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Comparative analysis of the thermal decomposition kinetics of β-cyclodextrin inclusion complexes with anabasine at different heating rates

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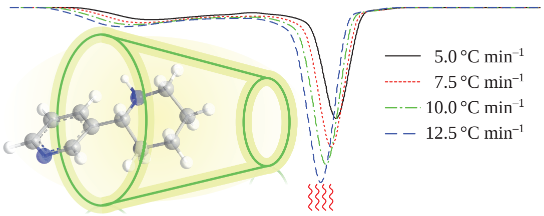
The results of analysis of the thermal decomposition kinetics of inclusion complexes of β-cyclodextrin with the alkaloid anabasine at different heating rates are presented. The kinetic characteristics of the processes are determined based on the Friedman, Flynn–Wall–Ozawa and nonparametric kinetics methods.



Keywords: dynamic thermogravimetry, cyclodextrins, anabasine, pre-exponential factor, thermal analysis, activation energy, thermodestruction.

Cyclodextrins (CDs) are cyclic oligosaccharides consisting of six or more glucose units linked by a glycosidic bond.[1,2] Due to their toroidal structure and the presence of an internal hydrophobic cavity, they are able to form guest–host inclusion complexes with various organic molecules.[3,4] This provides significant changes in the physicochemical properties of the substrate molecules associated with CD, *e.g.*, an increase in the stability of guest substances sensitive to oxygen or light,[5,6] an improvement in the solubility of substances in water,[7,8] the transfer of liquid substances into a powder form[9,10] and masking the unpleasant odors and taste.[11,12] Thus, studying the ability of CD to bind to biomolecules is of practical importance.

In this work, we evaluated the thermal stability and thermal degradation of supramolecular inclusion complexes of β-CD with the alkaloid anabasine prepared in 3 : 1, 2 : 1 and 1 : 1 ratios and referred to below as β-CD–An (3 : 1, 2 : 1, 1 : 1), respectively.[†]

The TG/DTG and DSC curves obtained at different heating rates of β-CD and its inclusion complex β-CD–An (1 : 1) in a nitrogen atmosphere are shown in Figure 1. The DSC curve of β-CD exhibits three endoeffects, accompanied by weight loss on the TG and DTG curves [Figure 1(*a*),(*b*)]. The low temperature endoeffect at 110.3 °C refers to the removal of water from the β-CD cavity. Two other thermal effects are associated with the destruction of alcohol groups and glucopyranose units. This conclusion is also confirmed by the results of the IR spectrometric analysis of the obtained anabasine clathrates with β-CD. In the IR spectrum [Figure 2(*a*)] of the decomposition products of β-CD, a broad band appears with a maximum at 3431 cm^{-1}, which belongs to the stretching vibrations of the O–H bond of hydroxyl groups linked by a hydrogen bond. There is also an absorption band of

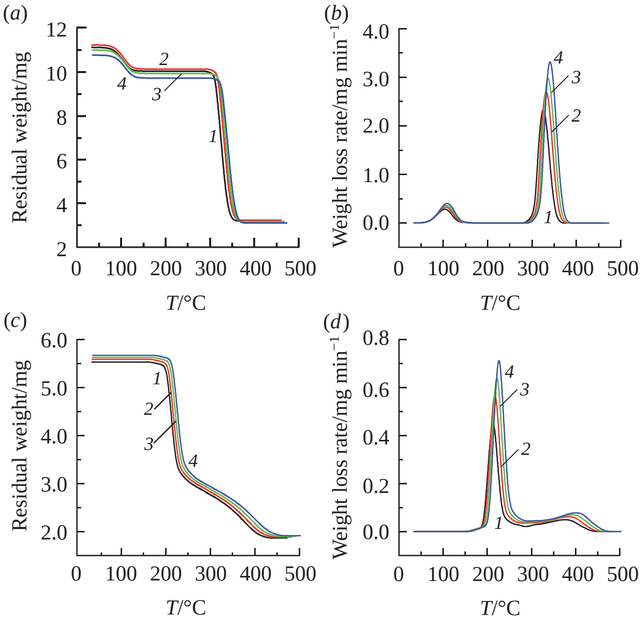


Figure 1 Temperature dependences of (*a*),(*c*) weight change and (*b*),(*d*) weight change rate for (*a*),(*b*) β-CD and (*c*),(*d*) β-CD–An (1 : 1) inclusion complex at heating rates of (*1*) 5.0, (*2*) 7.5, (*3*) 10.0 and (*4*) 12.5 °C min^{-1} in a nitrogen atmosphere.

[†] The investigation of the thermal decomposition kinetics of β-CD–An inclusion complexes was performed on a Setaram LabSys Evolution DTA/DSC differential scanning calorimeter in dynamic mode in the temperature range of 0–600 °C at heating rates of 5.0, 7.5, 10.0 and 12.5 °C min^{-1} in a nitrogen atmosphere (in an Al_2O_3 crucible). TC/DG data were obtained on a Setaram LABSYSTMEVO 16000C model with 30 mg samples at heating rates of 5.0, 7.5, 10.0 and 12.5 °C min^{-1}. The IR spectra were recorded on an FSM-1201 IR Fourier spectrometer. Methods for the preparation of cyclodextrin complexes of anabasine, vitamins and other biologically active substances, as well as their spectral characterization by FTIR, ^{1}H and ^{13}C NMR, ^{1}H–^{1}H COZY and ^{1}H–^{13}C HMQC methods, were previously published by us.[13–16]

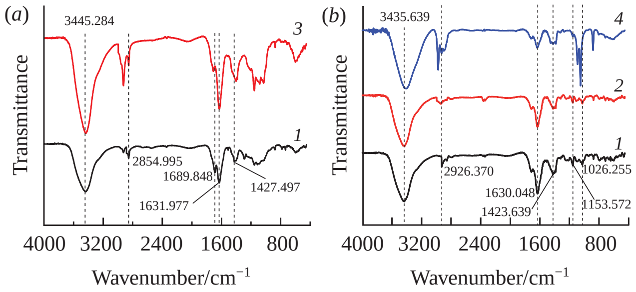


Figure 2 IR spectra of the decomposition products of (*a*) β-CD and (*b*) β-CD–An (1 : 1) inclusion complex after heating in the temperature ranges (*1*) 0–200, (*2*) 200–400, (*3*) 200–500 and (*4*) 400–600 °C.

stretching vibrations of C–H bonds in CH and CH_2 groups at 2924 cm^{-1}. Bands of bending vibrations of the O–H bond in COH groups and in water molecules appear at 1630 cm^{-1}. In the region of 1400, 1155 and 1030 cm^{-1} there are absorption bands of bending vibrations of C–H bonds in C–O and C–O–C.[17] The thermal destruction of β-CD–An inclusion complexes occurs similarly. At the same time, the intensity of the band of stretching vibrations of C–O–C groups (1051 cm^{-1}) in the IR spectrum increases with the decomposition of the β-CD–An (1 : 1) complex at a temperature of 400–600 °C.

The thermogram [Figure 1(*b*)] of the β-CD–An (1 : 1) inclusion complex shows thermal effects belonging to both anabasine and β-CD. In contrast to anabasine and its equimolar mixture with β-CD, the thermal effects of anabasine in inclusion complexes are shifted to the high-temperature region, and the melting temperatures of anabasine in inclusion complexes also increase. These results are consistent with the direct determination of the melting points of β-CD and its inclusion complexes (Table 1, Figure 1). Similar patterns are also observed in the IR spectrometric study of the decomposition products of β-CD–An complexes upon heating. Thus, the destruction of inclusion compounds begins with the removal of water molecules from the cavity, then anabasine, and only after that the thermal destruction of β-CD begins. Thermograms and IR spectra of clathrates are given in Figure S1 (see Online Supplementary Materials).

To compare the thermal stability of the inclusion complexes β-CD–An (3 : 1, 2 : 1, 1 : 1), the activation energies of their thermal decomposition reaction were determined. Processing of thermogravimetric curves taken at different heating rates (5.0–12.5 °C min^{-1}) was carried out by Friedman (FR)[18] and Flynn–Wall–Ozawa (FWO)[19] isoconversion methods. The choice of these methods is due to the possibility of comparing the activation energies obtained by the differential and integral methods. The results of the analysis are presented in Table 1, and graphical dependencies are given in Figure S2. Kinetic analysis was performed according to the ICTAC-2000 Protocol.[20]

Table 1 shows that β-CD has the highest value of the average activation energy ($\bar{E}_{FR}$ = 83.41 kJ mol^{-1}). Therefore, β-CD requires more energy to break down the cyclic oligosaccharide. The same activation energies in the β-CD–An inclusion complexes with a component ratio of 2 : 1 and 1 : 1 are explained by the fact that their formation occurs due to the same intermolecular interactions (see Table 1).

Table 1 Activation energies of the thermal decomposition of β-CD and β-CD–An inclusion complexes of various compositions in a nitrogen atmosphere.

Compound	$\bar{A}$/s^{-1}	$\bar{E}_{FR}$/kJ mol^{-1}	$\bar{A}$/s^{-1}	$\bar{E}_{FWO}$/kJ mol^{-1}
β-CD	2.72×10^{15}	83.41	23.4	78.91
β-CD–An (3 : 1)	4.65×10^{4}	74.62	0.11	70.60
β-CD–An (2 : 1)	4.50×10^{4}	71.86	0.11	67.99
β-CD–An (1 : 1)	9.63×10^{-1}	70.17	2.23	50.27

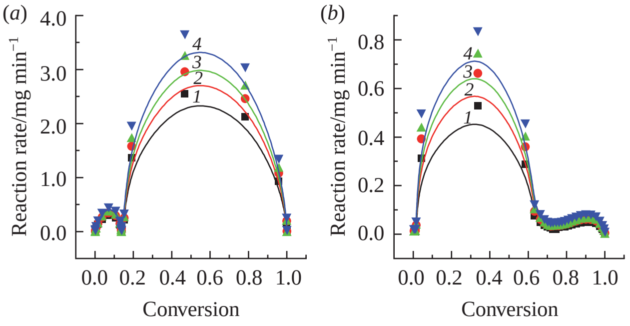


Figure 3 Dependence of the reaction rate dα/dT on the degree of conversion α for (*a*) β-CD and (*b*) the β-CD–An (1 : 1) inclusion complex at heating rates of (*1*) 5.0, (*2*) 7.5, (*3*) 10.0 and (*4*) 12.5 °C min^{-1}.

The statement that the activation energies of the thermal decomposition of β-CD and the β-CD–An inclusion complex are different at the same degrees of conversion (α) is based on a comparison of thermal destruction calculations at various ratios of the β-CD–An inclusion complexes. The use of isoconversion methods makes it possible to obtain the dependence of $\bar{E}$ on the degree of conversion α. Experimental data are presented as plots of dα/dT *versus* α. Figure 3 shows a family of curves obtained at different heating rates for β-CD and the β-CD–An (1 : 1) inclusion complex. Each value of α corresponds to a number of velocity values dα/dT. Thus, for any value of α, one can construct the plot of ln(dα/dT) *versus* T^{-1} and calculate the value of the activation energy for a given value of *a*.

Figure 3 shows the experimental data in the (dα/dt)–α coordinates, which are well described by the law $f(\alpha) = \alpha^m(1-\alpha)^n$, known as the empirical extended Šesták–Berggren model.[21] The condition for the maximum reaction rate corresponds to the expression: dT/dt (dα/dt) = 0, where dT/dt = β. The choice of $f(\alpha)$ was carried out according to the Šesták–Berggren method by selecting the most appropriate model in the coordinates (dα/dT)–α at different heating rates (β). As a function $f(\alpha)$ we used $f(a) = \alpha^m(1-\alpha)^n$. The parameters *m* and *n* affect the shape and position of the maximum of the dα/dT curve (see Figure 3).

To determine the kinetic parameters *m* (combined equation) and *n* (dimension), Šesták and Berggren[21] proposed the expression: $p = \alpha_{max}/(1-a_{max})$, where the kinetic parameter *p* can be calculated as $p = m/n$, while the second parameter *m* is determined from the relation $m = p \times n$. Table 2 shows the values of the exponents *m* and *n* for the experimental data obtained as a result of differential thermal analysis.

For β-CD, the most appropriate function is $f(a) = \alpha^{0.47}(1-\alpha)^{0.53}$ [Table 2 and Figure 3(*a*)], and for the β-CD–An (1 : 1) inclusion complex is $f(\alpha) = \alpha^{0.34}(1-\alpha)^{0.66}$. The highest decomposition rate (see Figure 3) is observed in β-CD. At the beginning of decomposition, the rate rapidly increases due to self-acceleration, reaching a maximum value at α_{max} = 0.47, and then rapidly decreases until almost complete cessation of decomposition [see Figure 3(*a*)]. The decomposition of the β-CD–An (1 : 1) inclusion complex also proceeds with self-acceleration up to α_{max} = 0.34, then the rate gradually decreases [Figure 3(*b*)].

To check the correctness of the obtained data, we also tried to compare the isoconversion methods with the calculation ones using the technique of nonparametric kinetics (NPK).[22] The NPK method is often used for processes occurring in parallel with thermal degradation. This mathematical model is a consequence of the equation $r_{i,j} = f(\alpha_i) \times k(T_j)$.[23,24]

The NPK method uses the singular value decomposition algorithm to decompose the matrix *M* into two vectors, u_0 and v_0.

Table 2 Kinetic parameters of thermal decomposition of β-CD and β-CD–An inclusion complexes with different component ratios, calculated by the NPK method.

Compound	$\bar{E}_{\mathrm{NPK}}$/ kJ mol^{-1}	$\bar{A}$/s^{-1}	Šesták–Berggren $\alpha^m(1-\alpha)^n$		$\bar{E}_{\mathrm{S-B}}$/ kJ mol^{-1}	$\bar{A}$/s^{-1}
			m	*n*		
β-CD	83.94	1.56×10^{15}	0.47	0.53	84.60	4.01×10^{16}
β-CD–An (3 : 1)	74.62	4.44×10^{4}	0.34	0.66	74.66	2.22×10^{5}
β-CD–An (2 : 1)	71.86	4.29×10^{4}	0.34	0.66	73.95	2.23×10^{5}
β-CD–An (1 : 1)	71.18	8.23×10^{7}	0.34	0.66	74.22	1.32×10^{7}

The matrix M is analyzed as follows: $M = U(\mathrm{diag}\times S)\times V^{\mathrm{T}}$. The experimental values of the reaction rates are placed in a matrix, which is expressed as a product of two vectors, u_0 and v_0, containing information about $k(T)$ and $f(\alpha)$. The vectors were compared with the Šesták–Berggren equation[21] $f(\alpha) = \alpha^m(1-\alpha)^n$ (see Figure 3), and the vectors v_1 and v_2 were compared with the Arrhenius equation. Figure 4 shows the dependence of the reaction rate ($\beta\times\mathrm{d}\alpha/\mathrm{d}T$) of β-CD and the β-CD–An (1 : 1) complex on temperature (T) and degree of conversion α in the form of a 3D surface. The main results of clathrate decomposition modeling for β-CD and inclusion complexes β-CD–An (3 : 1, 2 : 1, 1 : 1) are presented in Figure S3 in the form of a 3D surface.

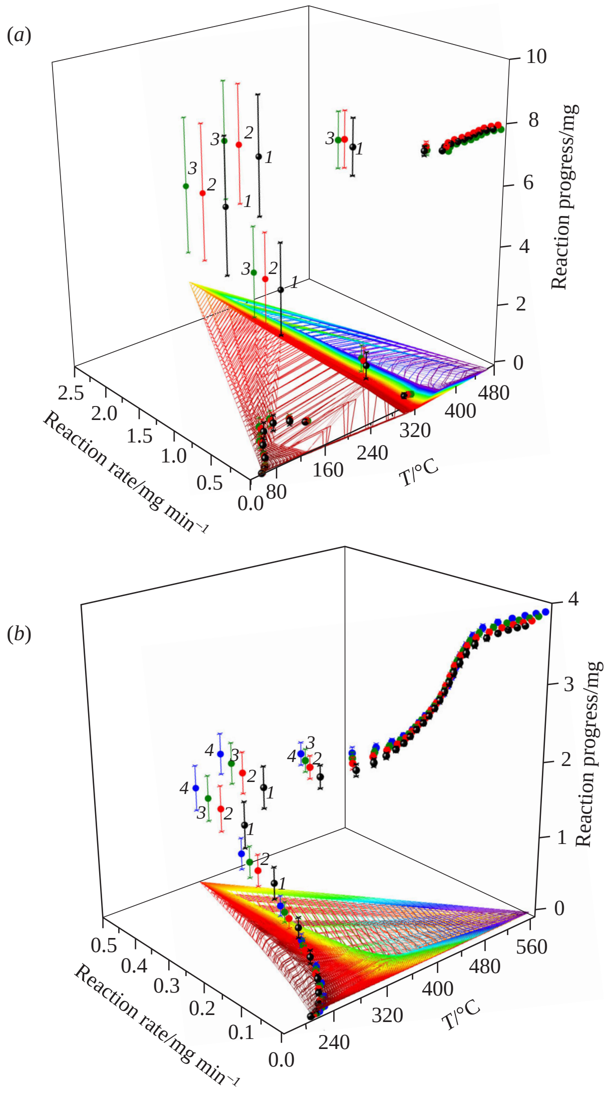


Figure 4 Dependence of the reaction rate ($\beta\times\mathrm{d}\alpha/\mathrm{d}T$) in thermal decomposition of (*a*) β-CD and (*b*) the β-CD–An (1 : 1) complex at heating rates of (*1*) 5.0, (*2*) 7.5, (*3*) 10.0 and (*4*) 12.5 °C min^{-1} on temperature T and degree of conversion α in the form of a 3D surface.

The values of the kinetic parameters of the thermal decomposition of β-CD–An inclusion complexes with different component ratios were calculated by the NPK method (Table 2). The average value of the activation energy determined by this method agrees with the results obtained by the differential isoconversion technique (see Table 2). Based on the analysis of the data in Figure 3 and Table 2, it can be assumed that the values of the empirical power exponents m and n in the Šesták–Berggren equation reflect the mechanism of the process, which, therefore, proceeds according to the chain autocatalytic mechanism.

In conclusion, the effect of complexation on the kinetic parameters of thermal destruction of β-CD and its inclusion complexes with the anabasine molecule was investigated. Thermal decomposition of β-CD and its clathrates is a complex set of parallel thermal degradation processes. The data of thermogravimetric analysis at different heating rates showed that β-CD and β-CD–An clathrates differ in the onset temperature of the thermal destruction reaction and in the nature of sample weight loss upon heating to 500 °C. The kinetic parameters of thermal degradation of β-CD–An (3 : 1, 2 : 1, 1 : 1) clathrate complexes were calculated by the FR and FWO methods, as well as by the NPK method. The activation energies of the processes calculated by the FR and FWO methods are in good agreement with the results of the NPK method. In accordance with the ICTAC recommendations, the obtained kinetic parameters can be used to describe and optimize the reaction conditions for the preparation of the β-CD inclusion complex with anabasine.

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Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2022.11.036.

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