Size-dependent growth kinetics of continuous mass crystallization of L-sorbose from its water solutions

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The kinetics of a continuous mass crystallization of L-sorbose from its water solutions was studied. A precise kinetic model assuming size-dependent growth (SDG) mechanism was employed. Influences of concentration of L-sorbose in a feeding mixture and mean residence time of suspension on the minimum and maximum values of linear growth rate and on nucleation rate were established. Comparison with kinetic data provided by size–independent growth (SIG) kinetic model was also made. All \( G(\infty) \) values predicted by SDG model (2.43 \( \times \) 10\(^{-8} \) – 1.20 \( \times \) 10\(^{-12} \) ms\(^{-1} \)) are of the same magnitude as \( G \) values provided by the simplest SIG model (1.89 \( \times \) 10\(^{-8} \) – 7.61 \( \times \) 10\(^{-8} \) ms\(^{-1} \)). Nucleation rate values, \( B \), estimated from SIG model are, however, highly devaluated (\( B = 1.85 \times 10^7 \) – 1.87 \( \times \) 10\(^7 \) m\(^{-3} \) s\(^{-1} \)) compared to the ones provided by SDG approach (\( B = 5.45 \times 10^18 \) – 1.0 \( \times \) 10\(^{21} \) m\(^{-3} \) s\(^{-1} \)) in which the \( n(L) \) predictions are more compatible with the experimental \( n(L) \) data in a whole size range tested.

Keywords: Kinetics, L-sorbose, Mass crystallization

L-sorbose (LS, C\(_6\)H\(_{12}\)O\(_6\)) is an intermediate, key–substrate in chemical synthesis of L(+)-ascorbic acid (vitamin C) according to Reichstein procedure\(^{1-4} \). As a semi–product in pharmaceutical industry it has to meet high quality and purity standards\(^5 \). Synthesized in industrial conditions, technical grade L-sorbose is subjected to purification using multistage batch cooling mass crystallization from its water solutions\(^5-8 \). To increase the unit productivity of the plant as well as to improve the crystal properties a third component (methanol or ethanol) is sometimes introduced into the system\(^9,10 \).

Besides the author’s works\(^{11-13} \), there is no significant report concerning application of a continuous process mode for this purification technology. This is due to the technical problems arising during the implementation of this regime into the industrial conditions. Relatively low production scale, necessity of preliminary concentrate of the feed solutions, higher constructional requirements compared to a batch variant, possibility of decomposition of L–sorbose during purification process, specific physicochemical properties of its supersaturated solutions\(^{14} \) are some factors making this process mode especially difficult in practical realization.

In the present article, the experimental results related to the kinetic aspects of continuous mass crystallization of L-sorbose from its water solutions are presented and discussed. The most simplified kinetic model of a continuous mass crystallization process in MSMPR crystallizer, assuming \( G(L) = G = \text{const.} \) (size–independent growth – SIG kinetic model) proved to be not fully adequate to correctly predict the population density distribution courses in the full size range, especially to render the characteristic, initial curvature in \( \ln n – L \) system for the smallest crystals (\( L < 100 \mu m \))\(^{11} \). Taking this fact into account, the measurement data were elaborated with a more adequate kinetic model (\( G(L) \neq \text{const.} \), size–dependent growth, SDG model) which takes into consideration the intrinsic nonlinearity observed in the experimental population density \( \ln n(L) \) course.

Experimental Procedure

The experiments were carried out in a continuous laboratory DT MSMPR (draft tube, mixed suspension mixed product removal) crystallizer of working volume \( V_w = 0.6 \text{ dm}^3 \) (main dimensions: \( D = 120 \text{ mm}, H = 123 \text{ mm} \)) with internal circulation of suspension provided by three–paddle propeller mixer (\( d_m = 55 \text{ mm} \)) installed inside the circulation profile.
(DT) element (of \( d = 61 \text{ mm} \) and \( h = 53 \text{ mm} \), 3 mm clearance). During all measurements the mixer’s revolution number was set constant at \( N = 10 \pm 0.2 \text{ s}^{-1} \). Stable isothermal process conditions (\( T_{cr} = 293 \pm 0.2 \text{ K} \)) were provided by the computer controlled automatic heating/cooling system. A detailed scheme of laboratory stand with the control systems arrangement is presented elsewhere\(^{11}\). Influence of concentration of L-sorbose in a feed solution (55–70 mass %) and mean residence time of suspension in a crystallizer working volume (900–3600 s) on the resulting crystal size distributions (CSDs) of the product – L-sorbose crystals – were the subject of current investigations. Experimental methods and analytical procedures used for the final products (both solid and liquid) examination were the same as presented elsewhere\(^{11}\). Selected test results are summarized in Table 1. The relationships for solubility (\( \rho_{sat} = f(T) \)) and density of saturated solutions (\( \rho_{sat} = f(T) \)) in L-sorbose – water system used in the calculations were derived and reported earlier\(^{5,6}\).

In the previous study\(^{11}\), it was concluded that the undischarged supersaturation \( \Delta c_{sat} \) observed in a postprocessed mother solution gradually reaches higher and higher values (from 2.0 up to 4.1 mass %), roughly correlated with the increase in the concentration of L-sorbose in a feed stream, \([LS]_{im}\) (assuming \( \tau = \text{const.} = 900 \text{ s} \)) in spite of the increase in the specific surface area of the crystal phase (since \( M_T = 191 \rightarrow 551 \text{ kgm}^{-3} \)). These values of supersaturation are relatively high and the most probably result from the occurrence of high values of maximal supersaturation in the solution, \( \Delta c_{max} \). Such values can be met especially at the crystallizer’s feed point (from 10.2 even up to 25.2 mass %; Table 1). This effect is coupled with too short mean residence time of crystal suspension in the crystallizer providing it with such arranged conditions of mass transfer. Some other reason can be a constant revolution number of a mixer applied for all measurements regardless of current magma concentration. It considerably devaluated mixing efficiency since about 3–fold increase in \( M_T \) parameter value was observed. More and more ineffective mixing in the bulk magma could be another factor responsible for the supersaturation peaks occurrence within the system. However, analyzing the values of some indicators of crystal product quality (\( L_m, \text{ CV} \)) one can conclude, that increase in a feed stream concentration is correlated with the advantageous improvement of mean crystal size and homogeneity within the population (\([LS]_{im} = 55 \rightarrow 70 \text{ mass } \% \) effects in \( L_m = 0.224 \rightarrow 0.245 \text{ mm} \) and \( \text{CV} = 62.2 \rightarrow 48.7\% \)). It can be thus assumed, that the negative effect of ineffective distribution of supersaturation within the system is compensated by positive effect of suppressed attrition, facilitating the growth of the crystals. It should also be noticed, that all CV values presented in Table 1 (\( \text{CV} = 44.0–68.8\% \)) are not remote from the CV = 50% value, theoretically predicted for MSMPR crystallizer configuration. Elongation of mean residence time of crystal suspension, \( \tau = 900 \rightarrow 3600 \text{ s} \), results in small increments in \( M_T \) value only (\( M_T = 191 \rightarrow 219 \text{ kgm}^{-3} \) and \( M_T = 430 \rightarrow 464 \text{ kgm}^{-3} \), for \([LS]_{im} = 55 \text{ and } 65 \text{ mass } \% \), respectively). Corresponding changes in \( L_m \) are: 0.224 \( \rightarrow \) 0.265 mm and 0.258 \( \rightarrow \) 0.280 mm, whereas in case of CV these are as follows: 62.2 \( \rightarrow \) 68.8\% and 44.0 \( \rightarrow \) 56.3%. Slight devaluation of product’s quality (\( \text{CV} \)) resulting from elongation of mean residence time and strong decrease in productability, in spite of a slight \( L_m \) improvement, are the main factors responsible for application in practice lower values of \( \tau \) (for \([LS]_{im} = 55–70 \text{ mass } \% \) it is \( M_T/\tau = 764 – 2204 \text{ kg of L-sorbose m}^{-3}\text{h}^{-1} \) for \( \tau = 900 \text{ s} \)) since for \([LS]_{im} = 55 \text{ mass } \% \) with \( \tau = 900 \rightarrow 3600 \text{ s} \), \( M_T/\tau = 764 \rightarrow 219 \text{ kg of L-sorbose m}^{-3}\text{h}^{-1} \) and for \([LS]_{im} = 65 \text{ mass } \% \) with \( \tau = 900 \rightarrow 3600 \text{ s} \), \( M_T/\tau = 1720 \rightarrow 464 \text{ kg of L-sorbose m}^{-3}\text{h}^{-1} \)).

In Fig. 1, two exemplary population density distributions of L-sorbose product crystals (in \( \text{ln} – \text{L} \)) were plotted, comparing their aspect to the integral of the calculated with the use of Eq. (4) and kinetic data from Table 3. Fig. 1-Comparison of population density distributions of L-sorbose crystals produced in a continuous DT MSMPR crystallizer: points (\( \Delta, \bigcirc \)) – experimental data, solid lines – values calculated with the use of Eq. (4) and kinetic data from Table 3.
coordinate system), corresponding to \([LS]_{rm} = 55\) and 70 mass % for mean residence time \(\tau = 900\) s \((\Delta, o – \text{experimental data} – \text{samples No. 1 and No. 4, Table 1})\) are presented.

From Fig. 1 it is obvious that in \(\ln n – L\) coordinate system, within the crystal fraction of \(L < 100\ \mu m\) the experimentally determined population density distributions \(\ln n(L)\) are clearly concave to top. Characteristic, strongly nonlinear segments of these function courses can be interpreted as a qualitative indicator of a more complex intrinsic kinetics of the crystal phase growth than it results from the most simplified SIG model approach. Deviation from \(\ln n(L)\) function’s linearity can result, among others, from the occurrence of growth rate dispersion \((G_i = \text{const.}, \text{GRD})\) phenomena, secondary nucleation within the dispersed crystal phase, as well as size–dependent differences in the solubility and relative fluid–crystal velocities, producing diversified convective mass transfer conditions (attributed especially to larger size fractions of the population under study)\(^{15–21}\). All these phenomena contribute up to various extent to the observed curvature of \(\ln n(L)\) plot, thus in practice their individual effects are undistinguishable considering the population density distribution data only. For the design or practical engineering calculation purposes, however, all they can be recognized as an integrity – complex set of the interrelated partial processes finally producing identical external effect observed in \(\ln n – L\) system. From this point of view they may be a subject of a unified, general description using any size–dependent growth, SDG model, mathematically convenient for the design–oriented, (substitute–) kinetic data evaluation.

### Results and Discussion

For the basic, simplified approach to the mass crystallization process kinetics, assuming steady state established in a continuous crystallizer with ideally mixed content and withdrawal of a non–classified, representative to the bulk magma product (MSMPR type crystallizer), population balance equation is a simple differential Eq. (1):\(^{22}\)

\[
-\frac{dn(L)}{n(L)} = \frac{dL}{G(L)\tau} + \frac{dG(L)}{G(L)}
\]

However, it is clear from the experimentally obtained population density distributions \(\ln n(L)\) of L-sorbose crystals (Fig. 1), that for the smallest crystals (especially for \(L < 100\ \mu m\)) their courses are clearly concave to top. Nonlinear, sudden increase in the number of crystal fines is of primary importance in many technical applications since within this size range the largest fraction of the whole crystals number is located. Considering its morphology, this crystal fraction provides the largest specific surface area in respect to the whole population contribution. A more detailed description of this process kinetics, considering SDG mechanism, thus rendering the experimentally observed strong nonlinearity in \(\ln n(L)\) function for L-sorbose crystals of \(L < 100\ \mu m\) requires to assume some form of \(G(L)\) dependency before solving such updated general population

<table>
<thead>
<tr>
<th>Sl No</th>
<th>([LS]_{rm}) [mass %]</th>
<th>(\tau) [s]</th>
<th>(\Delta c_{max}) [mass %]</th>
<th>(M_r) [kgm(^{-3})]</th>
<th>(L_m) [mm]</th>
<th>CV [%]</th>
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<tr>
<td>1</td>
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<td>900</td>
<td>10.2</td>
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<td>2</td>
<td>60</td>
<td>900</td>
<td>15.2</td>
<td>308</td>
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</tr>
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<td>900</td>
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<td>551</td>
<td>0.245</td>
<td>48.7</td>
</tr>
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<td>55</td>
<td>1800</td>
<td>10.2</td>
<td>207</td>
<td>0.230</td>
<td>66.2</td>
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<tr>
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<td>3600</td>
<td>10.2</td>
<td>219</td>
<td>0.265</td>
<td>68.8</td>
</tr>
<tr>
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<td>1800</td>
<td>20.2</td>
<td>450</td>
<td>0.268</td>
<td>52.4</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
<td>3600</td>
<td>20.2</td>
<td>464</td>
<td>0.280</td>
<td>56.3</td>
</tr>
</tbody>
</table>

\(\Delta c_{max} = [LS]_{rm} – [LS]_{eq, \text{Tcr}}\)

Process temperature in DT MSMPR crystallizer: \(T_{cr} = 293±0.2\) K

\([LS]_{eq} = 44.8\) mass % in \(T_{cr} = 293\) K
balance equation of MSMPR crystallizer i.e. Eq. (1). It must be, however, followed by statistical verification of a resulting n(L) function in respect to its ability for the experimental data reproduction.

Empirical or semiempirical G(L) equations, published by Canning and Randolph (CR)23, Abegg, Stevens and Larson (ASL)24, Rojkowski (exponential model, RE)25, hyperbolic model, RH26 and hyperbolic II model, RHII27) were analyzed in detail in respect to their mathematical limitations, both in G(L) and in corresponding n(L) forms28. Their accuracy for the experimental population density data lnn(L) modeling was verified using variance analysis. For each n(L) function derived (n_{calc}) and for each experimental p–element data set (n_{exp}) a mean square deviation (variance) was calculated, Eq. (2):

\[
\text{(RMSD)}^2 = \frac{\sum [\ln n_{calc}(L) - \ln n_{exp}(L)]^2}{p-1} \quad \ldots (2)
\]

Comparison of sums of variances \(\Sigma(\text{RMSD})^2\) for all 8 measurement series (corresponding to various process conditions) using all 5 SDG models (Table 2) enabled one to select an n(L) equation (thus – matched G(L) source–equation) which is statistically the best for 127 experimental n_{exp}(L) data description [assumed criterion – a minimal value of \(\Sigma(\text{RMSD})^2\)].

After verification procedure it was concluded, that the Rojkowski exponential (RE)25 model [\(\Sigma(\text{RMSD})^2\) = 6.344], Eqs (3) and (4):

\[
G = G_\infty - (G_\infty - G_0)\exp(-aL) \quad \ldots (3)
\]

suits well to the experimental n_{exp}(L) data. This SDG model renders both sudden curvature of lnn(L) course within the initial L range, as well as its apparent linearity within the remaining L range correctly enough. Knowing the nuclei population density, \(n_0\), and their linear growth rate (a minimum one), \(G_0\) (after estimation of the function’s parameter values using the nonlinear regression methods based on experimental data set), nucleation rate B can be calculated from the following formula, Eq. (5):

\[
B = n_0 G_0 \quad \ldots (5)
\]

Kinetic parameter \((n_0, G_0, G_\infty, a, B)\) values calculated with RE SDG model frame, corresponding to 8 various sets of process conditions ([LS]_m, \(\tau\)), are presented in Table 3.

With the increase in suspension density of L-sorbose crystals, \(M_T\), from 191 to 551 kg LS m\(^{-3}\) (as a consequence of increase in [LS]_m = 55 \(\rightarrow\) 70 mass %), assuming constant value of mean residence time of suspension in a crystallizer working volume, \(\tau = 900\) s (tests No. 1 – No. 4 in Tables 1 and 3), it is observed that:

- Maximal linear growth rate, \(G_\infty\), rises insignificantly from 8.41\cdot10^{-8} to 12.10\cdot10^{-8} ms\(^{-1}\) (excluding an unexpected value of \(G_\infty = 7.87\cdot10^{-8}\) ms\(^{-1}\) – test No. 3 – remote from the
clearly observed main trend). Average value of $G_\infty$ from all measurements (No. 1 – No. 4) is 9.20·10^{-8} \, \text{ms}^{-1}. It can be thus assumed, that feeding crystallizer with the solution meeting the technologically recommended range of L-sorbose concentration (55–60 mass %, No. 1 and No. 2), maximal growth rate, $G_\infty$, is about 8.4·10^{-8} \, \text{ms}^{-1}. For comparison, average value of linear growth rate, $G$, estimated from a simplified SIG model in the identical process conditions is 7.1·10^{-8} \, \text{ms}^{-1} only^{11}. This difference results from taking under consideration the linear segment’s slope only in SIG model, calculated using linear regression method, contrary to the potentially slightly different, asymptotic final slope for L \rightarrow \infty used by SDG nonlinear model for the adequate kinetic parameter value prediction.

- Nuclei population density, $n_0$, increases from 4.56·10^{-14} to 27.1·10^{-14} \, \text{m}^{-3} \cdot \text{m}^{-3} while some insignificant decrease in their (minimal) linear growth rate value (G_0 = 5.40·10^{-15} \rightarrow 4.06·10^{-15} \, \text{ms}^{-1}) is observed; average value of G_0 is 4.23·10^{-15} \, \text{ms}^{-1}.

- Nucleation rate, B, increases from 2.46·10^{-20} to 11.0·10^{30} \, \text{m}^{3} \cdot \text{s}^{-1}.

It can be concluded, that higher concentrations of L-sorbose in a feed solution (assuming unmodified $\tau$ value) produce higher supersaturation levels (Table 1, No. 1 – No. 4), which discharge runs towards creating new crystals within the system rather than towards intensification of growth of the existing crystal phase (since larger increase in B than in $G_\infty$ is observed for the runs 1–4, Table 3, Fig. 1).

With the elongation of mean residence time, $\tau$, from 900 up to 3600 s (tests No. 1, 5, 6 and 3, 7, 8, Tables 1 and 3) the values of maximal linear growth rate decrease significantly, $G_\infty = 8.41·10^{-8} \rightarrow 2.49·10^{-8} \, \text{ms}^{-1}$ ($M_T = 191 \rightarrow 219 \, \text{kg LS} \, \text{m}^{-3}$) and $G_\infty = 7.87·10^{-8} \rightarrow 2.43·10^{-8} \, \text{ms}^{-1}$ ($M_T = 430 \rightarrow 464 \, \text{kg LS} \, \text{m}^{-3}$), for [LS]_m = 55 and 65 mass %, respectively. A visible decrease in the nucleation rate values is simultaneously observed: $B = 246·10^{18} \rightarrow 5.45·10^{18} \, \text{m}^{3} \cdot \text{s}^{-1}$ and $B = 331·10^{18} \rightarrow 6.83·10^{18} \, \text{m}^{3} \cdot \text{s}^{-1}$, respectively. Significant decrease in $n_0$ parameter value is also observed: $n_0 = 4.56·10^{-14} \rightarrow 1.34·10^{-14} \, \text{m}^{-3}$ and $n_0 = 12.9·10^{-34} \rightarrow 3.84·10^{-34} \, \text{m}^{-3}$ for [LS]_m = 55 and 65 mass %, respectively.

In Fig. 1, two exemplary experimental population density distributions $n^{exp}(L)$ of L-sorbose product crystals, corresponding to [LS]_m = 55 and 70 mass % ($M_T = 191$ and 551 kgm $^{-3}$, respectively) and to mean residence time, $\tau = 900 \, \text{s}$ (feeding solution Nos 1 and 4 and Tables 1 and 3, respectively) are presented. In the same figure there are also overlaid the n(L) courses provided by Rojkowski exponential (RE) SDG model [Eq. (4), into which frame the adequate kinetic data from Table 3 were inserted for the simulation purposes]. Compatibility between the calculated and experimental n(L) data sets, resulting from the model flexibility, can be regarded satisfactory. Parallel, seemingly linear segments of ln(nL) courses suggest apparent stabilisation of $G_\infty$ value within the range of larger sizes. Some diversification between these curves results from higher nucleation rate, B, value for [LS]_m = 70 mass % which produces higher $M_T$, proportionally contributed by all crystal fractions. It thus produces practically parallel shift of the second curve upwards.

### Table 3-Nucleation rate and linear growth rates of L-sorbose crystals in a continuous DT MSMPR crystallizer. Rojkowski exponential (RE) SDG kinetic model applied ($T_\tau = 293 \, \text{K}$).

<table>
<thead>
<tr>
<th>Feeding solution (see Table 1)</th>
<th>$n_0$ [m$^{-3}$]</th>
<th>$G_0$ [m$^{-1}$]</th>
<th>$G_\infty$ [m$^{-1}$]</th>
<th>a [m$^{-3}$]</th>
<th>B [s$^{-1}$]</th>
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<td>1</td>
<td>4.56·10^{-14}</td>
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<td>8.41·10^{-8}</td>
<td>7.21</td>
<td>2.46·10^{20}</td>
</tr>
<tr>
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<td>7.68·10^{-14}</td>
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<td>8.42·10^{-8}</td>
<td>7.39</td>
<td>3.76·10^{20}</td>
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<tr>
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</tr>
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<td>7.75</td>
<td>6.83·10^{18}</td>
</tr>
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</table>
Conclusions

The concept of L-sorbose purification technology based on continuous mass crystallization process was tested in a laboratory DT MSMPR crystallizer. The effects of [LS]_m and τ changes were identified experimentally and compared. Kinetic data of the process were derived on the basis of Rojkowski exponential (RE) size–dependent growth rate (SDG) model. For practical engineering calculations the n(L) predictions provided by RE SDG model are sufficiently compatible with the experimental population density data. The characteristic curvature of ln(n(L)) function within the smallest size range is reproduced by RE SDG model correctly. All G_m values predicted by the model (2.43·10^{-8}–12.10·10^{-8} m^{-1}s^{-1}) are of the same magnitude as G values provided by a considerably simpler SIG approach (1.89·10^{-8}–7.61·10^{-8} m^{-1}s^{-1})^{11}. Corresponding values of G_m are, however, slightly higher, what can be related to the asymptotical levels provided by a nonlinear SDG approach for the theoretically infinite values of L (L → ∞). On the other hand, the values of nuclei population density, n_0, provided by SDG model vary from 1.34·10^{14} to 27.1·10^{14} m^{-1}m^{-3} since, for the identical experimental data, the SIG model provides only (so called “effective”) n_0 values from within the 0.98·10^{15}–2.48·10^{15} m^{-1}m^{-3} range^{11}. Consequently, the nucleation rate values, B, estimated from the SIG model seem to be highly devaluated (B = 1.85·10^{7}–18.87·10^{7} m^{-1}s^{-1})^{11} compared to the ones provided by a more accurate and more compatible with the experimental ln(n(L)) data RE SDG approach (B = 5.45·10^{15}–1.10·10^{15} m^{-1}s^{-1}). Thus, an RE SDG model enables one to evaluate the expected size distributions of L-sorbose crystals more accurately than it would be possible with the use of an alternative SIG approach.

Both the experimental results and their theoretical interpretation according to a more complex SDG kinetic model can be useful in design works concerning this process improvement or for selection of the optimal technological variant of L-sorbose purification in pharmaceutical and food industries.

Acknowledgements

Crystal size distributions of L-sorbose were determined by means of particle size analyzer COULTER LS–230 in the Institute of Inorganic Chemistry, Gliwice, Poland.

Nomeclature

- a: parameter in SDG kinetic equation, [m^{-1}]
- B: nucleation rate, [m^{-1}s^{-1}]
- c: concentration (mass fraction), [mass %]
- c_eq: solubility concentration, [mass %]
- ∆c: supersaturation of LS, [mass %]
- ∆c_max: maximal supersaturation of LS, [mass %]
- ∆c_ml: undischarged supersaturation of LS in a postprocessed mother solution, [mass %]
- CV: coefficient of variation (of crystal size), [%]
- d: draft tube’s diameter, [m]
$d_m$ agitator’s diameter, [m]
D crystallizer’s diameter, [m]
G linear growth rate of crystals, [ms$^{-1}$]
$G_0$ minimal linear growth rate of crystals (growth rate of nuclei), [ms$^{-1}$]
$G_m$ maximal linear growth rate of crystals, [ms$^{-1}$]
h draft tube’s height, [m]
H crystallizer’s height, [m]
L crystal’s characteristic size, [m]
$L_m$ mean size of crystal population, [m]
$[LS]_{eq}$ equilibrium concentration (solubility) of LS, [mass %]
$[LS]_{eq}$ concentration of LS in a feed solution, [mass %]
$M_T$ suspension density (mass of crystals per unit volume of suspension), [kg m$^{-3}$]
$n$ population density, [m$^{-3}$]
$n_0$ population density of nuclei (zero–size crystals), [m$^{-1}$ m$^{-3}$]
N mixer’s revolution number, [s$^{-1}$]
p number of elements in a data set, [–]
$q_v$ volumetric flow rate of crystal suspension, [m$^3$ s$^{-1}$]
T temperature, [K]
$T_{cr}$ temperature of mass crystallization process, [K]
$V_w$ working volume of a crystallizer, [m$^3$]

Greek letters
$\rho_{sat}$ density of saturated solution, [kg m$^{-3}$]
$\tau$ mean residence time of suspension in a crystallizer’s working volume, defined as $V_w/q_v$, [s]

Abbreviations
CSD crystal size distribution
DT draft tube (crystallizer)
GRD growth rate dispersion (kinetic model)
LS L-sorbose
MSMPR mixed suspension mixed product removal (crystallizer)
RE Rojkowski exponential (SDG kinetic model)
RMSD root mean square deviation
SDG size-dependent growth (kinetic model)
SIG size-independent growth (kinetic model)
calc calculated value
exp experimental value

References