Interconnected Software Modules to Aid the Learning of Fuel Cell Courses

Mr. Amjad Aman, University of Central Florida

Amjad Aman is a PhD student at the Department of Mechanical and Aerospace Engineering at the University of Central Florida. His research interests include fuel cells, fuel cell materials, perovskites and numerical modeling.

Prof. Yunjun Xu, University of Central Florida

Dr. Yunjun Xu is an Associate Professor in the Department of Mechanical and Aerospace Engineering at the University of Central Florida. His research interests are robotics, controls, and aerospace system.

Dr. Haiyan Bai, University of Central Florida

Haiyan Bai, PhD., is an Associate Professor of Quantitative Research Methodology in the College of Education and Human Performance at the University of Central Florida. Her interests include resampling method, propensity score analysis, research design, measurement and evaluation, and the applications of statistical methods in educational research and behavioral sciences. She has been involved in several large projects of instructional technology use in educational settings. She has published books and many professional articles in refereed national and international journals. She has won several competitive awards at the University of Central Florida for her excellent teaching and research. Dr. Bai also served on several professional journal editorial boards, such as Journal of Experimental Education, Frontiers in Quantitative Psychology and Measurement, and Journal of Data Analysis and Information Processing. She is also the Fellow of the Academy for Teaching, Learning, and Leadership and the Faculty Fellow at The University of Central Florida.

Prof. Nina Orlovskaya, University of Central Florida

Prof. Nina Orlovskaya is an Associate Professor of Mechanical and Aerospace Engineering at the University of Central Florida. Her research interests are in field of ceramics for energy applications - solid oxide fuel cells, oxygen separation membranes, sensors and catalysis.

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1 Abstract

Along with the recent trend in research and development of alternative energy sources such as fuel cells, there is an urgent need of highly motivated engineers with system level thinking to satisfy the ever-growing fuel cell and hydrogen industry. In this paper, we will present an interactive software package that was recently developed and used as a secondary learning tool for students who are interested in fuel cell technologies. The emphasis of the software package is on the interconnected fuel cell modules including "introduction", "applications", "fuel cell system", "cell level", and "fuel cell science". The software modules have been tested in a group of senior design students and the assessment results showed that it can enhance students' motivation in learning and increase students' learning outcomes in fuel cell related knowledge.

2 Introduction

As the energy demands are increasing, the need for more efficient and versatile power conversion devices has become paramount[1-3]. The use and commercialization of fuel cells as power conversion devices have escalated in the past few decades due to their scalability, versatility, ability to be integrated with other power conversion devices, and minimal environmental impact[4]. The fuel cell industry sales are estimated to reach $1.3 billion in 2013[5].

According to one prediction, the fuel cell and hydrogen industry worldwide will grow to be a $180 billion dollar industry by 2050[6], and generate up to 180,000 job positions by 2020[7].

To meet the employment demands of the fuel cell industry, educating the current and future generations of engineers and scientists in fuel cells has become of utter significance. Many educational institutions offer courses related to fuel cell or hydrogen technology[8, 9], and mostly the courses follow the conventional teaching style based on classrooms and books. Furthermore, very few present the educational contents in an inter-connected manner that brings together different perspectives on fuel cell systems. The purpose of this work is to show the development, testing, and evaluation of a software package that is to be used as an augmented learning tool in undergraduate fuel cell courses. The emphasis of this tool is the system level thinking of fuel cells and the interconnection among different levels of fuel cell knowledge. The targeted users mainly include undergraduate students in the majors of materials, mechanical, and aerospace engineering.

The effect of the software in enhancing students' learning is also evaluated. Quasi-experimental research is designed to evaluate the effectiveness of the developed software modules. The test group for the current study included around 145 senior undergraduate students in a senior design course.

In this paper, first we will describe the methodology we used in developing the software package. Then several examples in the software modules will be illustrated. After that, the results from the evaluation of the tool in a senior undergraduate student group will be discussed; followed by a conclusion and future work.

3 Methodology of Software Development

The software was designed with deliberate consideration and a trial-and-error method to find the best way to present the educational material to maximize retention of the material. The main goals of the software are that it has to be easy to use, be highly interactive, gives the student the freedom to learn in their own style, and serves as a supplemental learning tool for fuel cell courses.

The software is designed using Adobe Flash Professional and Microsoft PowerPoint 2013. The software can be accessed and used by students on computers with a standard operating system, a web browser, and an internet connection. The minimal hardware and software requirements make it easy for students to use the software. The instructor could give the students the option to open the software and follow along in the classroom or they could just have the students go over the software outside the classroom.

The software is divided into five modules; each module has sub-modules that contain “slides” with animations or videos. The five modules are: (i) introduction, (ii) applications, (iii) fuel cell systems, (iv) cell level, and (v) fuel cell science. There are two important standpoints in the development of this software: (a) contents, and (b) interconnectedness among software modules. First, the educational content is presented in the form of text, video, and animations with audio.

All the material contents are verified by the instructor of the fuel cell courses. The design, sequence and flow or continuity of the animations and videos have been deliberately planned out. At the same time, the animations/videos are made to keep student's attention and be highly interactive.

Second, the interconnected feature among the five main modules as well as between the sub-modules and slides makes this software unique The plan of the interconnections is demonstrated in Fig. 1. As shown in Fig. 1, the modules and sub-modules are connected through hyperlinks. Clickable buttons are used to establish the interconnections. For example, students most interested in applications can go straight to applications and from there they can go on to learn about fuel cell science, fuel cell systems, or cell level. Or they could start with the fundamental fuel cell science, then go on to learn the working of a fuel cell stack/system and finally the applications. This gives students the freedom to learn and adapt themselves to the material in a way they feel comfortable. This could result in higher retention of the educational content as it reinforces what the students have already learned in class, improve their performance, and can maximize retention of students in the class.

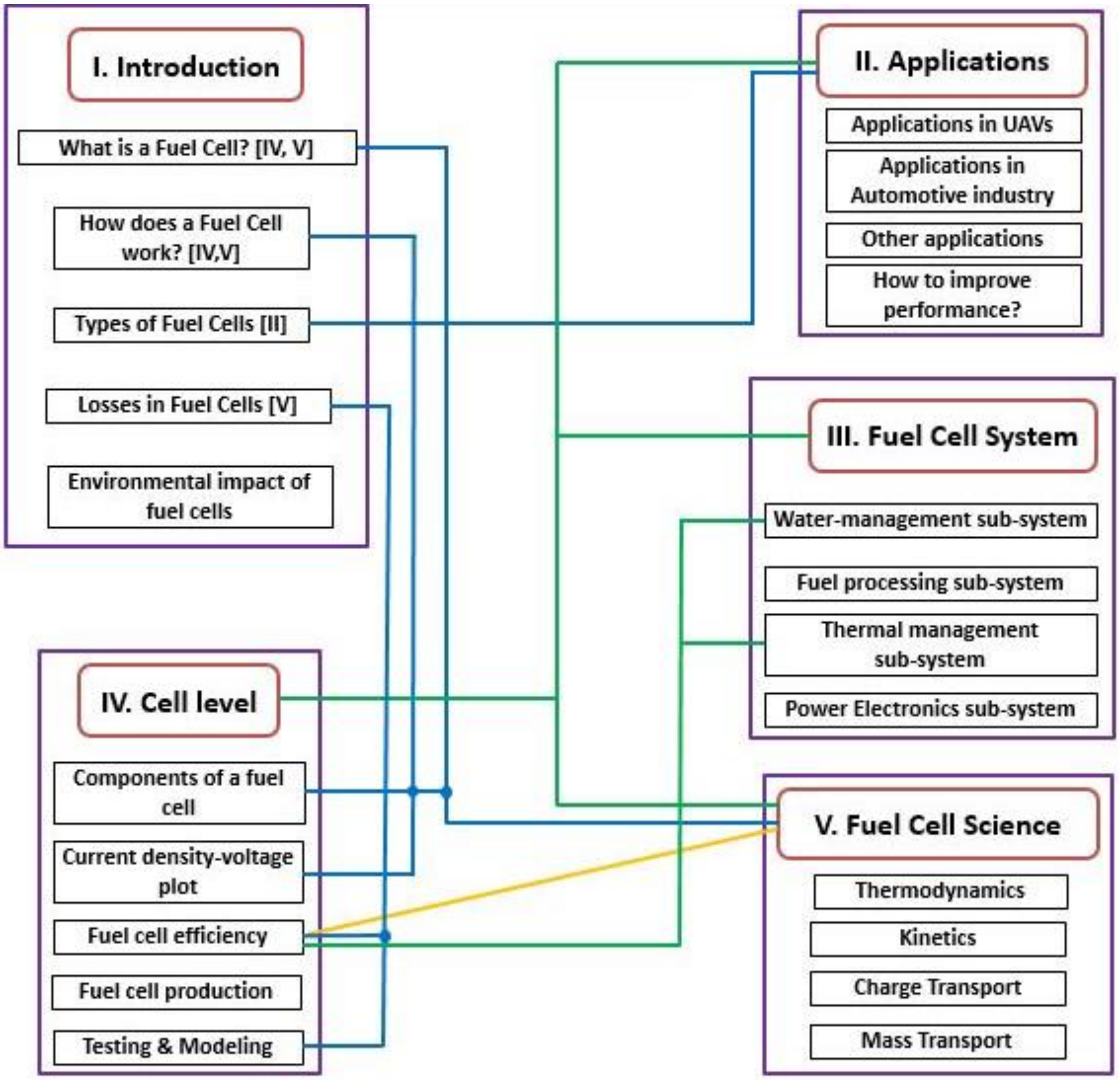

Figure 1. The interconnections among the five main modules of the software

4 Module Examples

Here five examples are shown of the five software modules. Each example is explained with the use of a figure.

Example 1: An example of one of the animations in the Introduction module is demonstrated using Fig. 2. The animation gives an introduction to the losses in fuel cells. The sequence of the animations is shown in Fig. 2 (a) through (f). It starts with the interface of the "Introduction" module in (a). When the button "Losses in Fuel Cells" is clicked, the animation begins as seen in (b). It shows that in the ideal scenario one would want a 100% of the chemical energy of the fuel could be converted to electrical energy, but that's not the case based on the laws of thermodynamics[10, 11]. Figure 2 (c) shows a man trying to obtain as much work from a fuel cell as possible; and in (d) the man has succeeded in extracting the maximum work from a fuel cell. The thermodynamic equations of maximum theoretical work output from a fuel cell are shown. The thermodynamic or reversible voltage for a hydrogen-oxygen fuel cell is 1.23 V and is presented as the upper limit of the voltage achievable, and also points to the fact that there always are other losses to consider[10]. Finally Fig. 2 (f) shows the current-voltage plot with the regions of different losses in a fuel cell.

From here if the student wants to go deeper into the understanding of the science behind the three different types of losses, the student could click on any of the three colored regions in the current-voltage plot, which will take them to the Fuel Cell Science module where the concept of Reaction Kinetics will help explain activation losses[10, 12]. The Charge Transport sub-module will explain Ohmic losses and the Mass Transport sub-module will make the concept of concentration losses[10, 12] clear.

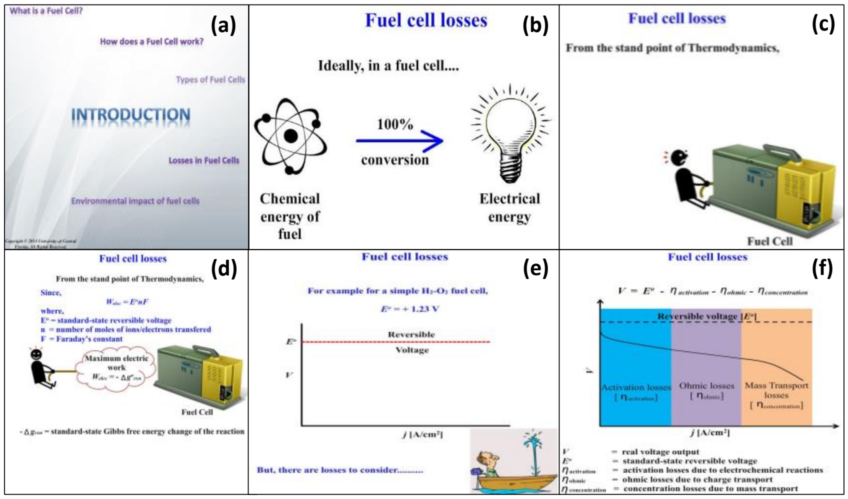

Figure 2. Example of an animation and the interconnections shown in the Introduction module. Part (a) shows the interface of the module; and parts (b) – (f) screen shots of the "Fuel Cell Losses" animation.

Example 2: Figure 3 (a) shows the menu of the Fuel Cell Applications module. The applications of fuel cell in UAVs and automotive industry and other applications such as stationary power generation are discussed in this module. Part (b) shows the menu of the sub-module "Applications in UAVs"; this is followed by a sequence of animations. An animation of the three most suitable types of fuel cells that could be used in UAVs can be seen in (c). As seen in (d), Solid Oxide Fuel Cell is not feasible due to the challenge of the high operating temperature of this type of fuel cell. An additional thermal management system will be required to maintain the operations of fuel cells that operate way above the room temperature[13]. This will add to the weight of the UAV that increases the overall cost. Use of Alkaline Fuel Cells is also not very favorable due to their operating temperature, as shown in (d). Part (e) explains that Polymer Electrolyte Membrane Fuel Cells (PEMFC) are most suitable due to their operating temperature range and other factors[14]. Finally, a screenshot of the video of the flight of a UAV is shown in (f). This UAV employed PEMFC as the energy conversion device with a hydrogen tank as the fuel source. Students could click on any of the type of fuel cell, which will take them to the explanation of how each type of fuel cell works under the Introduction module.

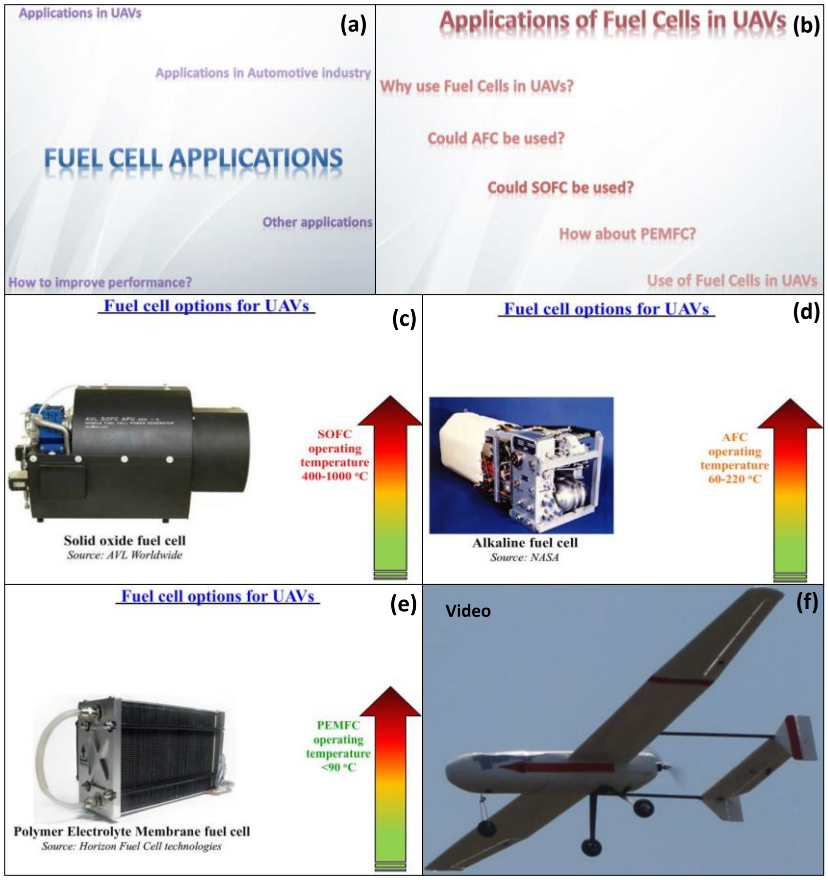

Figure 3. (a) the menu of the Fuel Cell Applications module; (b) the menu of the sub-module Applications in UAVs; (c) animation that presents the three types of fuel cells, here Solid Oxide Fuel Cell (SOFC); (d) Alkaline Fuel Cells; (e) Polymer Electrolyte Membrane Fuel Cells (PEMFC); and(f) video showing the flight of a UAV powered by PEMFC

Example 3: The Fuel Cell System module is discussed in Fig. 4. Part (a) shows the menu of the module. The screen shot in (b) is the sub-menu that appears when the "Water-management system" is clicked. Polymer Electrolyte Membrane Fuel Cells (PEMFCs) operate below 100^{o}C and have the issue of water flooding since the water in the cell will remain in the liquid form. The two contributing factors of this issue is electro-osmotic drag and back diffusion[10]. Parts (c), (d) and (f) show the three progressive steps in the animation that explains the concept of electro-osmotic drag in PEMFCs. This sub-module is connected with the sub-module called Efficiency & How to Improve It under the Cell-Level module. Water flooding is a serious issue and brings down the overall efficiency of the fuel cell[15].

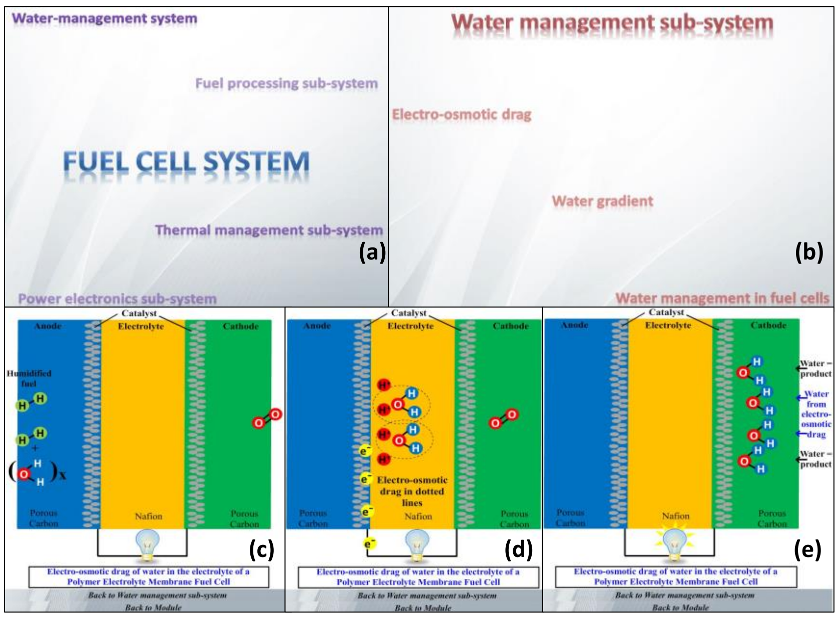

Figure 4. One example animation in the Fuel Cell System module. Part (a): the interface of the module; and part (b): the menu of the “Water management system” sub-module. Screenshots of the “Electro-osmotic drag” animation are shown in parts (c) – (e).

Example 4: The Cell Level module explains various aspects like the components, production, testing, modeling, and study on efficiency of individual fuel cells. In Fig. 5 (a), the interface of the Cell Level module is seen. When the “Fuel cell production” button is clicked, an animation pops up as displayed in (b) that explains the steps involved in producing electrolytes for solid oxide fuel cells. Part (c) has a screen shot of the video that shows the spin coating of Gadolinia

Doped Ceria layer over the surface of the fuel cell electrolyte. Part (d) is a snap shot of the video showing the screen printing of anode and cathode inks over either side of the electrolyte. The final sintering process of the fuel cell is described in the video in part (e). This sub-module is connected to the other sub-module called "Components of a fuel cell" within the same module.

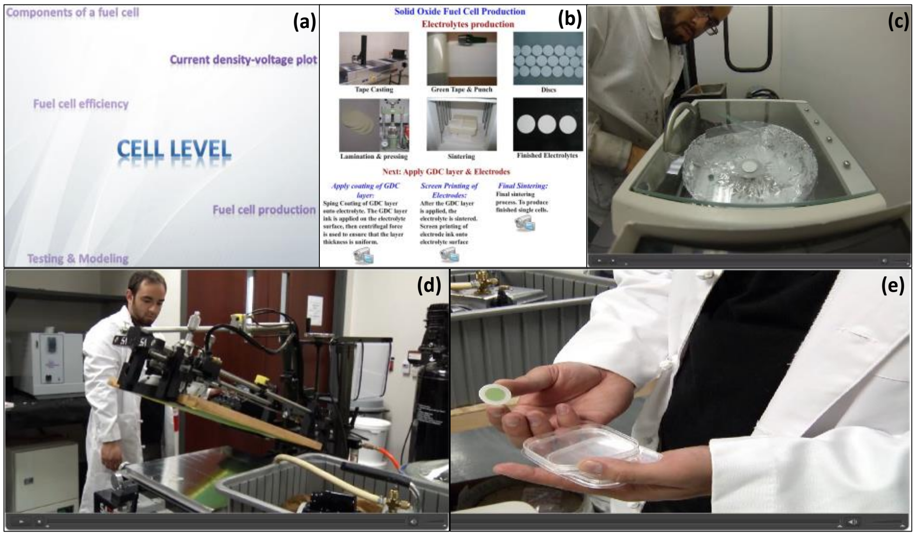

Figure 5. The Cell Level module is explained here. The main menu of the module is displayed in (a); followed by the animation that appears when "Fuel cell production" is clicked; and (c) – (e) are screenshots of three different videos.

Example 5: Fig. 6 describes one of the animations in the Fuel Cell Science modules starting with the menu of the module in part (a). Part (b) similarly shows the sub-menu that opens up when the "Charge Transport" item is clicked. Animation explaining the concept of Ohmic resistance in fuel cells is seen in part (c) [10, 12]. Part (d) describes the additive nature of resistance in fuel cell components, and part (e) demonstrates the effect of Ohmic losses using the voltage plot across the cross section of the fuel cell. Finally, part (f) clarifies the effect of varying magnitudes of Ohmic losses using the current-voltage plot. This sub-module is linked with the sub-module under Cell Level which goes over the concept of current-voltage or power-voltage plots and how to interpret them.

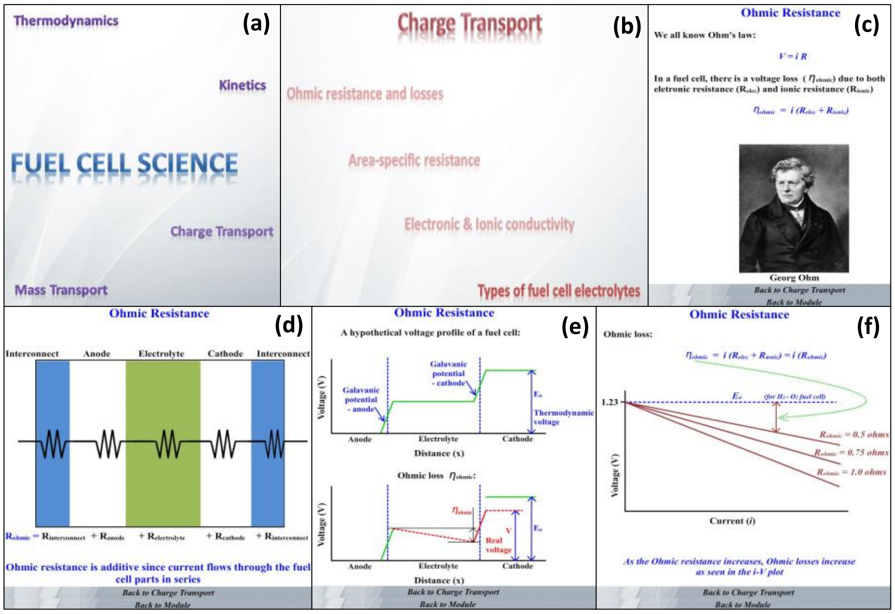

Figure 6. Interface and screenshots of one animation in the Fuel Cell Science module

5 Evaluation/Assessment Method

Pre- and post- quantitative data analyses are used to evaluate the effectiveness of the interconnected software modules for increasing engineering students' learning outcomes and motivations in fuel cell courses.

A random clustered sample of 145 senior college students majoring in Mechanical and Aerospace Engineering from a large university in the south-east of the United States is used. IRB approval at the authors' university was obtained in the Fall of 2014. The *Student Learning Motivation* (SLM) survey[16] based on ARCS[17] model was used to collect student course learning motivation data. SLM has been reported as a reliable instrument for collecting students' course motivation data[16]. The Cronbach alpha value is 0.91 for the current data. The researchers created a *Fuel Cell Knowledge Test* which was used to collect student learning outcome data before and after the software intervention period.

Data Collection Procedure: Paper-based test and survey were given to the students in a normal classroom setting. Before the class, the researchers distributed the test papers and questionnaires to the students in one large classroom along with the consent form approved by IRB as the cover page of the survey package. One of the researchers read the consent form to the students and made students aware that they were invited to participant the research on a volunteer basis. Students were asked to complete the *Student Learning Motivation* survey and the *Fuel Cell Knowledge Test* as the pretests before class. Then one of the researchers taught the entire class with the software modules as the intervention for 20 minutes. After the intervention, students were asked to complete the *Student Learning Motivation* survey and the *Fuel Cell Knowledge Test* again as the post-tests. Students' demographic data were also collected.

Data Analysis Results*:* Repeated measure test was used to analyze the pre- and post-test data for comparing test differences in their motivation scores and knowledge test scores between pre-test and post-test. The analysis results showed that after the software treatment, students' motivation was significantly improved with $F(1) = 5.44$ ($p = .02 < .05$) (See Table 1), and the mean of post-test motivation score ($M = 69.10$; $SD = 14.13$) was 2.09 points higher than the mean of pre-test score ($M = 67.01$, $SD = 13.01$). The analysis also revealed that the learning outcomes of students were significantly increased with $F(1) = 20.59$ ($p < .001$) (See Table 2) while controlling for the motivation of students. The mean of students' post knowledge test score

(*M* = 22.08, *SD* = 5.07) was 14.47 points higher than the mean of pre-test score (*M* = 7.67, *SD* = 4.48).

Table 1. *Motivation Tests of Within-Subjects Effects*

Source		Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Motivation	Sphericity Assumed	266.496	1	266.496	5.436	.021
	Greenhouse-Geisser	266.496	1	266.496	5.436	.021
	Huynh-Feldt	266.496	1	266.496	5.436	.021
	Lower-bound	266.496	1	266.496	5.436	.021
Error(Motivation)	Sphericity Assumed	5932.004	121	49.025		
	Greenhouse-Geisser	5932.004	121	49.025		
	Huynh-Feldt	5932.004	121	49.025		
	Lower-bound	5932.004	121	49.025		

6 Conclusion

In this paper, a recently developed software tool is discussed, which can be used as a secondary learning tool for students who are interested in fuel cell and hydrogen related technologies. The technical contents are presented in the form of videos, figures, animations, and text; and all the modules and sub-models in this tool are interconnected. Up to now, a total of five modules have been developed with system level thinking, and some pedagogical effects have been assessed in one senior undergraduate class. It is shown that both students’ motivation and learning outcome are significantly improved.

Table 2. *Knowledge Tests of Within-Subjects Effects*

Source		Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Test	Sphericity Assumed	232.161	1	232.161	20.586	<.001
	Greenhouse-Geisser	232.161	1	232.161	20.586	<.001
	Huynh-Feldt	232.161	1	232.161	20.586	<.001
	Lower-bound	232.161	1	232.161	20.586	<.001
test * CMS_pre_T	Sphericity Assumed	55.540	1	55.540	4.925	.028
	Greenhouse-Geisser	55.540	1	55.540	4.925	.028
	Huynh-Feldt	55.540	1	55.540	4.925	.028
	Lower-bound	55.540	1	55.540	4.925	.028
Error(test)	Sphericity Assumed	1477.400	131	11.278		
	Greenhouse-Geisser	1477.400	131	11.278		
	Huynh-Feldt	1477.400	131	11.278		
	Lower-bound	1477.400	131	11.278		

7 Acknowledgement

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