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Advanced Level Chemistry Students' Understanding of Stoichiometry: Evidence from Four Schools in Zimbabwe.

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Abstract

This study surveyed Zimbabwean Advanced Level chemistry students' understanding of stoichiometry and related concepts. The methods of exploring students' understanding consisted of paper and pencil surveys (two-tier multiple-choice items) and interviews. Four schools of the thirteen (13) high schools offering Advanced level chemistry in Masvingo province were purposively sampled. All the one hundred and three (103) students in the four sampled schools participated in the study. Simple descriptive statistics was used to analyse data. Some of the surveyed students revealed some unique misconceptions of stoichiometry and related concepts while other findings were consistent with those from earlier studies conducted in other countries. Students had difficulty with: (i) coefficients and subscripts (ii) interpretations of representations in equations and formulae (iii) understanding of molar quantities (iv) comprehension and identification of limiting reagents and (v) solving reaction efficiency problems. The sources of these difficulties are largely attributed to the lack of understanding of fundamental stoichiometry concepts and meta language of expression. Further research in unexplored areas such as, the influence of the school factor on the type and complexity of misconceptions is recommended.

Keywords: Advanced level, High school, Learning, Misconceptions, Stoichiometry, Students

Introduction

Students learning chemistry have many difficulties in understanding the concepts involved because of the complexity of chemistry itself (Gabel, 1998; Calyk, Ayas and Ebenezer, 2005). The concepts involved in chemistry are closely related to each other and understanding of the concepts depends on prerequisite knowledge gained in stoichiometry. Therefore, students with difficulties in learning chemistry may have more of conceptual blocks as their barrier to learning than lack of facts (Garner, 1992). According to Schmidt (1997), conceptions can either reinforce each other or act as barriers to further learning. Misconceptions are viewed as conceptions that deviate from existing scientific ideas and act as barriers to further learning (Zoller, 1990). Misconceptions may arise from students' inadequate and incorrect conceptual knowledge (BouJaoude, 1994; Mas, Perez and Harris, 1987).

There are many diverse terms used to describe the various conceptions held by students. These include, "misconceptions" (Bodner, 1986; Griffiths and Preston, 1992), "alternative frameworks" (Driver, 1981; Skelly and Hall, 1993), "children's science" (Gilbert, Osborne, and Fensham, 1982), and "preconceptions"

(Novak, 1977). There is no consensus amongst researchers regarding the appropriate term to use. The term misconception is used in this study. A variety of students' sources of misconceptions and possible reasons have been put forward (Skelly and Hall, 1993; Yip, 1998; De Jong, 1995; Schmidt, 1999; Schmidt, et al., 2003; Evans and Hestenes, 2001; Kikas, 2004). These are classified as the complexity of stoichiometry content itself (Gabel, 1998), experiential and instructional (Skelly and Hall 1993).

The complexity of stoichiometry content may be attributed to students' difficulty in the conceptualisation of stoichiometry concepts as it demands the integration of "sub-microscopic," "macroscopic" and "symbolic" levels (Gabel, 1998; Harrison and Treagust, 2000; Treagust, *et al,*2003). Consequently, if students possess difficulties at one of the levels, it may influence the other. For example, students who assume that substances always react in a 1:1 ratio consequently make different types of errors in areas of chemical formula, balancing chemical equations, stoichiometry ratios as well as in calculations (Dennistron, 2001). However, it may be argued that misconceptions arising from the complexity of stoichiometry content may be minimized through effective instruction.

Instructional misconceptions relate to classroom practices whilst experiential misconception ideas arise from the students' everyday experiences and language use. Nakhleh (1992), Schmidt (1997) and Sherpard (1997) posit that many misconceptions held by students are largely attributed to the lack of proper introduction of fundamental chemical concepts. Lawson (1988) argues that misconceptions in more complex or abstract chemistry concepts such as stoichiometry are most likely linked to instruction, as according to Skelly and Hall (1993), the existence of atoms and molecules is not directly within the realm of everyday experience. Kikas, (2004) noted that teachers often pass their misconceptions inadvertently to their students.

Stoichiometry concepts are fundamental and central in chemistry learning (Chanyah and Coll, 2007; Schmidt and Jigneus, 2003). The concepts of stoichiometry provide the prerequisite knowledge to the understanding of topics such as solution chemistry, acids and bases, electrochemistry, bonding and chemical equilibrium. If students fail to grasp stoichiometry concepts and develop misconceptions they will find subsequent learning of other chemistry concepts arduous (Sherpard, 1997). Inquiring into students' conceptions of the stoichiometry concepts becomes significant in view of the fact that stoichiometry is a central topic to the school chemistry curriculum.

Although several studies on students' misconceptions in chemistry exist (Bradley, Berrans and Long, 1990; Renstrom, Anderson and Marton, 1990; Barnerjee, 1991; Garnett, Garnett, and Hackling, 1995; Treagust, Chittleborough, and Mamiala, 2003; Michelene, 2005) there has not been much research in stoichiometry. Studies on students' misconceptions in stoichiometry have reported that many middle and high school students find stoichiometry and related concepts difficult to comprehend (Heron and Greenbowe, 1996; Schmidt and Jigneus, 2003; Michelene, 2005; Kolobe, 2007). However, most studies on students' conceptions of stoichiometry concepts exist within the developed nations, with much less in non-western countries (Chanyah and Coll and Coll; 2007). Furthermore, in Zimbabwe public examination reports have revealed stoichiometry and related concepts as a recurrent source of problem to many A-level chemistrystudents (UCLES, 1994; 1998; 1999; 2000; 2001). Thus it became imperative to look into and understand the profiles of students' stoichiometry learning difficulties in the context of Zimbabwe.

To achieve the primary motive of study, answers to the following research questions were sought.

1. What are students' common conceptions and difficulties in stoichiometry?
2. What attributes to common stoichiometry misconceptions held by students?

This study has much value to chemistry education researchers, teachers, curriculum developers, and policy makers. The study will give researchers insight into the students' common conceptions and difficulties in stoichiometry. Curriculum developers may use the information as a basis for designing contextually relevant instructional approaches, teaching activities and resources (Treagust, 1988; Blanco and Prieto, 1997). The difficulties encountered by students in understanding stoichiometry concepts are categorised in some meaningful form so that teachers may be able to predict difficulties and proactively design teaching strategies to help students overcome problematic areas.

Research methodology

The study was conducted in Masvingo Province in Zimbabwe during the period January to April 2007. The focus of the study of gaining insights into students' conception of stoichiometry necessitated the purposive sampling (Bogdan and Biklen, 1998) of four schools from a total of thirteen (13) high schools offering Advanced level (A-level) chemistry in the Province. The number of schools offering A-level chemistry was determined from a list provided by the Masvingo Provincial Education Office. The four schools were selected based on set criteria of enrollment, reputation, establishment and teacher experience as well as qualification as desired by purposive sampling.

A chemistry enrollment of twenty (20) or above upper sixth students was considered to provide a relatively large sample size from which insights into students' understanding of stoichiometry are reasonably assessed. A provincial ranking of seven and below in the A-level provincial 2007 chemistry public examination performance according to the Zimbabwe School Examination Council (ZIMSEC) as well as a percentage pass rate of ninety (90%) and above was used. The establishment considered was the offering of A- level chemistry for more than ten years and an A-level chemistry teacher experience of at least two years with a professional qualification was also taken into account. The thirteen schools were ranked in accordance with each criterion and the four schools which best suited the criteria were selected. A total of one hundred and three (103) upper sixth students from the four schools participated in the study.

Students' conception of stoichiometry was mainly surveyed using a researcher developed and pilot tested two-tier pencil and paper stoichiometry multiple-choice test. To ensure reliability of the test, standardised items were selected from literature at the discretion of the authors' experiences of teaching stoichiometry at A-level. Literature consulted included previous studies for students' age range of 17 to 20 years, A-level chemistry textbooks and past examination (ZIMSEC, ULCESS) papers and reports. The test items were brainstormed by the researchers and two ZIMSEC A-level chemistry item writers, pilot studied and items redesigned in an effort to ensure validity of the data collected by the test.

The first tier consisted of only one scientifically correct answer from the two to four alternatives provided. Alternative answers were common misconceptions revealed either from previous studies or common errors from the public examination board reports. The second tier called for justification of the choice that probed the learners' reasoning processes and causes of conceptual problems (Hernadez and Caraballo, 1993; Odom, 1995).

The test was administered to all the one hundred and three (103) upper sixth students doing chemistry in the year 2007 in their respective schools on the same day at the same time. Each student was given a coded question paper which enabled the researchers to identify and trace the student where it was deemed necessary. Each student submitted the answer script after writing the test for as long as he/she needed to work. This enabled each student to answer the questions to the best of his/her ability. Students took thirty (30) minutes to two (2) hours to complete the test. On average the students took about forty five (45) minutes to complete the test. Individual submission of scripts ensured a hundred percent return of the test scripts. The average completion rate per test item was ninety five percent (95%). The test was invigilated by one of the researchers under normal class conditions which provided the students with a natural setting (Bogdan and Biklen, 1998) where the students worked individually in a relaxed atmosphere.

A preliminary data analysis of the marked scripts was necessary to identify types of stoichiometry misconceptions held by the participants and possible causes of such conceptual problems. The data analysis involved determination of the frequency distribution of the responses of the first tier of each item to identify types of errors and misconceptions and was based on Birk and Kurtz's (1999) proposition that any incorrect option chosen by at least 10% of the students revealed some kind of noteworthy misconceptions. The open-ended section of each item was analysed to understand the reasons behind the identified levels of understanding. Some students left blank spaces on the second tier while other students' explanations lacked clarity and necessitated further probing into the students' reasoning processes and causes of conceptual problems through interviews. The time lapse between writing tests and follow-up interviews was three weeks.

Findings from the preliminary analysis guided the formulation of interview questions and identification of interviewees. Twelve students who had common misconceptions with all other participants were interviewed individually. While an interview schedule was used, the interviewer remained flexible and responsive to the students' reasoning.

Results

Table 1 summarises the study results.

Table 1: Students' response to stoichiometry concept items

	Percent Response					
			Incorrect			
Item	**Correct**	**NR**	**Alternative**			**Total**
1.Coefficients and subscripts	D 67.0	0.0	A 5.8	B 22.3	C 4.9	**33.0**
2 Limiting reagent	B 27.2	4.8	A 13.6	C 49.5	D 4.9	**68.0**
3.Molar quantity	A 69.9	3.9	B 12.6	C 12.6	D 1.0	**26.2**
4.Reaction efficiency	D 43.7	2.9	A 15.5	B 31.1	C 6.8	**53.4**
5.Formulae and equations	C 23.4	7.9	A 20.7	D 38.4	*	**59.1**
6.Limiting reagent	A 21.4	22.3	B 32.0	C 13.6	D 10.7	**56.3**
7 Coefficients and subscripts	B 77.2	0.0	B 22.3	*	*	**22.3**
8.Molar quantity	C 55.4	6.8	A 34.0	B 1.9	D 1.9	**37.8**
9.Coefficients and subscripts	D 41.7	3.9	A 23.3	B 14.6	C 16.5	**54.4**
10.Limiting reagent	D 32.0	31.1	A 17.5	B 13.6	C 5.8	**36.9**
11.Reaction efficiency	B 22.3	29.1	A 9.7	C 32.0	D 6.8	**48.6**

KEY: * **No option:** - alternative answer not provided
NR: - No response

Table 1 depicts an incorrect response range of 22% to 68% on all stoichiometry concept test items. This incorrect response range reveals the different kinds of stoichiometry misconceptions held by students which are summarised into five categories of coefficients and subscripts, chemical formulae and equations, molar quantity, limiting reagent and reaction efficiency (% yield). All items except for 6, 10 and 11 had a no response of less than 8%. The explanations provided for the no response categories were given as "*no idea*", "*have not covered the work*" initially evidencing lack of facts. Interviews revealed that students respond incorrectly to test items, leave blank spaces, write incorrect explanations or phrases such as "*no idea*" on spaces provided mainly because of a lack of facts and/or meta language to express themselves.

Coefficients and subscripts (Items 1, 7 and 9)

The majority of the students (67%) correctly identified the equation representing a reaction depicted diagrammatically while 33% chose incorrect responses for question 1. B implies that Y is diatomic; A identifies the coefficients as number of atoms instead of moles and C deduces the product formula from mole ratios. The common explanation provided by the students who chose an incorrect response was particles *of Y reacts with 3 particles of X.* Twenty three percent (23, 3%) of the students who chose the correct response D gave similar chemically incorrect/incomplete explanations.

In question seven, 77.7% of the students correctly selected option B and 22.3% of students chose option A. The explanations given by those who opted for incorrect responses included: *1 particle of X reacts with 1 particle of Y; The ratio of X: Y reaction is 1: 2.* Twenty-two point seven percent (22.7%) of the 77.7% of the students who correctly selected option B also provided incorrect explanations. And in question 9, 41.7% correctly chose D while 54.4% choose incorrect responses.

Interviews revealed that some students explained the reaction ratios using everyday terminology *"particle"* as exemplified by the following quotations; "*I determined the reaction ratio of X to Y by counting the particles in the diagram*" or "*I at first counted the number of Y particles bonded to X particles in diagram, then determined the formulae of reacting substances as in equation* $3X + 3Y_2\ 3XY_2$".

Chemical formulae and equations (item 5)

Only twenty three point four percent (23.4%) of the students identified the correct chemical formula of the substances involved in the reaction whilst the majority, 59.1 %, selected incorrect responses for question 5 further revealing that students have problems with deducing chemical formulae and balancing equations. Interestingly, the majority of students, thirty eight point four percent (38.4%) who responded incorrectly chose an unbalanced equation. Twenty point seven percent (20.7%) chose an equation with the wrong formulae of calcium phosphate ($CaPO_4$) and calcium silicate ($CaSiO_2$). The open question part and interviews revealed that the students use coefficients and subscripts interchangeably and deduce both from the valances of ions and as a result, they experience problems with deducing chemical formula and balancing equations. For example: The valency of Ca^{2+} is 2 and of PO_4^{2-} is 2 giving a formula $CaPO_4$.

Molar quantity (mass and volume) (items 3 and 8)

The majority of the students (69.9%) gave correct responses to question 3 while 26.2 % (chose B. 12.6%; C. 12.6% and D. 1.0%) responded incorrectly and 3.9% left blank spaces. Students who chose option B showed how they arrived at the working as follows: mass of compound = 2g, mass of Cu =1g; mass of sulphur is 2-1=1g, Ratio of Cu:S =1:1. They used mass ratio strategy to determine the formula of copper sulphide. The working provided by those who opted for C as mass of Cu =32g; mass of sulphur is 16-1=1g, Ratio of Cu:S =2:1, used the molar mass ratio strategy to determine the formula of copper sulphide. An insignificant proportion 1%, selected option C and left the explanation section blank. The results reveal an incorrect way (mass ratio or molar mass ratio strategy) of deducing the formula of a compound given the mass.

Question 8 tested students' understanding of the molar gas volume at room temperature and pressure and at standard temperature and pressure. Fifty five point three percent (55.3%) of the students responded correctly, 37.8 % responded incorrectly and 6.8 % gave no response. Options A, B and D reveal the kinds of misconceptions held by the students. Interestingly, 34.0% of the students chose option A and explained their answer in terms of mass ratio, that is (H_2: He =2:4). The misconception revealed is that mass ratio gives the ratio of the volume of two gases at room temperature and pressure (rtp). Surprisingly, 17.7% of the students who correctly chose option C provided explanations that suggest that they ignore phases of substances when considering molar volumes. For example: (i) any mass of gas has the same volume at room temperature and pressure. (ii) One mole of any substance has a volume of $24dm^3$ at room temperature and pressure. A low proportion of 3.8% selected options B and D (1.9% each), indicating that most students can distinguish molar volumes of gases under different conditions (rtp and stp).

Interviews confirmed that students lacked understanding of the interrelationship between the number of moles, volume, molar mass and their use in determining the formula. Problems with symbolic representations and interpretations coupled with general mathematical problems were detected as exemplified by the following extract from the interview: "*I have problems with the mole concept as we deal with unseen particles. In fact it is difficult to identify the type of particles you will be dealing with at any given time and also the use of coefficient and subscripts differs from the mathematical use.*"

Limiting reagent (items 2, 6, and 10)

Questions 2, 6 and 10 intended to explore students' comprehension and identification of limiting reagents. In question 2, the majority of the students (68%) showed problems of identifying the correct limiting reagent whilst 27.2% positively identified the limiting reagent. Almost half of the students (49.5%) in this sample chose response C. The explanations provided, such as *$KMnO_4$ has less number of moles as compared to H_2O_2* suggest that these students understand a limiting reagent as the reactant with the smallest coefficient number (less number of moles) from the given chemical equation. This further demonstrated the students' lack of understanding of the significance of the persistent potassium manganate (VII) purple colour. Interestingly, 13.6% of the students chose A, considering the acid as one of the reactants instead of identifying it as medium reaction. Surprisingly, quite a low proportion of students 4.9% selected option D failing to realize K_2SO_4 as one of the products. All the students who chose options A and D did not provide the explanations to their choice revealing lack of understanding of the meaning of limiting reagent and its significance in a chemical reaction.

Results for question 6 are consistent with those of question 2 as only 21.4% of the students correctly identified the limiting reagent (option A) and successfully used it to calculate the required volume of gas. 56.3% chose incorrect options B, C and D. 13.6% of the students who chose option C simply summed up the volumes of the reacting gases ($10cm^3 + 15cm^3 = 25cm^3$). Thirty two percent (32.0%) of the students chose option B on the basis that nitrogen has the least number of moles. This is similar to the reason given for the choice of option C question 2.

Question 10 was designed to test students' ability to identify a limiting reagent as well as use it to calculate the mass of product produced during a chemical reaction. Thirty-two percent (32.0%) of the students correctly identified the limiting reagent and successfully calculated the mass of product as required (option D). Notably a sizeable 31.1% of A-level students left blank spaces. About 36.9% of the students selected incorrect options (A 17.5%; B 13, 6%; C 5.8%). Students chose B after adding up the masses of the reactants (80g +112g = 192g) reflecting the same reasoning as those who chose option C in question 6. Barker (1995) reported a similar finding where the most common incorrect response, given by 32% was to add the two figures generating 192g. 17.5% who chose A said *sulphur is the limiting reagent because its given mass is less than that of iron.* Then they worked out the answer as: 32g Sulphur 88g iron (II) sulphide 80g Sulphur yields 8032 x 88 = 220g). Students have problems with the identification of limiting reagents. The interviews further confirmed that most of the students had problems with the mathematical application of the problem in addition to meta language expression.

Reaction efficiency / percentage yield (Items 4 and 11)

The percentage yield is expressed as an amount of product actually formed in a reaction divided by the amount theoretically possible and multiplied by 100% (Zumdahl, 1992). Therefore the percentage yield is based on the limiting reagent. Question 4, probed the students' understanding of the concept of percentage yield. Only 43.7% of the students correctly chose option D in response to question 4 as compared to a substantial proportion (53.4%) of the students who responded incorrectly. Of these, 31.1 % of the students chose option B, 15.5% option A and 6.8% option C.

Question 11 was designed to uncover students' misconceptions about reaction efficiency. 22.3 % of the students correctly chose option B and demonstrated that they know how to calculate the percentage yield. Most of the students (48.5%) however hold misconceptions regarding reaction efficiency whilst a relatively high percentage of students (29.1%) left blank spaces. Consistent with choice B in question 4, 32.0% of the students chose C explaining that the mass of the actual product is equal to the mass of the limiting reagent and therefore the reaction is 100% efficient. Students do not understand these concepts: limiting reagent; reactant in excess and percentage yield, and in turn their relationships.

Discussion

This study reveals that students hold many misconceptions about stoichiometry and related concepts which were grouped into five categories identified as coefficients and subscripts, chemical formulae and equations, molar quantity, limiting reagent and reaction efficiency (% yield). Findings of this study are similar to others elsewhere. For example, that students confuse or lack understanding of subscripts and coefficients using them interchangeably (Yarroch, 1985), have difficulties in determining the formula of compounds in the reaction (Abraham, Grzybowski, Renner, and Marek, 1992) and balancing of equations (Huddle and Pillay, 1996). Such stoichiometry misconceptions held by students possibly explain the poor performance by A-level students in Zimbabwe in the area of stoichiometry reported by ZIMSEC and ULCES (1994 – 2006).

According to Garner (1992), misconceptions result in conceptual blocks that hinder subsequent learning. Therefore, though not conclusive, the problems experienced by students with chemical formulae and equations may be largely attributed to their lack of understanding of subscripts and coefficients. The students' problems with the understanding of subscripts and coefficients may be traced to difficulties students experience in visualizing and representing chemical events symbolically and diagrammatically, distinguishing types of particles (atoms, ions and molecules) used in stoichiometry, as well as understanding the relationship between particles, moles and volumes. For example, some students failed to identify the correct valences of the ions involved and as a result could not deduce the formulae of reactants and products of reaction while others showed a lack of understanding of the mole-mass and the mole-volume relationships. Such observations were also noted by Dennistron (2001) who pointed out that those students who assume that substances always react in a 1:1 ratio make different types of errors in areas of chemical formula, balancing chemical equations, and stoichiometry ratios.

Lack of meta language for explanation was also revealed as another major source of stoichiometry misconceptions held by students. Other studies have also reported that students' experience of problems with explaining chemical phenomena in appropriate chemistry language was not unique to this study (Fraser, 1994). Meta language problems may be attributed to the medium of instruction. Students usually experience severe problems when the medium of instruction used is the second language as in the case of students in Zimbabwe who are taught in their second language (English). Some studies have shown that incompetence in the language of instruction is directly related to low achievement in science (Fraser, 1994; Hohn, 1995). This indicates lack of understanding of concepts.

Though the findings in this study are limited to the students who participated directly in the study, they give insights into, and understanding of the misconceptions A-level students hold in stoichiometry and related concepts.

Conclusion

The findings from this study reveal that students hold misconceptions of stoichiometry and related concepts. Students have difficulty with: (i) coefficients and subscripts (ii) interpretations of representations in equations and formulae (iii) understanding of molar quantities (iv) comprehension and identification of limiting reagents and (v) solving reaction efficiency problems. The misconceptions held by the students may be attributed to a lack of understanding of fundamental concepts and/or meta language for expression. This sheds light on the persistently poor performance by A-level chemistry students in this section of the syllabus. Teachers need to adopt professional development strategies to overcome the obstacle of misconception in the teaching and learning of A-level chemistry. Further research needs to explore the area on a wider scale and unexplored areas such as the influence of the school factor on the type and complexity of misconceptions is recommended.

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