5 h residence time.

From the results presented above it can be concluded that an increasing temperature profile should be used in GI reactor to maintain a constant reactor outlet conversion. The temperature increase with time is significant only at relatively high degree of conversion and at relatively short residence time.

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