J Mater Sci (2007) 42:9622–9631
DOI 10.1007/s10853-007-1971-5

Empirical equations for electrical conductivity and density of Zn, Cd and Mn sulphate solutions in the range of electrowinning and electrorefining electrolytes

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Received: 22 February 2007 / Accepted: 27 June 2007 / Published online: 31 July 2007

Abstract Electrical conductivities and densities of acidic zinc, cadmium and manganese sulphate solutions were measured. Empirical equations have been derived to represent the measured values with high accuracy. Electrical conductivity of solutions has been shown to be expressed as a logarithmic function of temperature, a second order polynomial function of sulphuric acid concentration and a linear function of metal ion concentration. It can be deduced that the density of solution can be described as a linear function of metal ion concentration, temperature and sulphuric acid concentration. These equations could be used to improve the electrowinning or electrorefining process conditions.

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Introduction

In hydrometallurgical industries, acidic sulphate solutions are widely employed as electrolytes. A current method for zinc production is its extraction from acid zinc sulphate solution. Zinc electrowinning can be affected by some parameters such as current efficiency, cell potential, power consumption, deposit quality and overall polarization behavior of the cathode [1].

Physical properties such as electrical conductivity and density of the electrolyte are major importance in the electrowinning process. It has been found that electrical conductivity has impact on electrical energy consumption and density influences cell engineering design and rate of production [2, 3].

In general electrowinning and electrorefining processes should be carried out under conditions of high electrical conductivity and low density [3, 4].

In electrowinning of zinc from sulphate electrolyte the overall cell reaction is:

$$2ZnSO_4 + 2H_2O \rightarrow 2Zn + 2H_2SO_4 + O_2 \quad \varepsilon^{o}_{theoritical} = 1.989\,V \tag{1}$$

It is better to protect the cathode from the strong acid electrolyte otherwise hydrogen gas would be formed in competition with zinc deposition according to the following reaction, which could seriously reduce the current efficiency of the cell [5].

$$2H^+ \rightarrow H_2 \quad \varepsilon^{o} = 0.0\,V \tag{2}$$

Generally zinc electrowinning process is operated under the conditions mentioned in Table 1 [6, 7].

Table 1 Industrial ranges for current density, voltage, electrolyte temperature, zinc and sulphuric acid concentrations and current efficiency in zinc electrowinning process

Property	Range
Current density	400–500 A m^{-2}
Voltage	2.5–3.5 V
Temperature	30–60 ° C
Zinc concentration	50–150 g L^{-1}
Sulphuric acid concentration	100–200 g L^{-1}
Current efficiency	85–95%

Ohmic resistance of the cell electrolyte is one of the factors which affect the actual voltage of the process, according to the following expression. A reduction in the ohmic drop during zinc electrowinning process could substantially save operational cost.

$$E_{\text{actual}} = E_{\text{theoritical}} + E_{\text{ohmic}} + E_{\text{overpotential}} + E_{\text{resistance}} \quad (3)$$

A number of studies have been investigated the ways to improve zinc electrowinning process including the effect of free sulphuric acid concentration and current density [8, 9], utilizing alkaline electrolysis technique [10] and the effect of additive [1, 5, 11]. Review of the published papers show that there are a few information available on the electrical conductivity and density of zinc sulphate electrolyte. Su et al. established a valuable equation for the H_2SO_4–$ZnSO_4$–MSO_4–H_2O system as following [12]:

$$\begin{aligned} k(\mathrm{S\,cm^{-1}}) = {} & 0.004 + 0.00115\,T + 0.00282\,[\mathrm{H_2SO_4}]\,T \\ & - 0.00114\,[M]\,T + 0.3442\,[\mathrm{H_2SO_4}] \\ & - 0.045\,[\mathrm{H_2SO_4}]^2 - 0.1058\,[M]\,[\mathrm{H_2SO_4}] \\ & - 0.0224\,[M] + 0.02862[M]^2 \end{aligned} \quad (4)$$

where T is temperature in ° C, $[H_2SO_4]$ is the sulphuric acid concentration in mole L^{-1} and $[M]$ described by following expression:

$$[M](\mathrm{mole\,L^{-1}}) = [\mathrm{Zn}] + [\mathrm{Mg}] + [\mathrm{Mn}] + 0.39[\mathrm{Na}] + 0.23[\mathrm{K}] \quad (5)$$

It seems that utilization and adaptation of the suggested equation (Eq. 4) by Su et al. [12] is difficult and complicated, especially when dealing with different electrolyte solutions. Another study [13] also compared some equations that seem not to be functional because their complication or big standard error.

The main aim of this investigation is to measure the electrical conductivities and densities of zinc sulphate solutions. Zinc and sulphuric acid concentration and temperature as the most important factors have been measured. Based on these results, empirical and simple equations expressing the measured values are also developed.

Predicting the performance of zinc electrowinning in nonconventional electrolytes requires estimates of certain properties of the electrolyte, such as the reversible potential for zinc deposition, electrolyte conductivity, viscosity, density, and the diffusion coefficient for zinc ions. Although this information often exists in the literature, it appears scattered and sometimes conflicts from one source to another, making it difficult to decide which data to employ in engineering calculations. This article focused on measuring electrical conductivities and densities for calculating the properties of zinc, cadmium and manganese electrolytes and, where deemed necessary, offers new expressions for calculating those properties in order to create a single reliable source to assist in the design and optimization of these metal electrowinning reactors.

Experimental procedure

The measurements for both electrical conductivity and density were carried out over the following range of compositions and temperatures covering the typical of industrial zinc electrowinning conditions shown in Table 2.

The experimental solutions used through the work were prepared from analytical reagent grade $ZnSO_4 \cdot 6H_2O$ and H_2SO_4 (Panreac Analytical Reagents & Fine Chemical) and distilled water. All concentrations were calculated in grams per liter of solution, measured at 25 °C.

Electrical conductivity and density were measured with a conductivity/TDS meter (Jenway model 4510) and a density meter (Mettler-Toledo model DE40) respectively. The measured data was then used for obtaining empirical equations.

Result and discussion

Electrical conductivity

As shown in Eq. 3, ohmic drop is an important factor in the total energy requirement for the electrowinning process in

Table 2 Typical ranges for electrolyte temperature, and zinc and sulphuric acid based on zinc electrowinning concentration

Property	Range
Temperature	10–70 °C
Zinc concentration	10–70 g L^{-1}
Sulphuric acid concentration	25–200 g L^{-1}

addition to the thermodynamic energy requirement. Generally the total energy requirement for zinc electrowinning is approximately 2.673 kWh kg^{-1} at a current density of 400 A m^{-2} [7].

The ohmic drop V_o is inversely proportional to the specific conductivity of the electrolyte and is proportional to the distance between two electrodes and the current density as shown by Eq. 6:

$$V_o = k^{-1} \times L \times i \qquad (6)$$

where k is the specific conductivity of electrolyte, L is the distance between two electrode and i is the current density. In order to decrease the ohmic drop, increasing the electrical conductivity of electrolyte, decreasing the distance between two electrode or decreasing the current density is possible. The last two parameters are difficult to change because of cell design limitation and production rate requirement; however an increase in electrical conductivity could be considered. Also, higher electrolyte electrical conductivity could noticeably reduce energy consumption due to applying lower voltage.

The results of the electrical conductivity measurements are reported in Table 3 and Figs. 1–3.

Effect of zinc concentration

An increase in zinc concentration would lead to decreased conductivity (Fig. 1). In constant sulphuric acid concentration and temperature as seen in Fig. 1, there is a linear relationship between the electrical conductivity and zinc concentration. Error bars represent the estimation of 95% confidence interval.

Effect of sulphuric acid concentration

Figure 2 demonstrates the non-linear effect of sulphuric acid concentration on the electrical conductivity. The electrical conductivity increases with increasing the sulphuric acid concentration. Under the conditions of constant zinc concentration and constant temperature, a second order polynomial relationship between the conductivity and acid concentration may well be established.

Effect of temperature

Under constant zinc and acid concentration, as shown in Fig. 3, an ascending logarithmic relationship between the electrical conductivity and temperature can be assumed.

Table 3 Results of electrical conductivity measurements

T (°C)	H_2SO_4 (g L^{-1})	Zn (g L^{-1})							
		10 Specific conductivity (mS cm^{-1})	20	30	40	50	60	70	80
10	25	180	176	172	170	169	164	157	156
10	50	221	216	212	209	208	203	194	193
10	75	258	249	239	238	235	231	219	213
10	100	329	308	290	292	284	278	264	255
10	125	337	326	312	310	304	294	279	272
10	150	365	359	353	343	337	327	310	303
10	175	377	370	365	356	350	340	323	312
10	200	400	392	385	377	370	365	343	331
20	25	201	195	190	187	186	183	175	173
20	50	248	241	235	232	231	226	215	213
20	75	289	278	266	264	261	255	242	238
20	100	363	341	323	324	315	308	293	282
20	125	377	362	347	344	337	329	311	303
20	150	404	399	392	382	374	363	343	336
20	175	420	413	404	395	388	379	358	349
20	200	446	436	428	418	413	406	382	367
30	25	209	205	202	199	198	194	186	184
30	50	258	253	249	246	242	239	231	230
30	75	300	290	282	279	275	268	258	253
30	100	376	359	341	340	331	324	310	300
30	125	391	377	365	360	353	343	329	319

Table 3 continued

T (°C)	H_2SO_4 (g L^{-1})	Zn (g L^{-1})							
		10	20	30	40	50	60	70	80
		Specific conductivity (mS cm^{-1})							
30	150	418	413	406	396	389	379	363	356
30	175	435	428	420	411	403	395	379	369
30	200	464	454	443	435	429	426	406	395
40	25	224	223	221	219	215	212	208	206
40	50	276	275	274	271	266	263	256	255
40	75	322	314	310	305	300	294	286	282
40	100	399	388	377	369	360	353	340	331
40	125	415	406	396	389	381	373	360	353
40	150	444	439	432	425	415	406	396	391
40	175	462	454	446	439	432	426	417	411
40	200	495	483	468	464	461	459	452	444
50	25	239	235	231	230	226	224	220	216
50	50	297	290	285	282	279	276	272	267
50	75	341	334	327	323	315	310	303	298
50	100	426	414	402	391	384	373	360	353
50	125	441	431	421	411	403	394	384	376
50	150	467	461	455	447	439	432	426	420
50	175	481	473	465	458	451	446	439	432
50	200	505	493	484	477	473	468	461	455
60	25	249	242	237	235	232	231	226	223
60	50	307	300	292	290	286	284	279	275
60	75	355	344	336	330	326	319	311	307
60	100	440	428	415	403	395	384	370	363
60	125	455	444	435	422	415	406	395	389
60	150	481	476	468	459	451	447	441	436
60	175	490	484	477	468	461	457	451	446
60	200	507	498	491	484	481	473	467	461
70	25	261	252	245	239	238	234	232	226
70	50	323	311	301	297	293	289	285	278
70	75	376	359	343	337	331	324	315	310
70	100	472	446	421	411	402	386	373	369
70	125	483	459	439	429	420	410	399	395
70	150	502	486	470	461	452	450	444	441
70	175	506	491	480	472	464	458	454	451
70	200	513	505	494	490	486	477	470	465

This rise in electrical conductivity is most significant at sulphuric acid concentration and temperature up to 175 g L^{-1} and 50 °C, respectively.

Hinatsu et al. [6] claimed that the electrical conductivity of sulphate solution lowers with increasing zinc sulphate concentration at sulphuric acid concentration higher than 20 g L^{-1}. Also it has been mentioned that, this effect is the result of decreasing in the amount of free water through solvation effects.

In some studies the relationship between the electrical conductivity, metallic ion concentration, temperature and sulphuric acid concentration has been approximated with a linear relationship [2, 3, 5]. However with some assumptions, a better equation can be proposed. These assumptions are according to the best curve fit which can be obtained from the Figs. 1 to 3 under mentioned conditions.

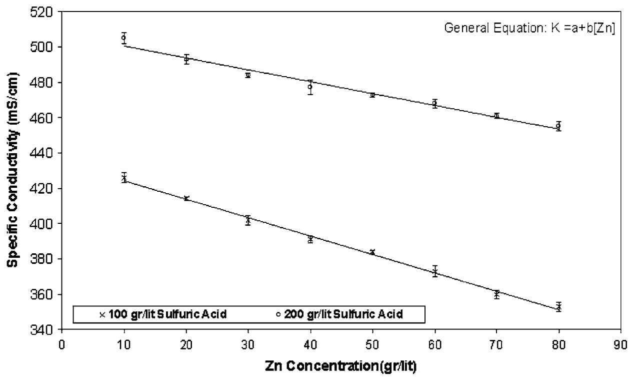

Fig. 1 The effect of zinc concentration on the specific conductivity of zinc sulphate solution at 50 °C

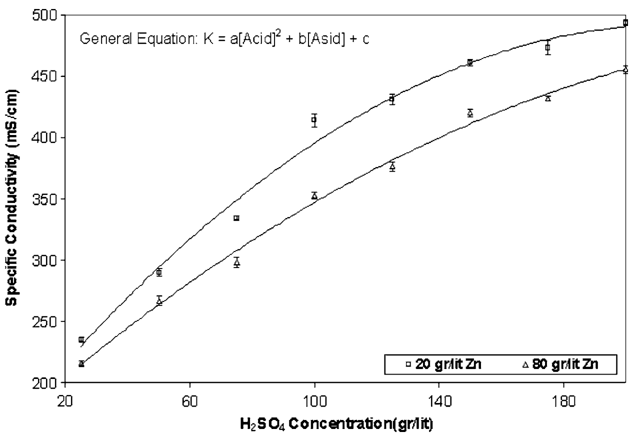

Fig. 2 The effect of sulphuric acid concentration on the specific conductivity of zinc sulphate solution at 50 °C

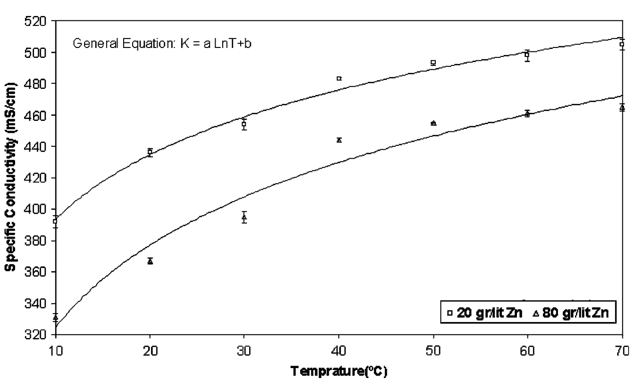

Fig. 3 The effect of temprature on the specific conductivity in $[H_2SO_4]$ = 200 g L^{-1}

Empirical equation for computation of electrical conductivity

Establishing a relationship between the conductivity and zinc and sulphuric acid concentration and temperature can be reasonable:

$$k(\mathrm{mS\,cm^{-1}}) = \mathrm{A[Zn]} + \mathrm{B[H_2SO_4]}^2 + \mathrm{C[H_2SO_4]} + \mathrm{D}\log T + \mathrm{E} \quad (7)$$

where A, B, C, D and E are constants, zinc concentration and sulphuric acid concentrations are in grams per liter and temperature is in °C.

In order to determine the constant values of Eq. 7 the obtained data (Table 1) has been analyzed through application of multi variable analysis software called SPSS for windows V.8.0.

Taking into account the mentioned assumptions the electrical conductivity can be expressed by the following equation:

$$k(\mathrm{mS\,cm^{-1}}) = -0.741[\mathrm{Zn}] - 4.857 \times 10^{-3}[\mathrm{H_2SO_4}]^2 + 2.453[\mathrm{H_2SO_4}] + 84.602\log T + 0.726\,T + 24.023 \quad (8)$$

As it can be seen, there is an extra term of temperature (0.726 T) in the Eq. 8 compared with Eq. 7. It is found that this term improves the better correlation of proposed equation (Eq. 8). Standard error of the estimated data from Eq. 8 and experimental data is ±12.25 (mS cm^{-1}) and the variance is within 4%.

For the comparison, the linear approximation equation can also be obtained:

$$k(\mathrm{mS\,cm^{-1}}) = -0.741[\mathrm{Zn}] + 1.360[\mathrm{H_2SO_4}] + 1.848\,T + 154.055 \quad (9)$$

The standard error of calculated data from Eq. 9 and experimental data is ±19.62 (mS cm^{-1}) and the variance is within 9%. Therefore, it can be concluded that Eq. 8 has improved the correlation.

It can be illustrated that an additional term in Eq. 8 leads to a negligible change in standard error and variance. Moreover, the introduction of new terms would just complicate the equation.

Cd & Mn results

For Cadmium and Manganese the following results were obtained:

Cd conductivity:

$$k(\mathrm{mS\ cm^{-1}}) = -0.783[\mathrm{Cd^{2+}}] - 3.704 \times 10^{-3}[\mathrm{H_2SO_4}]^2 + 2.038[\mathrm{H_2SO_4}] + 49.478\log T + 0.976\,T + 57.84 \quad (10)$$

Mn conductivity:

$$k(\text{mS cm}^{-1}) = -0.88[\text{Mn}^{2+}] - 1.618 \times 10^{-3}[\text{H}_2\text{SO}_4]^2 + 1.526[\text{H}_2\text{SO}_4] + 33.417 \log T + 1.244\,T + 122.044 \quad (11)$$

It was seen that there is no difference among these ions at all.

Density

Table 4 presents the measured density values. Figures 4–6 illustrate the effect of zinc and sulphuric acid concentration and temperature on the density.

Effect of zinc concentration

Figure 4 depicts the variation of density with zinc concentration. This variation can be expressed with a linear relationship between the density and zinc concentration.

Effect of sulphuric acid concentration

Figure 5 shows that a linear relationship exists between sulphuric concentration and density.

Effect of temperature

Although an increase in zinc and sulphuric acid concentrations causes an increase in density, the elevation of temperature has an opposite effect on density through a linear relationship.

Empirical equation for computation of density

A data bank for density of solution was developed. This data also has been applied for multi variable SPSS for windows V.8.0. Based on the linear dependency of density

Table 4 Results of absolute density measurements

T (°C)	Zn (g L^{-1})	H_2SO_4 (g L^{-1})							
		25	50	75	100	125	150	175	200
		Absolute density (g cm^{-3})							
10	10	1.0454	1.0668	1.0791	1.096	1.1068	1.1223	1.1381	1.1531
20	10	1.0426	1.0632	1.0751	1.0914	1.102	1.1169	1.1324	1.1469
30	10	1.039	1.0591	1.0706	1.0865	1.0969	1.1114	1.1266	1.1408
40	10	1.0347	1.0544	1.0656	1.0813	1.0915	1.1058	1.1207	1.1346
50	10	1.0299	1.0493	1.0602	1.0757	1.0858	1.0998	1.1145	1.1283
60	10	1.0246	1.0438	1.0546	1.0699	1.0799	1.0938	1.1084	1.122
70	10	1.0188	1.0378	1.0486	1.0638	1.0737	1.0875	1.102	1.1155
10	20	1.0711	1.0848	1.1027	1.1044	1.1298	1.1382	1.1608	1.1657
20	20	1.068	1.0809	1.0984	1.0999	1.1245	1.1326	1.1547	1.1595
30	20	1.0641	1.0766	1.0936	1.0949	1.119	1.127	1.1486	1.1533
40	20	1.0596	1.0718	1.0884	1.0896	1.1134	1.1212	1.1424	1.1471
50	20	1.0545	1.0664	1.0828	1.084	1.1074	1.1151	1.1361	1.1407
60	20	1.0491	1.0607	1.077	1.0781	1.1014	1.109	1.1297	1.1343
70	20	1.0438	1.0547	1.0708	1.0718	1.095	1.1025	1.1232	1.1277
10	30	1.0955	1.1065	1.1231	1.134	1.1529	1.1675	1.184	1.198
20	30	1.092	1.1027	1.1184	1.1289	1.1472	1.1615	1.1775	1.1912
30	30	1.0879	1.0983	1.1134	1.1235	1.1415	1.1554	1.1712	1.1846
40	30	1.0832	1.0936	1.108	1.1179	1.1356	1.1493	1.1648	1.1781
50	30	1.078	1.0883	1.1022	1.1119	1.1294	1.1429	1.1583	1.1714
60	30	1.0724	1.0828	1.0962	1.1058	1.1231	1.1364	1.1518	1.1647
70	30	1.0664	1.0768	1.0898	1.0994	1.1165	1.1297	1.145	1.1579
10	40	1.1176	1.1312	1.1516	1.1605	1.1761	1.1854	1.2058	1.2205
20	40	1.1139	1.1268	1.1465	1.155	1.1702	1.1793	1.1991	1.2136
30	40	1.1096	1.1219	1.1411	1.1494	1.1641	1.1731	1.1925	1.2068
40	40	1.1048	1.1167	1.1354	1.1435	1.158	1.1668	1.186	1.2

Table 4 continued

T (°C)	Zn (g L^{-1})	H_2SO_4 (g L^{-1})							
		25 Absolute density (g cm^{-3})	50	75	100	125	150	175	200
50	40	1.0995	1.111	1.1294	1.1373	1.1516	1.1603	1.1792	1.1931
60	40	1.0938	1.105	1.1232	1.1309	1.1451	1.1537	1.1725	1.1863
70	40	1.0876	1.0986	1.1166	1.1242	1.1383	1.1469	1.1656	1.1793
10	50	1.1465	1.1695	1.176	1.1915	1.2046	1.2206	1.236	1.2486
20	50	1.1425	1.1646	1.1707	1.1857	1.1984	1.2139	1.229	1.2413
30	50	1.1375	1.1595	1.1652	1.1797	1.1921	1.2073	1.2222	1.2343
40	50	1.1329	1.154	1.1594	1.1736	1.1857	1.2007	1.2156	1.2273
50	50	1.1275	1.1482	1.1532	1.1671	1.1791	1.1938	1.2085	1.2202
60	50	1.1216	1.142	1.1468	1.1606	1.1724	1.187	1.2015	1.2131
70	50	1.115	1.1354	1.1401	1.1538	1.1655	1.18	1.1944	1.206
10	60	1.1711	1.1852	1.1991	1.2013	1.2252	1.2443	1.2577	1.2632
20	60	1.1667	1.1803	1.1936	1.1954	1.2187	1.2375	1.2506	1.2559
30	60	1.1621	1.175	1.1878	1.1895	1.2123	1.2307	1.2435	1.2488
40	60	1.1569	1.1694	1.1818	1.1833	1.2058	1.2239	1.2366	1.2417
50	60	1.1513	1.1634	1.1754	1.1769	1.199	1.2169	1.2294	1.2345
60	60	1.1454	1.1572	1.1689	1.1703	1.1922	1.2099	1.2223	1.2274
70	60	1.1391	1.1506	1.1621	1.1634	1.1851	1.2027	1.2151	1.2202
10	70	1.1936	1.2073	1.2231	1.2376	1.2534	1.266	1.2807	1.2944
20	70	1.189	1.2021	1.2176	1.2314	1.2468	1.2591	1.2734	1.2869
30	70	1.1841	1.1966	1.2117	1.2252	1.2401	1.2522	1.2662	1.2796
40	70	1.1789	1.1909	1.2056	1.2188	1.2335	1.2452	1.2591	1.2724
50	70	1.173	1.1847	1.1992	1.2122	1.2265	1.2382	1.2519	1.265
60	70	1.167	1.1783	1.1926	1.2054	1.2195	1.2311	1.2446	1.2577
70	70	1.1604	1.1716	1.1857	1.1983	1.2123	1.2238	1.2372	1.2503
10	80	1.2089	1.2222	1.2375	1.252	1.2731	1.2813	1.3015	1.3076
20	80	1.2042	1.2171	1.2316	1.2458	1.2663	1.2741	1.2943	1.2994
30	80	1.1993	1.2117	1.2256	1.2396	1.2595	1.2671	1.287	1.2925
40	80	1.1941	1.2061	1.2195	1.2331	1.2525	1.2602	1.2796	1.2852
50	80	1.1883	1.2	1.213	1.2264	1.2457	1.253	1.2718	1.2777
60	80	1.1823	1.1938	1.2064	1.2196	1.2383	1.2459	1.2635	1.2702
70	80	1.1758	1.1871	1.1995	1.2126	1.2314	1.2385	1.2553	1.2626

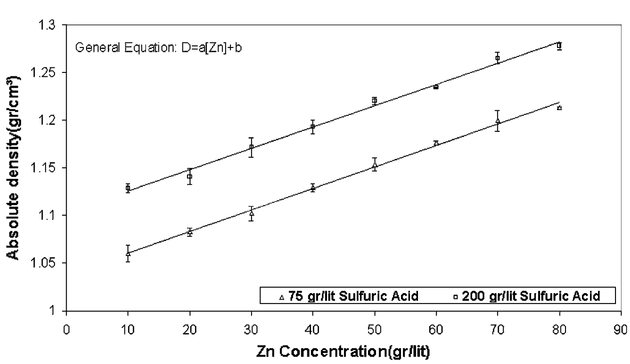

Fig. 4 The effect of zinc concentration on the absolute density at 50 °C

on the zinc and sulphuric acid concentrations and temperature, the electrolyte density can be expressed by the following equation:

$$D(\mathrm{g\,cm^{-3}}) = 2.308\times10^{-3}[\mathrm{Zn}] + 5.399\times10^{-4}[\mathrm{H_2SO_4}] - 6.113\times10^{-4}\,T + 1.024 \qquad (12)$$

where zinc and sulphuric acid concentrations are in grams per liter, temperature is in °C and the value of density has been estimated in grams per cubic centimeter. From Eq. 12, the standard error of the estimated data and experimental data is $\pm4.47\times10^{-3}$ (g cm^{-3}) and the variance is only within 0.35%.

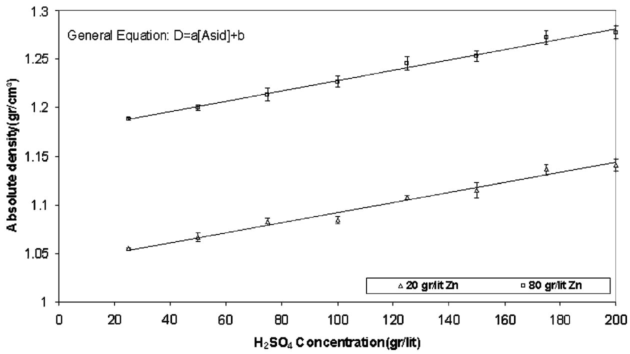

Fig. 5 The effect of sulphuric acid concentration on the absolute density at 50 °C

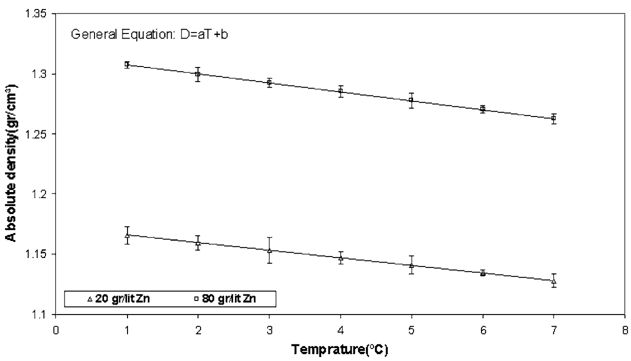

Fig. 6 The effect of temprature on the absolute density in $[H_2SO_4]$ = 200 g L^{-1}

Cd & Mn results

For Cadmium and Manganese the following results were obtained:

Cd density:

$$D(\mathrm{g\ cm^{-3}}) = 1.677 \times 10^{-3}[\mathrm{Cd^{2+}}] + 5.796 \times 10^{-4}[\mathrm{H_2SO_4}] - 5.792 \times 10^{-4}[T] + 1.017 \quad (13)$$

Mn density:

$$D(\mathrm{g\ cm^{-3}}) = 2.327 \times 10^{-3}[\mathrm{Mn^{2+}}] + 5.558 \times 10^{-4}[\mathrm{H_2SO_4}] - 6.032 \times 10^{-4}[T] + 1.021 \quad (14)$$

Again it was seen that there is no difference among these ions at all.

Conclusion

(a) Empirical equations have been derived to express the electrical conductivity and density of zinc sulphate solution as a function of temperature, sulphuric acid concentration and zinc concentration as follows:

$$k(\mathrm{mS\,cm^{-1}}) = -0.741[\mathrm{Zn}] - 4.857 \times 10^{-3}[\mathrm{H_2SO_4}]^2 + 2.453[\mathrm{H_2SO_4}] + 84.602\log T + 0.726T + 24.023$$

$$D(\mathrm{g\,cm^{-3}}) = 2.308 \times 10^{-3}[\mathrm{Zn}] + 5.399 \times 10^{-4}[\mathrm{H_2SO_4}] - 6.113 \times 10^{-4}T + 1.024$$

(b) The effects of sulphuric acid concentration and temperature is found to be more significant on electrical conductivity of zinc sulphate solution. Therefore these two parameters can be applied to decrease the ohmic drop and electrical energy consumption.

(c) Density will increase with increasing zinc and sulphuric acid concentration, while temperature rise causes the opposite effect.

(d) Generally, electrowinning and electrorefining processes should be carried out under conditions of high electrical conductivity. This is promoted by high temperatures and large acid concentrations.

(e) There is no difference among the various metal ions in this study.

Acknowledgements The authors would like to thank Mr. Mehdi Sorouri for his assistance with some of the experiments.

Appendix (Aptness criteria of regression models)

Table A1 Residuals, Sum Square of Errors (SSE), and coefficient of determination (R^2) for specific conductivity–zinc concentration relation at 50 °C

	Residuals								SSE	R^2	Regression relation
	Zn										
	10	20	30	40	50	60	70	80			
H_2SO_4 = 100	1.666	0.083	–1.500	–2.083	1.333	0.750	–1.833	1.583	17.583	99.6%	SC = 435 – 1.04(Zn)
H_2SO_4 = 200	4.583	–0.726	–3.035	–3.345	–0.654	1.035	0.726	1.416	45.976	97.6%	SC = 507 – 0.669(Zn)

Table A2 Residuals, SSE, and coefficient of determination (R^2) for specific conductivity–H_2SO_4 concentration relation at 50 °C

	Residuals								SSE	R^2	Regression relation
	H_2SO_4										
	25	50	75	100	125	150	175	200			
Zn = 20	4.875	–4.077	–15.089	18.839	–1.291	0.517	–6.732	2.958	679.005	98.9%	SC = –0.0071 $(H_2SO_4)^2$ + 3.09(H_2SO_4) + 157
Zn = 80	0.958	3.196	–9.767	6.065	–5.303	9.125	–3.648	–0.625	268.434	99.5%	SC = –0.00384 $(H_2SO_4)^2$ + 2.24(H_2SO_4) + 161

Table A3 Residuals, SSE, and coefficient of determination (R^2) for specific conductivity–temperature relation at [H_2SO_4] = 200 g L^{-1}

	Residuals							SSE	R^2	Regression relation
	Temperature									
	10	20	30	40	50	60	70			
Zn = 20	–1.365	1.376	–4.757	7.118	3.836	–2.016	–4.191	113.419	98.9%	SC = 59.5(Ln(T)) + 256.3
Zn = 80	6.428	–10.095	–12.819	14.381	8.472	0.656	–7.024	635.94	96.2%	SC = 75.7(Ln(T)) + 150.1

Table A4 Residuals, SSE, and coefficient of determination (R^2) for absolute density–zinc concentration relation at 50 °C

	Residuals × 10^{-3}								SSE × 10^{-5}	R^2	Regression relation
	Zn										
	10	20	30	40	50	60	70	80			
H_2SO_4 = 75	–0.266	–0.226	–3.385	1.254	2.495	2.135	3.376	–5.383	6.4326	99.7%	AD = 1.04 + 0.00226(Zn)
H_2SO_4 = 200	2.925	–7.1	1.175	0.450	5.125	–3.00	5.075	–4.650	14.319	99.3%	AD = 1.10 + 0.00224(Zn)

Table A5 Residuals, SSE, and coefficient of determination (R^2) for absolute density–H_2SO_4 concentration relation at 50 °C

	Residuals × 10^{-3}								SSE × 10^{-5}	R^2	Regression relation
	H_2SO_4										
	25	50	75	100	125	150	175	200			
Zn = 20	0.800	–0.064	3.571	–7.992	2.642	–2.421	5.814	–2.350	12.9462	98.1%	AD = 1.04 + 0.000511(H_2SO_4)
Zn = 80	0.650	–1.032	–1.414	–1.396	4.521	–1.560	3.857	–3.625	5.6334	99.3%	AD = 1.17 + 0.000535(H_2SO_4)

Table A6 Residuals, SSE, and coefficient of determination (R^2) for absolute density–temperature relation at [H_2SO_4] = 200 g L^{-1}

	Residuals × 10^{-3}							SSE × 10^{-5}	R^2	Regression relation
	Temperature									
	10	20	30	40	50	60	70			
Zn = 20	–0.164	–0.042	0.078	0.200	0.121	0.042	–0.235	0.0145	100%	AD = 1.17 – 0.000632 T
Zn = 80	0.264	–0.500	0.035	0.171	0.107	0.042	–0.121	0.038	100%	AD = 1.31 – 0.000744 T

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