DEVELOPMENT OF SMALL – SCALE AND LOW-COST GALVANIC CELLS AS A TEACHING TOOL FOR HIGH SCHOOL STUDENTS

PHETVILAY KHATTIYAVONG

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
MAJOR IN CHEMISTRY
FACULTY OF SCIENCE
UBON RATCHATHANI UNIVERSITY
YEAR 2015
COPYRIGHT OF UBON RATCHATHANI UNIVERSITY

UBON RATCHATHANI UNIVERSITY

UBON RATCHATHANI UNIVERSITY

THESIS APPROVAL

MASTER OF SCIENCE

IN CHEMISTRY FACULTY OF SCIENCE

TITLE DEVELOPMENT OF SMALL–SCALE AND LOW-COST GALVANIC CELLS AS A TEACHING TOOL FOR HIGH SCHOOL STUDENTS

AUTHOR MISS PHETVILAY KHATTIYAVONG

EXAMINATION COMMITTEE

ASST. PROF. DR. SAKSRI SUPASORN	CHAIRPERSON
DR. PURIM JARUJAMRUS	MEMBER
DR. KULTHIDA NUGULTHAM	MEMBER

ADVISOR

....
(DR. PURIM JARUJAMRUS)

....
(ASSOC. PROF. DR. UTITH INPRASIT) (ASSOC. PROF. DR. ARIYAPORN PONGRAT)
DEAN, FACULTY OF SCIENCE VICE PRESIDENT FOR ACADEMIC AFFAIRS

COPYRIGHT OF UBON RATCHATHANI UNIVERSITY

ACADEMIC YEAR 2015

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Purim Jarujamrus for his constant advice and guidance. I would like to thank all committees, Dr. Kulthida Nugultham and Dr. Suparb Tamuang for comments and suggestions.

I also would like to thank Asst. Prof. Dr. Saksri Supasorn for being a chair person of my thesis defense and invaluable discussions. I would like to thank the Thailand International Development Cooperation Agency (TICA) and Savannakhet Teacher Training College (STTC) for financial support. Thanks to Ubon Ratchathani University for providing all laboratory facilities. I would like to thank all of my friends for being here with me every time when I have encountered problems.

Finally, my deepest and most sincere appreciation goes to my family for their constant encouragement, unconditional support, and endless love. Their compassion, sacrifice and dedication always move me deeply and inspire me to become a goodness and valuable person to serve the community.

Phetvilay Khattiyavong

Researcher

บทคัดย่อ

เรื่อง : การพัฒนาชุดการทดลองเซลล์กัลวานิกแบบย่อส่วนและต้นทุนต่ำเพื่อใช้เป็นอุปกรณ์ในการสอนระดับมัธยมศึกษา

ผู้วิจัย : เพชรวิไล ขัตติยะวงษ์

ชื่อปริญญา : วิทยาศาสตรมหาบัณฑิต

สาขาวิชา : เคมี

อาจารย์ที่ปรึกษา: ดร. ปุริม จารุจำรัส

คำสำคัญ : ชุดการทดลองแบบย่อส่วน, เซลล์กัลวานิก, เมนทอลโมเดล, การจัดการเรียนการสอนแบบสืบเสาะ, โรงเรียนชั้นมัธยมศึกษา

งานวิจัยนี้ประกอบด้วยสองส่วน ส่วนแรกเป็นการพัฒนาเซลล์กัลวานิกแบบย่อส่วนและต้นทุนต่ำ โดยมีวิธีการสร้างที่ง่ายเพื่อใช้เป็นอุปกรณ์สำหรับการสอนไฟฟ้าเคมีในระดับมัธยมศึกษาตอนปลาย การออกแบบครั้งนี้ใช้แนวคิดเคมีสีเขียวคือลดปริมาณการใช้สารเคมี ทำให้ของเสียจากสารเคมีมีปริมาณน้อยลง และเวลาที่ใช้ในการทดลองลดลง แต่ยังคงรักษาสภาวะที่สมบรูณ์ของการทดลองไว้ได้อย่างวิธีมาตรฐาน ในงานวิจัยนี้ได้พัฒนาเซลล์กัลวานิกที่ประกอบด้วยขั้วไฟฟ้าทองแดง (Cu) สังกะสี (Zn) อลูมิเนียม (Al) แมกนีเซียม (Mg) และเหล็ก (Fe) สะพานเกลือทำมาจากเส้นด้ายชนิดฝ้ายราคาถูก (ยาว 9 เซนติเมตร) ชุบด้วยสารละลายอิเล็กโทรไลต์ อุปกรณ์ที่พัฒนาขึ้นมีความสอดคล้องกับการทดลองมาตรฐาน แต่ใช้ปริมาตรสารละลายอิเล็กโทรไลต์ที่น้อยลง (2 มิลลิลิตร) จากการศึกษาสภาวะที่เหมาะสมดังต่อไปนี้ ความเข้มข้นของสารละลายอิเล็กโทรไลต์ที่เหมาะสมของแต่ละเซลล์ (0.01 โมลต่อลิตร) สารละลายที่ใช้ชุบสะพานเกลือ โพแทสเซียมไนเทรต ความเข้มข้น 0.01 โมลต่อลิตร และอายุการใช้งานของสารละลายอิเล็กโทรไลต์ในสภาวะที่เหมาะสม 720 ชั่วโมง ผลการทดลองที่ได้จากการสร้างเซลล์กัลวานิกเปรียบเทียบกับวิธีแบบมาตรฐาน เมื่อใช้ t-test ในการทดสอบค่าศักย์ไฟฟ้าของวิธีทั้งสองไม่มีความแตกต่างอย่างมีนัยสำคัญ (t_{stat} = 2.414, $t_{critical}$ = 2.447) ที่ระดับความเชื่อมั่นร้อยละ 95 สำหรับส่วนที่สอง งานวิจัยนี้เป็นการนำชุดการทดลองเซลล์กัลวานิกแบบย่อส่วนที่พัฒนาขึ้นมา โดยเป็นการจัดการเรียนการสอนแบบสืบเสาะแบบ 5 ขั้น เพื่อเสริมสร้างให้นักเรียนมีความเข้าใจมโนมติของไฟฟ้าเคมี โดยเครื่องมือในการวิจัยประกอบด้วย การทดลองแบบย่อส่วนไฟฟ้าเคมีจำนวน 4 ชุดได้แก่ ปฏิกิริยาออกซิเดชันและปฏิกิริยารีดักชัน เซลล์กัลวานิก การป้องกันการผุกร่อนของตะปูและการต่อแบตเตอรี่แบบอนุกรม โดยเครื่องมือในการรวบรวมข้อมูลประกอบด้วย 1) แบบทดสอบแนวคิดเกี่ยวกับไฟฟ้าเคมีและ 2) วาดภาพเมนทอลโมเดล กลุ่มตัวอย่างได้แก่ นักเรียนชั้นมัธยมศึกษาปีที่ 6 จำนวน 28 คน โดยนักเรียนกลุ่มนี้ได้เข้าร่วมกิจกรรมทั้งหมด 10 ชั่วโมง จากการวิเคราะห์โดยการทดสอบค่าที่กลุ่มตัวอย่างไม่เป็นอิสระต่อกัน พบว่านักเรียนมีคะแนนเฉลี่ยของการทดสอบหลังเรียน (ค่าเฉลี่ย 38.29 และส่วนเบี่ยงเบนมาตรฐาน 5.62) มีค่าสูงกว่าคะแนนเฉลี่ยของการทดสอบก่อนเรียน (ค่าเฉลี่ย 19.29 และส่วนเบี่ยงเบนมาตรฐาน 5.43) ที่ระดับความเชื่อมั่นร้อยละ 95 (หรือ p=0.05) นอกจากนี้คะแนนเฉลี่ยจากการวาดภาพเมนทอลโมเดลของเมนทอลโมเดลของเซลล์

กัลวานิกหลังเรียนในระดับมหภาค (ค่าเฉลี่ย 3.82 และส่วนเบี่ยงเบนมาตรฐาน 0.55) และระดับกึ่งจุลภาค (ค่าเฉลี่ย 4.75 และส่วนเบี่ยงเบนมาตรฐาน 1.23) มีค่าสูงกว่าคะแนนเฉลี่ยก่อนเรียนทั้งในระดับมหภาค (ค่าเฉลี่ย 1.68 และส่วนเบี่ยงเบนมาตรฐาน 1.32) และระดับกึ่งจุลภาค (ค่าเฉลี่ย 1.18 และส่วนเบี่ยงเบนมาตรฐาน 1.50) ที่ระดับความเชื่อมั่นร้อยละ 95 จะเห็นได้ว่าก่อนที่นักเรียนจะได้เรียนด้วยกิจกรรมการทดลองแบบย่อส่วน นักเรียนส่วนใหญ่มีมโนมติอยู่ในกลุ่มต่ำได้แก่ กลุ่มความเข้าใจบางส่วนร่วมกับความเข้าใจผิด (PMU) จนถึงกลุ่มที่ไม่มีความเข้าใจ (NU) แต่หลังจากการเรียนด้วยกิจกรรมการทดลองแบบย่อส่วน พบว่านักเรียนส่วนใหญ่มีมโนมติที่อยู่ในกลุ่มที่ถูกต้องมากขึ้นได้แก่ความเข้าใจบางส่วน (PU) ถึงกลุ่มความเข้าใจสมบูรณ์ (SU) แสดงว่าการจัดกิจกรรมการเรียนรู้ด้วยการทดลองแบบย่อส่วนโดยใช้รูปแบบการเรียนรู้แบบสืบเสาะ สามารถพัฒนาความเข้าใจมโนมติเกี่ยวกับไฟฟ้าเคมี และเมนทอลโมเดลเกี่ยวกับเซลล์กัลวานิกได้อย่างมีประสิทธิภาพ

ABSTRACT

TITLE : DEVELOPMENT OF SMALL – SCALE AND LOW-COST GALVANIC CELLS AS A TEACHING TOOL FOR HIGH SCHOOL STUDENTS

AUTHER : PHETVILAY KHATTIYAVONG

DEGREE : MASTER OF SCIENCE

MAJOR : CHEMISTRY

ADVISOR : PURIM JARUJAMRUS, Ph.D.

KEYWORDS : SMALL-SCALE, GALVANIC CELLS, MENTAL MODELS, 5E INQUIRY LEARNING, HIGH SCHOOL STUDENT

In this work consists of two parts. In the first part a simple method for the fabrication of small-scale and low-cost galvanic cells was developed as a teaching tool for electrochemistry of high school students. The method was designed according to the concept of "Green chemistry" reducing use of chemicals, less waste generation, and time consumption while retaining the experimental concepts. In this work, these galvanic cells contain various electrodes, including Cu, Zn, Al, Mg and Fe and a low cost salt bridge which was made from a cotton thread (with the length of 9 cm) soaked with electrolyte solutions. Our experimental setup corresponded to the conventional platform; however, herein using much less electrolyte volume (2.00 mL). The cells were studied for the optimum conditions including concentration of electrolyte of each cell (0.01 M), the solutions employed as salt bridge (0.01M KNO_3) as well as the study of reagent lifetime of electrolyte (720 h). The results obtained from the constructed galvanic cells were in agreement with those obtained from the conventional method considering by the t-test (t_{stat} = 2.414, $t_{crictical}$ = 2.447) at p value of 0.05. In the second part, the application of developed small-scale was implemented based on 5E inquiry learning approach to enhance students' conceptual understanding of electrochemistry. The research tools consisted of four small-scale experiments involving electrochemistry, which was oxidation and reduction reactions, galvanic cells, cathodic protection of iron nails, and connecting batteries in series. The data collecting tools included 1) a conceptual test of electrochemistry and 2) the mental model drawing of a galvanic cell. Twenty-eight Grade 12 students participated in the series of four 5E learning activities for a total of 10 hours. Paired samples T-test analysis revealed that the mean scores of the post-conceptual test (mean 38.29, SD 5.62) was statistically higher than that of the pre-conceptual test (mean 19.29, SD 5.43) at p value of 0.05. In addition, the mean scores of the post-mental models in both the macroscopic (mean 3.82, SD 0.55) and sub-microscopic features (mean 4.75, SD 1.23) were statistically higher than those of the pre-mental models (mean 1.68, SD 1.32 and mean 1.18, SD 1.50) at p value of 0.05. Prior to intervention, most students were in the categories of less correct conceptions, Partial Understanding with Specific Mis -understanding (PMU) to No Understanding (NU). However, after the intervention, they moved to the categories of more correct conceptions, Partial Understanding (PU) to Sound Understanding (SU). This indicated that this intervention can enhance students' conceptual understanding of electrochemistry and mental models of galvanic cells.

CONTENTS

	PAGE
ACKNOWLEDGEMENTS	**I**
THAI ABSTRACT	**II**
ENGLISH ABSTRACT	**IV**
CONTENTS	**VI**
LIST OF TABLES	**VIII**
LIST OF FIGURES	**XI**
CHAPTER 1 INTRODUCTION	
1.1 Introduction and background	1
1.2 Objectives	6
1.3 Scope of this research	6
CHAPTER 2 LITERATURE REVIEWS	
2.1 Electrochemistry	7
2.2 Galvanic cell	7
2.3 The development of small-scale and low cost galvanic cell as a teaching tool in galvanic cell for high school student and related researches	17
2.4 The investigationof students' conceptual understanding of electrochemistry and mental model of a galvanic cell prior to and after the performance of corresponding experiments and model kit based on 5E inquiry learning activities and related researches.	24
CHAPTER 3 EXPERIMENTAL	
3.1 Chemicals	29
3.2 Apparatus	30
3.3 Experimental	30

CONTENTS (CONTINUED)

PAGE

CHAPTER 4 RESULT AND DISSCUSION

4.1 Result of experimentation of electrochemical cell based on the institute for the promotion of teaching science and technology Thailand (conventional method) 52

4.2 Result of the developed method 55

4.3 Application 66

CHAPTER 5 CONCLUSION

5.1 Conclusion 76

5.2 Implication 77

5.3 Limitation 77

REFERRENCES **79**

APPENDICE

A Development of small-scale and Low cost galvanic cells as a teaching tool for high school students 89

B Application of small-scale and low-cost of galvanic cell for high school students 97

C Conference 117

CURRICULUM VITAE **130**

LIST OF TABLES

TABLE		PAGE
2.1	Chemical Compsition of Cotton	12
3.1	Chemicals	29
3.2	Apparatus	30
3.3	The experiments of galvanic cell included 7 cells.	31
3.4	The reactions of metals in various solutions (20 mL, 1 M of solutions)	33
3.5	The set up of galvanic cells	35
3.6	The reactions of metals in various solutions (oxidation-reduction reaction) (2 mL, 0.01 M of solutions)	37
3.7	Key 5E learning activities of galvanic cells.	41
3.8	Criteria for categorizing students' mental models of a galvanic cell.	49
4.1	The reaction of metal invarious solutions (oxidation-reduction reaction).	53
4.2	The cell potential of galvanic cells using 20 mL and 1 M of electrolytes in both half-cells. (n = 3), instant collection of cell potential	55
4.3	The reaction of metal in various solutions (oxidation-reduction reaction)	59
4.4	Mean (M), standard deviation (SD) and relative standard deviation (%RSD) values of ECu|Cu2 + ||Mg2 + |Mg using 2.00 mL and 0.01 M of electrolytes in both half-cells at different application time.	62
4.5	The reaction of metal in various solution (oxidation-reduction reaction)	64
4.6	The cell potential of galvanic cell using 2 mL and 0.01 M of electrolytes in both half-cells. (n = 3), instant collection of cell potential	64
4.7	Students' scores assessed by the conceptual test of electrochemistry (n=28)	67
4.8	Percentages of students in 5 levels of understanding in the explanation tier of conceptual tests (n = 28).	69
4.9	Students' mental model scores on a galvanic cell (n = 22)	71
4.10	Percentages of students in 5 conceptual categories in mental model drawings (n = 22).	72

LIST OF TABLES (CONTINUED)

TABLE		PAGE
A.1	Mean (M), standard deviation (SD) and relative standard deviation half- (%RSD) values of $E_{Cu\|Cu^{2+}\|\|Zn^{2+}\|Zn}$ using 2.00 mL and 0.01 M of electrolytes in both cells at different application time	92
A.2	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Cu\|Cu^{2+}\|\|Fe^{2+}\|Fe}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	93
A.3	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Cu\|Cu^{2+}\|\|Al^{2+}\|Al}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	93
A.4	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Zn\|Zn^{2+}\|\|Fel^{2+}\|Fe}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	94
A.5	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Mg\|Mg^{2+}\|\|Fel^{2+}\|Fe}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	94
A.6	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Zn\|Zn^{2+}\|\|Mgl^{2+}\|Mg}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	95
A.7	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Zn\|Zn^{2+}\|\|All^{2+}\|Al}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	95
A.8	Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Fe\|Fe^{2+}\|\|All^{2+}\|Al}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time.	96

LIST OF TABLES (CONTINUED)

TABLE **PAGE**

A.9 Mean (M), standard deviation (SD) and relative standard deviation cells at (%RSD) values of $E_{Mg|Mg^{2+}||Al^{2+}|Al}$ using 2.00 mL and 0.01 M of electrolytes in both half- different application time. 96

LIST OF FIGURES

FIGURE **PAGE**

1.1	The development of small scale experiments A) Conventional method and B) Small-scale method	3
2.1	The structure of an agarose polymer (agar-agar).	9
2.2	The Filter paper as salt bridge	10
2.3	The structure of an cellulose fiber that used as salt bridge.	10
2.4	Salt Bridge using Cotton Swab	11
2.5	Physical Structure of Cotton Fiber	12
2.6	Chemical structure and repeating unit of 1,4 β-D anhydroglucopyranose	13
2.7	Galvanic cell based on the redox reaction in equation (2.3).	15
2.8	Miniware of galvanic cell	18
2.9	Simply small-scale a galvanic cell	19
2.10	Simply small scale two galvanic cell	19
2.11	Copper reference electrode	20
2.12	The voltage between a hydrogen electrode (-) sign and chlorine electrode (+) sign.	21
2.13	The voltage between copper and standard hydrogen electrode.	21
2.14	(A) Six lemon juice cuvet cells connected in series to form a 9-V battery. (B) Aschematic of a six-cell 9-V lemon cell battery.	22
2.15	Galvanic cell of KNO_3 using small scale apparatus.	23
2.16	A galvanic cell model kit by Cullen and Pentecost	27
3.1	The reaction of metals in various solutions (20 mL, 1 M of solutions)	33
3.2	Conventional of Voltaic cell (galvanic cell)	34
3.3	The reaction of metals in various solutions (2 mL, 0.01 M of solutions)	36
3.4	Small-scale of galvanic cell (voltaic cell)	38
3.5	Connecting batteries in series of $Zn(s)Zn^{2+}(aq||Cu^{2+}(aq)|Cu(s)$.	39
3.6	Small-scale experiments involving electrochemistry.	44

LIST OF FIGURES (CONTINUED)

FIGURE		PAGE
3.7	The task for mental model drawing of a randomly given galvanic cell (i.e., $Mg|Mg^{2+}$, $Zn|Zn^{2+}$, $Fe|Fe^{2+}$, $Cu|Cu^{2+}$ and $Ni|Ni^{2+}$ half-cells)	47
4.1	(A) Influence of the electrolytes volume (mL) at fixed concentration of electrolytes at 0.01M of cathode half cell and 0.01 M of anode half cell.	56
4.2	(B) Dependence of electrolyte concentration (M) at the fixed volume of 2 mL and fixed of the concentrations of one half cell at 0.1 M.	57
4.3	Stability test of the cell prepared with the salt bridge containing KNO_3(aq) and NaCl (aq) of $Cu|Cu^{2+}||Mg^{2+}|Mg$ cells concentration2 mL in 0.01M of electrolyte	58
4.4	Comparison of potential values of different cells being developed by the conventional method and the developed method	60
4.5	Sub-microscopic mental models for a Ni-Cu galvanic cell of Student A	83
A.1	Experiments and observations of reactions of metals in various solution	90
A.2	The standard reduction of cell potentials at 25°C	90
A.3	The cell potential of galvanic cells (developed method) using 2 mL and 0.01 M of electrolytes in both half-cells at different application time. (n = 3)	91
A.4	The cell potential of galvanic cells (conventional method) using 20 mL and 1 M of electrolytes in both half-cells at different application time. (n = 3).	91
A.5	Stability test of the cell prepared with the salt bridge containing KNO_3(aq), NaCl (aq) and $NaNO_3$of $Cu|Cu^{2+}||Mg^{2+}|Mg$ cells concentration 2.00 mL in 0.01 M of electrolyte	92

CHAPTER 1
INTRODUCTION

1.1 Introduction and background

Almost all high school students are required to study electrochemistry in both lecture and laboratory settings. Many students revealed that it is one of the difficult chemistry topics since it involves intangible concepts that cannot be accessed with direct perception [1-3].

Focused on laboratory setting, in several parts of the world, higher education institutions are still depending on use of macro scale experiments (traditional approach) for an educational illustration in chemistry. Thus, lack of instrumentations, apparatuses, chemicals or laboratories in many schools suppresses learning process to students. There are two important aspects in "Green Chemistry" (modern approach) which can be applied for the improvement of the learning process. One is based on the idea of miniaturization in way that experiments in chemistry (oxidation and reduction, electrochemistry, galvanic cell, electron transfer, acid and base etc.) can be scaled down which are carried out in simpler and smaller platforms (*e.g.* using injection bottles, dropper bottles, syringes, well plates, plastic pipettes) as well as being more economic than the traditional macro scale approach (*e.g.* employing glassware in the laboratory). The other aspect is to perform effective chemical experiments which consume less chemical and reduces generation of waste with high product yields. Thus, the small-scale and effective experiments have a potential to enable teaching materials for students in huge classes, as well as for many institutions in developing countries lacking technical services (*i.e.* electricity, running water) and standard-type equipment.

Electrochemistry has been regarded as one of the most difficult topics by both students and teachers [1]. High school students find it difficult to understanding the fundamental concepts of electrochemical cells and electrolytes which involve the processes of oxidation-reduction, electron transfer and ion conduction [3-5].

A key challenge is to provide better insight into the flow directions of ions in electrolyte and electrons in electrodes [2]. Chemists normally apply particle models to provide an explanation for such problems. However, the chemist's conceptual models have been found to be complex for many students [6-9]. As a result, the students are not enthusiastic in learning electrochemical phenomena. This also results in difficulty for many teachers teaching electrochemistry.

Electrochemical processes involve oxidation-reduction (redox) reactions transferring electrons from one species to the others. Galvanic cells (traditionally presented in the form called Daniell cells) are widely used for illustration of the electrochemical processes applied in either qualitative or quantitative analysis. In most applications, a galvanic cell contains two electrodes partly immersed into two separated electrolyte solutions. The two electrode ends, which are not in contacted with the electrolytes, are connected via conductive wires. Providing that there is potential difference between the two electrodes, redox reactions occur at the electrode/electrolyte interfaces facilitating flows of electrons (or electric current in the wires) and ions (in electrolytes) [10]. The two separated half-cells (each of which contains the electrode and electrolyte) are connected via a salt bridge resulting in a closed electrical circuit within the cell. The salt bridge functions as an electrical contact between the two electrolyte solutions maintaining the ion flow as well as preventing a mixing of the solutions [11, 12]. Conventionally, a galvanic cell is constructed by using considerably large volume of electrolyte with the use of either agar or paper as a supporting material in the salt bridge (Figure 1.1 A).

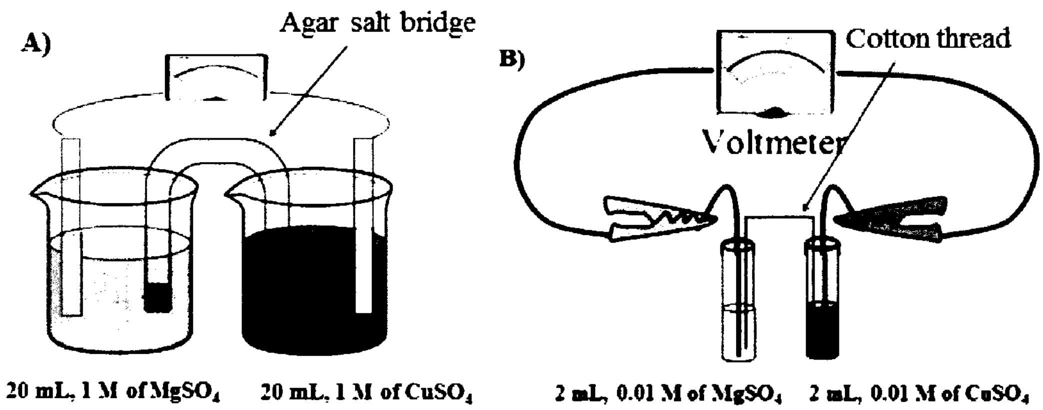


Figure 1.1 The development of small scale experiments A) Conventional method and B) Small-scale method

Source: Khattiyavong et al. (2014: 146-154)

The concepts of small-scale chemistry and "Green Chemistry" have been further described in many articles [13-24]. Mini galvanic cells were developed as a teaching platform illustrating semi quantitative analysis in electrochemistry [13]. The cell consists of two droppers clogged by cotton plugs which were dipped into a 2-dram vial (17 mm × 60 mm) containing ammonium nitrate (functioning as a salt bridge in aqueous state). Each dropper contains electrolyte solution and a small metal electrode. Although the cell performance was good, such a platform is slightly different from the conventional platform employing a solid supporter as a salt bridge (*e.g.* as illustrated in Figure 1.1 A) which is usually shown in many text books. The unsteady voltage of the previously reported cell caused by inconsistency in cotton plug packing was also noted [13]as well as short cell lifetime which may be another disadvantage. The first part of this work aimed to develop small-scale and low-cost galvanic cells as teaching materials in galvanic cells for high school students. To the best of our knowledge, a small platform of galvanic cells with approximately 10-fold reduction of electrolyte volume using cotton thread as a material in the salt bridge has not been previously reported. The first part of this work is to develop such a platform (Figure 1.1 B) aimed to be used in high school laboratories.

Moreover, some students may hold alternative conceptions – conceptions that are not consistent with the consensus of the scientific community which may be partially right but incomplete, or just simply wrong [25]. Students' misunderstandings, alternative conceptions, or misconceptions, some of which cannot be measured by traditional instruments [26], influence their future learning. Therefore, instructors should encourage learning by the use of activities that promote students' conceptual change [27]. Requiring students to draw and explain molecular representations of some electrochemistry experiments, such as reactions in galvanic cells, may reveal their understandings and identify some of their alternative conceptions.

There are many research studies that investigated students' alternative conceptions involving electrochemistry and utilized various intervention tools to improve students' conceptions. It is reported that not only high school students [13-17], and college (university) students [18, 19] but also pre-service and in-service science and chemistry teachers [9, 20, 21] tended to have alternative conceptions and misconceptions in electrochemistry and its related topics. These studies found that both high school and college students had learning difficulties and misconceptions about galvanic, electrolytic, and concentration cells. The identification of misconceptions is important to help learners understand these topics meaningfully [19].

Karsli and Çalik (2012) reviewed many articles and summarized major alternative conceptions encountered in electrochemistry as follows: 1) the cathode is a negative electrode, an oxidation half-cell that loses electrons, and decreases mass over time, 2) the anode is a positive electrode, a reduction half-cell that gains electrons, and increases mass over time, 3) the salt bridge allows electrons to travel from the anode to the cathode, supplies the ions which are necessary to move from the cathode to the anode, allows the cations to migrate toward the anode electrode, whereas the anions migrate towards the cathode electrode, and 4) a lack of reporting the cell reaction correctly.

Cullen and Pentecost (2011) reported evidence that chemistry textbooks and instructors are responsible for many students' alternative conceptions involving electrochemistry. Instructors tend to use everyday language that can lead to misinterpretation by their students[28]. They then designed a paper model to teach about galvanic (voltaic) cells to address students' alternative conceptions by adaptation of an inexpensive, portable, and flexible teaching model by Huddle, White and Roger (2000)[29]. This paper model was used in conjunction with electrochemistry laboratory activities and allows students to visualize that no electrons pass into the solutions and how mass of electrodes is gained and lost. The researchers also commented that as students demonstrated and discussed the model within their groups, they were constructing their own understanding of galvanic cells.

Based on the information above, the term 'mental models' in the second part of thisstudy are the models of understanding (in form of drawings) that students use to relate and describe their understanding of how a galvanic cell functions at a macroscopic, symbolic, and sub-microscopic levels. The implementation of corresponding experiments through the 5E inquiry learning approach is effective to enhance students' conceptual understanding of the corresponding concepts. The use of inquiry experiments in conjunction with a corresponding model featuring the sub-microscopic level could be more effective to enhance students' conceptual understanding and mental models of the corresponding concepts. Therefore, the combination of 5E inquiry experiments and a galvanic cell model kit featuring sub-microscopic level will be used as the intervention tools in this part of study to minimize students' difficulty in visualizing and relating what occurs at the sub-microscopic level to the macroscopic and symbolic levels of galvanic cells.

Based on results from a pilot study, the implementation of small-scale experiments via the 5E inquiry learning approach (the first part of this study) is effective to enhance students' conceptual understanding at the macroscopic and symbolic levels, but not at the sub-microscopic level [30]. This view arose from the fact that the implemented experiments contained insufficient information regarding sub-microscopic features. As a result, the galvanic cell model kit featuring macroscopic, sub-microscopic, and symbolic levels will be developed to help students relate these representations to each other. The main purpose of the second part was to investigate students' conceptual understanding of electrochemistry and mental model of a galvanic cell prior to and after the performance of corresponding experiments and model kit based on 5E inquiry learning activities.

1.2 Objectives

1.2.1 To develop small-scale and low-cost galvanic cells as teaching tools in galvanic cells for high school students

1.2.2 To investigate students' conceptual understanding of electrochemistry and mental model of a galvanic cell prior to and after the performance of corresponding experiments based on 5E inquiry learning activities

1.3 Scope of this research

1.3.1 To develop and validate small-scale and low-cost galvanic cells for high school laboratories

1.3.2 To study the students' scores on the conceptual test of electrochemistry and on the mental model drawings of galvanic cells change before and after they performed the experiments in conjunction with the model kit of galvanic cells

1.3.3 To study the percentages of students in each conceptual understanding category in the conceptual test of electrochemistry and in the mental model of galvanic cells change before and after they performed the experiments

CHAPTER 2
LITERATURE REVIEWS

2.1 Electrochemistry

Electrochemistry is the study of the interchange of chemical and electrical energy. A redox (oxidation-reduction) reaction is a reaction in which one or more electrons are transferred. Electrochemical cells which generate an electric current are called voltaic cell or galvanic cells, and common batteries consist of one or more such cells. In other electrochemical cells and externally supplied electric current is used to drive a chemical reaction which would not occur spontaneously are called electrolytic cell. In this research we focus on galvanic cell.

2.2 Galvanic cell

In 1780, Luigi Galvani [31] discovered that when two different metals were connected together and then both touched to different parts of a nerve of a frog leg at the same time, they made the leg contract. He called this "animal electricity". The Voltaic pile, invented by Italian scientist Alessandro Volta in the 1800s, is a similar concept. These discoveries paved the way for all electrical batteries. A general example of a galvanic cell is the copper/zinc Daniell cell, invented by British chemist John Frederic Daniell in 1836. In the Daniell cell, the solutions are $CuSO_4$ and $ZnSO_4$. Each solution has a corresponding metal strip in it, and a salt bridge connecting the two solutions and allowing SO_4^{2-} ions to flow freely between the copper and zinc solutions. In order to calculate the electric potential one looks up copper and zinc's half reactions as shown in Figure 2.7 in equation 2.1.

$$Zn(s) \longrightarrow Zn^{2+}(aq) + 2e^- \text{ (oxidation)}$$

$$Cu^{2+}(aq) + 2e^- \longrightarrow Cu(s) \text{ (reduction)}$$

$$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu^{2+}(aq) \text{ (redox reaction)} \qquad (2.1)$$

Anode

The half-cell in which oxidation occurs is called the anode. Anode is a half-cell in which atoms loss of electrons (are oxidized) to form positively charged ions (which go into solution). The electrons flow into the external circuit from the anode.

Cathode

The half-cell in which reduction occurs is called the cathode. This is the half-cell in which metal ions from the solution gain electrons (are reduced) and plate out onto the electrode as uncharged atoms. The electrons flow out of the circuit into the cathode.

Electrolytes

An electrolyte is a compound which produces an ionic solution when dissolved in an aqueous solution. For example, a salt like KNO_3 would produce an electrolyte solution. Those compounds which produce a large number of ions in solution are called strong electrolytes. KNO_3, because it is highly soluble, would be a strong electrolyte. On the other hand, those compounds which produce a small number of ions in solution are weak electrolytes. Notice that nonionic compounds can produce electrolyte solutions too. Common examples are acids produced by dissolving molecules such as HCl in water. Soluble compounds that produce no dissolved ions are called non-electrolytes.

Salt bridge

A salt bridge is a device indispensable in electrochemical and has been used over 100 years. This salt bridge allows the flow of charged ions between two half-cells, but prevents diffusional mixing of the two different metal salt solutions. Many things can be used as a salt bridge: a piece of string, cotton, or filter paper soaked in an electrolyte solution or an electrolyte solution in a gel such as agar. Occasionally, fritted glass (porous glass), though not a salt bridge, is used to connect two half-cells. The presence of the liquid-junction potential between two electrolyte solutions was recognized in the end of the nineteenth century [32]. Salt bridge interactions are among the more thoroughly investigated functional groups in protein research. Salt bridging plays an important role in the structure and function of proteins [33-36]. Salt bridges allow the migration of these ionic charges from one half-cell to the other to maintain electro neutrality. In effect, a salt bridge minimizes the liquid junction potential, with the potential difference arising at the interface of electrodes and electrolytes. To maintain the cells as electrically neutral, the electrons released must travel through the wire resulting in electrical energy. Alternate approaches to building salt bridges for electrochemical cells are reviewed [37]. Materials such as filter paper, cotton, semi-micro tubes, human beings, Soil Moist, vials, etc. have been used to construct salt bridges in instructional laboratory settings.

(1) Agar-agr salt bridge

A traditional salt bridge would consist of a U-shaped glass tube, which is filled with an electrolyte solution such as KCl, KNO_3, $NaNO_3$. The electrolyte may be contained by agar or gelatin to prevent intermixing of the solutions. The Agar is actually the resulting mixture of two components: the linear polysaccharide agarose, and a heterogeneous mixture of smaller molecules called agaropectin as shown in Figure 2.1.

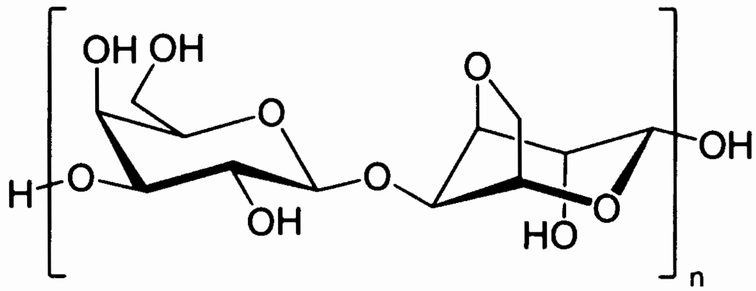


Figure 2.1 The structure of an agarose polymer (agar-agar)

(2) Filters paper as salt bridge

Filters paper strips 1.5 cm x 2mm soaked in 0.1 M KCl solution are used to bridge various pairs of half-cells in a 24 well culture plate [38]. Use a pair of tweezers to handle the KCl soaked filter papers, and place them between two half-cell wells as show in Figure 2.3. Make sure the filter paper strips are immersed in the liquids in adjacent wells. Thick blotting paper or a set of four to five filter papers soaked in an electrolyte also have been reported in the literature as a salt bridge in a voltaic pile involving Cu|Zn and Cu|Pb metal pairs [39]. Paper towel strips could be used in place of a filter.

Another way to make a salt bridge is to soak a piece of filter paper size 1.0 cm x 8.0 cm with saturated electrolyte such KNO_3 in curriculum of the promotion of teaching science and technology in Thailand (IPST) and size 0.5 cm x 2.5 cm for general small-scale and place ends of the filter paper in each side of the half-cell [36].

Whatman cellulose filters paper is manufactured from high-quality cotton linters which have been treated to achieve a minimum alpha cellulose content of 98%. These cellulose filter papers are used for general filtration and used as salt bridge because these filter papers high absorbency solution and have high capacity to clean.

Figure 2.2 Filter paper as salt bridge

Source: Joesten, 1991

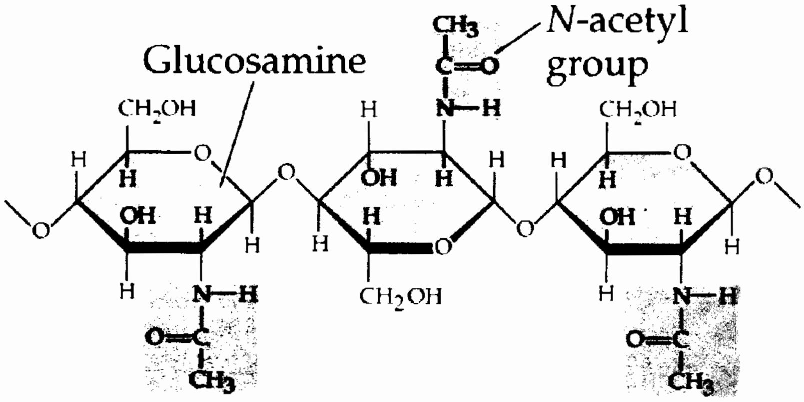


Figure 2.3 The structure of an cellulose fiber that used as salt bridge

(3) Cotton cellulose swab

Using a syringe, inject 0.1 M KNO_3 solution prepared in 1.0 gram agar-agar into the hollow plastic cotton swab stem (approximate. 75 mm in length) [40] as shown in Figure 2.5. (Note: Stems of certain types of cotton swabs (e.g., Q-tips) are not hollow.) Make sure the cotton tips on both ends of the swab are saturated with the KNO_3 solution. Use this cotton swab to bridge various pairs of half-cells in a standard 12-depression spot plate. Reported voltage measurement is within 0.03 V of the expected values [40]. Note: To avoid any personal injuries, firmly hold the cotton swab stem with a pair of tongs when injecting the KNO_3 solution.

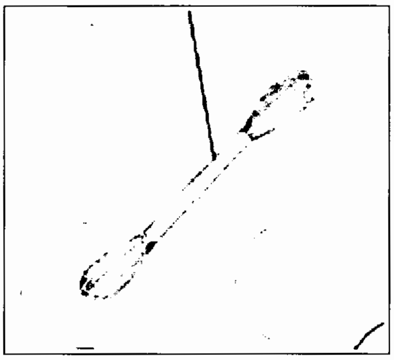


Figure 2.4 Cottons as salt bridge

Source: Dobrzynski, 1996

(4) Cotton fibers

Cotton is a natural cellulosic fiber with a soft handle. The raw cotton contains almost 85 to 90 percent cellulose in its composition. This fluffy staple fiber grows in a bowl or protective capsule. Cotton plants are under the genus Gossypium. In the present world the most important, widespread and inexpensive textile fiber is cotton, a strong, thin and hygroscopic fiber. It develops on the seeds of the cotton plant. Today it is the most used textile fiber in the world. Its current market share is 56 percent among all the textile fibers. It is used for apparel and home furnishing materials and another contribution is attributed to non-woven textiles and personal care items. Compare to other fibers, it is recognized as the most consumers prefer fiber as show in Figure 2.6.

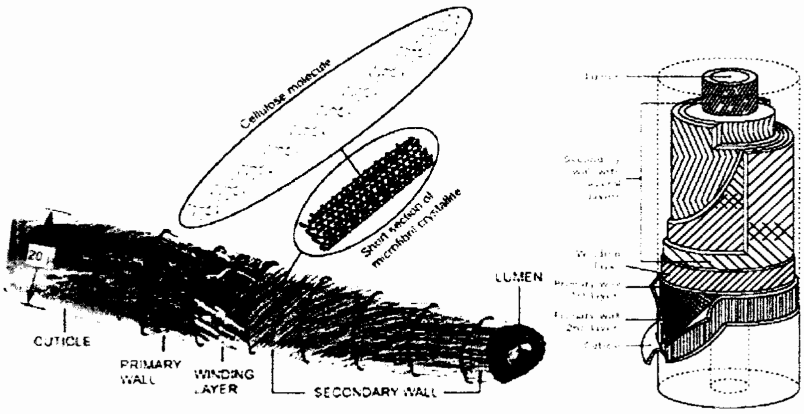


Figure 2.5 Physical structure of cotton fiber

Table 2.1 Chemical Composition of Cotton

Component	Percentage (%)
Cellulose	85.5
Water/Moisture	8
Protein	1.3
Hemicelluloses & Pectin	1.2
Waxes and fats	0.6
Pigments and Others	1.4
Ash	1.2
Total	100

The anhydroglucose units are linked together as beta-cellobiose; therefore, anhydro-beta-cellobiose is the repeating unit of the polymer chain. The number of repeat units linked together to form the cellulose polymer is referred to as the degree of polymerization as shown in Figure 2.7.

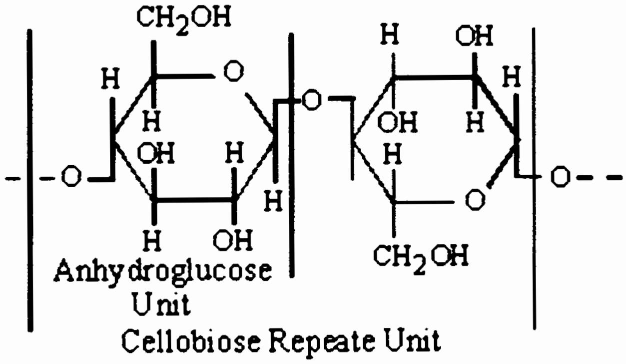


Figure 2.6 Chemical structure and repeating unit of 1,4 β-D anhydroglucopyranose

Electrode

Electrodes are sometimes referred to as "conductivity cells." All electrodes sense ions within a solution, and then return either a measured voltage or a potential difference to a corresponding meter. Maintaining and properly storing electrodes is of paramount importance. Contamination of electrode surfaces can result in severe polarization errors. To avoid this, users are typically advised to rinse electrodes with deionized water after each use; electrodes which have been used with water-immiscible solvents should be cleaned with a miscible solvent to avoid contamination. Storage of electrodes requires constant immersion in deionized water, conditioning, clean and re-polish them before re-use. There are five electrodes used in this thesis:

Cu

Copper is a chemical element with the symbol Cu (from Latin: cuprum) and atomic number is 29, atomic mass 63.546 g. Copper is a transition metal, one of several elements found in rows 4 through 7 between Groups 2 and 13 in the periodic table. Copper metal is fairly soft and ductile. Copper has a melting point of 1,083°C (1,982°F) and a boiling point of 2,595°C (4,703°F). Its density is 8.96 grams per cubic centimeter with a valence of 1 or 2. Copper is also used to make many alloys. An alloy is made by melting and mixing two or more metals. Most electrical equipment has copper wiring. The most important application of copper metal is electrical wiring. Nearly every electrical device relies on copper wiring because copper metal is highly conductive and inexpensive.

Zn

Zinc has the symbol Zn and atomic number is 30, atomic mass 65.39 g. The space between Groups 2 and 13 is occupied by the transition metals. Zinc is a lustrous bluish-white and fairly soft metal. It is found in group II B of the periodic table. The density of zinc is 7.140 grams per cubic centimeter with a valence of 1 or 2. Its melting point of 419.6°C (787.1°F) and a boiling point of 907°C (1,670°F). It is brittle at ambient temperatures but is malleable at 100 to 150°C and Zinc does not corrode (rust) as easily as iron and other metals. So the thin layer of zinc protects iron and other metals from corrosion. It is a reasonable conductor of electricity.

Mg

Magnesium has the symbol Mg, situated in group IIa in the periodic table, atomic number: 12, atomic weight: 24,312 grams. The density of magnesium is 1.738 grams per cubic centimeter, which means the metal will sink in water, but it is still relatively light weight. The surface of magnesium metal is covered with a thin layer of oxide that helps protect the metal from attack by air. Magnesium is known for a long time as the lighter structural metal in the industry, due to its low weight and to its capability of forming mechanically resistant alloys. It is lighter than aluminum, and is used in alloys used for aircraft, car engine casings, and missile construction.

Fe

Iron is a chemical element with the symbol Fe (from Latin: ferrum). Iron is a transition metal. The transition metals are the elements that make up Groups 3 through 12 in the periodic table. The melting point of pure iron is 1,536°C (2,797°F) and its boiling point is about 3,000°C (5,400°F). Its density is 7.87 grams per cubic centimeter. The melting point, boiling point, and other physical properties of steel alloys may be quite different from those of pure iron. Iron is a silvery-white or grayish metal. It is ductile and malleable. Ductile means capable of being drawn into thin wires. Malleable means capable of being hammered into thin sheets. It is one of only three naturally occurring magnetic elements. The other two are nickel and cobalt.

Al

Aluminium or aluminumwith the symbol Al. Aluminiumm is found in row 2, group 13 of the periodic table. Aluminum is a silver-like metal with a slightly bluish tint. It has a melting point of 660°C (1,220°F) and a boiling point of 2,327-2,450°C

(4,221 - 4,442°F). The density is 2.708 grams per cubic centimeter. Aluminum is both ductile and malleable. Aluminium has one interesting and very useful property. In moister air, it combines very slowly with oxygen to form aluminum oxide so, It is an excellent conductor of electricity that silver and copper are better conductors than aluminium but are much more expensive. Engineers are looking for ways to use aluminum more often in electrical equipment because of its lower costs.

Oxidation-reduction reaction

Many chemical reactions can be classified as oxidation-reduction or redox reactions. Redox replacement reactions are a common type of chemical reaction. In these reactions one species loses electrons or is oxidized while another species gains electrons or is reduced. In some cases the same species can both gain and lose electrons in a disproportionation reaction [41]. A redox reaction always consists of an oxidation reaction and a reduction reaction.

Oxidation is the loss of electron with oxidation number increases. Reduction is the gain of electron with oxidation number decreases.

It is convenient to consider such reactions as two half-reactions, one oxidation and one reduction. In the following reaction zinc loses electrons while copper ions gains electrons. The overall redox reaction and the two half-reactions are shown in Figure 2.7 in equation 2.1.

Office of Academic Resources Ubon Ratchathani University

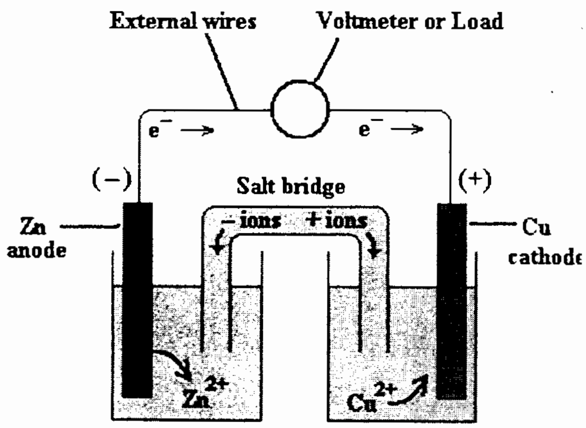


Figure 2.7 Galvanic cell based on the redox reaction in equation 2.1

Cell potential (E^0_{cell})

The theoretical cell potential or cell voltage is E^0_{cell} can be determined using the electrochemical series and is given by the difference between the standard electrode potential at the cathode, $E^0_{cathode}$, and the standard electrode potential at the anode, E^0_{anode} as shown in equation 2.2 below.

$$E^0_{cell} = E^0_{cathode} - E^0_{anode} \tag{2.2}$$

At standard conditions, indicated by the superscript °, the standard cell potential, E°_{cell}, is based upon the standard reduction potentials [42, 43], as shown in equation (2.3).

$$E^0_{cell} = E^0_{reduction} - E^0_{oxidation} \tag{2.3}$$

Based on the values for the standard reduction potentials for the two half-cells in equation (2.1), – 0.76 V for zinc anode and + 0.34 V for copper cathode as shown in appendix, the standard cell potential, E^0_{cell}, for the galvanic cell in Figure 2.7 would be:

$$E^0_{cell} = + 0.34 \text{ V} - (- 0.76 \text{ V}) = 1.10 \text{ V}$$

The positive voltage for E°_{cell} indicates that at standard conditions the reaction is spontaneous. Recall that $\Delta G_o = -nFE^0_{cell}$, so that a positive E°_{cell} results in a negative ΔG_0, so the redox reaction in equation (2.3) would produce an electric current when set up as a galvanic cell.

When conditions are not standard, the Nernst equation, equation (2.6), is used to calculate the potential of a cell. In the Nernst equation, R is the universal gas constant with a value of 8.314 J/(Kmol), T is the temperature in K, and n is the number of electrons transferred in the redox reaction, for example, 2 electrons in equation (2.4). Q is the reaction quotient for the ion products/ion reactants of the cell. The solid electrodes have constant "concentrations" and so do not appear in Q. F is the Faraday constant with a known value of 96,500 J/(Vmol) [10, 11].

$$E_{cell} = E^{0}_{cell} - \left(\frac{RT}{nF}\right)(\ln Q) \qquad (2.4)$$

2.3 The development of small-scale and low-cost galvanic cells as teaching materials in galvanic cells for high school students and related researches

2.3.1 Small-scale chemistry and related researches

Small-scale chemistry is simply the process of conducting chemical experiments on a much smaller scale. Instead of using large amounts of instrument, equipment, chemicals, etc. Small-scale chemistry builds pollution prevention, waste minimization, and student safety at the design stage rather than controlling it at the disposal stage [17, 19, 44]. Originally, small-scale chemistry was introduced in the organic chemistry laboratory at Bowdoin College, Maine. It was later expanded to cover general, inorganic, analytical, and environmental chemistry. The National small-scale Chemistry Center was established at Merrimack College in 1992–1993 as the first center to offer formal small-scale chemistry training to teachers and chemists at all levels from high school to university. Small-scale chemistry is a laboratory-based green chemistry approach. The application of green chemistry or small-scale chemistry to this laboratory product would then be a modification of the electrolytes, solution, experimental methodology, and/or products to allow the gaining of this knowledge with simply to construction in many schools and the minimum hazard to human health or the environment for industry. There are many research studies the concepts of small-scale chemistry and "Green Chemistry" have been further described in many articles [13-24, 45].

Craig. N. C. et, al (1989: 85-86) [13] were developed the simply construction of mini-ware for galvanic cell experiments to measure equilibrium constants for several reaction. The simply mini-galvanic cell consist of a small vial contains 2 M of NH_4NO_3 used as salt bridge and two medicine dropper tubes contain strip metals as show in Figure 2.10. These simply construction of this experiment provided an excellent opportunity for students to design the other experiment for the future.

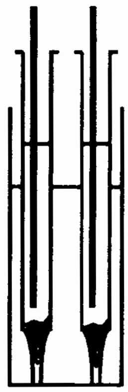


Figure 2.8 Miniware of galvanic cell

Source: Norman C. Craig, Martin N. Ackermann, and William 9. Renfrow, 1989

Eggen, Cronneberg, and Kvittingen (2006: 1201-1202) were studied of the construc-tion of galvanic cell that can be apparatus for measurement that have small-scale and low cost that students can be made in any class room. Eggen et al were used vial with saturated $CuSO_4$ and piece of floral foam after that fills it at least half of a well and place it in the well. The piece of foam should be slightly taller than the depth of the well then push a magnesium strip (3-4 cm) into floral foam, then put a graphite rod in the empty space of the vial with adding inert salt solution onto the floral foam and connect a light diode to the magnesium ribbon (anode) and the graphite rod (cathode) with crocodile clips as show in Figure 2.11 indicated that the diode will shine [21].

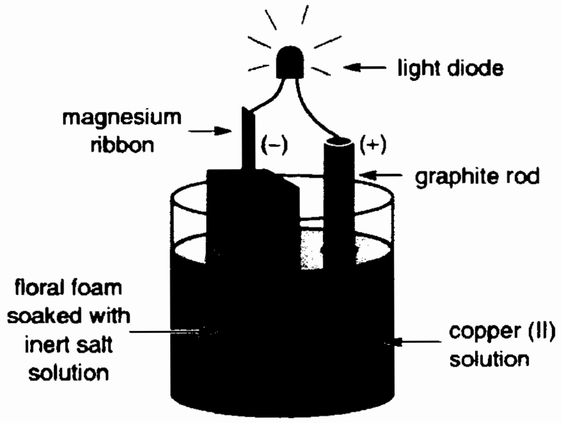


Figure 2.9 Simply small-scale a galvanic cell

Source: Eggen, Cronneberg, and Kvittingen, 2006

In addition, they are try to construct of easy cell battery from this galvanic cell that there made in 2 cells but use iron strip or galvanized nail represent magnesium ribbon push into the floral foam in both well by twist one end of a silver wire attach a graphite rod to the nail in one well, then connect both of them with diode by iron nail of the first cell is anode and graphite is cathode as show in Figure 2.12.

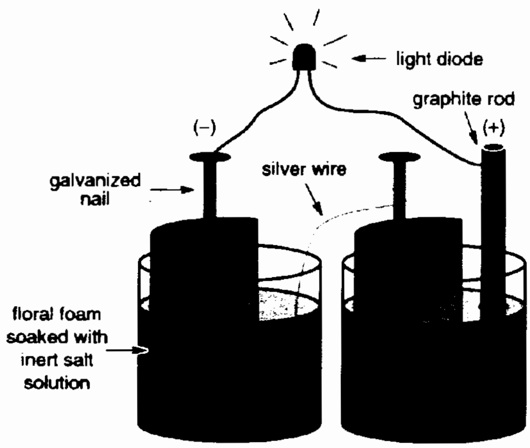


Figure 2.10 Simply small-scale two galvanic cell

Source: Eggen, Cronneberg, and Kvittingen, 2006

Eggen, Cronneberg, and Kvittingen (2006: 671-673) were described how to construct of some electrode that can be material that small-scale and low cost for measurement of cell potential of half cell reduction by establish in three electrodes: Copper electrode, Hydrogen electrode, and Chlorine electrode [22, 46]. For copper reference electrode made from a plastic pipette by filled with 1.0 mol/l of $CuSO_4$, the tip is blocked with become agar-agar in 1.0 mol/L of KNO_3 then push copper wire into the bulb and soak in solution of $CuSO_4$ as show in Figure 2.13.

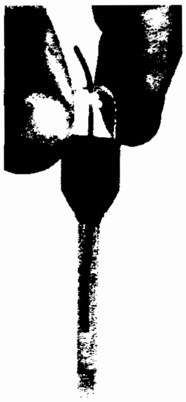


Figure 2.11 Copper reference electrode

Source: Eggen, Cronneberg, and Kvittingen, 2007

For Hydrogen and Chlorine electrode, used platinum wire push through the top of the bulbs and half way down the stem in both pipettes then fill both pipettes with 1.0 mol/L of HCl and replace the two pipettes into small vial. Finally, connect the Pt wire to a 9 voltage battery until occur gas in both bulbs, indicated hydrogen gas will occur show that hydrogen electrode is in (-) bulb and a chlorine is in the (+) bulb. The voltage measured over for this cell is 1.36 V as show in Figure 2.14.

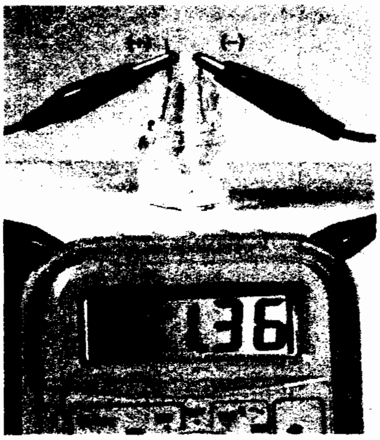


Figure 2.12 The voltage between a hydrogen electrode (-) sign and chlorine electrode (+) sign.

Source: Eggen, Cronneberg and Kvittingen, 2007

Then, they bring this electrode hydrogen electrode and copper electrode that there made to measure the voltage standard reduction, indicated that the voltage of this cell is +0.34 V. It is the same as of calculated from theory as show in Figure 2.15.

Figure 2.13 The voltage between copper and standard hydrogen electrode.

Source: Eggen, Cronneberg and Kvittingen, 2007

Muske, K. R.et al. (2007: 632-636) presented the power source for the 9-V electric dc motor from lemon juice. The lemon cell battery is constructed a copper strip on one side of a cuvet and the other side is magnesium strip. Cells may be connected in series by contacting the bent portion of the magnesium strip of one cell with the bent portion of the copper strip of another cell until six cell. The last, used an alligator clip to connected in each series and the cells are activated by filling with lemon juice for the final [47]. A schematic of this cell shown in Figure 2.16.

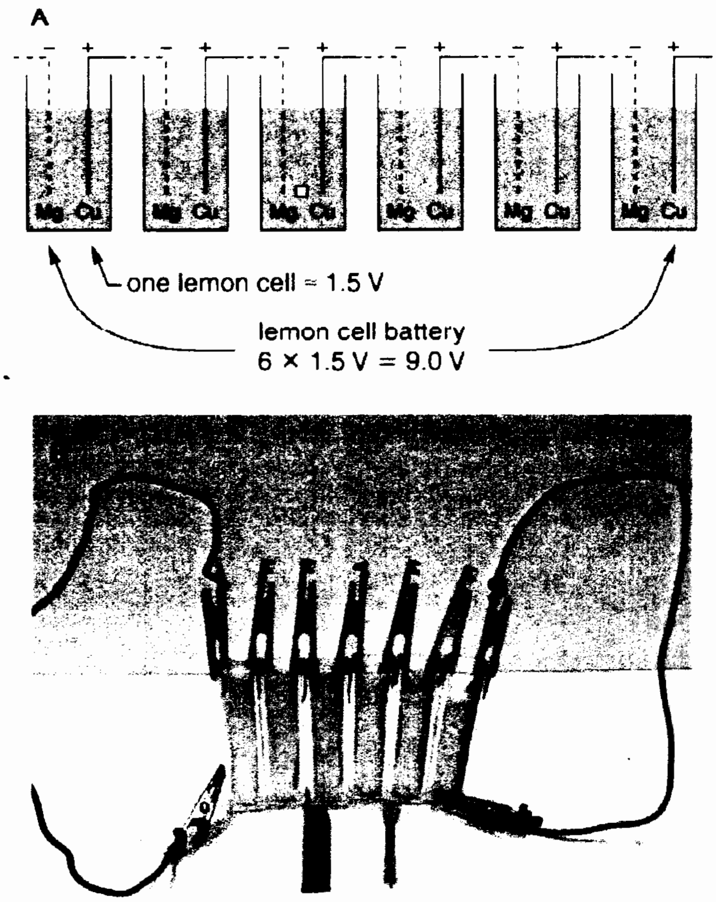


Figure 2.14 (A) Six lemon juice cuvet cells connected in series to form a 9-V battery. (B) A schematic of a six-cell 9-V lemon cell battery.

Source: Muske, Nigh and Weinstein, 2007

Udnan, Y.et al. (2008: 535 - 537) developed and successfully applied of micro-scale apparatus for electrochemical cells such galvanic and electrolytic cells. The micro-electrochemical cell was made from small glass tubes. A liquid junction was prepared by mixing 2:1 (by volume) of plaster and saturated about 5 mol/L of KCl in a 50 milliliter beaker and stirring. The glass tubes were dipped 0.5 cm into the mixture and left to harden for about 5 minutes, then carefully pulled out. Each tube was then filled with an appropriate solution and an appropriate metal electrode was dipped into the tube by used multimeter to measure the potential of the galvanic cell [45] as show in Figure 2.17.

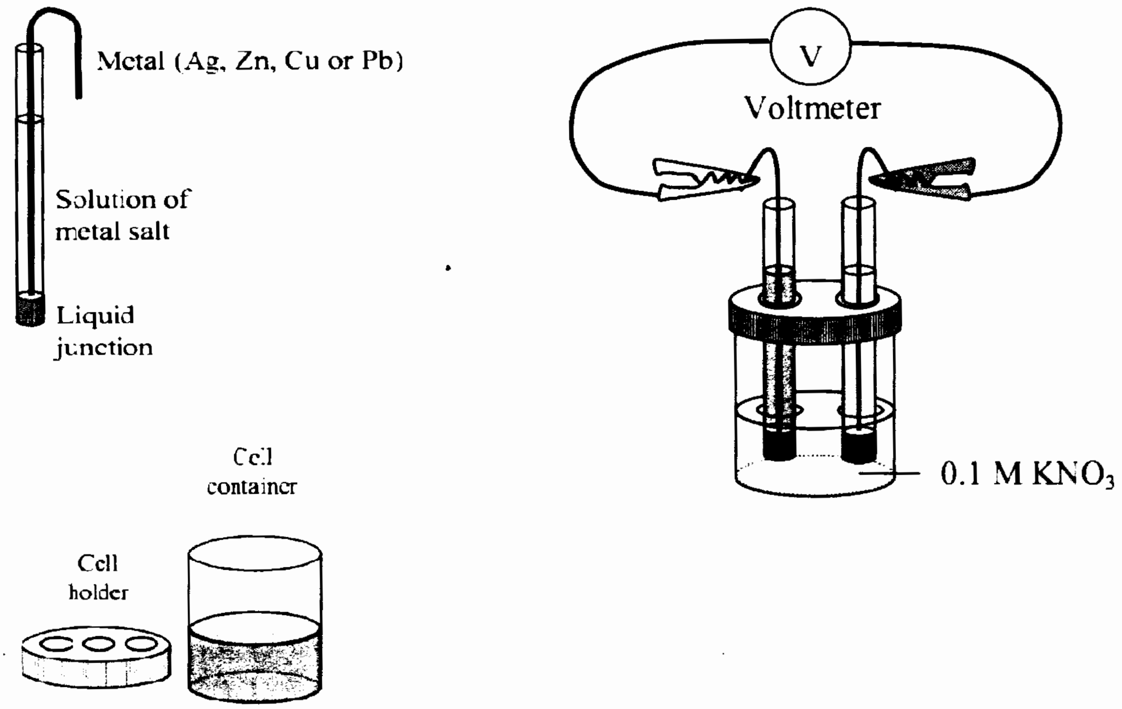


Figure 2.15 Galvanic cell of KNO_3 using small scale apparatus.

Source: Udnan, Wipharat and Ratana, 2008

However the cell performance was good, such a platform is slightly different from the conventional platform employing a solid supporter as a salt bridge (*e.g.* as illustrated in Figure 1.1A) which is usually shown in many text books. The unsteady voltage of the previously reported cell caused by inconsistency in cotton plug packing was also noted [13] as well as short cell lifetime which may be another disadvantage.

This study aimed to develop small-scale and low-cost galvanic cells as teaching materials in electrochemistry for high school students. To the best of our knowledge, a small platform of galvanic cells with approximately 10-fold reduction of electrolyte volume using cotton thread as a material in the salt bridge has not been previously reported. The aim of this part is to develop such a platform (Figure 1.1B) aimed to be used in high school laboratories.

2.4 The investigation of students' conceptual understanding of electrochemistry and mental model of a galvanic cell prior to and after the performance of corresponding experiments and model kit based on 5E inquiry learning activities and related researches

2.4.1 Three levels of representations in chemistry and related researches

Previous studies reported that many alternative conceptions in some intangible concepts arose from the fact that students have difficulty in understanding the relationship among representations in chemistry [28, 48]. Representations in chemistry, also called chemical representations, refer to various types of formula, structures, an symbols used to represent chemical processes and conceptual entities, such as molecules and atoms. They can be viewed as metaphors, models, and theoretical constructs of chemists' interpretations of nature and reality (Hoffmann & Laszlo, 1991). Previous research highlighted three levels of representations in chemistry [49-51]:

(1) Macroscopic representation. This describes bulk properties of tangible and visible phenomena in the everyday experiences of learners when observing changes in the properties of matter, such as color changes, formation of gases, and precipitates in chemical reactions.

(2) Sub-Microscopic Representation. This is also called molecular representation, and provides explanations at the particulate level in which matter is composed of atoms, molecule and ions.

(3) Symbolic Representation. This involves the use of chemical symbols, formula, and equations, as well as molecular structure drawings, diagrams, and models to symbolize matter. It can provide information for both macroscopic (relative

amounts or moles of involved substances) and molecular levels (numbers of formula unit of involved substances).

Çalik et al (2010) [48] considered studies of students' alternative conceptions in such topics as electrochemistry, acids and bases, chemical equilibrium, and rates of reactions. They concluded that some alternative conceptions arose because many students find it difficult to visualize chemical phenomena and/or processes at the sub-microscopic level and to link the macroscopic, submicroscopic, and symbolic levels to each other. They also explored Turkish grade 11 students' conceptions of chemical reaction rates. Their intervention consisted of nine classes of 45 minutes using three guide sheets and 11 computer animations. The students were first given a student guide sheet containing scientific questions to promote curiosity and draw out their prior knowledge. They then were asked to interact with the animations followed by group discussions. Next, they were introduced to the concepts and processes of rates of reactions to enhance their conceptual understanding. Finally, they attempted to extend their understandings of the concept which were assessed by means of questions at the bottom of each guide sheet. The researchers reported that this teaching intervention could help students correct their alternative conceptions but may not completely eliminate them. Therefore, instructors should utilize more than one intervention model to overcome students' alternative conceptions.

2.4.2 Roles of mental model in learning chemistry and related researches

Students' conceptual understanding, especially intangible concepts in phenomena/processes/systems, involves the ability to relate to the three representations in chemistry. The term mental model was introduced to describe how students construct a model of understanding of a specific process by the incorporation of new received information into their existing knowledge [49]. Mental models are representations of objects, ideas, thinking, or processes which individuals intrinsically construct during cognitive functioning [52, 53]. People use these models to reason, describe, explain, and/or predict scientific phenomena, processes, or systems. Mental model can be generated in various formats to communicate ideas to other people or to solve problems [52, 53], and can represent either physical entities via verbal descriptions, diagrams, simulations, and concrete models, or conceptual understanding, such as models of ideas, thinking, or intangible concepts [54, 55]. If their mental models fail to assimilate new experiences, students may modify their existing models or generate alternative models [56]. Mental models are considered as an important part of learners' conceptual frameworks [56] and they play a potential role in learning chemistry at the molecular level because much of chemistry involved at this level cannot be access by direct perception [57]. Full understanding of chemical processes involves the ability to connect events at a macroscopic level with events at the molecular level [49].

Therefore, students need to transform these invisible events or phenomena into equivalent mental or conceptual models or representations, which is difficult for many students [58-60].

Based on the information above, the term 'mental models' in this study context are the models of understanding (in form of drawings) that students use to relate and describe their understanding of how a galvanic cell functions at a macroscopic, symbolic, and sub-microscopic levels.

Cullen and Pentecost (2011: 1562-1564) [28] reported evidence that chemistry textbooks and instructors are responsible for many students' alternative conceptions involving electrochemistry. Instructors tend to use everyday language that can lead to misinterpretation by their students. They then designed a paper model (figure 2.18) to teach about galvanic (voltaic) cells to address students' alternative conceptions by adaptation of an inexpensive, portable, and flexible teaching model by Huddle, White and Roger (2000). This paper model was used in conjunction with electrochemistry laboratory activities and allows students to visualize that no electrons pass into the solutions and how mass of electrodes is gained and lost. The researchers also commented that as students demonstrated and discussed the model within their groups, they were constructing their own understanding of galvanic cells.

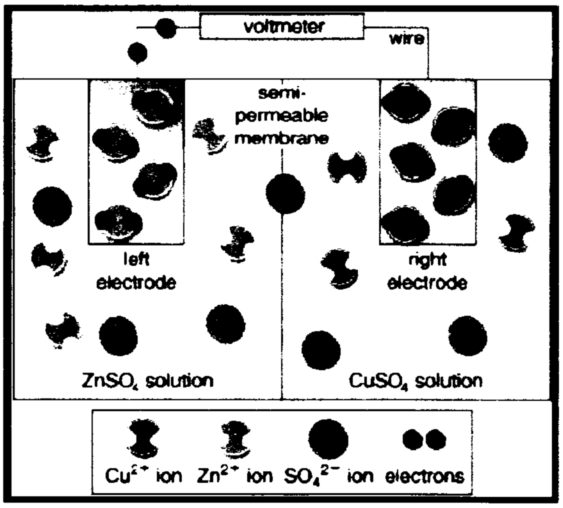


Figure 2.16 A galvanic cell model kit

Source: Cullen and Pentecost, 2011

2.4.3 5 E inquiry learning activities

Inquiry learning activities were considered to be effective in teaching chemistry and have been highly advocated in the last few decades [61]. These types of activities possess more advantages over traditional approaches. These advantages include the encouragement of students to practice using learning resources and working in groups to enhance their conceptual understandings, and the opportunities for teachers to play roles as facilitators who motivate and challenge students to carry out the activities through a science inquiry process [62]. The 5E learning cycle has been proven to be one of the most effective inquiry learning in chemistry [63]. It involves students through the following steps: 1) students are engaged in inquiry questions, 2) students explore answers to the questions by planning, designing, and carrying out their experiment, and recording the experiment data, 3) students make explanations from the experimental data to answer the questions, 4) students elaborate, extend, or apply their findings in a new context, and 5) students evaluate their experimental processes and results in a variety of ways. This learning cycle is effective to support students to notice and correct their alternative conceptions [63, 64].

The literature review above suggests that the implementation of corresponding experiments through the 5E inquiry learning approach is effective to enhance students' conceptual understanding of the corresponding concepts. The use of inquiry experiments in conjunction with a corresponding model featuring the sub-microscopic level could be more effective to enhance students' conceptual understanding and mental models of the corresponding concepts. As a result, the combination of 5E inquiry experiments and a galvanic cell model kit featuring sub-microscopic level was used as the intervention tools in this study to minimize students' difficulty in visualizing and relating what occurs at the sub-microscopic level to the macroscopic and symbolic levels of galvanic cells.

CHAPTER 3
EXPERIMENTAL

3.1 Chemicals

All chemical used in this thesis were an analytical grade as shown in Table 3.1

Table 3.1 Chemicals

Chemicals	Formula	Assay (%)	Manufacturer
Copper (II) sulfatepentahydrate	$CuSO_4 \cdot 5H_2O$	98.0–102 %	CARLO ERBA
Zinc sulfateheptahydrate	$ZnSO_4 \cdot 7H_2O$	99.0–100 %	CARLO ERBA
Iron (II) sulfateheptahydrate	$FeSO_4 \cdot 7H_2O$	$\geq$ 99.0 %	CARLO ERBA
Magnesium sulfateheptahydrate	$MgSO_4 \cdot 7H_2O$	98.0–102 %	Istalmal
Aluminiumsulfate octadecahydrate	$Al_2(SO_4)_3 \cdot 18H_2O$	53.4 %	Ajax Finechem
Potassium nitrate	KNO_3	ACS	Ajax Finechem
Sodium nitrate	$NaNO_3$	ACS	CARLO ERBA
Sodium chloride	$NaCl$	98.0–102%	Ajax Finechem
Sulfuric acid	H_2SO_4	$\geq$ 99.0 %	CARLO ERBA
Deionization water	H_2O	17.2 mΩ	Faculty of Science, UBU

The details of apparatus for small-scale and low cost of experiment kits for high school student were listed in Table 3.2.

3.2 Apparatus

Table 3.2 Apparatus

Apparatus	Model	Company
Digital multimeter	AT9205B	ATTEN® INSTRUMENT
Electric balance	F00414	JEOL
Electric balance	F00415	JEOL
Alligator clips	XE-100	PARK
Digital camera	L25	Nikon Corp,Japan
Zinc strip	-	-
Copper strip	F-27106	CARLO ERBA
Magnesium strip	-	CARLO ERBA
Aluminium strip	-	CARLO ERBA
Ferrous strip	-	-
Vial	M2026	Sigma Aldrich
Filter paper	24001	Teachtech.co.th
Volume metric flask	22031	Teachtech.co.th

3.3 Experimental

The method was designed according to the concept of “Green chemistry” reducing use of chemicals, less waste generation, and time consumption while retaining the experimental concepts. In this research, these galvanic cells contain various common electrodes, including Cu, Zn, Al, Mg and Fe because these electrodes can be made by most students in any laboratory or most classrooms. The experiments of galvanic cell included 7 cells as shown in table 3.3.

Table 3.3 The experiments of galvanic cells included 7 cells

List	Cells
1	$Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$
2	$Cu(s)|Cu^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$
3	$Zn(s)|Zn^{2+}(aq)||Mg^{2+}(aq)|Mg(s)$
4	$Zn(s)|Zn^{2+}(aq)||Al^{2+}(aq)|Al(s)$
5	$Zn(s)|Zn^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$
6	$Al(s)|Al^{3+}(aq)||Mg^{2+}(aq)|Mg(s)$
7	$Fe(s)|Fe^{2+}(aq)||Mg^{2+}(aq)|Mg(s)$

3.3.1 Preparation of electrolytes and electrodes

3.3.1.1 Preparation of Electrolytes

All electrolytes were prepared with laboratory grade reagents and deionized (DI) water

$CuSO_4$ Solution in 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $CuSO_4$ solutions were prepared by dissolving 24.96 g, 2.49g, and 0.24g of $CuSO_4{\cdot}5H_2O$ in 100 mL of DI water using volumetric flask, respectively.

$ZnSO_4$ Solution in 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $ZnSO_4$ solutions were prepared by dissolving 28.74 g, 2.87 g, and 0.28 g of $ZnSO_4{\cdot}7H_2O$ in 100 mL of DI water using volumetric flask, respectively.

$MgSO_4$ Solution in 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $MgSO_4$ solutions were prepared by dissolving 24.64 g, 2.46 g, and 0.246 g of $MgSO_4{\cdot}7H_2O$ in 100 mL of DI water using volumetric flask, respectively.

$FeSO_4$ Solution in 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $FeSO_4$ solutions were prepared by dissolving 27.80 g, 2.78 g, and 0.278 g of $FeSO_4{\cdot}7H_2O$ in 100 mL of DI water (60 °C) using volumetric flask, respectively. Alternatively, $FeSO_4$ solution was also prepared in the laboratory by reacting iron oxide Fe_2O_3 with diluted sulfuric acid H_2SO_4 [65].

$Al_2(SO_4)_3$ Solution 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $Al_2(SO_4)_3$ solutions were prepared by dissolving 66.59 g, 6.65 g, and 0.66 g of $Al_2(SO_4)_3 \cdot 18H_2O$ in 100 mL of DI water using volumetric flask, respectively.

KNO_3 Solution 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of KNO_3 solution were prepared by dissolving 10.10 g, 1.01 g, and 0.10 g of KNO_3 in 100 mL of DI water using volumetric flask, respectively.

$NaNO_3$ Solution 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of $NaNO_3$ solutions were prepared by dissolving 8.46g, 0.84 g, and 0.08 g of $NaNO_3$ in 100 mL of DI water using volumetric flask, respectively.

NaCl Solution 1 M, 0.1 M, 0.01 M

1 M, 0.1 M, and 0.01 M of NaCl solutions were prepared by dissolving 5.84 g, 0.58 g, 0.05 g of NaCl in 100 mL of DI water using volumetric flask, respectively.

3.3.1.2 Preparation of electrodes

Electrodes or strips of different metals were polished by sandpaper and/or dipping in 3 M HCl and cut into the dimension of 0.054 cm x 9 cm.

3.3.2 Experimental of electrochemical cell based on the institute for the promotion of teaching science and technology Thailand (conventional method)

3.3.2.1 Study of the reaction of metals in various solution (oxidation-reduction reaction)

In this experiment, general of metals such as copper (Cu), zinc (Zn), iron (Fe), magnesium (Mg), and aluminum (Al) are used as shown in figure 3.1

1) Place polished strips of Cu, Zn, Mg, Fe and Al into the electrolytes solutions as an information show in the table 3.4 by keeping the volume of solution constant at 20 mL.

2) The electrolytes should be located at the electrode about three-quarters.

3) The oxidation-reduction reactions of various metals which were placed in various metal ions solutions as demonstrated in Table 3.4 were observed.

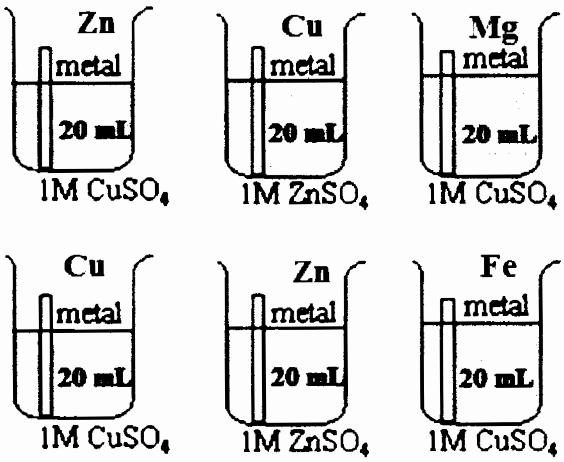


Figure 3.1 The reaction of metals in various solutions (20 mL, 1 M of solutions)

Table 3.4 The reactions of metals in various solutions (20 mL, 1 M of solutions)

Solutions	**Metals**				
1M, 20 mL	**Cu(s)**	**Zn(s)**	**Mg(s)**	**Fe(s)**	**Al(s)**
$CuSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$ZnSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$MgSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$FeSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$Al_2(SO_4)_3$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR

Note: NR means no reaction

R means reaction was occurred; including corrosion of metals and bubble of gas

3.3.2.2 Study of electron transfer in galvanic cells

1) All electrolytes were prepared by 20 mL of 1 M $CuSO_4$ and 20 mL of 1 M $ZnSO_4$ solutions into the beakers. Place the Zn electrode into $ZnSO_4$ solution and the Cu electrode in the $CuSO_4$ solution, for instance.

2) The salt bridge was prepared by cutting of filter paper into the dimension of 1.5 cm x 25cm. The solution was soaked into the solution of 1M KNO_3 (saturated). One side of salt bridge was dipped into $ZnSO_4$ solution and another side of salt bridge was dipped to $CuSO_4$.

3) The black wire (anode) was connected to the Zn electrode and the red wire (cathode) was connected to the Cu electrode. The cell potential was not shown any signal until the circuit was completely set as demonstrated in the figure 3.2.

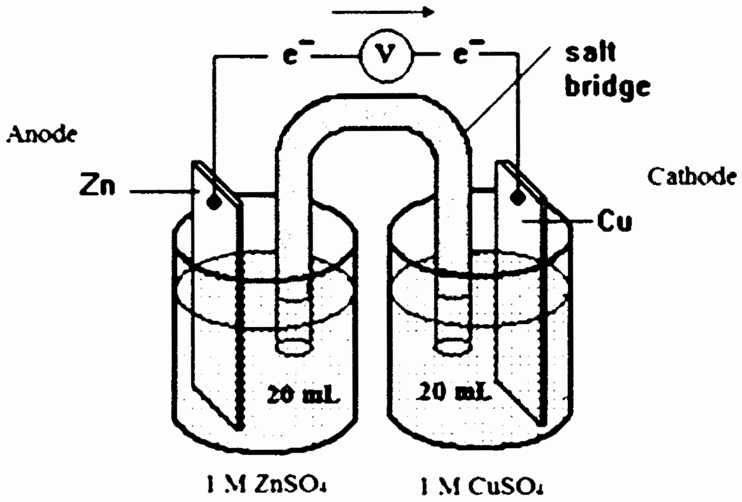


Figure 3.2 Conventional of galvanic cell (voltaic cell)

4) The other cells were set up as same as above mentioned by following the information demonstrated in Table 3.5.

5) The cell potential was measured by digital multimeter which was compared with the value obtained from the standard value which was obtained from the calculation.

6) All metals strip and salt bridge can be reused

Table 3.5 The set up of galvanic cells

List	Cells
1	$Cu(s)|Cu^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$
2	$Zn(s)|Zn^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$
3	$Zn(s)|Zn^{2+}(aq)||Mg^{2+}(aq)|Mg(s)$
4	$Zn(s)|Zn^{2+}(aq)||Al^{2+}(aq)|Al(s)$
5	$Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$
6	$Al(s)|Al^{3+}(aq)||Mg^{2+}(aq)|Mg(s)$
7	$Fe(s)|Fe^{2+}(aq)||Mg^{2+}(aq)|Mg(s)$

3.3.3 Experimental on the small scale method (developed method)

3.3.3.1 The study of parameters that affected on the developed method

The experimental in this section were set up as same as 3.3.3.2 by observing in 7 cells in table 3.3. The statistics were analyzed by the use of mean (M), standard deviation (SD), relative standard deviation (%RSD) and paired samples t-test.

Effect of electrolyte volume

The volume of electrolyte in galvanic cells was varied in the range of 0.5 - 3.0 mL by fixed the concentration of electrolyte at 0.01 M at room temperature (~29 ° C). Meanwhile, the cell potential was measured by digital multimeter.

Effect of electrolyte concentration

The concentration of electrolytes solution in galvanic cell was varied in the range of 0.005 M, 0.010 M, 0.015 M, 0.020 M, 0.025 M and 0.030 M by fixed the volume of electrolyte at 2 mL at room temperature (~29 ° C). Meanwhile, the cell potential was measured by digital multimeter.

Effect of solution types used in a salt bridge

The effect of solution types used in a salt bridge was investigated. The cotton thread was selected to be a salt bridge in this study. Since the cotton thread was available everything and inexpensive. The 0.01 M of KNO_3, $NaNO_3$ and NaCl were selected to be a candidate solution for salt bridge in this study by optimum of electrolytes volume (2 mL) and electrolytes concentration (0.01 M). The cell potential was measured by digital multimeter.

Effect of electrolytes life time

The stability life times of electrolyte were studied using the optimum conditions in the range of 0-4 h, overnight and one month 720 h. The cell potential was measured by digital multimeter.

Method validation of developed and conventional method

These optimum experiments were set of 7 galvanic cells: Zn-Cu, Cu-Fe, Cu-Al, Zn-Mg, Zn-Al, Zn-Fe, Al-Mg and Fe-Mg by compared the cell potential between the developed method and conventional method using t-test.

3.3.3.2 Study of the reaction of metals in various solutions (oxidation-reduction reaction)

1) Place polished strips of Cu, Zn, Mg, Fe and Al into the electrolytes solutions as an information show in the table 3.4 by keeping the volume of solution constant at 2 mL.

2) The electrolytes should be located at the electrode about three-quarters.

3) The oxidation-reduction reactions of various metals which were placed in various metal ions solutions as demonstrated in Table 3.6 were observed.

Figure 3.3 The reaction of metals in various solutions (2 mL, 0.01 M of solutions)

Table 3.6 The reactions of metals in various solutions (oxidation-reduction reaction) (2 mL, 0.01 M of solutions)

Solutions	**Metals**				
0.01M, 2 mL	**Cu(s)**	**Zn(s)**	**Mg(s)**	**Fe(s)**	**Al(s)**
$CuSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$ZnSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$MgSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$FeSO_4$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR
$Al_2(SO_4)_3$(aq)	R/NR	R/NR	R/NR	R/NR	R/NR

Note: NR means no reaction

R means reaction was occurred; including corrosion of metals and bubble of gas

3.3.3.3 Study of electron transfer in galvanic cell

1) All electrolytes were prepared by 2 mL adding of 0.01 M $CuSO_4$ and 2 mL of 0.01 M $ZnSO_4$ solutions into the beakers. Place the Zn electrode into $ZnSO_4$ solution and the Cu electrode in the $CuSO_4$ solution, for instance.

2) The salt bridge was prepared by cutting of cotton thread into the dimension of 0.032 cm x 18 cm. The solution was soaked into the solution of 0.01 M KNO_3 (saturated). One side of salt bridge was dipped into $ZnSO_4$ solution and another side of salt bridge was dipped to $CuSO_4$.

3) The black wire (anode) was connected to the Zn electrode and the red wire (cathode) was connected to the Cu electrode. The cell potential was not shown any signal until the circuit was completely set as demonstrated in the figure 3.4.

4) The other cells were set up as same as above mentioned by following the information demonstrated in Table 3.5.

5) The cell potential was measured by digital multimeter which was compared with the value obtained from the standard value which was obtained from the calculation.

6) All metals strip and salt bridge can be reused

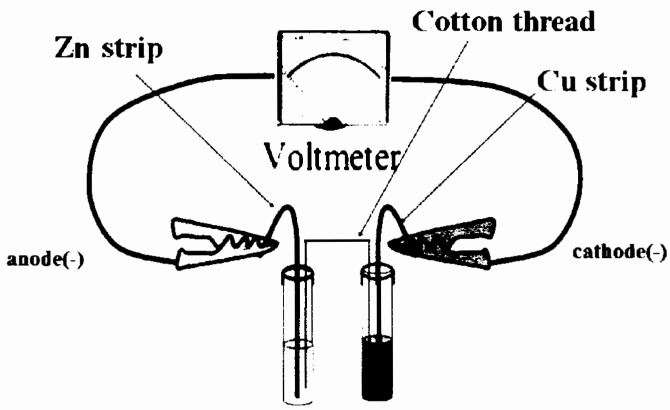


Figure 3.4 Small-scale of galvanic cell (voltaic cell)

3.3.3.4 Application of developed method for batteries

Battery is a device consisting of two or more galvanic cells that converts stored chemical energy into electrical energy. A battery is defined as a set of galvanic cells connected in series. In a series connection, the negative electrode of one cell is connected to the positive electrode of the next cell. Zn-Cu and Mg-Zn were chosen to study the batteries. The set up was fixed to 3 cells of batteries as demonstrated in figure 3.5. All electrolytes were prepared by 2 mL of 0.01 M $CuSO_4$ and 2 mL of 0.01 M $ZnSO_4$ solutions into the vial. Place the Zn electrode into $ZnSO_4$ solution and the Cu electrode in the $CuSO_4$ solution, for instance.

1) The salt bridge was prepared by cutting of cotton thread into the dimension of 0.032 cm x 9 cm. The solution was soaked into the solution of 0.01 M KNO_3 (saturated). One side of salt bridge was dipped into $ZnSO_4$ solution and another side of salt bridge was dipped to $CuSO_4$.

2) The black wire (anode) was connected to the Zn electrode and the red wire (cathode) was connected to the Cu electrode. The cell potential was not shown any signal until the circuit was completely set as demonstrated in the figure 3.5.

3) The cells of Mg-Zn were set up as same as above mentioned.

4) The cell potential was measured by digital multimeter which was compared with the value obtained from the standard value which was obtained from the calculation.

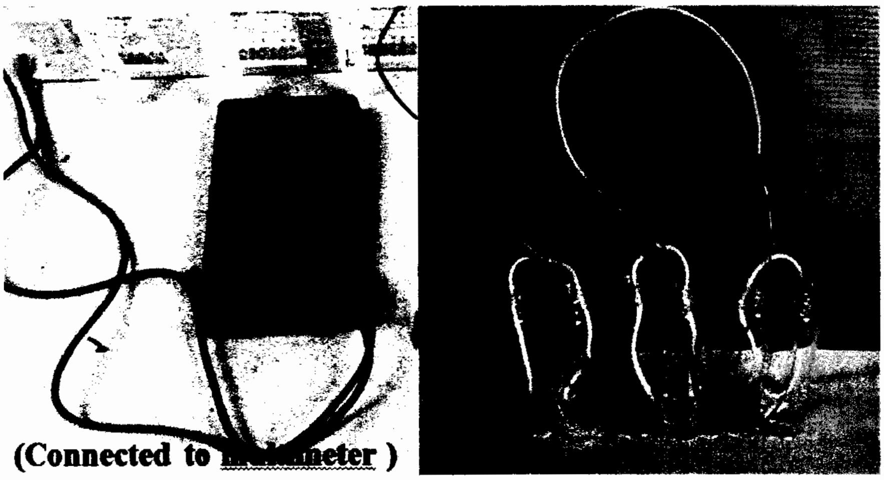


Figure 3.5 Connecting batteries in series of $Zn(s)Zn^{2+}(aq||Cu^{2+}(aq)|Cu(s)$

3.3.4 Application of small-scale experiment to high school student

3.3.4.1 Participants

The study was conducted in July during the first semester of academic year 2014. A total of 28 participants within the age range of 14-16 year-old (one classroom) who attended all activities throughout the study were purposively selected as the participants for the conceptual test. They are in the Gifted in Science classroom at Satrisiriket School in Srisaket Province. However, only 22 students completed the post-mental model drawings, so the participants for the mental models were 22 students. The participants were asked for permission to use their conceptual test information and to reproduce their drawings for the study report and publication.

Notice that all research tools both treatment tools (lesson plans) and data collecting tools (conceptual tests and mental model drawings) were in Thai language. The class was taught in Thai language and all examples included in this article involved translation into English as shown in appendix b. In addition, these students had a chance to experience a two-tier conceptual test in which they were asked to explain their choices in the second tier in the previous semester. This could support students to be able to provide fruitful information in their explanation.

3.3.4.2 Implementation

Prior to the series of four 5E inquiry learning activities, the participants spent one hour to complete the conceptual test of electrochemistry and mental model drawing of a galvanic cell (pre-test and pre-mental model). The students were then divided into groups of four or five students and requested to participate in four 5E inquiry learning activities as shown in Table 3.7. They then started the inquiry activities in order of oxidation and reduction of metals in metal ion solutions, generation of galvanic cells, connection of series and parallel batteries, and cathodic protection of iron nails by using Zn and Mg metals. In each 5E learning activity, the students were requested to participate in the following process.

1) Engagement: They were engaged in a scientifically-oriented question in regard to electrochemistry (one main question in each experiment, see Table 3.7).

2) Exploration: They explored and gathered data to answer the question by planning and carrying out an experiment.

3) Explanation: They formulated explanations based on their summarized data and scientific knowledge to answer the question.

4) Elaboration: They elaborated, extended, related, or applied their macroscopic and symbolic findings from the experiment to the sub-microscopic level by interacting in regard of the question "Based on your experiment results at a macroscopic level and the equation at a symbolic level, how does the reaction occur at a sub-microscopic level?"

5) Evaluation: They were evaluated their understanding by means of class and group discussions regarding the experiment concepts.

The oxidation and reduction topic was raised as an example of 5E inquiry learning activities in this study. The students were firstly engaged with the inquiry question "How does each metal (Mg, Fe, Al, Zn, and Cu) react with various metal ion solutions?" The instructor then summarized and wrote students' responses on the whiteboard. After that the instructor divided them into small groups and allowed them to plan and conduct an experiment to answer the engaged question by using the provided metals, solutions, and equipment.

The instructors and two teaching assistants acted as facilitators during this step. After they completed their experiments, they were asked to summarize their experimental data and then formulate explanations to answer the engaged question. This step involved both macroscopic and symbolic representations. Next, they were asked to interact to explain what happens at the sub-microscopic level based on their experiment results about how each metal (Mg, Fe, Al, Zn, and Cu) reacts with various metal ion solutions in front of the class. This step allowed students to elaborate what they experienced at the macroscopic and symbolic levels to the sub-microscopic level. Finally, they were evaluated their conceptual understanding by requesting them to generate oxidation and reaction reactions for other metals (i.e., Sn, Ni and Ag) and write chemical equations. Please note that group and class discussions were encouraged during the explanation and elaboration steps.

Table 3.7 Key 5E learning activities of galvanic cells

Plan (hours)	Key activities
1. Pre-test (1.0)	- Pre-conceptual test and pre-mental model drawing.
2. 5E learning (6)	
2.1 Oxidation and reduction (2.0)	Main question: How do metals react with metal ion solutions? - Observing oxidation and reduction reactions of metals (Mg, Zn, Fe, Al, Cu) in metal ion solutions (Mg^{2+}, Zn^{2+}, Fe^{2+}, Cu^{2+}). - Discussing oxidation and reduction reaction.
2.2 Galvanic cells (2.0)	Main question: How can galvanic cells be generated from variety of half-cells? How do they react? - Constructing galvanic cells from various half-cells ($Mg|Mg^{2+}$, $Zn|Zn^{2+}$, $Fe|Fe^{2+}$, $Cu|Cu^{2+}$) and measuring their cell voltages.

Table 3.7 Key 5E learning activities of galvanic cells (continued)

Plan (hours)	Key activities
2.2 Galvanic cells (2.0)	- Discussing what occurs at the sub-microscopic level of galvanic cells by interacting with the model.
2.3 Batteries (1.0)	Main question: How can series and parallel batteries be generated and how do their reactions occur? - Connecting batteries in series and in parallel using highest voltage galvanic cell obtained from previous experiment. Discussing what occurs at sub-microscopic level of batteries.
2.4 Cathodic protection (1.0)	Main question: How can Mg and Zn metal protect iron nails from rusting? - Observing cathodic protection of iron nails by using Mg and Zn as anode. - Discussing how cathodic protection works by using the model kit.
3 Post-test (1.0)	- Post-conceptual test and post-mental model drawing

After the completion of the four learning activities for a total of 10 hours, the students were asked to complete the conceptual test of electrochemistry (the same test with rearrangement of choice and item orders) and make changes to their mental model drawings or draw a new one (post-test and post-mental model). Finally, participants in each of "Sound Understanding: SU", "Partial Understanding: PU", "Partial Understanding with Specific Misunderstanding: PMU", "Specific Misunderstanding: MU", and "No Understanding: NU" categories were purposively selected for informal unstructured interview regarding their supplied reasons in the explanation tiers of the conceptual test and in their mental model drawings.

3.3.4.3 Treatment Tools

Two types of treatment tools were developed in this study, small-scale experiments and the galvanic cell model (zinc metal chart). The small-scale experiments consisted of 1) oxidation and reduction reactions (Figure 3.6 a), 2) galvanic cells (Figure 3.6 b), 3) cathodic protection of iron nails (Figure 3.6 c), and 4) connecting batteries (Figure 3.6 d).

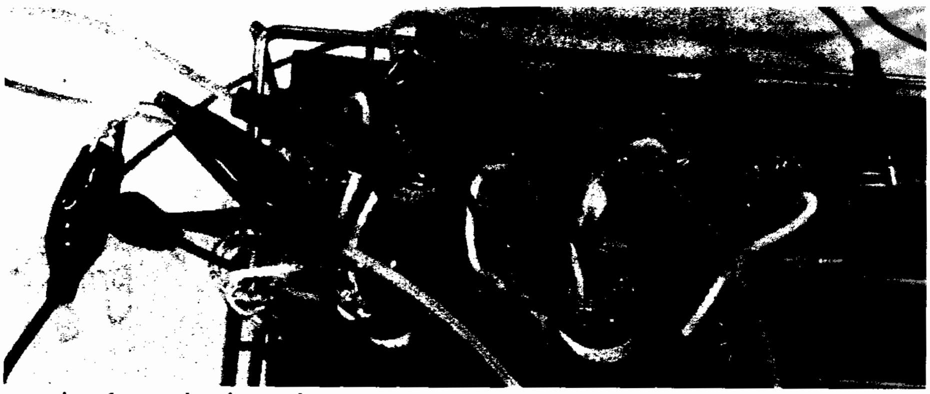
The experiments were designed with regard to some 'green' chemistry principles, such as reducing the amounts of chemicals used, toxic chemicals, and generated wastes [66]. The concentration and volume of solutions used in this study were 2.00 mL and 0.01 M. The terms 'small-scale' and 'low-cost' were applied since these experiments reduced the scale of the normal experiments by at least 1,000 or 2,000 times and used inexpensive equipment, chemicals, and substances. A cotton thread (with the length of 15-20 cm) pre-treated in 4.00 mL of 0.01 M of saturated potassium nitrate solution was used as a salt bridge [67].

The experiments were tried out with grade 12 students studying at Satrisiriket School in Srisaket Province of Thailand [68]. Comments and suggestions from the students were used to improve the effectiveness of the experiments.

a) Experiments and observations of reactions of metals in various solutions

b) Connecting a galvanic cell

c) Cathodic protection of iron nails



d) Connecting batteries in series

Figure 3.6 Small-scale experiments involving electrochemistry

3.3.4.4 Data Collection Tools

There were two types of data collection tools in this study. The first one was the conceptual test of electrochemistry containing 24 items in a two-tier three-choice test. There were 9 and 15 items regarding the concepts of oxidation-reduction reactions and galvanic cells, respectively. The concepts of batteries (3 out of 15 items) and cathodic protection (3 out of 15 items) were considered as sub-concepts of galvanic cells so they were included in the concepts of galvanic cells in this study. Students were required to make their choices of answers in the first tier and then provide their explanations for those choices in the second tier (examples of the test are shown in example 1 and appendix C) [50, 69]. The test was content-validated by two senior chemistry lecturers and one chemistry education professor. There were four main concepts in the test including oxidation-reduction reactions, galvanic cells, batteries, and cathodic protection.

Examples 1: Examples of two-tier three choice items in electrochemistry

Question 1: Consider the reaction below.

$$Fe\ (s) + Cu^{2+}(aq) \rightarrow Fe^{2+}(aq) + Cu(s)$$

1.1 Which statement is correct?

A. Fe^{2+}(aq) is a reducing agent, while Cu^{2+}(aq) is an oxidizing agent.

B. Cu^{2+}(aq) is a reducing agent, while Fe(s) is an oxidizing agent.

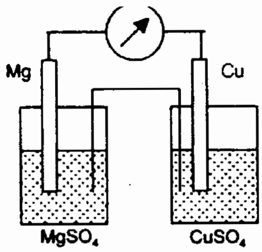
C. Fe(s) is a reducing agent, while Cu^{2+}(aq) is an oxidizing agent.

1.2 Please supply your reason or explanation for your response above.

....

....

Question 2: Consider the diagram below.



2.1 Which statement is correct?

A. Electrons transfer from Cu^{2+}(s) to Mg(s).

B. Electrons transfer from Mg(s) to Cu^{2+}(aq).

C. Electrons transfer from SO_4^{2-}(aq) to Cu^{2+}(aq).

2.2 Please supply your reason or explanation for your response above.

....

....

Question 3: Consider the reaction below in which the reduction potential (E^0) of the Zn|Zn^{2+} and Cd|Cd^{2+} half-cells are -0.76 and -0.40 V, respectively.

$$Zn(s) + Cd^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cd(s)$$

3.1 What is the standard reduction potential (E^0_{cell}) of this cell?

A. -0.36. B. +0.36. C. +1.16.

3.2 Please supply your calculation method for your response above.

....

....

The test items were analyzed by the use of software called Simple Item Analysis (SIA) which commonly used in Thailand. The difficulty index (P) for each item was in the range of 0.20-0.70, in which the percentages of items with P in the ranges of 0.20-0.39 (difficult), 0.40-0.59 (medium), and 0.60-0.80 (easy) were 20.00, 30.00, 40.00, and 10.00 respectively. The discrimination index (r) for each item was in the range of 0.30-0.90, in which the percentages of items with r in the ranges of 0.20-0.39 (fair), 0.40-0.59 (medium), 0.60-0.79 (good), and 0.80-1.00 (excellent) were 12.50, 20.83, 41.67, and 25.00 respectively. In addition, the reliability based on Kuder-Richardson Formula 20 or KR20 for the entire test was 0.87.

The second data collection tool was a mental model drawing of a galvanic cell. Students were asked to draw their understandings of what happens at the molecular level in a galvanic cell from two half-cells randomly provided $Zn|Zn^{2+}$, $Cu|Cu^{2+}$, and $Ni|Ni^{2+}$ half-cells (see Figure 3.7). For example, if students were asked to draw a mental model of a galvanic cell from $Cu|Cu^{2+}$ and $Ni|Ni^{2+}$half-cells, they had to consider which one was an oxidation or a reduction half-cell, and to provide how ions and atoms in each half-cell (both in solutions and electrodes) changed regarding the progress of the reaction.

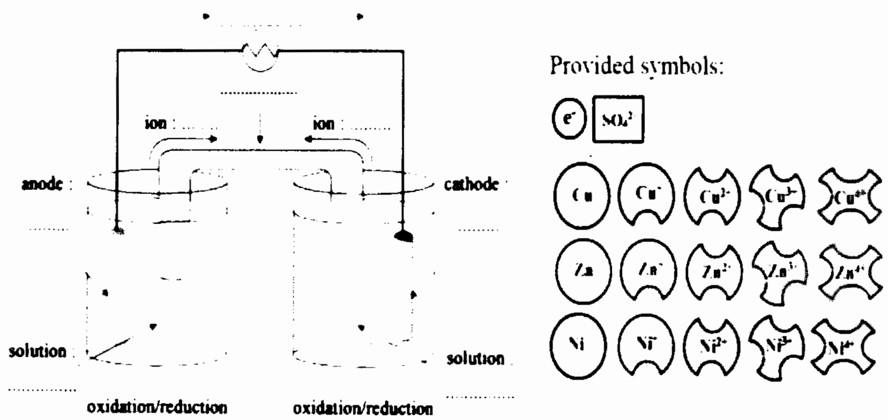


Figure 3.7 The task for mental model drawing of a randomly given galvanic cell (i.e., $Mg|Mg^{2+}$, $Zn|Zn^{2+}$, $Fe|Fe^{2+}$, $Cu|Cu^{2+}$ and $Ni|Ni^{2+}$ half-cells)

3.3.4.5 Data Analysis

The data collected in this study were analyzed as follows:

1) The pre- and post-conceptual test answers were awarded 1.00 and 0.00 point for each correct and incorrect choice respectively in the first tier. Please note that the first tier may not enough to identify if students accommodate misconceptions, while the explanation tier contain more relevant information about students' conception. Each explanation provided in the second tier was awarded 0.00, 0.25, 0.50, 0.75, or 1.00 point regarding the completeness of their explanation. The total possible score for each item was 2.00 points. Consider the explanation score, the total possible score in this part was 24 points. Students were categorized into five categories according to their explanation scores. Students whose percentages of explanation scores fell in the ranges of 0-19, 20-39, 40-59, 60-79, and 80-100 were classified as 'very poor', 'poor', 'fair', 'good', and 'excellent' categories, respectively [70].

2) The pre- and post-mental model drawings were categorized into five groups according to the information expressed in their drawing both macroscopic (including symbolic) and sub-microscopic (molecular) levels. The macroscopic and symbolic levels were combined in this study as MacSym criteria as sometimes they were difficult to separate symbolic information from macroscopic information in students' mental drawings. There were three criteria (5 points available) for the macroscopic and symbolic features (MacSym A1, A2, and A3) and the other three criteria (10 points available) for the sub-microscopic features (Mol B1, B2, and B3). Therefore, the total available score was 15 points. Four main scientific concepts were considered in each criterion (see Table 3.8). Drawings with information corresponding to none, one, two, three, and four out of four scientific concepts in each criterion were classified as "Sound Understanding: SU", "Partial Understanding: PU", "Partial Understanding with Specific Misunderstanding: PMU", "Specific Misunderstanding: MU", and "No Understanding: NU" categories, respectively. These drawings were respectively awarded 100%, 75%, 50%, 25%, and 0% of the possible score in each criterion.

Table 3.8 Criteria for categorizing student's mental models of a galvanic cell

Criteria	Scientific concepts
1. Macroscopic and symbolic	*The following concepts are considered.*
1.1 MacSym A1 (2 points)	Electrodes, solutions and salt bridges. 1. Provide correct cathode (Mac). 2. Provide correct anode (Mac). 3. Provide correct salt-bridge (Mac). 4. Provide correct solution in each half-cell (Mac).
1.2 MacSym A2 (2 points)	Atoms, ions and electrons (particles). 1. Show right Ox. No. for metal cations in each half-cell (Sym). 2. Show right Ox. No. for electrolytic anions in each half-cell (Sym). 3. Define particles in electrodes as neutral atoms (Sym). 4. Show free electrons (e^-) only on wire (Sym).
1.3 MacSym A3 (1 point)	Oxidation and reduction half-cells. 1. Identify correct oxidation and reaction half-cells (Mac). 2. Provide right oxidation reaction for oxidation half-cell (Sym). 3. Provide right reduction reaction for reaction half-cell (Sym). 4. Provide right total oxidation-reaction reaction (Sym).
2. Molecular	*The following concepts are considered. Please note that sizes of particles are not included in these criteria.*
2.1 Mol B1 (4 points)	Position of particles and oxidation number. 1. All neutral atoms appear only on electrodes. 2. All ions appear only in solutions or in salt-bridge. 3. Free electrons appear only on a wire. 4. Ox. No. of metal ions in each half-cell is correct.

Table 3.8 Criteria for categorizing students' mental models of a galvanic cell (Continued)

Criteria	Scientific concepts
2.2 Mol B2 (4 points)	Numbers of particles in solutions and electrodes. 1. Numbers of neutral atoms increases in cathode, while decreases in anode. 2. Numbers of metal cations increases in oxidation half-cell, while decreases in reduction half-cell. 3. Number of metal ions relate to the gain and loss of electron in each half-cell (mole concept). 4. Total number of metal atoms plus metal ions in each half-cell remains constant (conservation of mass).
2.3 Mol B3 (2 points)	Transfer (movement) of particles in solution and salt bridge. 1. Salt-generated cations transfer to reduction half-cell. 2. Salt-generated anions transfer to oxidation half-cell. 3. Electrons transfer from anode to cathode via a wire. 4. Electrolytic anions transfer from one to the other half-cell via salt-bridge.

Source: applied from Supasorn, 2015 [70]

3) Students' scores from the pre- and post-conceptual tests and mental model drawings were analysed by the use of paired-samples T-test to identify the mean differences between the pre- and post-intervention scores at the significance level of 0.05.

4) Class normalized learning gains or <g> of students' scores from pre- and post-conceptual tests and mental model drawings were applied to minimize the floor and ceiling effects calculated by the equation:

$$\langle g \rangle = [(\%\ \text{post–test})-(\%\ \text{pre-test})]\ /\ [(100\ \%)-(\%\ \text{pre-test})]$$

The floor and ceiling effects are the effects that students who begin with low pre-test scores may have more chance to have large percentage gains, while students who begin with large pre-test scores may gain only small percentage scores. In other words, it is common for students with higher pre-test scores to have results of smaller absolute gains (post-test scores minus pre-test scores). The floor and ceiling effects can be minimized by using normalized gain <g> analysis. The topics with <g> ≤ 0.30, 0.30<<g>> 0.70, and <g> ≥ 0.70 were classified into low-, medium-, and high gain categories, respectively [71].

CHAPTER 4
RESULT AND DISCUSSION

4.1 Result of experimentation of electrochemical cell based on the institute for the promotion of teaching science and technology Thailand (conventional method)

4.1.1 Result of the reaction of metals in various solutions (oxidation – reduction reaction)

The reaction of metals in various solutions was studied. The results were shown in table 4.1. Considering of R case; R means reaction was occurred; including corrosion of metals and bubble of gas. In the case of Zn metal dipped into a solution of Cu (II) ions (copper (II) sulfate). The possible reactions were occurred as following:

For a half reaction of oxidation reaction: Zn metal was lost two electrons which reduced by Cu (II) ions as shown in equation 4.1, since its standard reduction of cell potential is higher than Zn (II) ion as demonstrated in appendix A (figure A.2). Cu metal (black powder) was observed on the zinc metal, rather than the usual gas bubble (R). For the other reactions of R case were explained by this explanation.

$$Zn(s) \rightarrow \quad Zn^{2+}(aq) + 2e^- \text{ (Oxidation)} \quad E^0_{cell} = -0.76 \text{ V} \qquad (4.1)$$

For a half reaction of reduction reaction: The Cu (II) ions were gained two electrons which oxidized by Zn metal as shown in equation 4.2. Since, its standard reduction of cell potential is lower than Cu (II) ions.

$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s) \text{ (Reduction)} \quad E^0_{cell} = 0.34 \text{ V} \qquad (4.2)$$

The overall reaction of this R case was demonstrated in equation 4.3

$$Zn(s) + Cu^{2+} \rightarrow \quad Zn^{2+}(aq) + Cu(s) \text{ (redox reaction)} \qquad (4.3)$$

For the NR case; NR means no reaction. Considering of copper metal dipped in all electrolytes as shown in table 4.1. Cu metal has no reaction. This case indicated that Cu is higher standard reduction of cell potential than the other metals, suggesting that Cu metal cannot reduce to the other metals as shown table 4.1.

Table 4.1 The reaction of metal in various solutions (oxidation-reduction reaction)

Solutions			**Metals**		
1 M, 20 mL	**Cu(s)**	**Zn(s)**	**Mg(s)**	**Fe(s)**	**Al(s)**
Cu^{2+}(aq)	NR	R	R	R	R
Zn^{2+}(aq)	NR	NR	R	NR	R
Mg^{2+}(aq)	NR	R	NR	R	R
Fe^{2+}(aq)	R	R	R	NR	R
Al^{3+}(aq)	NR	NR	R	R	NR

Note: NR means no reaction

R means reaction was occurred; including corrosion of metals and bubble of gas

4.1.2 Result of electron transfer in galvanic cell

This experiment was studied of the electron transfer in galvanic cells. The cell potential of the galvanic cells was measured and compared to the theoretical value which was calculated from the following equation:

$$E^0_{cell} = E^0_{cathode} - E^0_{anode}$$

$$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$$

In generally, the cell potential, E^0_{cell}, for the spontaneous chemical reactions is always a positive value. For example, the galvanic cell of $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$, the two half cells reaction was demonstrated as following:

$$Zn(s) \rightarrow \quad Zn^{2+}(aq) + 2e^- \text{ (oxidation)} \quad E^0_{cell} = -0.76 \text{ V}$$

$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s) \text{ (reduction)} \quad E^0_{cell} = 0.34 \text{ V}$$

The overall cell reaction (redox reaction):

$$Zn(s) + Cu^{2+} \rightarrow \quad Zn^{2+}(aq) + Cu(s) \text{ (redox reaction)}$$

$$E^0_{cell} = 0.34 \text{ V} - (-0.76 \text{ V})$$

$$E^0_{cell} = 1.10 \text{ V} \qquad (4.4)$$

The values of cell potentials were collected. The theoretical cell potentials, E^0_{cell} (theor) for the cell $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$ was 1.10 V as shown in equation 4.4, while the observed cell potentials, E_{cell} (obsd) was 0.99 V. From the results, it was found that the E_{cell} (obsd) values produced by the galvanic cell (conventional method) were close to the theoretical (calculation) values. Furthermore, it was found that the precision of the triplicate measurements (n=3) indicated by the relative standard deviations (%RSD) of the E_{cell} (obsd) values was good in the range of 0.45% - 2.06%. The others cell potential of galvanic cells was demonstrated in table 4.2.

Table 4.2 The cell potential of galvanic cells using 20 mL and 1 M of electrolytes in both half-cells (n = 3), instant collection of cell potential

Galvanic cells	E_{cell} (theor)	E_{cell} (obsd) ± SD		% RSD
Cu-Zn	1.10	0.99	±0.02	2.06
Cu-Fe	0.78	0.61	±0.01	2.83
Al-Mg	0.68	1.29	±0.00	0.45
Al-Zn	0.92	0.36	±0.02	5.02
Mg-Fe	1.93	1.20	±0.01	0.48
Zn-Mg	1.61	0.89	±0.01	0.65
Zn-Fe	0.32	0.38	±0.00	1.53

4.2 Result of the developed method

A simple method for the fabrication of small-scale and low-cost galvanic cells has been developed as a teaching tool for electrochemistry of high school students. The method was designed according to the concept of "Green chemistry" reducing use of chemicals, less waste generation, and time consumption while retaining the experimental concepts. The parameters that affected on the developed method has been demonstrated as followed;

4.2.1 Result of parameters that affected on the developed method

4.2.1.1 Effect of electrolytes volume

The effect of electrolyte volume on the cell potential was shown in Figure 4.1 A). The cell potential increased with increasing volume of electrolyte until 2 mL since the contact surface areas between electrodes and electrolytes increased which enhanced E_{cell}, *e.g.* due to reduction of resistance within the electrode/ electrolyte junction (Allen, 1995). The increasing E_{cell} values reached the saturated values at 2–3 mL. Thus, this condition was selected minimizing amount of used solution.

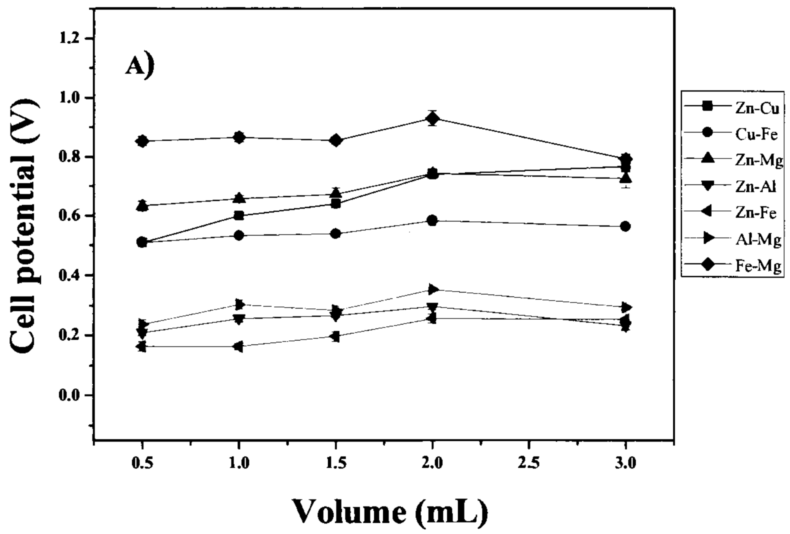


Figure 4.1 (A) Influence of the electrolytes volume (mL) at fixed concentration of electrolytes at 0.1M of cathode half cell and 0.01 M of anode half cell

4.2.1.2 Effect of electrolytes concentration

Parameters affecting cell potential were examined using the separated cells. Figure 4.2 B) shown that the cell potential increased with the increasing electrolyte concentration. The experiment was performed by fixing concentration of two half-cell (0.1M) whilst, further increase in the concentration from 0.005 M to 0.03 M resulted in the potential decrease. Therefore, 0.01 M was chosen for further experiments. The potential values of the galvanic cells with different pairs of electrodes and electrolytes using cotton thread as salt bridges were compared to the theoretical values which were calculated by using Nernst's equation as followed.

$$E_{cell} = E^{o}_{cell} - \frac{0.0591}{n}\log Q \tag{4.5}$$

Where E^{o}_{cell} is the standard reduction potential the cell which can be calculated from the standard reduction potential of each half cell. Q is the reaction quotient depending on activity ratio of ions in electrolytes employed in the two half- cells. The activity ratio can be approximated to be the ratio of ion concentrations. According to the Equation 4.5, values of E_{cell} relative to that of E^{0}_{cell} depend on Q. If Q is more than, less than, or equal to 1 resulting E^{o}_{cell} less than, more than, or equal to 1, respectively.

Any increase in Q of the cell results in reduction of E_{cell}, while decrease in Q increases E_{cell}. Thus, E_{cell} can be tuned by changing Q value which can be simply performed by varying concentration ratio of two electrolytes used in the cell [72]. For a galvanic cell prepared using $[Zn^{2+}]$ = $[Cu^{2+}]$ = 1.0 M, the Q value is 1 ($\log_{10}Q$ 1 = 0). The potential of this cell ($E_{Zn|Zn^{2+}||Cu^{2+}|Cu}$) is the same as the cell potential at the standard state ($E^0_{Zn|Zn^{2+}||Cu^{2+}|Cu}$) which is calculated to be 1.10 V, for instance. When the concentration of Zn^{2+} (aq) is increased to be 10 times of $[Cu^{2+}]$ (with $[Zn^{2+}]$ = 1.0 M and $[Cu^{2+}]$ = 0.1 M), the corresponding Q value is 10 ($\log_{10}Q$ = 1). The calculated $E_{Zn|Zn^{2+}||Cu^{2+}|Cu}$ is decreased to be 1.07 V. If $[Zn^{2+}]$ = 0.01M and $[Cu^{2+}]$ = 0.1M, the resulting Q is 0.1($\log_{10}Q$ =-1). The calculated $E_{Zn|Zn^{2+}||Cu^{2+}|Cu}$is increased to be 1.13 V. Which corresponded to our experiment shown in Figure 4.2 B).

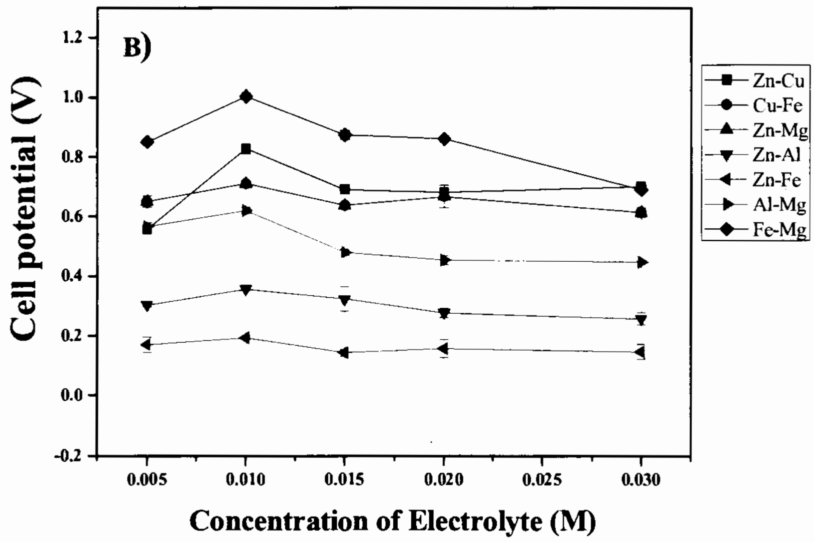


Figure 4.2 (B) Dependence of electrolyte concentration (M) at the fixed volume of 2 mL and fixed of the concentrations of one half cell at 0.1 M and one half cell at 0.01 M

4.2.1.3 Effect of solution type use as a salt bridge

The effect of salt types used as salt bridges on the cell potential was also studied. Although high E_{cell} was obtained with the use of 0.01 M NaCl(aq), the cell lifetime is relatively short (about 0.33 h). 0.01 M KNO_3(aq) was observed to be better salt resulting in very stable cells as well as providing high cell potential, as illustrated in Figure 4. Potassium ion is remarkably nonreactive, and most potassium salts are soluble in water [11]. Also noted that NaCl(aq) might not be a good choice when zinc, silver or lead electrodes were applied, it may be ascribed from the precipitation with many common anions e.g. $ZnCl_2$, AgCl, $PbCl_2$ [73, 74] and during the long time of operation NaCl(aq) causes the imbalance of ions in the electrochemical cell. The results of other studied cells were also in good agreement with Figure 4.3. Therefore, 0.01M KNO_3 (aq) was selected for further study. The other salt types used as salt bridges on the cell potential were shown in appendix A_2.

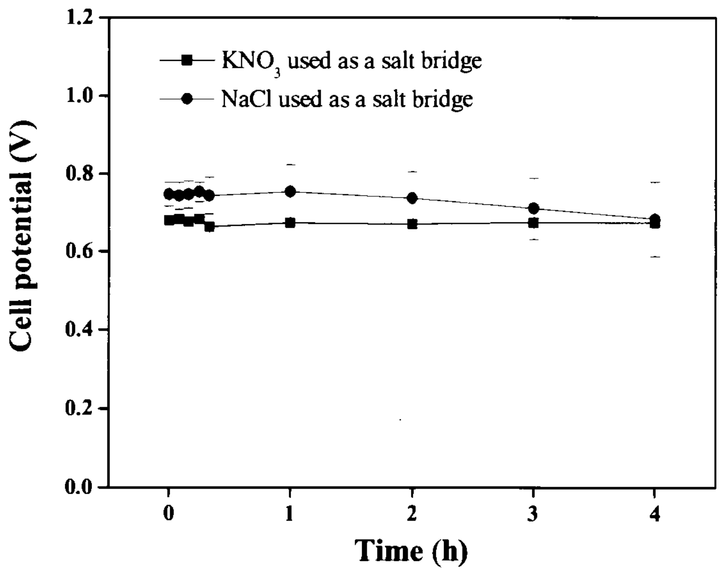


Figure 4.3 Stability test of the cell prepared with the salt bridge containing KNO_3(aq) and NaCl (aq) of Cu|Cu^{2+}||Mg^{2+}|Mg cells concentration 2 mL in 0.01M of electrolyte

4.2.1.4 Effect of electrolytes lifetime

The lifetime of the developed small-scale cells was investigated as shown in Table 4.3 for the lifetime of the $Cu(s)|Cu^{2+}(aq)||Mg^{2+}(aq)|Mg(s)$ cell and the other cells studied also corresponded to Table 4.5 and the other cells as shown in table A 1(in appendix A) 1. The cell potential values measured in different sets of the experiments were not significantly different within %RSD < 5, suggesting that the precision of the developed small-scale cells is high and workable. It could also be concluded that the reagent can be effectively used up to one month.

Table 4.3 Mean (M), standard deviation (SD) and relative standard deviation (%RSD) values of $E_{Cu|Cu^{2+}||Mg^{2+}|Mg}$ using 2 mL and 0.01 M of electrolytes in both half-cells at different application time

Cell of $Cu\|Cu^{2+}\|\|Mg^{2+}\|Mg$	Cell potential (V)						
	Time (h)						
	0	1	2	3	4	24	720
Set 1	1.38	1.40	1.39	1.40	1.42	1.41	1.43
Set 2	1.38	1.41	1.39	1.37	1.42	1.38	1.40
Set 3	1.40	1.43	1.42	1.39	1.44	1.40	1.39
M	1.39	1.41	1.40	1.39	1.43	1.40	1.41
SD	0.01	0.01	0.01	0.01	0.01	0.01	0.02
%RSD	0.83	1.08	1.23	1.10	0.80	1.09	1.47

4.2.1.5 Method validation of developed method

The comparison between conventional and the herein developed cells was illustrated in Figure 4.4 for different half-cell couples. Both methods were observed to be comparable. According to the t-test, the cell potential of each 7 cell was not significantly different (t_{stat}= 2.414, $t_{critical}$= 2.447) at P=0.05. The Cu-Fe, Zn-Mg, Cu-Zn and Al-Mg cells developed in this study reveals significantly lower E_{cell} compared to the conventional cells. However, qualitative analysis of different cells is considered to be the same using either conventional or herein approaches. With the benefits of low cost and small scale, it is worthwhile applying the developed cells in this study as teaching materials in the future.

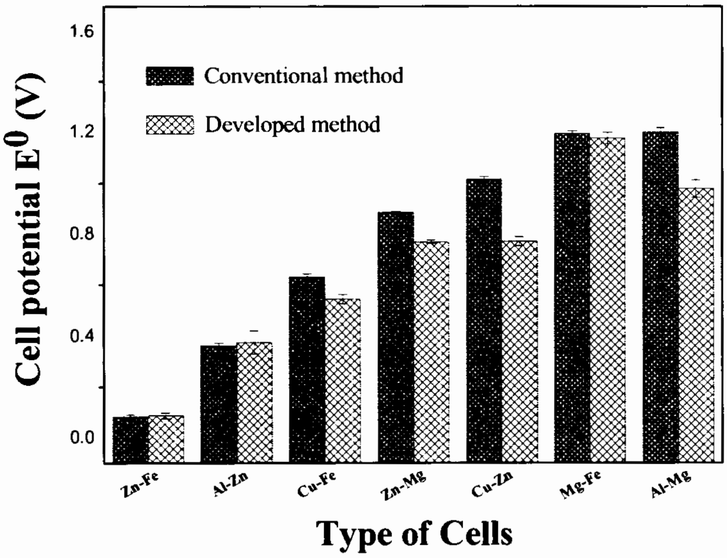


Figure 4.4 Comparison of potential values of different cells being developed by the conventional method and the developed method

4.2.1.6 Application of developed method for batteries

Application of developed method for batteries has been studied. Battery is a device consisting of two or more galvanic cells that converts stored chemical energy into electrical energy. A battery is defined as a set of galvanic cells connected in series. In a series connection, the negative electrode of one cell is connected to the positive electrode of the next cell. $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$ and $Zn(s)|Zn^{2+}(aq)||$ $Mg^{2+}(aq)|Mg(s)$ were chosen to study for application of batteries. The set up was fixed to 3 galvanic cells which were set up as demonstrated in figure 3.5. For example, $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$, the cell potential of the batteries was measured (E_{cell} (obsd)) and compared to the theoretical value (E_{cell} (theor)) which was calculated from the equation 4.6 based on the values of the standard reduction of cell potentials for the two half-cells which was calculated from equation 4.4. As the connection was fixed to 3 galvanic cells. Therefore, the standard reduction of cell potential (E°_{cell}) of $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$ will be 3.30 V.

Batteries of Zn(s) $|Zn^{2+}||Cu^{2+}|Cu(s)$:

$$E^0_{battery} = E^0_{cell1} + E^0_{cell2} + E^0_{cell3}$$

$$E^0_{battery} = 1.10 + 1.10 + 1.10$$

$$E^0_{battery} = 3.30 \text{ V} \tag{4.5}$$

The values of the standard reduction of cell potentials, E^0_{cell} (theor) for the batteries of Zn(s)| Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s) is 3.30 V, while the observed of cell potentials, E_{cell} (obsd) was 2.45 V with high stability around 2 h (%RSD <2, Table 4.4). It was found that the E_{cell} (obsd) values produced by the batteries were comparable to the theoretical (calculation) values with a good precision of the triplicate measurements (n=3), indicated by the relative standard deviations (%RSD) which was lower than 2 %. However, qualitative analysis of different cells is considered to be the same using either E^0_{cell} (theor) or E_{cell} (obsd). With the benefits of low cost and small scale, it is worthwhile applying the developed cells in this study as teaching materials in the future.For the Zn(s)|Zn^{2+}(aq)|| Mg^{2+}(aq)|Mg(s) batteries was also demonstrated in the table 4.4.

Table 4.4 Mean (M), standard deviation (SD) and relative standard deviation (%RSD) values of Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s) and Zn(s)|Zn^{2+}(aq)||Mg^{2+}(aq) |Mg(s) using 2 mL and 0.01 M of electrolytes in both half-cells at different application time

Batteries in 3 series	Set	Cell potential			
		Time (h)			E^0_{cell}
		0.33	1	2	
Zn(s)| Zn^{2+}||Cu^{2+} |Cu(s)	Set 1	2.45	2.44	2.42	3.30
	Set 2	2.39	2.42	2.45	3.30
	Set 3	2.49	2.45	2.49	3.30
	M	2.44	2.44	2.45	3.30
	SD	0.05	0.02	0.04	
	%RSD	2.05	0.82	1.63	
Zn(s)| Zn^{2+}||Mg^{2+} |Mg(s)	Set 1	2.29	2.28	2.33	4.83
	Set 2	2.34	2.31	2.36	4.83
	Set 3	2.29	2.35	2.29	4.83
	M	2.31	2.31	2.33	4.83
	SD	0.03	0.04	0.04	
	%RSD	1.30	1.73	1.72	

4.2.2 The reaction of metals in various solution (oxidation-reduction reaction)

This experiment was studied of the reaction of metals in various solutions. The result was shown in table 4.3. Considering of R case; R means reaction was occurred; including corrosion of metals and bubble of gas. In the case of Mg metal dipped into a solution of Fe (II) ions (iron (II)) sulfate). The possible reactions were occurred as following:

The oxidation reaction: Mg metals was lost two electrons which reduced by Fe (II) ions as shown in equation 4.6, since its standard reduction of cell potential is higher than Mg (II) ion as demonstrated in appendix A (figure A.2). The results of this experiment were shown in table 4.3. This reaction was occurred so rapidly, the particle of iron (Fe) was observed as a black color, rather than the usual gas bubble (R). For the other reactions of R case were explained by this explanation.

$$Mg(s) \rightarrow Mg^{2+}(aq) + 2e^{-} \text{ (Oxidation reaction) } E^{0}_{cell} = -2.37 \text{ V} \quad (4.6)$$

For the half reaction of reduction reaction: The Fe (II) ions were gained two which oxidized by Mg metal as shown in equation 4.7. Since, its standard reduction of cell potential is lower than Fe (II) ions.

$$Fe^{2+}(aq) + 2e^{-} \rightarrow Fe(s) \text{ (Reduction reaction) } E^{0}_{cell} = -0.45 \text{ V} \quad (4.7)$$

The overall reaction of this R case was demonstrated in equation 4.8

$$Mg(s) + Fe^{2+} \rightarrow Mg^{2+}(aq) + Fe(s) \text{ (Redox reaction)} \quad (4.8)$$

For the NR case; NR means no reaction. Considering of copper metal dipped in all electrolytes as shown in table 4.5. Cu metal has no reaction. This case indicated that Cu is higher standard reduction of cell potential than the other metals, suggesting that Cu metal cannot reduce to the other metal as shown table 4.5.

Table 4.5 The reaction of metal in various solutions (oxidation-reduction reaction)

Solution 0.01 M, 2 mL	Metals				
	Cu(s)	Zn(s)	Mg(s)	Fe(s)	Al(s)
Cu^{2+}(aq)	NR	R	R	R	R
Zn^{2+}(aq)	NR	NR	R	R	R
Mg^{2+}(aq)	NR	R	NR	R	R
Fe^{2+}(aq)	R	R	R	NR	NR
Al^{3+}(aq)	NR	NR	R	NR	NR

Note: NR means no reaction

R means reaction was occurred; including corrosion of metals and bubble of gas

4.2.3 Study of electron transfer in galvanic cell

This experiment was to study the transfer electron to electrical energy. And the result of this experiment was shown in table 4.6.

Table 4.6 The cell potential of galvanic cell using 2 mL and 0.01 M of electrolytes in both half-cells. (n = 3), instant collection of cell potential

Galvanic cells	E_{cell} (theor)	E_{cell} (obsd) ± SD		% RSD
Cu-Zn	1.10	0.78	±0.01	0.74
Cu-Mg	2.71	1.41	±0.03	1.88
Cu-Fe	0.78	0.55	±0.01	1.06
Al-Mg	0.68	1.10	±0.01	0.45
Al-Zn	0.92	0.38	±0.04	5.05
Mg-Fe	1.93	1.20	±0.04	0.48
Zn-Fe	0.32	0.30	±0.01	4.31

This experiment was studied of the electron transfer in galvanic cells. The cell potential of the galvanic cells was measured and compared to the theoretical value which was calculated from the following equation:

$E^0_{cell} = E^0_{cathode} - E^0_{anode}$

$E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$

The cell potential, E_{cell}, for the spontaneous chemical reactions is always a positive value. For example, the galvanic cell of $Zn(s)|Zn^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$, the two half cells reaction as following:

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ (Oxidation) $E^0_{cell} = -\ 0.76$ V

$Fe^{2+}(aq) + 2e^- \rightarrow Fe(s)$ (Reduction) $E^0_{cell} = -\ 0.45$ V

The overall cell reaction:

$Zn(s) + Fe^{2+} \rightarrow Zn^{2+}(aq) + Fe(s)$ (Redox reaction)

$E^0_{cell} = -0.454 \text{ V} - (-0.76 \text{ V})$

$$E^0_{cell} = 0.31 \text{ V} \tag{4.9}$$

The values for the half standard reduction of cell potentials were collected instantly*. E^0_{cell} (theor) for the cell $Zn(s)|\ Zn^{2+}(aq)||Fe^{2+}(aq)|Fe(s)$ is 0.31 V, while the observed cell potentials, E_{cell} (obsd) was 0.30 V. From the results it was found that the E_{cell} (obsd) values produced by the galvanic cell of developed method were close to the theoretical values and the reproducibility of the triplicate measurements indicated by the standard deviations (SD) of the E_{cell} (obsd) values was in the range of 0.00 - 0.03, respectively. Furthermore, it was found that the precision of the triplicate measurements (n = 3) indicated by the relative standard deviations (%RSD) of the E_{cell} (obsd) values was good in the range of 0.45- 5.05%, respectively. The other cell potential of galvanic cells was demonstrated in table 4.4.

Note: by observing the optimum application time as demonstrated in appendix A.

4.3 Application

There were four sections of results in this study: 1) students' scores in the conceptual tests of electrochemistry, 2) student conceptual categories in the conceptual tests of electrochemistry, 3) students' scores in the mental model drawings of a galvanic cell, and 4) students' conceptual categories in the mental models of a galvanic cell.

4.3.1 Students' scores in the conceptual tests of electrochemistry

Students' conceptual test scores from 28 grade 12 students were divided into two categories, oxidation-reduction reactions and galvanic cells. The mean pre-test scores for the first and second tiers and the totals were 6.11 (SD 1.50), 3.12 (SD 1.50), and 9.22 (SD 2.67) respectively for the topic of oxidation-reduction reactions, and 7.54 (SD 2.70), 2.53 (SD 1.81), and 10.06 (SD 3.81) respectively for the topic of galvanic cells, as shown in Table 4.8. After the completion of the four small-scale experiments, the mean post-test scores for the first and second tiers and the totals were 8.11 (SD 0.96), 6.94 (SD 1.40), and 15.29 (SD 2.31) respectively for the topic of oxidation-reduction reactions, and 12.39 (SD 1.77), 10.35 (SD 2.77), and 23.00 (SD 3.92) respectively for the topic of galvanic cells. The normalized learning gains or $\langle g \rangle$ for the first and second tiers and the totals were 0.69, 0.65, and 0.69 respectively for the topic of oxidation-reduction reactions, and 0.65, 0.63, and 0.65 respectively for the topic of galvanic cells. The $\langle g \rangle$ was in the medium gain range of 0.30 and 0.70 in all cases except the choice tier of the topic of oxidation-reduction reactions ($\langle g \rangle$ = 0.72, high gain). This arose because the oxidation-reduction reactions topic involves just one half-cell (one vial or beaker observation), while the galvanic cells topic involves two half-cells (two vials or beakers) which is more difficult to observe and understand. Therefore, the students provided clearer explanations in the oxidation-reduction section than in the galvanic cells section which involves and assumes knowledge of oxidation-reduction.

Table 4.7 Students' scores assessed by the conceptual test of electrochemistry (n=28)

Tiers	Avai-lable	Pre-test mean	Pre-test SD	Pre-test %	Post-test mean	Post-test SD	Post-test %	Gain %	Gain <g>	T
Ox. - Red.	18	9.22	2.67	51.22	15.29	2.31	84.94	33.72	0.69	7.78*
- Choice	9	6.11	1.50	67.89	8.11	0.96	90.11	22.22	0.69	15.73*
-Explanation	9	3.12	1.50	34.67	6.94	1.40	77.11	42.44	0.65	10.28*
Galvanic cells	30	10.06	3.81	33.53	23.00	3.92	76.67	43.13	0.65	8.28*
- Choice	15	7.54	2.70	50.27	12.39	1.77	82.60	32.33	0.65	14.8*
- Explanation	15	2.53	1.81	16.87	10.35	2.77	69.00	52.13	0.63	14.81*
Total	**48**	**19.29**	**5.43**	**40.19**	**38.29**	**5.62**	**79.77**	**39.58**	**0.66**	**9.08***
- Choice	24	13.64	3.41	56.83	20.50	2.03	85.42	28.58	0.66	19.5*
- Explanation	24	5.64	2.91	23.50	17.29	3.79	72.04	48.54	0.63	15.16*

Note: Statistically different at the significance level of 0.05.

The paired-samples T-test analysis indicated that the differences between the mean scores of the pre- and post-conceptual tests were statistically significant in all cases. In the galvanic cells topic, students obtained much higher percentages of scores in the choice tier than the explanation tier for both the pre- (50.27 and 16.87) and post-conceptual tests (82.60 and 69.00). This situation arose because sometimes the students knew the answers without a complete scientific conceptual explanation of galvanic cells. As a result, they may provide partial understandings, alternative understandings, or misunderstandings in their answers [75]. The improvements in the percentages of the post-test scores indicated that the corresponding small-scale experiments of electrochemistry in conjunction with the model of galvanic cells were effective in the enhancement of students' conceptual understandings of electrochemistry.

4.3.2 Levels of Students' Understanding in the Explanation Tier of Conceptual Tests of Electrochemistry

The students were categorized into five levels of understanding regarding their explanations in the conceptual tests. Prior to the involvement of 5E inquiry experiments and the model kit of electrochemistry, the percentages of students in the very poor, poor, fair, good, and excellent categories were 37.30, 13.49, 27.38, 17.06, and 4.76 respectively for the oxidation-reduction reactions topic, and 63.10, 14.52, 15.00, 6.67, and 0.71 respectively for the galvanic cell topic (Table 4.8). After the intervention, the percentages of students in the very poor, poor, fair, good, and excellent categories were 6.75, 9.52, 11.51, 16.27, and 55.95 respectively for the oxidation-reduction reactions topic, and 13.10, 13.10, 8.81, 14.76, and 50.24 respectively for the galvanic cell topic. Notice that the percentages of students decreased in the less understanding categories but increased in the more correct categories.

Table 4.8 Percentages of students in 5 levels of understanding in the explanation tier of conceptual tests (n = 28)

Conceptual test (no. of items)	Percentage of students (%)				
	Very poor	Poor	Fair	Good	Excellent
Pre-test (24)	**53.42**	**14.14**	**19.64**	**10.57**	**2.23**
- Ox. - Red. (9)	37.30	13.49	27.38	17.06	4.76
- Galvanic (15)	63.10	14.52	15.00	6.67	0.71
Post-test (24)	**10.71**	**11.76**	**9.82**	**15.33**	**52.38**
- Ox. - Red. (9)	6.75	9.52	11.51	16.27	55.95
- Galvanic (15)	13.10	13.10	8.81	14.76	50.24
Change (24)	**-42.71**	**-2.38**	**-9.82**	**4.76**	**50.15**
- Ox. - Red. (9)	-30.55	-3.97	-15.87	-0.79	51.19
- Galvanic (15)	-50.00	-1.42	-6.19	8.09	49.53

4.3.2.1 Examples of Students' Responses in Conceptual Test

Consider the students' responses in the explanation tier for Question 1 in the conceptual test of electrochemistry (see also Figure 3). Please note that if students did not supply any response in the explanation tier, they were awarded 0.00 point automatically. Some students chose the correct choice (C) but supplied incorrect explanation such as 'Fe(s) is a reducing agent because it gained electrons, while Cu^{2+}(aq) is an oxidizing agent because it lost electrons'. This case was awarded 0.25 point in the explanation tier because it was considered as misunderstood. Some students chose incorrect choice (A) and provided almost correct explanation such as 'Fe^{2+}(aq) is a reducing agent because its oxidation number increased from 0 to +2, while Cu^{2+}(aq) is an oxidizing agent because its' oxidation number decreased from +2 to 0'. This case was awarded 0.75 point in the explanation tier. Although the explanation about decreasing and increasing oxidation numbers was correct, the consideration of oxidation number of Fe(s) and Fe^{2+}(aq) was switched from right to left hand-side of chemical equation (incorrect). Some students chose incorrect choice (B) but provided correct explanation such as 'Cu^{2+}(aq) is a reducing agent because it gained electrons and became Cu(s), while Fe(s) is an oxidizing agent because it lost electrons and became Fe^{2+}(aq)'. This case was awarded 1.00 point in the explanation tier because the explanation about gaining and losing electrons of reducing and oxidizing agents was correct.

Students' alternative conceptions and misconceptions in the explanation tier of the conceptual tests were consistent with the summarized alternative conceptions in electrochemistry by Karsli and Çalik (2012)[76]. The alternative conceptions included: 1) the cathode electrode is negatively charged, which allows an oxidation reaction to occur, 2) the anode electrode is positively charged, which allows a reduction to occur, and 3) there was a lack of ability to write the correct cell reactions. The misconceptions were also consistent with the common misconceptions summarized by Sanger and Greenbowe (1997b) [77], such as the anode is positively charged and getting smaller because it lost electrons, while the cathode is negatively charged and getting larger because it gained electrons.

The improvement of students' conceptual understanding and the conceptual changes to the more correct scientific conception categories are consistent with the studies by Cullen and Pentecost (2011) [28] and White and Roger (2000) [29] who found that the use of a paper model of a galvanic cell in conjunction with electrochemistry laboratory activities allowed students to visualize what happens at the sub-microscopic level of a galvanic cell. As a result, students gained more conceptual understanding of galvanic cells.

4.3.3 Students' Scores in the Mental Models of a Galvanic Cell

Students' mental models from 22 grade 12 students were analyzed. Prior to the intervention, students' mean scores for the pre-mental models in the macroscopic and symbolic (MacSym) and sub-microscopic (Mol) features were 1.68, 1.18, and 2.86 respectively. After the intervention, their mean scores for the post-models were 3.82, 4.75, and 8.57, respectively (Table 4.10). The percentages of the actual gains in their mental model scores were 42.80, 35.70, and 38.07 respectively. In addition, the normalized gains for their mental models were 0.64, 0.40, and 0.47, all falling in the medium gain range. The paired-samples T-test analysis indicated that these changes from pre- to post-drawings were statistically significant in all cases. Students obtained a percentage for the pre-mental model score of 37.00 for macroscopic features, much higher than the 23.50 for sub-microscopic features. An explanation of this may be that students find sub-microscopic features difficult to understand due to their intangibility and/or invisibility [54, 55]. However, after involvement in the corresponding experiments and models, the percentage in the mean post-mental model score regarding sub-microscopic features increased to 47.50. This improvement of 35.70 indicated that the small-scale experiments of electrochemistry in conjunction with the model kit of galvanic cells were effective in the enhancement of the students' mental models.

Table 4.9 Students' mental model scores on a galvanic cell (n = 22)

Criteria**	Avai	Pre-models			Post-models			Gain		T
(score)	-lable	mean	SD	%	mean	SD	%	%Actual	<g>	
MacSym A1 (2)	2	0.95	0.71	47.50	1.93	0.23	96.5	49.00	0.93	5.89*
MacSym A2 (2)	2	0.30	0.48	15.00	0.91	0.40	45.5	30.50	0.36	4.83*
MacSym A3 (1)	1	0.43	0.46	43.00	0.98	0.17	98.00	55.00	0.96	4.96*
MacSym Total (5)	5	1.68	1.32	33.60	3.82	0.55	76.40	42.80	0.64	6.74*
Mol B1 (4)	4	0.59	0.85	14.75	2.05	0.58	51.25	36.50	0.43	7.09*
Mol B2 (4)	4	0.36	0.66	9.00	1.91	0.53	47.75	38.75	0.43	9.06*
Mol B3 (2)	2	0.23	0.30	11.50	0.80	0.40	40.00	28.50	0.32	5.38*
Mol Total (10)	10	1.18	1.50	11.80	4.75	1.23	47.50	35.70	0.40	9.22*
Grand total (15)	15	2.86	2.39	19.07	8.57	1.44	57.13	38.07	0.47	9.65*

Note: Statistically different at the significance level of 0.05.

4.3.4 Students' Conceptual Categories in Mental Models of a Galvanic Cell

The students were categorized into five groups regarding their information expressed in their mental model drawings. When asked to draw mental models of how they understand what happens at the molecular (or sub-microscopic) level in galvanic cells, the categorization of the students' macroscopic and symbolic (MacSym) information at the pre-stage fell mostly in NU (33.23%), MU (21.83%), and PMU (14.39%), and their molecular information for the same stage was also categorized mostly in NU (52.56%), MU (20.58%), and PMU (13.72%), see Table 4.7. This indicated that prior to the intervention most students accommodate specific misconceptions at both macroscopic (including symbolic) and sub-microscopic features in all scientific concepts of galvanic cells (see also Table 4.11). In addition, there were no students in the SU group at sub-microscopic feature in this stage.

After the intervention, their models moved to more correct conceptual understanding categories. For macroscopic and symbolic information, most students were in SU (56.79%) and PU (12.96%) and no students in NU. MacSym A3 (oxidation and reduction half-cells) and MacSym A1 (electrodes, solutions and salt bridges) were criteria that most students obtained sound understanding (81.48%, 81.48%) over partial understanding (5.56%, 9.26%), while MacSym A2 (particles) was the criterion that most students obtained partial understanding (24.07%) over sound understanding (7.41%). However, there were some students fell in the MU. The scientific concepts that many students tended to accommodate misconceptions at macroscopic and symbolic levels included 1) switching anode and cathode (Mac), 2) proving incorrect oxidation number for metal ions (Sym), 3) switching oxidation and reduction half-cells (Mac), and 4) providing total oxidation-reaction equation without awareness of mole of electrons (Sym).

Table 4.10 Percentages of students in 5 conceptual categories in mental model drawings (n = 22)

Mental models	**Percentage of students (%)**				
	NU	**MU**	**PMU**	**PU**	**SU**
Total pre-test	51.91	23.66	12.98	0.76	10.69
MacSym criteria	33.23	21.83	14.39	5.96	24.59
- MacSym A1	14.81	20.37	29.63	9.26	25.93
- MacSym A2	48.15	27.78	7.41	5.56	11.11
- MacSym A3	36.73	17.35	6.12	3.06	36.73
Mol criteria	52.56	20.58	13.72	5.63	7.50
- Mol B1	51.85	12.96	22.22	5.56	7.41
- Mol B2	57.69	17.31	11.54	5.77	7.69
- Mol B3	48.15	31.48	7.41	5.56	7.41

Table 4.10 Percentages of students in 5 conceptual categories in mental model drawings (n = 22) (Continued)

Mental models	Percentage of students (%)				
	NU	MU	PMU	PU	SU
Total post-test	0.73	18.61	37.96	11.31	31.39
MacSym criteria	0.59	15.43	14.81	12.96	56.79
- MacSym A1	0.76	1.85	7.41	9.26	81.48
- MacSym A2	0.57	35.19	33.33	24.07	7.41
- MacSym A3	0.43	9.26	3.70	5.56	81.48
Mol criteria	1.28	18.99	51.84	16.99	10.90
- Mol B1	0.00	12.50	53.13	21.88	12.50
- Mol B2	0.00	15.63	56.25	15.63	12.50
- Mol B3	3.85	28.85	46.15	13.46	7.69
Total change	-51.18	-5.05	24.98	10.55	20.70
MacSym criteria	-32.64	-6.40	0.43	7.00	32.20
- MacSym A1	-14.05	-18.52	-22.22	0.00	55.55
- MacSym A2	-47.58	7.41	25.92	18.51	-3.70
- MacSym A3	-36.30	-8.09	-2.42	2.50	44.75
Mol criteria	-51.28	-1.59	38.12	11.36	3.39
- Mol B1	-51.85	-0.46	30.91	16.32	5.09
- Mol B2	-57.69	-1.68	44.71	9.86	4.81
- Mol B3	-44.30	-2.63	38.74	7.90	0.28

For sub-microscopic information, most were categorized in PU (16.99%) and PMU (51.84%), while some of them were in SU (10.90%). Most students obtained partial understanding over partial understanding with specific misconception in all criteria of molecular feature. Mol B1 (position of particles) was the criterion that students tended to have sound understanding over Mol B2 (numbers of particles) and Mol B3 (transfer of particles). However, there were some students fell in the MU and

NU. The scientific concepts that many students tended to accommodate misconceptions at molecular level included 1) numbers of neutral atoms increases in anode, while decreases in cathode, 2) numbers of metal cations increases in reduction half-cell, while decreases in oxidation half-cell, 3) proving wrong oxidation number or oxidation state of metal ions in each half-cell, 4) no transfer of salt-generated ions from one to the other half-cell, and 5) no electrolytic anions transfer from one to the other half-cell.

For the conceptual changes, the majority of students moved from the less understanding (NU+MU) to the more understanding (PU+SU) categories in the macroscopic features. The order of decreases were MacSym A3 (44.39%), MacSym A2 (40.17%), and MacSym A1 (32.57%), respectively. On the other hand, the order of PU+SU increases were MacSym A1 (55.55%), MacSym A3 (47.25%), and MacSym A2 (14.81%), respectively. In other word, the conceptual changes from the less understanding (NU+MU) to the more understanding (PU+SU) categories of MacSym A3, A1, and A2 were 91.64%, 88.12% and 54.98%. This finding indicated that this intervention promoted students' conceptual changes at macroscopic level in scientific concepts of MacSym A3 over concepts of MacSym A1 and MacSym A2. For the sub-microscopic features, the order of NU+MU decreases were Mol B2 (59.37%), Mol B1 (52.31%), and Mol B3 (46.93%), respectively. On the other hand, the order of PU+SU increases were Mol B1 (21.41%), Mol B2 (14.67%), and Mol B3 (8.18%), respectively. In other word, the conceptual changes from the less understanding (NU+MU) to the more understanding (PU+SU) categories of Mol B2, B1, and B3 were 74.04%, 73.72% and 55.11%. This finding indicated that this intervention promoted students' conceptual changes at sub-microscopic level in scientific concepts of Mol B2 over concepts of Mol B1 and Mol B3.

The improvement of students' mental models of galvanic cells and the changes of their mental model categories to the more correct categories may arise from fact that the model of galvanic cells provided students a chance to access the sub-microscopic level to direct perception. The students can construct or transform their own mental models based on the sub-microscopic information obtained from the model and macroscopic information from the experiments [56-59]. This supported students to relate macroscopic and symbolic information to sub-microscopic information. They then generated reasonable mental (or conceptual) models and used these models to achieve full understanding of these intangible electrochemistry concepts [49, 58-60].

Examples of Students' Mental Models of Galvanic Cells

Consider the mental model drawings of a Ni-Cu galvanic cell of Student A. Prior to the involvement of the experiment, Student A provided partial understanding (PU) information that Ni^{2+} and Cu^{2+} ions appear in solution, as shown in Figure 4.5a.

However, she provided incomplete information, no Ni and Cu atoms presented. After involvement of the corresponding experiment, she noticed her incomplete information and changed her post-mental model to the more correct understanding (Figure 4.5b). However, she provided new mis-understanding (MU) information that Ni^{2+} and Cu^{2+} ions transferred from one to the other half-cell and electron transferred via the salt bridge. She also provided mis-understanding (MU) information that when Cu^{2+} ions received 2 electrons they became the Cu atoms and appeared in the solution instead of cathode electrode. She provided partial understanding (PU) information that when Ni atoms gave two electrons they became Ni^{2+} ions and appeared in solution.

CHAPTER 5
CONCLUSIONS

5.1 Conclusion

For the first part of this thesis, the small-scale and low-cost galvanic cells have been developed and successfully applied as the teaching materials in electrochemistry. It was found that the developed cells have a potential to reduce the solution consumption, at least by 15 mL per experiment as well as producing less amount of waste in the laboratory. The application of this approach is thus environmentally friendly and worthwhile. Besides the 'Green' chemistry aspect, the developed cell efficiency is comparable to the results obtained from the conventional macro-scale cells.

The second part, the study results verified that the intervention of the low-cost and small-scale experiments of electrochemistry in conjunction with the inexpensive, portable, reproducible, and flexible model kit by using the 5E inquiry learning approach was effective to enhance students' conceptual understanding and mental models of corresponding concepts. The students obtained the mean post-conceptual test score statistically higher than the pre- conceptual test score. The majorities of the pre-conceptual test were from the choice part but after the intervention, the explanation part played more important role in their post- than in their pre-conceptual test scores. Before the intervention, most students were in the partial understanding with specific misunderstanding (PMU) to no understanding (NU) categories, but after the intervention they moved to the more correct scientific conceptions, partial understanding (PU) to partial understanding with specific misunderstanding (PMU) categories. For the mental models, the students obtained the mean post-mental model score statistically higher than the pre-mental model score. The majorities of the pre-experiment scores were from the macroscopic part in their mental models, but the sub-microscopic part played more important role in their post-experiment scores than in the pre-experimental scores. Prior to the intervention, the majority of students were in the partial understanding with specific misunderstanding (PMU) to no understanding (NU) categories, but they moved to the better scientific conceptions, partial understanding (PU) to partial understanding with specific misunderstanding (PMU) categories, after the intervention. The major misconceptions encountered in students' mental models of galvanic cells included 1) number of neutral atoms increases in anode, while decreases in cathode, 2) number of metal cations increases in reduction half-cell, while decreases in oxidation half-cell, 3) identified incorrect oxidation state for metal cations in each half-cell, 4) salt-generated cations transferred from reduction to oxidation half-cell, while anions transferred from oxidation to reduction half-cell, and 5) unaware of transfer of electrolytic anions from reduction to oxidation half-cell.

5.2 Implications

This study may have implications for chemistry instructors in that teaching or directing students to perform an experiment might be not enough to help students understand important concepts at the molecular level. Chemistry instructors should consider using a corresponding model featuring sub-microscopic level or various tools such as jigsaws, simulations, animations, virtual laboratory (*Hawkins, & Phelps, 2013*) or other visualization tools (*Osman &Tien Lee, 2014)* to help students visualize concepts at the molecular level and then connect these concepts to the corresponding macroscopic experiment observations (Doymus, Karacop&Simsek, 2010). The use of cooperative learning approach should be considered to let students learn and understand the concepts from their peers (*Acar&Tarhan, 2007)*. As a result, students may achieve a complete and lasting conceptual understanding (Doymus, Karacop&Simsek, 2010). It is advisable that numbers of neutral atoms, metal cations, and electrons should be emphasized in regard of mole concepts.

5.3 Limitations

There were some limitations in this study. One of these was about the use of two-tier multiple choice test with the open explanation/reason in the second tier. The researcher found it difficult to encourage students to supply their reasons for their responses in the first tier. The use of two-tier test with multiple choices or other forms of test may be considered to diminish this limitation. In addition, using students' explanations to construct 2-tier multiple-choice items is advisable to avoid this limitation. Another limitation was that the same pre- and post-tests were used in this study. This was considered as a weak methodology because improvements could be observed with almost any other learning approach. The parallel test or equivalence test should be used to avoid this limitation. The last limitation was about one group pre-test/post-test design without control group. This could be questionable about the effectiveness of this intervention. The design with control and treatment group is advised to diminish this limitation.

REFERRENCES

REFERRENCES

[1] Finley, F. N., Stewart, J. and Yarroch, W. L. "Teachers' perceptions of important and difficult science content", **Science Education.** 66: 31-538, 1982.

[2] Sanger, M. J. and Greenbowe, T. J. "Students' Misconceptions in Electrochemistry Regarding Current Flow in Electrolyte Solutions and the Salt Bridge", **Journal of Chemical Education.** 74(7): 819-823; July, 1997.

[3] Lin, H.-S. and et al. "Students' difficulties in learning electrochemistry", **PROCEEDINGS-NATIONAL SCIENCE COUNCIL REPUBLIC OF CHINA PART D MATHEMATICS SCIENCE AND TECHNOLOGY EDUCATION.** 12: 100-105, 2002.

[4] Ringnes, V. "Oxidation-reduction-learning difficulties and choice of redox models", **School Science Review.** 77: 74-77, 1995.

[5] Ebenezer, J. V. "A hypermedia environment to explore and negotiate students' conceptions: Animation of the solution process of table salt", **Journal of Science Education and Technology.** 10: 73-92, 2001.

[6] Garnett, P. J. and Treagust, D. F. "Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations", **Journal of Research in Science Teaching.** 6(29): 121-142, 1992.

[7] Garnett, P. J., Garnett, P. J. and Treagust, D. F. "Implications of research on students' understanding of electrochemistry for improving science curricula and classroom practice", **International Journal of Science Education.** 12: 147-156; 04 January, 1990.

[8] Özkaya, A. R. "Conceptual difficulties experienced by prospective teachers in electrochemistry: Half-cell potential, cell potential, and chemical and electrochemical equilibrium in galvanic cells", **Journal of Chemical Education.** 79(6): 735-738; June, 2002.

[9] AHTEE, M., ASUNTA, T. and Helena, P. "STUDENT TEACHERS'PROBLEMS IN TEACHING 'ELECTROLYSIS'WITH A KEY DEMONSTRATION", **Chemistry Education Research and Practice.** 3: 317-326, 2002.

REFERRENCES (CONTINUED)

[10] Varkey, J. T., Anjali, P. and Menon, V. L. "Electrochemical Cell and Thermodynamics", **Nanostructured Ceramic Oxides for Supercapacitor Applications.** 11, 2014.

[11] Whitney, W. R. "TEXT-BOOK OF ELECTROCHEMISTRY", **Journal of the American Chemical Society.** 25: 104-106; 1 January, 1903.

[12] Umland, J. B. and Bellama, J. M. **General chemistry**. Brooks/Cole Publishing Company, 1999.

[13] Craig, N. C., Ackermann, M. N. and Renfrow, W. B. "Miniware for galvanic cell experiments", **Journal of Chemical Education.** 66(1): 85-86; January, 1989.

[14] Epp, D. N. "Small Scale One-Pot Reactions of Copper, Iron, and Silver", **Journal of Chemical Education.** 72(6): 545-546; January, 1995.

[15] Waterman, E. L. and Thompson, S. "Small Scale Chemistry", **ed: Addison-Wesley: Menlo Park CA**, 1995.

[16] Anderson, G. E. "Small Scale Electrolytic Cells", **Journal of Chemical Education.** 73: A172-A173; 8 August, 1996.

[17] Singh, M. M., Szafran, Z. and Pike, R. M. "Microscale Chemistry and Green Chemistry: Complementary Pedagogies", **Journal of Chemical Education.** 76(12): 1684-1686; December, 1999.

[18] Kelkar, S. L. and Dhavale, D. D. "Microscale experiments in chemistry: The need of the new millennium", **Resonance.** 5: 24-31; 1 October, 2000.

[19] Bradley, J. "Small-scale chemistry", **Chemistry International.** 24(3): 8-10, 2002.

[20] Kvittingen, L. and Verley, R. "Construction of a small-scale and low-cost gas apparatus", **Journal of chemical education.** 81(9): 1339-1340; September, 2004.

[21] Grønneberg, T., Kvittingen, L. and Eggen, P.-O. "Small-Scale and Low-Cost Galvanic Cells", **Journal of Chemical Education.** 83(8): 1201-1203; August, 2006.

REFERRENCES (CONTINUED)

[22] Grønneberg, T., Eggen, P.-O. and Kvittingen, L. "Small-Scale and Low-Cost Electrodes for "Standard" Reduction Potential Measurements", **Journal of Chemical Education.** 84(4): 671-673; April, 2007.

[23] Liberko, C. A. "A Simple and Inexpensive Salt Bridge for Demonstrations Involving a Galvanic Cell", **Journal of Chemical Education.** 84: 597; 4 January, 2007.

[24] Kamata, M. and Yajima, S. "Microscale electrolysis using coin-type lithium batteries and filter paper", **Journal of Chemical Education.** 90: 228-231, 2013.

[25] Mulford, D. R. and Robinson, W. R. "An inventory for alternate conceptions among first-semester general chemistry students", **Journal of Chemical Education.** 79(6): 739-744; June, 2002.

[26] Stears, M. and Gopal, N. "Exploring alternative assessment strategies in science classrooms", **South African Journal of Education.** 30: 591-604, 2010.

[27] Demirbaş, M. and Ertuğrul, N. "A study on preschoolers' conceptual perceptions of states of matter: a case study of Turkish students", **South African Journal of Education.** 34(3): 1-13; August, 2014.

[28] Cullen, D. M. and Pentecost, T. C. "A Model Approach to the Electrochemical Cell: An Inquiry Activity", **Journal of Chemical Education.** 88: 1562-1564, 2011.

[29] Rogers, F., Huddle, P. A. and White, M. D. "Using a teaching model to correct known misconceptions in electrochemistry", **Journal of Chemical Education.** 77(1): 104-110; 1 January, 2000.

[30] Supasorn, S. and Promarak, V. "Implementation of 5E inquiry incorporated with analogy learning approach to enhance conceptual understanding of chemical reaction rate for grade 11 students", **Chemistry Education Research and Practice.** 16: 121-132, 2015.

[31] Piccolino, M. "Luigi Galvani's path to animal electricity", **Comptes rendus biologies.** 329: 303-318, 2006.

REFERRENCES (CONTINUED)

[32] Kakiuchi, T. "Salt bridge in electroanalytical chemistry: past, present, and future", **Journal of Solid State Electrochemistry.** 15: 1661-1671; 12 May, 2011.

[33] Østerberg, N. O., Sørensen, T. S. and Jensen, J. B. "Practical and theoretical aspects concerning the use of salt bridges in electrochemistry", **Journal of Electroanalytical Chemistry and Interfacial Electrochemistry.** 119: 93-108, 1981.

[34] Howell, B. A., Cobb, V. S. and Haaksma, R. A. "A convenient salt bridge for electrochemical experiments in the general chemistry laboratory", **Journal of Chemical Education.** 60: 273; 4 April, 1983.

[35] Musafia, B., Buchner, V. and Arad, D. "Complex salt bridges in proteins: statistical analysis of structure and function", **Journal of molecular biology.** 254: 761-770, 1995.

[36] Donald, J. E., Kulp, D. W. and DeGrado, W. F. "Salt bridges: Geometrically specific, designable interactions", **Proteins: Structure, Function, and Bioinformatics.** 79: 898-915, 2011.

[37] Kumar, D. D. "ALTERNATE FORMS OF SALT BRIDGES".

[38] Joesten, M. "Experiments for chemistry 102B", **Vanderbilt University, Nashville, TN,** 1991.

[39] Scharlin, P. and Battino, R. "The voltaic pile: A stimulating general chemistry experiment", **Journal of chemical education.** 68(8): 665-666; 8 August, 1991.

[40] Dobrzynski, E. D. "Voltaic cell measurements on a spot plate with a cotton swab salt bridge", **Journal of Chemical Education.** 73(6): A6, 1996.

[41] Burgot, J.-L. "Redox Reactions and Electrochemical Cells", **in Ionic Equilibria in Analytical Chemistry, ed: Springer.** 205-227, 2012.

[42] Kumar, R. V. and Sarakonsri, T. "A Review of Materials and Chemistry for Secondary Batteries", **High Energy Density Lithium Batteries: Materials, Engineering, Applications.** 53-80, 2010.

REFERRENCES (CONTINUED)

[43] Brosmer, J. L. and Peters, D. G. "Galvanic Cells and the Determination of Equilibrium Constants", **Journal of Chemical Education.** 89: 763-766; 23 March, 2012.

[44] Singh, M. M. and et al. "A Comparative Study of Microscale and Standard Burets", **Journal of Chemical Education.** 77(5): 625-626; May, 2000.

[45] Udnan, Y., Chuachuad, W. and Sanunmuang, R. "Microscale electrochemical cell using plaster ($CaSO_4$) as liquid junction", **MAEJO INTERNATIONAL JOURNAL OF SCIENCE AND TECHNOLOGY.** 2(3): 535-541; 28 October, 2008.

[46] Eggen, P.-O. "A Simple Hydrogen Electrode", **Journal of Chemical Education.** 86 (3): 352-354; March, 2009.

[47] Muske, K. R., Nigh, C. W. and Weinstein, R. D. "A Lemon Cell Battery for High-Power Applications", **Journal of Chemical Education.** 84(2): 635-638; 4 April, 2007.

[48] Çalik, M., Kolomuç, A. and Karagölge, Z. "The effect of conceptual change pedagogy on students' conceptions of rate of reaction", **Journal of Science Education and Technology.** 19: 422-433; 17 February, 2010.

[49] Johnstone, A. H. "The development of chemistry teaching: A changing response to changing demand", **Journal of chemical education.** 70(9): 701, 1993.

[50] Chandrasegaran, A., Treagust, D. F. and Mocerino, M. "The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation", **Chemistry Education Research and Practice.** 8: 293-307, 2007.

[51] Taber, K. S. "Three levels of chemistry educational research", **Chemistry Education Research and Practice.** 14: 151-155, 2013.

[52] Ibrahim, B. and Rebello, N. S. "Role of mental representations in problem solving: Students' approaches to nondirected tasks", **Physical Review Special Topics-Physics Education Research.** 9(2): 1-17; 10 July, 2013.

REFERRENCES (CONTINUED)

[53] Liu, C.-J. and et al. "An Exploration of Secondary Students' Mental States When Learning About Acids and Bases", **Research in Science Education.** 44: 133-154; 21 August, 2014.

[54] Coll, R. K. and Treagust, D. F. "Learners' mental models of metallic bonding: A cross-age study", **Science Education.** 87: 685-707, 2003.

[55] Chandrasegaran, A., Treagust, D. F. and Mocerino, M. "Facilitating high school students' use of multiple representations to describe and explain simple chemical reactions", **Teaching Science.** 57: 13-20; 4 December, 2011.

[56] Glynn, S. M. and Duit, R. "Learning science meaningfully: Constructing conceptual models", **Learning science in the schools: Research reforming practice.** 3-33, 1995.

[57] Briggs, M. and Bodner, G. "A model of molecular visualization" **in Visualization in science education, ed: Springer.** 61-72; Spring, 2005.

[58] Doymus, K., Karacop, A., and Simsek, U. "Effects of jigsaw and animation techniques on students' understanding of concepts and subjects in electrochemistry", **Educational Technology Research and Development.** 58: 671-691, 17 April, 2010.

[59] Dixon, R. A. and Johnson, S. D. "Experts vs. novices: differences in how mental representations are used in engineering design", 2011.

[60] Duis, J. M. "Organic chemistry educators' perspectives on fundamental concepts and misconceptions: An exploratory study", **Journal of Chemical Education.** 88(3): 346-350; March, 2011.

[61] Sanger, M. J. "How does inquiry-based instruction affect teaching majors' views about teaching and learning science?", **Journal of Chemical Education.** 85(2): 297-302; February, 2008.

[62] Deters, K. M. "Student opinions regarding inquiry-based labs", **Journal of Chemical Education.** 82(8): 1178-1180; 8 August, 2005.

[63] Bybee, R. and et al. "The BSCS 5E instructional model", **Origins, effectiveness and applications.** 719: 531-5550; 12 June, 2006.

REFERRENCES (CONTINUED)

[64] Balci, S., Cakiroglu, J. and Tekkaya, C. "Engagement, exploration, explanation, extension, and evaluation (5E) learning cycle and conceptual change text as learning tools", **Biochemistry and Molecular Biology Education.** 34(3): 199-203; 18 October, 2005.

[65] Rickard, D., Schoonen Martin, A. A. and Luther, G. W. "Chemistry of Iron Sulfides in Sedimentary Environments in Geochemical Transformations of Sedimentary Sulfur", **American Chemical Society.** 612: 168-193, 1995.

[66] Poliakoff, M. and Licence, P. "Sustainable technology: green chemistry", **Nature.** 450: 810-812, 2007.

[67] Khattiyavong, p. "Galvanic cell", **JCEd.** 4, 2015.

[68] Supasorn, S., Khattiyavong, P. and Promarak, V. "Small-Scale Inquiry-Based Experiments to Enhance High School Students' Conceptual Understanding of Electrochemistry", In **the 4th International Conference on Education, Research and Innovation (ICERI2014).** p 85-91. Education, 2014.

[69] Treagust, D. F. "Development and use of diagnostic tests to evaluate students' misconceptions in science", **International Journal of Science Education.** 10: 159-169, 1988.

[70] Supasorn, S. "Grade 12 students' conceptual understanding and mental models of galvanic cells before and after learning by using small-scale experiments in conjunction with a model kit", **Chemistry Education Research and Practice.** 1-13, 2015.

[71] Hake, R. R. "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses", **American journal of Physics.** 66: 64-74, 1998.

[72] Oldfield, J. W. "Electrochemical theory of galvanic corrosion", **Galvanic Corrosion.** 5-22, 1988.

[73] Ohno, H., **Electrochemical aspects of ionic liquids:** John Wiley & Sons, 2011.

[74] Iverson, M. L. and Duke, F. R. "Complex metal halides in fused alkali nitrates", December, 1957.

REFERRENCES (CONTINUED)

[75] Sözbilir, M., Pınarbaşı, T. and Canpolat, N. "Prospective chemistry teachers' conceptions of chemical thermodynamics and kinetics", **Eurasia Journal of Mathematics, Science & Technology Education.** 6(2): 111-120; 12 December, 2010.

[76] Karsli, F. and Çalik, M. "Can freshman science student teachers' alternative conceptions of 'electrochemical cells' be fully diminished", **Asian Journal of Chemistry.** 24: 485-491, 2012.

[77] Sanger, M. J. and Greenbowe, T. J. "Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells", **Journal of Research in Science Teaching.** 34: 377-398, 1997.

CURRICULUM VITAE

NAME	Miss Phetvilay Khattiyavong
BIRTH DATE	28 December 1984
BIRTH PLACE	Savannakhet Province, Laos
EDUCATION	B. Sc. (Chemical education), Department of Chemistry, Faculty of Education, National University of Lao, Laos (2003-2007) M. Sc. (Chemistry), Department of Chemistry, Faculty of Science, Ubon Ratchathani University, Thailand (2012-2015)
SCHOLARSHIP	The Thailand International Development Cooperation Agency (TICA), 2012-2015.
PUBLICATION	"The Development of Small Scale and Low-Cost Galvanic Cells as a Teaching Tool for Electrochemistry" Journal of Research on Science, Technology and Environment for Learning. Volume 5. No. 2 (July – December 2014), 146-154.
PRESENTATIONS	Pure and Applied chemistry International conference (PACCON 2015), 21 - 23 January 2015 Amari Watergate Hotel, Bangkok, Thailand.

Office of Academic Resources Ubon Ratchathani University