STUDENTS' CONCEPTUAL UNDERSTANDING OF CHEMICAL REACTIONS AT THE ELECTRODES IN THE ELECTROLYTIC CELL

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Abstract

This paper describes students' conceptual understanding with regards to the chemical reactions that occur in the electrolytic cell. The chemical reactions at the electrodes in the electrolytic cell are less emphasized in educational research in comparison to the voltaic cell. Some empirical evidence on 16-year-old secondary school students' conceptual understanding of chemical reaction are presented. This study involved eight science classes in eight different schools (convenience samples) in Penang. The results show that most students in this study have difficulties in generating details on the chemical reactions that take place at the electrodes in the electrolytic cell. This may be due to students' inability to make connections on the relationship between macroscopic, sub-microscopic, and symbolic entities.

Introduction

Research in chemistry education has shown that students often have difficulty in understanding chemistry concepts due to their abstract nature and many attempts have been made by researchers to assist students' learning by identifying the difficulties experienced by students and possible solutions to overcome this problem (Sanger & Greenbowe, 1997a & 1997b; Niaz & Chacon, 2003; Ozmen, 2004; Ozkaya et al., 2006). There are three levels of representation of chemical phenomena: macroscopic, sub-microscopic and symbolic (Treagust et al., 2003). The macroscopic level is an observable chemical event, e.g. observing the production of a new substance. In order to communicate regarding this macroscopic event, chemists commonly use symbolic representations such as chemical equations, reactions mechanisms, models and many other techniques (Treagust et al., 2003). Treagust et al. further add that the sub-microscopic level of representation is usually based on the particulate theory of matter, where the sub-microscopic entities are real, but are too small to be observed.

Electrochemistry has been widely reported as being one of the most difficult topics in chemistry because it contains many ambiguous and abstract terms and has an apparent lack of consistency and logic in its representation (Sanger & Greenbowe, 1997a & 1997b; Ozmen, 2004; Ozkaya et al., 2006; Schmidt et al., 2007). Some teachers find the topic difficult to teach and reason that the lesson plans are hard to prepare (Ahtee et al., 2002). Terms like 'ions,' 'atoms,' 'electrons,' 'equilibrium,' and 'delocalise' have no precise meaning in everyday life, but pose a defined meaning in chemistry. These terms are initially introduced by teachers, as students do not just discover the terms or concepts by themselves.

It is found that students from different countries hold common difficulties due to many factors discussed above. The studies found are repetitious or are the replication of another; for example, Africa (Huddle et al., 2000; Ogude & Bradley, 1994 & 1996), America (Greenbowe, 1994; Sanger & Greenbowe, 1997a, 1997b, 1999, & 2000), Australia (Garnett et al.,1990; Garnett and Treagust, 1992a & 1992b), Belgium (Brandt et al., 2001), Finland

(Ahtee et al., 2002), Germany (Schmidt & Volke, 2003; Schmidt et al., 2007), Jamaica (Thompson & Soyibo, 2002), Taiwan (Chou, 2002), Turkey (Ozkaya, 2002; Ozkaya et al., 2006), and Venezuela (Niaz, 2002; Niaz & Chacon, 2003). These studies suggest that throughout the world students generally have difficulties in learning electrochemistry; hence, further studies in this area are required. Note that some of the studies are conducted and repeated by the same researchers, and research in this area seems to be less reported in the literature after 2007. In Malaysia, based on the literature review, only one study is found on the use of animations as a teaching tool in order to enhance matriculation students' conceptual understanding of electrochemistry (see Talib et al., 2005 & 2006); however, there is yet a study on students' conceptual difficulties on the chemical reactions in the electrolytic cell. Thus, this study may provide some insights on students' conceptual understanding in this learning area.

Statement of problem

Electrochemistry is the study of the inter-conversion of electrical and chemical energy which involves many examples of chemical observations, chemical reactions and symbols. There are two main electrochemical cells: the electrolytic and voltaic (galvanic) cells. These two cells have similar related features such as having two electrodes that are dipped into a solution known as electrolytes, and these two electrodes are connected to positive and negative terminals. Even though both electrochemical cells have similar terminologies, but the outcomes for their chemical changes and reactions are different from one another. For example, in the electrolytic cell, the 'positive terminal' is known as the 'anode', whilst in the voltaic cell, the 'negative terminal' is similarly known as the 'anode'. Thus, statements found in text books such as 'electrolytic cell is the reverse of the voltaic cell is an over generalised statement because not all features of both cells are the opposite of each other because the outcomes of the chemical changes and reactions and products at the electrodes are different.

In addition, some studies on this topic focus more on the voltaic cell (e.g. Boulabiar et al., 2004; Morikawa & Williamson, 2001; Eilks et al., 2009), and others on comparing the chemical reactions in the electrolytic cell with the voltaic cell (Garnet & Treagust, 1992b; Sanger & Greenbowe, 1997b); however, not so many concentrate on the electrolytic cell itself (see Ahtee et al., 2002). Even though the structure, chemical changes and reactions of the voltaic cell are more complicated than the electrolytic cell; however, an understanding of the structure of the electrolytic cell and its related features serves as a starting point for students to understand the whole process of electrochemistry. Thus, students need to be well versed in and appreciate the structure, chemical processes and reactions of the electrolytic cell because it is introduced in the first part of the electrochemistry syllabus before the voltaic cell. Also, students often fail to relate macroscopic observation with sub-microscopic entities, and cannot represent the chemical changes and reactions using symbolic entities (e.g. half cell equation). Thus, there is a need to do a research on students' conceptual understanding in this content-specific area.

Insights into students' understanding of electrode terminologies, chemical changes and reactions at the electrodes

Students experience difficulties in understanding the chemical reactions at the electrodes, even though they are able to observe the chemical changes. This is because the changes at the macroscopic level need to be explained with reference to sub-microscopic entities. For example:

> 'During the electrolysis of an aqueous copper chloride ($CuCl_2$) with graphite (carbon) electrodes, a brown deposit is formed at one of the electrodes'.

This phenomenon indicates macroscopic observation of the changes that happen on the electrode and the explanations are based on the electron transfers and ion selections at the sub-microscopic level, which results in the deposit of atoms at the electrode. Some examples related to students' difficulties with chemical reactions and processes in electrochemical cells can be found in Sanger and Greenbowe (1997b) which is a study about predicting the products of electrolysis and the transfer of charge in the electrolytic cell during electrolysis, and in Schmidt et al. (2007) which is a study about the end products of electrolysis.

Sanger and Greenbowe (1997b) report that students have difficulties identifying the anode and cathode in electrolytic and voltaic cells (see also: Schmidt et al., 2007; Ogude & Bradley, 1996), and these differences in electrode terminologies (anode, cathode, positive and negative electrodes) have created confusion for students and led to misinterpretation of the 'electrode event'. Ogude and Bradley (1996) found that pre-college and college students have difficulties assigning the anode and cathode in electrolytic and voltaic cells. Students tend to describe electrodes as positive and negative electrodes and indicate that both electrodes are 'charged', and these 'charged' electrodes will influence the 'attraction of ions' to the electrolyte. In their findings, 71% of pre-college students and 63% of first year college students agreed that in voltaic cells 'chlorine gas is formed when chloride ions are neutralised by the charge on the positive electrode, rather than the Cl^- ions losing electrons to form atoms' (Ogude & Bradley, 1996, p. 1146).

The same findings have been reported in Garnett and Treagust (1992b, pp. 1091-3) with grade 12 students in Australia where one major problem for students is identifying the anode and cathode of the electrochemical cells. The students' responses include 'the anode is negatively charged and because of this it attracts cations', 'the cathode is positively charged and because of this it attracts anions', 'anode is negatively charged because it is designated by a negative sign'. These types of responses show that the representation of the electrochemical cell, such as when the anode is assigned as a 'positive electrode', can lead students to think that the anode is always positively charged or vice versa for the cathode. Another reason for students' belief that the anode is negatively charged is that they think 'electrons move from regions of high electron concentration (anode) to regions of low electrons (cathode) during oxidation'. Due to the confusion on the electrode terminologies in the electrochemical cell, students often find it difficult to explain the chemical changes and reactions at the electrodes.

Subject and Sample size

Eight classes of 16-year-old students (Form 4) from eight different schools in Penang, Malaysia (189 students), served as convenience samples, were selected in order to compare the differences on their conceptual understanding of aspects of electrochemistry in a wider sample. The number of students is not representative of the whole population of Malaysian students, but is considered to be a reasonable size to provide some empirical evidence representing the conceptual understanding of typical Malaysian secondary school students who followed a similar curriculum and normal classroom teaching. In other words, the findings in this study can provide some empirical evidence regarding students' conceptual understanding on the chemical reactions at the electrodes after the students had been taught the topic following normal classroom teaching.

Data analysis

The data collected in this study was mainly focused on the responses in the post diagnostic test. The post diagnostic test papers were given to the students after they had been taught electrochemistry. Only four items in the post diagnostic test are discussed in this paper (item 3a-d).

The analysis in this study starts by using the ideographic approach, followed by the nomothetic approach (Driver & Erickson, 1983). After the ideographic analysis of the students' responses, the following coding schemes are applied as a means to analyse students' responses using the nomothetic approach.

For example, one of the students' responses:

> 'There is a flow of electricity in the wire' (Student X)

This response shows that 'Student X' understood that there is a flow of electricity in the wire that makes it possible to light up the bulb, but the response does not contain the taught key features; that is, 'this is because electrons move in the wire from the anode to the cathode'. Thus, this response is analysed ideographically. However, as this response is coded as partially correct, this is a nomothetic analysis. Based on the students' responses, four types of categories (set) were developed, as follows:

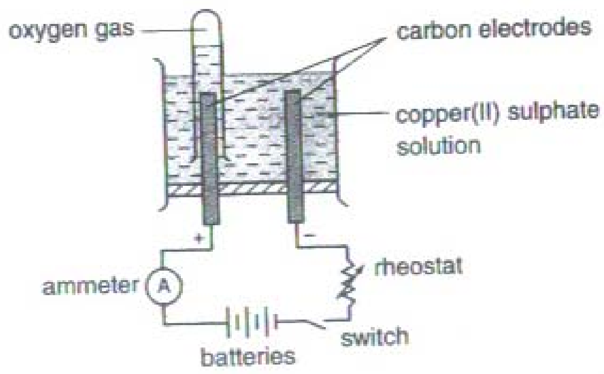
1. Scientifically correct (SC)
2. Partially correct (PC)
3. Other (O)
4. Not attempted (NA)

The results are presented in the form of percentages as the values are compared to determine the numbers of 'scientifically correct' and other categories.

Results

The questions for items in 3a-3d are shown below. Item 3a and 3b required students to explain the reactions at the electrodes when carbon electrodes are used in the experiment whilst items 3c and 3d required them to explain the reactions at the electrodes when copper electrodes are used (active electrodes), both having aqueous copper sulphate solution.

> 3. *Tiara* and her group are required to set up two experiments in electrolysis. In Experiment I, the figure below shows the arrangement of the apparatus for the electrolysis of aqueous copper sulphate solution and the results are provided in the box below.



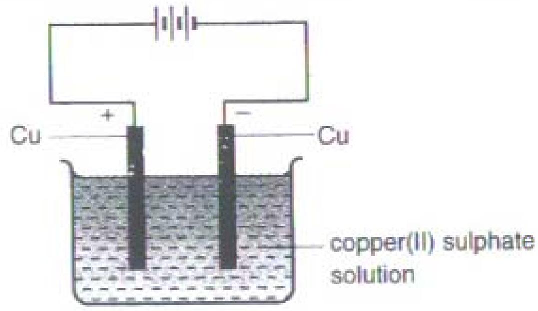
Experiment I

Their observations are as follows:

Observations
At the cathode (negative terminal): brown deposit is formed. This is copper.
At the anode (positive terminal): gas bubbles are formed. This is oxygen.
Colour of electrolyte: the blue colour of the solution becomes paler.

3a. Explain how oxygen is produced at the anode. 3b. Explain how copper is produced at the cathode.

For Experiment II, *Tiara* and her group have set up the electrolytic cell shown below and their observations are provided in the box.



Experiment II

These are *Tiara* and her group's observation:

Observations
At the cathode (negative terminal): formation of brown deposit makes the cathode thicker.
At the anode (positive terminal): anode erodes and becomes thinner.

Colour of electrolyte: the blue colour of the solution remains unchanged.

3c. Explain as carefully as you can why the anode erodes. 3d. Explain as carefully as you can why the cathode increases in mass.

Table 1 and 2 below show the results of the classes under investigation which is aimed to investigate students' conceptual understanding about the reactions at the carbon electrodes.

Table 1
Results of students' performance for item 3a

Class/Coding	SC	PC	O	N	Total (n)	% SC	% PC	% O	% NA
A	5	0	6	26	37	13.5%	0.0%	16.2%	70.3%
B	0	2	18	9	29	0.0%	6.9%	62.1%	31.0%
C	0	0	13	14	27	0.0%	0.0%	48.1%	51.8%
D	3	2	18	0	23	13.0%	8.7%	78.3%	0.0%
E	0	1	10	11	22	0.0%	4.5%	45.4%	50.0%
F	0	0	11	11	22	0.0%	0.0%	50.0%	50.0%
G	0	0	8	7	15	0.0%	0.0%	53.3%	46.7%
H	0	0	1	13	14	0.0%	0.0%	7.1%	92.9%

Table 2
Results of students' performance for item 3b

Class/Coding	SC	PC	O	N	Total (n)	% SC	% PC	% O	% NA
A	4	0	6	27	37	10.8%	0.0%	16.2%	73.0%
B	0	3	18	8	29	0.0%	10.3%	62.1%	27.6%
C	0	0	14	13	27	0.0%	0.0%	51.8%	48.1%
D	2	7	14	0	23	8.7%	30.4%	60.9%	0.0%
E	0	1	10	11	22	0.0%	4.5%	45.4%	50.0%
F	0	1	10	11	22	0.0%	4.5%	45.4%	50.0%
G	0	0	8	7	15	0.0%	0.0%	53.3%	46.7%
H	0	0	1	13	14	0.00%	0.00%	7.14%	92.9%

The results show that the percentage of students' with *scientifically correct answers* (SC) was very low, indicating that many of them did not know how to explain the production of oxygen at the anode (item 3a) and the deposit of copper metal at the cathode (item 3b) in terms of the position of ions in electrochemical series (ECS), the ions selected to be discharged at the electrodes and the transfer of electrons at the electrodes.

Similar findings were discovered for items 3c and 3d in Tables 3 & 4 where students were asked to explain the reactions at the electrodes when copper electrodes are used (active electrodes) in aqueous copper sulphate solution. The students' performances were very weak where five classes obtained 0.0% of the 'scientifically correct' answer. The students were unable to explain the end products at the anode and cathode. The results are presented in Tables 3 and 4 shown below.

Table 3
Results of students' performance for item 3c

Class/Coding	SC	PC	O	N	Total (n)	% SC	% PC	% O	% NA
A	2	1	13	21	37	5.4%	2.7%	35.1%	56.8%
B	0	4	14	11	29	0.0%	13.8%	48.3%	37.9%
C	0	0	8	19	27	0.0%	0.0%	29.6%	70.4%
D	3	3	16	1	23	13.0%	13.0%	69.6%	4.3%
E	0	0	4	18	22	0.0%	0.0%	18.2%	81.8%
F	1	2	6	13	22	4.5%	9.1%	27.3%	59.1%
G	0	0	5	10	15	0.0%	0.0%	33.3%	66.7%
H	0	0	0	14	14	0.0%	0.0%	0.0%	100.0%

Table 4
Results of students' performance for item 3d

Class/Coding	SC	PC	O	N	Total (n)	% SC	% PC	% O	% NA
A	4	2	10	21	37	10.8%	5.4%	27.0%	56.8%
B	2	4	13	10	29	6.9%	13.8%	44.8%	34.5%
C	0	0	6	21	27	0.0%	0.0%	22.2%	77.8%
D	3	7	9	4	23	13.0%	30.4%	39.1%	17.4%
E	0	1	3	18	22	0.0%	4.5%	13.6%	81.8%
F	0	2	6	14	22	0.0%	9.1%	27.3%	63.6%
G	0	0	4	11	15	0.0%	0.0%	26.7%	73.3%
H	0	0	0	14	14	0.0%	0.0%	0.0%	100.0%

Referring to all the tables, the results indicate that for *partially correct* (PC) category, the percentage of students who were able to obtain partial points for the answers was also quite low. Furthermore, the results also show that many students did not attempt the questions as the percentages were quite high in non-attempted (NA) category in all four items. For instance, Class A and H had 70.3% and 92.9% respectively for the non-attempted category.

Discussions

Following the above results, students were found to have difficulties in generating detailed explanations of the chemical events, and students were also found to have difficulties relating the three entities, which are: macroscopic, sub-microscopic and symbolic even though it was not necessary for the students to present the symbolic entities (e.g. half cell equations). However, by providing the half cell equation in the responses to symbolize the chemical reactions; for example, in item 3b (the deposit of copper), the students showed good understanding of the learning area in addition to macroscopic observation and sub-microscopic explanation.

Furthermore, when the students were asked to explain why oxygen is produced at the anode, most of them were not able to explain the concepts that were necessary to successfully answer this question. For example:

Which ions move to the electrodes?

Which ions are selected?
What happens at the electrodes?
Which ions donate or receive electrons?

As discussed earlier, students were often found to be unable to generate a satisfactory explanation of the chemical event in the electrochemical cell due to confusion about the electrode terminology and the structure of the electrochemical cell. For example, they mistakenly identified 'anion' as a 'positive ion' where it should be a 'negative ion'. Another example is: 'anode is always a positive electrode'. In fact, some students were also confused with the terms such as 'anion', 'anode, 'cation' and 'cathode', resulting in difficulties explaining the movements of ions to the electrodes. Since the students did not understand the ions' selection at the electrodes based on ECS, the use of inert and active electrodes, and other related features connected to the terminology and the structure of the electrochemical cell; these may be the reasons why the students were unable to generate a detailed explanation of the chemical event such as the production of the gas bubbles and the ionisation of the metal electrodes.

Furthermore, most of the *scientifically correct* responses were very short and simple, and probably students may have difficulty generating detailed explanations in English as it is not their first language. However, there is not enough evidence to make this claim. For example, most students wrote statement such as:

'because OH^- is attracted to anode'

The above statement did not reflect the complete chemical reactions that occur in the electrolytic cell as it needs more elaboration on the chemical event.

The responses in the *partially correct* answers were very low as only one class (Class D) obtained about 30% for 2 items (items 3b & 3d) whilst the rest of the classes obtained less than 14% for *partially correct answer*. Furthermore, most responses coded as *other* (O) were mainly incorrect responses because most of the responses indicate that students experienced difficulties in generating explanations from the taught content; for example, explaining the concepts, the terms, and the chemical changes and reactions that occur in the electrolytic cell. In addition, as shown in the given tables above, there were many students who did not attempt the questions, which might be because they found the questions difficult; and it is also possible that they may not have taken the questions seriously because the test is not an examination paper.

Conclusion

As the students were provided with some hints on how to generate the answers, the results were quite unexpected; meaning that those students were expected to perform better. Furthermore, the questions were mostly adapted from the textbook, and the questions were aimed at ensuring students' understanding in the stated leaning objectives and learning outcomes as mentioned in the chemistry syllabus. From the results concerning the reactions at the electrodes as discussed above, it can be seen that most students were unable to explain how oxygen is produced at the anode (3c), or how the cathode gains mass (in 3d). Thus, these findings show that students did not understand the ions' selection at the electrodes based on ECS, or the end product when using inert and active electrodes, or familiar with the features connected to the terminology and the structure of the electrochemical cell in general.

Furthermore, many of the students were unable to generate detailed explanations of the chemical event such as the production of the gas bubbles and the ionisation of the metal electrodes.

The eight classes that were chosen as a reference group reflect typical schools in Malaysia who followed normal classroom teaching with the same content as stated in the chemistry syllabus. The findings in this study have provided some empirical evidence of many students facing conceptual difficulties in this learning area. This is a serious matter to be tackled in the classroom teaching and learning regarding a specific, difficult area in chemistry. It is also found that many students were unable to generate an explanation of the chemical event based on factual recall. Thus, the main difficulties that are faced by the students were not about developing misconceptions after they had been taught the topic; but rather the difficulties lie more with generating detailed explanations regarding the chemical event. Thus, some of the teaching and learning following the normal classroom may contribute to this problem. Also, from findings suggest that some typical classroom teaching and learning may be unsuitable for improving students' conceptual understanding in relating the three levels of representation in learning chemistry when connecting the macroscopic, sub-microscopic and symbolic entities. Thus, more detailed studies on designing a teaching on the electrolytic cell are required for improving students' conceptual understanding of the chemical reactions.

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