An Experiment-based Approach in the Context of Electrified Aviation to Increase the Interest of K-12 Pupils in STEM

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***Abstract*—This work in progress paper presents an approach to combine inductive and deductive learning methods with hands-on experiences to increase the interest of K-12 pupils in Science, Technology, Engineering and Mathematics (STEM). Didactive methods are shown and a suitable approach is highlighted. Possible electrochemical experiments in the context of electrified aviation are discussed and theoretical basics for the selected hands-on activities are explained. Furthermore, a way of quantifying the results is described and further ideas for the future expansion of the laboratory are presented. The developed experiments may be used for training purposes internally in the institute, for public relations activities during public events as well as a building block in the architecture of the DLR_School_Lab network. In conclusion, the presented approach could not only help fascinate more pupils for STEM studies and careers, but also enables disruptive technologies like electrified aviation to gain more acceptance in society.**

Keywords—STEM, K-12, inductive learning, problem-based learning, electrified aviation, hydrogen fuel cell

I. Introduction

Graduates in Science, Technology, Engineering and Mathematics (STEM) are necessary to solve the technological challenges that arise in the context of climate change. However, in Germany student numbers in these courses have been declining, whilst dropout rates have been rising for years [1]. This trend can be related to a new record high in study courses, making it harder for high school graduates to identify their suitable field of study [2]. A possible approach to ease this decision making and improve the study success of high school graduates are relevant hands-on experiences in the respective fields of interest during the K-12 high school education. Earlier studies show that these experiences are especially valuable from grade nine onwards [3], [4]. High school pupils are having full schedules and only limited time in the curriculum for such measures nowadays. Hence, ways of learning have to be identified, which offer the required practical tasks other than long-term projects.

Previous studies either tried using conventional methods, virtual laboratories or experiments from different topics without a broader context [5], [6]. In contrast, this paper combines inductive and deductive learning methods with hands-on applications from scientifically relevant topics to create a problem-based learning approach featuring electrochemical experiments in the context of electrified aviation. This balanced combination of inductive and deductive methods together with practical tasks may offer a more comprehensive approach than conventional instruction methods [3]. Another synergy to be used is the integration of this project into the DLR_School_Lab infrastructure of the German Aerospace Center (DLR), where other singular topics are already taught through experiment- and problem-based approaches [7]. During the experiment sessions, students will need to use their existing knowledge from science courses to solve the proposed tasks. Thus, they will reinforce what they already know about certain topics and gain a deeper understanding. Further beneficial effects of this course of action are additional experience in the application of their skills, gaining new knowledge in the respective fields of the experiments as well as giving the students an opportunity to make a more qualified decision concerning their field of study [8].

To achieve the aforementioned benefits, a framework programme for a school laboratory with electrochemical experiments concerning electrified aviation is introduced, possible methods of instruction are discussed and the theoretical framework for the used experiments is shown. Afterwards, the experiment set-ups are shown, ways to measure the effects and the actual results are discussed and possible future developments of this project are outlined.

II. Didactive Methods

In contrast to the conventional chalk and talk technique, hands-on activities and experiments offer a more interesting learning environment for pupils to learn complex topics as well as an enhanced long-term learning effect [9], [10]. In the following sections, potential approaches for such activities are shown and suitable approaches are highlighted.

A. Teacher-centred approach

Teacher-centred teaching, also called direct instruction, is a conventional and deductive way of teaching. A given topic is presented by the instructor with little room for deviations. The relevant content for a session is predetermined by the instructor. Thus, this method is good to teach novice learners the basics of a field in a structured way at the cost of not having flexibility [3].

B. Project-based approach

Project-based learning is an inductive learning method. Students take part in a long-term project, like designing a product, in which they bear a responsibility for not just the result but also for what they deem important enough to learn or not, compare Kazula et al. [11]. Through this approach, students can dive into a topic holistically and focus on topics fitting to their skills as well as concentrate their learning efforts on topics they deem important for the success of the project. On the downside, the gained knowledge in project-based approaches is not as structured as in direct instruction, which could pose a difficulty for students without previous knowledge in the field [11], [12].

C. Problem-based approach

Similarly, to project-based approaches, problem-based learning is an inductive learning method. Students are faced with a problem, which, in general, is relatable to them and their daily lives. As described for project-based learning, the students decide how to solve the problem and what to learn from that with two important differences. First, problem-based learning happens on short-term time frames. Secondly, to ensure that students stay engaged, problems may be streamlined to be more fitting for education purposes. As with project-based approaches, problem-based learning offers more degrees of freedom to students on what to learn compared to direct instruction whilst also giving practical examples for the application of the gained knowledge. Still, knowledge gained through this approach may not be as structured as through direct instruction, though that can be compensated by the aforementioned streamlining of the chosen problems [3].

Due to the boundary conditions set by the educational system and the School_Lab infrastructure, students will only have limited time to participate in the planned activities and experiments. Visiting student groups also tend to be of heterogenous knowledge levels. To provide as much of an innovative learning space as possible under the given circumstances, a problem-based approach in combination with deductive direct instruction for the theoretical framework is favourable.

D. Selected Combined Approach

For the presented framework programme during a DLR_School_Lab visit, a combined approach of inductive and deductive methods has been selected to introduce the experiments. The general didactic approach is as follows:

- First, theoretical basic knowledge is taught. Hereby, a short presentation of at most five minutes is combined with interactive communication methods.
- Then, the experimental setup and procedure are introduced, e.g. by worksheets or presentations.
- Subsequently, the experiment is conducted by the participants in groups of two and evaluated in the colloquium.

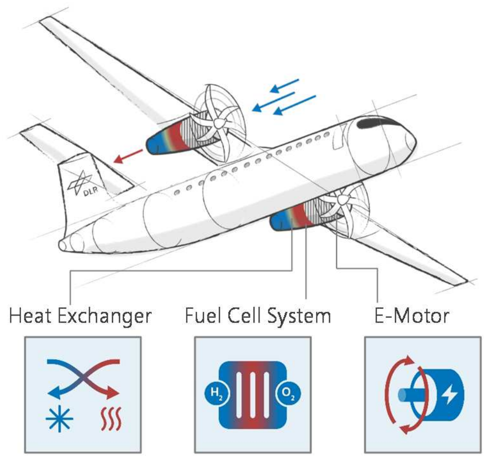

Fig. 1. Nacelle-integrated fuel cell-powered aircraft [14]

Thus, the specific knowledge of the respective experiment is gained through practical insights and experience, instead of learning from direct instructions. In case of a malfunction of an experiment, prerecorded videos of the experiment are shown and questions are discussed. After all questions have been answered, the next experiment is explained and so on.

III. PLANNED EXPERIMENTS

The aviation industry is a major source of greenhouse gas emissions. To meet the goals set in the Paris Climate Agreement, decarbonisation in the aviation industry is one major necessary step. Several approaches for this decarbonisation are currently being explored. Most of them feature a change in aircraft propulsion systems from gas turbines to electrified aero engines, as shown in Fig. 1. Thus, research concerning electrified aero engines has to be conducted in the coming years to ensure their reliability and efficiency for aviation purposes [13].

To offer a holistic approach, we assume a propulsion system with a fuel cell fed by green hydrogen, a puffer battery and an electric-driven propulsor, see Fig. 2. Due to the intended context of electrified aviation, three major fields of interest for experiments arise. These are means for electrochemical energy conversion, power electronics and electric machines for electrified propulsion. This paper will focus on the first field, featuring electrochemical experiments.

To identify suitable experiments and activities, it is important to analyse points, where energy conversion happens in electrified aviation. Thus, our possible energy conversions, which serve as primary experiments, are:

- **(A)** the electrolysis of hydrogen before it is fed into a hydrogen storage system
- **(B)** the conversion into electrical energy in a fuel cell
- **(C)** the storage of electrical energy in accumulators.

All proposed experiments would be so called galvanic elements or cells. In these galvanic elements, chemical reactions and electrical currents form an equilibrium, which can be used for technical purposes. These elements can further be subdivided into three categories [15].

- Primary cells work with the chemical energy provided through non-reversible chemical reactions and cannot be recharged. Examples are standard, non-rechargeable batteries like AA mignon cells/batteries.
- Secondary cells use reversible chemical reactions and thus can be recharged if being fed an electrical current. Examples are lithium-ion accumulators or Daniell-cells as in experiment **(C)**.
- Tertiary cells use reversible chemical reactions and feature an external source for the fuel, which is needed for the chemical reactions. E.g. in fuel cells as seen in experiment **(B)** or electrolysers as in experiment **(A)**.

A. Electrolysis of hydrogen

This experiment aims at providing students a better grasp on hydrogen as a fuel as well as trends and the state of the art in hydrogen production and storage. The key question to be solved during this experiment is “How can hydrogen be produced?”. Knowledge of these topics is important, because hydrogen will form an irreplaceable and growing part of future energy systems.

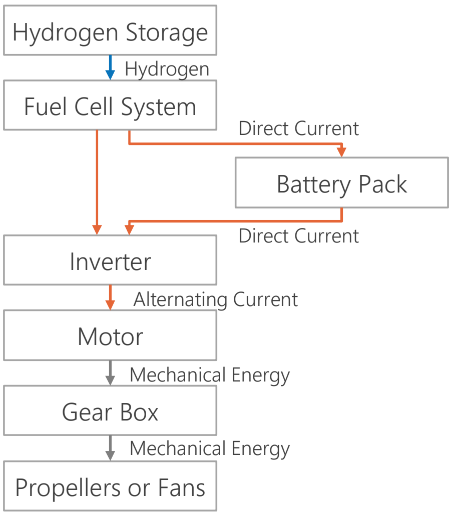

Fig. 2. Fuel cell-based aircraft propulsion system [14]

Basics in atomic structure and redox reactions will form the theoretical framework of this activity. A Hofmann electrolyser, as shown in Fig. 3 will be the backbone of this experiment. This device is used to electrochemically split water H_2O into hydrogen H_2 and oxygen O_2 via a redox reaction using a direct current of 1.23 V or more. On the anode side, two molecules of H_2O dissociate into one molecule of O_2, four electrons e^- and four hydrogen cations H^+. On the cathode side, four H^+ and four e^- react into two H_2 molecules and can be captured for further use [16], see Fig. 4.

Fig. 3. Experimental electrolyser set-up

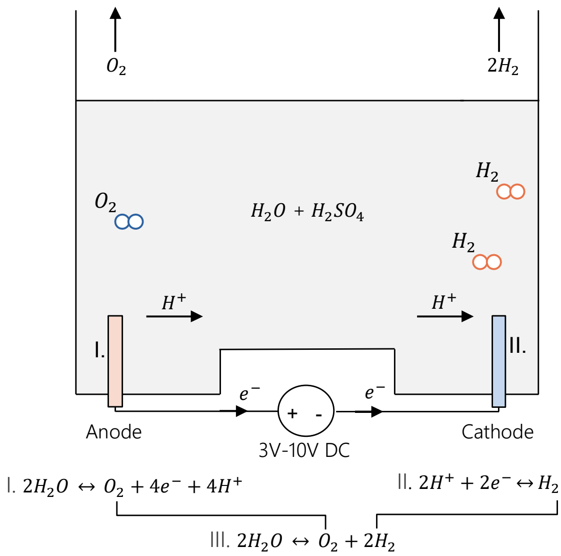

Fig. 4. Working principle of an electrolyser

B. *PEM fuel cell*

During this experiment, students will learn the basic working principle of a proton-exchange-membrane fuel cell (PEM-FC) as shown in Fig. 5. The key question for this experiment is "How can electrical energy be generated from hydrogen?".

The PEM-FC is the most relevant fuel cell type for current developments in electrified aviation due to its efficiency factor and its developmental state. In essence, a fuel cell reaction is the chemical reversal of the electrolysis reaction. Due to this, students can inductively understand the theory behind the functionality of a fuel cell after conducting experiment (A). To emphasise hands-on activities, this activity will feature a dismountable PEM-FC, see Fig. 6. Students will assemble the working FC out of the disassembled parts and fuel it with the hydrogen produced in experiment (A).

On the anode side of the FC, a hydrogen molecule will catalytically split into two hydrogen cations H^+ and two electrons e^-. While the cations, which are basically just protons, can pass through the membrane, the electrons need to run through an exterior conductor. This electron movement causes a usable current of roughly 0.8 V DC. On the cathode side, the two e^- and an oxygen molecule O_2 catalytically react to two oxygen anions O^{2-}. Two H^+ and one O^{2-} then react to one molecule of water H_2O and the fuel cell reaction is finished [17].

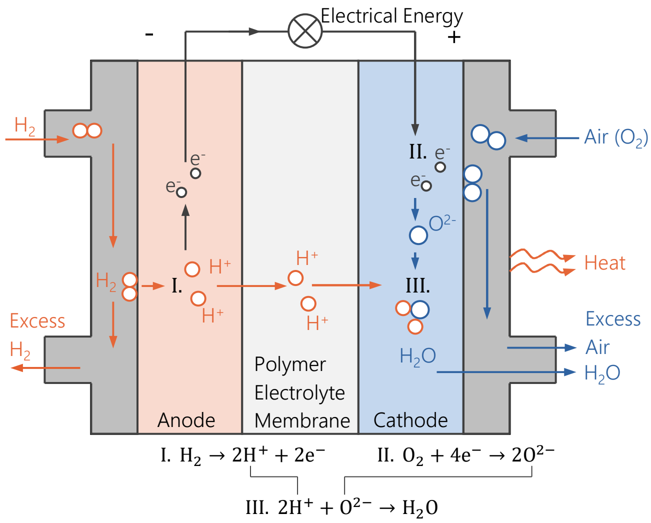

Fig. 5. Working principle of a PEM fuel cell [18]

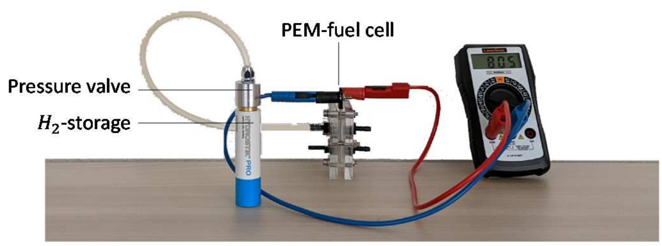

Fig. 6. Experimental fuel cell set-up

C. Daniell-cell accumulator

With this experiment, students learn the basics of accumulators and batteries using the example of the Daniell-element. The key question to be solved here is "How can electrical energy be stored electrochemically?". Due to accumulators forming the backbone of current energy storage systems, knowledge on the working principles of accumulators is imperative to gain a deeper understanding of electrified mobility in general and electrified aviation in particular. This kind of accumulator combines the fundamental workings of state-of-the-art accumulators with an easy to use set up. With the knowledge acquired in the experiments **(A)** and **(B)**, students can inductively understand how accumulators can be charged and discharged. To achieve this, students will build a Daniell-Element with basic laboratory equipment, as seen in Fig. 7. The required equipment for this experiment consists of 2 beakers, filled with a solution of $CuSO_4$ and $ZnSO_4$ each, a Cu-electrode and a Zn-electrode, cables and alligator clamps as well as tissue paper. The anode-side of this accumulator includes a beaker filled with $ZnSO_4$-solution and the Zn-electrode, the cathode side consists of the other beaker filled with $CuSO_4$ and the Cu-electrode. To form a circuit, both electrodes are connected via cables and alligator clamps and the solutions are connected via the tissue paper, due to capillarity effects it acts as a transport bridge for ions in solution.

This simple setup can work as a galvanic element due to the different electrochemical values of the used metals. Zn has a low electrochemical standard potential E_{Zn} of -0.76 V and thus a high solution tension. This means, it strives to form ions in aqueous solution. Cu on the other hand, has a high electrochemical standard potential E_{Cu} of 0.34 V and thus a low solution tension. Due to that, copper tends to de-ionise and form atoms in aqueous solutions. These chemical properties can be used to gain a usable current.

When a Zn-atom from the electrode goes into solution and ionises into Zn^{2+} on the anode side, 2 electrons e^- get freed up in the electrode. To maintain electrical balance in the system, these e^- move out of the anode and into the Cu-cathode. With these 2 e^- available, a copper ion Cu^{2+} from the solution binds these 2 e^- and turns into a Cu-atom and deposits on the electrode. The freed-up sulphate ion SO_4^{2-}can travel from the cathode- to the anode-side via the ion bridge and thus the electrical circuit is completed. The equivalent cell voltage of this circuit ΔE is determinable by the following equation:

$$\Delta E = E_{Cathode} - E_{Anode} = E_{Cu} - E_{Zn} = 0.34\,V — 0.76\,V = 1.10\,V \qquad (1)$$

This process can be seen in Fig. 8.

Fig. 7. Experimental accumulator set-up

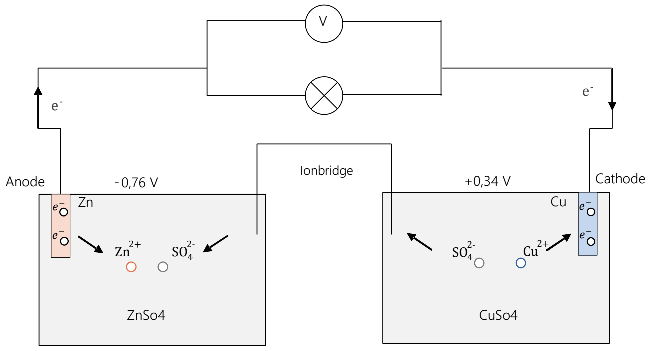

Fig. 8. Working principle of a Daniell-type accumulator

IV. Results

Due to the institute and laboratory being newly commissioned, no student data with the laboratory in use could be generated yet. Thus, this paper focuses on the planning for the initial set-up and current state of the laboratory. The result of the experience for the students is to be collected and documented in the form of a questionnaire. This questionnaire would be filled out by the students after the laboratory experience to quantify the expectations and results from the students' point of view, compare Worlitz et al. [19].

V. Discussion and Conclusion

After initial positive trials, the given approach could be expanded with more experiments covering more sophisticated aspects of electrified aviation. For example, fields such as power electronics or means of electrified propulsion could be added to the framework programme.

Also, the experiments concerning electrochemical energy conversion could be expanded further, including other types of fuel cells like direct methanol fuel cells, more advanced electrolysers like PEM-electrolysers as well as improved accumulators like lithium-ion accumulators.

In addition to this, experiments could be expanded to allow students to measure certain quantities of the experiments, for example electrical currents. These quantified datasets could then be analysed and compared to other datasets by the students. Thus, they could gain additional valuable impressions of tasks in the STEM sector to help them in their choice of studies.

To conclude, problem-based learning and hands-on activities may help to solve difficulties concerning the relation between pre-collage K-12 students and STEM education. Students may be enabled to make a more informed decision on their study subject in college, thus reducing dropout rates by students choosing the wrong subject. Additionally, this laboratory can help innovative new aviation technologies to gain more acceptance due to interactions with members of the general public.

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