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A New Method of Solving Chemical Equations

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ABSTRACT

Equalization of chemical reactions is one of the main interests of chemistry. In chemistry teaching today, equations are balanced either by guessing or by using methods such as the ion-electron method. Forecasting is difficult to implement because it is time-consuming. The ion-electron method is of limited use since it is necessary to know the oxidation steps of the elements. The Guiding Equation Method we propose in this study has a wide range of applications since it can be applied to all chemical reactions. It is also fast because it uses mathematical methods for the solution and the results are reliable. Our method has the potential to calculate reaction yields differently, change reaction designs and improve chemical productions. In addition, our method is thought to facilitate the teaching and understanding of stoichiometry in chemistry education.

Keywords: Guiding Equation Method, Equalizing Chemical Equations, Ion Electron Method, Regulating Product Yield in

Ethical Statement

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INTRODUCTION

A chemical reaction, the chemical equations must be balanced in terms of both mass and charge in order to calculate the number of reactants that will interact and how much product will come out of the reaction. The Half Reaction Method (HRM) (or Ion-Electron Method (IEM)) is used to equilibrate redox reactions. Both methods require knowledge of the oxidation steps of the elements, the number of electrons exchanged, and the number of electrons given and received, and the element from which element they leave and in which element they go. Although not common, the Mathematical Method (Algebraic Method, Gauss Method, Gauss-Jordan Method or Matrix Method) is also used for balancing all reactions.

It was first suggested in the literature by Bottomley that a mathematical method could be used to balance reactions (Bottomley., 1878). The other method used to ensure equivalence is the oxidation number method, which was proposed in 1880 (Johnson, 1880). According to Peter B. Yde, the half-reaction method was defined in a book written by Alexander Smith in 1916 (Yde, 1989).

It should not be expected that there is a universal solution method that compensates for all chemical reactions. The half-reaction method is exclusively employed to solve redox reactions and yields notably favorable outcomes. From this perspective, it serves as both navigator and completer. Having a variety of methods at one's disposal is highly valuable for industrial applications, especially when a single method proves to be inadequate. If the solution given by one technique is inefficient, another method can be preferred to compensate. This kind of preference will be especially useful for increasing efficiency in education, research and industrial applications.

The problem of equating chemical equations has attracted the attention of both chemists and mathematicians and, in recent years, computer programmers. The subject has been studied by chemists using heuristics, trial and error, and techniques developed on the basis of conservation of matter and charge. The subject has been studied by mathematicians with solution methods based on algebraic equations and matrix operations. The issue is tried to be solved by computer programmers using software developed with various programming languages.

The algebraic method is based on the principle of conservation of mass in chemical transmissions and attempts to find a solution using algebraic equations and matrix techniques. Bottomley based his solution on conservation of mass. Jette and La Mer on Balancing Oxidation-Reduction Reactions (Eric R. Jette, 1927), Bart Park on Equalization of the equations of the cleavage reaction (Park, 1929), In 1944, Steinbach demonstrated that the algebraic balancing method allows for the balancing of reactions with various sets of coefficients. Steinbach once more employed mass equivalence as the basis for applying the technique (Steinbach, 1944). A. Lehrmann raised objections to Steinbach's practice of introducing additional equations when resolving simultaneous reactions (Lehrman, 1944). Porges also proposed that chemical reactions can be balanced on the basis of mass equality (Porges A. , 1945), Vanderwerf and Ferguson dealt with the Equalization of Organic Oxidation-Reduction Reactions in a manner similar to the ion-electron method (Vanderwerf, 1945), (Ferguson, 1946), researchers such as Bennett and Carrano tried to balance the reactions by using the half-reaction method and the algebraic method together (mixed method) (Bennett G. W., 1954), (Carrano, 1978). In his study, Kolb compared the algebraic method with other methods (oxidation number method, ion-electron method and algebraic method). Kolb considered the advantage of the algebraic method that it was not necessary to determine the oxidizing and reducing elements and oxidation numbers. The disadvantage of this method is that algebraic equations have more than one solution (Kolb D. , 1978). In 1982, Blakley published his study on matrix methods (Gauss-Jordan method) for equalization of chemical reactions (Blakley, 1982). Tóth proposed a systematic trial-and-error method for balancing chemical equations by estimation, which he called the “chain method”, based on Harjadi's ping-pong method (Tóth, 1997), (Harjadi, 1986), In his 1997 paper, Olson analyzed algebraic methods for balancing chemical reactions (Olson, 1997), Risteski published a technique for equalizing equations using the von Neumann pseudoinverse matrix in 2008 (Risteski I. B., 2008) and the Drazin pseudoinverse matrix in 2009, both matrix techniques can be successfully applied to all equations (Risteski I. , 2009), In 2010 Lawrence R. Thorne published a simplified inverse matrix technique (Thorne, 2010), In 2019, Emilee Barrett investigated the equalization of chemical equations using Diophantine equations (Barrett, 2019), In 2019, Hamid published his paper on balancing chemical equations using algebraic methods and the law of conservation of matter (Hamid, 2019), Sultan et al. applied algebraic techniques to the steady-state approximation and balanced the chemical equations (Faisal Sultan, 2020), Madhuri et al. tried to balance the equations using the Gaussian Jordan Elimination method (Madhuri A. Gaikwad, 2021).

Recently, in parallel with the development of computer and software technologies, some scientists have developed programs using various software languages to equalize chemical equations. These studies can be summarized as follows. Juan Miguel Campanario developed a software to help chemistry students in his 1995 paper (Campanario, 1995), In his 2001 paper, Kumar discussed computer-based approaches to balancing chemical equations (Kumar, 2001), Sena and colleagues published their study using the “Cheminpsolver” program in 2006 (S.K. Sena, 2006), Ceyhun and their team employed Maple 4.0, a computer program designed for matrix solving, to address a considerable quantity of chemical equations (Ceyhun İ., 2009), Gabriel and Onwuka balanced the chemical equations using both the algebraic method and MATLAB software and published their research in 2015 (Cephas Iko-ojo Gabriel, 2015), Farahnaz et al. conducted a similar comparative study using Matematica software (Farahnaz Soleimani, 2015), Carpenter, Moore and Perkins presented their paper at the CofChem conference in 2015, where they investigated the effects of a special software called PhET, which aims to improve students' equation equating skills (Carpenter, 2015), Yousaf et al. investigated mathematical approaches for balancing chemical equations and tested their performance using MATLAB and TORA software (Mumtaz Yousaf, 2020), Krishna et al. also investigated equalization of equations using Gauss-Jordan Elimination Method and used MATLAB software in this research (Y Hari Krishna, 2020), Bharat et al. also studied Gauss-Jordan Elimination Method but used Pyton language as software (Bharat Udawat, 2022), In their paper, Cachon and Apte equalized equations using matrix algebra and published their Python algorithm on GitHub (Chacon, 2023).

As can be seen from the studies in the literature, the equalization of chemical equations has been a popular topic that has attracted the attention of chemists, mathematicians and recently computer programmers for about 150 years.

Research Questions

There are three questions that our research tries to clarify. We can list them as follows.

1. Can chemical reactions be equated without knowing the oxidation steps of the elements?
2. Is there only one set of coefficients for balancing chemical reactions or is it possible to have more sets of coefficients?
3. Is it sufficient to use algebraic equations directly to equilibrate chemical reactions or is a preliminary adjustment necessary?

Materials

According to the reviewed literature, the present study aims to investigate the feasibility of a new algebraic method for the equalization of chemical reactions. Algebraic equalization of equations has been used before, but these studies were based on mass equality.

In this method, unlike the others, we first establish a guiding equation that ensures mass equivalence and then write the algebraic mass equations. Secondly, the charge equation of the guiding equation is established. In the last step, the mass equations of the elements and the charge equation of the guiding equation are solved using algebraic methods (Substitution, Gauss or Gauss-Jordan methods).

In our study, since the solution step involves a guiding equation and all the algebraic equations required for the solution are defined through this equation, we named this method the Guiding Equation Method (GEM). The Half Reaction Method (IRM) or Ion Electron Method (IEM) can only be applied to oxidation and reduction reactions. The Guiding Equation Method proposed in this study can be applied to both redox reactions and other reaction types and gives successful results.

In this study, 83 different chemical equations with their solutions appearing in the list given in the appendix have been equated by the proposed Guiding Equation Method (GEM) and then compared with the Half-Reaction Method (HRM) (Ion-Electron Method (IEM) when necessary).

The chemical equations used in our research were taken from the textbooks used in General Chemistry (Fundamental Chemistry) courses taught in Chemistry departments. (Yavuz, 1978), (Raymond & Goldsby, 2014), (Petrucci, Harwood, & Herring, 2005).

METHODOLOGY

Research Design

In this study, we used the proposed Guiding Equation Method (GEM) as the method of equating the equations and then the traditional methods, the Half-Reaction Method (HRM) and the Ion-Electron Method (IEM). The use of the traditional methods is explained in the textbooks and therefore does not need to be explained, but it is necessary to explain how to use the new method.

Using the Guiding Equation Method

In the Guiding Equation Method, a guiding equation is first established. The following rules are applied for establishing the guiding equation.

Application steps of the Guiding Equation Method:

Rule 1: Balance the other element: The other elements (except oxygen and hydrogen) on both sides of the reaction equation are mass balanced.

Rule 2: Balance the oxygen: The oxygen element is then compensated. For this purpose, H2O is added to the appropriate side as needed.

Rule 3: Equalize the hydrogen: Finally, the equivalence of the element hydrogen is achieved. For this purpose, as much H^+ ion as necessary is added to the appropriate side. As a result of these operations, our guiding equation is set up as acidic. H_2O and H^+ species could be added to the left and right side of the guiding equation.

Rule 4: Symbol assignment: Once mass equivalence is achieved, each component of the reactants and products is assigned a different symbol (R1, R2, R3,...,Rn and P1, P2, P3,...,Pn; where R stands for reactant and P for product).

Rule 5: Writing algebraic equations of elements: For each element in the equation, the algebraic mass term is written in accordance with the assigned symbol and the number of moles in the compound. The amounts of the same element on the left and right sides of the equation are equalized. Terms on the same side are summed together. As a result of these processes, the mass equivalence of the elements is achieved.

Rule 6: Writing the algebraic equation of the amount of charge: Write the algebraic charge expression for the left and right sides of the chemical equation. The acidic guiding equation is solved with the help of mass and charge expressions.

Rule 7: Transforming the equation into its basic form: If equality is not achieved, the equation is set up as basic by adding the number of moles of OH^- to both sides of the H^+ ion and the solution is tried again.

Rule 8: Displacement: If the coefficient of an element is "-" after the solution process, that element is passed to the opposite side of the equation with its coefficient.

Rule 9: Simplification: If necessary, the coefficients are simplified.

After all the operations, the equations look like this:

Raw equation:

$$A + B + C + \cdots + N \longrightarrow X + Y + Z + \cdots + N$$

Guiding equation:

$$\underset{R_1}{aA} + \underset{R_2}{bB} + \underset{R_3}{cC} + \cdots + \underset{R_n}{nN} \longrightarrow \underset{P_1}{xX} + \underset{P_2}{yY} + \underset{P_3}{zZ} + \cdots + \underset{P_n}{nN}$$

Equalized guiding equation after the algebraic method:

$$(R_1 * a)A + (R_2 * b)B + (R_3 * c)C + \cdots + (R_n * n)N$$

$$\downarrow$$

$$(P_1 * x)X + (P_2 * y)Y + (P_3 * z)Z + \cdots + (P_n * n)N$$

Example analysis to understand the use of the Guiding Equation Method

In order to understand how to set up the guiding equation and how to analyze it in the proposed method, an example analysis is given below. Initially, we will start with an unbalanced raw equation.

Raw equation:

$$Cr_2O_7^{2-} + H_2O_2 \longrightarrow Cr^{3+} + O_2$$

Application of the rules for constructing a guiding equation:

Rule 1: Balancing the other element: The other element besides oxygen and hydrogen is chromium, which is equalized by writing "2" on the right side.

$$Cr_2O_7^{2-} + H_2O_2 \longrightarrow 2Cr^{3+} + O_2$$

Rule 2: Oxygen equalization: H_2O is added to the missing side by the number of oxygens. There are 9 oxygen on the left side and 2 on the right side. Add 7 moles of H_2O to the right side.

$$Cr_2O_7^{2-} + H_2O_2 \longrightarrow 2Cr^{3+} + O_2 + 7H_2O$$

Rule 3: Equalizing hydrogen: There are 2 hydrogens on the left side of the equation and 14 hydrogens on the right side. Add 12 moles of H^+ to the left side.

$$12H^+ + Cr_2O_7^{2-} + H_2O_2 \longrightarrow 2Cr^{3+} + O_2 + 7H_2O$$

After these operations, the guiding equation is established. Then the elements of the guiding equation need to be assigned symbols.

Rule 4: Symbol assignment:

$12H^+$	+	$Cr_2O_7^{2-}$	+	H_2O_2	$\longrightarrow$	$2Cr^{3+}$	+	O_2	+	$7H_2O$
R_1		R_2		R_3		P_1		P_2		P_3

Rule 5: Writing algebraic equations of elements:

H $12R_1+2R_3=14P_3$

O $7R_2+2R_3=2P_2+7P_3$

Cr $2R_2=2P_1$

Rule 6: Writing the algebraic equation of the amount of charge:

Q $12R_1- 2R_2=6P_1$

Solution:

Since $R_2=P_1$ from Cr equation, I make the other "P_1" as "R_2":

H $12R_1+2R_3=14P_3$ $6R_1+R_3=7P_3$

O $7R_2+2R_3=2P_2+7P_3$

Q $12R_1- 2R_2=6R_2$ $3R_1=2R_2$

According to the load (Q) equation, $3R_1=2R_2$. If I replace "$3R_1$" with "$2R_2$" in the oxygen equation:

H $2*(3R_1)+R_3=7P_3$ $2*(2R_2)+R_3=7P_3$

O $7R_2+2R_3=2P_2+7P_3$ $7R_2+2R_3-2P_2=7P_3$

In case both equations at $7P_3$ are equalized:

$4R_2+R_3=7R_2+2R_3-2P_2$

$2P_2=3R_2+R_3$

Arbitrarily, I say $P_2=2$.

$3R_2+R_3=4$. In this case $R_2=1$ and $R_3=1$.

Note that in this solution "P_2" takes the minimum value of "R_2" and "R_3". According to these values, other coefficients are formed as follows.

R_1	R_2	R_3	P_1	P_2	P_3
2/3	1	1	1	2	5/7
14	21	21	21	42	15

Find the values of R_1, R_2 and P_1 using the formulas $R_1=(2R_2)/3$ and $R_1=R_2$. The algebraic coefficients are multiplied by the element/molecule coefficients in the equation to form the final coefficient.

$$14 * 12H^+ + 21 * 1Cr_2O_7^{2-} + 21 * 1H_2O_2 \longrightarrow 21 * 2Cr^{3+} + 21 * 2O_2 + 15 * 7H_2O$$

$$168H^+ + 21Cr_2O_7^{2-} + 21H_2O_2 \longrightarrow 42Cr^{3+} + 42O_2 + 105H_2O$$

The equation is simplified by dividing by 21.

$$8H^+ + Cr_2O_7^{2-} + H_2O_2 \longrightarrow 2Cr^{3+} + 2O_2 + 5H_2O$$

The last equation obtained is the solution of the Guiding Equation Method. The solution of the same equation by the Half Reaction Method is as follows:

$$8H^+ + Cr_2O_7^{2-} + 3H_2O_2 \longrightarrow 2Cr^{3+} + 3O_2 + 7H_2O$$

As can be seen, the two solutions are different.

CONCLUSIONS

After analyzing 83 different chemical equations, the results produced by the proposed Guiding Equation Method, when compared with the conventional methods, show a number of situations. These situations can be listed as follows.

1- The case where the Guiding Equation Method gives a single solution with the same set of coefficients as the Half Reaction Method.

2- The case where the Guiding Equation Method gives a single solution with a different set of coefficients than the Half Reaction Method.

3- The case where the Guiding Equation Method gives multiple solutions with different sets of coefficients including the solution of the Half Reaction Method.

4- The case where the Guiding Equation Method gives multiple solutions with different sets of coefficients that do not include the solution of the Half Reaction Method.

5- The case where the Guiding Equation Method fails to produce a solution when the equation is acidic but produces a solution when the equation is basicized.

6- The situation where the Guiding Equation Method cannot produce a solution.

7- The situation where the Guiding Equation Method produces a solution but the Half Reaction Method does not.

The data obtained as a result of our studies are analyzed and interpreted below for each case through two different examples.

1- The case where the Guiding Equation Method gives a single solution with the same set of coefficients as the Half Reaction Method

In the following reactions, the guiding equation method produces a single solution with the same set of coefficients as the half-reaction method. Our first example is as follows:

$$PbO_2 + Cl^- \longrightarrow Pb^{2+} + Cl_2$$

The solution of the Half Reaction Method and the Guiding Equation Method for this reaction are the same:

$$PbO_2 + 2Cl^- + 4H^+ \longrightarrow Pb^{2+} + Cl_2 + 2H_2O$$

Our second example is the following reaction:

$$S_2F_2 \longrightarrow S_8 + H_2S_2O_6 + HF$$

For this reaction, the Half Reaction Method and the Guiding Equation Method give the same solution:

$$6H_2O + 5S_2F_2 \longrightarrow S_8 + H_2S_2O_6 + 10\,HF$$

In these reactions, both solution methods produce a single solution with the same set of coefficients.

2- The case where the Guiding Equation Method gives a single solution with a different set of coefficients than the Half Reaction Method

In the reactions that follow, the guiding equation method yields a unique solution with coefficients that differ from those obtained using the half-reaction method. The first example is:

$$MnO_4^- + H_2O_2 \longrightarrow Mn^{2+} + O_2$$

The solution of the Half Reaction Method for this reaction is as follows.

$$6H^+ + 2MnO_4^- + 5H_2O_2 \longrightarrow 2Mn^{2+} + 5O_2 + 8H_2O$$

The solution of the Guiding Equation Method is as follows.

$$6H^+ + 2MnO_4^- + H_2O_2 \longrightarrow 2Mn^{2+} + 3O_2 + 4H_2O$$

Although the solutions of the two methods contain the same elements and molecules, the amounts of hydrogen peroxide used and oxygen produced are different.

Our second example is the oxidation of ethylene with dichromate:

$$C_2H_4 + Cr_2O_7^{2-} \longrightarrow CO_2 + 2Cr^{3+}$$

According to the Half Reaction Method, the equilibrated form of the reaction is below.

$$C_2H_4 + Cr_2O_7^{2-} \longrightarrow 2CO_2 + 2Cr^{3+} + 3H_2O$$

The same reaction equates according to the Guiding Equation Method as follows.

$$16H^+ + C_2H_4 + 2Cr_2O_7^{2-} \longrightarrow 2CO_2 + 4Cr^{3+} + 10H_2O$$

In our second reaction, the moles of the reactant ethylene and the carbon dioxide produced are the same, while the moles of the other reactant dichromate and the products Cr(III) ion and water are different. The most important difference is that according to the Guiding Equation Method, this reaction takes place in an acidic environment. The Half Reaction Method has no prediction about the pH of the medium.

3- The Difference of the Guiding Equation Method, Including the Solution of the Half Reaction Method Multiple Solutions with Multiple Sets of Coefficients

In certain reactions, our proposed method indicates the presence of multiple solutions, each with distinct sets of coefficients. One of these solutions is the same as the solution of the Half Reaction Method, while the others are different.

Our first example here is the reduction of perchlorate with chloride:

$$ClO_4^- + Cl^- \longrightarrow Cl_2 + ClO_3^-$$

The solution of the Half Reaction Method is as follows:

$$2H^+ + ClO_4^- + 2Cl^- \longrightarrow Cl_2 + ClO_3^- + H_2O$$

For this reaction, the Guiding Equation Method has 8 different solutions. The solutions are listed below. The first solution (a) is identical to the solution of the Half Reaction Method, while the others are different. The first four solutions (a, b, c, d) contain the same reactants and products as the Half Reaction Method, but with different mole numbers. In the other four solutions (e, f, g, h), the roles of some of the reactants and products have changed.

$$2H^+ + ClO_4^- + 2Cl^- \longrightarrow Cl_2 + ClO_3^- + H_2O \quad \text{a}$$

$$2H^+ + 7ClO_4^- + 4Cl^- \longrightarrow Cl_2 + 9\,ClO_3^- + H_2O \quad \text{b}$$

$$2H^+ + 4ClO_4^- + 3\,Cl^- \longrightarrow Cl_2 + 5\,ClO_3^- + H_2O \quad \text{c}$$

$$6H^+ + 6ClO_4^- + 7Cl^- \longrightarrow 3Cl_2 + 7ClO_3^- + 3H_2O \quad \text{d}$$

$$2H^+ + 3ClO_3^- + Cl^- \longrightarrow Cl_2 + 2ClO_4^- + H_2O \quad \text{e}$$

$$6H^+ + 5ClO_3^- + 4Cl^- \longrightarrow 3Cl_2 + 3ClO_4^- + 3H_2O \quad \text{f}$$

$$2H^+ + 7ClO_3^- \longrightarrow Cl_2 + 5ClO_4^- + H_2O \quad \text{g}$$

$$6H^+ + ClO_3^- + 5Cl^- \longrightarrow 3Cl_2 + 3H_2O \quad \text{h}$$

Equations where reactants and products are the same can be used to achieve the desired reaction yield.

Reactions in which the roles of reactants and products change can be interpreted as follows. The chlorate formed by the reduction of perchlorate is oxidized back to chlorate in the presence of chloride. In the last reaction (h), chlorate is converted to chlorine molecule in the presence of chloride. In all reactions, one of the products is a chlorine molecule and the other is water. Side reactions may be one of the factors preventing the desired yield from being achieved.

Our second example reaction under this heading is the reduction of permanganate to manganese (II)oxide.

$$MnO_4^- + H_2O_2 \longrightarrow MnO + O_2$$

According to the solution of the Half Reaction Method, the reaction takes place in acidic medium, and 2 moles of manganese(II) oxide and 5 moles of molecular oxygen are formed from 2 moles of permanganate.

$$2H^+ + 2MnO_4^- + 5H_2O_2 \longrightarrow 2MnO + 5O_2 + 6H_2O$$

The Guiding Equation Method has 2 different solutions. Both reactions take place in acidic medium.

$$4H^+ + 4MnO_4^- + 4H_2O_2 \longrightarrow 4MnO + 7O_2 + 6\,H_2O \quad \text{a}$$

$$2H^+ + 2MnO_4^- \longrightarrow 2MnO + H_2O_2 + 2O_2 \quad \text{b}$$

In the first solution (a), the reactants and products match those of the Half Reaction Method, but the mole amounts are varied.

The interpretation of the second solution (b) of the Guiding Equation Method is interesting. This reaction suggests that permanganate will form hydrogenperoxide when reduced to manganese (II) oxide in acidic media. Since part of the permanganate will be used for the production of hydrogen peroxide during the reaction, there is no chance for the reaction to reach full efficiency.

4- The case where the Guiding Equation Method gives multiple solutions with different sets of coefficients that do not include the solution of the Half Reaction Method

The Guiding Equation Method suggests multiple solutions for some reactions. The interesting thing is that none of these equations is the same as the solution given by the Half Reaction Equation. Both examples here are internal redox reactions.

Our first reaction is like this:

$$ClO_3^- \longrightarrow ClO_4^- + ClO_2^- + ClO^- + Cl_2$$

The solution of the Half Reaction Method is as follows.

$$2\,H^+ + 12\,ClO_3^- \longrightarrow 8\,ClO_4^- + ClO_2^- + ClO^- + Cl_2 + H_2O$$

The reaction takes place in an acidic environment and oxides are formed in which the element chlorine is both oxidized and reduced. The Guiding Equation Method has 6 different solutions. All of the solutions are different both from the solution of the Half Reaction Method and from one another. (For ease of interpretation of all reactions, the molar amount of the acid is equal to 16).

$$16\ H^+ + 96\ ClO_3^- \longrightarrow 64\ ClO_4^- + 8\ ClO_2^- + 8\ ClO^- + 8\ Cl_2 + 8\ H_2O \quad \text{YRM}$$

$$16\ H^+ + 61\ ClO_3^- \longrightarrow 43ClO_4^- + ClO_2^- + ClO^- + 8Cl_2 + 8H_2O \quad \text{a}$$

$$16\ H^+ + 63\ ClO_3^- \longrightarrow 44ClO_4^- + 2ClO_2^- + ClO^- + 8Cl_2 + 8H_2O \quad \text{b}$$

$$16\ H^+ + 64\ ClO_3^- \longrightarrow 45ClO_4^- + ClO_2^- + 2ClO^- + 8Cl_2 + 8H_2O \quad \text{c}$$

$$16\ H^+ + 59\ ClO_3^- \longrightarrow 42ClO_4^- + ClO^- + 8Cl_2 + 8H_2O \quad \text{d}$$

$$16\ H^+ + 58\ ClO_3^- \longrightarrow 41ClO_4^- + ClO_2^- + 8Cl_2 + 8H_2O \quad \text{e}$$

$$16\ H^+ + 56\ ClO_3^- \longrightarrow 40ClO_4^- + 8Cl_2 + 8H_2O \quad \text{f}$$

There are similarities in the solutions of both methods. For instance, 16 moles of acids are generated, along with 8 moles of molecular chlorine and 8 moles of water. Acid and chlorate are reactants in all equations. is located on its flank. On the product side, variable quantities of chlorate, chlorite, and hypochlorite are observed, while molecular chlorine and water remain constant at 8 moles each. The last three equations are those without chlorite, hypochlorite and chlorite+hypochlorite. The solution of the Half Reaction Method and the solution of the Guiding Equation Method are completely different. Our second example reaction is the following reaction for which McGavock (McGavock, 1945) gave the solution in his paper. The preliminary equation for the reaction is below:

$$C_8H_{18} \longrightarrow C_2H_4 + C_3H_6 + CH_4$$

The solution of the Half Reaction Method is as follows.

$$8\ C_8H_{18} \longrightarrow 7\ C_2H_4 + 14\ C_3H_6 + 8\ CH_4$$

The Guiding Equation Method has 5 different solutions. All of the solutions are different both from the solution of the Half Reaction Method and from one another.

$$2\ C_8H_{18} \longrightarrow 7\ C_2H_4 + 2\ CH_4 \quad \text{a}$$

$$3\ C_8H_{18} \longrightarrow 7\ C_3H_6 + 3\ CH_4 \quad \text{b}$$

$$3\ C_8H_{18} \longrightarrow 3\ C_2H_4 + 5\ C_3H_6 + 5\ CH_4 \quad \text{c}$$

$$C_8H_{18} \longrightarrow 2\ C_2H_4 + C_3H_6 + CH_4 \quad \text{d}$$

$$3\ C_8H_{18} \longrightarrow 9\ C_2H_4 + C_3H_6 + 3\ CH_4 \quad \text{e}$$

The first two solutions of the Guiding Equation Method are the cases where one of the oxidizing species is present and the other is absent. Since methane is a reducing species, it must be present in all solutions. All five solutions are different from the solution of the half-reaction.

5- The case where the Guiding Equation Method fails to produce a solution when the equation is acidic, but produces a solution when the equation is basicized

In the Guiding Equation Method, when mass equivalence is established in a chemical equation, the equation is acidic. In some reactions, this acidic equation cannot be balanced, but if the equation is basicized by adding OH^- ions to both sides of the equation in the amount of H+, the Guiding Equation Method produces a solution.

Our first example is the oxidation of the element Aluminum.

$$Al + NO_2^- \longrightarrow AlO_2^- + NH_3$$

The solution of the Half Reaction Method is as follows.

$$2H_2O + NO_2^- + 2Al \longrightarrow 2AlO_2^- + NH_3 + H^+$$

In the Guiding Equation Method, when mass equivalence is achieved, the guiding equation is formed as follows:

$$3H^+ + Al + NO_2^- \longrightarrow AlO_2^- + NH_3$$

This acidic equation cannot be solved by algebraic methods. If 3 moles of OH- ions are added to each side of the equation and then simplified, the equation takes the following form:

$$3OH^- + 3H^+ + Al + NO_2^- \longrightarrow AlO_2^- + NH_3 + 3OH^-$$

$$3H_2O + Al + NO_2^- \longrightarrow AlO_2^- + NH_3 + 3OH^-$$

The last equation is the basicized guiding equation. This equation can be solved algebraically, and the Guiding Equation Method gives the following result.

$$H_2O + 2Al + NO_2^- + OH^- \longrightarrow 2AlO_2^- + NH_3$$

In this solution, if 1 mol H+ ion is added to both sides of the equation, the equation obtained is the same as the solution of the Half Reaction Method.

The second example is methane combustion:

$$CH_4 + O_2 \longrightarrow CO_2$$

In the Guiding Equation Method, when mass equivalence is achieved, the guiding equation is formed as follows:

$$CH_4 + O_2 \longrightarrow CO_2 + 4H^+$$

This equation has no algebraic solution. If 4 moles of OH- ions are added to each side of the equation, the equation takes the following form:

$$4OH^- + CH_4 + O_2 \longrightarrow CO_2 + 4H^+ + 4OH^-$$

$$4OH^- + CH_4 + O_2 \longrightarrow CO_2 + 4H_2O$$

The resulting equation is the basicized guiding equation. This equation can be solved algebraically and gives the following result.

$$2CH_4 + 4O_2 \longrightarrow 2CO_2 + 4H_2O$$

If this equation is simplified, our final equation is as follows:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

As seen in these two examples, when some equations are basicized, they are equalized by the Guiding Equation Method.

6- When the Guiding Equation Method Fails to Produce a Solution

The Guiding Equation Method fails to produce solutions for some reactions. There are several reactions that fall into this group. The most interesting is the following bromate-iodate conversion reaction.

$$IBr + BrO_3^- \longrightarrow IO_3^- + Br^-$$

The solution of this equation according to the Half Reaction Method is given below.

$$3\,H_2O + 3\,IBr + 2\,BrO_3^- \longrightarrow 3\,IO_3^- + 5\,Br^- + 6\,H^+$$

This equation cannot be solved with the Guiding Equation Method. Once the guiding equation is created and the symbol is assigned, the solution proceeds as follows.

Symbol assignment:

IBr	$+$	BrO_3^-	$\longrightarrow$	IO_3^-	$+$	$2Br^-$
R_1		R_2		P_1		P_2

The algebraic equations of the elements are as follows.

O $3R_2=3P_1$

Br $R_1+R_2=2P_2$

I $R_1=P_1$

The algebraic equation of the amount of charge is as follows.

Q $-R_2=-P_1-2P_2$

The solution is as follows.

$R_2=P_1$ $R_1=P_1$

$R_1+R_2=2P_2$ $2R_1=2P_2$ $R_1=P_2$

$R_1=R_2=P_1=P_2$

In this case in the charge equation (Q equation):

$R_1 \neq 3R_1$

An inequality arises. Since the guiding equation cannot be basicized, no other solution is possible. The second of the situations where the Guiding Equation Method cannot produce a solution is the following reaction:

$$H_5IO_6 + I_2 \longrightarrow IO_3^-$$

The solution of this equation according to the Half Reaction Method is as follows.

$$5H_5IO_6 + I_2 \longrightarrow 7\ IO_3^- + 9\ H_2O + 7\ H^+$$

This equation cannot be balanced with the Guiding Equation Method. The first guiding equation is acidic, but the coefficients produced by this equation do not balance the final equation.

$$3\ H_2O + H_5IO_6 + I_2 \longrightarrow 3\ IO_3^- + 11\ H^+$$

When the Guiding Equation is basicized, the following equation is formed:

$$11\ OH^- + H_5IO_6 + I_2 \longrightarrow 3\ IO_3^- + 8\ H_2O$$

The coefficients produced by the basic equation do not equalize the final equation. The Guiding Equation Method has no solution for some reactions. In such cases it is necessary to use the Half Reaction Method.

7- The situation where the Guiding Equation Method produces a solution, but the Half Reaction Method does not

While the Half Reaction Method produces solutions in reactions with electron transfer, it cannot produce solutions in other reaction types. So, this method is limited to redox reactions. For example, the Guiding Equation Method solves the following reactions that the Half Reaction Method cannot solve.

$$CCl_4 + CrO_4^{2-} \longrightarrow COCl_2 + CrO_2Cl_2 + Cl^-$$

In this reaction, the oxidation step of C remains constant at "+4", the oxidation step of Cr at "+6", the oxidation step of Cl at "-1" and the oxidation step of oxygen at "-2". Since the oxidation steps do not change, the Half Reaction Method cannot produce a solution. Here the Guiding Equation Method produces the following solution.

$$3H_2O + 5CCl_4 + CrO_4^{2-} \longrightarrow 5COCl_2 + CrO_2Cl_2 + 8Cl^- + 6H^+$$

Another reaction is the following combustion reaction.

$$C_4H_{10}O + O_2 \longrightarrow CO_2$$

In this reaction carbon is oxidized, oxygen is reduced and the oxidation step of hydrogen remains constant. Carbon goes to CO_2 and oxygen goes to both CO_2 and H_2O. We can write the half-reactions as follows:

Oxidation reaction: $7H_2O + C_4H_{10}O \longrightarrow 4CO_2 + 24H^+ + 24\bar{e}$

Reduction reaction: $H_2O + C_4H_{10}O + O_2 \longrightarrow 4CO_2 + 12H^+ + 12\bar{e}$

Since the electron is on the same side in both cases, the Half Reaction Method cannot equalize the combustion reactions. When compensating for this oxidation, the guiding equation is as follows:

$$5\ H_2O + C_4H_{10}O + O_2 \longrightarrow 4\ CO_2 + 20\ H^+$$

When the solution is done with the Guiding Equation Method, the coefficients are formed as follows:

$$C_4H_{10}O + 6\ O_2 \longrightarrow 4\ CO_2 + 5\ H_2O$$

While the Half Reaction Method cannot equalize combustion reactions, the Guiding Equation Method can successfully equalize them.

INTERPRETATION OF THE RESULTS

In the study, 83 different reactions were equated using the Guiding Equation Method and the solutions of the Half Reaction Method were used as a control. As a result of these analyzes:

1- 56 of the equations are balanced with the state in which the Guiding Equation was formed, that is, with the acidic state. Of these:

- **a)** In 40 equations, the Guiding Equation Method and the Half Reaction Method produced the same result. In 2 of these, there is no need to solve because the direct guiding equation is equivalent.
- **b)** In 14 equations, the Guiding Equation Method has more than one solution. In one of them, all three solutions of the algebraic method are equal to the solution of the half-reaction method.
- **c)** For three equations, at least one of the solutions of the Guiding Equation Method is the same as the half-reaction method.
- **d)** Two of them have a single solution of the Guiding Equation Method, but different from the solution of the half-reaction method.
- **e)** Eight of them have more than one solution of the Guiding Equation Method. The solutions are different from the solution of the half-reaction method and from each other.
- **f)** One equation is interesting because it can be balanced in the half-reaction method without adding electrons and the result is the same as in the guiding equation method.

2- 17 of the equations became equivalent when the Guiding Equation was basicized.

- **a-** In 12 of these 17 equations, when the equation is acidified, the result is the same as the half-reaction method.
- **b-** The basic solution of the four equations is equal to the solution of the half-reaction method.
- **c-** In one of the basic equations, the solution of the Guiding Equation Method and the solution of the half-reaction method are different.
- **d-** Again, there are 3 different solutions of the Guiding Equation Method in one of the basic equations. One of these solutions is the same as the solution of the half-reaction method, while the other two are different.

3- Seven reactions did not equilibrate with the Guiding Equation Method in both acidic and basic states.

4- 3 of the reactions studied were not equalized by the Half Reaction Method but were equalized by the Guiding Equation Method. Combustion reactions are not balanced by the Half Reaction Method, while they are easily balanced by the Guiding Equation Method.

Based on these results, we can say that the Guiding Equation Method is easy to use and can be easily applied by people with intermediate mathematical knowledge.

Equilibration of a chemical reaction is very important in the fields of chemical education and chemical production. So far, many studies in this field have been designed with chemistry education in mind. However, equalization of equations is more important in the field of chemical production. It is thought that the equalizations made with the Guiding Equation Method proposed in this study will offer alternatives in different fields. These can be expressed as follows:

a- A reaction balanced with different sets of coefficients provides engineers with alternatives to produce the desired output. It allows to increase efficiency and reduce costs in the chemical industry.

b- Different sets of coefficients give researchers an idea of which reactants or products should be variable when observing a reaction. It also provides researchers with information about possible sub-reactions and side reactions in the observed reaction system.

c- It enables students to produce solutions by using their knowledge of mathematics and chemistry together. It provides the opportunity to use mathematical knowledge more effectively in the field of chemistry.

d- It allows teachers and students to equalize equations without knowing the oxidation steps of elements. Therefore, it is useful for chemistry education.

This study provides chemistry teachers, chemistry researchers (chemists) and chemistry practitioners (chemical engineers) with an alternative way to equalize chemical equations of all types.

The proposed Guiding Equation Method sometimes provides alternative solutions to the solutions of the Half-Reaction Method and sometimes comes to the rescue by providing solutions when the Half-Reaction Method cannot produce solutions.

According to our results, all three propositions of the article are realized.

Chemical reactions can be equated without knowing the oxidation steps of the elements.

Chemical reactions can be balanced in more than one set of coefficients.

A preliminary adjustment before directly using algebraic equations to balance chemical reactions gives a positive result.

The Guiding Equation Method introduced in this research can be used for a wide range of reaction types, including redox reactions, and consistently produces accurate results.

It is thought that this proposed method will be useful to chemists and chemical engineers in the field of research and application, and to educators and students in the field of chemistry education. Especially since it is not compulsory to know the oxidation steps of the elements, it is thought that it will provide convenience to the students.

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