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Kinematic Viscosity and Density of Binary and Ternary Mixtures Containing Hydrocolloids, Sodium Chloride, and Water

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Abstract The kinematic viscosity and density of binary aqueous solutions containing xanthan gum and ternary aqueous solutions containing carboxymethyl cellulose and sodium chloride have been measured from 303 K to 318 K at different values of pH. The viscosity and density for binary and ternary systems showed increases with a higher concentration of hydrocolloids (xanthan gum or carboxymethyl cellulose) and reductions with increasing temperature. The presence of NaCl in the ternary systems produced an electro-viscous effect that influenced the viscosity and density of the system. The models used to predict the viscosity, density, and apparent specific volume demonstrated satisfactory results in comparisons with experimental data.

Keywords Apparent specific volume · Density · Hydrocolloids · Modeling · Viscosity

1 Introduction

Hydrocolloids are polymeric substances that are soluble or dispersible in water and applied in various sectors of industry. Proteins and polysaccharides are included in this type of substance. In the food industry, hydrocolloids have several applications due to their functional properties as well as their ability to form gels in aqueous solutions—thickener powder—thus inhibiting the formation of sugar crystals, controlling

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the "flavors" of processed foods, stabilizers of emulsions, foams, and dispersions, etc. [1–3]. Among the hydrocolloids used as main ingredients in the food industry are included whey protein, soy protein, egg proteins, gelatin, pectin, gum (xanthan, arabic, guar, etc.), carrageenan, and carboxymethyl cellulose (CMC).

Carboxymethyl cellulose is an anionic polymer derived from cellulose, that is soluble in water and has a huge diversity of applications. CMC has different functions and properties, acting as a thickener, binder, stabilizer, a suspension agent, water retainer, and a rheological controller, for example, the thixotropic. And it also forms a resistant film to oils, greases, and organic solvents, and it is very soluble in hot or cold water and physiologically inert [2]. These properties make CMC a versatile polymer use in paints, electrodes, drilling fluids, detergents, food, cosmetics, paper, textiles, ceramics, and mining, among others [1,2,4].

Xanthan gum (XG) is an extracellular polysaccharide secreted by the microorganism *Xanthomonas campestris* [5]. Commercially, XG is produced from a pure culture of the bacterium by an aerobic process of submerged fermentation. As it has unique rheological properties and because of its stability against heat, salt, and acid, XG has been used extensively as a suspension agent, thickener, emulsifier, and stabilizer principally in the food industry [2,4,6].

The physical properties of food polysaccharide systems have been greatly investigated not only from a scientific point of view to clarify the nature of biopolymers but also from a practical standpoint, because a knowledge of the macroscopic physical properties including the viscosity, density, elasticity, and thermal properties of food is essential to the development of processes in the food industry [2,7].

In this work, experimental data for the kinematic viscosity and density were obtained for binary mixtures containing concentrations of XG + water and ternary mixtures of CMC + sodium chloride + water as a function of temperature and pH.

2 Experimental

2.1 Materials

Binary aqueous solutions of XG (keltrol ® F, CP Kelco, Brazil) containing concentrations of (0.0005, 0.0010, 0.0015, and 0.0020) mass fraction and ternary aqueous solutions of CMC (Cekol ® 30000, CP Kelco, Brazil) containing concentrations of (0.0005, 0.0010, 0.0020, and 0.0030) mass fraction and sodium chloride of (0.0016, 0.0029, and 0.0058) mass fraction, were prepared using an analytical balance (Tecnal, Model TEC-B-210A, Brazil) with a given uncertainty of ±0.0001 g. The pH of the solutions was adjusted to 3.0, 7.0, and 9.0 with HCl or NaOH solutions (Vetec, Brazil) using a pH meter (Gehaka, PG-100, Brazil) with a precision of ±0.01. The pH meter was previously calibrated with buffer solutions of 3.0 and 7.0 (Vetec, Brazil). All the experiments were carried out at temperatures of 303.1 K, 308.1 K, 313.1 K, and 318.1 K. The viscosity data were correlated using a model proposed in the literature, and a polynomial regression was performed to fit the models to the density data. The suitability of the fitted models was evaluated using relative average deviations (*RAD*) and standard deviations (*SD*). All of the samples were made in duplicate, and the experiments were repeated twice. Statistical analysis was made using the SAS® statistical package [8].

2.2 Apparatus and Measuring Procedures

The specific mass (ρ) was determined by using a standard volumetric pycnometer ($\sim$10 cm^3) with a reproducibility of ±0.001 %. The pycnometer was calibrated using double-distilled water. The calibrated Cannon-Fenske glass capillary viscometer (sizes 50, 75, 100, and 150) was used to measure the kinematic viscosity (v) (Schott-Geräte, Germany). The viscometers were placed in a thermostatic water bath (Schott-Geräte, CT 53 HT, Germany) for temperature control with an estimated uncertainty of 0.1 K. The coefficient of variation of the experimental measurements can be estimated as being not higher than 5.0 %.

3 Results and Discussion

Tables 1, 2, 3 give the experimental results for the viscosity, density, and apparent specific volume for different temperatures (303 K to 318 K), pH (3.0, 7.0, and 9.0), and concentration of binary and ternary mixtures.

An equation was used to correlate the viscosity data as a function of temperature and mass fraction at each value of pH for the binary and ternary mixtures. The following equation, proposed by Gonzales-Tello et al. [9], has been used to correlate the viscosity of polymeric solutions:

$$v \times 10^6 = P_1 \exp\left(\frac{P_2 + P_3 w}{T/K - P_4}\right), \tag{1}$$

where v is the kinematic viscosity of the solution, w is the mass fraction of XG, or CMC, and T is the temperature of the system. P_1, P_2, P_3, and P_4 were obtained by nonlinear regression. In Tables 4 and 5, the values of these parameters are listed. The relative average deviations (*RAD*) and standard deviations (*SD*) were used for comparisons of experimental and correlated results according to the following equations:

$$RAD(\%) = 100\left[\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\left|v_{\exp,i} - v_{\mathrm{cal},i}\right|}{v_{\exp,i}}\right)\right], \tag{2}$$

$$SD = \left[\frac{\sum_{i=1}^{m}\left(v_{\exp,1} - v_{\mathrm{cal},1}\right)^2}{(m-p)}\right]^{\frac{1}{2}}, \tag{3}$$

where $v_{\exp,i}$ and $v_{\mathrm{cal},i}$ are the experimental and calculated values for the kinematic viscosities, respectively; m is the number of experimental points, and p is the number of adjusted parameters.

Table 1 Density, ρ, viscosity, v, and apparent specific volume, V, for binary systems of water (1) + xanthan gum (2) from $T = 303.1$ K to 318.1 K and pH = 3.0, 7.0, and 9.0

pH	T (K)	w_1	w_2	ρ_{1+2} ($kg \cdot m^{-3}$)	$v_{1+2} \times 10^6$ ($m^2 \cdot s^{-1}$)	V_{1+2} ($m^3 \cdot kg^{-1}$)
3.0	303.1	0.9995	0.0005	998.577 ± 0.114	2.274 ± 0.033	0.0048
	308.1	0.9995	0.0005	997.733 ± 0.189	2.051 ± 0.038	0.0064
	313.1	0.9995	0.0005	996.957 ± 0.123	1.839 ± 0.021	0.0085
	318.1	0.9995	0.0005	995.679 ± 0.250	1.645 ± 0.006	0.0100
	303.1	0.9990	0.0010	998.829 ± 0.149	4.591 ± 0.056	0.0021
	308.1	0.9990	0.0010	998.728 ± 0.247	4.104 ± 0.072	0.0037
	313.1	0.9990	0.0010	997.405 ± 0.450	3.688 ± 0.063	0.0042
	318.1	0.9990	0.0010	996.064 ± 0.170	3.367 ± 0.096	0.0049
	303.1	0.9985	0.0015	999.779 ± 0.179	7.471 ± 0.035	0.0017
	308.1	0.9985	0.0015	998.998 ± 0.164	6.754 ± 0.034	0.0023
	313.1	0.9985	0.0015	997.289 ± 0.248	6.013 ± 0.035	0.0024
	318.1	0.9985	0.0015	996.168 ± 0.168	5.427 ± 0.001	0.0030
	303.1	0.9980	0.0020	1000.172 ± 0.130	13.252 ± 0.513	0.0012
	308.1	0.9980	0.0020	999.071 ± 0.136	14.554 ± 0.131	0.0015
	313.1	0.9980	0.0020	997.854 ± 0.125	12.859 ± 0.260	0.0018
	318.1	0.9980	0.0020	996.682 ± 0.101	11.469 ± 0.293	0.0022
7.0	303.1	0.9995	0.0005	1004.169 ± 0.254	2.588 ± 0.017	0.0160
	308.1	0.9995	0.0005	1002.413 ± 0.136	2.329 ± 0.010	0.0158
	313.1	0.9995	0.0005	1001.016 ± 0.122	2.104 ± 0.008	0.0167
	318.1	0.9995	0.0005	1000.512 ± 0.240	1.913 ± 0.008	0.0197
	303.1	0.9990	0.0010	1004.823 ± 0.187	5.580 ± 0.015	0.0081
	308.1	0.9990	0.0010	1003.027 ± 0.123	5.040 ± 0.008	0.0080
	313.1	0.9990	0.0010	1002.279 ± 0.810	4.547 ± 0.030	0.0091
	318.1	0.9990	0.0010	1001.513 ± 0.350	4.160 ± 0.014	0.0103
	303.1	0.9985	0.0015	1004.975 ± 0.148	10.570 ± 0.132	0.0052
	308.1	0.9985	0.0015	1003.529 ± 0.111	9.505 ± 0.183	0.0053
	313.1	0.9985	0.0015	1002.408 ± 0.360	8.453 ± 0.118	0.0058
	318.1	0.9985	0.0015	1001.667 ± 0.440	7.691 ± 0.061	0.0066
	303.1	0.9980	0.0020	1005.646 ± 0.122	19.991 ± 0.171	0.0039
	308.1	0.9980	0.0020	1003.698 ± 0.233	17.738 ± 0.154	0.0038
	313.1	0.9980	0.0020	1002.690 ± 0.115	15.391 ± 0.562	0.0042
	318.1	0.9980	0.0020	1001.684 ± 0.169	13.806 ± 0.521	0.0047
9.0	303.1	0.9995	0.0005	1006.169 ± 0.910	2.406 ± 0.040	0.0200
	308.1	0.9995	0.0005	1005.413 ± 0.450	2.182 ± 0.029	0.0217
	313.1	0.9995	0.0005	1004.016 ± 0.147	1.976 ± 0.033	0.0226
	318.1	0.9995	0.0005	1003.500 ± 0.880	1.798 ± 0.026	0.0257
	303.1	0.9990	0.0010	1006.212 ± 0.258	4.539 ± 0.010	0.0095
	308.1	0.9990	0.0010	1005.527 ± 0.380	4.198 ± 0.029	0.0104
	313.1	0.9990	0.0010	1004.079 ± 0.110	3.740 ± 0.088	0.0109

Table 1 continued

pH	T (K)	w_1	w_2	ρ_{1+2} (kg · m^{-3})	$v_{1+2} \times 10^6$ (m^2 · s^{-1})	V_{1+2} (m^3·kg^{-1})
	318.1	0.9990	0.0010	1003.513 ± 0.180	3.480 ± 0.001	0.0123
	303.1	0.9985	0.0015	1006.375 ± 0.900	10.091 ± 0.113	0.0061
	308.1	0.9985	0.0015	1005.529 ± 0.104	9.031 ± 0.043	0.0066
	313.1	0.9985	0.0015	1004.408 ± 0.350	8.249 ± 0.008	0.0071
	318.1	0.9985	0.0015	1003.667 ± 0.202	7.496 ± 0.017	0.0080
	303.1	0.9980	0.0020	1006.646 ± 0.370	18.052 ± 0.033	0.0044
	308.1	0.9980	0.0020	1005.698 ± 0.460	16.403 ± 0.160	0.0048
	313.1	0.9980	0.0020	1004.690 ± 0.460	15.040 ± 0.266	0.0052
	318.1	0.9980	0.0020	1003.684 ± 0.114	14.005 ± 0.327	0.0057

w_1 = water mass fraction, w_2 = mass fraction of xanthan gum

Table 2 Kinematic viscosity, v, for ternary systems of water (1) + NaCl (3) + carboxymethyl cellulose (4) from $T = 303.1$ K to 318.1 K and pH = 3.0 (a), 7.0 (b), and 9.0 (c)

T (K)	w_1	w_3	w_4	$v^{a}_{1+3+4} \times 10^6$ (m^2 · s^{-1})	$v^{b}_{1+3+4} \times 10^6$ (m^2 · s^{-1})	$v^{c}_{1+3+4} \times 10^6$ (m^2 · s^{-1})
303.1	0.9979	0.0016	0.0005	1.196 ± 0.025	1.760 ± 0.025	2.223 ± 0.008
308.1	0.9979	0.0016	0.0005	1.039 ± 0.482	1.565 ± 0.028	1.980 ± 0.001
313.1	0.9979	0.0016	0.0005	0.915 ± 0.125	1.400 ± 0.025	1.774 ± 0.001
318.1	0.9979	0.0016	0.0005	0.789 ± 0.087	1.260 ± 0.023	1.601 ± 0.001
303.1	0.9974	0.0016	0.0010	2.584 ± 0.957	3.024 ± 0.007	4.185 ± 0.121
308.1	0.9974	0.0016	0.0010	2.301 ± 0.012	2.664 ± 0.006	3.730 ± 0.122
313.1	0.9974	0.0016	0.0010	2.035 ± 0.005	2.351 ± 0.008	3.314 ± 0.113
318.1	0.9974	0.0016	0.0010	1.819 ± 0.001	2.098 ± 0.008	2.963 ± 0.102
303.1	0.9964	0.0016	0.0020	6.717 ± 0.896	8.538 ± 0.150	11.509 ± 0.173
308.1	0.9964	0.0016	0.0020	5.757 ± 0.048	7.474 ± 0.001	10.073 ± 0.127
313.1	0.9964	0.0016	0.0020	4.961 ± 0.008	6.428 ± 0.001	8.835 ± 0.061
318.1	0.9964	0.0016	0.0020	3.321 ± 0.298	5.538 ± 0.039	7.727 ± 0.108
303.1	0.9954	0.0016	0.0030	7.045 ± 0.178	19.728 ± 0.038	27.321 ± 0.018
308.1	0.9954	0.0016	0.0030	5.972 ± 0.015	16.698 ± 0.179	23.233 ± 0.198
313.1	0.9954	0.0016	0.0030	4.980 ± 0.147	14.088 ± 0.053	19.994 ± 0.194
318.1	0.9954	0.0016	0.0030	4.176 ± 0.054	11.895 ± 0.125	17.151 ± 0.272
303.1	0.9966	0.0029	0.0005	1.631 ± 0.008	1.729 ± 0.002	1.904 ± 0.002
308.1	0.9966	0.0029	0.0005	1.435 ± 0.001	1.538 ± 0.001	1.699 ± 0.002
313.1	0.9966	0.0029	0.0005	1.288 ± 0.003	1.373 ± 0.004	1.524 ± 0.003
318.1	0.9966	0.0029	0.0005	1.139 ± 0.041	1.237 ± 0.005	1.374 ± 0.003
303.1	0.9961	0.0029	0.0010	2.455 ± 0.089	3.022 ± 0.139	3.681 ± 0.089
308.1	0.9961	0.0029	0.0010	2.120 ± 0.369	2.691 ± 0.072	3.256 ± 0.085
313.1	0.9961	0.0029	0.0010	1.863 ± 0.011	2.376 ± 0.068	2.881 ± 0.072

Table 2 continued

T (K)	w_1	w_3	w_4	$v^a_{1+3+4} \times 10^6$ ($m^2 \cdot s^{-1}$)	$v^b_{1+3+4} \times 10^6$ ($m^2 \cdot s^{-1}$)	$v^c_{1+3+4} \times 10^6$ ($m^2 \cdot s^{-1}$)
318.1	0.9961	0.0029	0.0010	1.648 ± 0.036	2.117 ± 0.051	2.564 ± 0.062
303.1	0.9951	0.0029	0.0020	5.269 ± 0.023	8.005 ± 0.167	9.099 ± 0.203
308.1	0.9951	0.0029	0.0020	4.594 ± 0.017	6.966 ± 0.025	7.945 ± 0.279
313.1	0.9951	0.0029	0.0020	3.799 ± 0.018	6.002 ± 0.029	6.818 ± 0.066
318.1	0.9951	0.0029	0.0020	3.100 ± 0.012	5.218 ± 0.025	5.899 ± 0.120
303.1	0.9941	0.0029	0.0030	11.08 ± 0.035	17.931 ± 0.003	18.657 ± 0.006
308.1	0.9941	0.0029	0.0030	9.353 ± 0.008	15.199 ± 0.463	16.371 ± 0.134
313.1	0.9941	0.0029	0.0030	7.921 ± 0.029	12.855 ± 0.311	14.114 ± 0.119
318.1	0.9941	0.0029	0.0030	6.753 ± 0.063	10.935 ± 0.269	12.192 ± 0.159
303.1	0.9937	0.0058	0.0005	1.423 ± 0.015	1.751 ± 0.034	1.796 ± 0.012
308.1	0.9937	0.0058	0.0005	1.271 ± 0.002	1.559 ± 0.032	1.601 ± 0.003
313.1	0.9937	0.0058	0.0005	1.138 ± 0.007	1.392 ± 0.027	1.433 ± 0.002
318.1	0.9937	0.0058	0.0005	1.020 ± 0.012	1.252 ± 0.022	1.291 ± 0.003
303.1	0.9932	0.0058	0.0010	1.911 ± 0.001	3.108 ± 0.069	3.100 ± 0.023
308.1	0.9932	0.0058	0.0010	1.688 ± 0.458	2.726 ± 0.033	2.728 ± 0.010
313.1	0.9932	0.0058	0.0010	1.507 ± 0.078	2.414 ± 0.017	2.441 ± 0.032
318.1	0.9932	0.0058	0.0010	1.368 ± 0.098	2.150 ± 0.023	2.170 ± 0.023
303.1	0.9922	0.0058	0.0020	4.483 ± 0.368	7.671 ± 0.225	8.134 ± 0.168
308.1	0.9922	0.0058	0.0020	4.024 ± 0.415	6.598 ± 0.207	6.982 ± 0.101
313.1	0.9922	0.0058	0.0020	3.448 ± 0.064	5.696 ± 0.144	5.944 ± 0.001
318.1	0.9922	0.0058	0.0020	3.013 ± 0.128	4.930 ± 0.131	5.266 ± 0.088
303.1	0.9912	0.0058	0.0030	13.190 ± 0.008	18.395 ± 0.609	17.005 ± 0.193
308.1	0.9912	0.0058	0.0030	10.837 ± 0.120	15.417 ± 0.450	14.714 ± 0.136
313.1	0.9912	0.0058	0.0030	9.169 ± 0.004	13.030 ± 0.402	12.606 ± 0.083
318.1	0.9912	0.0058	0.0030	7.269 ± 0.018	11.067 ± 0.362	10.773 ± 0.115

w_1 = water mass fraction; w_3 = mass fraction of NaCl; w_4 = mass fraction of carboxymethyl cellulose

Table 3 Density, ρ, and apparent specific volume V, for ternary systems of water (1) + NaCl (3) + carboxymethyl cellulose (4) from $T = 303.1$ K to 318.1 K and pH = 3.0 (a) and 9.0 (c)

T (K)	w_1	w_3	w_4	ρ^a_{1+3+4} ($kg \cdot m^{-3}$)	V^a_{1+3+4} ($m^3 \cdot kg^{-1}$)	ρ^c_{1+3+4} ($kg \cdot m^{-3}$)	V^c_{1+3+4} ($m^3 \cdot kg^{-1}$)
303.1	0.9979	0.0016	0.0005	999.248 ± 0.014	0.0062	1001.092 ± 1.293	0.0099
308.1	0.9979	0.0016	0.0005	997.593 ± 1.019	0.0061	1000.874 ± 0.048	0.0127
313.1	0.9979	0.0016	0.0005	996.186 ± 0.093	0.0070	999.977 ± 0.257	0.0146
318.1	0.9979	0.0016	0.0005	995.812 ± 0.021	0.0103	999.396 ± 0.850	0.0175
303.1	0.9974	0.0016	0.0010	1001.663 ± 0.092	0.0050	1001.839 ± 0.556	0.0052
308.1	0.9974	0.0016	0.0010	1001.813 ± 0.270	0.0068	1000.701 ± 0.397	0.0056
313.1	0.9974	0.0016	0.0010	1000.039 ± 0.153	0.0068	1000.193 ± 0.733	0.0070

Table 3 continued

T (K)	w_1	w_3	w_4	ρ^{a}_{1+3+4} $(kg \cdot m^{-3})$	V^{a}_{1+3+4} $(m^3 \cdot kg^{-1})$	ρ^{c}_{1+3+4} $(kg \cdot m^{-3})$	V^{c}_{1+3+4} $(m^3 \cdot kg^{-1})$
318.1	0.9974	0.0016	0.0010	999.159 ± 0.497	0.0080	999.605 ± 1.906	0.0084
303.1	0.9964	0.0016	0.0020	1002.726 ± 0.305	0.0025	1002.213 ± 2.380	0.0022
308.1	0.9964	0.0016	0.0020	1001.883 ± 0.163	0.0029	1001.542 ± 1.822	0.0027
313.1	0.9964	0.0016	0.0020	1000.767 ± 0.224	0.0032	1000.030 ± 2.065	0.0029
318.1	0.9964	0.0016	0.0020	998.973 ± 0.099	0.0034	999.121 ± 0.815	0.0034
303.1	0.9954	0.0016	0.0030	1003.444 ± 0.397	0.0015	1003.512 ± 2.772	0.0016
308.1	0.9954	0.0016	0.0030	1002.548 ± 0.259	0.0018	1002.042 ± 2.437	0.0016
313.1	0.9954	0.0016	0.0030	1001.565 ± 0.578	0.0021	1001.422 ± 1.496	0.0021
318.1	0.9954	0.0016	0.0030	1000.491 ± 0.280	0.0024	999.686 ± 1.586	0.0022
303.1	0.9966	0.0029	0.0005	994.908 ± 0.060	0.0024	1001.604 ± 3.241	0.0109
308.1	0.9966	0.0029	0.0005	995.037 ± 0.018	0.0010	1001.016 ± 2.567	0.0130
313.1	0.9966	0.0029	0.0005	995.244 ± 0.031	0.0051	1000.709 ± 1.105	0.0161
318.1	0.9966	0.0029	0.0005	995.401 ± 0.035	0.0095	998.131 ± 2.215	0.0150
303.1	0.9961	0.0029	0.0010	1001.295 ± 0.320	0.0046	1002.566 ± 2.654	0.0059
308.1	0.9961	0.0029	0.0010	1000.382 ± 0.352	0.0053	1001.854 ± 2.383	0.0068
313.1	0.9961	0.0029	0.0010	1000.048 ± 0.213	0.0068	1001.141 ± 2.382	0.0079
318.1	0.9961	0.0029	0.0010	998.964 ± 0.530	0.0078	998.390 ± 3.127	0.0072
303.1	0.9951	0.0029	0.0020	1002.379 ± 0.580	0.0023	1005.657 ± 0.776	0.0039
308.1	0.9951	0.0029	0.0020	1001.657 ± 0.882	0.0028	1002.880 ± 1.185	0.0034
313.1	0.9951	0.0029	0.0020	1000.181 ± 0.793	0.0030	1001.869 ± 0.985	0.0038
318.1	0.9951	0.0029	0.0020	999.168 ± 1.337	0.0035	1000.173 ± 0.332	0.0040
303.1	0.9941	0.0029	0.0030	1004.124 ± 0.053	0.0018	1005.702 ± 2.554	0.0023
308.1	0.9941	0.0029	0.0030	1003.238 ± 0.000	0.0020	1003.503 ± 0.950	0.0021
313.1	0.9941	0.0029	0.0030	1002.013 ± 0.199	0.0022	1002.278 ± 1.114	0.0023
318.1	0.9941	0.0029	0.0030	1001.222 ± 0.678	0.0026	999.893 ± 0.276	0.0022
303.1	0.9937	0.0058	0.0005	1002.597 ± 0.991	0.0129	1005.152 ± 1.290	0.0179
308.1	0.9937	0.0058	0.0005	1001.726 ± 1.033	0.0144	1003.070 ± 1.490	0.0171
313.1	0.9937	0.0058	0.0005	1001.366 ± 1.302	0.0174	1001.074 ± 2.316	0.0168
318.1	0.9937	0.0058	0.0005	1000.065 ± 1.600	0.0188	999.229 ± 0.343	0.0172
303.1	0.9932	0.0058	0.0010	1003.015 ± 1.660	0.0063	1004.998 ± 1.550	0.0084
308.1	0.9932	0.0058	0.0010	1001.628 ± 0.796	0.0066	1002.081 ± 1.077	0.0070
313.1	0.9932	0.0058	0.0010	1000.820 ± 1.451	0.0076	1000.697 ± 0.866	0.0075
318.1	0.9932	0.0058	0.0010	999.937 ± 1.511	0.0088	999.019 ± 0.452	0.0078
303.1	0.9922	0.0058	0.0020	1003.587 ± 0.216	0.0029	1005.659 ± 1.359	0.0039
308.1	0.9922	0.0058	0.0020	1002.264 ± 0.099	0.0031	1004.807 ± 1.658	0.0043
313.1	0.9922	0.0058	0.0020	1000.970 ± 0.492	0.0034	1002.039 ± 1.059	0.0039
318.1	0.9922	0.0058	0.0020	1000.115 ± 0.096	0.0039	1000.088 ± 0.275	0.0039
303.1	0.9912	0.0058	0.0030	1005.348 ± 0.177	0.0022	1007.167 ± 1.022	0.0028
308.1	0.9912	0.0058	0.0030	1003.441 ± 0.117	0.0021	1005.987 ± 0.082	0.0029

Table 3 continued

T (K)	w_1	w_3	w_4	ρ^{a}_{1+3+4} $(kg \cdot m^{-3})$	V^{a}_{1+3+4} $(m^3 \cdot kg^{-1})$	ρ^{c}_{1+3+4} $(kg \cdot m^{-3})$	V^{c}_{1+3+4} $(m^3 \cdot kg^{-1})$
313.1	0.9912	0.0058	0.0030	1002.464 ± 0.152	0.0024	1004.300 ± 0.014	0.0030
318.1	0.9912	0.0058	0.0030	1002.251 ± 0.085	0.0030	1001.283 ± 1.585	0.0027

w_1 = water mass fraction; w_3 = mass fraction of NaCl; w_4 = mass fraction of carboxymethyl cellulose

Table 4 Parameters of Eq. 1 for xanthan gum + water system

pH	P_1	P_2	P_3	P_4	RAD (%)	SD $(mm^2 \cdot s^{-1})$
3.0	0.253	405.386	371071.953	18.224	0.71	0.6314
7.0	0.128	454.807	244652.117	116.299	0.24	0.2064
9.0	0.150	514.252	329098.041	58.807	0.28	0.3666

Table 5 Parameters of Eq. 1 for water, sodium chloride, and carboxymethyl cellulose system

pH	w_3	P_1	P_2	P_3	P_4	RAD (%)	SD $(mm^2 \cdot s^{-1})$
3.0	0.0016	0.261	144.38	37381.28	227.77	0.71	0.6314
	0.0029	0.197	116.27	96331.07	206.66	0.48	0.2280
	0.0058	0.012	845.09	142476.51	115.47	0.40	0.0902
7.0	0.0016	0.119	329.09	124414.83	165.79	0.27	0.3135
	0.0029	0.083	410.02	128972.71	154.90	0.57	0.2677
	0.0058	0.062	456.37	137237.17	150.43	0.65	0.1224
9.0	0.0016	0.348	196.779	116645.75	177.93	0.11	0.4367
	0.0029	0.072	551.344	144920.98	126.16	0.42	0.4320
	0.0058	0.046	604.879	147594.55	125.87	0.77	0.3324

As observed from Tables 1 and 2, for the binary and ternary mixtures at higher temperatures, the viscosity decreases, and at higher concentrations, the viscosity increases, which is in agreement with the literature [10–15]. The effect of the temperature was more intense at higher concentrations. The viscosity of the solutions increased with a rise of XG or CMC concentration at all temperatures and pH values. When the solute concentration increases, the viscosity increases because of the rise in hydrogen bonds with hydroxyl groups and the distortion in the velocity pattern of the liquid by hydrated molecules, the solute. The intermolecular distances are also a factor that affects the viscosity, which is inversely proportional to the temperature [12].

For ternary mixtures, it is observed that a rise in the concentration of NaCl in the system produces a modification in the viscosity of the solution, probably produced by the electrostatic contributions of the ionic particles in the viscosity system. This phenomenon is known as the electro-viscous effect [16]. The same effects have been reported in the literature by different authors to study the viscosity of polymer solutions influenced by the presence of ionic salts [17–19].

Table 6 Parameters values used in Eq. 4 for xanthan gum + water systems

pH	a	b	c	RAD (%)	SD $(\text{kg} \cdot \text{m}^{-3})$
3.0	1064.1637	−0.2166	785.3505	0.06	0.2741
7.0	1074.7357	−0.2349	888.0479	0.01	0.3526
9.0	1063.7518	−0.1904	275.4010	0.02	0.1519

Table 7 Parameters of Eq. 4 for water, sodium chloride, and carboxymethyl cellulose system

pH	w_3	a	b	c	RAD (%)	SD $(\text{kg} \cdot \text{m}^{-3})$
3.0	0.0016	1064.772	−0.216	1598.800	0.01	1.0975
	0.0029	1037.030	−0.133	2525.144	0.02	1.5821
	0.0058	1062.812	−0.200	767.578	0.02	0.4989
9.0	0.0016	1056.060	−0.180	493.702	0.01	0.3989
	0.0029	1093.308	−0.300	1050.508	0.04	0.7125
	0.0058	1122.068	−0.390	1128.686	0.02	0.5635

Table 8 Parameters of Eq. 6 for xanthan gum + water systems

pH	T (K)	$V_{2\varphi}^{\infty}$ $(\text{m}^3 \cdot \text{kg}^{-1})$	b_v	b_{vv}	RAD (%)	SD $(\text{m}^3 \cdot \text{kg}^{-1})$
3.0	303.1	0.008101	−7.756	2198.810	0.72	0.0003
3.0	308.1	0.009975	−8.076	1936.362	0.01	0.0009
3.0	313.1	0.014491	−13.838	3771.866	0.17	0.0001
3.0	318.1	0.016915	−16.088	4408.272	0.11	0.0002
7.0	303.1	0.026449	−24.457	6653.578	0.07	0.0004
7.0	308.1	0.025777	−23.465	6297.618	0.04	0.0005
7.0	313.1	0.026682	−23.215	6033.786	0.03	0.0003
7.0	318.1	0.031937	−28.444	7480.114	0.03	0.0005
9.0	303.1	0.033543	−32.017	8809.829	0.01	0.0006
9.0	308.1	0.036404	−34.534	9441.526	0.02	0.0007
9.0	313.1	0.037862	−35.919	9883.479	0.01	0.0007
9.0	318.1	0.042925	−40.627	11110.64	0.02	0.0008

Experimental data for density are presented in Tables 1 and 3 for the binary and ternary mixtures. From the tables, it can be observed that the density is inversely proportional to the temperature and directly proportional to the concentration of the binary and ternary mixtures studied. A linear model was fitted to the experimental data as follows:

$$\rho = a + bT + cw, \tag{4}$$

where a, b, and c are constants determined by linear regression. The values of these parameters are listed in Tables 6 and 7 for the binary and ternary systems, respectively.

Table 9 Parameters of Eq. 6 for water + sodium chloride + carboxymethyl cellulose system

pH	w_3	T (K)	$V_{2\varphi}^{\infty}$ ($m^3 \cdot kg^{-1}$)	b_v	b_{vv}	RAD (%)	SD ($m^3 \cdot kg^{-1}$)
3.0	0.0016	303.1	0.0081	−3.787	536.575	0.10	0.0001
	0.0016	308.1	0.0078	−2.091	10.914	0.57	0.0008
	0.0016	313.1	0.0089	−2.997	232.580	0.74	0.0005
	0.0016	318.1	0.0142	−7.838	1302.712	0.41	0.0003
	0.0029	303.1	0.0087	−4.912	873.360	0.15	0.0014
	0.0029	308.1	0.0097	−5.264	902.552	0.21	0.0003
	0.0029	313.1	0.0139	−8.607	1575.751	0.36	0.0015
	0.0029	318.1	0.0157	−9.567	1748.675	0.85	0.0083
	0.0058	303.1	0.0185	−13.736	2799.728	0.55	0.0008
	0.0058	308.1	0.0207	−15.726	3216.247	0.22	0.0011
	0.0058	313.1	0.0252	−19.721	4083.827	0.66	0.0014
	0.0058	318.1	0.0272	−20.863	4306.406	0.74	0.0074
9.0	0.0016	303.1	0.0142	−10.276	2048.359	0.54	0.0005
	0.0016	308.1	0.0181	−13.759	2789.480	0.44	0.0011
	0.0016	313.1	0.0212	−16.124	3281.666	0.83	0.0010
	0.0016	318.1	0.0253	−19.067	3822.747	0.45	0.0012
	0.0029	303.1	0.0143	−8.852	1646.261	0.14	0.0009
	0.0029	308.1	0.0182	−12.684	2474.168	0.09	0.0008
	0.0029	313.1	0.0227	−16.448	3257.800	0.13	0.0011
	0.0029	318.1	0.0207	−14.646	2866.909	1.05	0.0012
	0.0058	303.1	0.0257	−19.471	3988.864	0.27	0.0014
	0.0058	308.1	0.0239	−18.161	3780.322	0.57	0.0019
	0.0058	313.1	0.0240	−18.337	3826.609	0.12	0.0015
	0.0058	318.1	0.0244	−18.391	3758.219	0.08	0.0014

The apparent specific volume of the mixtures was computed from the experimental density using the following equation [20]:

$$V = \frac{1}{\rho}\left[1 + \left(\frac{\rho_0 - \rho}{w\rho_0}\right)\right], \tag{5}$$

where ρ and ρ_0 are the densities of the mixture and solvent, respectively. The calculated values of V for the two systems along with the experimental density data are given in Tables 1 and 2. From the tables, it can be observed that V decreases with increasing w and decreasing temperature. Studies of various models of solutes have demonstrated that a rise in the partial volume occurs with a loss of solvation [21]. The same behavior was reported in the literature [21–24]. Assuming the observations above for polymeric solutions and considering the behavior of V for binary and ternary solutions at various temperatures, we may conclude that the loss of solvation of XG or CMC increases with increasing temperature and that the apparent specific volume increases with increasing temperature. The V values were correlated with the following equation [20]:

$$V = V_{2\varphi}^{\alpha} + b_v w + b_{vv} w^2, \quad (6)$$

where $V_{2\varphi}^{\alpha}$ is the apparent specific volume of a polymer at infinite dilution, and b_v and b_{vv} are empirical parameters that depend on the solute, solvent, and temperature. The obtained parameters for Eq. 6 are reported in Tables 8 and 9 for the binary and ternary systems, respectively. As demonstrated in these tables, the quality of the fit for this equation in the correlation of the apparent specific volume is satisfactory.

4 Conclusions

Data for the viscosity and density for binary and ternary systems studied here showed an increase with increases in the concentration of the biopolymer and a decrease with increasing temperature. The intermolecular distances are also a factor that affects the viscosity, which is inversely proportional to the temperature. The presence of NaCl in the ternary systems produced an electro-viscous effect that influenced the viscosity and density of the system. The models used to predict the viscosity, density, and apparent specific volume demonstrated satisfactory results in relation to the experimental data.

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