Aqueous solution of *N*-methylmorpholine *N*-oxide as a stationary liquid phase in steam chromatography

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The retention of more than 70 volatile organic compounds of different classes was studied by steam chromatography using aqueous solutions of *N*-methylmorpholine *N*-oxide as the stationary liquid phase (SLP). The effects of temperature and composition of the mobile phase on the retention factors (k) for polar and nonpolar sorbates were elucidated. An unusual order of elution of aliphatic alcohols was noted, namely, *tert*-butyl alcohol < *sec*-butyl alcohol < isopentyl alcohol < isobutyl alcohol < isopropyl alcohol < *n*-pentyl alcohol < *n*-butyl alcohol < *n*-propyl alcohol < ethanol < methanol. The retention of cyclohexanol was longer than those of benzyl alcohol and *n*-hexyl alcohol. Nitrogen-containing compounds were selectively separated on the water-organic SLP studied. For example, the retention of aniline was much longer than those of its derivatives, *N*,*N*-dimethylaniline and *N*,*N*-diethylaniline, having higher boiling points.

Key words: steam chromatography, selective stationary liquid phase, *N*-methylmorpholine oxide, retention factor, separation of alcohols, amines, and monoterpenes.

Development of steam chromatography (SC), in which steam is used as the mobile phase,[1—5] opens the way for designing new polar and selective stationary liquid phases. We showed previously[6—10] that under SC conditions, aqueous solutions of inorganic salts, acids, and bases form stationary liquid phases (SLP), which show sustained performance in separating homologs of polar compounds with unusually high selectivity.

The purpose of this work is to study aqueous solutions of *N*-methylmorpholine *N*-oxide (MMO), $C_5H_{11}NO_2$, as an SLP of a new type for SC. This compound is infinitely soluble in water, ether, and ethanol; it has a low volatility, is capable of donor-acceptor interactions, and at present, is widely used as a solvent for cellulose in manufacturing cellulose fibers.[12,13]

Experimental

Equipment. SC studies were carried out using a Biokhrom-1 gas chromatograph, design 21 (Special Design Office, Institute of Organic Chemistry of the RAS, Moscow), retrofitted for work in water vapors and equipped with a flame ionization detector (FID). The mobile phase, *viz.*, nitrogen saturated with water vapor, was prepared in a specially designed bubbler.[11] Some GC experiments were carried out on an LKhM-8MD with an FID using dry nitrogen as the carrier gas.

Preparation of the sorbent. MMO used in the work was a white crystalline powder containing 3—5% water and melting at ~150 °C. The sorbent was prepared by impregnating the solid support, Chromaton N-AW (Chemapol, Czech Republic), 0.16—0.20 mm fraction, with 8 wt% of MMO. The impregnation was effected by evaporating the volatile solution at ~20 °C from a suspension consisting of the solid support particles in an aqueous solution of MMO. The dried sorbent was placed in stainless-steel columns (200×0.3 cm) and studied in the 40—90 °C temperature range by GC and SC; the partial pressure of steam (p_{H_2O}) in nitrogen varied from 25 to 420 Torr.

Sorbates. Chromatography was performed for compounds of different chemical nature: aliphatic and aromatic alcohols, esters, ketones, alkanes and aromatic hydrocarbons, aliphatic and aromatic amines, amides, terpenes, and complex mixtures of various origins. The sample volume was 0.02—0.2 μL; that used for determination of impurities in organic compounds was 0.5—1.0 μL and that in analyses of water samples with trace impurities of organic compounds was 5—50 μL.

Chromatographic characteristics. The data on absolute retention times of sorbates were used to calculate the retention factor (k), taking methane to be a nonsorbable gas. To estimate polarity, the retention indices (RI) were determined. In addition, peak resolution (R_s), the asymmetry coefficients of peaks (A_s) at 0.1 height, the column efficiency (the number of theoretical plates, N), and the height equivalent to theoretical plates (HETP, H) were determined.

Results and Discussion

The physicochemical properties of MMO are summarized in Table 1.[13—18] The high hygroscopicity, pronounced dependence of the properties on the composition of the MMO hydrate, and low thermal stability restrict the use of this compound as a stationary phase in GC. Nevertheless, in analytical GC, the scope of practical application of some selective phases with a relatively low temperature

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Table 1. Physicochemical properties of *N*-methylmorpholine *N*-oxide (MMO)[12–18]

Parameter	Value
Hygroscopicity/% water	
2,5-hydro-MMO (2MMO · $5H_2O$)	28
monohydrate (MMO · H_2O)	13
M.p./°C	
2,5-hydro-MMO	36
MMO monohydrate	74–76
anhydrous MMO	184
Dec.p./°C	
anhydrous MMO	80–180
pK_a	
MMO monohydrate	~5
μ/D	
anhydrous MMO	4.1
2,5-hydro-MMO	5.0
n_d^{20} of an aqueous solution of MMO (%)	
60	1.431
50	1.414
40	1.398
20	1.365
Viscosity η/P s	
MMO monohydrate at 80 °C	0.075

limit, such as β,β′-oxydipropionitrile with a maximum operating temperature of 80 °C, is wide enough.

In view of the infinite solubility of MMO in water and the stability of its aqueous solutions, it is proposed to use the tertiary amine oxide in the SC analysis. Preliminary experiments were carried out simulating the formation of an aqueous solution of the organic SLP in the column. For this purpose, a mixture of nitrogen with a minor content of water vapor (p_{H_2O} = 25 Torr) was passed through a 2-cm layer of bulk MMO placed in a test tube. At 40 °C, a nontransparent aqueous solution of MMO was formed in the tube; at ~20 °C, it solidified. However, when similar experiments were carried out at higher temperatures, 70 and 90 °C, a stable light yellow transparent solution was formed. This suggests that, when MMO is used under SC conditions, an aqueous solution of the organic phase is formed in the column on the surface of the solid support, as this occurs during the formation of water-containing inorganic SLP.[19] The concentration of solutions of these SLP is determined by the temperature of the column and by the partial pressure of water vapor in the mobile phase. Therefore, columns with water-containing SLP are conditioned in a flow of steam or a carrier gas with a known partial pressure of water vapor; this is done every time the temperature of analysis changes. Since the column is immediately connected to a detector, the attainment of equilibrium between the mobile and stationary phases is indicated by stabilization of the zero line and by invariable retention parameters of the components of a standard mixture, for example, a 5% benzene solution of aliphatic C_1—C_4 *n*-alcohols. After this preliminary stage, a column with an aqueous solution of MMO as the SLP can be used to measure chromatographic characteristics by SC.

Retention. Water is known[1] to be an active polar SLP due to the presence of hydrogen bonds. In a binary liquid phase, MMO acts as a proton-donating solvent. The high dipole moment of the MMO molecule (see Table 1) is due to the presence of the semipolar ≡N→O coordination bond and two polar ≡C—O bonds in the morpholine ring.[14–16] The MMO molecule has two lone electron pairs on the O atom of the ≡N→O bond and exists as three thermodynamically equilibrated hydrated forms, namely, μ-MMO (monohydrate), δ-MMO (bihydrate), and 2,5-hydro-MMO. As the molecule of the tertiary amine becomes more saturated with water, its affinity to proton-containing compounds decreases. Due to the enhanced electron density on the ≡N→O bond in δ-MMO and μ-MMO, they react with hydroxy-containing molecules to give charge transfer H-complexes. In addition to high polarity, a MMO molecule is characterized by fairly high basicity (see Table 1, pK_a).

In a MMO solution containing more than 28% H_2O (*i.e.*, more than 2.5 water molecules per MMO molecule), a hydrogen bond network is formed.[16] A solution of this type is an assemblage of quasiplanar ring structures formed by water molecules and having MMO molecules on each side. This suggests that aqueous solutions of MMO are unusual phases.

Table 2 presents the data on the retention of volatile compounds of various classes under SC conditions. High-boiling C_{10}—C_{16} *n*-alkanes, whose molecules are able to interact only through dispersion forces, are eluted at temperatures 150–200 °C below their boiling points; the chromatographic zones of nonpolar compounds on the polar SLP are only slightly asymmetric (A_s = 1.2). It can be seen in Fig. 1 (plot *1a*) that the logarithm of the retention factor of *n*-alkanes varies linearly as a function of the boiling point of the nonpolar sorbate under conditions of SC. A similar dependence for these *n*-alkanes has been obtained using a dry carrier gas and a sorbent with anhydrous MMO (see Fig. 1, plot *1b*). However, the GC retention of *n*-alkanes is shorter than that with moist nitrogen and the sorbent with an aqueous solution of MMO. It should be noted that upon decreasing the temperature to 60 °C, *n*-alkanes with lower boiling points, *i.e.*, octane, nonane, and decane, can be separated on columns with anhydrous MMO or with aqueous solutions of MMO.

Polar compounds, for example, aliphatic alcohols, able to form strong hydrogen bonds under GC conditions show a type of behavior similar to alkanes. They are eluted from a column with MMO in accordance with their boiling points (see Fig. 1, plot *2b*). A different pattern of retention of aliphatic alcohols was found for a column with an aqueous solution of MMO. It is shown in Fig. 1 (plot *2a*) that under SC conditions, the ln*k* values of aliphatic C_1—C_8 *n*-alcohols vary nonlinearly with T_{boil} of the sorbates. The reverse order of elution of *n*-alcohols was found for a water-organic SLP, namely, butanol < pentanol < propanol < hexanol+ethanol < heptanol < methanol < octanol. The chromatographic

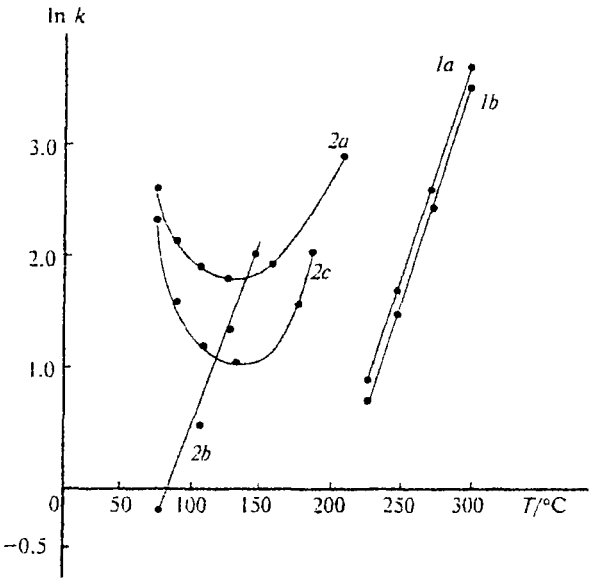

Fig. 1. Logarithms of the retention factor (log*k*) *vs.* the boiling points (*T*) of sorbates determined at 80 °C on columns with an aqueous solution of MMO (*1a*, *2a*), anhydrous MMO (*1b*, *2b*), and an aqueous solution of $LiNO_3$ (*2c*). Sorbates: C_{12}—C_{16} *n*-alkanes (*1a*), C_1—C_8 *n*-alcohols (*2b*). For *1*, *2*, and *2c*, p_{H_2O} = 350 Torr.

zones of both lower and higher alcohols are regularly shaped.

In our previous study,[8] a similar pattern of variation was found for *n*-alcohols on inorganic SLP, which were aqueous solutions of salts, for example, of lithium nitrate (see Fig. 1, curve *2c*). However, despite the similarity of experimental conditions, the retention of alcohols on an inorganic water-containing SLP is substantially shorter than that on the water-organic phase. This may be due to both different film thicknesses and different SLP compositions.

It follows from the data of Table 2 that the retention factors of *iso*-alcohols on an aqueous solution of MMO are lower than those for *n*-alcohols with the same number of C atoms. Due to steric hindrance, the contact of the hydroxy group of the alcohol with SLP molecules and the formation of hydrogen bonds is hampered. In the series of butyl alcohol isomers, *n*-butanol is retained most strongly, while the weakest retention is observed for *tert*-butyl alcohol, whose molecule contains three bulky methyl groups, which markedly shield the hydroxy group. Since the functional group in the isobutyl alcohol molecule is less shielded than that in the *tert*-butyl alcohol molecule, a stronger interaction between the *iso*-alcohol molecule and the SLP can be expected. A hydroxy group located in the center of the molecule of an aliphatic alcohol is also shielded by an alkyl radical; as a consequence, *sec*-butyl alcohol is retained more weakly than isobutyl alcohol.

The order of elution of butanol isomers from inorganic aqueous salt SLP[6] is the same as that observed for water-organic SLP. In the case of polar SLP (for example, polyethylene glycol[20]) in traditional GC, the retention of *sec*-butyl alcohol is greater than that of isobutyl alcohol. The aliphatic C_1—C_5 alcohols elute from a column with an aqueous solution of MMO in the order (T_{boil} are given): *tert*-C_4 (82.9 °C) < *sec*-C_4 (99.5 °C) < *iso*-C_5 (131.4 °C) < *iso*-C_4 (107.8 °C) < *iso*-C_3 (82.4 °C) < *n*-C_5 (137.8 °C) < *n*-C_4 (117.0 °C) < *n*-C_3 (97.8 °C) < C_2 (78.4 °C) < C_1 (64.7 °C). This SLP exhibits unusually high selectivity in the homologous series of alcohols. For example, isopropyl alcohol is retained three rimes as long as *tert*-butyl alcohol, while the difference between the boiling points of these compounds is 0.5 °C. The retention of *n*-propyl alcohol is two times longer than *sec*-butyl alcohol, with the difference between the boiling points being 1.7 °C (see Table 2). A similar sequence of elution of the C_1—C_5 aliphatic alcohols in traditional GC is known only for the gas—solid version on a column with sorbitol (a hexahydric alcohol with the gluco configuration) as the solid stationary phase.[20]

It can be seen from the data given in Table 2 that cyclic alcohols react with an aqueous solution of MMO more strongly than aliphatic or aromatic alcohols. Cyclohexanol is retained three times as long as *n*-hexyl alcohol (the difference between the boiling points of these compounds is 2.8 °C) and two times as long as benzyl alcohol, although the boiling point of the latter is almost 45 °C higher; menthol is retained 1.5 times as long as the aromatic alcohol, although the boiling point of the terpene alcohol is higher by only 8 °C.

X-ray diffraction and conformational studies have shown[16] that, irrespective of the number of hydration water molecules, MMO molecules exist as a chair conformation with a short (1.392 Å) axial N→O bond and the equatorial Me group. The similarity of the geometric configurations of six-membered saturated rings in cyclohexanol and MMO is apparently the crucial factor determining the higher selectivity of interaction of an aqueous solution of MMO with cyclic alcohols compared to aliphatic and aromatic alcohols.

Like alcohols, nitrogen-containing compounds tend to form strong hydrogen bonds. However, bases behave in water-organic SLP in different ways (see Table 2). The C_3—C_5 primary aliphatic amines are eluted in accordance with their boiling points, whereas in an inorganic alkaline aqueous SLP, these compounds come out of the column in the reverse order.[9] Triethylamine, whose molecules are unable to form hydrogen bonds, is eluted from a column with aqueous MMO between *n*-propylamine and *n*-butylamine; a cyclic amine, cyclopentylamine, is retained twice as long as *n*-pentylamine, although their boiling points are similar. A high retention factor is also typical of a low-boiling secondary amine, dimethylamine.

Aromatic amines are weaker bases than aliphatic amines because the electron density at the N atom decreases due to the conjugation of the lone electron pair with the π-electrons of the benzene ring. The interaction of aromatic amines with a water-organic SLP

Table 2. Retention factors (k) of compounds of various chemical natures on a column with an aqueous solution of *N*-methylmorpholine *N*-oxide by the SC method

Sorbate	B.p. /°C	k	
		80 °C, 350 mm H_2O	90 °C, 350 mm H_2O
	n-Alkanes		
Dodecane	214.5	2.6	0.8
Tridecane	234.0	5.5	4.0
Tetradecane	252.5	11.2	7.8
Pentadecane	270.5	23.2	17.6
Hexadecane	278.5	48.0	39.3
Heptadecane	303.0		50.0
	Alcohols		
Methanol	64.7	13.9	8.4
Ethanol	78.4	9.6	5.2
n-Propyl alcohol	97.8	8.0	4.7
n-Butyl alcohol	117.0	8.0	4.6
n-Pentyl alcohol	137.8	8.0	4.6
n-Hexyl alcohol	157.2	8.0	5.2
n-Heptyl alcohol	175.0	11.7	5.8
n-Octyl alcohol	194.5	18.3	6.4
Isopropyl alcohol	82.4	6.9	
Isobutyl alcohol	107.8	5.8	3.6
sec-Butyl alcohol	99.5		2.8
tert-Butyl alcohol	82.9	2.1	
Isopentyl alcohol	131.4	3.3	1.6
4-Methylpentan-1-ol	151.2		4.7
Cyclohexanol	160.0	22.1	14.7
Benzyl alcohol	204.4	10.3	5.85
α-Naphthol	288.0	9.6	
	Nitrogen-containing compounds		
n-Propylamine	49.0		5.6
n-Butylamine	77.8		6.9
n-Pentylamine	104.0		7.1
Cyclopentylamine	107.0		15.5
Dimethylamine	7.4	39.8	
Triethylamine	89.4	6.1	
Aniline	184.4		44.0
2,6-Dimethylaniline	214.0	35.9	41.6
N,N-Dimethylaniline	193.0		3.9
N,N-Diethylaniline	216.0		3.5
Pyridine	115.6	11.2	5.75
Quinoline	237.0		88.1
2,6-Dimethylphenol	180.0		115.1
p-Toluidine	200.3		64.5
Nitrobenzene	210.9		13.1
N-Methylbenzylamine	181.0		23.65
Diethyleneimide oxide	128.0		7.0
Acrylamide	215.0	7.6	
Dimethylformamide	153.0	3.2	
Acrylonitrile	78.0	1.6	
	Ethers and esters		
Methyl acetate	57.1	0.4	
Ethyl acetate	77.1	0.5	
n-Propyl acetate	101.3	0.3	
n-Butyl acetate	125.0	1.1	
n-Pentyl acetate	148.0	0.6	
Dioxane	80.0	4.0	
	Ketones		
Acetone	56.5	0.6	
Methyl ethyl ketone	79.6	1.0	
Cyclohexanone	155.0	6.6	4.9
	Unsaturated hydrocarbons		
1-Cetene	274.0		33.1
	Aromatic and other hydrocarbons		
p-Xylene	138.5	0.5	
Naphthalene	180.0	8.3	6.9
Biphenyl	254.9	18.8	15.6
Indene	180.0		25.2
	Terpene hydrocarbons		
Camphor	212.0	6.1	3.6
Camphene	160.0	0.5	
α-Pinene	154.0	6.1	
Menthol	212.0	16.5	
Menthone	205.0	3.6	
n-Cymene	177.0	1.0	
Borneol	212.0	23.0	
Bornyl acetate	228.5	3.9	
Thujone	203.0	6.7 (75 °C)	
Eugenol	253.5	7.2	
Geraniol	229.0	75.0	

is stronger than the interaction with an aqueous solution of potassium hydroxide[9] but they are eluted in the same order in both cases (in accordance with the boiling points). Pyridine is eluted prior to *n*-pentylamine, although it has a higher boiling point than the aliphatic amine. In the presence of SLP, strong retention of quinoline, which is almost 20 times longer than the retention of pyridine, was found (see Table 2 and Fig. 2).

Peculiar features of retention were found for aniline and its derivatives (see Table 2). The replacement of active hydrogen in the aniline amino group by methyl or ethyl groups (*N,N*-dimethylaniline and *N,N*-diethylaniline) decreases the retention factor by an order of magnitude. The amine group in the aniline molecule is markedly shielded by alkyl substituents in positions 2 and 6. Due to steric reasons, the amino group interacts more weakly with the molecules of the SLP; therefore, 2,6-dimethylaniline is eluted before aniline, although its boiling point is 20 °C higher. The retention of *N*-methylbenzylamine is almost twice as low as that of aniline; however, the chromatographic zone of this amine, unlike those of other nitrogen-containing compounds under analysis, is highly diffuse and skewed (A_s = 4.2).

It follows from Table 2 that diethyleneimide oxide and nitrobenzene interact fairly strongly with MMO, while acrylonitrile, dimethylformamide, and acrylamide show weaker interaction. Among the polar sorbates subjected to chromatography, 2,6-dimethylphenol and *p*-toluidine were retained most strongly by the water-organic SLP and came out of the column at a temperature above 90 °C.

In addition to dispersion interactions, aromatic compounds are capable of specific interactions due to π-complexation. Monoaromatic C_6—C_9 hydrocarbons

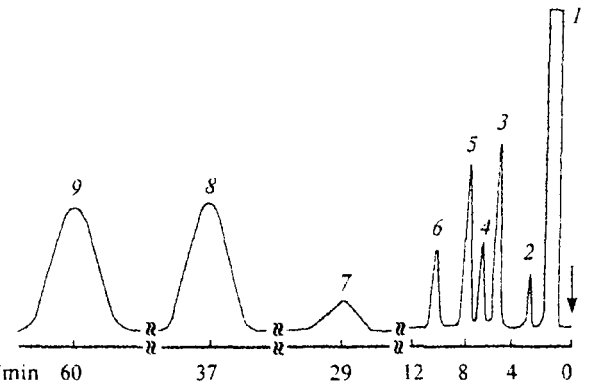

Fig. 2. Chromatogram of compounds with different chemical natures with similar properties obtained by the SC method on a column with an aqueous solution of MMO at 80 °C and p_{H_2O} = 350 Torr. Sorbates: benzene (*1*); *n*-tridecane (*2*); naphthalene (*3*); pyridine (*4*); methanol (*5*); *n*-octanol (*6*); 2,6-dimethylaniline (*7*); aniline (*8*); quinoline (*9*).

(see Table 2) are held weakly by an aqueous solution of MMO ($k < 1$). The retention of polyaromatic hydrocarbons (for example, naphthalene and biphenyl) exceeds several times the retention of *n*-alkanes with nearly the same boiling points, namely, decane and tridecane. A fairly strong retention was found for indene; its retention factor is 1.5 times as great as that of biphenyl, whose boiling point is 75 °C higher.

Figure 2 shows the chromatogram of compounds of various classes obtained at 80 °C with the SC technique. The chromatogram demonstrates the high selectivity of the water-organic SLP and the symmetry of the zones of polar and nonpolar components including high-boiling compounds.

Ethers and esters are capable of forming weak hydrogen bonds; values $k < 1$ were found for these compounds in a column with an aqueous solution of MMO (see Table 2). However, the retention of a cyclic ether, dioxane, is much longer than the retention of ethyl acetate, while the difference between the melting points is 2.9 °C.

Compounds with a carbonyl group experience stronger interactions with water-organic SLP than ethers or esters. Indeed, the retention of methyl ethyl ketone is twice that of ethyl acetate, while the retention of cyclohexanone is 10 times greater than that of pentyl acetate, despite the close boiling points of these ketone/ester pairs (see Table 2).

Table 3. Retention indices (*I*) of polar compounds determined on a column with *N*-methylmorpholine *N*-oxide under SC conditions

Sorbate	*I*		ΔI
	A	B	
Naphthalene	1367.26	1154.92	212.34
Octan-1-ol	1423.10	1052.32	370.78
2,6-Dimethylaniline	1666.56	1132.33	534.23
2,6-Dimethylphenol	>1800	1079.18	>700

Note. A: SLP is an aqueous solution of MMO, 90 °C (N_2 + H_2O); B: SLP is SE-30, 90 °C (He + H_2O).[22]

A specific field of gas chromatographic analysis important for pharmaceutical chemistry is related to compounds of the terpene series. It follows from the data of Table 2 that the SC method using a water-organic SLP provides selective separation of monoterpenes with different functional groups and close boiling points (camphor, menthol, and borneol). The carbonyl group of the camphor molecule is less accessible for molecules of MMO in an aqueous solution than this group in the cyclohexanone molecule.

Polarity. The chromatographic polarity of a SLP of the (MMO+H_2O) type was estimated based on the RI of polar compounds contained in the Grob mixture and characterizing different specific interactions[21] (Table 3). For comparison, Table 3 presents data[22] on the RI of octan-1-ol, naphthalene, 2,6-dimethylaniline, and 2,6-dimethylnaphthalene determined on a nonpolar SLP, namely, SE-30 (methylsiloxane rubber) under SC conditions. The data given in Table 3 indicate that, unlike the order of elution from the nonpolar SLP, the sequence of elution of the test compounds from the water-organic SLP does not correlate with their boiling points. The RI of compounds of the test mixture show appreciable differences ($\Delta I > 1800$ index units). Thus, an aqueous solution of MMO is a highly polar and a highly selective SLP for steam chromatography.

Efficiency. The van-Deemter dependences obtained experimentally for methanol and *n*-tridecane are shown in Fig. 3. It can be seen from Fig. 3 that there exists a fairly broad region of optimal velocity of the mobile phase (4.5—7 cm s^{-1}), which is matched by an efficiency normal for packed columns: H = 1.2 mm for *n*-tridecane and H = 1.4 mm for methanol. An increase in the velocity of the mobile phase above 8 cm s^{-1} results in a sharp decrease in the column efficiency.

It should be noted that under GC conditions (with dry nitrogen as carrier gas), a column with MMO has a higher efficiency for *n*-tridecane, H = 0.6 mm, at 70 °C and at the optimal velocity of nitrogen, equal to 5 cm s^{-1}. However, even at this temperature, a drift of the zero line appears due to the insufficient thermal stability of anhydrous MMO.

Effect of temperature. In traditional GC analysis, the selectivity of organic SLP depends on the temperature because the heats of dissolution of sorbates change with temperature. In the SC analysis using columns with water-containing SLP, temperature determines the composition of the SLP (the concentration of the aqueous solution of an inorganic or organic substance) and the film thickness. Figure 4 shows that the retention factor of *n*-tridecane varies linearly in the 70—90 °C temperature range (plot *4a*), while in the case of C_1—C_3 *n*-alcohols, this dependence is nonlinear (curve *1*—*3*). In addition, in the 70—80 °C temperature range, the retention factors of methanol, ethanol, and propanol

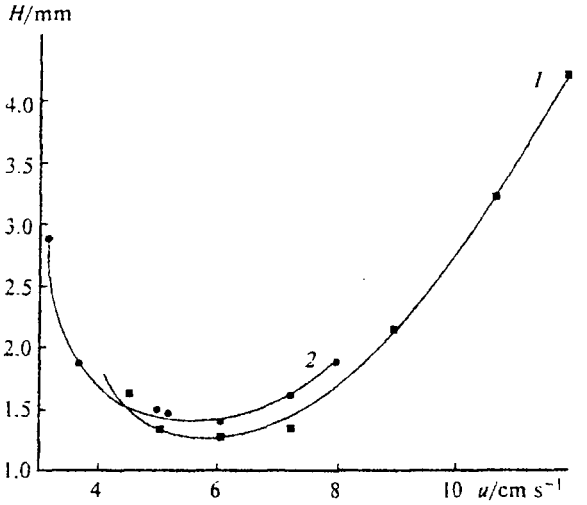

Fig. 3. Height equivalent of the theoretical plate (H) for a column with an aqueous solution of MMO *vs.* the linear velocity (u) of the mobile phase (nitrogen + water vapor) at 80 °C and p_{H_2O} = 350 Torr. Sorbates: *n*-tridecane (*1*); methanol (*2*).

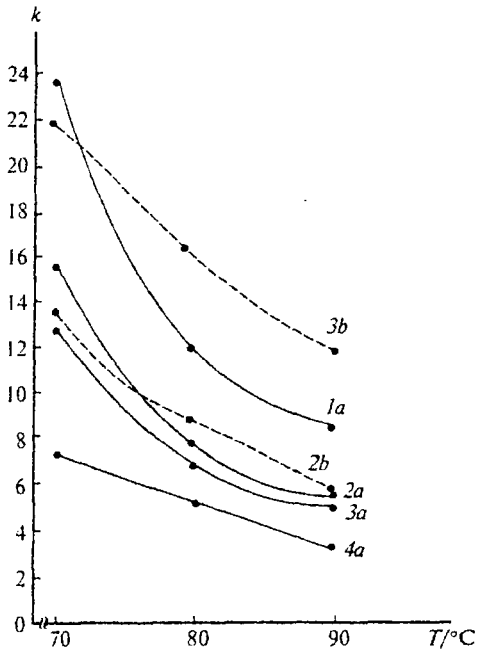

Fig. 4. Effect of temperature (T) on the retention factor (k) of the sorbates on a column with an aqueous solution of MMO (*a*) under conditions of SC and on a column with dry MMO (*b*) under GC conditions (for *a*, p_{H_2O} = 180 Torr). Sorbates: methanol (*1*); ethanol (*2*); *n*-propanol (*3*); *n*-tridecane (*4*).

decrease more sharply than in the 80—90 °C range. As the temperature of the column increases, the content of water in the SLP decreases and the selectivity of water-organic SLP with respect to sorbates that form hydrogen bonds decreases. As a consequence, ethanol and *n*-propanol are no longer separated, while for the methanol/ethanol pair, resolution markedly diminishes (at 70 °C, R_s = 3.5, and at 90 °C, R_s = 2.0).

Effect of the mobile phase. As has been noted previously,[4] retention of polar sorbates in SC analysis with columns filled, for example, with silica gel decreases with an increase in the water content in the carrier gas because the adsorbent activity and the surface area decrease. In the case of inorganic aqueous-salt SLP,[7] retention of, for example, aliphatic alcohols increases with an increase in the partial pressure of water in the mobile phase. Figure 5 shows the influence of the water partial pressure in the carrier gas on the retention factors of nonpolar or polar sorbates on a column with an aqueous solution of MMO. As the content of water vapor in nitrogen increases, first, the film thickness changes and, what is more important, the composition of SLP also changes. It can be seen from Fig. 5 that the retention of *n*-tridecane is slightly influenced by the change in p_{H_2O} in the region of 170—400 Torr. The retention of methanol, ethanol, and *n*-propanol markedly increases when p_{H_2O} is above 350 Torr. When the SLP film becomes thicker, the column efficiency diminishes. Thus, the HETP value for methanol increases from 1.9 to 2.1 mm, this value for ethanol changes from 1.5 to 2.8 mm, that for *n*-propanol increases from 1.7 to 2.6 mm, and that for *n*-tridecane, from 1.4 to 4.9 mm. However, when the content of water in the mobile phase increases to 400 Torr one more parameter changes, namely, the peak resolution is improved; for example, resolution R_s of the ethanol/*n*-propanol pair increases by almost 20%.

Practical application. The use of selective SLP increases the accuracy of qualitative and quantitative analysis including analysis of traces. Owing to the unusual order of elution in the series of polar compounds, impurity components can be analyzed using the SC technique on a column with an aqueous solution of MMO under mild conditions. As an example, Fig. 6, *a* shows the chromatogram of *n*-butyl alcohol. Admixtures of heavy hydrocarbons and isopentyl alcohol, which are difficult to determine in GC (because they are retained most strongly by traditional SLP), are eluted from the column with the water-organic SLP prior to *n*-butanol. The chromatogram of a cyclic alcohol is shown in Fig. 6, *b*. Normally, it is difficult to

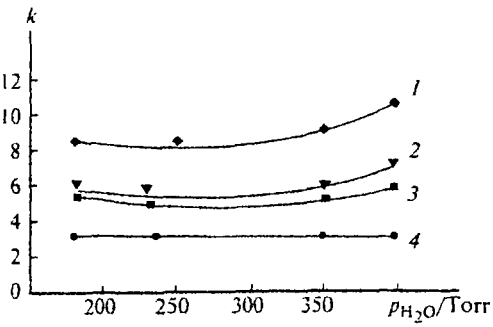

Fig. 5. Effect of the content of water vapor in the carrier gas (nitrogen) on the retention factor (k) of the sorbates on a column with an aqueous solution of MMO at 90 °C. Sorbates: methanol (*1*); ethanol (*2*); propanol (*3*); *n*-tridecane (*4*).

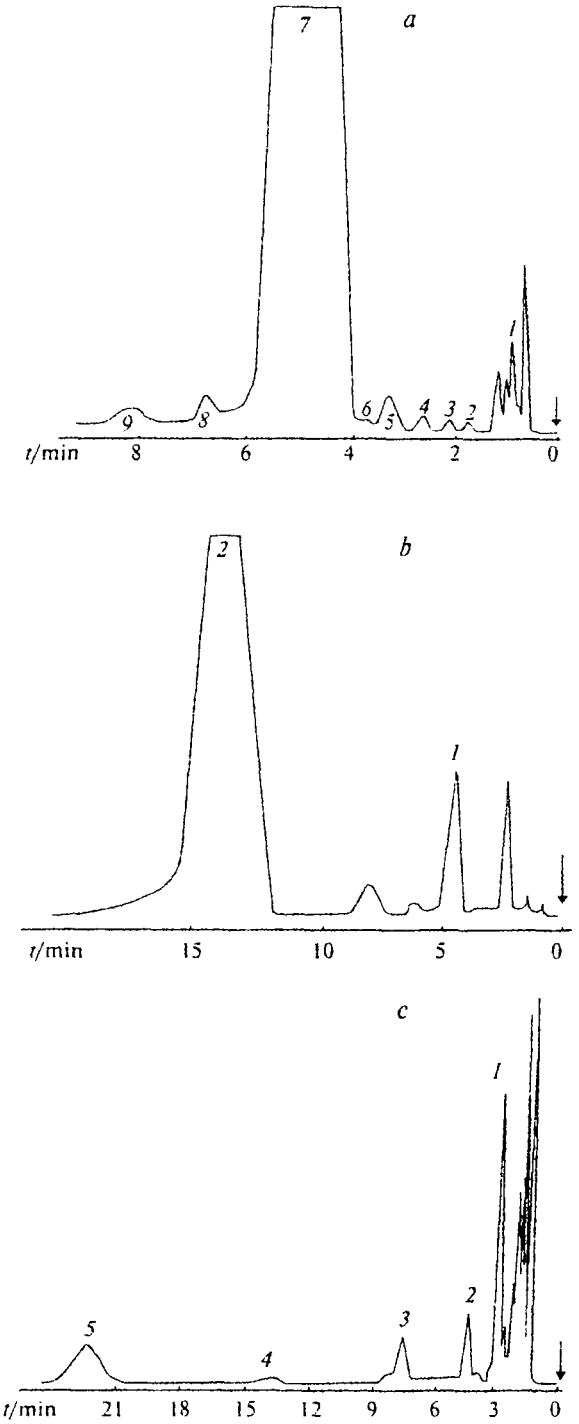

Fig. 6. Chromatograms of impurities in *n*-butyl alcohol (*a*), cyclohexanol (*b*), and AI-95 gasoline (*c*) obtained by the SC method on a column with an aqueous solution of MMO at 80 °C and p_{H_2O} = 350 Torr. Components for *a*: diethyl ether (*1*); *tert*-butyl alcohol (*2*); isopentyl alcohol (*3*); isobutyl alcohol (*4*); isopropyl alcohol (*5*); *n*-pentyl alcohol (*6*); *n*-butyl alcohol (*7*); ethanol (*8*); methanol (*9*); for *b*: cyclohexanone (*1*); cyclohexanol (*2*); for *c*: *n*-undecane (*1*); *n*-dodecane (*2*); *n*-tridecane (*3*); *n*-tetradecane (*4*); methanol (*5*).

separate cyclohexanol and cyclohexanone, whose boiling points differ by only 5 °C, on a packed column. In our case, a column with an aqueous solution of MMO made it possible to attain high resolution (R_s = 3.5) for this pair. Figure 6, *c* shows determination of methanol impurity in gasoline using the SC method. It can be seen from the chromatogram that the alcohol is efficiently separated from nonpolar hydrocarbons on a column with an aqueous solution of MMO. The accuracy of determination of methanol can be increased by increasing the sample volume, while the duration of the analysis can be decreased by increasing the temperature.

Figures 7, *a* and 7, *b* show chromatograms of pharmaceuticals containing high-boiling thermally unstable

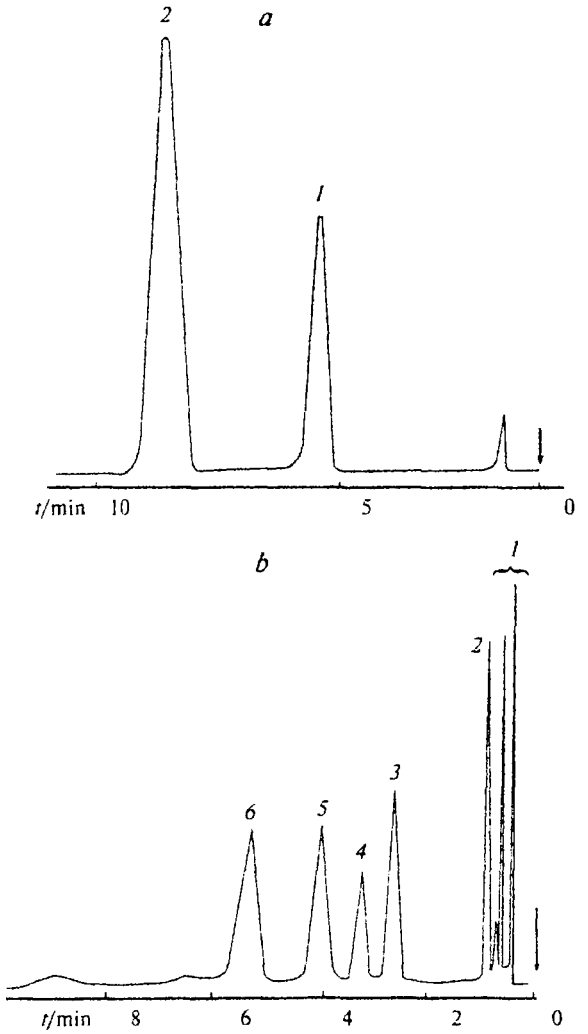

Fig. 7. Chromatograms for the separation of 10% spirit of camphor (*a*) and the aerosol "Kameton" (*b*) obtained by the SC method on a column with an aqueous solution of MMO under SC conditions at 80 °C (*a*) and 90 °C (*b*) and p_{H_2O} = 350 Torr. Components for *a*: camphor (*1*); ethanol (*2*); for *b*: eucalyptus oil components (*1*); 1,8-cineole (*2*); camphor (*3*); naphthalene (internal standard) (*4*); chlorobutanol hydrate (*5*); menthol (*6*).

monoterpene hydrocarbons. The use of the SC method and a column with water-organic SLP provides complete separation of the components at 80 and 90 °C, whereas under GC conditions on a column with a polar SLP, for example, PEG-20M, the temperature of analysis is at least 160 °C. It is known[23] that inorganic aqueous-salt SLP do not separate camphor from ethanol.

Effect of the sample volume. It is known from the theory and practice of GC that the column efficiency depends on the volume of the injected sample.[4] It has been found experimentally[24] that, even when sorbents with a high content of an SLP are used, for example, 20% dinonyl phthalate on Chromosorb W, an increase in the sample volume from 10 to 40 μL results in a sharp decrease in the column efficiency (by a factor of ~2). We found that in the case of SC on water-containing SLP, the volume of aqueous samples with organic impurities can be increased to 50 μL without noticeable deterioration of the column efficiency.

Thus, in this study, a new selective SLP consisting of an aqueous solution of *N*-methylmorpholine *N*-oxide was proposed for the steam-chromatography separation of polar organic compounds forming hydrogen bonds (for example, alcohols or amines). It was shown that temperature of the column and partial pressure of the water vapor in the mobile phase have a substantial influence on the retention of polar sorbates. Examples of practical use of water-organic SLP in chemistry, petrochemistry, and pharmaceutical chemistry were presented.

References

1. A. Nonaka, in *Advances in Chromatography*, Eds. J. C. Giddings, E. Grushka, R. A. Keller, and J. Gazes, M. Dekker, New York, 1975, **12**, 223.
2. M. S. Vigdergauz, A. V. Garusov, V. A. Ezrets, and V. I. Semkin, *Gazovaya khromatografiya s neideal'nymi elyuentami* [*Gas Chromatography with Nonideal Eluents*], Nauka, Moscow, 1980, 145 (in Russian).
3. M. S. Vigdergauz and Sh. N. Rakhmankulov, *Usp. Khim.*, 1967, **67**, 337 [*Russ. Chem. Rev.*, 1967, **67** (Engl. Transl.)].
4. J. Gioshon and K. Giiemin, *Kolichestvennaya gazovaya khromatografiya* [*Quantitative Gas Chromatography*], Part 1, Mir, Moscow, 1991, 286 (Russ. Transl.).
5. B. A. Rudenko, M. A. Baidarovtseva, and M. A. Agaeva, *Zh. Analit. Khim.*, 1975, **30**, 1191 [*J. Anal. Chem. USSR*, 1975, **30** (Engl. Transl.)].
6. V. G. Berezkin, E. N. Viktorova, and E. Yu. Sorokina, in *Khromatograficheskie metody v khimii, biologii i meditsine*, Minsk, 1995, 10 (in Russian).
7. L. G. Berezkina, V. G. Berezkin, E. N. Viktorova, E. Yu. Sorokina, and T. G. Andronikashvili, *Izv. Akad. Nauk. Ser. Khim.*, 1996, 1733 [*Russ. Chem. Bull.*, 1996, **45**, 1642 (Engl. Transl.)].
8. L. G. Berezkina, E. N. Viktorova, E. Yu. Sorokina, and V. G. Berezkin, *Zh. Analit. Khim.*, 1997, **52**, 167 [*J. Anal. Chem.*, 1997, **52** (Engl. Transl.)].
9. E. Yu. Sorokina, V. G. Berezkin, and L. G. Berezkina, *Izv. Akad. Nauk, Ser. Khim.*, 1999, 1507 [*Russ. Chem. Bull.*, 1999, **48**, 1488 (Engl. Transl.)].
10. L. G. Berezkina, V. G. Berezkin, E. N. Viktorova, and E. Yu. Sorokina, *Analyt. Sciences*, 1995, **11**, 776.
11. L. G. Berezkina, E. Yu. Sorokina, and G. F. Shalygin, *Zh. Fiz. Khim.*, 1996, **70**, 1124 [*Russ. J. Phys. Chem.*, 1996, **70** (Engl. Transl.)].
12. N. F. Franks and J. K. Varga, Pat. 4196282 (USA), 1980.
13. L. I. Golova, *Khimicheskie Volokna* [*Chemical Fibers*], 1996, 1, 13—23 (in Russian).
14. L. I. Golova, V. G. Kulichikhin, and S. P. Pankov, *Vysokomolekulyar. Soedin.*, 1986, **A28**, 1795 [*Polym. Sci., Ser. A*, 1986, **28** (Engl. Transl.)].
15. L. I. Golova, T. P. Stepanova, L. Ya. Burgotin, V. G. Kulichikhin, T. I. Boranova, and S. P. Pankov, *Khimiya Drevesiny* [*Wood Chemistry*], 1987, **2**, 33 (in Russian).
16. E. Maria and S. Perer, *Cellulose Organic Solvents II. The Structure of N-Methylmorpholine N-Oxide 2,5 H_2O, Crystallogr.*, 1982, **1338**, 849.
17. N. V. Bleidshmidt, Ph.D. (Chem.) Thesis, Institute of Petrochemical Synthesis, Moscow, 1998 (in Russian).
18. K. S. Petrov, A. M. Bochek, and V. N. Shek, *Khimiya Drevesiny* [*Wood Chemistry*], 1987, **2**, 3 (in Russian).
19. V. G. Berezkin, *Izv. Akad. Nauk, Ser. Khim.*, 1999, 1831 [*Russ. Chem. Bull.*, 1999, **48**, 1807 (Engl. Transl.)].
20. G. M. Sal'nikova and Ya. I. Yashin, in *Gazovaya khromatografiya* [*Gas Chromatography*], NIITEKhIM, Moscow, 1971, **12**, 28 (in Russian).
21. K. Grob Jr., K. Grob, and G. Grob, *J. Chromatography*, 1978, **156**, 1.
22. V. G. Berezkin and A. A. Korolev, *Zh. Analit. Khim.*, 1995, **50**, 1057 [*J. Anal. Chem.*, 1995, **50** (Engl. Transl.)].
23. A. I. Sokolov, A. P. Arzamastsev, V. G. Berezkin, and E. Yu. Sorokina, *Khim.-Farm. Zhurn.*, 1999, **4**, 54 [*Pharm. Chem. J.*, 1999, **4** (Engl. Transl.)].
24. I. Rans, I. N. Rozhenko, and K. I. Sakodynskii, in *Tekhnika khromatograficheskogo eksperimenta* [*Experimental Techniques in Chromatography*], NIITEKhIM, Moscow, 1980, 30 (in Russian).

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