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Experimental Evaluation of SOFC System Exposed to Marine Inclination Conditions

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Marine actors are showing an increased interest in the application of Solid Oxide Fuel Cells (SOFCs) for deep sea shipping, because of their high conversion efficiency, low pollutant emissions, and fuel flexibility. However, it is unknown how the operation of SOFC systems is affected by large inclinations and motions, which can be present in ships for instance by seawaves. The goal of this research is to evaluate the influence of static and dynamic inclinations on the operation and safety of SOFC systems. Ship motions are emulated using a one-axial oscillation platform up to 30 degrees of inclination. The SOFC system was successfully operated on the platform and demonstrated stable power production under a variety of test conditions without any noticeable safety hazards. The results of the experiments are used to propose design improvements for marine SOFC systems, ultimately contributing to reduce the emissions of the shipping industry.

Introduction

The last decade, the allowable nitrogen oxide and particulate matter (PM) emissions from ship operations is limited, especially in emission control areas (ECAs) (1). From 2020, all ships have to comply with sulphur regulations by the International Marine Organisation (IMO) of 0.5% mass of sulphur in the used fuel (2). Moreover, the marine industry is looking into options to decarbonize its operations, which is in line with the greenhouse gas (GHG) strategy adopted by IMO (3). The goal is to reduce GHG emissions by 50% by 2050 compared with the levels of 2008.

Solid Oxide Fuel Cell (SOFC) systems are considered a high-potential solution for reducing carbon and pollutant emissions (4). Compared to marine diesel engines, SOFC systems offer higher efficiency which contributes to a reduction in carbon emissions. Moreover, SOFC systems barely emit NOx, SOx, and CO. Furthermore, they fit the marine application, because of their fuel flexibility and high redundancy (5).

Originally, SOFCs were mainly considered for stationary applications (6). For instance, small scale applications like residences or large-scale applications like data centres or heavy industry. In contrast to these applications, the power plant of a ship is exposed to accelerations and inclination. Different aspects of SOFC integration ships have recently been evaluated by various researchers. For example, sizing of the power plant, energy management strategies, and load-following behaviour (7, 8). However, the effect of inclinations and accelerations on SOFC systems is to our knowledge rarely explored.

One of the advantages of SOFCs is their modularity. This makes it possible, opposed to engines, to install them decentralized on a ship (9). Although this reduces the size and losses of the power grid and increases system reliability, it increases the distance to the centre of rotation of the ship and subsequently increasing the accelerations the SOFC experiences. This makes it even more relevant to evaluate the consequences of motions on SOFC systems.

The goal of this research is to evaluate the influence of marine conditions in terms of static and dynamic inclinations on the operation and safety of SOFC systems. The results will be used to identify safety risks, in order to propose design improvements for SOFC systems and develop well-founded class rules.

Marine conditions and regulations

The amplitude of the inclinations and accelerations due to ship motions can be described by a spectrum of the ocean waves and the response of the ship (10). The actual motions of equipment at a specific location in the ship are highly dependent on:

- Ship type and dimensions
- Loading conditions of the ship
- Sea state of operating location
- Ship speed and ship manoeuvring
- Position of equipment in the ship

In seagoing ships, the roll motion generally leads to the largest inclinations. The period of these roll motions depends on the characteristics listed above. The roll periods of different seagoing ship types are obtained and shown in **Table I**.

Table I. Minimum, maximum and typical roll periods for most common sea going ship (11).

Shiptype	Roll period [s]		
	Min	Max	Typical
Bulk carrier	8	16	-
Tanker	10	20	-
Container vessel	10	40	-
Cruise vessel	14	25	-
Ferry	10	25	15
General cargo	10	20	-
Naval ship	10	15	12
OSV/PSV	8	16	11
Overall	**8**	**40**	**-**

Following certification of for example Lloyd's Register, fuel cell modules or systems must be tested on an inclination bench to receive maritime certification (12). The equipment must be able to operate under 22.5 degrees and up to 30 degrees if they are part of emergency power generation, see **Table II**. The certification states dynamic inclinations with a period of 10 seconds. The listed roll periods and certification requirements are used to define suitable test conditions.

Table II. Inclination requirements for fuel cell modules (12).

Component	Angle of Inclination			
	Heel angle [°]		Trim angle [°]	
	Static	Dynamic	Static	Dynamic
Fuel cell for propulsion or auxiliary power	22.5	22.5	22.5	22.5
Fuel cell for safety systems or emergency power services	30	30	30	30

Methodology

Used SOFC system

A 1.5 kW SOFC system produced by SolydEra S.p.A. was tested. The fuel cell module contains all high-temperature components and consists of a stack with 70 anode-supported planar cells, a pre-reformer, an integrated heat exchanger and a combustor. The cold balance of plant consists of a desulpheriser, an air supply system, a water treatment system, power conditioning equipment, and a waste heat recovery unit. The width and depth of the module are 0.55 and 1 meter, the module is 1.2 meters high and has a mass of 250 kg. The main characteristics are also listed in **Table III**.

Table III. Main characteristics of tested SOFC system.

Measure	Amount	Unit
Width	1200	mm
Depth	550	mm
Height	1014	mm
Mass	250	kg
Electrical efficiency	Up to 57%	-
Electrical power	0.5 to 1.5	kW

Experimental setup

A one-axial harmonic oscillation platform is used to impose static and dynamic inclinations. By using different inclinations and periods it is possible to reproduce a large variety of ship motions. **Figure 1** shows the design of the used test bench. The SOFC system is secured on the inclination platform with a steel frame and lashing straps. A cabinet with flow control is connected to the SOFC module with flexible mounting. The exhaust stream will also be flexibly mounted. The hydraulic platform is electrically controlled from a safe distance. The operational data of the SOFC module is logged every second.

During the experiment, the water level sensors in the condensate tank are switched off. Under large inclinations, the low-level sensor would be positioned higher than the high-level sensor, because they are on opposite sides of the tank. This would result in an error in the control system, leading to an automatic shutdown of the module.

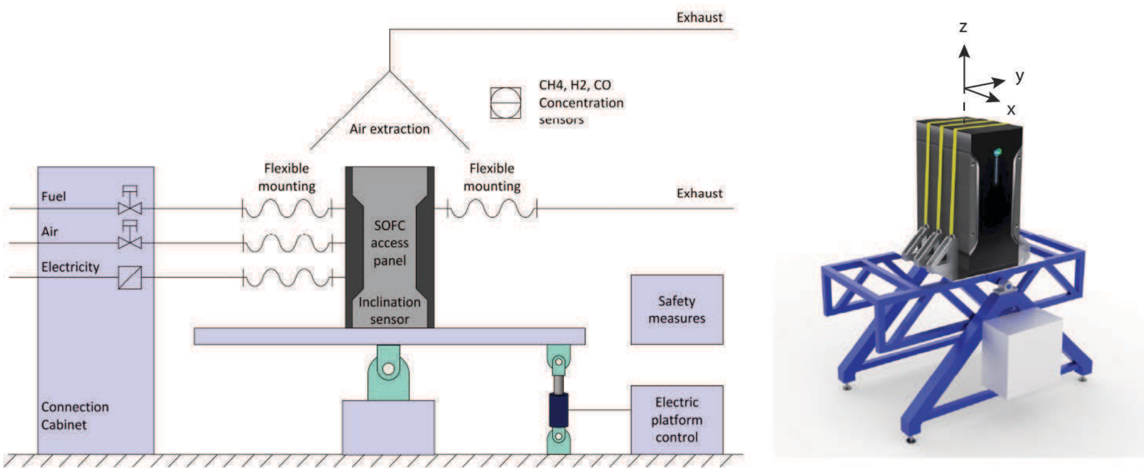

Figure 1. Schematic overview of used test set-up [own images].

Test conditions

The experimental conditions of the executed tests are shown in **Table IV**. The SOFC was operating at nominal load during the tests. First, a static test was performed, for which the test conditions are shown in **Table V**. The SOFC system was inclined from -30º to 30º with steps of 5. Every step was tested for 3 minutes. This relatively short duration was choses because of the limited availability of the test set-up. The test conditions of the dynamic test are shown in **Table VI**. Three different outer angles were used for the natural oscillation movement: 15º, 22.5º and 30º. These are the only 3 options with the used inclination platform for dynamic oscillations. To include a wide variety of ship types (see **Table I**), different oscillation periods were tested: 10, 13, 20, and 40 seconds, corresponding to frequencies of 0.1, 0.75, 0.5 and 0.25 Hz. The whole SOFC module was rotated with 90° on the platform between experiments two rotational axis (referred to as X and Y).

Table IV. Experimental conditions during executed tests.

Condition	Amount	Unit
Room temperature	25 - 28	°C
Natural gas composition	94.3 CH_4 3.2 C_2H_6 0.8 C_3H_8 0.2 C_4H_{10} 0.5 CO_2 1.0 N_2	%vol
Pressure of gas line	17	mbarg

Table V. Test conditions of static inclination experiment.

Static experiment	Minimum angle [º]	Maximum angle [º]	Step size [º]	Duration per step [min]
Angle X-axis	-30	30	5	3
Angle Y-axis	-30	30	5	3

Table VI. Test conditions of dynamic inclination experiment.

Dynamic experiment	Oscillation angle [º]	Oscillation periods	Duration per step [min]
Rotation X-axis	15, 22.5, 30	0.1, 0.075, 0.05, 0.025 Hz 10, 13, 20, 40 s	4
Rotation Y-axis	15, 22.5, 30	0.1, 0.075, 0.05, 0.025 Hz 10, 13, 20, 40 s	4

Table VII. Overview of test campaign.

Test phase	Experiment
1	Static test Y-axis
2	Dynamic test X-axis
3	Static test X-axis
4	Dynamic test Y-axis

Results

Both the static and dynamic experiments are successfully completed. The SOFC module has delivered power over the full test duration, and no gas leakages or safety hazards were detected. Small water leakages occurred at inclined positions, possibly due to overflowing of the condensate tank.

During test phase 1 (see **Table VII**), when the SOFC module was inclined with positive inclinations, the module was not yet in a stable operating point. The temperature was still rising resulting from the proceeding start-up. This led to large deviations in the recorded fuel cell parameters. Due to a lack of time, this test could not be repeated and the data of the static test around the X-axis with positive angles has been removed from the dataset.

After the tests with inclinations around the x-axis (**Table VII**), there was an irreversible deviation in the operating conditions of the SOFC module. A significant voltage drop resulted in a higher current to maintain nominal power. This resulted in lower electric efficiency and cell temperature, and thus higher fuel, air, and steam flow. This behaviour could be explained by a cell defect. It is not known whether this was a consequence of the earlier inclination tests, as it happened during the night while the SOFC module was not inclined and operating at nominal conditions.

Static experiment

The stack voltage during the static inclination test is shown in **Figure 2**. The voltage difference between X-axis and Y-axis from the change of operating conditions during the night is clearly visible. During the static experiment, nothing extraordinary was observed and the deviations in stack voltage are not much different from non-inclined operation.

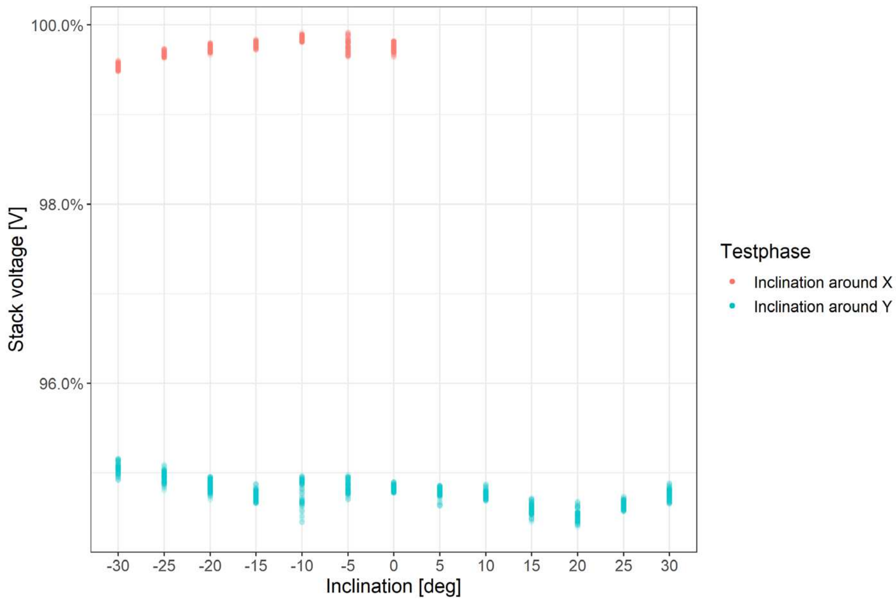

Figure 2. Experiment results of static inclination test (test phases 1 and 3). Every dot represents one measurement point. Experiment data during positive inclinations around the X-axis were excluded because the SOFC module was not in stable operation. 100% refers to the voltage at the nominal operating point of the SOFC module.

Dynamic experiment

The dynamic experiment is also successfully completed with stable power production during different oscillation periods and inclinations. **Figure 3** shows the stack voltage measurements over time for each test condition. The voltage measurements indicate forced oscillation behaviour with the same period as the oscillation of the platform. Especially, the large amplitudes of the oscillation behaviour with a period of 40 seconds are remarkable. The deviations in voltage are largest during dynamic inclinations around the X-axis and for the inclination condition of 30°, see **Figure 4**. Forced oscillation behaviour is also observed for stack current, burner temperature, fuel utilization, fuel flow, and steam flow. Consequently, these variations also occur in power production and electric efficiency.

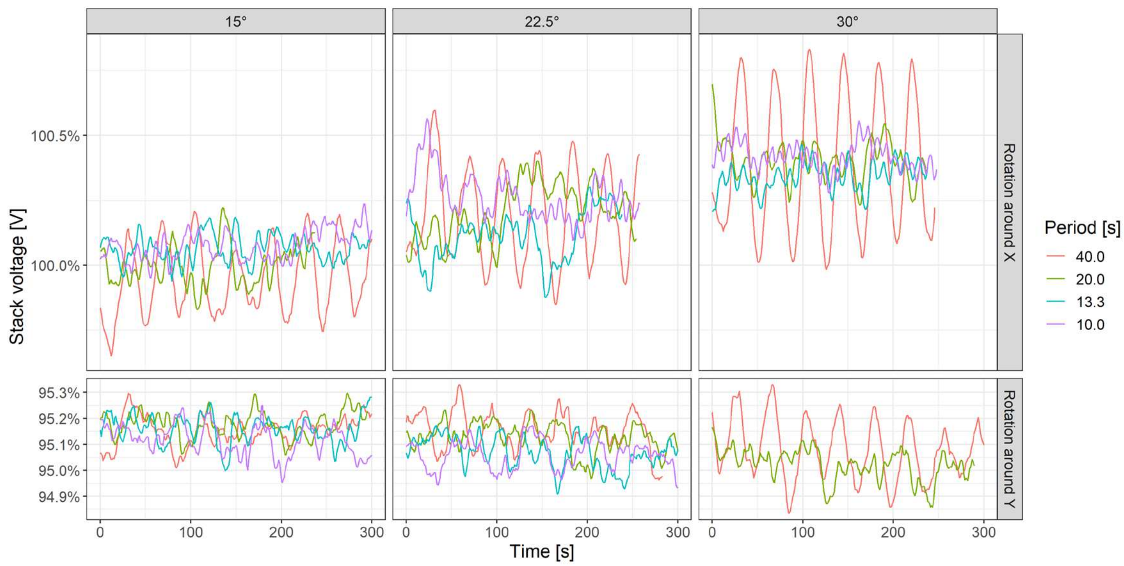

Figure 3. Experiment results from dynamic inclination experiment (test phase 2 and 4). Rows and columns show different test conditions. Data for angle of 30° around Y-axis and period of 10 and 13.3s are excluded due to a power drop during the experiment caused by a false alarm of the water contamination sensor.

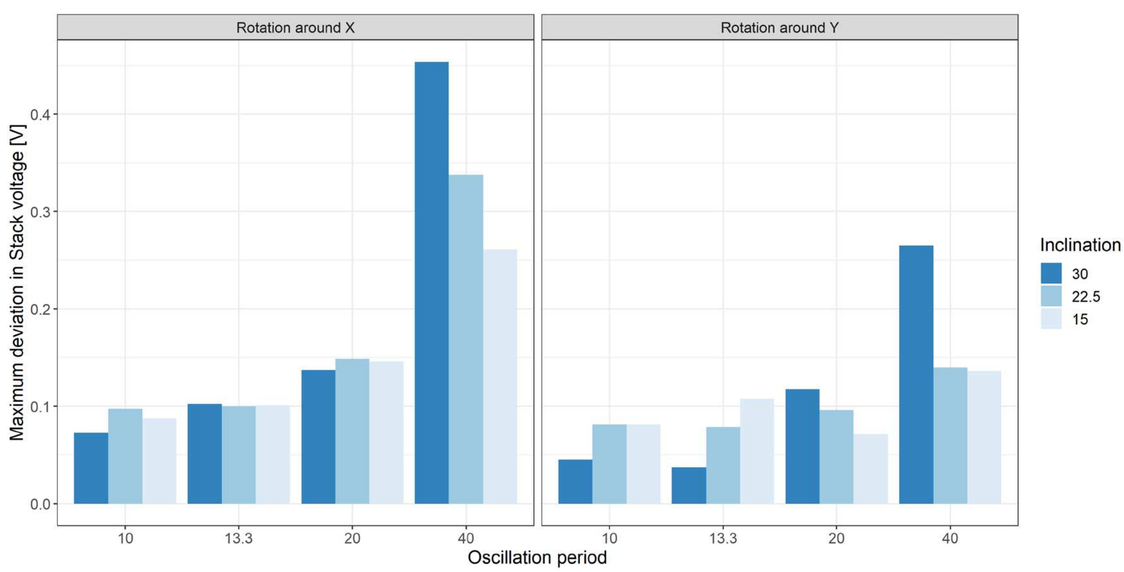

Figure 4. Maximum deviations in stack voltage during one oscillation period for the different test conditions of the dynamic experiment.

Discussion

<u>Cause of oscillation behaviour in operational parameters</u>

The question is what causes the oscillation in the operational parameters of the SOFC system. The SOFC module is an integrated system with many components, a complex control strategy, and many safety constraints. Most of the operational parameters are strongly correlated, or coupled through physical or control system interactions. In this section, some of the possible causes of the oscillation behaviour are discussed.

<u>Inhomogeneous distribution in cell channels</u>. Inertia effects of the stack could lead to an uneven distribution of the gases through the channels. This could be the consequence of inertia of the gases, although low-pressure gas flows are usually not influenced much by inertia effects. It could also be a consequence of compression and tension of the fuel and oxygen channels due to the high weight of the stack. Both these effects could lead to fuel excess on one side of the fuel channels and fuel starvation on the other side of the fuel channels, see **Figure 5**. These deviations in the fuel flow could lead to changes in the voltage and current produced by the cell, as well as changes in the efficiency of the system. The size of the inertia effects would depend much on the directions of fuel and gas channels concerning the direction of the acceleration.

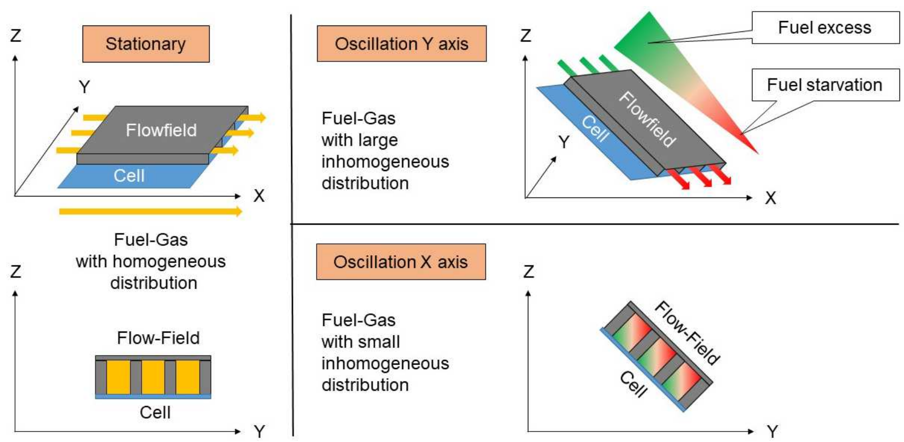

Figure 5. Schematic explanation of the possibility of inhomogeneous fuel distribution through fuel channels due to dynamic oscillations [own image].

<u>Inertia effects in the balance of plant components</u>. Inclining or accelerating an SOFC system can cause the flow of fluids within the system to change. Changes in the water flow or water pressure could affect the steam flow, which has an influence on the steam-to-carbon ratio, which in the end could cause voltage deviations. Moreover, an inclined surface level or sloshing of liquids could lead to a discrepancy between the level in the tank and the measured level in a tank. If this would be the case for the steamdosing tank the supplied steam could be different than the requested steam, also effecting the voltage. The feed of the gas or air could also be affected if the plunger of the valve is oriented in the acceleration direction that the rotation imposes, see **Figure 6**. Variations in air or fuel supply could also result in the witnessed voltage fluctuations. In this SOFC module, the water pump is volumetric, and the flow sensors are mass-based so they are not expected to be influenced by inertia effects, but if different equipment is used they could also be a source of oscillation behaviour.

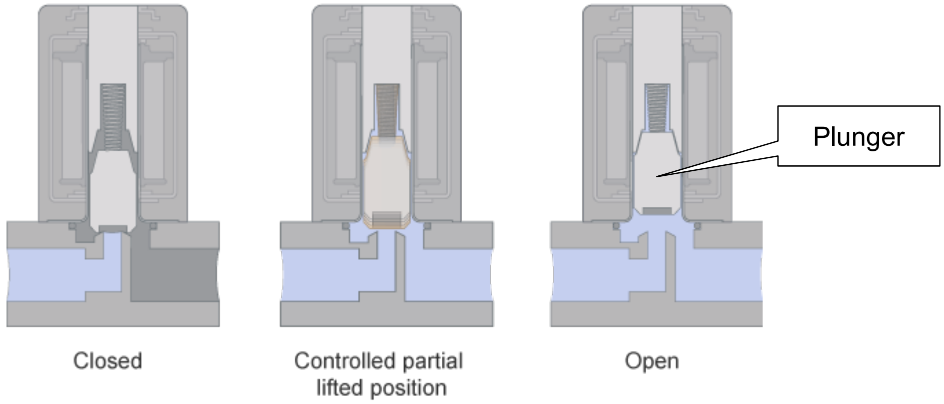

Figure 6. Schematic overview of typical flow control valve.

Control strategy. Since the control strategy of SOFC systems intertwines the operational parameters, deviations in the sensors could propagate through the system. Based on the control strategy and the response time, larger than normal deviations in the operational parameters could result in overcompensation or over- and undershoot. Excessive deviations could even result in instability of the regulator which would shut down the module.

The measured operational parameters at the start of an oscillation motion are shown in **Figure 7**. This indicates that the air flow and fuel flow are first affected by the dynamic inclination, which in turn affects the other operational parameters. The combination of the inertia of pressure regulators and a slow response time of the control system could explain the large deviations at slow oscillations (40-second period) at large angles.

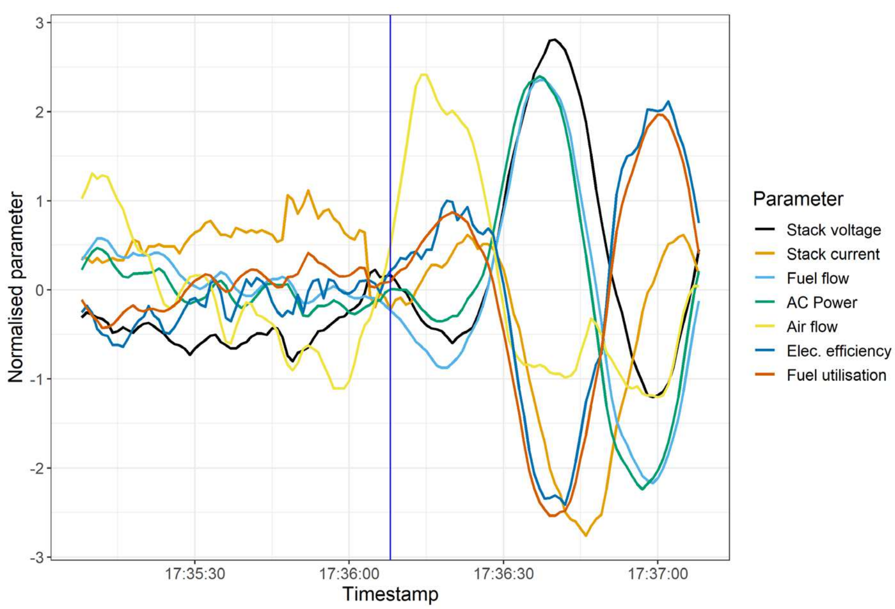

Figure 7. Normalised operational parameters during start of motion. The blue line shows the start of a test condition around the x-axis with a period of 40 seconds and inclinations up to 30 degrees.

Consequences of oscillation behaviour

Although the deviations do not compromise proper functioning of the module, they could still have consequences for the lifetime of the system. There are always fluctuations in the operational parameters of the SOFC system, but the question is: how much larger are the fluctuations during the dynamic experiment and are they within the allowable range? **Figure 8** shows the difference in voltage fluctuations between non-inclined operation and dynamic operation at the start of a test with inclinations up to 30 degrees and an oscillation period of 40 seconds. The voltage variations increase substantially, but it is unknown whether this reduces the lifetime of the stack. A long-term experiment is recommended to indicate potential accelerated cell degradation during dynamic inclinations. Moreover, the dynamic oscillation was only tested with 4 different periods. The oscillation amplitudes were largest at a motion period of 40 seconds, but there might be even larger amplitudes at different periods. A smaller step size of the oscillation period is necessary to make sure the worst-case scenario is not overlooked.

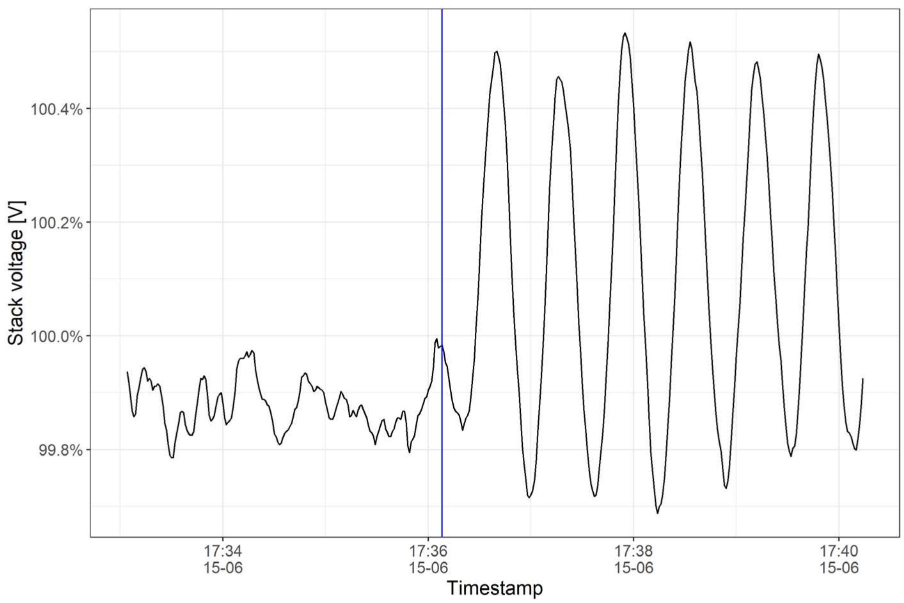

Figure 8. Start of dynamic inclination experiment (blue line) around the X-axis with an angle of 30 degrees and a period of 40 seconds.

Conclusion and further work

SOFC systems could reduce emissions from seagoing ships, but, it is unknown whether wave-induced inclinations influence the safety, operability, and lifetime of SOFC systems. In this research, a 1.5 kW SOFC module was operated in nominal conditions on an inclination platform that simulates ocean waves. The module was inclined statically and dynamically around two horizontal axes of rotation up to 30°. For the dynamic test, oscillation periods of 10, 13, 20 and 40 seconds were used, which coincides with the natural roll periods of common seagoing vessels.

The module was tested successfully without any notable damage or safety hazards. From the data analysis forced oscillation behaviour was found during the dynamic test. Especially large inclination angles (30°) combined with slow motions (40-second period) caused larger than normal deviations in stack voltage, stack current, burner temperature, fuel utilization, fuel inflow, steam inflow, delivered power, and electric efficiency.

From the test observations and result analysis, the following can be recommended for the design of marine SOFC systems:

- Consider the implications of inclinations up to 30 degrees early in the design of SOFC modules and systems to reduce the consequences of inertia, sloshing and backflow of liquids, and faulty sensor signals.
- Besides the required oscillation period for marine certification of 10 seconds, other motion periods should also be considered.
- Although there were no issues with the structural integrity of the SOFC module during inclination testing, the construction should be engineered to handle angles of 30 degrees and moderate accelerations. This requires attention due to the high weight of SOFC systems.

The variety of test conditions and test durations in this research is limited due to time constraints. For this reason, a second test campaign is planned. The second test campaign will focus on:

- Longer test durations per inclination condition.
- A wider variety and finer resolution of motion periods for the dynamic inclination experiment.
- Finding the cause of the oscillation behaviour in the operational parameters of the SOFC module.
- A long-duration degradation experiment to find out whether the oscillation motions have a negative impact on the lifetime of the cells, the stack, and the fuel cell system.
- Part-load tests to find out whether there are different safety and lifetime considerations at non-nominal operational conditions.

The executed and planned experiments help in understanding the fundamentals and design considerations of marinising SOFC systems.

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