CHEMISTRY STUDENTS' DIFFICULTIES IN LEARNING OXIDATION-REDUCTION REACTIONS

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Abstract. The study explored students' learning difficulties in oxidation-reduction reactions at the senior high school level; as part of a major research project. The research approach for the project was a four-stage design-based research, using qualitative and quantitative methods. At the preliminary stage which is reported in this study, 213 third year students were sampled. All samples were selected through stratified and simple random sampling procedures. The students responded to a two-tier diagnostic test and interviews on conception of oxidation-reduction reactions. In analysing the data, descriptive statistics and themes were used. The findings show that students had conceptual difficulties in the form of alternative conceptions and other difficulties such as conceptualising oxidising agents using the combined concept of oxidation and ionic charge. It was therefore recommended that Chemistry teachers should deploy the most appropriate pedagogical content knowledge that could help students conceptualise very well the concept of oxidation number and not to confuse it with ionic charges of particles involve in chemical equations.

Keywords: alternative conceptions; difficulties; models; oxidation; reduction; reactions

Introduction

The formation of new substances which are different from the starting substances is associated with chemical change. The process through which new substances are formed as a result of chemical change is referred to as chemical reaction. There are several types of chemical reactions and these can be classified in more than one way. In one class of chemical reactions, oxidation numbers of atoms in the substance are changed. This is an oxidation-reduction reaction (Ameyibor & Wiredu, 1993; Bodner & Pardue, 1995; Chang, 2008). The oxidation-reduction reaction is commonly referred to as redox reaction.

The history of oxidation-reduction reactions is an interesting one. It started with the phlogiston theory (where all materials that can burn were said to contain phlogiston) through to the concept of Lewis (where atoms forming molecules were said to share electron pair). Österlund & Ekborg (2009) identified from the literature that there are four different models for the teaching and learning of oxidation-reduction reactions in Chemistry education. These models are oxygen model, which is loss of oxygen for reduction and gain of oxygen for oxidation; hydrogen model, which is gain of hydrogen for reduction and loss of hydrogen for oxidation; electron transfer model, which is gain of electrons for reduction and loss of electron for oxidation; and oxidation number model, which is decrease in oxidation number for reduction and increase in oxidation number for oxidation. These four models of oxidation-reduction reactions are currently being used by academic institutions for teaching the concept of oxidation-reduction reactions. Chang (2008) asserted that the concept of oxidation-reduction reactions was basically used to denote reactions involving oxygen but the concept has a much broader meaning to chemists in today's world. This is why academic institutions world over present the concept of oxidation-reduction reactions using the four models instead of the use of only the oxygen model.

High school Chemistry students from countries such as Gambia, Ghana, and Nigeria are examined by the West African Examination Council (WAEC) using a certain designed syllabus. In the WAEC Chemistry syllabus, oxidation-reduction reactions are considered as one of the important areas for member countries to focus on. In Ghana, from the WAEC syllabus, the planners of the senior high school (SHS) Chemistry syllabus consider oxidation-reduction reactions as one of the important reactions for students to learn. The Section 5 of the second year outline of the Ghanaian Chemistry syllabus has been assigned to the teaching of oxidation-reduction reactions (MOE, 2012).

In Ghana, there are two general objectives for the teaching and learning of oxidation-reduction reactions in the Chemistry Teaching Syllabus at the SHS level (MOE, 2010). These general objectives are the students will: "(1) understand the nature of oxidation-reduction reactions and apply its principles to electrochemical cells and (2) show awareness of corrosion as an oxidation-reduction process and its economic cost" (MOE, 2010). The implication of the first general objective is that there is the need for students to conceptualise the meaning of oxidation-reduction reactions in order to appreciate their usage in everyday life such as its usage in electrochemical cells. To achieve these two general objectives, the Section 5 of the second year aspects of the Chemistry syllabus is structured with six units sequenced as: "oxidation-reduction processes and oxidising-reducing agents; balancing of redox reactions; redox titrations; electrochemical cells; electrolytic cells; and corrosion of metals" (MOE, 2010).

The Unit 1 of the Section 5 of the second year aspects of the Ghanaian Chemistry syllabus is where the meaning of the chemical concept of oxidation-reduction reactions is taught and learnt. It could be seen from the Chemistry Syllabus that the concept of oxidation-reduction reactions is treated as addition and removal of hydrogen and oxygen; loss and gain of electrons; and change in oxidation state. The planners of the syllabus have then identified the four models of oxidation-reduction reactions and therefore require that students are given the opportunity to learn the four models at approximately the same time. However, when it comes to the evaluation aspects of the syllabus, the planners of the syllabus only asked that students "define oxidation and reduction in terms of electron transfer and oxidation numbers" (MOE, 2010). It could be inferred from this evaluation exercise that the planners of the syllabus have realised and appreciated the challenge the four models place on the door steps of students. It could also be inferred that the planners of the Chemistry syllabus appreciated that the electron transfer and oxidation number models can just help students to appreciate the concept of oxidation-reduction reactions. It could further be that for want of space, the planners of the Chemistry syllabus limited the number of evaluation questions raised.

According to Harrison & Treagust (1998), students are faced with the difficulty of and even at times confused with the conception of the four models of the concept of oxidation-reduction reactions. Barke (2012) has suggested that only one model of oxidation-reduction reactions should be taught at one particular time or the other and that the oxygen model of learning oxidation-reduction reaction should be avoided. This is because the oxygen transfer model has an appeal to students such that students most of the time conceptualise the oxidation-reduction reactions in terms of oxygen transfer model. However, it could be said that not all compounds are formed as a result of transfer of oxygen.

In Ghana, the WASSCE Chief Examiners' Report on Chemistry has continuously identified the concept of oxidation-reduction reactions as one of the difficult areas for most students (WAEC, 2004; 2005; 2006; 2007; 2008; 2009; 2011; 2012; 2013). For instance, in 2004, the Chief Examiner's Report explained that the candidates' performance under a question on oxidation-reduction reactions was poor. This is because the candidates could not identify the strongest oxidising and reducing agents in these three chemical equations:

$$Mg(s) + Zn^{2+}(aq) \rightarrow Mg^{2+}(aq) + Zn(s),$$
$$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s),$$
$$Cu(s) + Ag^{2+}(aq) \rightarrow Cu^{2+}(aq) + Ag(s)$$

(WAEC, 2004).

In 2005, the Chief Examiner's Report showed that some candidates could not determine the number of moles of electrons transferred in the chemical equation:

$$MnO_4^-(aq) + 4H^+(aq) + xe^- \rightarrow MnO_2(s) + 2H_2O(aq)$$

(WAEC, 2005). This so happened because the candidates could not balance the chemical equation. In 2006, the report revealed that the candidates could not arrange elements in the order of reactivity with respect to electrochemical series and that the candidates also had no practical experience in the area of oxidation-reduction reactions. In 2008, the Chief Examiner's Report showed:

> [I]n question 4 most of the candidates could not distinguish between oxidation and oxidising agents as well as reduction and reducing agent. Candidates were asked to define the terms oxidising agent and reducing agent in terms of electron transfer. However, most of them defined oxidising agent as a substance which adds oxygen. Rather oxidising agent is a substance which accepts electrons or electron accepter and reducing agent is a substance which donates electrons/electron donor (WAEC, 2008).

These reports suggest that students have difficulties in responding to examination questions on oxidation-reduction reactions at the high school level. There was therefore the need to find out students' learning difficulties in oxidation-reduction reactions to appreciate the alternative conceptions and other difficulties at the SHS level. The research question that guided the study was: what are the students' difficulties in learning oxidation-reduction reactions?

Research methodology

Research design

This research paper is taken from a major research project on improving students' conception in redox reactions, which adopted design-based research approach. The approach consisted of four stages. The first stage of the design-based research approach was the preliminary stage. At the preliminary stage, a number of activities were conducted including investigating difficulties of students in learning oxidation-reduction reactions. The preliminary stage adopted mixed methods using quantitative and qualitative approaches. A cross sectional survey design was used to collect and analyse quantitative and qualitative data. During the survey, a two-tier diagnostic test was used to collect data from SHS Chemistry students.

Sample and sampling procedure

The study was carried out in SHS in the Ashanti Region of Ghana. There were 30 Metropolitan, Municipal, and District Assemblies (MMDAs) in Ashanti Region. The population for the study was selected from schools in three out of the 30 MMDAs. In the three MMDAs, there were 14 public and one private SHS. From the 15 schools, science students (who offered Biology, Chemistry, Physics, and E-mathematics, referred to as elective science students in Ghana) were involved in the study. The target population for the study comprised all SHS 3 Chemistry students for the 2013/2014 academic year.

The 30 MMDAs were stratified into one Metropolitan assembly, seven Municipal assemblies, and 22 District assemblies. Three MMDAs were simple randomly selected (with one from among the Municipal assemblies and two from among the District assemblies). The Metropolitan assembly was excluded because it was a very large study area with large number of public and private schools. Also, schools from the Municipal and District assemblies were selected as the study areas because their characteristics were similar to those in the Metropolitan assembly.

The 15 schools were stratified into elective science and non-elective science schools. The elective science schools were seven in number and the non-elective science schools were eight in number (including the private school). Three schools were simple randomly selected from the seven elective science schools from the three MMDAs for the study.

The accessible population of SHS 3 students was 213. The population of students comprised high and low achieving; fast and slow learning; and male and female students. All the students in SHS 3 from the three randomly selected schools (A, B, and C) in the three districts responded to the diagnostic test assessing students' conceptual difficulties on oxidation-reduction reactions. The schools could be described as well-endowed (A); endowed (B); and less-endowed (C). The 213 students consisted of 83, 69, and 61 respectively from Schools A, B, and C. A 100 percentage sample selection of students was used and this became necessary as only three schools were involved in the study. This further helped minimized and accounted for the possibility of non-response attrition.

Research instruments

The research instrument for collecting data for the study was test in the form of diagnostic test. From Andriessen (2006), the diagnostic testing stage of design-based research approach provided an opportunity for assessing whether the practice problem was in line with the application domain for which an intervention was to be designed. Items on diagnostic test was constructed through the following means: First, the SHS Chemistry curriculum (MOE, 2012) was studied carefully to identify the various areas of oxidation-reduction reactions as outlined in the curriculum. The study of the curriculum further helped to appreciate the nature of evaluation exercises under oxidation-reduction reactions. After the study of the curriculum, some test items were constructed.

Teacher-made assignments, class exercises, and class tests on oxidation-reduction reactions for high school students from three of the elective science schools outside the study zone were also studied. This helped to identify test items used by the teachers and the profile dimension at which teacher-made test items were assessing. Of the teacher-made assignments, class exercises, and class tests, items at application of knowledge level of profile dimension were selected and reworded.

Literature on Chemistry Education in the area of oxidation-reduction reactions was then studied. From the review, some items were also collected from the literature on oxidation-reduction reactions (Barke, 2012; Chang, 2008; Osterlund & Ekborg, 2009). The test items collected from literature were reworded to suit the current study.

The diagnostic test consisted of 30 multiple choice items. Under each item, students were expected to provide reasons for the respective choice of response. The areas of the diagnostic test for the purposes of this paper were oxidation and reduction processes, oxidising and reducing agents, and half reactions. The diagnostic test structured in this form provided the study with quantitative data from the scores and qualitative data from the explanations written for each response provided. This helped to investigate students' conceptual difficulties in oxidation-reduction reactions. Each item scored 2 marks; 1 mark for the selection of correct option and other, for correct explanation given for the selection of the correct option.

To ensure the content validity of the test items, the items were constructed in such a way that the items covered identification of oxidation and reduction processes, half reactions, and everyday application of oxidation-reduction reactions. These areas were in line with the Chemistry curriculum (MOE, 2012). The test items were further compared to the standardised test items in the area of oxidation-reduction reactions set by WAEC. This further ensured the content validity of the test instrument.

The content of the test items was further validated by three seasoned WAEC Assistant Examiners teaching Chemistry at high school level and two experts in Instructional Design and Chemistry Education from the University of Cape Coast. The five individuals gave professional judgments about the relevance and sampling of the content of oxidation-reduction reactions to the intended purposes of the test instruments. Upon the critique and suggestions of the WAEC Assistant Examiners and the experts, five of the test items were dropped leaving 25 items. The items dropped were identify as too challenging and could be ambiguous to students at the SHS level.

The items on the diagnostic test were pilot-tested with 10 students selected by simple random sampling respectively from a class of 55 SHS 3 students from a high school in the Cape Coast Metropolis. The students involved in the pilot test were of such characteristics similar to those from the main study zone. After the pilot test, the test instrument was subjected to item analysis. The purpose of the item analysis was to establish the item difficulty and discrimination indices. This enhanced the internal consistency of the test instruments. During the test item analysis, all items that were found to be too difficult or too easy were deleted. KR-20 coefficient of reliability was calculated for the test instruments. The KR-20 was selected as there were unequal item difficult indices for items on the test instruments (Brennan & Lee, 2006). The KR-20 values assisted to determine whether the diagnostic test was reliable. After deletion of seven items from the diagnostic test, the KR-20 coefficient of reliability for the 18-diagnostic test item was calculated as 0.87. The value of KR 20 showed that the test instrument was reliable.

Data collection procedure

Permission was sought from the authorities of the schools where the study was conducted. The purpose was to enable author 1 asked for consent of the school authorities for the conduction of the study. This in one breath helped prevented any unforeseen interruptions that the study could have encountered from the authorities and the science teachers. The concerned authorities were further briefed on the purpose and the benefits of the study to the schools and Chemistry Education in the country as a whole. A briefing session on the purpose and various stages of the study was organised for Chemistry students. This helped the students to understand and appreciate what was expected of them during the study. The administration of the research instrument was performed by the researcher in the presence of school science teachers. The purpose was partly to ensure that students felt comfortable responding to the test items seeing their regular science teachers around.

The researcher administered the two-tier diagnostic test to students moving from School A to B and C in three respective days. In each school, the test was administered and collected in the same day of visit. The diagnostic test was scored immediately after the test administration to facilitate the calculation of the mean scores of students. With the help of the mean scores, students from each school were stratified into the below average, average, and above average groups for the group interactions with author 1 in the same week.

Data analysis

The research question was answered using percentages, means, standard deviations, and themes. In the analysis of the diagnostic test, which was a two-tier multiple choice test, percentages of students' correct responses and foils to each oxidation-reduction reaction test item were presented and discussed. In the discussion of students' scores, the description was broadened to cover the percentage-scores of the conceptual difficulties to the test items. The explanations given by students for each of the options in the diagnostic test were categorised and analysed under alternative conceptions and other conceptual difficulties using open coding and constant comparison. The themes so constructed were based on the interpretations the researcher gave to students' explanations to each test item.

Results and discussion

The research question sought to find out chemistry students' conceptual difficulties in oxidation-reduction reactions. The research question is in two parts. The first part sought to find out the students' difficulty in terms of performance using a diagnostic test. The mean score of students in the diagnostic test was 18.7 (SD = 8.1) with minimum and maximum scores of 2 and 36 respectively out of the total score of 36 marks. Two-thirds of the 213 students scored marks ranging from 10.6 to 26.8. The standard deviation of 8.1 is high indicating a wide spread of students' scores. A large number of students involved in the study could be said to have difficulties in responding to test items on oxidation-reduction reactions. The study confirms difficulties of students in oxidation-reduction reactions seen in the WAEC results (WAEC, 2004; 2005; 2006; 2007; 2008; 2009; 2011; 2012; 2013). Students' difficulty leading to their weak performance could be attributed to the confusion associated with the concept of the four models of oxidation-reduction (Harrison & Treagust, 1998) and could be seen from the presentation that follows.

Reduction half-reaction

Items 13 and 17 investigated difficulties in reduction half reactions. The items were less difficult as the difficulty index for each item was 0.8. For Item 13 which required students to identify the reduction half-reaction of the $Mg + Zn(NO_3)_2 \rightarrow Mg(NO_3)_2 + Zn$, majority of the students (76.5%) identified $Zn^{2+} \rightarrow Zn$ as the correct reduction half-reaction of the reaction, but 13.1% opted for $Mg \rightarrow Mg^{2+}$ as the reduction half-reaction, 2.3% opted for $Mg + Zn^{2+} \rightarrow Mg^{2+} + Zn$ as the reduction half-reaction, and 8.0% of the students opted for none of the three options.

For Item 17, 74.6% of the students correctly identified the reduction half-reaction of $Fe^{2+} + Cr_2O_7^{2-} \rightarrow Fe^{3+} + Cr^{3+}$ as $Cr_2O_7^{2-} \rightarrow Cr^{3+}$, but 16.0% opted for $Fe^{2+} \rightarrow Fe^{3+}$ as the reduction half-reaction and 9.4% failed to respond to Item 17. The results of Items 13 and 17 show that it was less difficult for the students to deduce the reduction half-reaction from a full or an ionic equation of oxidation-reduction reaction.

This means that though students have difficulty with the concept of oxidation-reduction reaction in general, deducing reduction half equations was less difficult for them. It could be that all the reduction half-reactions involved oxygen atoms. This is because students usually appreciate and conceptualize oxidation-reduction reactions best using addition and removal of oxygen model (Barke, 2012) and conceptual difficulties seen as: (i) alternative conceptions: reduction half-reaction involves loss of electrons. An excerpt is: "because $Cr_2O_7^{2-}$ losses electron and became Cr^{3+} which made it reduction half reaction". Reduction half-reaction involves decrease in oxidation state as a result of loss of electrons. An excerpt is: "$Zn^{2+} \rightarrow Zn$; because reduction half is the loss of electron. That is there is a decrease in oxidation state, from +2 state to +3 state". Reduction half-reaction involves reduction in ionic charge. An excerpt is: "because Zn^{2+} decrease to Zn. Meaning there is a decreased in the charges and that makes Zn^{2+} goes through reduction". Reduction half-reaction involves the released of 'positive' charges at the product side of reactions. An excerpt is: "$Fe^{2+} \rightarrow Fe^{3+}$; because it has release a charge of +3 at the product side"; (ii) *Other conceptual difficulties*: students had difficulty in conceptualising gain of electrons in reactions. It was considered as increased in the charge on atoms involved in reactions. An excerpt is: "Fe^{2+} has gain electron to form Fe^{3+} which means there is an increase in electron and is reduced".

Oxidation half-reactions

For Item 18, 75.1% of the students correctly identified the oxidation half-reaction of $Fe^{2+} + Cr_2O_7^{2-} \rightarrow Fe^{3+} + Cr^{3+}$ as $Fe^{2+} \rightarrow Fe^{3+}$, but 15.5% of the students opted for $Cr_2O_7^{2-} \rightarrow Cr^{3+}$ as the oxidation half-reaction and 9.4% of the students gave no response. For Item 14, 74.6% of the students correctly identified $Mg \rightarrow Mg^{2+}$ as the oxidation half-reaction of $Mg + Zn(NO_3)_2 \rightarrow Mg(NO_3)_2 + Zn$, but 13.1% of the students identified $Zn^{2+} \rightarrow Zn$ as the oxidation half-reaction and 1.4% of the students identified $Mg + Zn^{2+} \rightarrow Mg^{2+} + Zn$ as the oxidation half-reaction as well as 10.8% of the students failed to select an option as oxidation half-reaction. The results of Items 14 and 18 show that it was less difficult for students to identify the oxidation half-reaction from a full or an ionic equation. This is because the students can identify the reduction half-reactions and thereby the remaining of either full or ionic equation is the oxidation half-reaction.

Alternative conceptions: oxidation half-reactions involve decrease in oxidation number. An excerpt is: "because the oxidation number in the reactant side decreased after the equation at the product side".

Oxidation half-reactions involve gain of electrons. An excerpt is: "the one which undergoes oxidation is the oxidation half which has gain electrons; and change from 1 to +2 that is Mg^{+} to Mg^{2+}".

Oxidation half-reaction involves loss of oxygen atoms. An excerpt is: "$Cr_2O_7^{2-} \rightarrow Cr^{3+}$ because its oxygen has been taken out".

Oxidation half-reaction involves removal of oxygen and increase in oxidation state. An excerpt is: "in this reaction, $Fe^{2+} \rightarrow Fe^{3+}$; because there has been removal of oxygen and increment of oxidation number of iron".

Oxidation half-reaction involves gain of electrons to increase oxidation state of atoms. An excerpt is: "oxidation half is the gain of electrons. That is there is an increase in oxidation state of Mg from 0 state to +2 state".

Oxidation half-reaction involves gain of ionic charge. An excerpt is: "Mg has gain a charge of +2 in Mg^{2+}"; and "since the charge of Fe increase from +2 to +3".

Oxidation half-reaction involves decrease in ionic charges. The excerpts were: $Zn^{2+} \rightarrow Zn$; because it reduces a charge of +2 to zero" ; and "because zinc has reduced the charge of +2 to zero (0) charge".

Oxidation half-reaction involves increase in ionic charges. The excerpts were: "$Mg \rightarrow Mg^{2+}$; since the charge in the reactant has increased"; and "$Fe^{2+} \rightarrow Fe^{3+}$; because of the charge in the reactant has increased".

Oxidation half-reaction involves gain of electrons and oxygen atoms. An excerpt is: "$Mg \rightarrow Mg^{2+}$ is the answer because Mg gained electrons and also oxygen was added".

Other conceptual difficulties: students had difficulty deducing and explaining the oxidation state of atoms (substances) involved in oxidation half-reactions. Examples are: "$Mg \rightarrow Mg^{2+}$ because the oxidation number has increased at the product side"; and "Fe^{2+} is oxidation half because it increased in oxidation state".

Species oxidised

The Items 2 and 8 on oxidised species were difficult to the students. This is because the difficult index for this area was 0.5. For Item 2, 54.0% of students identified Zn as the specie oxidised in $Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$, but 16.4% identified $CuSO_4$, 15.0% identified $ZnSO_4$, 12.2% identified Cu as the specie oxidised in the reaction and 2.3% failed to provide the specie which was oxidised. The Item 6 was also used to find out the difficulty of the students in identifying a specie oxidised in $Cl_2 + 2Br^- \rightarrow 2Cl^- + Br_2$. The results show that 61.0% of the students found it very difficult to identify Br^- as the substance oxidised in the reaction and the difficulty index was calculated as 0.4. Out of the 61.0% students, 18.3% identified Cl_2, 4.7% identified Cl^-, 26.8% identified Br_2 as oxidised and 11.3% failed to provide any specie as oxidised in the reaction. The results of Items 2 and 6 show that it was difficult for the students to deduce species that were oxidised in oxidation-reduction reaction involving metals (that is substances formed through purely ionic bonding) but very difficult when substances involved were non-metals (that is substances formed through purely covalent bonding). This could be that the students found it difficult identifying which specie was causing another specie to oxidise (Österlund & Ekborg, 2009).

Alternative conceptions: oxidised species decrease in oxidation state. An excerpt is: "Cl_2 is oxidised as there is a decreased in its oxidation number".

Oxidised species accept electrons in reactions. The excerpts are: "the answer is Br^- because it accepts an electron to become Br_2"; and "Zn is oxidised because Zn has accepted electrons".

Oxidised species contain oxygen atoms. An excerpt is: "$ZnSO_4$; this is because there is an increase in oxygen. Oxidation is defined as the gain of oxygen".

Oxidised species loss oxygen atoms in reactions. The excerpt are: "Cu is oxidised because it decreased in the number of oxygen atoms"; and "$CuSO_4$ is oxidised because it has lost oxygen at the product side".

Oxidised species in reactions have oxygen atoms removed resulting in decreased in oxidation state of other atoms. The excerpts are: "Cu; this is because oxygen has being removed from it and thus has reduced in oxidation state"; and "Cl^-; this is because the oxidation state of it is reduced by the removal of oxygen from it making it oxidised".

Oxidised species accept electrons to decrease in oxidation state. The excerpts are: "$CuSO_4$ is oxidised because it decreased in oxidation number and accepted electron …"; and "Cl_2; this is because it has gained electron, and reduced in oxidation number".

Oxidised species increase in ionic charge. The excerpts are: "Cu; because from the reactant side, the charge of $CuSO_4$ equals 0 but at the product side Cu is not equal to 0"; and "Br_2 is the answer because in the reactants Br has a charge of -2 but in the products Br has a charge of +2".

Oxidised species gain electrons to increase ionic charge. An excerpt is: "$CuSO_4$ is oxidised because it will be the one which will be gaining electron to increase charges from the others".

Oxidised species loss electrons to change ionic charges. An excerpt is: "Br^- is the answer; because it lost electron to change its charge to neutral".

Oxidised species accept hydrogen atoms and lose oxygen atoms. The excerpts are: "Zn; because oxidation is the substance that accepts hydrogen and donates oxygen in a redox reaction" (176); and "Cl^- is oxidised and it losses oxygen and will gain hydrogen".

Other conceptual difficulties: student consideration of the moles as having effect on the oxidation state of atoms in reactions. The excerpts are: "$2Br^-$ undergoes oxidation by increasing in oxidation number from -2 to 0 but increase in oxidation defined oxidation".

Students had difficulties in seeing that the atoms in the reactant side transfer electrons but not those in the product side of reactions. An excerpt is: "the answer is Br_2 because of $2Br^- \rightarrow Br_2 + 2ě$. Since the Br_2 gains electrons, it becomes oxidised".

Student had difficulty in seeing that atoms (substances) at the reactant side are oxidised by increasing in oxidation state but not those at the product side of reactions. The excerpts are: "the answer is Br_2 because there is an increased in oxidation number"; and "$ZnSO_4$ is the correct answer because the oxidation number has been increased from 0 to +2".

Students had difficulties in using the combined concept of oxidation state and electron transfer to conceptualise oxidised species. An excerpt is: "oxidation is the removal of electrons and Cl_2 has lost electrons to become Cl^- with 0 oxidation state".

Species reduced

For Item 7, 48.4% of the students found it less difficult to identify Cl_2 as the substance reduced in $Cl_2 + 2Br^- \rightarrow 2Cl^- + Br_2$, but 15.5% identified Br^-, 16.9% identified Cl^-, 8.9% identified Br_2 as the specie reduced in the reaction and 10.3% of the students failed to provide any specie they thought was reduced. Item 3 on reduced species was very difficult with calculated index of 0.3. The results show that only 31.9% of the students identified Cu^{2+} in $CuSO_4$ correctly as the substance reduced in $Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$, but 22.5% identified Zn, 5.2% identified $ZnSO_4$, 36.6% identified Cu as the substance reduced and 3.8% of the students provided no specie as reduced in the reaction. The results of Items 3 and 7 show that it was very difficult for students to identify species reduced in full or net ionic equations as well as substances involve in reactions of ionic bonding or covalent bonding. This could be that the students found it difficult to identify the specie in the reaction causing the reduction contrarily to that being reported elsewhere that students find it easy to identify reducing agents (Osterlund & Ekborg, 2009).

Alternative conceptions: reduced species increase in oxidation state. An excerpt is: "Cl_2 has increased in oxidation state at the product side thus Cl_2 is said to be reduced in the reaction".

Reduced species lose electrons in reactions. An excerpt is: "Cl^- is reduced because it was neutral at the reactant side and it lost electron at the product side and became Cl^- which made it reduced".

Reduced species lose electrons to change ionic charges. An excerpt is: "$ZnSO_4$ will be my answer. This is because it has lost electrons to change the charge to +2".

Reduced species lose electrons as a result of loss of oxygen atoms. An excerpt is: "Br_2 is the answer because it loss electrons from loss of oxygen".

Other conceptual difficulties: students had difficulty in identifying that the atoms (species) in the reactant side of reactions were reduced instead of the product side. The excerpts are: "$ZnSO_4$; because it is decreasing in oxidation number"; and "Br^-; is reduced in this reaction, because of the decreased in oxidation state from $2Br^-$ to Br_2".

Students had difficulty in seeing that a positive charge was indication of loss of electron but not gain of electron. An excerpt is: Zn; $Zn \rightarrow Zn^{2+}$ which means Zn has gain electron and hence is reduced and from the definition, reduction is the gain of electron".

Students had difficulty in conceptualising reduced species as species from which oxygen atoms were removed. That is what should be considered as removal of oxygen atoms. An excerpt is: "$ZnSO_4$; because 4 oxygen atoms can be removed from the compound to get ZnS".

Students had difficulty in conceptualising the transfer of hydrogen model as the concept was used even when there was no hydrogen atoms directly involved in the reactions. An excerpt is: "Cl^- is the answer because it gains hydrogen from the reactants to form Cl^- in the products".

Students had difficulty in conceptualising species reduced in reactions using the combined concept of oxidation state and electron transfer. The excerpts are: "Zn; at the reactant side have no oxidation number but at the product side have gain electrons"; and "Br^-; this is because it has lost electron, and increased in oxidation number".

Students had difficulty conceptualising reduced species using ionic charge. The excerpts are: "Zn; comparing Zn and $ZnSO_4$ with respect to charges, Zn is not equal to 0 but $ZnSO_4$ equals to 0"; and "Br^-; the charge is increased from 0 to -2.

Reducing agents

Item 5 was difficult with an index of 0.5. This is because 46.5% of the students identified Zn as the reducing agent in $Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$, but 16.9% identified $CuSO_4$, 6.1% identified $ZnSO_4$, and 21.6% identified Cu as the reducing agent and 8.9% of the students provided no response as the reducing agent of $CuSO_4$ in the reaction. For Item 9, 41.8% of the students found it less difficult to identify Br^- as the reducing agent of $Cl_2 + 2Br^- \rightarrow 2Cl^- + Br_2$ with item difficulty index calculated as 0.4. However, 23.5% of the students identified Cl_2, 13.6% identified Cl^-, and 8.9% identified Br_2 as the reducing agent and 12.2% of the students could not provide any response as the reducing agent. The results of Items 5 and 9 show that the students found it difficult and not easy to identify the reducing agent from any given oxidation-reduction reaction (Osterlund & Ekborg, 2009). This could be the reason why the students found it difficult to deduce any substance reduced in a given oxidation-reduction reaction as seen above.

Alternative conceptions: reducing agents are species that have their oxidation state reduced in reactions. The excerpts are: "Cl^-; is a reducing agent because it has reduced in its oxidation state"; and "$ZnSO_4$; it is a reducing agent because it decreases in oxidation number".

Reducing agents are atoms (species) that accept electrons in reactions. The excerpts are: "Br^-; because of addition of electrons to Br^-"; and "$CuSO_4$; is reducing agent because it has gain electron".

Reducing agents are species in reactions with no oxygen atoms bonded to. An excerpt is: "my answer is Zn and Cu as they have no oxygen but they take oxygen later".

Reducing agents cannot accept hydrogen atoms because they have already increased in oxidation state. An excerpt is: "the answer is $CuSO_4$ because it cannot take on hydrogens because the oxidation number of Zn had increased".

Reducing agents accept electrons and lose oxygen atoms. The excerpts are: "Zn; addition of electrons and loss oxygen atom to a substance makes it a reducing agent"; and "Br_2; there is removal of oxygen and it's gaining electron".

Other conceptual difficulties: students had difficulty in using the combined concept of oxidation state and transfer of oxygen atoms. The excerpts are: "Zn is reducing agent because it caused element to undergo oxidation process thereby making the element accept oxygen and also increase the oxidation state of that element".

Students had difficulties in conceptualising reducing agents using the concept of oxidation number and electron transfer. An excerpt is: "the answer is Br_2 because it accepts electrons produced from Cl_2 making Cl_2 reduced. That is Br_2 decreased in oxidation number".

Students had difficulties in conceptualising reducing agents using ionic charge. An excerpt is: "Cu on the reactant side has a charge of +8 by calculation but on the product side Cu has a charge of zero (0) and it is therefore reducing agent".

Students had difficulties in conceptualising reducing agents as atoms (species) oxidised in reactions. The excerpts are: "$CuSO_4$ is a reducing agent because it causes the reduction of Zn and is oxidised itself"; and "Cl_2; because Cl_2 has oxidised and reducing agent is a substance in a redox reaction that undergoes oxidation".

Oxidising agent

For Item 4, only 38.0% of the students found it less difficult to identify $CuSO_4$ as the oxidising agent of Zn in $Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$ with item difficulty index of 0.4. However, 22.5% of the students identified Zn, 15.0% identified $ZnSO_4$, 16.9% identified Cu as the oxidising agent, and 7.5% of the students failed to identify any of the species as oxidising agent. Item 8 had difficulty index of 0.5 and 44.6% of the students identified Cl_2 as the correct oxidising agent in $Cl_2 + 2Br^- \rightarrow 2Cl^- + Br_2$, but 22.1% identified Br^-, 8.0% identified Cl^-, 11.3% identified Br_2 as the oxidising agent, and 14.1% of the students could not identify any species as the oxidising agent. The results of Items 4 and 8 show that it was difficult for the students to identify an oxidising agent (Österlund & Ekborg, 2009) in a full or net ionic equation as well as purely covalent or ionic boning forms of oxidation-reduction reaction.

Alternative conceptions: oxidising agents help to deduce the oxidation state of atoms in oxidation reactions. An excerpt is: "Br^- is an agent helping us to find the oxidation state of oxidation reactions".

Oxidising agents are atoms (species) oxidised by loss of electrons. The excerpts are: "$CuSO_4$; because it was oxidised at the reactant side and losses it electron at the product side, thus it made the Zn oxidised which makes it an oxidising agent" (104); and "Cl_2; it oxidises (ie, give out electrons to the $2Br^-$ on the reactant side, and oxidising agent donates electrons".

Oxidising agents accept oxygen atoms to result in change in oxidation state. The excerpts are: "$ZnSO_4$; because it received the oxygen so therefore is the oxidising agent. This is because in Zn the oxidation number was +2 but in $ZnSO_4$ its oxidation number is 0" (207); and "Br_2 is oxidised due to the addition of oxygen that caused increased in its oxidation state".

Oxidising agents donate electrons and oxygen. The excerpts are: "$CuSO_4$; it has lost SO_4^{2-} to Zn atom. Removal of oxygen atom"; and "Br^-; there is an addition of oxygen and its gaining electron".

Other conceptual difficulties: students had difficulty in identifying oxidising agents using the concept of oxidation numbers. An excerpt is: "Br_2 is an oxidising agent because its oxidising number decreased from +7 to 0".

Students had difficulty in seeing atoms that gain electrons in reactions. An excerpt is: "Br_2; it has gain electron".

Students had difficulty using ionic charge to conceptualise oxidising agents. The excerpts are: "Cu; it has charge of positive which make it oxidising agent"; and "Br^-; because it has reduced the charge of Cl_2^+ to $2Cl^-$".

Students had difficulty conceptualising oxidising agents using the combined concept of oxidation and ionic charge. An excerpt is: "Cu; because in the reactants copper has an oxidation number of 0 but in the products it has a charge of +2".

Students had difficulties in conceptualising oxidising agents as atoms (species) reduced in reactions. The excerpts are: "$ZnSO_4$ is an oxidising agent in the reaction because it is reduced"; and "Br^- because the oxidising agent is the one which is reduced in the reaction".

Identification of oxidation-reduction reactions

Item 1 had a difficulty index of 0.4 and only 36.6% of the students found it less difficult to identify $2HCl + Zn \rightarrow ZnCl_2 + H_2$ as an oxidation-reduction reaction from a given number of reactions. However, 36.2% of the students identified $2HCl + ZnO \rightarrow ZnCl_2 + H_2O$ and 19.2% identified $2HCl + Zn(OH)_2 \rightarrow ZnCl_2 + 2H_2O$ as oxidation-reduction reactions which was not necessary the case and 8.0% of the students failed to identify any of the three reactions as oxidation-reduction reactions. The results of Item 1 show that students had a difficulty in even identifying a reaction which is an oxidation-reduction oriented. This could be attributed to the fact that there was no oxygen in the reaction which was oxidation-reduction oriented as compared to the other two.

Alternative conceptions: the presence of oxygen atoms in reactions makes such reactions oxidation-reduction reaction. An excerpt is: "Zn was first ZnO but it turned into $ZnCl_2$ showing loss of oxygen and hence it is a redox reaction and also it has gain oxygen".

The presence of hydrogen atoms in reactions makes such reactions oxidation-reduction reactions. An excerpt is: "because 2HCl has lost the hydrogen to form $ZnCl_2$ in $2HCl + Zn(OH)_2 \rightarrow ZnCl_2 + 2H_2O$".

In reactions, removal of oxygen atoms from species results in oxidation state of the other atoms. An excerpt is: "the reaction $2HCl + ZnO \rightarrow ZnCl_2 + H_2O$ is a redox reaction because there is an increase in the oxidation number of hydrogen because of removal of oxygen".

Other conceptual difficulties: students had difficulty in determination of the correct oxidation state of atoms involved in a given reaction. The excerpts are: "because the oxidation number of Zn decreases from -2 to +2", and "because Cl changes from -2 in HCl to +1 state in $ZnCl_2$ and Zn changes from 2".

Students had difficulty in explaining the change in oxidation state of species being reduced or oxidised in a reaction. An excerpt is: "there is changed in oxidation number of HCl and $ZnCl_2$".

Students had difficulty in conceptualising oxidation-reduction reactions using the oxygen transfer model. It was used even when there were no oxygen atoms involved in the reactions. An excerpt is: "$2HCl + Zn \rightarrow ZnCl_2 + H_2$ is a redox reaction because oxygen is not in or oxygen has been removed from it".

Students conceptualised oxidation-reduction reactions as simultaneous reactions of oxidation and reduction processes but had difficulty in showing both processes in the given reactions. The excerpts are: in $2HCl + Zn(OH)_2 \rightarrow ZnCl_2 + 2H_2O$, "redox reaction is when both oxidation and reduction are occurring simultaneously"; and "because it has both oxidation and reduction".

The results show that students had conceptual difficulties in learning oxidation-reduction reactions. The conceptual difficulties were most evident as alternative conceptions. These alternative conceptions were in (i) identification of oxidation-reduction reactions, (ii) oxidised and reduced species, (iii) oxidation half-reactions, and (iv) reduction half-reactions. The alternative conceptions, such as reduction half-reaction involves loss of electrons; oxidation half-reaction involves decrease in oxidation number; oxidised species contain oxygen atoms; and reduced species lose electrons as a result of loss of oxygen (Osman & Sukor, 2013). This is because oxidation state (number), electron transfer, oxygen and hydrogen transfer are models of oxidation-reduction reactions which are learnt in the classroom.

Students' alternative conceptions were partly due to students' use of the concept of loss and gain of oxygen or hydrogen. Students used these concepts to conceptualise reactions where there was no change in the oxidation state of the atoms involved or transfer of electrons as oxidation-reduction reactions. This means students felt comfortable using the loss and gain of oxygen or hydrogen models of oxidation-reduction reactions (Barke, 2012).

Students' conceptual difficulties in terms of alternative conceptions such as reducing agents accept electrons and lose oxygen atoms; oxidising agents accept oxygen atoms to result in change in oxidation state; and oxidised substances accept electrons to increase ionic charge and other conceptual difficulties were due to the use of combined concepts of the four models of oxidation-reduction reactions. The combined concepts included oxidation number and electron transfer; oxidation number and oxygen transfer; electron transfer and oxygen transfer; oxidation number and ionic charge; and electron transfer and ionic charge. This could be due to misunderstanding, miseducation or misapplication (Wenning, 2008) of the four models of oxidation-reduction reactions. Hence, students were confused in using more than one model of oxidation-reduction reaction (Harrison & Treagust, 1998) to conceptualise any aspects of chemical reactions.

Other conceptual difficulties existed in identifying a particular reaction as an oxidation-reduction type, a specie as oxidised or reduced, and as oxidising agent or reducing agent using the four models of oxidation-reduction reactions. In the case of oxidation number, students could not explain which atom (specie) was decreasing or increasing in oxidation state and even where they were able, the students cannot determine the correct oxidation state of the atoms. In situations where the given reaction was not oxidation-reduction reaction or the given specie was not oxidised or reduced, and not oxidising agent or reducing agent students made explanations by just saying the oxidation state of the atom has changed, decreased, or increased. This shows that it is difficult for students to conceptualise oxidation-reduction reaction using the oxidation number.

It was difficult for students to conceptualise oxidation-reduction reactions in terms of electron transfer (De Jong et al., 1995) and even notwithstanding the number of times they did try they still had difficulty in explaining oxidation-reduction reaction using the concept of electron transfer (Österlund & Ekborg, 2009). Though the use of the concept of transfer of electrons led some students to identify a given reaction as oxidation-reduction reaction and to deduce species being oxidised or reduced as well as oxidising or reducing agent in reactions, in most instances they could not explain the concept of transfer of electrons very well. That is the number of electrons transferred and the direction of the electron flow (that is gaining or losing electrons) to achieve such results. The chemistry is that the gain or loss of electrons should be from the reactant side to the product side of the chemical equation so represented.

Students' conception of oxidation-reduction reaction as a simultaneous reaction involving oxidation and reduction processes was interesting to note. Students, however, shared conceptual difficulties. This is because in most instances students could not explain where the oxidation or the reduction was but only justified that the identified reaction was a simultaneous reaction. This seems to suggest that the students conceptualise oxidation-reduction reactions as reactions where the oxidation and reduction reactions occur at the same but not as reported elsewhere that students' difficulties in oxidation-reduction reaction are as the result of the fact that they consider oxidation and reduction processes as mutually exclusive reactions (Österlund & Ekborg, 2009).

The results further show that students conceptualised oxidation and reduction processes using ionic charge. This concept contributed to students' alternative conceptions and other conceptual difficulties. The difficulty here was that students cannot distinguish between oxidation number and ionic charge of species involve in reactions. It must be emphasized that in some simple ions the oxidation number and the ionic charge were the same but in complex ions such as the oxoanions they are not. It was also evident that students had difficulty in conceptualising moles of substances in a balanced chemical equation which wrongfully influence their determination of the oxidation number or ionic charge of species in chemical reactions.

Conclusions

The study has shown that students' conceptual difficulties in the form of alternative conceptions and other conceptual difficulties (such as reduction half involves loss of electrons, oxidation half involves decrease in oxidation state, oxidised substances decrease in oxidation number, and reduced substances loss oxygen to result in loss of electrons) exist in learning of oxidation-reduction reactions. This is consistent with the findings of Adu-Gyamfi et al. (2015) who showed that students' alternative conceptions exist on the introduction of H_2O, H^+, and OH^- into balancing of oxidation-reduction reactions. The current study has added to the literature on students' alternative conceptions and other conceptual difficulties on oxidation-reduction reactions with the use of the four models (oxidation number, electron transfer, addition and removal of oxygen, and addition and removal of hydrogen) approach.

Studies on oxidation-reduction reactions have shown that students have difficulty in conceptualising oxidation-reduction reactions using the concept of electron transfer (Österlund & Ekborg, 2009) and the difficulty with electron transfer is conceptualising the direction of flow of electrons. Students have an appeal for conceptualising oxidation-reduction reaction using the loss and gain of oxygen (Barke, 2012). The current study has added that not only is the oxygen transfer model appealing to students but the hydrogen model is also appealing to students as they conceptualise oxidation-reduction reaction in terms of transfer of hydrogen atom even when the hydrogen atom has no direct influence on the formation of new substance. Students' alternative conceptions and other conceptual difficulties on oxidation-reduction reactions using the oxidation number model are due to the difficulty in deducing correctly the oxidation state of the atoms of the substances involved in reactions. The current study has shown that students conceptualise charge of ions as the oxidation state of the atoms involved in the reaction but this is only possible when the substance is a simple ion such as Cl^-, Br^-, or Cr^{3+} but not for oxoanion such as $Cr_2O_7^{2-}$ or SO_4^{2-}. This could imply that a 'false' fifth model (ionic charge model) of oxidation-reduction reactions is evolving.

The study has further showed that there are instances when students are confused about the use of the four models of oxidation-reduction reaction (Harrison & Treagust, 1998). The study has shown even in using just two of the four models is a source of students' alternative conceptions and other conceptual difficulties on the aspects of oxidation-reduction reactions used in the current study. The following are such combinations: oxidation number and transfer of electrons, transfer of electrons and ionic charge, loss/gain of oxygen and hydrogen, oxidation number and ionic charge, and oxidation number and loss/gain of oxygen. The rest are oxidation number and loss/gain of hydrogen, transfer of electron and loss/gain of oxygen, and transfer of electron and loss/gain of hydrogen.

The study has disconfirmed that the difficulty of students in oxidation-reduction reactions is their failure to conceptualise that in this type of reaction oxidation and reduction reactions occur simultaneously (Österlund & Ekborg, 2009). The current study has added that students have less or no difficulty identifying a reaction as oxidation and reduction processes simultaneously but the difficulty is how to identify and explain the simultaneous nature of oxidation and reduction processes to justify that a particular reaction is of that type.

Recommendations

As students' conceptual difficulties in terms of alternative conceptions exist using the addition and removal of oxygen atoms and the oxygen transfer model being appealing students, it is therefore recommended that Chemistry educators and researchers should conduct further studies to ascertain how best the concept of transfer of oxygen and hydrogen in oxidation-reduction reactions could be presented to students to ease the difficulty associated with their use.

Since students conceptualise charge of ions as simply the oxidation number of the atoms involved, which is only possible in simple ions but not in oxoanions, it is therefore recommended that Chemistry teachers should deploy the most appropriate pedagogical content knowledge that could help students conceptualise very well the concept of oxidation number and not to confuse it with ionic charges of particles involve in chemical equations.

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