INTEGRATION OF HYDROGEN KNOWLEDGE INTO MECHANICAL ENGINEERING CURRICULA

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Abstract

Hydrogen seems to be one of the most promising chemical substances regarding actual transition of energy technology. It could be produced easily from surplus electricity, could be stored with common technology, and its usage is free of greenhouse gases. With these characteristics hydrogen could replace fossil-based fuels in automotive powertrains, in aerospace applications and in space heating systems.

Due to these facts an appropriate knowledge of hydrogen and its technologies must be part of future mechanical engineering curricula. Basic knowledge could be included into chemistry lectures. Material related items like hydrogen embrittlement or hydride storage would fit to lectures in material science. Special items like fuel cells or hydrogen based internal combustion engines should be integrated in lectures of energy systems, automotive powertrain technology and similar topics. Furthermore, knowledge of safety aspects regarding handling with hydrogen should be imparted, too.

In this work we describe, how we integrated knowledge of hydrogen into two different courses. Automotive powertrains is a Bachelor course. Here lectures were complemented by basic information on hydrogen and hydrogen fuel cells. Additionally, laboratory exercises with a hydrogen education laboratory, a fuel cell engineering kit and a hybrid RC model car were established. Automotive engineering is a Master course. Here lectures were enriched by fundamental contents on hydrogen and its chemical and physical properties as well as by special topics like hydrogen storage and refuelling systems, fuel cell technology and hydrogen usage in internal combustion engines. As examination type in this Master course is a written homework assignment, each semester one topic regarding hydrogen technology in combination with experimental laboratory work is offered.

Actually, first rounds of both enhanced lectures were concluded. Student feedback are evaluated and resulting adaptions are implemented in both courses.

Keywords: *hydrogen knowledge, mechanical engineering education, Bachelor courses, Master courses, lecture contents, laboratory exercise design*

1. INTRODUCTION

As human development and prosperity depends on usage of energy, in the last century consumption of fossil-based energy sources increased dramatically and resulted in tremendous CO2-deposit in atmosphere. As CO2-deposit in atmosphere is main reason for climate change and increasing ambient temperatures, energy consumption has to transition from fossil-based sources to decarbonised technologies. Here, hydrogen seems to be one of the most promising options [1-4]. However, hydrogen-based technology as well as corresponding R&D activities has to cover 360 degree awareness of production, storage, transportation, usage and safety as well as public awareness, public comprehension and public behaviour [5-9].

Especially mobility – either commercial or individual – shows an enormous potential for decarbonisation technologies [10]. Actually, hydrogen technology has found its way into the mobility sector with two main occurrences – on one hand hydrogen fuel cell driven electric vehicles [11-14] and on the other hand replacement of fossil fuels in internal combustion engines [15-18]. In doing so, particlar attention is given to the transport sector [19, 20], special issues like backfiring [21] or blended usage of hydrogen in combination with other, mostly fossil fuels [18, 22-25]. Some research work is even done with e-scooters [26, 27]. Could they be driven by hydrogen fuel cells instead of batteries for faster recharging/refueling processes? As all these activities mentioned so far are related to chemistry, electrochemistry, thermodynamics and power machinery, another field of interest is belonging to material science. Here, focus is on investigation of metal hydride alloys for usage as hydrogen hydride storage. Metal hydrides are common material of Ni-MH-batteries for example [28]. These alloys could be used as solid-state hydrogen storage with the large advantage of low risk in case of accident, damage or other malfunction compared with gaseous or liquid state hydrogen storage [29-31].

All technical fields of interest mentioned above results in an immediate need for including at least basic knowledge of hydrogen into mechanical engineering education.

2. RELATED WORK

Based on the awareness of including hydrogen topics into mechanical engineering curricula a first step was to conduct a literature review focused on hydrogen activities in education of different level. The main result was, hydrogen activities are widespread from secondary school to universities and even to adult education. Important key issues are described in detail, now.

In primary school education hydrogen plays no role. It is to difficult to understand for pupils on that education level. However, in secondary school education hydrogen could be of interest. But implementation depends strongly on knowledge and motivation of teachers [32, 33]. Nevertheless, taught contents are limited by available budgets. Here the “Open Fuel Cell (OFC)” initiative could be helpful as it offers low-cost solutions for creating fuel cells by easily available materials processed by additive manufacturing based on simple 3D-printers [34].

In higher education of both types, universities of applied sciences and universities, hydrogen is very often included already in curricula, especially in practical laboratory exercises. However, these hydrogen contents are of many different characteristics. Very basic training systems use just electrolysers, hydrogen storage, fuel cell and measurement equipment to analyse system performance and sometimes to improve controller design [35]. More complex training systems are designed as micro grids and contain energy sources like solar, wind, hydro or even bicycle ergometers, energy storage in the form of batteries or electrolysers in combination with pressure vessels to store hydrogen, energy converters like transformers, rectifiers, inverters or fuel cells, and energy users as any type of electrical engine [36-38]. Here students get written instruction manuals and fulfill requirements by working them through, often supplemented by data analysis and some kind of oral presentation or written report. Other lecturers attach importance to project-based learning in groups of several students and in combination with hands-on laboratory work [39, 40]. Therefore, soft skills like experimental design, cooperation as well as division of labour, and teamwork are trained, too. Further training equipment is related to automotive engineering and is made up of model vehicles driven by batteries in combination with hydrogen fuel cells. Here the range is from freshman design courses with toy vehicles [41] to a two-piece course of electrochemical propulsion systems containing topics like system-level modeling, design, control, and parameter estimation [42]. A completely different approach is to include special topics like green hydrogen and advanced composite materials into engineering curricula. As universities have often limited resources for such special technologies, cooperations with appropriate industrial enterprises are established. Based on continous feedback loops between university and industry curricula are permanently adapted to new requirements [43].

In the field of post-graduate education and adult education focus is nearly exclusive on safety issues [5-7, 44]. Engineers in professional life have to be trained in the new field of hydrogen technology as this was not subject during their studies. Additionally, issues of hydrogen production, storage as well as transportation, and usage could be included [7]. Due to focus on engineers in professional life temporary courses like summer schools or online offered training courses will have higher popularity [44].

3. CURRICULA ADAPTIONS

Based on all information of related work literature review and an additional internal discussion, two necessary options for action were detected:

- Theoretical contents of appropriate level have to be included in lectures. If necessary relevant literature has to be included in stock of books, either hardcopy or e-book.
- Corresponding practical laboratory exercises have to be developed. At the same time suitable equipment has to be purchased.

Involved courses are the Bachelor course Automotive Powertrains, included in mechanical engineering curriculum in 5th semester, and the Master course Automotive Engineering, included in mechanical engineering and mechatronics curriculum in each winter semester.

3.1. Lectures of Bachelor course Automotive Powertrains

The actual outline of Bachelor course Automotive Powertrains comprises 28 lectures of 90 min. duration. As shown in Tab. 1, column “old curriculum”, hydrogen is not included, so far.

By balancing actual trends in automotive powertrains, it was decided to reduce number of lectures of ICE powertrains, hybrid powertrains as well as energy sources and energy storage for the benefit of including hydrogen topics. Furthermore, focus of lectures ICE powertrains and hybrid powertrains was adjusted to more hydrogen relevant topics. The outcome of this is shown in Tab. 1, column “new curriculum”.

Topic	**No. of lectures “old curriculum**	**No. of lectures “new curriculum”**
Powertrain architecture	1	1
BEV powertrains	4	4
ICE powertrains - fossil fired - especially gas engines	 5 --	 -- 3
Hybrid powertrains - especially FC-HEV	5 --	-- 3
Energy source and energy storage	4	3
Hydrogen (production, storage, fuel cell basics)	--	5
Driving resistance	5	5
Traction power limits	4	4
Total number of lectures	***28***	***28***

Table 1. Outline of Bachelor course Automotive Powertrains

Thus, a minimum of hydrogen knowledge is included already in Bachelor studies. Acquirement of books is not necessary, as university library gives access to an appropriate e-book in German language [45].

3.2. Lectures of Master course Automotive Engineering

The actual outline of Master course Automotive Engineering comprises 42 lectures of 90 min. duration. Course language is English, because Master courses are offered to foreign students, too. As Master courses are thought by two lecturers complementing one another, lectures of second person should remain unaffected. As shown in Tab. 2, column “old curriculum”, hydrogen knowledge is included at a minimum, so far.

Again, by balancing actual trends in automotive powertrains, it was decided to reduce number of lectures of ICE and hybrid topics for the benefit of including more hydrogen contents. Lectures of second lecturer remain the same. The outcome of this is shown in Tab. 2, column “new curriculum”.

Topic	**Lecturer**	**No. of lectures “old curriculum”**	**No. of lectures “new curriculum”**
Powertrain systems (BEV, ICEV, FCV)	A	4	4
ICE design and analysis	A	8	3
Hybrid powertrains	A	8	3
Hydrogen basics	A		
- electrochemistry, fuel cell systems		2	--
- chemical and physical properties		--	2
Hydrogen technology (production, storage, transport)	A	--	4
Hydrogen engines (fuel cell, stack and system, hydrogen ICE, thermal management systems)	A	--	6
Driver assistance systems and autonomous driving	A	6	6
Road load data logging and data analysis	B	7	7
Road load data modelling and simulation	B	7	7
Total number of lectures		***42***	***42***

Table 2. Outline of revised Master course Automotive Engineering

Thus, hydrogen knowledge is enhanced to a sufficient amount. Acquirement of books was necessary, as in university library no appropriate literature in English language was available, neither hardcopies nor e-books. Hence, a sufficient amount of two expert books in hardcopy were purchased [46, 47].

3.3. Laboratory exercises of Bachelor course Automotive Powertrains

For providing laboratory exercises regarding hydrogen and fuel cells, it was necessary to purchase new equipment. In this connection, focus was on

- appropriate level of exercises for academic education,
- easy handling by students and supervisors,
- and safe supply of hydrogen.

After a market analysis and a benchmark against academic education requirements three different systems for laboratory exercises were purchased and one, already used system was integrated. In detail they are:

- leXsolar H2 Professional 2.0 [48]
- H-Tec Fuel Cell Monitor Pro 4.0 [49]
- H2 Engineering Kit [50]
- Fuel Cell Automotive Trainer [51]

Hydrogen supply for all four systems is managed by so called hydrosticks. As they store hydrogen as hydrids, they are very safe regarding malfunctions during charging and discharging [33, 52]. Charging could be done by using compressed hydrogen cylinders or with less danger by using electrolysers with integrated 30-bar-compressor and operated with distilled water [33, 53, 54]. Discharging is done by connecting the hydroscticks via connectors with integrated pressure reducing valves and low-pressure hoses to experimental equipment.

Next step was to develop a set of 3-5 laboratory exercises, that would cover all important aspects of hydrogen and fuel cells corresponding to new lecture contents and would last for approx. 60-90 minutes. Therefore, all exercises of enclosed experimental guides were carried out, evaluated, assessed and compared [55]. The outcomes are three new designed and one revised laboratory exercise.

3.3.1. Producing and consuming hydrogen (leXsolar H2 Professional 2.0)

This laboratory exercise combines hydrogen production with an electrolyser and afterwards hydrogen consumption with a fuel cell. Hence, students are able to assess the overall efficiency of this process.

The experimental setup of hydrogen production is shown in Fig. 1. The students will recognise the initial voltage to start the electrolyser operation, will measure the current-voltage-characteristic of the electrolyser as well as the dependency of hydrogen production rate and voltage level. Furthermore, losses due to internal resistances of electrolyser are visible in measurement data.

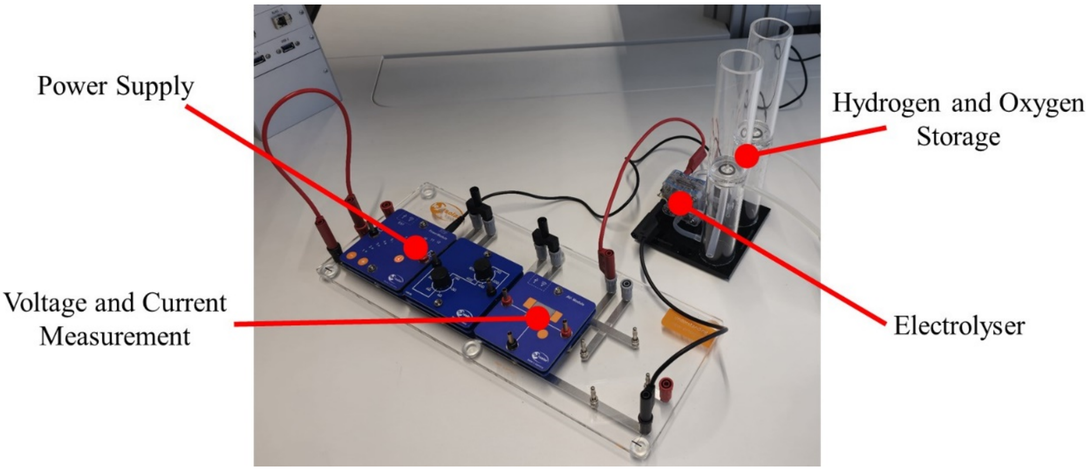

Fig. 1. Experimental setup of hydrogen production

As hydrogen and oxygen are stored in two Perspex vessels, on one hand the volumetric hydrogen-oxygen-relation of 2:1 is demonstratively visualised, on the other hand both gases could be used afterwards in a fuel cell for re-electrification of energy content.

Therefore, a stack of five fuel cells, as shown in Fig. 2, is used. Students again measure current-voltage-characteristic and assess losses due to internal resistances of the fuel cell. Finally, they could calculate the overall efficiency from an energetic point of view as well as based on Faraday's equations.

3.3.2. Analysing single cells of fuel cell stack (H-Tec Fuel Cell Monitor Pro 4.0)

Mostly, fuel cell systems depending on their global voltage level consists of a series connection of single fuel cells. Hence, this laboratory exercise is used to analyse single cells behaviour depending on actual setpoint of fuel cell stack characteristic.

The experimental setup is shown in Fig. 2. As hydrogen consumption is higher now, hydrogen supply is given by one single hydrostick. Additionally, a pressure gauge is implemented to monitor pressure level inside of hydrostick. Hydrogen supply to the fuel cell stack is carried out with low pressure hoses to the left side. On the right side an additional short hose with a clamp is used as purge valve. Here, from time-to-time waste water could be extracted from fuel cells hydrogen side by short opening. Otherwise, fuel cells performance will decrease due to blocking of membrane by waste water. Oxygen is taken from ambient air, which flows through the fuel cell as free flow. It is driven by diffusion based on differences in oxygen concentration along air flow path and additionally by gravity. All anodes of the single fuel cells are wired to the measurement board by a multi-pole wire. The voltage supply for the measurement board is given by a power connector. Furthermore, the measurement board itself is connected to the measurement computer by USB (see Fig. 3).

With the related software of fuel cell monitor it is possible to measure and visualise the U-I-characteristic of the whole fuel cell stack. The variation of current and the measurement of resulting voltage are carried out automatically. This procedure must be executed before each performance testing of single cells. Thereafter, single setpoints could be chosen by moving the crosslines along the U-I-characteristic. For each setpoint stack performance and performance of single fuel cells are displayed on the graphical user interface. Performance quality of single cells are displayed by red or blue colours of corresponding columns as shown in Fig. 4.

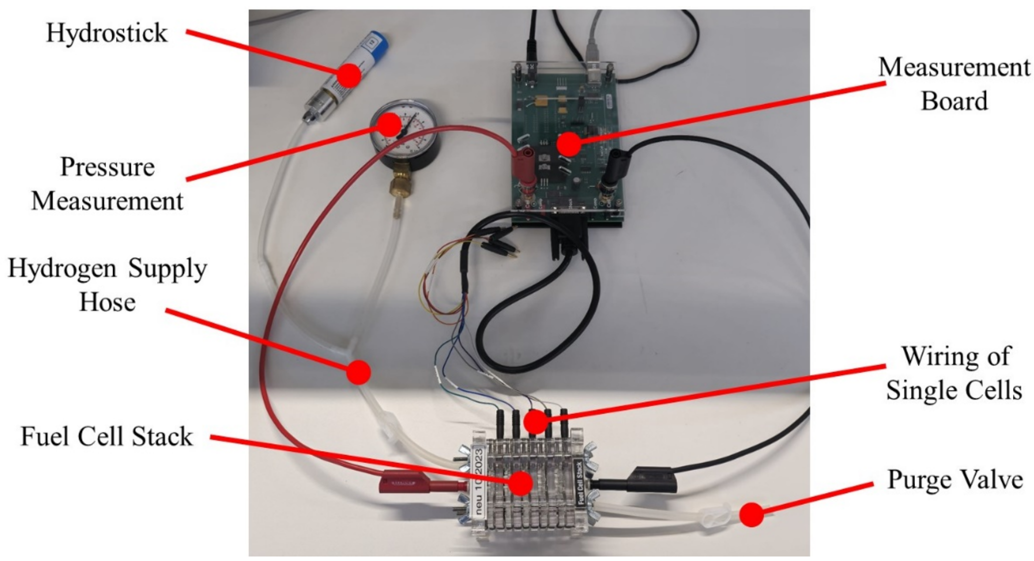

Fig. 2. Fuel cell stack with hydrogen supply and measurement equipment

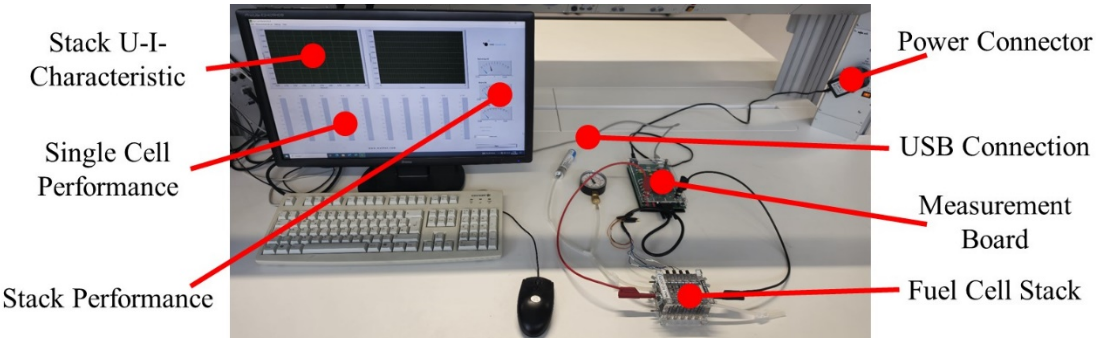

Fig. 3. Experimental setup of fuel cell monitor

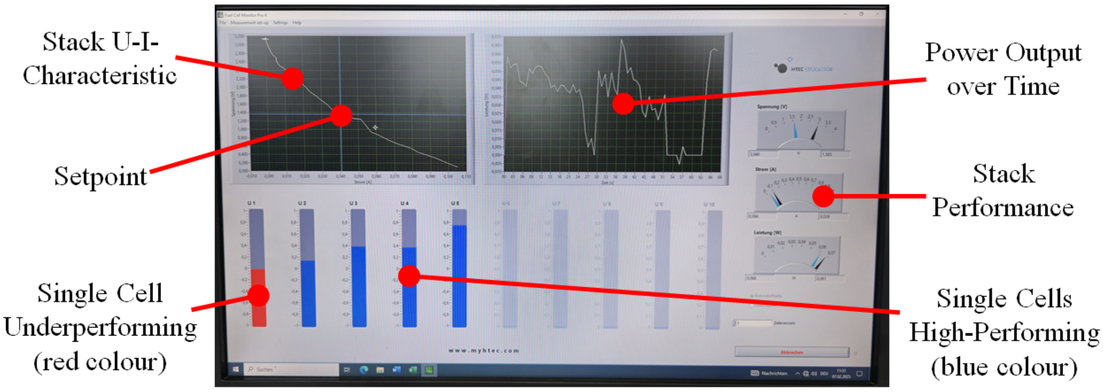

Fig. 4. Display of measurement data in graphical user interface

3.3.3. Assessing influence of different parameters on fuel cell performance (H2 Engineering Kit)

As both laboratory exercises described so far suffer from manual data recording, this lack is eliminated by working with the H2 Engineering Kit. The experimental setup consists of a fuel cell stack with 13 single PEM cells and a nominal power output of 20 W [56]. Hydrogen supply is given by a single hydrostick, again. The fuel cell stack is connected to the H2 Engineering Kit by two sets of multi-pole wires as shown in Fig. 5. On one hand they transmit operation signals for hydrogen supply valve, purge valve and fan. On the other hand, they transmit measurement data from pressure gauge, temperature sensor and fuel cell power as shown in Fig.6.

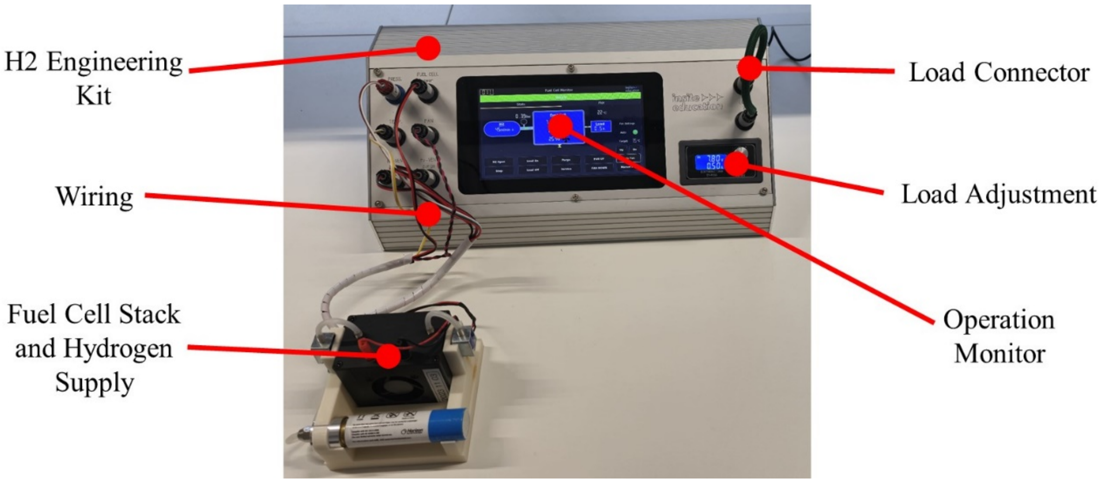

Fig. 5. Experimental setup of H2 engineering kit and fuel cell stack

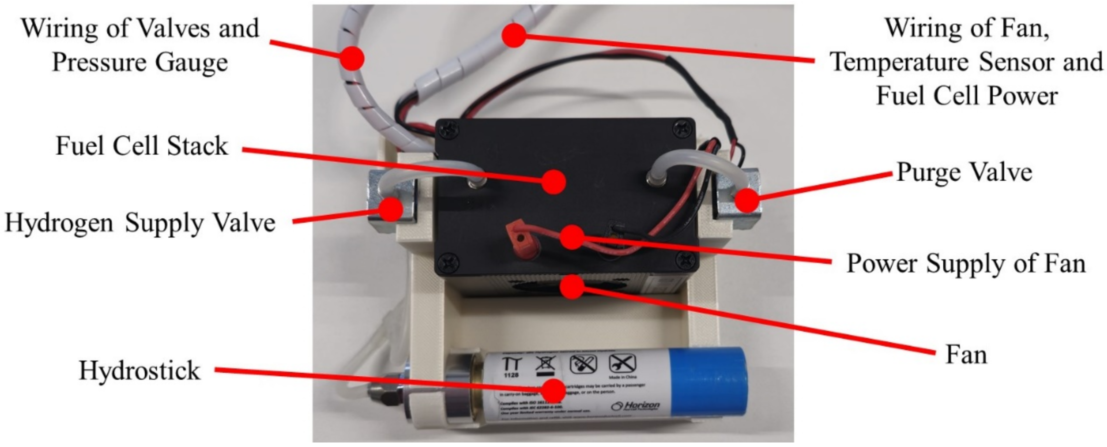

Fig. 6. Experimental setup of fuel cell stack and corresponding wiring

All process data like hydrogen flow rate, hydrogen pressure, stack voltage, stack temperature, relative fan speed and actual load current are displayed in the operation monitor (see Fig. 7, left side). As operation monitor is designed as touchscreen, all operation parameters/commands like start/stop of hydrogen supply, turning on/off of load, manually purging, adjustment of fan speed and choosing fan mode of manual/automatic are entered here, too. Furthermore, as stack performance depend on stack temperature, target of stack temperature could be set. Here, best results are obtained in combination with automatic fan speed adaption. The external load for fuel cell stack has to be connected with the load connector as shown in Fig. 5. Adjustment of load is done by a rotary potentiometer. Here, load current is set to values from 0 to 3 A.

Additionally, it is possible to get on-line data display in the plot area of operation monitor, as shown in Fig. 7, right side. Directly visualisation in the plot area is possible for only two values. They could be selected from drop-down menus. Available data is stack voltage, load current, power output, ambient and stack temperature, hydrogen pressure and hydrogen flow rate, and finally fan speed. Furthermore, all data could be exported to csv-format for later evaluation.

Fig. 7. Representative status monitor (left) and on-line data display (right)

As the system is more complex, students get access to a user manual before executing the laboratory exercise. With it, students have to prepare testing procedures as well as their own series of experiments. At the beginning of laboratory exercise, students have to pass a short survey by the supervisor to asses quality of preparation. Hence, well preparation as well as safe and productive laboratory work is ensured.

3.3.4. Operation of FC-HEV (Fuel Cell Automotive Trainer)

To gain insight of fuel cell hybrid electrical vehicles and their operations strategy, a final laboratory exercise is carried out by using a hybrid RC model car [57, 58]. Here, two hydrosticks and one Ni-MH-battery are used as energy storage. Fuel cell operates to supply energy for propulsion or to recharge battery in case of interruption. Decisions for this purpose are made by the implemented energy management system (see Fig. 8).

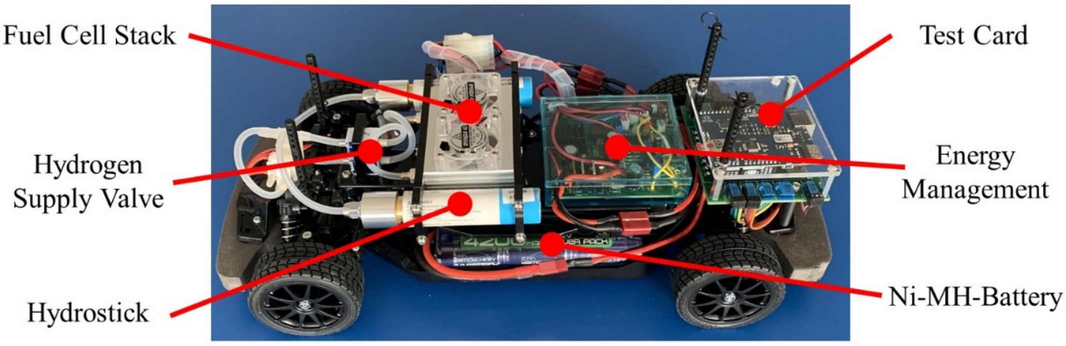

Fig. 8. Design of fuel cell hybrid electrical RC vehicle (FCAT)

Generally, there are two options to drive the RC vehicle. Either via remote control on a special designed test track as explained in [57]. Or on the additionally available test rack in the shape of a small chassis dynamometer as described in [58]. We prefer to carry out laboratory exercises with the chassis dynamometer as it bears lower risk of damaging the RC vehicle.

Operation data is recorded by the test card and could be either displayed via Bluetooth and a smartphone app or via USB wiring and a laptop with corresponding software as shown in Fig. 9. The Bluetooth version is sufficient for driven operation on test tracks, as it works wireless. The USB version is only suitable for chassis dynamometer operation, as it works wired. Furthermore, set points of vehicle speed and brake forces are adjusted by using scroll bars implemented in corresponding software. Additionally, all operation data, as shown in Fig. 9, could be exported to csv-format for later assessment and evaluation.

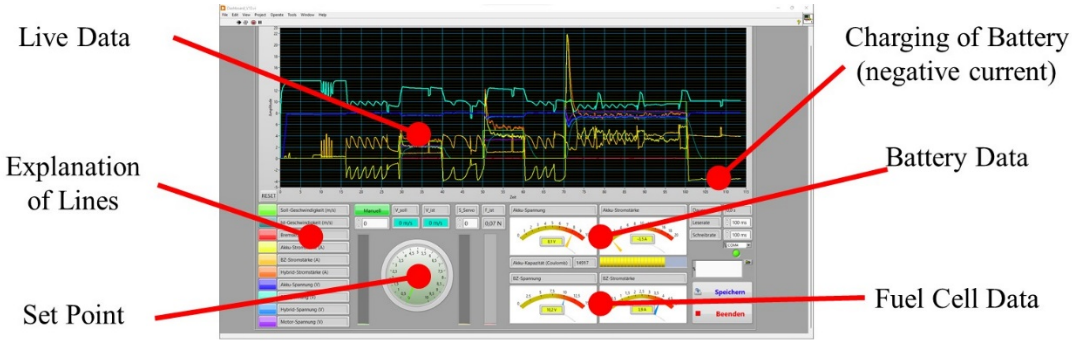

Fig. 9. Display of operation data by FCAT software

Before starting the laboratory exercise students get a short introduction to the system. Then they have the opportunity to test all functions with one partly discharged hydrostick. Afterwards they get something like 10 to 15 min. for creating a driving cycle with variation of speed and brake force. Adjacent they run the vehicle according to their driving cycle with a new hydrostick. Finally, they should continue until hydrostick is discharged completely to recognise its behaviour when hydrogen content expires.

3.3.5. Documentation of laboratory exercises

As students complete laboratory exercises in groups of 2-3 people, each of them is at least once in charge of realising the exercises. Therefore, a detailed documentation has to be prepared afterwards. To make copy and paste documentation among consecutive cohorts more difficult, between four different types of documentation is alternated. They are

- handwritten laboratory notebook with all information on preparation, execution, evaluation and display of results,
- full report of laboratory work by using word-processing programs of whatever type,
- presentation of laboratory set-up, measurement procedure, and representative results with beamer/smartboard/etc. to an audience of 4-5 people including critical questions of audience,
- and simulated customer meeting to discuss laboratory exercises including a handout.

In doing so, different soft skills are trained at once during laboratory exercises and prepare students for work live.

3.4. Homework assignment and experimental work of Master course Automotive Engineering

With Master course Automotive Engineering we follow a completely different approach. Students get information during lectures. At the end of semester several topics are introduced by the two lecturers. The students choose one topic and carry out their homework on this topic. Thereby, students could work as single person or in groups of up to 3 people.

Hydrogen specific topics include always some experimental share. Here, students have to frame their own problem in an appropriate manner. The whole process is surveyed, if necessary, hints to increase level to Master requirements are given. Afterwards, the students have to plan and organise their experimental work with the supervisor of their homework, normally one of the two lecturers. The final report of their work has to be submitted as a scientific paper of given number of pages.

In doing so, Master students are trained in all principles of operation necessary for future work in research and development. Here, especially intrinsic motivation and interest in research work are promoted [59].

4. PROVING OF LABORATORY WORK IN BOTH COURSES

In winter semester 2023/24 first groups of Bachelor students passed new designed lecture and laboratory exercises. The laboratory manual was just a rough sketch. Hence, additional support by supervisors was necessary. As laboratory documentation the handwritten notebook was chosen. Additionally, to their notes, students should write a small section in typical feedback style, what did you like, what didn't you like, how could these items be improved. Here is a summary of most significant items:

- Students appreciate including hydrogen topics into lectures.
- Students appreciate support of hydrogen topics by significant laboratory exercises.
- Students criticise the quality of laboratory manual.
- Students criticise the intensive preparation of Laboratory exercises, especially when further reading is necessary.
- Remedy would be a more detailed laboratory manual with suitable references for further reading.

For verification the same material was used with next groups of students in winter semester 2024/25. Results were nearly equal. Hence, all items were discussed. As result an improved laboratory manual is actually under progress. It will include instructions of experimental procedures as well as hints for evaluation and display of data. However, we still see preparation of laboratory exercises including further reading as an important feature, especially concerning lifelong learning. Hence, only information on relevant references will be given. Reading and reviewing is still in responsibility of students.

With Master students it was significantly different. First of all, each of them has already a Bachelor diploma and therefore, know how to work scientifically. Furthermore, as the students have the option to choose their homework topic, hydrogen issues are chosen by those who are interested in hydrogen per se. Definition of research problems was from ambitious to challenging, intervention of supervisor was not necessary. Likewise, was the quality of the submitted scientific papers. Some of them had a scientific level that would allow direct publishing in scientific journals. In one case, motivation and interest of the student in research work resulted in a remarkable Master thesis [60]. It was carried out subsequently to his homework.

5. CONCLUSION AND FUTURE WORK

Actual transition in energy technology from fossil-based fuels to decarbonised energy sources made it necessary to integrate hydrogen contents into mechanical engineering curricula. As hydrogen itself is a widespread topic from chemical and physical properties over production, storage and transportation to consumption in many kinds, an appropriate confinement was necessary. In this approach focus was on automotive engineering.

Regarding lectures obsolete topics, especially concerning fossil fuel based internal combustion engines, were neglected and replaced by hydrogen-based topics. This was done for Bachelor lectures as well as for Master lectures. Students feedback in both courses has shown, that the new orientation of lecture contents is appreciated by them. In particular Master students complimented the combination of theoretical basics and experimental work in corresponding homework topics.

Corresponding laboratory exercises, especially in the Bachelor course, had to be refurbished. Therefore, new equipment was purchased, tested extensively and a set of four hydrogen-based laboratory exercises was developed. These new laboratory exercises were given a try with students in two winter semesters. Based on their feedback a revised edition of laboratory manuals is prepared, actually. It will contain more detailed descriptions of exercises procedures and assessment of data. However, the often criticised preparation of laboratory exercises including further reading is retained, as it trains students in lifelong learning. This soft skill is absolutely mandatory for all future work life.

Future work will have three different directions. Firstly, it is necessary to improve the simple chassis dynamometer significantly. Goal is to automate settings of speed and braking force as well as data recording. Hence, it will be possible to simulate driving cycles and assess energy consumption. Together with dimension analysis from model vehicle to real vehicle this will be a very future-proof laboratory exercise. Secondly, all lecture contents as well as all laboratory exercises has to be adapted continuously to actual trends in transition of energy technology. Here, it is very important to separate sustainable developments from "nine-day wonders". Furthermore, over time it is possible and probably necessary to relocate contents from Master course to Bachelor course, as affected contents switched from special knowledge to general knowledge. Thirdly, with each accreditation of new mechanical engineering curricula there is the chance to create new fields of study. As it seems, that the split in mechanical engineering and electrical engineering is no longer adequate for today's requirements of automotive engineering, it would be desirable to create a suitable composition of both engineering sciences. Here, especially regarding hydrogen contents and its enormous cost and safety requirements, embedding of industrial based research facilities would be preferable [43].

Due to enormous safety requirements as well as varied design adaptions on engine and test rig laboratory exercises with hydrogen operated internal combustion engines are not taken into account, actually.

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