

GAS-LIQUID CHROMATOGRAPHY OF SULFIDES OF THE THIOPHENE SERIES.  
QUALITATIVE ANALYSIS AND THERMODYNAMICS OF SOLUTION

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Sulfides of the thiophene series boiling 180-460° are separated by gas-liquid chromatography. It is shown that treatment of the solid carrier with alkali leads to a marked decrease in retention time, the specific interaction with the stationary phase being unchanged. The thermodynamics of solution of sulfides of the thiophene series in the stationary phases, polyethyleneglycoladipate and silicone rubber, are considered. On a basis of excess heat of solution, an attempt is made to solve the problem of interaction of sulfide sulfur with the thiophene ring.

Development of the chemistry of thiophene compounds having sulfur in the side chain [1] necessitated, in some of its aspects, developing methods for analyzing complex mixtures, including sulfides of the thiophene series. Problems of analysis of mixtures of thiophene derivatives are also of great interest in connection with many thiophene compounds [2] being found in a number of natural products, particularly sulfur-containing petroleums and shales.

In 1959 one of the thiophene series sulfides, methyl-3, 4, 5-trimethyl-2-thienylsulfide [3], was isolated from the kerosene fraction of a petroleum, and identified. It is evident that there may be other sulfides of the thiophene series in petroleums, the effectiveness with which they can be uncovered being directly bound up with the analytical methods used. In that connection gas-liquid chromatography appears to be the most promising method. On the other hand it is considered that the thermodynamics of solution of a substance in the stationary phase enable certain problems connected with interaction of different groups in the molecule of a heterocyclic compound to be settled. The present paper contains a chromatographic study of the behavior of a series of sulfides of the thiophene series on polar and non-polar phases. In addition, consideration is given to the problem of the thermodynamics of solution in the stationary phase, and an attempt made to evaluate the structural peculiarities of the compounds studied by the excess heat of solution.

Experimental

The investigations were carried out with a LKhM (Chemical Materials Laboratory) gas-liquid chromatograph, made by Special Apparatus Division, Institute of Organic Chemistry, AS USSR. It had an air thermostat, automatic recording potentiometer, and thermal conductivity detector, and the carrier gas was helium. Columns were made up as follows: 1) polyethyleneglycoladipate (PEGA) (20 wt. %) supported on diatomaceous brick (DK) previously washed free from iron by boiling with hydrochloric acid, then treated with a 5% solution of sodium hydroxide in ethanol; column copper spiral 2.6 m long; 2) PEGA (20 wt. %) supported on diatomaceous brick not treated with alkali, column length 2.6 m; 3) silicone rubber SKTV (1 wt. %) supported on sodium chloride, column copper spiral length 6 m. In every case the solid carrier pieces were 0.25-0.5 mm, and the column 6 mm i.d.  $\odot$  indices were used to characterize separation [4]. The following formula [5] was used to calculate the corrected retention volume

$$V'_R = (t_R - t_0) \cdot W \cdot K_p \cdot K'_T \cdot K''_T,$$

where  $V'_R$  is the corrected retention volume;  $t_R$ , substance retention time in minutes;  $t_0$ , unadsorbed gas ( $N_2$ ) retention time in minutes (both these last quantities are calculated from a peak maximum);  $W$ , carrier gas speed, ml/min, measured at the exit, at room temperature;  $K_p$ , a pressure change correction (compression factor), equal to

$$\frac{3}{2} \cdot \frac{(p_i/p_0)^2 - 1}{(p_i/p_0)^3 - 1} \quad (p_i, \text{ pressure at the inlet; } p_0, \text{ pressure at the exit); } K'_T, \text{ temperature correction needed to reduce the}$$

gas volume to 0°, and equal to 273/T, where T is the operating temperature in °K;  $K''_T$ , temperature correction, equal to T/293, assuming that the flow meter is calibrated at room temperature, and that the gas passes through at column temperature T. The methods used for preparing most of the sulfides have been described previously [6-9]. Some alkyl thiophenes were also chromatographed for comparison.

Results and Discussion

The table gives the results obtained for relative retention volumes. It can be seen that substances boiling 180-460° can be chromatographed, and that those with the highest boiling points emerge as low as 210°, i. e., at a temperature 250° lower than the boiling point. A solid carrier, treated with alkali, made that possible. Alkali-treatment of the carrier results in certain effects: a) retention volume decrease (a consequence not extending to relative retention

Relative Retention Volumes, Heats of Vaporization, Heats of Solution, and Excess Heats of Solution of Thiophene Derivatives in Polyethyleneglycoladipate and SKTV Silicone Rubber

Serial No.	Compound	Bp, °C	PEGA/ DK + alkali	PEGA/DK			PEGA/ DK + alkali	Sili- cone on NaCl
			150°	160°	170°	180°		
			V <sub>R</sub> REL					
1	Methyl-2-thienylsulfide	182	1.0	1.00	1.00	1.00	1.00	1.00
2	Ethyl-2-thienylsulfide	196.5	1.33	1.13	1.11	1.10	1.07	—
3	Ethyl-3-thienylsulfide	210	1.50	1.56	1.52	1.48	1.42	1.26
4	Isobutyl-2-thienylsulfide	232.5	1.79	1.64	1.58	1.54	1.73	1.75
5	Tert-butyl-2-thienylsulfide	200	1.08	1.20	1.17	1.16	1.19	1.47
6	Tert-butyl-(5-methylthienyl-2)-sulfide	225	1.58	1.51	1.47	1.44	1.33	1.9
7	Isobutyl-(thienyl-2-methyl)sulfide	242.5	2.75	3.56	—	3.11	2.54	2.43
8	Isoamyl-2-thienylsulfide	235	2.00	—	—	—	1.85	2.33
9	Isobutyl-(5-methylthienyl-2-methyl)sulfide	284	4.2	—	—	—	3.9	2.07
10	n-Hexyl-2-thienylsulfide	267.5	—	—	—	—	—	3.93
11	n-Dodecyl-2-thienylsulfide	380	—	—	—	—	—	50.8
12	2, 5-Di (tert-butylmercapto) thiophene	285	—	—	—	—	—	—
13	2-Tert-butylmercapto-5-(isoamylmercapto) thiophene	410	—	—	—	—	—	15.6
14	2-Tert-butylmercapto-5-(n-hexylmercapto) thiophene	420	—	—	—	—	—	31.3
15	2, 2'-Dithienylsulfide	290	—	—	—	—	—	5.85
16	tert-Butyl-2-thienylsulfone	300	—	—	—	—	0.37	—
17	2, 5-Di-n-butylthiophene	245	1.92	1.44	1.37	1.31	1.87	2.90
18	2, 5-Di-tert-butylthiophene	223	—	0.61	0.617	0.62	—	1.6
19	2, 2'-Dithienylmethane	255	—	—	—	—	—	3.07
20	5, 5'-Dimethyl-2, 2'-dithienylmethane	285	—	—	—	—	—	—
21	3, 3'-Dithienylsulfide	305	—	—	—	—	—	6.19
22	2, 3'-Dithienylsulfide	305	—	—	—	—	—	6.38
23	Thiophene	84	—	0.19	—	0.25	—	—
24	Methyl-2-thienylsulfide Vr ml	—	239	602	465	388	119.5	49.5

PEGA/DK	PEGA/DK + alkali	Silicone on NaCl	PEGA/DK	PEGA/DK + alkali	PEGA/DK	PEGA/DK + alkali	Silicone on NaCl	$(\Delta H_v)_1$ kcal/mole	$(\Delta H_v)_2$ at 200° kcal/mole	PEGA/DK		Silicone on NaCl	
										$\Delta H_p$ kcal/mole	$\overline{\Delta H_S}^E$ kcal/mole	$\Delta H_p$ kcal/mole	$\overline{\Delta H_S}^E$ kcal/mole
200°			210°			220°							
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.52	—	11.0	-2.40	9.6	-1.92
1.10	1.07	—	1.06	1.09	1.07	1.00	—	9.85	—	11.4	-2.47	—	—
1.40	1.40	1.20	1.34	1.34	1.33	1.31	1.10	10.16	10.3	12.0	-2.48	11.0	-1.64
1.44	1.56	1.54	1.33	1.49	1.34	1.33	1.33	10.68	11.15	12.2	-1.83	12.6	-2.39
1.13	1.09	1.38	1.1	—	1.35	1.11	1.11	9.93	9.93	11.7	-2.53	11.0	-1.83
—	1.31	1.65	—	1.45	2.73	1.28	1.4	10.57	10.93	11.8	-1.30	12.9	-2.91
2.70	2.24	2.11	—	—	2.40	2.15	1.69	10.91	11.41	13.2	-2.29	13.6	-3.13
1.87	—	2.00	—	1.75	1.72	1.62	1.62	10.74	11.25	12.6	-2.46	13.5	-3.19
—	3.76	3.06	—	3.00	—	2.62	2.34	11.87	13.08	—	—	13.4	-1.26
2.85	2.92	2.91	2.56	2.63	2.43	2.43	2.24	11.49	12.48	14.05	-2.68	14.2	-2.66
16.0	—	25.2	12.5	—	11.0	—	14.1	14.13	16.64	15.65	-0.19	19.5	-3.80
—	—	—	—	3.1	—	2.93	—	—	—	—	—	—	—
—	7.0	9.4	—	4.85	2.12	5.0	6.02	14.84	17.77	—	—	1.60	0.83
—	10.3	17.0	—	9.6	—	7.9	9.4	15.07	18.11	—	—	17.6	-0.43
8.90	—	4.2	7.2	6.4	6.71	5.5	2.98	12.0	13.17	13.95	-1.87	15.1	-2.87
—	—	—	—	7.8	—	—	—	—	—	—	—	—	—
1.20	1.65	2.1	1.15	1.50	1.12	—	1.76	10.96	—	12.8	-1.98	13.4	-2.74
0.64	0.75	1.33	0.66	0.73	0.67	—	1.21	10.46	10.78	11.0	-1.0	12.6	-2.76
4.84	3.7	2.52	4.35	3.6	4.14	3.10	1.92	11.2	11.00	13.6	-2.71	13.2	-2.15
7.07	—	—	6.02	—	5.56	4.0	—	11.87	13.08	15.6	-3.62	—	—
11.7	—	4.37	10.3	3.8	9.48	7.3	3.46	12.36	13.84	14.95	-2.21	12.7	0.2
9.77	—	3.97	8.4	7.5	7.82	6.2	3.06	12.36	13.84	15.0	-2.26	12.0	-1.0
0.33	—	—	0.34	—	—	—	—	7.52	—	6.83	-1.96	—	—
243	79.7	41.4	212	71.2	185	57.1	34.1	—	—	—	—	—	—

volume); b) band broadening; c) appearance of an unsymmetrical peak. The first effect is positive, particularly when chromatographing high-boiling substances, the other two are negative, impairing the separation. In the majority of cases the relative retention volumes on PEGA/DK + alkali are equal to  $V_R^{\text{Rel}}$  on PEGA/DK or less than them; the dependence of  $\lg V_R^{\text{Rel}}$  on temperature for treated and untreated brick is the same. Thus generally alkali treatment of the solid carrier does not influence the specificity of the interaction of the compounds studied with the stationary phase. This is shown by

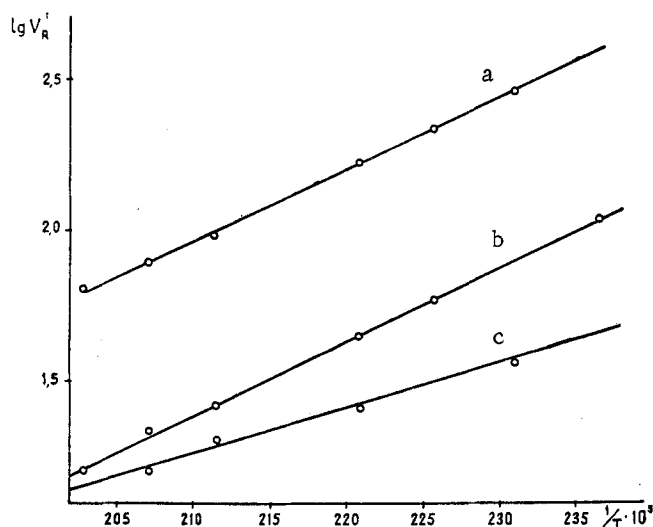


Fig. 1. Relationship between temperature and  $\lg V_R'$  for: a) Methyl-2-thienylsulfide on PEGA/DK, b) methyl-2-thienylsulfide on PEGA/DK + alkali, c) thiophene on PEGA/DK.

the uniform temperature relationship for the logarithm of the corrected retention volume for methyl-2-thienylsulfide on PEGA, supported on untreated and alkali-treated diatomaceous brick (Fig. 1). There is an approximately linear relationship between retention volume and the boiling points of the sulfides (Fig. 2). A characteristic of sulfides with two thiophene rings is a larger slope angle and hence a greater stationary phase selectivity than with sulfides with one thiophene ring. Inside the framework of the relationship between  $\log V_R^{\text{Rel}}$  and boiling point it is possible to trace the effect of sulfide structure on retention volume, allowing for difference in vapor viscosity. If there is a methylene group (No. 19) or sulfide sulfur (Nos. 15, 21, 22) between two thiophene rings, interaction with the stationary phase is unchanged, and the substances appear according to their boiling points. The same obtains with two sulfide sulfur atoms separated by an ethylene bridge, and joining two thiophene rings. The appearance of an alkylmercapto group in an alpha position in dithienylsulfide results in one of the thiophene rings being shielded through the immediate substitution in two alpha positions. This gives rise to a sharp decrease in retention volume, due to hindering of interaction with the stationary phase. From the bend in the plot in Fig. 2 it can be inferred that this effect is greater, the greater the volume of the alkylmercapto group. However, in order to reduce interaction with the phase, both alpha positions must immediately have bulky alkyl substituents (Nos. 13, 14) at both alpha positions. Interaction with the phase is practically unaffected whether the sulfur is directly joined to the thiophene ring, or whether this takes place through a methylene group, and the sulfide retention is in accord with its boiling point.

Consideration of the thermodynamics of solution in the stationary phase shows that the retention volume is connected with the free energy of solution, and depends on enthalpy and entropy terms [10]. The enthalpy component, i. e., the heat of solution ( $\Delta H_S$ ) can be found from the retention volume-temperature relationship. To avoid errors arising from changes of parameters during experiments, it is convenient to use relative retention volumes, and from the temperature relationship for them, the difference between the heat of solution of the compound under consideration and another chosen as standard, is calculated [10]. The heat of solution  $\Delta H_S$ , as determined experimentally, includes the heat of vaporization ( $\Delta H_v$ ) and excess heat of solution ( $\Delta \bar{H}_S^E$ ) [5, 11]

$$\frac{\partial \ln V_g}{\partial (1/T^\circ\text{K})} = \frac{\Delta H_v - RT - \Delta \bar{H}_S^E}{RT}$$

When near-ideal solutions are formed, the heat of solution is equal to the heat of vaporization, and  $\Delta \bar{H}_S^E = 0$ . Hence a conclusion can be drawn from the sign of  $\Delta \bar{H}_S^E$  and from its magnitude, regarding interaction between stationary phase and substance under study; here the relationship connected with difference in heats of vaporization is excluded. The heat of vaporization of sulfides at their boiling points was calculated by Kistiakowsky's equation

$$\Delta H_v/T_{bp} = 8.75 + 4.576 \lg T_{bp}$$

Watson's equation was used to calculate the heat of vaporization at the sulfides' chromatographing temperature [12]:

$$\frac{(\Delta H_v)_1}{(\Delta H_v)_2} = \left[ \frac{1-(T_r)_1}{1-(T_r)_2} \right]^{0.38}$$

where  $(\Delta H_v)_1$  and  $(\Delta H_v)_2$  are the heats of vaporization at the boiling point  $T_1$  and some other temperature  $T_2$ ;  $(T_r)_1 = T_1/T_c$  ( $T_c$  - critical temperature), and  $(T_r)_2 = T_2/T_c$ . The critical temperatures of sulfur compounds were found from

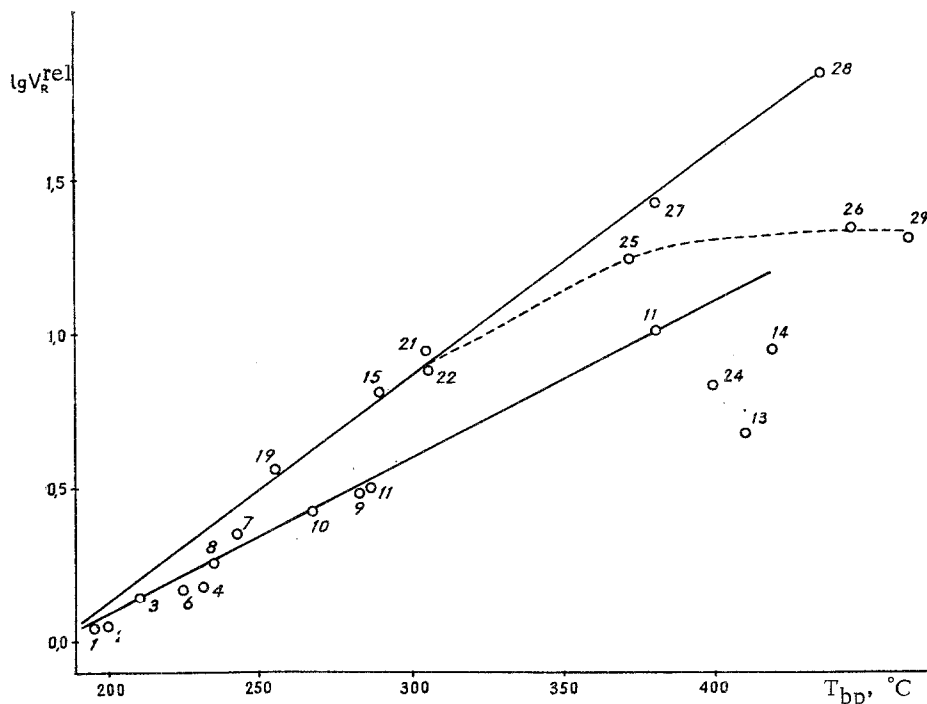


Fig. 2. Relationship between relative retention volumes of thiophene sulfides (internal standard methyl-2-thienylsulfide) and boiling points. Column PEGA/DK + alkali, 210°. 24) 2, 2-Dithienylsulfide; 25) 5-ethylmercapto-2, 2'dithienylsulfide; 26) 5-isobutylmercapto-2, 2'dithienylsulfide; 27) 1, 2-bis (2-thienylmercapto) ethane; 28) 1, 4-bis (2-thienylmercapto) butane; 29) bis (5-ethylmercaptothienyl-2) sulfide. (For other symbols see Table).

the formula [12]  $T_c = 1.41 \times T_{bp} + 66$ . In the case of thiophene there is a 3% difference between the value of  $\Delta H_v$  found experimentally (7.52 kcal/mole) [13], and that found from the Kistiakowsky equation (7.29 kcal/mole). The Table gives values obtained for  $\Delta H_v$ ,  $\Delta H_s$ , and  $\Delta H_s^E$ . In practically all cases the values of  $\Delta H_s^E$  are negative (exothermic effect on solution), corresponding to negative deviations from Raoult's law; negative deviations point to interaction between sulfide and stationary phase. The change in this interaction on passing from one substance to another will not be followed [Table]. Introducing the alkylmercapto group into the thiophene ring leads to increased interaction (Nos. 23 and 1). Replacement of the methylmercapto group by the ethylmercapto one leaves the value of the excess heat of solution unchanged (Nos. 1 and 2). Increasing the length of the alkyl chain, or the presence of a second alpha substituent causes a sharp decrease in interaction. Whether the alkylmercapto group is in the alpha or beta position makes practically no difference, and the same applies to whether the sulfur atom is linked directly to the thiophene ring or via a methylene group (Nos. 2 and 3; Nos. 7 and 8). Excess heat of solution is about the same for thiophene and compounds with two thiophene rings united through sulfide sulfur in the alpha position, i.e., replacement of an alkyl substituent in a thiophene ring by a sulfur atom does not increase, but even decreases interaction with the stationary phase. It is characteristic of alkylthiophenes that they have the same excess heat of solution as thiophene; that quantity decreases with branching of the alkyl side chain, on account of steric hindrance. The effect is not to be confused with the decrease in excess heat of solution when molecular dimensions are increased, on account of work which must be expended because of expansion of phase molecules [10]. It is interesting to consider, in the light of the above, the question of possible mutual influence of sulfide sulfur atom and thiophene ring. Replacement of the alkyl group in the thiophene ring by an alkylmercapto group increases the molecule's capacity to interact with the phase. However, this

effect can scarcely be connected with conjugation of sulfur with the ring and delocalization of the lone electron pair; transfer of the sulfide sulfur from the alpha to the beta position, or linking through a methylene bridge does not affect the interaction energy. The thiophene ring plays a basic role in interaction with the phase, as shielding the ring reduced the interaction. Obviously not only does sulfide sulfur not participate in conjugation with the thiophene ring, but further, it does not transmit conjugation. It must be noted that this conclusion is in agreement with chemical data regarding absence of transmission of conjugation through a sulfide sulfur atom in dithienylsulfides [14].

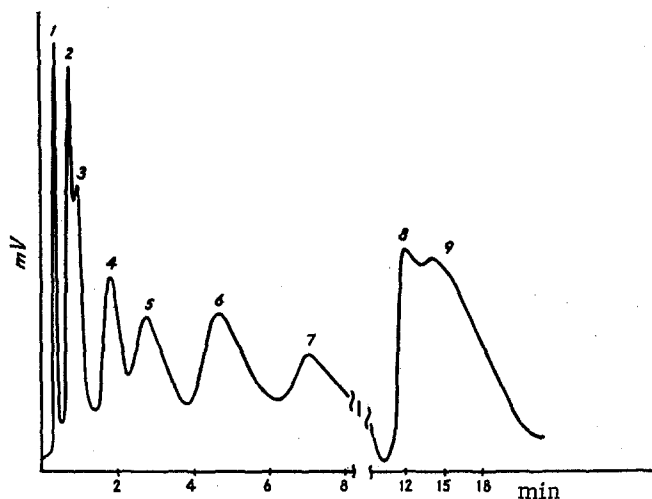


Fig. 3. Chromatogram of a mixture of sulfides of the thiophene series. Column: PEGA/DK + alkali, 210°. [numbers (1-4) omitted] hexyl-2-thienylsulfide; 5) 2, 5-bis(tert-butylmercapto) thiophene; 6) 2-tert-butylmercapto-5-(isoamylmercapto) thiophene; 7) 2-tert-butylmercapto-5-(n-hexylmercapto) thiophene; 8) 5-ethylmercapto-2, 2'-dithienylsulfide; 9) 5-isobutylmercapto-2, 2'-dithienylsulfide; 5-isobutylmercapto-2, 2'-dithienylsulfide.

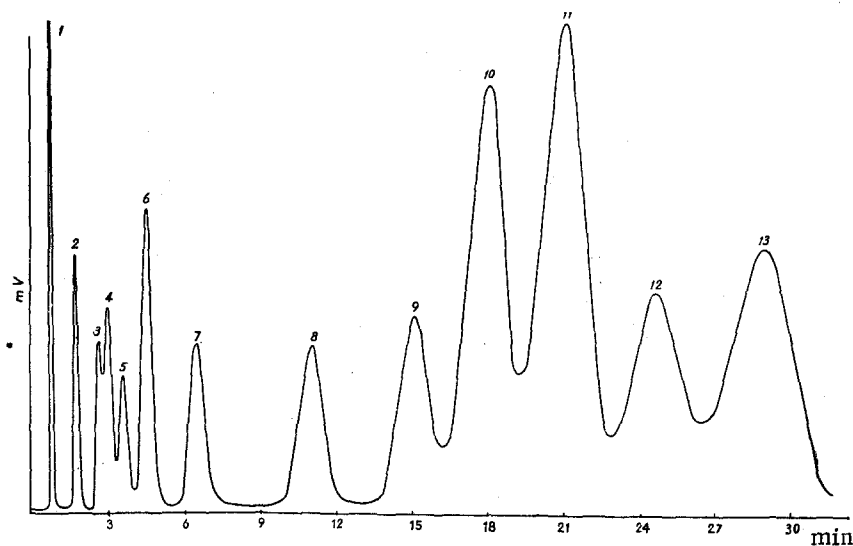


Fig. 4. Chromatogram of sulfur compounds (mainly sulfides of the thiophene series). Column: PEGA/DK, 220°. Peaks correspond to: 1) solvent; 2) 2, 5-di-tert-butylthiophene; 3) methyl-2-thienylsulfide; 4) 2, 5-di-n-butylthiophene; 5) isobutyl-2-thienylsulfide; 6) isoamyl-2-thienylsulfide; 7) n-hexyl-2-thienylsulfide; 8) 2, 2'-dithienylmethane; 9) 5, 5'-dimethyl-2, 2'-dithienylmethane; 10) 2, 2'-dithienylsulfide; 11) 2, 3'-dithienylsulfide; 12) 3, 3'-dithienylsulfide; 13) n-dodecyl-2-thienylsulfide.

In a non-polar solvent (silicone rubber SKTV), the basic role will be played by dispersion forces (and not dipole-dipole interaction as with PEGA), increasing as the number of groups approaching direct contact with one another increases [15]. However here too steric factors play a basic role. As the table shows, generally the nature of the change in

$\Delta\bar{H}_S^F$  for silicone rubber SKTV is the opposite of that for PEGA.

Figures 3 and 4, showing separation of 8 and 12 component mixtures, illustrate the analytical side of the problem of chromatographing thiophene sulfides. With polyethyleneglycoladipate supported on diatomaceous brick, it is possible to separate from one another isomeric dithienylsulfides (15, 21, 22),  $\alpha$ - and  $\beta$ -alkylmercaptothiophene (Nos. 2, 3),  $\alpha$ -tert-butylmercapto- and  $\alpha$ -isobutylmercaptothiophene (Nos. 4, 5), as well as a number of other sulfides;  $\Theta$  is equal to 0.7 or over. In particular it was shown that tert-butyl-2-thienylsulfide (No. 5), prepared by adding 2-thiophenethiol to isobutene, did not contain (within 1%) any admixture of isobutyl-2-thienylsulfide (No. 4);  $\alpha$ ,  $\beta'$ - and  $\beta$ ,  $\beta'$ -dithienylsulfides (Nos. 21, 22) prepared by reacting the appropriate lithium thiophenes with dithienylsulfides, likewise did not contain traces of isomers.

With some compounds so-called reaction chromatography was observed, a compound undergoing change before the column (this occurred with a copper evaporator). Sulfides Nos. 5-7, 12-14, gave several peaks. Common to those compounds is a tert-butyl group linked to sulfide sulfur, or linking of sulfide sulfur to a thiophene ring via a methylene group. If the tert-butyl group is directly linked to the thiophene ring, the compound does not decompose. This fact can be turned to account where it is impossible to establish the structure of a substance. It does not contradict the above conclusion that a sulfur atom does not enter into conjugation with the ring, as in the case in question it is a matter of stability of a C-S link, which does not directly affect interaction with the stationary phase.

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