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Solubilities of Menadione Sodium Bisulfite in Water + (Methanol, Ethanol, 1-Propanol, 2-Propanol, 1,2-Propanediol, and Glycerin, Respectively) from (297.67 to 337.76) K

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The solubilities of menadione sodium bisulfite in water + (methanol, ethanol, 1-propanol, 2-propanol, 1,2-propanediol, and glycerin, respectively) have been determined experimentally from (297.67 to 337.76) K by a dynamic method. The experimental data were correlated with the modified Apelblat equation.

Introduction

Vitamin K_3 (2-methyl-1,4-naphthoquinone, or menadione) is a synthetic quinone derivative of naphthalene and is highly unstable. It is a fat-soluble vitamin precursor, which can be converted into menaquinone in the liver. Menadione sodium bisulfite (MSB) is a water-soluble derivative of menadione and is relatively stable. The interest in this compound has grown because of its anticancer activity.[1−5] A more than 50 % decrease in colony formation occurred in 86 % of human tumors when tested at the 1 $\mu g \cdot mL^{-1}$ level.[3] It was also suggested that MSB prevented the action of certain carcinogens, such as benzopyrene and quinazoline in rat liver, and reduced the number of benzopyrene-induced tumors in rats significantly. In conclusion, it is significant to synthesize MSB using 2-methyl-1,4-naphthoquinone and sodium bisulfite as raw materials, and in the synthesis and purification process of MSB, examples of preferred recrystallization solvents include alcohols such as methanol, ethanol, propanol and butanol, acetone, etc., and these recrystallization solvents may contain water.[6] So it is necessary to know the solubility data of MSB and 2-methyl-1,4-naphthoquinone in a mixed solvent of water + alcohols (such as methanol, ethanol, 1-propanol, etc.). Song et al.[7] have reported the solubility data of 2-methyl-1,4-naphthoquinone in a mixed solvent of water + alcohols. In this study, the solubilities of MSB in water + (methanol, ethanol, 1-propanol, 2-propanol, 1,2-propanediol, and glycerin, respectively) have been measured experimentally from (297.67 to 337.76) K at atmospheric pressure. The experimental data were correlated with the modified Apelblat equation.[8−10]

Experimental Section

Materials. Analytical grade MSB obtained from the Peking Biotech. Co. Ltd. was further purified by recrystallizations from solution of ethanol, and its purity was determined by UV spectrophotometry (type UV-2401PC, Shimadzu Co. Ltd.) to be 0.997 in mass fraction. Methanol, ethanol, 1-propanol, 2-propanol, 1,2-propanediol, and glycerin were of AR grade, were obtained from the Shanghai Chemical Reagent Co., and had the purities of 0.995, 0.997, 0.995, 0.997, 0.990, and 0.990 in mass fraction, respectively. Water used in the experiments was double distilled.

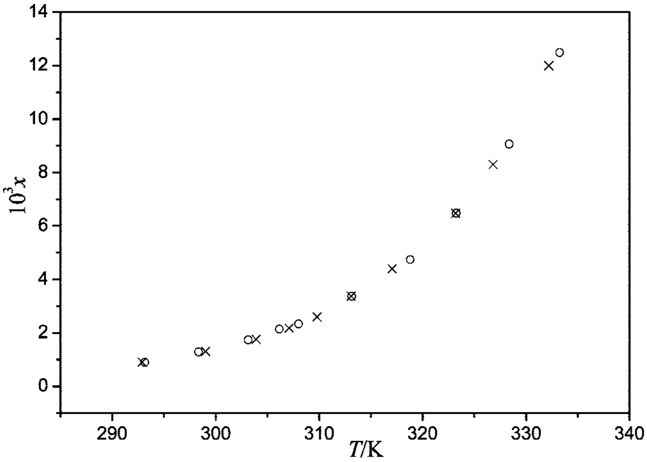

Figure 1. Solubility of 2-methyl-1,4-naphthoquinone in water + (w = 0.600) ethanol: ×, this work; ○, Song et al.[7] where T is the absolute temperature and x is the experimental solubility in mole fraction.

Apparatus and Procedure. The solubilities were measured by a dynamic method[11,12] at atmospheric pressure. The laser monitoring observation technique[13−16] was used to determine the dissolution temperature of a solid−liquid mixture of known composition. The laser monitoring system consists of a laser generator, a photoelectric transformer, and a recorder. The experiments were carried out in a magnetically stirred, jacketed glass vessel (60 cm^3). A constant temperature (± 0.01 K) was maintained by circulating water through the outer jacket from a thermoelectric controller (type 501, Shanghai Laboratory Instrument Works Co. Ltd.) at the required temperature. A condenser was connected with the vessels to prevent the solvents from evaporating. A mercury-in-glass thermometer was inserted into the inner chamber of the vessels for the measurement of temperature. The uncertainty of the temperature was ± 0.01 K.

Solvents for the solubility measurement were prepared by mass using an electronic balance (type AW120, Shimadzu Co.) with an uncertainty of ± 0.0001 g. Before the solubility measurement, through the condenser, high-purity nitrogen (99.9995 % by mass, 50 $mL \cdot min^{-1}$) was fed into the solvent for 1 h to remove the dissolved oxygen. Predetermined amounts of MSB were weighed and transferred into the vessel. The contents of the vessel were heated very slowly at rates less than 2 $K \cdot h^{-1}$ with continuous stirring, and the increasing rate of

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Table 1. Solubilities of MSB in Water + (Methanol, Ethanol, 1-Propanol, 2-Propanol, 1,2-Propanediol, and Glycerin, Respectively)

T/K	10^2x	rel dev/%	T/K	10^2x	rel dev/%
Water + (w = 0.750) Methanol					
300.07	2.509	0.093	317.34	5.399	−0.26
304.23	3.066	0.17	321.42	6.381	0.41
308.30	3.667	−0.56	325.57	7.433	0.11
312.83	4.504	0.26	329.80	8.616	−0.22
Water + (w = 0.750) Ethanol					
297.67	1.095	−0.089	316.05	2.875	0.034
302.25	1.456	0.10	321.40	3.507	−0.19
307.31	1.920	−0.085	325.63	4.019	−0.19
311.63	2.378	0.22	329.74	4.523	0.21
Water + (w = 0.750) 1-Propanol					
303.17	1.051	0.083	324.20	3.042	0.040
308.95	1.467	−0.31	329.47	3.713	−0.097
314.22	1.945	0.23	333.67	4.278	−0.25
318.85	2.421	0.11	337.76	4.874	0.20
Water + (w = 0.750) 2-Propanol					
302.04	0.6370	−0.57	319.82	1.616	−1.6
306.34	0.8200	−0.20	323.59	1.946	−0.23
310.45	1.047	1.7	327.71	2.328	−0.099
315.11	1.314	0.43	331.83	2.772	0.57
Water + (w = 0.750) 1,2-Propanediol					
299.95	3.224	0.076	317.09	5.899	−0.29
304.45	3.783	0.17	321.29	6.907	0.52
308.76	4.381	−0.43	325.50	7.995	0.14
312.57	5.040	0.055	330.53	9.531	−0.24
Water + (w = 0.750) Glycerin					
304.48	5.295	0.19	323.37	9.200	−0.29
309.25	6.152	−0.26	327.25	10.17	−0.0087
313.65	7.044	−0.12	331.37	11.27	0.49
318.15	8.046	0.29	336.31	12.48	−0.28

Table 2. Parameters of Equation 1 and the Absolute Average Deviation (AAD) for the MSB + Water + (Methanol, Ethanol, 1-Propanol, 2-Propanol, 1,2-Propanediol, and Glycerin, Respectively) Systems

solvent	A	B	C	10^4rmsd	10^2AAD
water + (w = 0.750) methanol	155.688	−10900.7	−21.5719	1.5	0.26
water + (w = 0.750) ethanol	637.248	−33439.3	−92.9470	0.53	0.14
water + (w = 0.750) 1-propanol	466.727	−26098.6	−67.4095	0.59	0.17
water + (w = 0.750) 2-propanol	253.033	−16232.1	−35.783	1.3	0.67
water + (w = 0.750) 1,2-propanediol	−152.108	3952.65	23.7560	1.8	0.24
water + (w = 0.750) glycerin	150.865	−9611.01	−21.3758	2.7	0.25

temperature was controlled by a TP technique (temperature controller type AI-708P, Xiamen Electronic Technology Co., Ltd.). In the early stage of the experiment, the laser beam was blocked by the turbidity of the solution, so the intensity of the laser beam penetrating the vessel was diminished. The intensity increased gradually along with the increase of the amount of MSB dissolved. When the last portion of MSB disappeared, the intensity of the laser beam penetrating the vessel reached the maximum, and the temperature was recorded as the liquidus temperature.[13] In the processes of solubility measurement, the high-purity nitrogen flowing at 1.5 mL·min^{-1} was maintained to prevent air from entering the vessel. Some of the solubility experiments were conducted two or three times to check the reproducibility. The reproducibility of the measurements was 0.1 K, which corresponds to a relative error in composition smaller than 1.0 %.

Results and Discussion

To verify the reliability of the measurement, the solubilities of 2-methyl-1,4-naphthoquinone in water + (w = 0.600) ethanol were measured by a dynamic method, and the results are shown in Figure 1 together with the measurements of Song et al.[7] It is clear from Figure 1 that our experimental results show good agreement with the literature data. Compared with the literature data, the deviations of the solubility are less than 2.0 %.

The measured solubilities of MSB in water + (methanol, ethanol, 1-propanol, 2-propanol, 1,2-propanediol, and glycerin, respectively) at different temperatures are presented in Table 1. For each mixed solvent system, the mass fraction of alcohol in the mixed solvents is 0.750. The temperature dependence of MSB solubility at fixed solvent composition is described by the modified Apelblat equation[8−10]

$$\ln x = A + \frac{B}{T/\mathrm{K}} + C\ln(T/\mathrm{K}) \qquad (1)$$

where x is the mole fraction solubility of MSB. T is the absolute temperature, and A, B, and C are the parameters in eq 1. The values of these parameters together with the root-mean-square deviations (rmsd values) are listed in Table 2. The rmsd is defined as

$$\mathrm{rmsd} = \left[\sum_{i=1}^{N}\frac{(x_{\mathrm{c}i} - x_i)^2}{N}\right]^{1/2} \qquad (2)$$

where N is the number of experimental points and x_c is the solubility calculated by eq 1. The relative deviations between the experimental value and calculated value are also listed in Table 1. Relative deviations are calculated according to

$$\text{relative deviations (\%)} = \left(\frac{x - x_\mathrm{c}}{x}\right)\cdot 100 \qquad (3)$$

The absolute average deviations (AAD) are also listed in Table 2. The AAD is defined as

$$\mathrm{AAD} = \frac{1}{N}\sum_{i}^{N}\left|\frac{x_i - x_{\mathrm{c}i}}{x_i}\right| \qquad (4)$$

From Tables 1 and 2, it can be found that the calculated solubilities show good agreement with the experimental data, and the overall rmsd of 48 data points for the water + alcohol system is $2.0\cdot10^{-4}$. The relative deviations among all these values do not exceed 2.0 %, which indicates that the modified Apelblat equation is fit to correlate the solubility data of MSB in six mixed solvent systems.

The graphical presentation of solubilities of MSB in water + alcohols is shown in Figure 2. It can be observed from Figure 2 that: the solubilities of MSB in water + (methanol, ethanol, and 1-propanol, respectively) decrease as the C content of the alcohol increases; the solubilities of MSB in water + (1-propanol, 1, 2-propanediol, and glycerin, respectively) increase as the HO content of alcohol increases; and the solubilities of MSB in water +1-propanol are higher than that in warter + 2-propanol.

All the solubilities follow the order: water + glycerin > water + 1,2-propanediol > water + methanol > water + ethanol > water + 1-propanol > water + 2-propanol; however, the dipole moment order of the investigated alcohols is as follows: glycerin (μ = 2.68) > 1,2-propanediol (μ = 2.27) > methanol (μ = 1.70) > ethanol (μ = 1.69) > 2-propanol (μ = 1.58) > 1-propanol (μ = 1.55).[17] We can find that the order of the solubilities of MSB in the water + alcohols almost agrees with

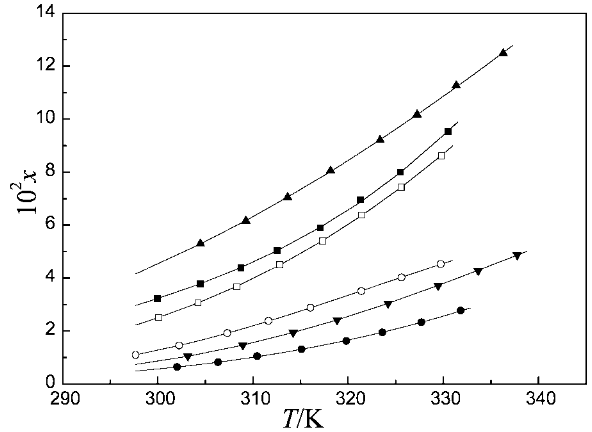

Figure 2. Solubilities of MSB in (w = 0.250) water + (w = 0.750) alcohols: ▲, water + glycerin; ■, water + 1,2-propanediol; □, water + methanol; ○, water + ethanol; ▼, water + 1-propanol; ●, water + 2-propanol; −, calculated from eq 1.

the dipole moment order of the investigated alcohols. However, the solubility of MSB in water + 2-propanol is lower than that in water + 1-propanol, and the reason for this phenomenon is probably the difference of the structural effects of 1-propanol and 2-propanol.

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