This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Aji, Arif T.; Kalliomäki, Taina; Wilson, Benjamin P.; Aromaa, Jari; Lundström, Mari

Modelling the effect of temperature and free acid, silver, copper and lead concentrations on silver electrorefining electrolyte conductivity

Published in:
Hydrometallurgy

DOI:
[10.1016/j.hydromet.2016.09.006](https://doi.org/10.1016/j.hydromet.2016.09.006)

Published: 01/12/2016

Document Version
Peer reviewed version

Published under the following license:
CC BY-NC-ND

Please cite the original version:
Aji, A. T., Kalliomäki, T., Wilson, B. P., Aromaa, J., & Lundström, M. (2016). Modelling the effect of temperature and free acid, silver, copper and lead concentrations on silver electrorefining electrolyte conductivity. *Hydrometallurgy*, 166, 154-159. <https://doi.org/10.1016/j.hydromet.2016.09.006>

Accepted Manuscript

Modelling the effect of temperature and free acid, silver, copper and lead concentrations on silver electrorefining electrolyte conductivity

Arif T. Aji, Taina Kalliomäki, Benjamin P. Wilson, Jari Aromaa, Mari Lundström

PII: S0304-386X(16)30208-0
DOI: doi: [10.1016/j.hydromet.2016.09.006](https://doi.org/10.1016/j.hydromet.2016.09.006)
Reference: HYDROM 4435

To appear in: *Hydrometallurgy*

Received date: 29 April 2016
Revised date: 30 August 2016
Accepted date: 24 September 2016

Please cite this article as: Aji, Arif T., Kalliomäki, Taina, Wilson, Benjamin P., Aromaa, Jari, Lundström, Mari, Modelling the effect of temperature and free acid, silver, copper and lead concentrations on silver electrorefining electrolyte conductivity, *Hydrometallurgy* (2016), doi: [10.1016/j.hydromet.2016.09.006](https://doi.org/10.1016/j.hydromet.2016.09.006)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Modelling the Effect of Temperature and Free acid, Silver, Copper and Lead Concentrations on Silver Electrefining Electrolyte Conductivity

Arif T. Aji*, Taina Kalliomäki, Benjamin P. Wilson, Jari Aromaa, Mari Lundström

Laboratory of Hydrometallurgy and Corrosion, Dept. of Materials Science and Engineering, School of Chemical Technology, Aalto University, P.O. Box 16300, FI-00076 AALTO, Finland

** Corresponding Author: arif.aji@aalto.fi*

Abstract

Conductivity is one of the key physico-chemical properties of electrolyte in silver electrefining since it affects the energy consumption of the process. As electrefining process development trends towards high current density operation, having electrolytes with high conductivities will greatly reduce the energy consumption of the process. This study outlines investigations into silver electrefining electrolyte conductivity as a function of silver, free acid, copper and lead concentration at different temperatures via a full factorial design comprising of 246 individual measurements. Regression analysis of the model was used to determine the goodness of fit R^2 , goodness of prediction Q^2 , model validity and reproducibility. Conductivity was shown to be enhanced by increases in free acid, copper, silver and lead, with free acid having the highest impact on conductivity. Temperature also increased conductivity in two ways: both as a single factor and as a combined effect with free acid, silver and copper concentration. Overall, this work produced a model of high accuracy that allows conductivity of a range of industrial silver electrefining conditions to be calculated.

Keywords: silver electrolyte, conductivity model, electrefining overpotential, industrial

1. Introduction

Electrefining to produce high purity silver is industrially undertaken via one of two methods: either the Balbach-Thum or the Moebius process. These processes have traditionally involved the use of silver anodes and stainless steel cathodes immersed in AgNO_3 electrolyte with $[\text{Ag}^+]$ concentration in the range of 30 to 150 g/dm^3 and 10 g/dm^3 free acid operating at temperature range of 25-50 °C (Pletcher., 1990; Claessens and Cromwell., 1999). While the same systems are still commonly used in industrial applications, more recent silver electrefining process development has focused on methods that allow for continuous processing, higher tolerance of anode impurities and an increased production rate (Auerswald and Radcliffe, 2005).

A majority (~60%) of the silver bullion that is used to make anodes for electrefining is produced as a by-product of gold, copper, lead and zinc mining and as result the most common impurities present in the silver electrefining process are gold, copper and to a lesser extent, lead. While gold is insoluble in dilute nitric acid (Walkiden and Jarman, 1994), copper and lead can readily dissolve and thus affect the physico-chemical properties of the process electrolyte like conductivity, density and viscosity. From the impurities of bullion and electrolyte composition, it was considered that in silver electrefining the predominant ion contributors would be silver, nitric acid, copper and lead.

In the current research, these ion contributors along with temperature were investigated to ascertain their effect on the electrolyte conductivity during silver electrorefining.

Early investigations of electrolyte conductivity theory (Onsager., 1927; Shedlovsky., 1934) have described the effect of the concentration of each ion in an electrolyte. Subsequently it was determined that each ion makes a unique and independent contribution to the total molar conductivity of the system, as defined by Kohlrausch law (Crow, 1988). The conductivity of an electrolyte can be measured using Ohm's law of electrical resistance approach, where conductivity (κ , mS/cm) is defined as the reciprocal of the specific resistance (ρ_{Ω} , Ωcm) (Jones and Bollinger, 1931). The correlation between conductivity and specific resistance is shown in equation (1).

$$\kappa = \frac{1}{\rho_{\Omega}} \quad (1)$$

By further substituting the value of specific resistance with conductivity of electrolyte, the resistance of electrolyte can be defined by equation (2).

$$R_{electrolyte} = \rho_{\Omega} \left(\frac{l}{A} \right) = \frac{l}{\kappa A} \quad (2)$$

In an electrorefining process, the electrical current flows through the electrolyte from anodes to cathodes and the presence of electrolyte resistance gives rise to an overpotential effect known as IR or ohmic drop within the system. With the typical parallel connections between anodes and cathodes that are used in industrial silver electrorefining cells (Figure 1), the overpotential caused by ohmic drop can be calculated for a system with a known current density (j , A/m²) and inter-electrode distance (l , cm) by using equation (3)

$$\eta_{IR} = IR_{electrolyte} = (jA) \frac{l}{\kappa A} = \frac{j l}{\kappa} \quad (3)$$

Figure 1. Schematic of silver electrorefining cell

As the cell potential during electrorefining is equal to zero, the applied overpotential is theoretically the extra energy needed to overcome the ohmic drop of the system. While there has so far been no intensive research into the silver electrorefining process, previous research based on copper electrorefining has demonstrated that the overpotential needed to overcome electrolyte resistance (0.11-0.13 V) is the highest contributor to the total overpotential (0.19-0.29 V) required (Aromaa, 2007). In contrast to the copper process, silver electrorefining cell voltage is usually between 2.0-2.8 V with a current density in the range of 300 to 400 A/m² and an energy consumption around 0.7 kWh/kg (Pawlek, 1983). There are several techniques to minimize potential in order to increase energy efficiency, which include increasing electrolyte conductivity and the reduction of the space between electrodes (Aromaa, 2007). Of these options, the conductivity of the electrolyte solution is the most important property.

Previous research by Gordon and Davenport calculated the electro-conductivity of a silver electrolyte as a function of silver, copper and free acid concentration at different temperatures (Gordon and Davenport, 1981). Their investigation concluded that silver and copper were the main contributors to conductivity, while temperature had a positive effect on conductivity, although to a lesser extent. Conversely, it was found that the free acid - as defined by the concentration of HNO₃ - only provided an insignificant increase in conductivity and therefore was excluded from the model calculations. The parameters that were used Gordon and Davenport in these measurements were silver concentration in the range of 0 to 150 g/dm³, copper concentration from 0 to 80 g/dm³ and temperature from 25 to 70 C, which hereafter will be referred to as the GD parameters. From these results it can be concluded that in order to have a highly conductive electrolyte that minimizes power consumption, silver electrorefining should be carried out using an electrolyte that contains a high concentration of silver and copper, locking high amount of silver in the electrolyte.

In contrast, an examination of the literature related to similar investigations of copper electrolyte physico-chemical properties, show that increase in free sulphuric acid and temperature have the most significant increasing impact on conductivity, while the concentration of copper, nickel and arsenic were calculated to lead to a decrease in the conductivity (Price and Davenport, 1980; Price and Davenport, 1981; Moats et al., 2000; Subbaiah and Das, 1989; Kalliomäki, 2015).

As electrolyte conductivity can have a significant impact on the electrorefining process, this study has investigated the effect of changing temperature and electrolyte concentration has on electrolyte conductivity. The research has placed particular emphasis on the optimisation of the electrolyte conductivity such that it can be increased without any adverse impact on the overall efficiency of the electrorefining process.

2. Materials and Methods

The range of parameters utilized in this investigation (temperature, silver electrolyte and free acid concentration) were selected in order to emulate industrial process conditions: the silver concentration was within the range of 40 g/dm³ to 100 g/dm³ and free acid concentration was between 5 to 15 g/dm³ of free acid for all electrolytes. Additionally, the copper and lead concentration of 0 to 20 g/dm³ and 0 – 6 g/dm³ respectively, were investigated to account for the

dissolved impurities in electrolyte. Electrolytes were prepared from the appropriate combinations of silver nitrate (AgNO_3 , 99.8%, VWR Chemicals), nitric acid (HNO_3 , 65%, Merck), lead (II) nitrate ($\text{Pb}(\text{NO}_3)_2$, 99%, Alfa Aesar), copper (II) nitrate trihydrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, 99%, VWR Chemicals) and distilled water with a conductivity of less than $2.0 \mu\text{S}/\text{cm}$ at 25°C . All experimental parameters are summarized in Table 1. In total 246 measurements were conducted.

Table 1. Experimental parameters of silver electrolyte conductivity measurements.

Factors	Levels	Unit
Ag	40; 70; 100	g/dm^3
HNO_3	5; 10; 15	g/dm^3
Pb	0; 3; 6	g/dm^3
Cu	0; 10; 20	g/dm^3
T	25; 30; 35	$^\circ\text{C}$

Conductivity measurements were carried out using a Knick Portamess® 913 Cond conductivity meter (Knick Elektronische Messgeräte GmbH & Co. KG) that was calibrated prior to measurement using Reagecon solution with a conductivity of $12.88 \text{ mS}/\text{cm}$ at 25°C . The temperature of all the electrolytes was controlled using a thermostatic MGW Lauda MT/M3 circulating water bath. During the heating procedure and between the measurements, the electrolytes were tightly covered in order to prevent evaporation and related water loss. Temperature accuracy for every measurement was 0.1°C and minimum of two measurements were performed for every data point to ensure the validity of the conductivity values recorded.

Data analysis and experiment design were carried out using the modelling and design tool MODDE 8.0 (MKS Data Analytics Solutions) that allows for design of experiments (DOE) and multivariate data analysis. The full experiments were designed using a full factorial method that incorporated three centre points with defining factors, responses and levels of the factors, which resulted in the need for 246 individual data points. The multivariate method used for the data processing was a Partial Least Square (PLS) regression as it can provide a better interrelationships analysis within the parameters (X axis) for the same result (Y axis) than the alternative Multiple Linear Regression (MLR).

Initial regression analysis was based on the assumption that each ion concentration has an independent effect on the conductivity, whilst the subsequent, second regression step was undertaken with a full factorial analysis to provide the best fit for the equation. Overall, the final model was checked to ensure that it met the required values of R^2 (accuracy of fit), Q^2 (accuracy of prediction), model validity and reproducibility (Eriksson et al, 2008). The value of R^2 varies from 0 to 1, where 1 indicates a perfectly modelled relationship between parameters and 0 that the model basis is inappropriate and does not reflect reality. In terms of Q^2 , a value >0.5 can be considered to be a good model while a value > 0.9 should be regarded as excellent. Furthermore, if a model attains a value of validity and reproducibility, above 0.25 and 0.5 respectively, it can be regarded as a valid and feasible.

By taking the best fit model from this study, further analysis into the effect of conductivity on energy consumption was also calculated to determine the optimum conductive electrolyte.

3. Results and Discussion

All the measurement results are summarized in the 3D scatter diagrams displayed in Figure (2) and it was shown that all the data points distributed statistically symmetrically as shown in histogram, Figure (3). Figure 2 shows that ion contributors (silver, acid, copper and lead) investigated were shown to have a positive impact to electrolyte conductivity. Effect of free acid concentration has larger effect to conductivity than silver concentration. Figure 3 shows that both copper and lead, being common impurities in silver electrorefining, also contribute positively to the electrolyte conductivity.

Figure 2. The effect of species present and temperature on the conductivity of silver electrolyte

Figure 3. Histogram of silver electrolyte conductivity data measured in the current study.

It has been earlier suggested that the free acid concentration does not significantly contribute into the value of conductivity (Gordon and Davenport, 1981). However, the current study showed that the acid concentration had the largest effect on conductivity. For the metal cations, it was observed that copper concentration had a strong effect on conductivity, higher effect of copper than silver concentration is in a good agreement to the result of previous work (Gordon and Davenport, 1981). Lead as additional cation measured in this work was shown to contribute the least effect. In terms of temperature effect, it was observed that along with the independent increase in conductivity with an increase in temperature, the model regression also indicated that there is a significant combined effect of temperature with some of the ions contributors (silver, free acid and copper).

3.1 Model 1 - Independent effect of ions

Free acid concentration in solution was found to have the strongest influence on electrolyte conductivity, both as an independent effect and as part of an combined effect with temperature as shown in the Figure 4. Although the interrelation effect between silver, acid and copper ions with temperature was observed to only provide a minor contribution to the overall conductivity, inclusion of these coefficients in the model was seen to provide an improved value for the model validity. The combined effect of lead ions and temperature was shown to have a high error thus was removed. The conductivity model for the independent effect of ions (Model 1) is shown in equation (4) and the results of the statistical analysis can be seen in Figures 4. From the value of Q^2 of 0.967, this Independent Ion Effect model can be regarded as an excellent model with sufficient but low validity (0.338).

$$\kappa = 10.8444 + 0.2772[Ag] + 3.2679[HNO_3] + 0.5725[T] + 0.6996[Cu] + 0.2037 [Pb] + 0.0084[Ag]T + 0.0493[HNO_3]T + 0.02 [Cu]T \quad (4)$$

Figure 4. Scaled and centred coefficients of conductivity for the independent effect of ions

3.2 Model 2 - Full factorial conductivity model

The second model was investigated by using a full factorial interrelation (Model 2) between all parameters. After the initial iterations some parameters that induced high error were removed and the final parameters utilised are shown in Figure 5. As was previously observed with Model 1, the full factorial analysis showed a similar qualitative effect of the contributor ions to the conductivity. Additionally the interrelation effect between these ions was also seen to provide negative coefficients when related to the conductivity. Model 2 is represented by Equation (5) and with a Q^2 value of 0.819 can be regarded as less representative than Model 1, although model validity was calculated to be higher.

$$\kappa = -4.0284 + 0.4402[Ag] + 4.3019[HNO_3] + 0.5725[T] + 1.499[Cu] + 0.2037[Pb] - 0.0098[Ag][HNO_3] + 0.0084[Ag]T - 0.0065[Ag][Cu] + 0.0493[HNO_3]T - 0.0346[HNO_3][Cu] + 0.02[Cu]T \quad (5)$$

Figure 5. Scaled and centred of coefficients for the full factorial conductivity model

3.3 Comparison between models

3.3.1 Model 1 and Model 2

Summary of fit values, generated using MODDE, between both models were compared to determine the most representative model to calculate conductivity. The summary of fit values and the minimum requirements can be seen on Table 2. Comparison of these models will be emphasized on the value accuracy of fit (R^2) and accuracy of prediction (Q^2) and the difference between these two values ($R^2 - Q^2$).

Table 2. Comparison of summary of fit values of Model 1 and Model 2

Criteria	Good model requirement	Model 1	Model 2
Accuracy of fit (R^2)	close to 1	0.992	0.9977
Accuracy of prediction (Q^2)	> 0.5	0.9677	0.8196
$R^2 - Q^2$	< 0.2	0.0246	0.1782
Validity	> 0.25	0.3384	0.7292
Reproducibility	> 0.5	0.9988	0.9988

These values show that both models can be considered as good models. Nevertheless, Model 1 has a better accuracy of prediction when compared Model 2 and by having a Q^2 value > 0.9, Model 1 was considered to be superior to the full factor conductivity approach of Model 2.

3.3.2 Model 1, Model 2 and Gordon and Davenport Model using the GD range of parameters.

Both the conductivity Models 1 and 2 were compared with the previous work of Gordon and Davenport as shown by Equation (6). Comparisons between models were made by plotting the real conductivity values measured by Gordon and Davenport with the prediction from Model 1, Model 2 and Model from Gordon and Davenport. The data is limited to electrolytes with the copper concentration lower than 60 g/dm^3 which considered to be the maximum copper concentration allowed in silver electrorefining electrolytes (Harris et al., 2008). The ideal regression of this real and predicted value should have both values of slope and R^2 closest to 1.

$$\kappa = 0.42[Ag] + 1.06[Cu] + 0.026T^2 + 16.58 \quad (6)$$

As can be seen in Figure 5 below, by having almost ideal slope value, Model 1 was able to predict accurate value of conductivity better than the other two models.

Figure 6. Comparison between Measured Conductivity against Predicted Conductivity of Models in Gordon and Davenport range of parameters.

3.3.3 Model 1, Model 2 and Gordon and Davenport at range of parameters in this study

Another comparison was made using the same method under the range of parameters used in this study. As clearly seen in the Figure 7, by excluding the effect of free acid in conductivity calculation, the previous model from Gordon and Davenport is unable to predict conductivity. And for both models from this study show good regression with slope value close to ideal. In this plot, the R^2 value for Model 2 is slightly better than Model 1 which consistent with the MODDE results. This could be caused by more parameters were put into the equation in Model 2, nevertheless these models are considered to be excellent model as both model 1 and model 2 have R^2 value above 0.9.

Figure 7. Comparison between Measured Conductivity against Predicted Conductivity of Models in Gordon and Davenport range of parameters.

3.4 Effect of Silver Concentration on Overpotential

In the silver electrorefining process, silver is not completely deposited on the cathode and as a result, dendritic silver crystal by-products can accumulate at the bottom of the electrolytic tank. Thus, it is highly likely that this dendritic silver will be re-dissolved back into the electrolyte solution as it is not cathodically protected and this phenomenon is one of the notable differences between the silver and copper electrorefining processes. Therefore, in contrast to what has been previously observed for copper electrorefining, a higher acid concentration in the silver electrolyte is not the best option to increase overall electrolyte conductivity. In addition, an increase in copper concentration as the second higher conductivity contributor will also have detrimental effect on the silver electrorefining process as copper could also be co-deposited into cathode, which would affect the purity of the final product. The consequence of the above phenomena means that silver concentration is considered to be the main component of electrolyte that provides both the required conductivity and ion supply in the electrolyte during the electrorefining process, therefore a high concentration of silver is necessary to lower the electrolyte polarization potential.

Modelling η_{IR} as a function of silver concentration was undertaken using the Ion Independency model (Model 1) by using equation (3) with 5 cm gap between electrodes. Ohmic drop was calculated for current densities of 500 A/m² as shown in Figure 8. Fresh electrolyte (impurities content of copper and lead equal to zero) and typical acid concentration of 10 g/dm³ was used to calculate the over potential as result of the conductivity of electrolyte.

Nevertheless, since the potential equation as function of silver concentration is expressed rather by non-linear, the addition of silver does not always lead to a significant reduction in the potential. With the wide range of silver concentration from 30-150 g/dm³ used in silver electrorefining (Pletcher and Walsh., 1990), an approach to determine the optimum concentration of silver was taken by drawing a linear regression at the beginning and the end of the range for points correlating linearly, Figure 8. The slope of regression at high silver concentration is less than half that at low silver concentration indicating lower reduction of over potential with increasing silver at high concentration. These two regression crossed over at the value approximately 80 g/dm³ which then considered to be the optimum silver concentration.

Figure 8. Solution polarization potential as function of silver concentration within the range of silver concentration according to Pletcher and Walsh (30 to 150 g/dm³) at 10 g/dm³ HNO₃, 0 g/dm³ Cu and 0 g/dm³ Pb at 25 °C temperature.

4. Conclusions

From this work it can be concluded that an increase in all ion concentrations (free acid, silver, copper and lead) and temperature have a positive effect on silver electrolyte conductivity. Of these, free acid concentration was found to have the most significant impact on electrolyte conductivity. A significant linear conductivity increase was also observed with copper, silver and temperature, however this was found to be less significant when compared to the free acid concentration.

Two models were calculated as part of this work: the first model calculation was based on the independent ion's effect and the interrelation effect of the ions with temperature (Model 1). The second model was determined using a full factorial equation that takes into account all the

interrelation effects between all the parameters, then removes any parameters that result in significant errors within the equation (Model 2). In general, both of the models outlined in this work were found to have high accuracy and sufficient validity.

Of the two models proposed, Model 1 was considered to be the superior one as it possess a higher Q^2 value ($Q^2 = 0.967$) when compared to Model 2 ($Q^2 = 0.819$). Moreover, Model 1 can accurately predict values close to those measured by the Gordon and Davenport model, even though the parameter ranges were outside those used in this investigation. In contrast, the Gordon and Davenport model was unable to accurately predict the conductivity values achieved within the parameter range of this work.

As mentioned previously, electrolyte resistance can be the major contributor factor to the total over potential, therefore a further calculation of the electrolyte polarization potential with Model 1 was also performed. It was found that the electrolyte polarization potential varies with a natural logarithmic curve as a function of silver concentration. This finding suggests that the addition of silver (up to an electrolyte concentration of approximately 80 g/dm³) could be the best way to reduce the over potential of the silver electrorefining process.

Furthermore, this investigation calculated that under industrial silver electrorefining conditions as defined by both Pawlek (parameter range of 300 to 400 A/m²) and Pletcher and Walsh (silver concentration from 30 to 150 g/dm³), overpotential caused by electrolyte resistance was found to vary between 1.05 to 2.36 Volts. This value range indicates that the overpotential contribution from the electrolyte can be considered to be dominant, since the cell voltage of silver electrorefining is to be between 2.0 to 2.8 Volts (Pawlek, 1983).

Acknowledgments:

This research has been performed within the SIMP (System Integrated Metal Production) project of FIMECC (Finnish Metals and Engineering Competence Cluster Ltd) and funding support from LPDP (Indonesian Endowment Fund for Education). Furthermore, discussions with Emeritus Prof. Olof Försen on the theoretical background of conductivity in copper refining are gratefully acknowledged.

References

- Aromaa, J., 2007, "Electrochemical Engineering: Aqueous Processing of Metals", Encyclopedia of Electrochemistry, VHC Verlag GmbH & Co, KGaA, pp. 161-196.
- Auerswald, D. A., Radcliffe, P. H., 2005, "Process technology development at Rand Refinery", Minerals Engineering 18, pp. 748-753.
- Claessens, P., Cromwell, J. L., 1999, "Silver Electrolysis Method in Moebius Cells", European Patent, EP 0775 763 B1.
- Crow, D. R., 1988, "Principles and Applications of Electrochemistry", Chapman and Hall, 3rd edition.

- Eriksson, L., Johansson, E., Kettaneh-Wold, N., Wikström, C and Wold, S., 2008, “Design of Experiments”, Umetrics Academy., pp 78.
- Gordon, N. L., Davenport, W. G., 1981, “Electrical conductivities, densities and viscosities of silver refining electrolyte”, Canadian Mining Quarterly, vol 20, No 3, pp 369-372.
- Harris, B., White, C., Aprahamian, V., 2008, “Method for Recovering Nitric Acid and Purifying Silver Nitrate Electrolyte”, Royal Canadian Mint, WO 2009000072 A1.
- Jones, G., Bollinger G. M., 1931, “The Validity of Ohm’s Law for Electrolytes”, Journal of the American Chemical Society, 53 (4), pp 1207–1212.
- Price, D.C., Davenport, W.G., 1980, “Densities, Electrical Conductivities and Viscosities of $\text{CuSO}_4/\text{H}_2\text{SO}_4$ Solutions in the Range of Modern Electrefining and Electrowinning Electrolytes,” Metallurgical Transactions B, vol. 11B, pp. 159–163.
- Kalliomäki, T, 2015, “Effect of Composition and Temperature on Physico-Chemical Properties of Copper Electrolyte”, Master Thesis, Aalto University.
- Moats, M.S., Hiskey, J.B. and Collins, D.W., 2000, “The effect of copper, acid, and temperature on the diffusion coefficient of cupric ions in simulated electrefining electrolytes”, Hydrometallurgy, vol. 56, pp. 255–268.
- Onsager, L., 1927, “Report on Revision of Conductivity Theory”, Trans. Faraday Soc, pp 341-349.
- Pawlek, F., 1983, “Metallhutenkunde“, Walter de Gruyter, Berlin, p 865
- Pletcher, D., Walsh, F. C., 1990, “Industrial Electrochemistry”, Springer.
- Price, D.C., Davenport, W.G., 1981, “Physico-Chemical Properties of Copper Electrefining and Electrowinning Electrolytes,” Metallurgical Transactions B, vol. 12B, pp. 639–643.
- Shedlovsky, T., 1932, “An Equation for Electrolytic Conductance”, Journal of the American Chemical Society, 54 (4), pp 1405–1411.
- Subbaiah, T., Das, S.C., 1989, “Physico-Chemical Properties of Copper Electrolytes,” Metallurgical Transactions B, vol. 20B, pp. 375–380.

Highlights

- Silver electrorefining electrolyte concentration and temperature effect to conductivity
- High accuracy conductivity model for industrial silver electrorefining electrolyte
- Optimizing electrolyte conductivity to reduce process overpotential