ISSN 0036-0244, Russian Journal of Physical Chemistry A, 2022, Vol. 96, No. 2, pp. 248–258. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022, published in Zhurnal Fizicheskoi Khimii, 2022, Vol. 96, No. 2, pp. 173–183.

Heat Capacity, Thermodynamic Functions, and the Glass Transition of Butyl Methacrylate–Methacrylic Acid Copolymers

V. F. Ur'yash[a,]*, **S. V. Chuprova**[a], **N. Yu. Kokurina**[a], **and A. V. Markin**[a]
[a] *Lobachevsky State University, Nizhny Novgorod, 603022 Russia*
**e-mail: su2101@rambler.ru*

Received July 11, 2021; revised August 7, 2021; accepted August 9, 2021

Abstract—The heat capacities of four samples of butyl methacrylate–methacrylic acid copolymers with 7.6 to 37.3 mol % acid are measured in the temperature range of 6 (80)–330 K. The thermodynamic characteristics (enthalpy, entropy, and Gibbs function) of the above copolymers are calculated. The isotherms of thermodynamic functions in the studied range of temperatures and copolymer compositions are plotted and analyzed. The ordering of the system (the entropy factor), rather than the energy of intermolecular interaction (the enthalpy factor), is found to make the main contribution to the change in the Gibbs function. BMA–MAA copolymer with 7.6 mol % acid is shown to be the best for use as a matrix for transdermal administration of drugs.

Keywords: heat capacity, thermodynamic functions, butyl methacrylate, methacrylic acid, copolymers, composition

DOI: 10.1134/S0036024422020285

INTRODUCTION

The design of macromolecular therapeutic systems, particularly transdermal ones (TTSes) that can deliver drugs at specific doses to a target organ in strictly scheduled time intervals is a promising field of the application of polymers in medicine [1–11]. Such therapeutic systems of the new generation are protracted and do not induce shock, and drugs are not exposed to destructive action in the gastrointestinal tract. Having such properties as nontoxicity, resistance to biological media, and the capability of withstanding sterilization with no appreciable change in properties is a prerequisite for the applicability of a polymer material in any area of medicine. The material also should not display sensibilizing, carcinogenic, mutagenic, and teratogenic action. These requirements are met by many types of polymers, including acrylic ones [4–6, 12, 13]. However, each material must be selected on a case-by-case basis. Physicochemical and especially thermodynamic characteristics are required along with the above properties of a material. The study of these allows us to optimize the composition of a copolymer so that it meets specified requirements even better and can be used to solve a particular problem [4, 14–16].

The aim of this work was to study the thermodynamic characteristics (heat capacity, enthalpy, entropy, and Gibbs function) of butyl methacrylate (BMA) copolymers with methacrylic acid (MAA) as a function of temperature and composition, in order to select the best composition of the polymer system for use as a TTS matrix on the basis of the resulting data.

EXPERIMENTAL

BMA–MAA copolymers with 7.6–37.3 mol % MAA were synthesized via suspension polymerization according to the patented procedure in [4, 17]. The authors of that work failed to obtain copolymers containing more than ~40 mol % MAA, due to the physical instability of the suspension. Our proposed procedure allows the synthesis of MBA–MAA copolymers with deep conversion of monomers (99.5–99.8%), free of residual BMA monomer, and containing negligible amounts of water (less than 0.5 wt %). The resulting copolymer is therefore nontoxic. Such copolymers can be used in medicine to create binders for TTSes. Synthesis was performed via the suspension polymerization of monomers in an aqueous medium at pH 3 using an initiator (benzoyl peroxide) in two steps: 2 h at 343 K and 2.5 h at 353 K, using the stabilizer (0.3–0.6 wt %) sodium methacrylate (84 wt %)–methacrylic acid (16 wt %) copolymer at an initiator concentration of 1.5 wt %. The polymer was then washed several times with distilled water and dried. The composition of the copolymer was determined via titration of the carboxyl groups of MAA as recommended in [18]. The molecular weight of the copolymer varied from 88000 to 100000, depending on the content of MAA. X-ray diffraction showed the random BMA–MAA copolymers were completely amor-

Table 1. Molar weights of the repeating unit of BMA–MAA copolymers, weights of samples upon measuring heat capacity [4], and parameters Θ_D, A, and B

Sample	1	2	3	4
Content of MAA in BMA–MAA copolymer, mol %	7.6	25.1	28.5	37.3
Molar weight of the repeating copolymer unit, g (conv. mol)$^{-1}$	137.90	128.12	126.21	121.25
Weight of the copolymer upon measuring $C_p^\circ = f(T)$ in the range of 80–320 K, g	2.8044	3.3105	3.3137	2.4363
Weight of the copolymer upon measuring $C_p^\circ = f(T)$ in the range of 6–80 K, g	0.4665	0.3750	–	–
Parameter Θ_D in Eq. (2), K	46.3	46.4	46.3	46.2
Coefficient A in Eq. (3)	–	–	0.99222	0.96391
Coefficient B in Eq. (3)	–	–	0.0003145	0.000454

phous. The molar weight of the repeating unit of copolymers (conv. mol) was calculated using the equation

$$M_{\text{copol}} = X_1M_1 + X_2M_2, \quad (1)$$

where X_1 and X_2 are the molar fractions of BMA and MAA, respectively, and M_1 and M_2 are the molar weights of the repeating units of BMA and MAA, respectively.

The BMA and MAA monomers were purified via fractionation under reduced pressure. Chromatographic data showed that the content of the main component in the taken monomer fractions was 99.9 wt %. Refractive indices n_D at 293 K for BMA and MAA were 1.4240 and 1.4314, which coincided with reliable literature data [19].

Heat capacity (C_p°) was measured in the range of 80–330 K on a vacuum adiabatic calorimeter designed at the Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine, Kharkiv [4, 16, 20, 21]. The temperature was measured with a platinum resistance thermometer. The energy equivalent of the calorimeter was determined by measuring the heat capacity of a calorimetric ampule filled with helium up to a pressure of 8.5 kPa. It did not exceed 40% of the heat capacity of the calorimeter with a substance in the studied range of temperatures. To verify the procedure, we determined the heat capacity of reference K-1 benzoic acid (Mendeleev Institute for Metrology, St. Petersburg). The difference between our data and those of [22] was 0.3% at T = 80–330 K. The rise in temperature in measuring heat capacity was 1–3 K, so we did not correct for the curvature of function $C_p^\circ = f(T)$. The deviation of the experimental data from the averaging curves was no more than 0.3%.

Heat capacity C_p° in the range of 6–80 K was measured on a BKT-3.07 vacuum adiabatic calorimeter with discrete heating and an automated system for maintaining the adiabaticity of measuring conditions [23, 24]. The calorimeter was designed and manufactured by AOZT Termis (Mendeleevo, Moscow oblast, Russia). The temperature was measured with a RIRT-2 iron-rhodium resistance temperature sensor ($R_0 \approx 100\ \Omega$). The absolute error of temperature measurements was $\pm 5 \times 10^{-3}$ K. The energy equivalent of the calorimeter was determined by measuring the heat capacity of an ampule filled with helium up to a pressure of 16 kPa. The heat capacities of references samples of K-1 benzoic acid and 11-4 high-purity copper were measured to verify the operational reliability of the calorimetric setup. The deviation of the obtained heat capacities from the instrument ratings and data in metrological works was 2% in the range of 6–20 K and did not exceed 0.5% in the range of 40–80 K.

We measured he heat capacities of four BMA–MAA copolymer samples (Table 1). The thermodynamic functions of substances $H^\circ(T) - H^\circ(0)$ and $S^\circ(T) - S^\circ(0)$ were calculated by integrating curves $C_p^\circ = f(T)$ and $C_p^\circ = f(\ln T)$, respectively, and Gibbs function $G^\circ(T) - G^\circ(0)$ was calculated using the Gibbs–Helmholtz equation. To calculate the thermodynamic functions of samples 1 and 2 (Table 1), their curves $C_p^\circ = f(T)$ were extrapolated from 6 to $T \to 0$ K using Debye' equation [4, 16, 25]:

$$C_p^\circ = nD(\Theta_D/T), \quad (2)$$

where $n = 1$ and Θ_D are ad hoc parameters (Table 1).

The heat capacities of samples 3 and 4 were measured from 80 K (Table 1), so their thermodynamic functions were calculated by extrapolating obtained dependences $C_p^\circ = f(T)$ of the above substances from 80 to $T \to 0$ K according to the Kelley–Parks–Huffman procedure [4, 16, 26]:

$$C_p^\circ = C_{p,\text{ref}}^\circ(A + BT), \quad (3)$$

where $C_{p,\text{ref}}^\circ$ is the heat capacity measured in the range of 6–80 K for the reference substance associated with the one studied (sample 2), and T is temperature, K.

Coefficients A and B in Eq. (3) were selected so that the solution to this equation coincided with the exper-

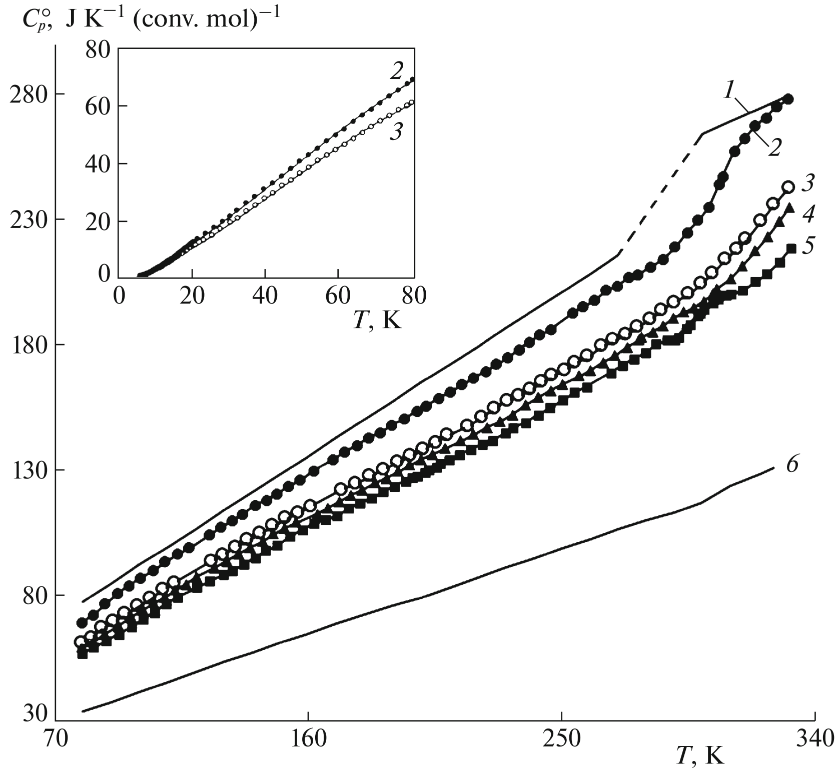

Fig. 1. Heat capacity–temperature dependences for the BMA–MAA copolymers with (*1*) 0 [30], (*2*) 7.6, (*3*) 25.1, (*4*) 28.5, (*5*) 37.3, and (*6*) 100 mol % MAA [27].

imental C_p° values of the substance in the range of 80–100 K with an error of no more than 0.3% (Table 1).

RESULTS AND DISCUSSION

Our experimental data are presented in Fig. 1 and Tables 2–5. Figure 1 also gives the heat capacities of PBMA (curve *1*) and PMAA (curve *6*) homopolymers. C_p° and the thermodynamic functions of PMAA have been studied since 1967 [27–30]. In [28, 30], C_p° of PMAA was measured in a vacuum adiabatic calorimeter with a batch energy supply in the range of 60–300 K and an error of 0.3%. In [29], it was measured in the range of 298–463 K in an adiabatic calorimeter with a continuous energy supply (heating rate, ~1 K min^{-1}) that had an error of 0.5% [31]. However, these articles never mention the content of residual water in the studied PMAA samples. Ur'yash et al. [27] measured $C_p^\circ = f(T)$ for PMAA (content of residual water, 2.5 wt %) in a vacuum adiabatic calorimeter in the range of 80–325 K. The content of water was calculated from thermochemical data while determining the enthalpy of combustion of PMAA. In [27], the heat capacity of anhydrous PMAA in the range of 80–325 K was calculated from existing data by assuming that C_p° is summed additively from the heat capacities of the polymer and water [32]. These data are shown in Fig. 1 (curve *6*). To calculate the thermodynamic functions of PMAA, its $C_p^\circ = f(T)$ was extrapolated from 80 to $T \to 0$ K with Eq. (3). The reference value was C_p° of sample 2. We obtained $A = 0.548326$ and $B = -0.0000227$.

Curve $C_p^\circ = f(T)$ for PMAA in the range of 295–306 K displayed a relaxation transition of endotermic nature that can be classified as a γ-transition ($T_\gamma = 300.6$ K) [4, 27] (Fig. 1, curve *6*). This transition occurs in glass-like polymers and is associated with the start of vibrations of pendant groups in the polymer chain [16]. Another two relaxation transitions (β and α) were detected via DTA in PMAA [4, 27]. The latter was associated with the glass transition of PMAA (T_g), and the β-transition was due to vibrations in the regions of polymer macromolecules that were smaller than the segment in [16]. Extrapolating T_g of PMAA as a function of the content of water in the sample to a zero content of H_2O allowed determination of T_g in anhydrous PMAA: 456 K [4, 27].

The first work on measuring the heat capacity of PBMA in a vacuum adiabatic calorimeter in the range of 93–433 K was published in 1971 [33]. These studies were continued by Wunderlich et al. [30] and Lebedev et al. [34] in the same calorimeter. In the latter work, $C_p^\circ = f(T)$ was measured in the range of 8–330 K with an error of ~1% around 10 K, 0.5% in the range of 10–

Table 2. Experimental heat capacities (J K^{-1} (conv. mol)$^{-1}$) of BMA–MAA (7.6 mol %) copolymer: M = 137.90 g (conv. mol) $^{-1}$

T, K	C_p°	T, K	C_p°	T, K	C_p°
6.112	0.8240	46.69	38.15	185.6	144.8
6.881	1.051	49.11	40.72	189.7	147.7
7.568	1.339	51.53	42.95	194.2	150.3
8.179	1.657	53.95	45.15	198.6	153.4
8.762	2.027	56.36	47.83	201.9	155.3
9.322	2.404	58.78	49.94	206.3	158.5
9.860	2.844	61.19	51.97	210.5	160.9
10.40	3.234	63.61	54.58	214.7	163.7
10.93	3.599	66.03	56.72	218.8	166.6
11.46	4.044	68.44	58.91	222.9	169.0
11.99	4.447	70.85	61.14	226.9	171.9
12.50	4.955	73.27	63.55	230.8	174.4
13.00	5.365	75.68	65.56	234.7	177.7
13.52	5.850	78.09	67.72	238.5	180.6
14.03	6.232	79.60	69.33	242.3	183.4
14.49	6.668	83.88	72.32	246.0	185.9
15.40	7.497	88.03	76.53	253.9	192.3
15.73	7.797	92.35	80.97	257.7	194.7
16.25	8.315	96.38	83.99	261.7	197.5
16.76	8.811	100.5	86.96	265.8	201.3
17.27	9,348	104.9	89.91	269.7	202.9
17.78	9.885	109.2	93.39	273.7	206.2
18.29	10.43	113.5	96.32	277.2	207.6
18.80	10.94	117.8	98.91	281.7	210.7
19.32	11.47	124.7	104.1	286.1	213.6
19.83	12.02	128.8	107.1	290.3	218.4
20.33	12.60	132.9	109.7	294.5	224.3
21.57	13.73	136.9	112.4	298.4	229.2
23.76	15.59	141.0	115.8	302.3	234.2
26.01	17.63	145.1	117.9	305.9	243.2
28.27	19.74	149.1	120.5	307.2	246.5
30.33	21.59	153.1	123.4	311.2	256.6
32.21	23.65	157.1	125.9	314.9	261.6
34.60	26.27	161.9	129.6	318.8	266.7
37.01	28.55	168.9	134.1	322.5	269.9
39.42	31.06	173.1	137.3	326.1	274.4
41.85	33.14	177.3	139.8	330.5	277.1
44.27	35.59	181.5	142.7		

Table 3. Experimental heat capacities (J K^{-1} (conv. mol)$^{-1}$) of BMA–MAA (25.1 mol %) copolymer: M = 128.12 g (conv. mol)$^{-1}$

T, K	C_p°	T, K	C_p°	T, K	C_p°
7.738	1.270	51.66	38.49	186.9	130.0
8.240	1.443	54.07	40.98	191.7	132.8
8.822	1.793	56.48	42.73	196.3	135.3
9.379	2.100	58.89	44.67	200.8	138.0
9.924	2.567	61.30	46.61	205.3	140.8
10.45	2.862	63.71	48.63	209.5	143.6
10.98	3.233	66.12	50.54	217.0	147.3
11.49	3.573	68.53	52.73	221.8	150.8
12.01	3.943	70.94	54.67	226.4	154.5
12.52	4.384	73.35	56.54	230.8	157.4
13.02	4.714	75.76	58.60	235.0	159.4
13.49	5.180	78.17	60.21	239.1	161.8
13.98	5.451	79.48	61.15	242.9	164.8
14.48	5.899	83.24	63.20	246.8	167.2
14.98	6.292	87.03	66.94	251.0	169.7
15.80	7.007	90.89	69.63	254.7	172.3
16.56	7.519	95.15	72.51	259.4	174.8
17.60	8.495	99.79	75.52	264.1	178.9
18.66	9.448	104.2	78.76	268.6	181.4
19.72	10.53	108.5	82.48	273.0	183.6
21.17	11.55	112.6	85.03	277.2	186.8
23.34	13.14	125.6	93.58	281.5	189.6
25.55	14.87	130.1	96.22	285.8	193.5
27.79	17.05	134.4	99.16	290.1	196.5
30.51	19.39	138.6	101.9	295.2	199.8
32.44	20.85	143.0	104.6	299.5	203.7
34.82	23.15	147.7	107.6	303.6	207.7
37.22	25.37	152.2	110.5	308.1	213.3
39.62	27.70	156.6	112.9	312.2	217.5
42.03	29.63	160.9	115.5	315.5	221.4
44.44	32.13	171.9	121.9	320.8	228.5
46.85	34.00	177.0	124.4	325.6	235.5
49.25	36.55	182.0	127.2	330.7	241.9

Table 4. Experimental heat capacities (J K^{-1} (conv. mol)$^{-1}$) of BMA–MAA (28.5 mol %) copolymer: M = 126.21 g (conv. mol)$^{-1}$

T, K	C_p°	T, K	C_p°	T, K	C_p°
79.77	59.54	171.1	117.3	260.4	169.6
83.70	61.42	175.3	119.9	264.6	172.7
88.02	64.75	179.4	122.1	268.9	175.3
92.71	67.78	183.6	124.8	273.2	178.8
97.26	71.30	187.7	126.5	277.6	181.6
101.3	74.20	191.9	129.3	278.3	182.4
105.2	77.11	196.0	131.9	282.3	184.8
109.0	79.07	200.2	134.2	286.1	187.4
112.8	82.14	204.3	136.1	289.8	190.4
116.6	84.44	208.5	138.5	293.4	192.7
120.6	87.58	214.1	141.5	296.9	194.4
126.9	90.97	218.8	144.0	300.4	196.9
131.2	93.65	223.5	146.7	303.7	199.6
135.5	96.72	228.1	149.0	305.2	201.9
139.6	99.13	232.6	151.9	309.8	205.8
143.7	101.5	237.1	155.6	314.3	211.2
147.7	104.4	241.6	158.8	318.7	216.9
151.7	106.7	246.0	161.4	323.1	222.6
155.7	109.1	250.4	163.9	327.3	228.8
163.3	112.4	256.2	167.2	330.8	234.2
167.2	114.9				

Table 5. Experimental heat capacities (J K^{-1} (conv. mol)$^{-1}$) of BMA–MAA (37.3 mol %) copolymer: M = 121.25 g (conv. mol)$^{-1}$

T, K	C_p°	T, K	C_p°	T, K	C_p°
79.74	57.21	178.2	116.8	258.8	163.1
83.91	59.48	182.4	118.6	267.4	168.5
88.23	62.03	186.4	121.1	271.7	171.5
92.64	64.65	190.5	123.6	275.6	174.2
97.10	67.52	194.6	125.5	279.6	176.4
101.3	70.62	198.6	127.3	283.4	179.9
105.4	73.37	202.8	129.9	287.6	181.4
109.6	76.79	206.9	132.4	291.5	182.6
113.7	79.38	196.9	126.8	295.4	187.5
120.5	83.16	201.6	129.0	299.1	192.4
124.7	85.79	205.7	131.1	289.9	181.8
129.8	88.29	209.8	133.9	294.3	186.1
132.9	89.88	213.8	136.2	298.1	191.0
137.0	92.41	217.7	138.3	303.6	196.4
141.0	95.18	221.6	140.2	308.1	199.2
145.0	97.88	225.4	141.8	300.7	193.8
149.0	99.89	229.8	144.5	305.3	197.7
153.4	103.6	232.8	146.8	309.9	199.8
158.0	106.4	237.3	148.9	314.3	201.2
162.2	108.7	241.6	151.9	318.7	204.8
166.2	110.1	245.9	154.7	322.9	207.8
170.2	111.8	250.2	157.8	327.2	212.5
174.3	114.6	254.5	160.8	331.4	218.1

30 K, and 0.2% in the range of 30–330 K. We also have DSC data obtained in the range of 240–400 K [35]. Figure 1 shows the C_p° values for PBMA from [30] (curve *1*), since only this work gave numerical C_p° values of PBMA in the range of 80–450 K. The T_g values given in the literature for PBMA are 290 [30], 293 [34], and 312 K [35]. The T_g values obtained in [30] and [34] coincide with the error of its determination. Close T_g values were obtained for PBMA (295 K) via DTA [4, 36]. To calculate the thermodynamic functions of PBMA, its $C_p^\circ = f(T)$ was extrapolated from 80 to $T \rightarrow 0$ K according to Eq. (3). The reference was C_p° of sample 1. The resulting values of the coefficients were $A = 1.34178$ and $B = -0.002776$.

The heat capacity of the copolymer with 7.6 mol % MAA (Fig. 1, curve *2*; Table 2) grows monotonically in the range of 6–290 K. An anomaly of endotermic nature caused by devitrification of the copolymer ($T_{g1} = 306$ K) was then observed. Several BMA–MAA copolymers were analyzed via DTA in [4, 36]. All copolymer samples with 7.6 to 37.3 mol % MAA displayed two (<20 mol % MAA) or three (>20 mol % MAA) intervals of devitrification with transition temperatures T_{g1}, T_{g2}, and T_{g3}. The obtained data thus testify to the multiphase nature of the random BMA–MAA copolymers. It is commonly assumed that random acrylic copolymers have one T_g. This is true for the methyl methacrylate (MMA)–MAA system [29], but several T_g have been observed for some acrylic copolymers. For example, one or two temperature ranges of devitrification were found in [37] for MMA–butyl acrylate and MMA–ethyl hexylacrylate copolymers, depending on the composition of the monomer

Table 6. Average heat capacities and thermodynamic functions of BMA–MAA copolymer with 7.6 mol % MAA

T, K	C_p°, J K^{-1} (conv. mol)$^{-1}$	$H^\circ(T) - H^\circ(0)$, kJ (conv. mol)$^{-1}$	$S^\circ(T) - S^\circ(0)$, J K^{-1} (conv. mol)$^{-1}$	$-[G^\circ(T) - G^\circ(0)]$, kJ (conv. mol)$^{-1}$
10	2.745	0.00940	1.363	0.00423
20	11.87	0.07960	5.709	0.03458
40	31.03	0.5053	19.82	0.2875
60	51.55	1.331	36.30	0.8470
80	69.26	2.540	53.58	1.746
100	86.48	4.105	70.96	2.991
120	101.0	5.983	88.05	4.583
140	114.6	8.139	104.6	6.505
160	128.2	10.57	120.8	8.758
180	141.4	13.26	136.7	11.35
200	154.4	16.22	152.3	14.24
220	167.3	19.44	167.6	17.43
240	181.6	22.92	182.7	20.93
260	196.7	26.71	197.9	24.74
273.15	206.1	29.36	207.8	27.40
280	209.1	30.78	213.0	28.86
298.15	229.6	34.73	226.6	32.83
300	232.8	35.16	228.1	33.27
320	268.5	40.18	244.3	38.00
330	276.6	42.92	252.7	40.47

mixture. Three T_g in hybrid alkyd–acryl water-based resins were recorded via DSC in [38].

We may assume there were two reasons for the emergence of several T_g in the BMA–MAA copolymers [4, 36]. The first could be the distribution of MAA over the aqueous phase and droplets of a BMA emulsion during the synthesis of the copolymer. The second could be inhomogeneity in the composition that emerges upon polymerization up to deep conversions [18, 39]. Suspension polymerization thus proceeds under the conditions described in [17] to yield a BMA–MAA copolymer where the adsorption of solution-polymerized molecules of BMA–MAA copolymer highly enriched with MAA occurs on the surfaces of its grains. All resulting grains of the BMA–MAA copolymer thus have copolymer shells highly enriched with MAA, the devitrification of which is matched by relaxation transition T_{g3}. Core–shell morphology is exhibited by, e.g., MMA/alkyd particles resulting from hybrid miniemulsion polymerization [40]. The shells are enriched by polyacrylate and the cores are enriched by alkyd.

DTA data show [4, 36] that samples with more than 20 mol % MAA are characterized by a third temperature range of devitrification with average temperature T_{g2}, which corresponds to devitrification of the copolymer fraction obtained at deep conversions, the composition of which differs from that of the copolymer obtained up to conversion of 90%.

The experimental heat capacities of the copolymer with 25.1 mol % MAA are described by curve *3* (Fig. 1) and given in Table 3. The heat capacity of this copolymer grew monotonically in the temperature range of 6–300 K. The more dramatic increase at 303 K is explained by incipient devitrification, the average temperature of which (according to DTA data) was T_{g1} = 321 K [4, 36]. A similar pattern is observed for the BMA–MAA (28.5 mol %) copolymer sample, the heat capacity of which (Fig. 1, curve *4*; Table 4) grew monotonically in the range of 80–303 K. A more dramatic increase corresponding to the start of devitrification was then observed as well. DTA data show [4, 36] its average temperature was T_{g1} = 327 K. The heat capacity curve for the copolymer with 37.3 mol % MAA (Fig. 1, curve *5*; Table 5) displays one physical transition with average temperature T_{g1} = 299.5 K and the onset of the subsequent transition, the average temperature of which (according to DTA data) was T_{g2} = 337 K [4, 36].

The average C_p° values and thermodynamic functions of the studied BMA–MAA copolymers as a function of temperature are given in Tables 6–10. Since devitrification did not end at 330 K (Fig. 1, curves *2*–*5*), the thermodynamic functions in the

Table 7. Average heat capacities and thermodynamic functions of BMA–MAA copolymer with 25.1 mol % MAA

T, K	C_p°, J K^{-1} (conv. mol)$^{-1}$	$H^\circ(T) - H^\circ(0)$, kJ (conv. mol)$^{-1}$	$S^\circ(T) - S^\circ(0)$, J K^{-1} (conv. mol)$^{-1}$	$-[G^\circ(T) - G^\circ(0)]$, kJ (conv. mol)$^{-1}$
10	2.432	0.00800	1.100	0.00300
20	10.25	0.06990	4.944	0.02898
40	27.79	0.4475	17.46	0.2509
60	46.15	1.188	32.23	0.7458
80	61.32	2.272	47.71	1.545
100	76.21	3.649	63.02	2.653
120	89.98	5.312	78.14	4.065
140	102.8	7.241	92.98	5.776
160	115.3	9.421	107.5	7.779
180	126.0	11.84	121.7	10.07
200	137.7	14.47	135.6	12.65
220	150.0	17.35	149.3	15.50
240	162.9	20.48	162.9	18.62
260	175.7	23.86	176.4	22.00
273.15	184.2	26.23	185.3	24.38
280	188.7	27.51	189.9	25.66
298.15	203.2	31.06	202.2	29.23
300	204.9	31.43	203.5	29.62
320	227.3	35.74	217.4	33.83
330	241.5	38.08	224.6	36.04

Table 8. Average heat capacities and thermodynamic functions of BMA–MAA copolymer with 28.5 mol % MAA

T, K	C_p°, J K^{-1} (conv. mol)$^{-1}$	$H^\circ(T) - H^\circ(0)$, kJ (conv. mol)$^{-1}$	$S^\circ(T) - S^\circ(0)$, J K^{-1} (conv. mol)$^{-1}$	$-[G^\circ(T) - G^\circ(0)]$, kJ (conv. mol)^{1}
10	2.405	0.00790	1.089	0.00299
20	10.11	0.06900	4.885	0.02870
40	27.22	0.4397	17.15	0.2463
60	44.92	1.162	31.56	0.7316
80	59.30	2.213	46.59	1.514
100	73.22	3.540	61.33	2.593
120	86.88	5.140	75.89	3.967
140	99.91	7.008	90.25	5.627
160	111.1	9.121	104.3	7.567
180	122.6	11.46	118.1	9.798
200	133.7	14.02	131.6	12.30
220	145.0	16.81	144.9	15.07
240	157.0	19.83	158.0	18.09
260	169.1	23.10	171.1	21.39
273.15	178.8	25.38	179.6	23.68
280	183.3	26,62	184,1	24.93
298.15	195.9	30.06	196.0	28.38
300	197.3	30.43	197.2	28.73
320	218.0	34.56	210.6	32.83
330	233.2	36.82	217.5	34.95

Table 9. Average heat capacities and thermodynamic functions of BMA–MAA copolymer with 37.3 mol % MAA

T, K	C_p°, J K^{-1} (conv. mol)$^{-1}$	$H^\circ(T) - H^\circ(0)$, kJ (conv. mol)$^{-1}$	$S^\circ(T) - S^\circ(0)$, J K^{-1} (conv. mol)$^{-1}$	$-[G^\circ(T) - G^\circ(0)]$, kJ (conv. mol)$^{-1}$
10	2.333	0.00800	1.165	0.00365
20	9.787	0.06720	4.843	0.02966
40	26.28	0.4254	16.70	0.2426
60	43.23	1.121	30.59	0.7144
80	56.88	2.131	45.03	1.471
100	70.00	3.403	59.16	2.513
120	82.65	4.931	73.05	3.835
140	94.98	6.708	86.73	5.434
160	107.0	8.728	100.2	7.304
180	117.6	10.97	113.4	9.442
200	128.5	13.43	126.3	11.83
220	139.4	16.11	139.1	14.49
240	151.0	19.01	151.7	17.40
260	164.0	22.16	164.3	20.56
273.15	172.6	24.37	172.6	22.78
280	177.0	25.57	176.9	23.96
298.15	190.9	28.88	188.4	27.29
300	193.2	29.24	189.6	27.64
320	205.2	33.23	202.5	31.57
330	216.4	35.34	208.9	33.60

temperature range of the relaxation transition were calculated from curves $C_p^\circ = f(T)$ for the studied samples. Analysis of the isotherms of the concentration dependence of C_p° for the BMA–MAA copolymers (Fig. 2a, Table 10) showed that at low temperatures where the copolymers were in a glass-like state throughout the range of compositions, this dependence of the isobaric heat capacity of the copolymer was close to linear and fell when the content of MAA in the copolymer was raised. The deviations from the additive dependence were in this case minor and comparable to the error in determining C_p°. The transition of the systems into a high-elasticity state was accompanied by negative deviation from the corresponding linear dependences (e.g., the isotherm at $T = 300$ K, Fig. 2a). Of great interest are the isotherms of the concentration dependences of enthalpy (Fig. 2b), entropy (Fig. 2c), and the Gibbs function of heating (Fig. 2d). The enthalpy isotherms are additive at all temperatures (Table 10), since vitrification is an enthalpy-free transition [16, 20, 41]. The entropy isotherms of the copolymers (Fig. 2c, Table 10) display negative deviations from additive straight lines. These deviations range from 3 to 9%, which greatly exceeds the error in calculating entropy. At the same time, summand $T[S^\circ(T) - S^\circ(0)]$ makes a greater contribution to the Gibbs function of heating than the enthalpy part of the Gibbs–Helmholtz equation at all the above temperatures. The corresponding isotherms of the Gibbs function therefore also have a negative deviation from linear dependences at 100–300 K (Fig. 2d, Table 10). In other words, it is the ordering of the system, rather than the energy of intermolecular interaction, that makes the main contribution to the change in the Gibbs function for all the studied BMA–MAA copolymers. The studied copolymers therefore differ from the MMA–MAA copolymers described in the literature [29], for which the heat capacity and enthalpy show negative deviation from additivity. This suggests that the increase in the intermolecular interaction

Table 10. Average heat capacities (C_p°, J K^{-1} (conv. mol)$^{-1}$) and thermodynamic functions of BMA–MAA copolymers ($T[S^\circ(T) - S^\circ(0)]$, $[H^\circ(T) - H^\circ(0)]$, $[G^\circ(T) - G^\circ(0)]$, kJ (conv. mol)$^{-1}$)

T, K	C_p°	$H^\circ(T) - H^\circ(0)$	$T\,[S^\circ(T) - S^\circ(0)]$	$-[G^\circ(T) - G^\circ(0)]$
PBMA [30]				
100	92.03	4.720	8.390	3.670
150	128.3	10.23	19.20	8.970
200	164.5	17.54	33.98	16.44
250	200.7	26.67	52.62	25.95
300	263.4	38.01	75.48	37.47
BMA–MAA (7.6 mol %) copolymer				
100	86.48	4.105	7.096	2.991
150	121.4	9.319	16.92	7.601
200	154.4	16.22	30.46	14.24
250	189.3	24.78	47.57	22.79
300	232.8	35.16	68.43	33.27
BMA–MAA (25.1 mol %) copolymer				
100	76.21	3.649	6.302	2.653
150	109.0	8.301	15.04	6.744
200	137.7	14.47	27.12	12.65
250	169.1	22.14	42.42	20.28
300	204.9	31.43	61.05	29.62
BMA–MAA (28.5 mol %) copolymer				
100	73.22	3.540	6.133	2.593
150	105.7	8.034	14.60	6.565
200	133.7	14.02	26.32	12.30
250	163.5	21.43	41.12	19.69
300	197.3	30.43	59.16	28.73
BMA–MAA (37.3 mol %) copolymer				
100	70.00	3.403	5.916	2.513
150	101.0	7.687	14.02	6.336
200	128.5	13.43	25.26	11.83
250	157.6	20.55	39.50	18.95
300	193.2	29.24	56.88	27.64
PMAA [27]				
100	41.50	2.014	3.549	1.535
150	61.30	4.590	8.416	3.826
200	79.20	8.116	15.25	7.134
250	98.70	12.57	24.02	11.45
300	116.9	17.96	34.71	16.75

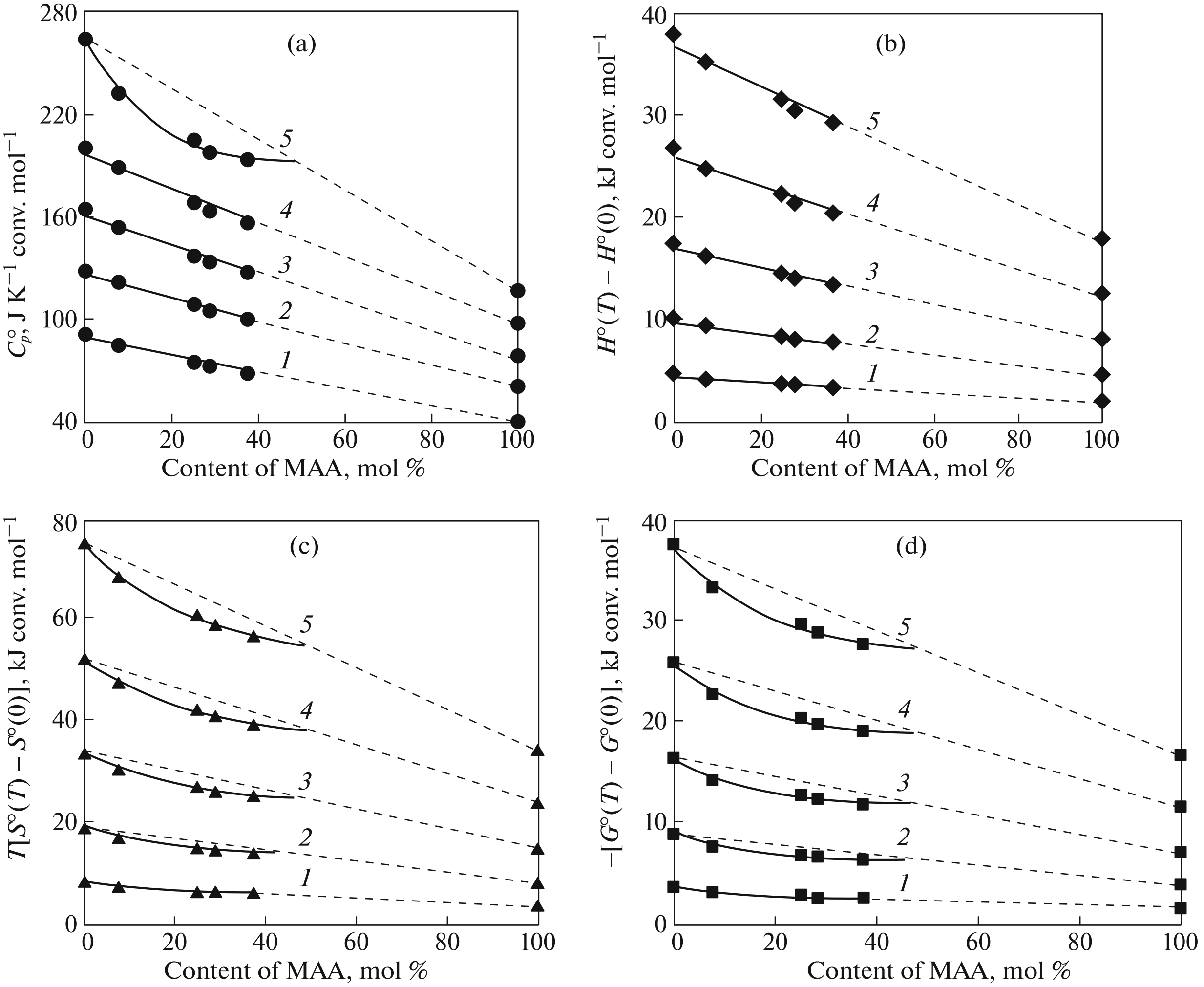

Fig. 2. Isotherms of the (a) heat capacity, (b) enthalpy, (c) entropy, and (d) Gibbs function for BMA–MAA copolymers at (*1*) 100, (*2*) 150, (*3*) 200, (*4*) 250, and (*5*) 300 K.

upon raising the content of MAA makes the main contribution to the Gibbs function of the MMA–MAA system.

CONCLUSIONS

Analysis of the thermodynamic characteristics and DTA data [4, 36] for BMA–MAA copolymers with 7.6 to 37.3 mol % of the acid showed that BMA–MAA (7.6 mol %) copolymer with two temperature ranges of devitrification ($T_{g1} = 306$ K and $T_{g3} = 419$ K) is the one best suited to be a matrix for the transdermal administration of β-adrenoreceptor blocking agents, nitroglycerin, chlorpropamide, acetylsalicylic acid, and other drugs. This was confirmed by studies on the diffusion of drugs from TTSes into the bodies of patients that were performed at the RF Ministry of Health's Shumakov Federal Research Center of Transplantology and Artificial Organs [6–8, 42].

CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest.

REFERENCES

1. *Artificial Organs,* Ed. by V. I. Shumakov (Meditsina, Moscow, 1990) [in Russian].
2. B*iocompatibility*, Ed. by V. I. Sevast'yanov (Inform. Tsentr VNIIgeosistem, Moscow, 1999) [in Russian].
3. *Progress in Biomedical Polymers,* Ed. by C. G. Gebelein and R. L. Dunn (Springer, New York, 2013).
4. V. Uryash, S. Chuprova, and N. Kokurina, *Thermodynamics and Thermal Analysis of Plasticized Copolymers Butyl Methacrylate with Methacrylic Acid, a Binder for Transdermal Therapeutic Systems* (LAP Lambert Academic, Saarbrücken, 2021).
5. N. A. Plate and A. E. Vasil'ev, Vysokomol. Soedin. A **24**, 675 (1982).
6. V. I. Sevast'yanov, L. A. Solomatina, A. A. Tikhobaeva, et al., Perspekt. Mater., No. 1, 46 (2004).

7. V. I. Sevast'yanov, L. A. Salomatina, N. V. Yakovleva, et al., Med. Tekh., No. 2, 3 (2000).
8. V. I. Shumakov, L. A. Salomatina, N. V. Yakovleva, et al., Vestn. Transplantol. Iskusstv. Organ., No. 4, 33 (1999).
9. M. I. Shtilman, Polymer Sci., Ser. A **52**, 884 (2010).
10. A. E. Vasil'ev, I. I. Krasnyuk, S. Ravikumar, and V. N. Tokhmachi, Khim.-Farm. Zh. **35** (11), 29 (2001).
11. *Biomaterials Science: An Introduction to Materials in Medicine,* Ed. by B. D. Ratner, A. S. Hoffman, F. J. Schoen, and J. E. Lemons (Elsevier Academic, London, 2004).
12. N. A. Lavrov and T. S. Kryzhanovskaya, Plast. Massy, No. 2, 42 (1995).
13. M. Dittgen, M. Durrani, and K. Lehmann, S. T. P. Pharma Sci. **7**, 403 (1997)
14. V. Kalous and Z. Pavliček, *Biofyzikální chemie* (SNTL, Prague, 1980).
15. G. M. Mrevlishvili, *Low-Temperature Calorimetry of Biological Macromolecules* (Metsniereba, Tbilisi, 1984) [in Russian].
16. V. Ur'yash and A. Gruzdeva, *Thermodynamics of Biologically Active Substances* (LAP Lambert Academic, Saarbrücken, 2017) [in Russian].
17. T. E. Knyazeva, V. A. Izvozchikova, and V. F. Ur'yash, RF Patent No. 2174522, Byull. Izobret., No. 28 (2001), p. 35.
18. T. E. Knyazeva, I. B. Myasnikova, and Yu. D. Semchikov, Polymer Sci., Ser. A **40**, 859 (1998).
19. Yu. S. Lipatov, A. E. Nesterova, T. M. Grishchenko, and R. A. Veselovskii, *Reference Book on Polymer Chemistry* (Nauk. Dumka, Kiev, 1971) [in Russian].
20. I. B. Rabinovich, V. P. Nistratov, V. I. Tel'noi, and M. S. Sheiman, *Thermodynamics of Organometallic Compounds* (Nizhegor. Univ., Nizh. Novgorod, 1996) [in Russian].
21. B. V. Lebedev and V. Ya. Lityagov, in *Thermodynamics of Organic Compounds, Interschool Collection* (Gor'k. Gos. Univ., Gorky, 1976), No. 5, p. 89 [in Russian].
22. A. A. Sklyankin and P. G. Strelkov, Zh. Prikl. Mekh Tekh. Fiz., No. 2, 100 (1960).
23. V. M. Malyshev, G. A. Mil'ner, E. L. Sorkin, and V. F. Shibakin, Prib. Tekh. Eksp., No. 6, 195 (1985).
24. R. M. Varushchenko, A. I. Druzhinina, and E. L. Sorkin, J. Chem. Thermodyn. **29**, 623 (1997).
25. N. V. Karyakin, *Principles of Chemical Thermodynamics, The Manual* (Akademiya, Moscow, 2003) [in Russian].
26. K. K. Kelley, G. S. Parks, and H. M. Huffman, J. Phys. Chem. **33**, 1802 (1929).
27. V. F. Ur'yash, N. Yu. Kokurina, V. N. Larina, and S. V. Chuprova, Polymer Sci., Ser. A **56**, 32 (2014)
28. I. B. Rabinovich, B. V. Lebedev, and T. I. Melent'eva, Vysokomol. Soedin., Ser. A **9**, 1699 (1967).
29. L. I. Pavlinov, I. B. Rabinovich, N. A. Okladnov, and S. A. Arzhakov, Vysokomol. Soedin., Ser. A **9**, 483 (1967).
30. U. Gaur, Sukfai Lau, B. Wunderlich, and B. Wunderlich, J. Phys. Chem. Ref. Data **11**, 1065 (1982).
31. M. M. Popov and G. L. Gal'chenko, Zh. Obshch. Khim. **21**, 2220 (1951).
32. *Thermodynamic Properties of Individual Substances, The Handbook,* Ed. by V. P. Glushko (Nauka, Moscow, 1978), Vol. 1, Part 2, p. 310 [in Russian].
33. R. Hoffmann and W. Knappe, Koll.-Z. Z. Polym. **247**, 763 (1971).
34. B. V. Lebedev, T. G. Kulagina, N. N. Smirnova, et al., Zh. Fiz. Khim. **69**, 581 (1995).
35. V. A. Bershtein, V. M. Egorov, and V. A. Ryzhov, Vysokomol. Soedin., Ser. B **28**, 268 (1986).
36. V. F. Uryash, T. E. Knyazeva, V. A. Izvozchikova, and N. Yu. Kokurina, in *Advances in Condensed Matter and Materials Research,* Ed. by F. Gerard (Nova Sci., New York, 2002), Vol. 3, pp. 169–175.
37. E. Yu. Ovchinnikov and Yu. P. Gorelov, Vysokomol. Soedin., Ser. B **30**, 677 (1988).
38. A. A. Yousefi, M. Pishvaei, and A. Yousefi, Prog. Color Colorants Coat. **4**, 15 (2011).
39. Yu. D. Semchikov, S. F. Zhil'tsov, and S. D. Zaitsev, *Introduction to Polymer Chemistry, The Manual* (Lan', Nizh. Novgorod, 2012) [in Russian].
40. J. G. Tsavalas, Y. Luo, L. Hudda, and F. J. Schork, Polym. React. Eng. **11**, 277 (2003).
41. D. F. Westrum, Jr. and J. P. Mccullough, in *Physics and Chemistry of the Organic Solid State,* Ed. by D. Fox, M. M. Labes, and A. Weissberger (Wiley, New York, 1965).
42. A. A. Tikhobaeva, L. A. Salomatina, and V. I. Sevast'yanov, Vestn. Transplantol. Iskusstv. Organov, No. 4, 50 (2003).

Translated by K. Utegenov