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Acoustic studies on anionic surfactant with sugars in aqueous media at different temperatures

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The density (*d*) and speed of sound (*v*) for an anionic surfactant sodium dodecyl sulphate (SDS) in the concentration range (1-14) mmol·dm^{-3} in aqueous solutions of sugars (fructose and maltose) at 293.15, 298.15, 303.15, 308.15 and 313.15 K, have been measured. The experimental data have been used to estimate various derived acoustical parameters such as intermolecular free length (L_f), relative association (*RA*), specific acoustic impedance (*z*), molar sound number (*U*), molar volume (V_m), Wada's constant (*W*) and Rao's constant (R_m), and some excess properties like excess molar volume (V_m^E), excess isentropic compressibility (κ^E_s) and excess free length ($L^E{}_f$).L_f values decrease but at the same time *RA* values increase with the concentration of sodium dodecyl sulphate. Comparatively, L_f values are found to be higher in aqueous fructose than maltose solutions. The variation of all these parameters have been interpreted in terms of various intermolecular interactions such as strong, weak, charge transfer, complex formation and hydrogen bonding interactions occurring in the ternary system. A good to excellent correlation between a given parameter and concentration of SDS/sugars is observed for all the studied systems.

Keywords: Sodium dodecylsulphate, Fructose, Maltose, Density, Speed of sound, Intermolecular free length, Relative association, Wada's constant, Rao's constant

1 Introduction

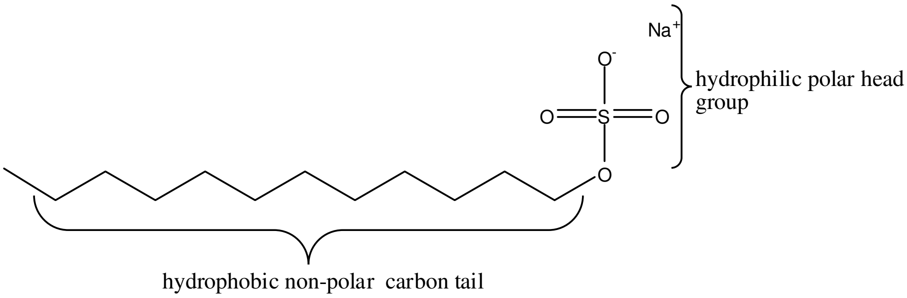
A number of researchers have recently used different experimental techniques to explore the molecular interactions between the components of ternary liquid mixtures[1-5]. Thermodynamic parameters derived from speeds of sound and the corresponding excess functions provide qualitative information regarding the nature and strength of interactions in liquid mixtures[6,7]. Sodium dodecylsulphate (SDS) is used in many cleaning and hygiene products. SDS, probably the most researched anionic surfactant compound (Fig 1), has critical micelle concentration (*CMC*) equal to 8 mmol·dm^{-3} in pure water[3] at 298.15 K.

Monosaccharides are the physiologically and industrially (medical and food) important members among carbohydrates. Fructose, a monosaccharide, retains its reducing properties as well as the property of mutarotation and due to mutarotation fructose shows structural changes in its molecule[8]. On the other hand, maltose is one of the most abundant disaccharides in the nature and formed from two units of glucose. It is a cleavage product of amylase and amylopectin, which are the starch components. Maltose in aqueous solution exhibit mutarotaion due to its anomeric carbon which can form α and β isomers. The molecular structures of fructose and maltose are shown in Fig. 2.

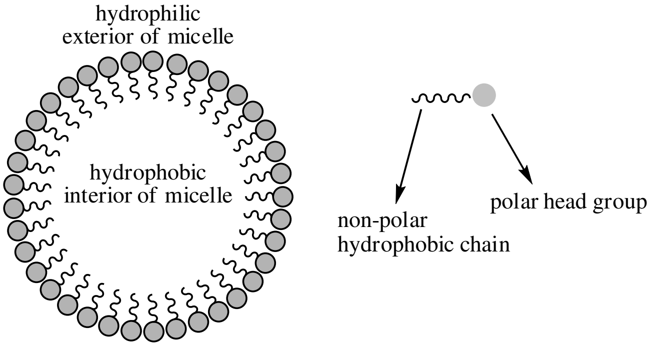
The effect of additives on the *CMC* of SDS in aqueous and mixed aqueous solvent systems has been well documented in the literature by using different experimental techniques[9-12]. Though, the effect of saccharides like fructose, maltose, etc. still has not been investigated, especially by using ultrasonic studies[3,13,14]. Consequently, the present study becomes more relevant regarding the effect of different saccharides on the micellization behaviour of SDS in aqueous solutions. Therefore, an attempt has been made to speculate the effects by comparing the results of different types of acoustical parameters and their excess values with our previous study[13].

2 Experimental Details

The deionized water was obtained from a Millipore-Elix system; the conductivity, κ and the *p*H of the water collected were (1-2 × 10^{-7} S·cm^{-1}) and (6.8-7.0), respectively. Both these parameters were measured at room temperature. Anionic surfactant

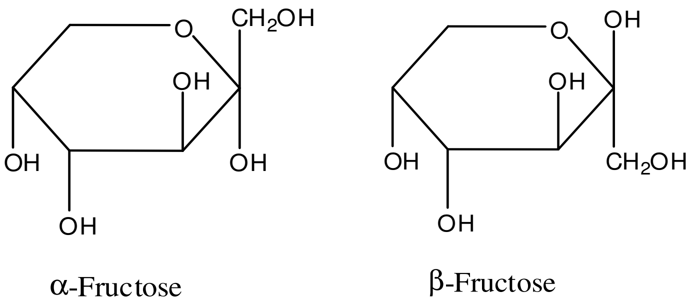


(a) Sodiumdodecylsulphate

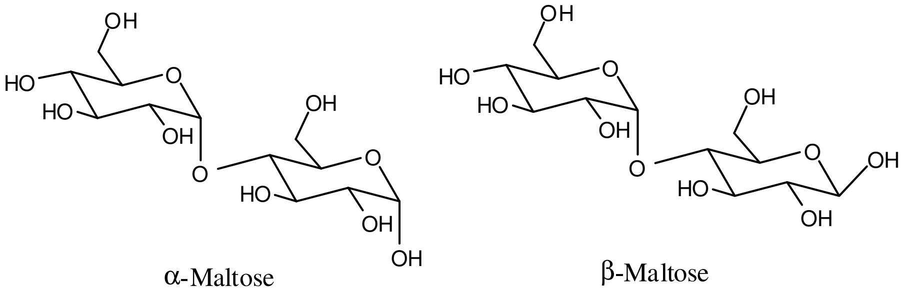


(b) Micelle formed by SDS

Fig. 1 — (a) Chemical structure of SDS and (b) spherical micelle formed by SDS



(a)



(b)

Fig. 2 — Isomeric forms of (a) fructose and (b) maltose

sodiumdodecyl sulphate (SDS) with purity 99.50% was obtained from Himedia Pvt Ltd (MW = 0.288 kg.mol^{-1}). Pure sample of SDS was obtained by giving additional treatment as reported in literature[13]. Fructose (MW = 0.180 kg·mol^{-1}) and maltose monohydrate (MW = 0.360 kg·mol^{-1}) were purchased from s d fine Pvt Chem Ltd and Lobachemie Pvt Chem Ltd, respectively and recrystallized from water twice.

Density and speed of sound measurements were performed with a high-precision digital Density and Sound Velocity Analyzer-5000 (DSA-5000), supplied by Anton Paar Gmbh, Graz, Austria. The instrument was calibrated periodically with distilled water, DMSO and 1,4-dioxane over a wide temperature range 293.15-313.15 K (± 0.01 K) at an interval of 5 K. The precision in the density and speed of sound data was found to be better than $\pm 2 \times 10^{-3}$ kg·m^{-3} and ± 0.2 m·s^{-1}. Densities and speeds of sound values of these solvents have been found in good compliance with literature values as reported elsewhere[13,15].

3 Results and Discussion

Density (d) and speed of sound (v) values for SDS in aqueous solution of fructose and maltose (0.01 and 0.10 mol·dm^{-3}) in different temperatures (293.15-313.15) K with an interval of 5 K were measured in the concentration range of (1-14 mmol·dm^{-3}). The d and v values have been reported in Table 1. Both these parameters are useful in describing the molecular interactions in the system. The observed increase in the density values with SDS is attributed to the volume shrinkage on addition of solute molecules and the structure making ability of SDS in aqueous solutions. On the other hand, the increase in speed of sound values with SDS is showing the presence of molecular association in the solvent mixtures, which may be due to the hydrophilic interactions. Such behaviour has also been reported in literature for different amino acids in aqueous sodium acetate mixtures[16].

Various acoustical parameters such as intermolecular free length (L_f), relative association (RA), specific acoustic impedance (z), molar sound number (U), molar volume (V_m), Wada's constant (W) and Rao's constant (R_m) of SDS in aqueous solution of fructose and maltose (0.01 and 0.10 mol·dm^{-3}) have been calculated from the density and speed of sound data by using the following relations[17]:

$$L_f = K\sqrt{\kappa_s} \quad \ldots(1)$$

$$RA = \left(\frac{d}{d_o}\right)\left(\frac{v_o}{v}\right)^{1/3} \quad \ldots(2)$$

$$z = v \times d \quad \ldots(3)$$

$$U = (v - v_o) / (v_o c) \quad \ldots(4)$$

$$V_m = \frac{M_{\mathrm{eff}}}{d} \quad \ldots(5)$$

$$W = \frac{M_{eff}}{d}\kappa_s^{-1/7} \quad \ldots(6)$$

$$R_m = \frac{M_{eff}}{d}v^{1/3} \quad \ldots(7)$$

where K = [(93.875+0.375.T) ×10^{-8}] refers to the temperature dependent constant, c concentration of solution, v, d, v_o and d_o are the speeds of sound and densities of the solution and solvent, respectively. M is the relative molar mass of the fructose / maltose and M_{eff} is the effective molecular weight of the solutions which is defined as follows:

$$M_{\mathrm{eff}} = M_{12} + \text{weight of SDS} \quad \ldots(12)$$

where $M_{12} = x_1M_1 + x_2M_2$; M_1 and M_2 are the molecular weights of solvents (fructose/maltose + water), and x_1 and x_2 are mole fractions of solvents (fructose/maltose + water).

Further, the excess parameters correspond to different acoustical parameters, have been calculated by using the relation:

$$A^E = A_{\exp} - A_{id} \quad \ldots(13)$$

where $A_{id} = \Sigma A_i X_i$, i =1 to n, A_i is any acoustical parameters and X_i is the mole fraction of the liquid components.

The calculated values of different parameters for SDS in aqueous solutions of fructose and maltose at different temperatures have been reported in Tables 2-6. However, the representative plots for the variation of L_f, RA, z, (U), W and R_m values with

Table 1 — Density (d) and speed of sound (v) of SDS in aqueous solutions of fructose and maltose at different temperatures (K).

C			d (kg·m^{-3})					v (m·s^{-1})		
(mmol·dm^{-3})	293.15	298.15	303.15	308.15	313.15	293.15	298.15	303.15	308.15	313.15
SDS in Aqueous Solutions of Fructose										
m_{Fruc} =0.00 mol·dm^{-3}										
1	998.321	997.152	995.747	994.124	992.299	1482.99	1497.13	1509.37	1520.08	1529.15
2	998.375	997.207	995.800	994.176	992.350	1483.37	1497.42	1509.44	1520.29	1529.37
3	998.419	997.249	995.840	994.212	992.386	1483.52	1497.59	1509.68	1520.45	1529.49
4	998.467	997.297	995.887	994.257	992.430	1483.80	1497.81	1509.85	1520.63	1529.65
5	998.520	997.350	995.935	994.306	992.475	1484.10	1498.05	1510.05	1520.82	1529.82
6	998.582	997.406	995.990	994.359	992.529	1484.21	1498.17	1510.25	1521.01	1529.99
7	998.622	997.456	996.038	994.406	992.574	1484.39	1498.42	1510.46	1521.12	1530.09
8	998.678	997.499	996.082	994.448	992.614	1484.64	1498.55	1510.59	1521.33	1530.28
9	998.725	997.548	996.128	994.493	992.658	1484.94	1498.87	1510.99	1521.48	1530.44
10	998.771	997.592	996.170	994.534	992.699	1484.87	1498.78	1510.90	1521.38	1530.32
11	998.807	997.625	996.204	994.567	992.731	1484.85	1498.76	1510.89	1521.36	1530.30
12	998.856	997.673	996.252	994.615	992.778	1484.87	1498.74	1510.85	1521.34	1530.28
13	998.899	997.712	996.291	994.653	992.814	1484.87	1498.72	1510.82	1521.31	1530.23
14	998.926	997.752	996.326	994.685	992.847	1484.86	1498.71	1510.81	1521.23	1530.22
m_{Fruc} =0.01 mol·dm^{-3}										
1	998.969	997.798	996.386	994.758	992.930	1483.79	1497.83	1510.08	1520.72	1529.78
2	999.029	997.865	996.442	994.821	992.988	1484.07	1498.08	1510.36	1520.99	1530.05
3	999.089	997.925	996.505	994.883	993.038	1484.33	1498.32	1510.61	1521.19	1530.24
4	999.159	997.982	996.563	994.928	993.097	1484.61	1498.57	1510.84	1521.38	1530.40
5	999.225	998.048	996.627	994.989	993.164	1484.89	1498.83	1511.08	1521.54	1530.53
6	999.283	998.105	996.684	995.043	993.216	1485.14	1499.06	1511.26	1521.69	1530.69
7	999.338	998.161	996.743	995.096	993.264	1485.36	1499.22	1511.39	1521.83	1530.83
8	999.391	998.218	996.791	995.145	993.317	1485.55	1499.36	1511.50	1521.92	1530.93
9	999.443	998.268	996.834	995.195	993.362	1485.58	1499.42	1511.51	1521.97	1530.93
10	999.506	998.319	996.887	995.249	993.412	1485.60	1499.43	1511.51	1521.95	1530.92
11	999.567	998.376	996.939	995.305	993.463	1485.61	1499.42	1511.50	1521.91	1530.87
12	999.632	998.429	996.994	995.363	993.520	1485.60	1499.42	1511.49	1521.89	1530.84
13	999.685	998.489	997.041	995.422	993.572	1485.60	1499.42	1511.48	1521.87	1530.82
14	999.741	998.531	997.091	995.476	993.618	1485.60	1499.42	1511.47	1521.85	1530.79
m_{Fruc} =0.10 mol·dm^{-3}										
1	1005.452	1004.225	1002.759	1001.083	999.210	1490.01	1503.77	1515.82	1526.14	1535.12
2	1005.512	1004.284	1002.812	1001.134	999.265	1490.31	1504.02	1516.05	1526.37	1535.29
3	1005.569	1004.335	1002.865	1001.186	999.313	1490.59	1504.26	1516.27	1526.57	1535.45
4	1005.623	1004.392	1002.918	1001.238	999.364	1490.87	1504.51	1516.48	1526.76	1535.58
5	1005.685	1004.448	1002.967	1001.288	999.415	1491.16	1504.72	1516.71	1526.94	1535.71
6	1005.733	1004.494	1003.016	1001.338	999.466	1491.41	1504.95	1516.93	1527.11	1535.83
7	1005.785	1004.545	1003.063	1001.386	999.516	1491.63	1505.19	1517.13	1527.27	1535.97
8	1005.838	1004.595	1003.115	1001.436	999.566	1491.78	1505.36	1517.20	1527.40	1536.06
9	1005.884	1004.643	1003.161	1001.480	999.606	1491.81	1505.41	1517.27	1527.41	1536.08
10	1005.928	1004.687	1003.207	1001.518	999.646	1491.84	1505.41	1517.27	1527.42	1536.09
11	1005.980	1004.735	1003.253	1001.565	999.682	1491.86	1505.40	1517.29	1527.41	1536.07
12	1006.019	1004.775	1003.295	1001.606	999.722	1491.91	1505.40	1517.27	1527.41	1536.06
13	1006.069	1004.818	1003.332	1001.649	999.758	1491.90	1505.41	1517.27	1527.39	1536.02
14	1006.121	1004.863	1003.37	1001.688	999.799	1491.92	1505.44	1517.28	1527.38	1536.01
SDS in Aqueous Solutions of Maltose										
m_{Mal} =0.01 mol·dm^{-3}										
1	999.646	998.476	997.064	995.435	993.607	1484.07	1498	1510.35	1520.96	1530.01
2	999.701	998.531	997.116	995.487	993.659	1484.33	1498.24	1510.54	1521.13	1530.18
3	999.761	998.585	997.168	995.535	993.709	1484.58	1498.53	1510.74	1521.33	1530.36
4	999.813	998.634	997.217	995.585	993.759	1484.84	1498.77	1510.94	1521.53	1530.53

Contd —

Table 1 — Density (d) and speed of sound (v) of SDS in aqueous solutions of fructose and maltose at different temperatures (K) — *Contd*

C	d ($kg \cdot m^{-3}$)					v ($m \cdot s^{-1}$)				
($mmol \cdot dm^{-3}$)	293.15	298.15	303.15	308.15	313.15	293.15	298.15	303.15	308.15	313.15
				SDS in Aqueous Solutions of Maltose						
				m_{Mal} =0.01 $mol \cdot dm^{-3}$						
5	999.870	998.686	997.266	995.634	993.803	1485.11	1499.00	1511.18	1521.71	1530.70
6	999.917	998.738	997.312	995.681	993.851	1485.32	1499.22	1511.37	1521.87	1530.88
7	999.969	998.783	997.358	995.726	993.894	1485.52	1499.40	1511.53	1522.01	1531.04
8	1000.019	998.834	997.405	995.768	993.938	1485.74	1499.54	1511.67	1522.16	1531.19
9	1000.071	998.879	997.454	995.805	993.972	1485.82	1499.66	1511.79	1522.27	1531.19
10	1000.118	998.923	997.499	995.848	994.011	1485.86	1499.71	1511.81	1522.29	1531.21
11	1000.171	998.971	997.544	995.89	994.051	1485.91	1499.72	1511.79	1522.26	1531.17
12	1000.218	999.018	997.589	995.925	994.092	1485.89	1499.70	1511.78	1522.25	1531.15
13	1000.259	999.062	997.629	995.961	994.125	1485.89	1499.70	1511.77	1522.22	1531.12
14	1000.298	999.104	997.669	996.002	994.165	1485.88	1499.66	1511.74	1522.18	1531.04
				m_{Mal} =0.10 $mol \cdot dm^{-3}$						
1	1011.731	1010.487	1009.009	1007.323	1005.444	1493.42	1507.00	1518.93	1529.23	1537.97
2	1011.793	1010.542	1009.067	1007.379	1005.503	1493.65	1507.22	1519.12	1529.41	1538.13
3	1011.847	1010.599	1009.119	1007.431	1005.556	1493.89	1507.45	1519.32	1529.59	1538.29
4	1011.902	1010.654	1009.171	1007.482	1005.604	1494.14	1507.67	1519.52	1529.77	1538.43
5	1011.954	1010.707	1009.221	1007.531	1005.651	1494.37	1507.9	1519.72	1529.96	1538.59
6	1012.005	1010.761	1009.272	1007.581	1005.698	1494.61	1508.13	1519.93	1530.14	1538.74
7	1012.057	1010.812	1009.321	1007.629	1005.743	1494.86	1508.37	1520.13	1530.32	1538.88
8	1012.105	1010.866	1009.373	1007.682	1005.790	1495.07	1508.58	1520.29	1530.49	1538.99
9	1012.157	1010.907	1009.421	1007.727	1005.835	1495.18	1508.65	1520.34	1530.49	1539.02
10	1012.204	1010.959	1009.464	1007.776	1005.878	1495.22	1508.67	1520.38	1530.46	1539.02
11	1012.253	1010.998	1009.509	1007.821	1005.918	1495.27	1508.69	1520.36	1530.46	1539.01
12	1012.297	1011.038	1009.549	1007.865	1005.955	1495.28	1508.69	1520.35	1530.45	1538.99
13	1012.344	1011.089	1009.593	1007.899	1005.995	1495.29	1508.69	1520.33	1530.42	1538.94
14	1012.383	1011.129	1009.631	1007.933	1006.024	1495.29	1508.69	1520.32	1530.40	1538.92

Standard uncertainties, u, are u(T) = ±0.01 K, u(C) = $\pm 3 \cdot 10^{-3}$ $mol \cdot dm^{-3}$, u(d) = $\pm 2 \cdot 10^{-3}$ $kg \cdot m^{-3}$ and u(v) = $\pm 2 \cdot 10^{-1}$ $m \cdot s^{-1}$.

Table 2 — Intermolecular free length (L_f), Relative association (*RA*), Specific acoustic impedance (*z*), Molar sound number (*U*), Wada's constant (*W*), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 293.15 K

C ($mmol \cdot dm^{-3}$)	$L_f \times 10^{10}$ (m)	*RA*	*z* ($kg \cdot m^{-2} \cdot s^{-1}$)	(*U*) ($kg \cdot mol^{-1}$)	$W \times 10^6$ ($atm^{-1/7} \cdot m^3 \cdot mol^{-1}$)	$R_m \times 10^6$ ($m \cdot s^{-1}$)	$V_m \times 10^5$ (m^3)	$V_m^E \times 10^5$ (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
				SDS in Aqueous Solutions of Fructose						
				m_{Fruc} = 0.01 $mol \cdot dm^{-3}$						
1	58.915	1.00000	14.823	0.1146	7.559	206.670	1.812	0.009	-1.191	-4.102
2	58.902	1.00000	14.826	0.1517	7.589	207.494	1.819	0.016	-1.390	-4.115
3	58.890	1.00000	14.830	0.1595	7.620	208.316	1.826	0.023	-1.576	-4.127
4	58.876	1.00001	14.834	0.1668	7.650	209.138	1.833	0.030	-1.779	-4.140
5	58.863	1.00001	14.837	0.1712	7.680	209.960	1.840	0.037	-1.981	-4.153
6	58.852	1.00001	14.841	0.1708	7.710	210.783	1.847	0.044	-2.160	-4.165
7	58.841	1.00002	14.844	0.1675	7.740	211.605	1.855	0.051	-2.319	-4.175
8	58.832	1.00003	14.846	0.1626	7.770	212.426	1.862	0.059	-2.459	-4.184
9	58.830	1.00007	14.848	0.1468	7.800	213.239	1.869	0.066	-2.501	-4.187
10	58.827	1.00013	14.849	0.1335	7.829	214.050	1.876	0.073	-2.542	-4.189
11	58.825	1.00019	14.850	0.1219	7.859	214.860	1.883	0.080	-2.576	-4.192
12	58.823	1.00026	14.851	0.1112	7.889	215.669	1.890	0.087	-2.599	-4.193
13	58.822	1.00031	14.851	0.1027	7.918	216.480	1.897	0.094	-2.623	-4.195
14	58.820	1.00037	14.852	0.0953	7.948	217.291	1.904	0.101	-2.648	-4.196

Contd —

Table 2 — Intermolecular free length (L_f), Relative association (*RA*), Specific acoustic impedance (*z*), Molar sound number (*U*), Wada's constant (*W*), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 293.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	*RA*	*z* (kg·m^{-2}·s^{-1})	(*U*) (kg·mol^{-1})	*W* × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Fructose										
m_{Fruc} = 0.10 mol·dm^{-3}										
1	58.479	0.99998	14.981	0.1477	7.635	208.600	1.826	-0.006	-7.873	-4.536
2	58.466	0.99998	14.985	0.1745	7.665	209.421	1.833	0.001	-8.080	-4.550
3	58.453	0.99997	14.989	0.1790	7.695	210.241	1.840	0.008	-8.273	-4.562
4	58.441	0.99996	14.993	0.1812	7.726	211.062	1.848	0.015	-8.465	-4.575
5	58.427	0.99996	14.996	0.1839	7.756	211.881	1.855	0.022	-8.667	-4.588
6	58.416	0.99995	15.000	0.1812	7.786	212.702	1.862	0.029	-8.838	-4.599
7	58.406	0.99995	15.003	0.1764	7.815	213.521	1.869	0.036	-8.993	-4.609
8	58.399	0.99997	15.005	0.1670	7.845	214.335	1.876	0.043	-9.107	-4.617
9	58.396	1.00001	15.006	0.1507	7.875	215.146	1.883	0.050	-9.145	-4.619
10	58.394	1.00005	15.007	0.1376	7.905	215.957	1.890	0.057	-9.183	-4.622
11	58.391	1.00009	15.008	0.1263	7.934	216.766	1.897	0.065	-9.218	-4.624
12	58.388	1.00012	15.009	0.1186	7.964	217.579	1.904	0.072	-9.265	-4.627
13	58.387	1.00017	15.010	0.1089	7.994	218.386	1.911	0.079	-9.281	-4.628
14	58.385	1.00022	15.011	0.1021	8.023	219.195	1.918	0.086	-9.316	-4.631
SDS in Aqueous Solutions of Maltose										
m_{Mal} = 0.01 mol·dm^{-3}										
1	58.884	0.99996	14.835	0.1752	7.569	206.919	1.814	0.011	-1.670	-4.133
2	58.872	0.99995	14.839	0.1752	7.599	207.743	1.821	0.018	-1.854	-4.145
3	58.860	0.99996	14.842	0.1730	7.629	208.565	1.828	0.025	-2.034	-4.156
4	58.848	0.99995	14.846	0.1735	7.659	209.389	1.835	0.032	-2.217	-4.168
5	58.836	0.99995	14.849	0.1752	7.690	210.212	1.842	0.039	-2.408	-4.181
6	58.826	0.99995	14.852	0.1696	7.720	211.035	1.850	0.047	-2.557	-4.190
7	58.817	0.99995	14.855	0.1646	7.750	211.856	1.857	0.054	-2.703	-4.200
8	58.806	0.99995	14.858	0.1626	7.780	212.678	1.864	0.061	-2.860	-4.210
9	58.802	0.99999	14.859	0.1505	7.810	213.494	1.871	0.068	-2.932	-4.215
10	58.799	1.00003	14.860	0.1382	7.839	214.308	1.878	0.075	-2.978	-4.218
11	58.795	1.00007	14.862	0.1287	7.869	215.122	1.885	0.082	-3.032	-4.221
12	58.795	1.00012	14.862	0.1168	7.899	215.933	1.892	0.089	-3.041	-4.222
13	58.793	1.00016	14.863	0.1078	7.929	216.747	1.899	0.096	-3.060	-4.223
14	58.793	1.00020	14.863	0.0996	7.959	217.560	1.907	0.103	-3.071	-4.224
m_{Mal} = 0.10 mol·dm^{-3}										
1	58.164	0.99999	15.109	0.1339	7.734	211.124	1.847	0.014	-12.675	-4.851
2	58.154	1.00000	15.113	0.1440	7.764	211.936	1.854	0.021	-12.839	-4.861
3	58.143	1.00000	15.116	0.1496	7.793	212.751	1.861	0.028	-13.005	-4.872
4	58.131	1.00000	15.119	0.1540	7.823	213.566	1.868	0.035	-13.177	-4.883
5	58.121	1.00000	15.122	0.1540	7.853	214.380	1.875	0.042	-13.336	-4.894
6	58.110	0.99999	15.126	0.1551	7.883	215.195	1.882	0.049	-13.500	-4.905
7	58.099	0.99999	15.129	0.1569	7.913	216.011	1.889	0.056	-13.671	-4.916
8	58.089	0.99999	15.132	0.1549	7.943	216.825	1.896	0.063	-13.816	-4.925
9	58.084	1.00002	15.134	0.1458	7.972	217.634	1.903	0.070	-13.904	-4.931
10	58.081	1.00005	15.135	0.1339	8.002	218.440	1.910	0.077	-13.948	-4.934
11	58.077	1.00009	15.136	0.1248	8.032	219.246	1.917	0.084	-13.999	-4.937
12	58.076	1.00013	15.137	0.1150	8.061	220.052	1.924	0.091	-14.024	-4.939
13	58.074	1.00018	15.137	0.1066	8.091	220.856	1.931	0.098	-14.050	-4.941
14	58.073	1.00022	15.138	0.0990	8.120	221.662	1.938	0.106	-14.067	-4.942

Standard uncertainties, u, are u(C) = ±0.003 mol·dm^{-3}, u(L_f) = ±0.002×10^{-10} m, u(*RA*) = ±0.0001, u(*Z*) = ±0.002 kg·m^{-2}·s^{-1}, u(*U*) = ±0.0004 kg·mol^{-1}, u(*W*) = ±0.005× 10^{-6} atm$^{-1/7}$ ·m^3·mol^{-1}, u(R_m) = ±0.002×10^{-6} m·s$^{-1,}$ u(V_m) = ±0.003×10^{-5}m^3, u(V_m) = ±0.003×10^{-5} m^3, u(V_m^E) = 0.003×10^{-5} m^3, u(κ_s^E) = 0.002 TPa^{-1} and u(L_f^E) = ±0.002×10^{-10} m.

Table 3 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 298.15 K

C (mmol·dm^{-3})	$L_f \times 10^{10}$ (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	$W \times 10^6$ (atm$^{-1/7}$·m^3·mol^{-1})	$R_m \times 10^6$ (m·s^{-1})	$V_m \times 10^5$ (m^3)	$V_m^E \times 10^5$ (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Fructose										
m_{Fruc} = 0.01 mol·dm^{-3}										
1	59.393	0.99998	14.945	0.1202	7.587	207.563	1.814	0.009	-1.089	-3.064
2	59.381	1.00000	14.949	0.1436	7.617	208.387	1.821	0.016	-1.268	-3.076
3	59.369	1.00000	14.952	0.1491	7.648	209.212	1.828	0.023	-1.438	-3.087
4	59.358	1.00000	14.955	0.1536	7.678	210.039	1.835	0.030	-1.612	-3.099
5	59.346	1.00001	14.959	0.1576	7.708	210.864	1.843	0.037	-1.796	-3.111
6	59.335	1.00002	14.962	0.1569	7.738	211.689	1.850	0.044	-1.959	-3.122
7	59.327	1.00004	14.965	0.1498	7.768	212.512	1.857	0.052	-2.079	-3.130
8	59.320	1.00007	14.967	0.1427	7.798	213.333	1.864	0.059	-2.188	-3.137
9	59.316	1.00010	14.968	0.1313	7.828	214.151	1.871	0.066	-2.246	-3.141
10	59.314	1.00015	14.969	0.1189	7.858	214.968	1.878	0.073	-2.274	-3.143
11	59.312	1.00021	14.970	0.1074	7.888	215.781	1.885	0.080	-2.294	-3.144
12	59.311	1.00026	14.971	0.0985	7.918	216.596	1.892	0.087	-2.317	-3.146
13	59.309	1.00032	14.972	0.0909	7.948	217.410	1.899	0.094	-2.344	-3.147
14	59.308	1.00037	14.972	0.0844	7.978	218.227	1.907	0.101	-2.363	-3.149
m_{Fruc} = 0.10 mol·dm^{-3}										
1	58.968	0.99998	15.101	0.1463	7.664	209.496	1.829	-0.006	-7.434	-3.487
2	58.957	0.99998	15.105	0.1563	7.694	210.318	1.836	0.001	-7.607	-3.500
3	58.946	0.99998	15.108	0.1574	7.724	211.141	1.843	0.008	-7.769	-3.511
4	58.935	0.99998	15.111	0.1596	7.754	211.963	1.850	0.015	-7.941	-3.522
5	58.925	0.99999	15.114	0.1556	7.784	212.783	1.857	0.022	-8.088	-3.532
6	58.914	0.99998	15.117	0.1552	7.814	213.607	1.864	0.029	-8.242	-3.542
7	58.903	0.99998	15.120	0.1558	7.844	214.430	1.871	0.036	-8.405	-3.553
8	58.895	0.99999	15.123	0.1505	7.874	215.250	1.878	0.043	-8.526	-3.561
9	58.892	1.00003	15.124	0.1375	7.904	216.064	1.885	0.051	-8.576	-3.565
10	58.891	1.00007	15.125	0.1237	7.934	216.877	1.892	0.058	-8.595	-3.566
11	58.890	1.00012	15.125	0.1119	7.963	217.689	1.899	0.065	-8.611	-3.567
12	58.888	1.00016	15.126	0.1025	7.993	218.503	1.907	0.072	-8.628	-3.568
13	58.887	1.00021	15.127	0.0952	8.023	219.316	1.914	0.079	-8.653	-3.570
14	58.884	1.00024	15.128	0.0898	8.053	220.130	1.921	0.086	-8.690	-3.572
SDS in Aqueous Solutions of Maltose										
m_{Mal} = 0.01 mol·dm^{-3}										
1	59.366	0.99997	14.957	0.1335	7.597	207.808	1.816	0.011	-1.493	-3.091
2	59.355	0.99997	14.960	0.1469	7.627	208.634	1.823	0.018	-1.661	-3.102
3	59.342	0.99996	14.964	0.1625	7.657	209.462	1.830	0.025	-1.858	-3.115
4	59.331	0.99996	14.967	0.1619	7.688	210.289	1.838	0.032	-2.022	-3.126
5	59.320	0.99996	14.970	0.1602	7.718	211.115	1.845	0.039	-2.182	-3.137
6	59.310	0.99996	14.973	0.1580	7.748	211.941	1.852	0.047	-2.336	-3.147
7	59.301	0.99997	14.976	0.1526	7.778	212.766	1.859	0.054	-2.463	-3.155
8	59.294	0.99999	14.978	0.1452	7.808	213.588	1.866	0.061	-2.569	-3.162
9	59.288	1.00000	14.980	0.1380	7.838	214.410	1.873	0.068	-2.661	-3.169
10	59.285	1.00004	14.981	0.1275	7.868	215.229	1.880	0.075	-2.710	-3.172
11	59.283	1.00008	14.982	0.1165	7.898	216.045	1.887	0.082	-2.737	-3.174
12	59.282	1.00014	14.982	0.1057	7.928	216.860	1.895	0.089	-2.746	-3.174
13	59.281	1.00018	14.983	0.0976	7.958	217.677	1.902	0.096	-2.766	-3.176
14	59.281	1.00023	14.983	0.0887	7.988	218.492	1.909	0.104	-2.761	-3.175
m_{Mal} = 0.10 mol·dm^{-3}										
1	58.659	1.00000	15.228	0.0863	7.762	212.023	1.849	0.014	-12.029	-3.796
2	58.649	1.00000	15.231	0.1161	7.792	212.839	1.856	0.021	-12.180	-3.806

Contd —

Table 3 — Intermolecular free length (L_f), Relative association (*RA*), Specific acoustic impedance (*z*), Molar sound number (*U*), Wada's constant (*W*), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 298.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	*RA*	*z* (kg·m^{-2}·s^{-1})	(*U*) (kg·mol^{-1})	*W* × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Maltose										
m_{Mal} = 0.10 mol·dm^{-3}										
3	58.639	1.00001	15.234	0.1283	7.822	213.656	1.863	0.028	-12.337	-3.816
4	58.629	1.00001	15.237	0.1327	7.852	214.473	1.870	0.035	-12.488	-3.827
5	58.618	1.00002	15.240	0.1367	7.882	215.291	1.877	0.042	-12.644	-3.837
6	58.608	1.00002	15.244	0.1394	7.912	216.108	1.884	0.049	-12.800	-3.848
7	58.597	1.00002	15.247	0.1422	7.942	216.926	1.892	0.056	-12.960	-3.858
8	58.587	1.00002	15.250	0.1419	7.971	217.743	1.899	0.063	-13.104	-3.868
9	58.583	1.00005	15.251	0.1313	8.001	218.555	1.906	0.071	-13.162	-3.872
10	58.581	1.00009	15.252	0.1195	8.031	219.363	1.913	0.078	-13.196	-3.874
11	58.579	1.00013	15.253	0.1098	8.061	220.173	1.920	0.085	-13.224	-3.876
12	58.578	1.00017	15.253	0.1007	8.090	220.983	1.927	0.092	-13.242	-3.877
13	58.576	1.00022	15.254	0.0929	8.120	221.789	1.934	0.099	-13.263	-3.879
14	58.575	1.00026	15.255	0.0863	8.150	222.598	1.941	0.106	-13.281	-3.880

Standard uncertainties, u, are u(C) = ±0.003 mol·dm^{-3}, u(L_f) = ±0.002×10^{-10} m, u(*RA*) = ±0.0001, u(*z*) = ±0.002 kg·m^{-2}·s^{-1}, u(*U*) = ±0.0004 kg·mol^{-1}, u(*W*) = ±0.005× 10^{-6} atm$^{-1/7}$ ·m^3·mol^{-1}, u(R_m) = ±0.002×10^{-6} m·s^{-1}, u(V_m) = ±0.003×10^{-5}m^3, u(V_m) = ±0.003×10^{-5} m^3, u(V_m^E) = 0.003×10^{-5} m^3, u(κ_s^E) = 0.002 TPa^{-1} and u(L_f^E) = ±0.002×10^{-10} m.

Table 4 — Intermolecular free length (L_f), Relative association (*RA*), Specific acoustic impedance (*z*), Molar sound number (*U*), Wada's constant (*W*), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 303.15 K

C (mmol·dm^{-3})	L_f ×10^{10} (m)	*RA*	*z* (kg·m^{-2}·s^{-1})	(*U*) (kg·mol^{-1})	*W* × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Fructose										
m_{Fruc} = 0.01 mol·dm^{-3}										
1	59.941	0.99999	15.046	0.0927	7.614	208.422	1.817	0.009	-0.917	-2.042
2	59.928	0.99998	15.050	0.1391	7.645	209.253	1.824	0.016	-1.105	-2.054
3	59.917	0.99999	15.053	0.1479	7.675	210.082	1.831	0.023	-1.278	-2.066
4	59.906	1.00000	15.056	0.1490	7.705	210.910	1.838	0.030	-1.438	-2.077
5	59.894	1.00001	15.060	0.1510	7.735	211.738	1.845	0.037	-1.606	-2.089
6	59.885	1.00003	15.062	0.1457	7.766	212.565	1.852	0.045	-1.736	-2.097
7	59.879	1.00006	15.065	0.1372	7.796	213.388	1.859	0.052	-1.837	-2.104
8	59.873	1.00008	15.066	0.1291	7.826	214.213	1.867	0.059	-1.922	-2.110
9	59.871	1.00012	15.067	0.1155	7.856	215.034	1.874	0.066	-1.947	-2.112
10	59.869	1.00017	15.068	0.1040	7.886	215.853	1.881	0.073	-1.970	-2.113
11	59.868	1.00023	15.069	0.0939	7.916	216.671	1.888	0.080	-1.987	-2.115
12	59.867	1.00029	15.069	0.0855	7.946	217.489	1.895	0.087	-2.006	-2.116
13	59.866	1.00034	15.070	0.0785	7.976	218.308	1.902	0.095	-2.021	-2.117
14	59.865	1.00039	15.071	0.0724	8.006	219.126	1.909	0.102	-2.037	-2.118
m_{Fruc} = 0.10 mol·dm^{-3}										
1	59.524	0.99998	15.200	0.1320	7.691	210.361	1.831	-0.006	-7.008	-2.458
2	59.514	0.99998	15.203	0.1419	7.721	211.186	1.838	0.001	-7.163	-2.469
3	59.503	0.99998	15.206	0.1430	7.751	212.011	1.845	0.008	-7.311	-2.480
4	59.494	0.99999	15.209	0.1419	7.781	212.836	1.853	0.015	-7.454	-2.489
5	59.483	0.99999	15.212	0.1438	7.811	213.662	1.860	0.022	-7.607	-2.500
6	59.473	0.99999	15.215	0.1441	7.842	214.488	1.867	0.029	-7.754	-2.510
7	59.464	0.99999	15.218	0.1423	7.872	215.313	1.874	0.037	-7.888	-2.519
8	59.459	1.00003	15.219	0.1303	7.902	216.131	1.881	0.044	-7.951	-2.523
9	59.455	1.00006	15.221	0.1210	7.932	216.950	1.888	0.051	-8.011	-2.528
10	59.454	1.00011	15.221	0.1089	7.962	217.766	1.895	0.058	-8.030	-2.529

Contd —

Table 4 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 303.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
				SDS in Aqueous Solutions of Fructose						
				m_{Fruc} = 0.10 mol·dm^{-3}						
11	59.452	1.00015	15.222	0.1002	7.991	218.583	1.902	0.065	-8.062	-2.531
12	59.451	1.00019	15.223	0.0907	8.021	219.398	1.909	0.072	-8.068	-2.531
13	59.450	1.00023	15.223	0.0837	8.051	220.216	1.916	0.079	-8.084	-2.533
14	59.449	1.00027	15.224	0.0782	8.081	221.034	1.924	0.086	-8.107	-2.534
				SDS in Aqueous Solutions of Maltose						
				m_{Mal} = 0.01 mol·dm^{-3}						
1	59.910	0.99998	15.059	0.1126	7.624	208.673	1.819	0.011	-1.374	-2.073
2	59.901	0.99999	15.062	0.1192	7.654	209.500	1.826	0.018	-1.507	-2.082
3	59.892	1.00000	15.065	0.1236	7.685	210.328	1.833	0.025	-1.646	-2.091
4	59.882	1.00000	15.067	0.1258	7.715	211.157	1.840	0.032	-1.784	-2.101
5	59.871	1.00000	15.070	0.1324	7.745	211.987	1.847	0.040	-1.945	-2.112
6	59.862	1.00000	15.073	0.1313	7.775	212.816	1.854	0.047	-2.076	-2.121
7	59.855	1.00001	15.075	0.1277	7.806	213.643	1.862	0.054	-2.189	-2.128
8	59.848	1.00003	15.077	0.1233	7.836	214.469	1.869	0.061	-2.291	-2.135
9	59.841	1.00005	15.079	0.1185	7.866	215.294	1.876	0.068	-2.382	-2.142
10	59.839	1.00009	15.080	0.1079	7.896	216.114	1.883	0.075	-2.414	-2.144
11	59.839	1.00014	15.081	0.0969	7.926	216.933	1.890	0.082	-2.422	-2.144
12	59.838	1.00019	15.081	0.0883	7.956	217.752	1.897	0.090	-2.436	-2.145
13	59.837	1.00023	15.082	0.0810	7.986	218.573	1.904	0.097	-2.448	-2.146
14	59.837	1.00028	15.082	0.0738	8.016	219.392	1.912	0.104	-2.448	-2.146
				m_{Mal} = 0.10 mol·dm^{-3}						
1	59.218	1.00001	15.326	0.0263	7.789	212.892	1.852	0.014	-11.453	-2.763
2	59.209	1.00003	15.329	0.0757	7.819	213.710	1.859	0.021	-11.585	-2.773
3	59.200	1.00003	15.332	0.0944	7.849	214.530	1.866	0.028	-11.720	-2.782
4	59.190	1.00004	15.335	0.1037	7.879	215.349	1.873	0.036	-11.855	-2.791
5	59.181	1.00005	15.337	0.1093	7.909	216.169	1.880	0.043	-11.989	-2.800
6	59.171	1.00005	15.340	0.1141	7.939	216.990	1.887	0.050	-12.129	-2.810
7	59.162	1.00006	15.343	0.1166	7.969	217.810	1.894	0.057	-12.263	-2.819
8	59.154	1.00007	15.345	0.1152	7.999	218.628	1.901	0.064	-12.375	-2.827
9	59.151	1.00011	15.347	0.1061	8.029	219.441	1.908	0.071	-12.424	-2.830
10	59.148	1.00014	15.348	0.0981	8.059	220.255	1.915	0.078	-12.465	-2.833
11	59.148	1.00019	15.348	0.0880	8.089	221.065	1.923	0.085	-12.473	-2.834
12	59.147	1.00023	15.349	0.0801	8.118	221.877	1.930	0.092	-12.484	-2.835
13	59.146	1.00028	15.349	0.0729	8.148	222.688	1.937	0.099	-12.491	-2.835
14	59.146	1.00032	15.350	0.0672	8.178	223.500	1.944	0.106	-12.502	-2.836

Standard uncertainties, u, are u(C) = ±0.003 mol·dm^{-3}, u(L_f) = ±0.002×10^{-10} m, u(RA) = ±0.0001, u(z) = ±0.002 kg·m^{-2}·s^{-1}, u(U) = ±0.0004 kg·mol^{-1}, u(W) = ±0.005× 10^{-6} atm$^{-1/7}$ ·m^3·mol^{-1}, u(R_m) = ±0.002×10^{-6} m·s^{-1}, u(V_m) = ±0.003×10^{-5}m^3, u(V_m) = ±0.003×10^{-5} m^3, u(V_m^E) = 0.003×10^{-5} m^3, u(κ_s^E) = 0.002 TPa^{-1} and u(L_f^E) = ±0.002×10^{-10} m.

Table 5 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 308.15 K

C (mmol·dm^{-3})	L_f ×10^{10} (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
				SDS in Aqueous Solutions of Fructose						
				m_{Fruc} = 0.01 mol·dm^{-3}						
1	60.553	0.99999	15.127	0.0986	7.640	209.252	1.820	0.009	-0.860	-1.043
2	60.540	0.99999	15.131	0.1381	7.671	210.085	1.827	0.016	-1.042	-1.056

Table 5 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 308.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Fructose										
m_{Fruc} = 0.01 mol·dm^{-3}										
3	60.531	1.00001	15.134	0.1359	7.701	210.915	1.834	0.023	-1.183	-1.066
4	60.522	1.00001	15.137	0.1332	7.731	211.747	1.841	0.030	-1.311	-1.075
5	60.513	1.00004	15.139	0.1276	7.762	212.575	1.848	0.037	-1.429	-1.083
6	60.506	1.00006	15.141	0.1228	7.792	213.404	1.855	0.045	-1.538	-1.091
7	60.499	1.00008	15.144	0.1184	7.822	214.232	1.863	0.052	-1.641	-1.098
8	60.494	1.00011	15.145	0.1110	7.852	215.059	1.870	0.059	-1.714	-1.103
9	60.490	1.00015	15.147	0.1023	7.883	215.884	1.877	0.066	-1.764	-1.106
10	60.489	1.00021	15.147	0.0908	7.913	216.705	1.884	0.073	-1.776	-1.107
11	60.489	1.00027	15.148	0.0801	7.943	217.524	1.891	0.080	-1.778	-1.107
12	60.488	1.00034	15.148	0.0723	7.973	218.343	1.898	0.088	-1.792	-1.108
13	60.487	1.00040	15.149	0.0658	8.002	219.163	1.905	0.095	-1.806	-1.109
14	60.486	1.00046	15.150	0.0601	8.033	219.983	1.912	0.102	-1.818	-1.110
m_{Fruc} = 0.10 mol·dm^{-3}										
1	60.147	0.99997	15.278	0.1245	7.717	211.190	1.834	-0.006	-6.657	-1.448
2	60.136	0.99998	15.281	0.1376	7.747	212.019	1.841	0.001	-6.808	-1.460
3	60.127	0.99998	15.284	0.1354	7.777	212.847	1.849	0.008	-6.943	-1.469
4	60.118	0.99999	15.287	0.1327	7.807	213.674	1.856	0.015	-7.072	-1.478
5	60.109	1.00000	15.289	0.1298	7.838	214.500	1.863	0.022	-7.194	-1.487
6	60.101	1.00002	15.292	0.1267	7.868	215.327	1.870	0.030	-7.311	-1.495
7	60.093	1.00003	15.294	0.1236	7.898	216.153	1.877	0.037	-7.421	-1.503
8	60.087	1.00005	15.296	0.1188	7.928	216.978	1.884	0.044	-7.515	-1.509
9	60.085	1.00009	15.297	0.1063	7.958	217.798	1.891	0.051	-7.540	-1.511
10	60.084	1.00013	15.297	0.0963	7.988	218.619	1.898	0.058	-7.562	-1.513
11	60.083	1.00018	15.298	0.0870	8.018	219.437	1.905	0.065	-7.576	-1.514
12	60.081	1.00022	15.299	0.0797	8.048	220.257	1.913	0.072	-7.594	-1.515
13	60.081	1.00027	15.299	0.0726	8.078	221.075	1.920	0.079	-7.601	-1.515
14	60.080	1.00031	15.300	0.0669	8.108	221.895	1.927	0.087	-7.612	-1.516
SDS in Aqueous Solutions of Maltose										
m_{Mal} = 0.01 mol·dm^{-3}										
1	60.523	0.99998	15.140	0.0986	7.650	209.502	1.822	0.011	-1.292	-1.073
2	60.515	0.99999	15.143	0.1052	7.680	210.332	1.829	0.018	-1.412	-1.082
3	60.505	1.00000	15.145	0.1140	7.711	211.164	1.836	0.025	-1.547	-1.091
4	60.496	1.00000	15.148	0.1184	7.741	211.996	1.843	0.032	-1.683	-1.101
5	60.487	1.00001	15.151	0.1184	7.771	212.826	1.850	0.040	-1.807	-1.109
6	60.479	1.00003	15.153	0.1162	7.802	213.657	1.857	0.047	-1.919	-1.117
7	60.472	1.00004	15.155	0.1127	7.832	214.486	1.865	0.054	-2.018	-1.124
8	60.465	1.00005	15.157	0.1110	7.862	215.317	1.872	0.061	-2.122	-1.131
9	60.460	1.00006	15.159	0.1067	7.893	216.147	1.879	0.068	-2.201	-1.137
10	60.457	1.00010	15.160	0.0973	7.923	216.972	1.886	0.075	-2.231	-1.139
11	60.457	1.00015	15.160	0.0867	7.953	217.794	1.893	0.083	-2.232	-1.139
12	60.457	1.00019	15.160	0.0789	7.983	218.619	1.900	0.090	-2.241	-1.140
13	60.457	1.00023	15.161	0.0713	8.013	219.442	1.908	0.097	-2.240	-1.139
14	60.457	1.00028	15.161	0.0643	8.043	220.264	1.915	0.104	-2.235	-1.139
m_{Mal} = 0.10 mol·dm^{-3}										
1	59.839	1.00001	15.404	0.0131	7.816	213.729	1.855	0.014	-11.027	-1.756
2	59.831	1.00003	15.407	0.0654	7.846	214.550	1.862	0.022	-11.150	-1.764
3	59.822	1.00004	15.410	0.0828	7.876	215.372	1.869	0.029	-11.272	-1.773
4	59.813	1.00005	15.412	0.0916	7.906	216.194	1.876	0.036	-11.393	-1.781
5	59.805	1.00006	15.415	0.0981	7.936	217.017	1.883	0.043	-11.519	-1.790

Contd —

Table 5 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 308.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Maltose										
m_{Mal} = 0.10 mol·dm^{-3}										
6	59.796	1.00007	15.417	0.1014	7.966	217.840	1.890	0.050	-11.640	-1.799
7	59.788	1.00008	15.420	0.1037	7.996	218.662	1.897	0.057	-11.760	-1.807
8	59.779	1.00009	15.422	0.1046	8.026	219.483	1.905	0.064	-11.876	-1.815
9	59.778	1.00014	15.423	0.0930	8.056	220.298	1.912	0.071	-11.895	-1.817
10	59.778	1.00019	15.424	0.0817	8.086	221.110	1.919	0.078	-11.899	-1.817
11	59.776	1.00024	15.424	0.0743	8.116	221.925	1.926	0.085	-11.918	-1.818
12	59.776	1.00028	15.425	0.0676	8.145	222.739	1.933	0.092	-11.931	-1.819
13	59.776	1.00032	15.425	0.0609	8.175	223.554	1.940	0.099	-11.929	-1.819
14	59.775	1.00036	15.425	0.0556	8.205	224.370	1.947	0.106	-11.932	-1.819

Standard uncertainties, u, are u(C) = ±0.003 mol·dm^{-3}, u(L_f) = ±0.002×10^{-10} m, u(RA) = ±0.0001, u(z) = ±0.002 kg·m^{-2}·s^{-1}, u(U) = ±0.0004 kg·mol^{-1}, u(W) = ±0.005× 10^{-6} atm$^{-1/7}$ ·m^3·mol^{-1}, u(R_m) = ±0.002×10^{-6} m·s^{-1}, u(V_m) = ±0.003×10^{-5}m^3, u(V_m) = ±0.003×10^{-5} m^3, u(V_m^E) = 0.003×10^{-5} m^3, u(κ_s^E) = 0.002 TPa^{-1} and u(L_f^E) = ±0.002×10^{-10} m.

Table 6 — Intermolecular free length (L_f), Relative association (RA), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 313.15 K

C (mmol·dm^{-3})	L_f ×10^{10} (m)	RA	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
SDS in Aqueous Solutions of Fructose										
m_{Fruc} = 0.01 mol·dm^{-3}										
1	61.227	0.99997	15.190	0.0915	7.665	210.053	1.823	0.009	-0.767	-0.054
2	61.215	0.99997	15.193	0.1340	7.696	210.890	1.830	0.016	-0.944	-0.067
3	61.206	0.99998	15.196	0.1307	7.726	211.725	1.837	0.023	-1.073	-0.076
4	61.197	1.00001	15.198	0.1242	7.757	212.556	1.844	0.030	-1.188	-0.084
5	61.190	1.00005	15.201	0.1164	7.787	213.384	1.852	0.038	-1.290	-0.092
6	61.182	1.00006	15.203	0.1144	7.817	214.217	1.859	0.045	-1.403	-0.100
7	61.175	1.00008	15.205	0.1111	7.848	215.050	1.866	0.052	-1.502	-0.107
8	61.169	1.00011	15.207	0.1054	7.878	215.879	1.873	0.059	-1.581	-0.112
9	61.168	1.00016	15.208	0.0937	7.908	216.706	1.880	0.066	-1.600	-0.114
10	61.167	1.00021	15.208	0.0837	7.938	217.531	1.887	0.073	-1.616	-0.115
11	61.167	1.00027	15.209	0.0731	7.968	218.354	1.895	0.081	-1.610	-0.115
12	61.167	1.00034	15.209	0.0654	7.999	219.176	1.902	0.088	-1.618	-0.115
13	61.166	1.00039	15.210	0.0593	8.029	220.000	1.909	0.095	-1.629	-0.116
14	61.166	1.00045	15.210	0.0537	8.059	220.825	1.916	0.102	-1.633	-0.116
m_{Fruc} = 0.10 mol·dm^{-3}										
1	60.822	0.99997	15.339	0.1238	7.742	212.000	1.838	-0.006	-6.431	-0.459
2	60.814	0.99998	15.342	0.1173	7.772	212.829	1.845	0.001	-6.548	-0.467
3	60.806	1.00000	15.344	0.1129	7.803	213.658	1.852	0.008	-6.657	-0.475
4	60.799	1.00002	15.346	0.1059	7.833	214.486	1.859	0.015	-6.751	-0.482
5	60.793	1.00004	15.348	0.1016	7.863	215.313	1.866	0.023	-6.844	-0.488
6	60.786	1.00007	15.350	0.0977	7.893	216.140	1.873	0.030	-6.932	-0.495
7	60.779	1.00009	15.352	0.0968	7.924	216.968	1.880	0.037	-7.031	-0.502
8	60.774	1.00012	15.354	0.0920	7.954	217.794	1.888	0.044	-7.101	-0.507
9	60.772	1.00015	15.355	0.0832	7.984	218.618	1.895	0.051	-7.129	-0.509
10	60.771	1.00019	15.355	0.0756	8.014	219.442	1.902	0.058	-7.152	-0.510
11	60.770	1.00023	15.356	0.0675	8.044	220.265	1.909	0.065	-7.156	-0.511
12	60.770	1.00027	15.356	0.0613	8.074	221.088	1.916	0.072	-7.168	-0.512
13	60.770	1.00032	15.356	0.0546	8.104	221.910	1.923	0.080	-7.161	-0.511
14	60.769	1.00036	15.357	0.0503	8.134	222.732	1.930	0.087	-7.168	-0.512

Contd —

Table 6 — Intermolecular free length (L_f), Relative association (*RA*), Specific acoustic impedance (z), Molar sound number (U), Wada's constant (W), Rao's constant (R_m), Molar volume (V_m), Excess molar volume (V_m^E), Excess isentropic compressibility (κ_s^E) and Excess free length (L_f^E) of SDS in aqueous solutions of fructose and maltose at 313.15 K — *Contd*

C (mmol·dm^{-3})	L_f ×10^{10} (m)	*RA*	z (kg·m^{-2}·s^{-1})	(U) (kg·mol^{-1})	W × 10^6 (atm$^{-1/7}$·m^3·mol^{-1})	R_m × 10^6 (m·s^{-1})	V_m ×10^5 (m^3)	V_m^E ×10^5 (m^3)	κ_s^E (TPa^{-1})	L_f^E (m)
				SDS in Aqueous Solutions of Maltose						
				m_{Mal} = 0.01 mol·dm^{-3}						
1	61.197	1.00000	15.202	0.0261	7.675	210.303	1.825	0.011	-1.190	-0.085
2	61.189	1.00001	15.205	0.0686	7.705	211.136	1.832	0.018	-1.308	-0.093
3	61.180	1.00003	15.207	0.0850	7.736	211.970	1.839	0.025	-1.430	-0.102
4	61.172	1.00004	15.210	0.0915	7.766	212.803	1.847	0.033	-1.547	-0.110
5	61.164	1.00005	15.212	0.0954	7.797	213.638	1.854	0.040	-1.662	-0.118
6	61.155	1.00006	15.215	0.0991	7.827	214.472	1.861	0.047	-1.784	-0.127
7	61.147	1.00006	15.217	0.0999	7.858	215.306	1.868	0.054	-1.892	-0.135
8	61.140	1.00008	15.219	0.0997	7.888	216.139	1.875	0.061	-1.995	-0.142
9	61.139	1.00011	15.220	0.0886	7.918	216.968	1.882	0.068	-2.010	-0.143
10	61.137	1.00014	15.220	0.0810	7.949	217.796	1.890	0.076	-2.038	-0.145
11	61.137	1.00019	15.221	0.0713	7.979	218.622	1.897	0.083	-2.033	-0.145
12	61.137	1.00024	15.221	0.0643	8.009	219.448	1.904	0.090	-2.039	-0.145
13	61.137	1.00028	15.221	0.0578	8.039	220.275	1.911	0.097	-2.037	-0.145
14	61.139	1.00034	15.221	0.0500	8.069	221.098	1.918	0.104	-2.009	-0.143
				m_{Mal} = 0.10 mol·dm^{-3}						
1	60.521	1.00001	15.463	0.0065	7.841	214.536	1.859	0.015	-10.619	-0.759
2	60.513	1.00003	15.466	0.0553	7.871	215.358	1.866	0.022	-10.731	-0.767
3	60.505	1.00005	15.468	0.0715	7.901	216.182	1.873	0.029	-10.841	-0.775
4	60.498	1.00007	15.471	0.0764	7.931	217.006	1.880	0.036	-10.937	-0.782
5	60.491	1.00008	15.473	0.0819	7.961	217.831	1.887	0.043	-11.044	-0.790
6	60.483	1.00009	15.475	0.0845	7.992	218.656	1.894	0.050	-11.146	-0.797
7	60.476	1.00011	15.477	0.0855	8.022	219.480	1.901	0.057	-11.241	-0.804
8	60.471	1.00013	15.479	0.0837	8.052	220.302	1.908	0.064	-11.320	-0.810
9	60.468	1.00017	15.480	0.0766	8.082	221.122	1.915	0.071	-11.356	-0.812
10	60.467	1.00021	15.481	0.0689	8.112	221.940	1.922	0.078	-11.374	-0.814
11	60.466	1.00025	15.481	0.0621	8.142	222.758	1.929	0.085	-11.385	-0.815
12	60.466	1.00029	15.482	0.0558	8.172	223.576	1.936	0.092	-11.389	-0.815
13	60.466	1.00034	15.482	0.0490	8.201	224.392	1.944	0.100	-11.379	-0.814
14	60.466	1.00038	15.482	0.0446	8.231	225.212	1.951	0.107	-11.380	-0.814

Standard uncertainties, u, are u(C) = ±0.003 mol·dm^{-3}, u(L_f) = ±0.002×10^{-10} m, u(*RA*) = ±0.0001, u(z) = ±0.002 kg·m^{-2}·s^{-1}, u(U) = ±0.0004 kg·mol^{-1}, u(W) = ±0.005× 10^{-6} atm$^{-1/7}$·m^3·mol^{-1}, u(R_m) = ±0.002×10^{-6} m·s^{-1}, u(V_m) = ±0.003×10^{-5}m^3, u(V_m) = ±0.003×10^{-5} m^3, u(V_m^E) = 0.003×10^{-5} m^3, u(κ_s^E) = 0.002 TPa^{-1} and u(L_f^E) = ±0.002×10^{-10} m.

SDS in 0.10 mol·dm^{-3} aqueous solution of fructose and maltose at different temperatures are shown in Figs 3(a-f) and 4 (a-f), respectively. The decrease in intermolecular free length (Tables 2-6) with SDS can be accounted to the solvent-solute and dipole-dipole interactions[18-20]. This observation further indicates that the molecules come closer with SDS and at a certain concentration i.e. at *CMC* (~7-8 mmol dm^{-3}) micelle formation takes place, as the L_f values become almost constant above this concentration (Figs 1(a) and 2(a)). Comparatively, L_f values in aqueous maltose solutions are smaller than in aqueous fructose solutions (Tables 2-6), probably due to stronger interactions in case of maltose due to the presence of large number of –OH groups. These trends in L_f values are well supported by the trends obtained for κ_s values as proclaimed in our previous study[13].

The specific acoustic impedance (z) focuses on the molecular packing of the system in terms of different types of interaction. There exists a strong intermolecular interactions in the SDS-sugar system[13], the increase in the z values with SDS, type of sugar [Figs 3(b) and 2(b)] and sugar, therefore, can be credited to strong interactions among the constituents of the mixtures mainly via hydrogen bonding[21,22]. Such type of increase in z values can be considered as a supporting evidence for the decline in the *CMC* values of SDS with sugar and type of sugar, as proposed in our previous study[13].

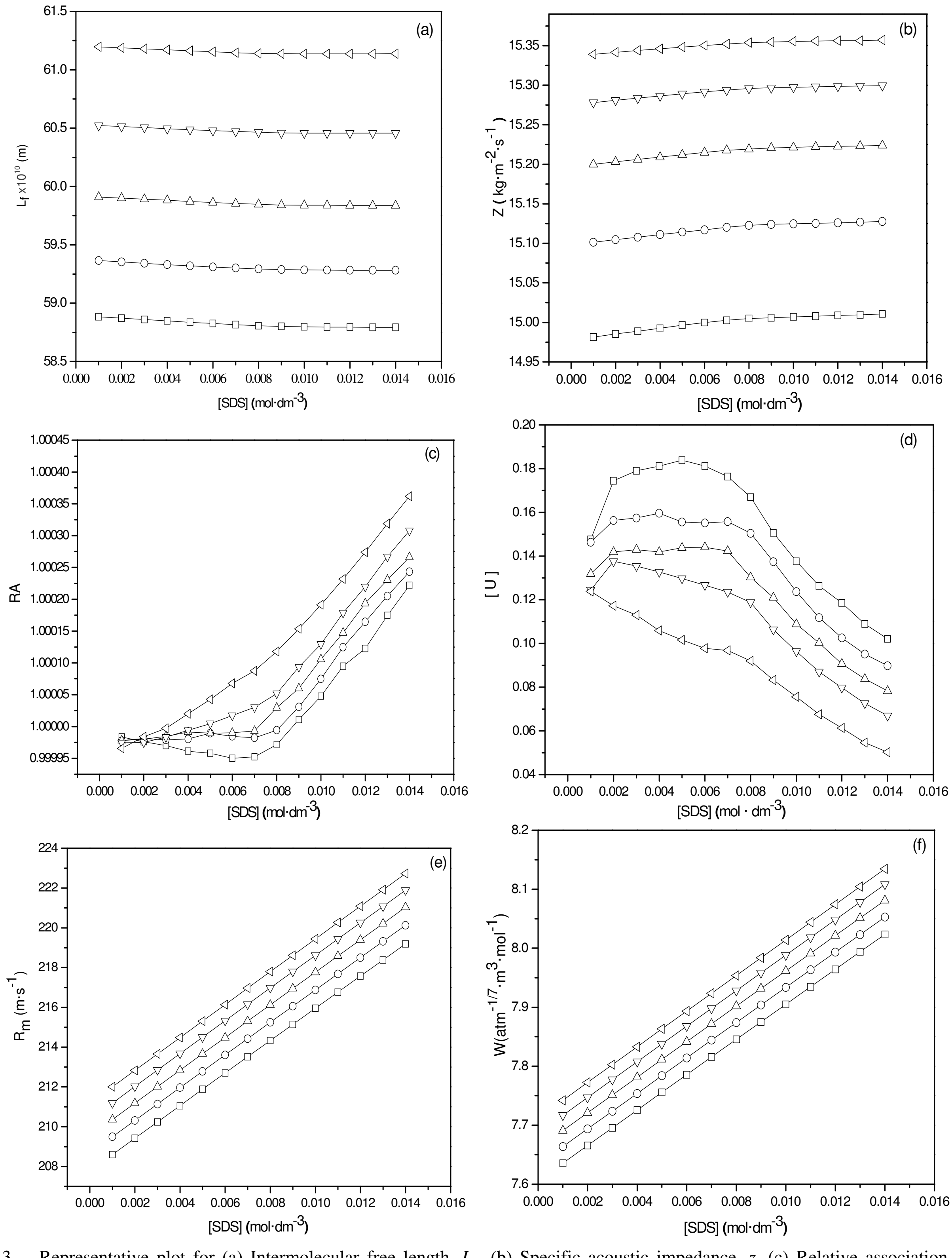


Fig. 3 — Representative plot for (a) Intermolecular free length, L_f, (b) Specific acoustic impedance, *z*, (c) Relative association, *RA*, (d) Molar sound number, (*U*), (e) Rao's constant, R_m and (f) Wada's constant, *W*of SDS in 0.10 mol·dm^{-3} aqueous solution of fructose. □, T = 293.15 K; ○, T = 298.15 K; Δ, T = 303.15 K; ∇, T = 308.15 K; ◁, T = 313.15 K

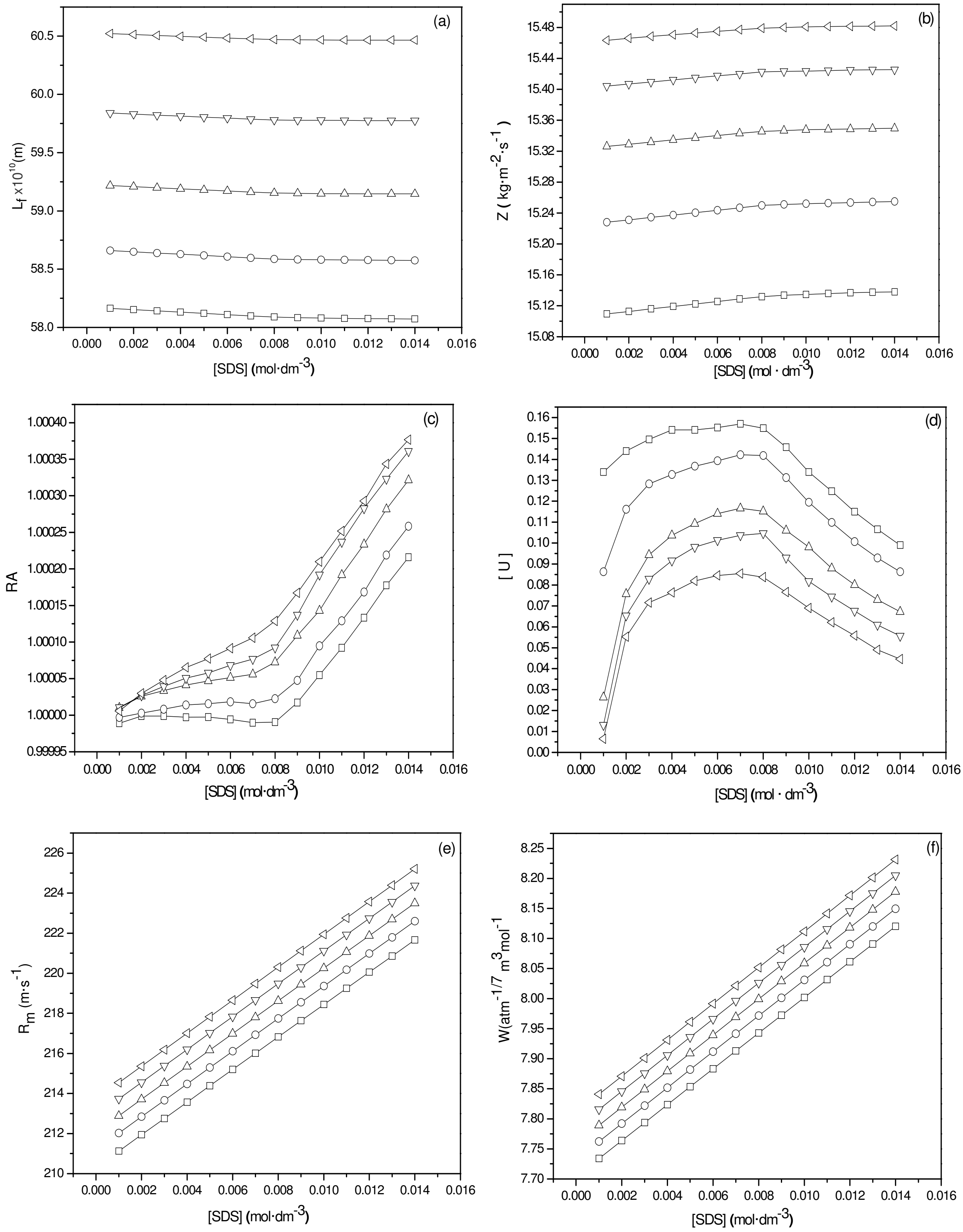


Fig. 4 — Representative plot for (a) Intermolecular free length, L_f, (b) Specific acoustic impedance, z, (c) Relative association, RA, (d) Molar sound number, (U), (e) Rao's constant, R_m and (f) Wada's constant, $W$of SDS in 0.10 mol·dm^{-3} aqueous solution of maltose. □, T = 293.15 K; ○, T = 298.15 K; Δ, T = 303.15 K; ∇, T = 308.15 K; ◁, T = 313.15 K

Eucken's theory[22] proposed that there is a decrease in the number of aggregates of solvent molecules as the concentration and temperature of the solution increase. Consequently, as the temperature rises the water molecules start to dissociate from the aggregate form. This effect is further enhanced by the introduction of a co-solute in the solvent environment. *RA* is used to understand two types of effects taking place in a solution when a solute is added to it[23]:

(i) the breaking of the solvent aggregates on addition of solute to it and
(ii) the simultaneous solvation of the solute by the solvent molecules.

From the perusal of Figs 3(c) and 2 (c), it can be noticed that relative association of the molecules increases with an increase in the amount of SDS in aqueous sugar solutions. Similar results have been reported in literature[24]. The experimental *RA* values increase as temperature rises from (293.15 to 313.15) K; which is indicative of disassociation of the solvent aggregates themselves thereby increasing the number of solvent molecules with temperature. A differentiable decrease in *RA* values with sugar revealing simultaneous solvation of co–solute molecules. Figs 3(c) and 2 (c) show that *RA* remains almost constant up to *CMC* and above *CMC* it shows a sharp increase with further addition of SDS. This suggests that up to *CMC* the dissociation of solvent aggregates and simultaneous solvation of the solute molecules are not so profound, which is also one of condition for the formation of micelle.

Molar sound number, (*U*) affords another evidence to explain intermolecular interactions or structural changes which are taking place in solution systems. The (*U*) values vary non–linearly with SDS at all studied temperatures and concentration of fructose/maltose (Figs 3(d) and 2(d)). The (*U*) values increase and reach a broad maximum near about *CMC*; after which it tends to decrease linearly as SDS is increased further. This kind of non-linear variation in (*U*) at lower SDS is indicative of various electrostatic and hydrophobic interactions taking place among different species present in solution. Similar behaviour has also been reported in case of drug (furosemide)-CTAB system showing the formation of drug-surfactant complex[10].

The linear increase in molar sound speed, R_m, (Rao's constant) and molar compressibility, *W*, (Wada's constant) with SDS [Figs 3(e–f) and 4 (e–f)] indicates the presence of more number of components in a given region which leads to a close packing of medium and thereby increasing various electrostatic and hydrophobic interactions. These results are in compliance with the results cited in literature[24]. Moreover, the increase in *W* values with temperature shows that the solute and solvent molecules are coming close to each other and space between them decrease; which supports the strong solute-solvent interactions in liquid mixture solutions at higher temperatures. The molar volume, V_m, values are positive and rise with SDS, sugar and temperature, simultaneously (Tables 2-6). This illustrates that different solute-solvent interactions increase with increase in these variables[17].

Specificity of the interactions, their nature and relative magnitudes can be obtained from the variation of excess properties. Thus, the excess properties are better measure of molecular interactions between component molecules of binary/ ternary mixture systems and hence play a major role in understanding the structure of liquid mixtures[25]. The values of excess functions can be qualitatively examined by considering the several physical and chemical contributions which affect these properties. The physical contribution consists of dispersion forces or weak dipole-dipole interactions that lead to positive values of excess functions. Another factor, which involves physical contribution, is the geometrical effect allowing the fitting of molecules of two different sizes into each other's structure resulting in negative excess functions values. Similarly, the chemical contribution includes breaking up of the associates present in pure liquids, resulting in positive excess functions and specific interactions such as the formation of hydrogen bonds, formation of charge transfer complexes and other complexes forming interactions between component molecules result in negative excess function values[25].

The various calculated excess functions viz. excess molar volume, V_m^E, excess isentropic compressibility, κ^E_s and excess free length, L^E_f for SDS in aqueous solution of fructose and maltose at different temperatures listed in Tables 2-6 manifest the existence of strong intermolecular interactions. The positive V_m^E values explain the breaking up of the associates present in pure liquids and interaction with the solute molecules via weak dipole–dipole interaction[26]. The decrease in magnitude of positive V_m^E values with sugar and increase with SDS may be attributed to the dissociation of large number of water associates with sugar and a lesser number with SDS. The negative κ^E_s and L^E_f values (Tables 2-6) inferred the geometrical effect which allows the fitting of molecules into each other's structure and specific interactions and other complexes forming interactions between component molecules[27]. Comparatively, the negative κ^E_s and L^E_f values are greater in magnitude for the SDS in aqueous maltose solutions then fructose solutions which are obvious due to the presence of large number of –OH groups in maltose than fructose. This further affirms the lower values of *CMC* for SDS in aqueous maltose solutions then fructose solutions as explained by *z* values.

4 Conclusions

The present study of SDS in aqueous solution of fructose and maltose shows a specific behaviour of acoustic parameters which reflects the strong solute–solvent interactions. The non-linear behaviour of these acoustical parameters and negative values of excess properties confirms the presence of complex formation, association between species and solute-solvent interactions. The present ternary systems are characterized by the presence of both types of weak and strong interactions as speculated by the nature of excess functions. The effect of sugars on *CMC* values of SDS as reported in our previous study is well supported by the trends of acoustical parameters and their excess functions.

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