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Freeze start strategies for fuel cell electric vehicles: balancing durability, reliability and practicability – an experimental approach on automotive-sized short stacks

Markus Schwarz^{1,2*} , Albert Albert¹ and Rüdiger-A. Eichel^{3,2,4}

Abstract

Fuel cells are considered a key technology for the energy transition, as hydrogen can serve as a sustainable energy carrier when produced from renewable sources. However, water generated during operation can freeze under sub-zero conditions, leading to start-up failure and accelerated degradation. Reliable freeze-start capability is therefore a critical requirement for fuel cell electric vehicles (FCEVs). In this study, the different phases of a freeze-start strategy, including freeze preparation, stack cooling, and freeze start with internal heat-up, were experimentally investigated on an automotive-sized 10-cell short stack equipped with an adapted cooling circuit to reproduce vehicle-relevant thermal boundary conditions. The influence of freeze-preparation parameters and freeze-start operating conditions was analyzed. The results show that the extent of membrane drying is the dominant factor determining freeze-start capability. Increasing the high-frequency resistance (HFR) threshold after drying from 0.20 to 0.25 to 0.60 $\Omega\cdot\text{cm}^2/\text{cell}$ improved the minimum achievable start temperature from approximately -10°C to -18°C without negative cell voltages. Furthermore, lower stack voltages during potentiostatic heat-up increased the heating rate from 0.26 to 0.32 K s^{-1} while simultaneously reducing the total water production from 10.3 g to 8.8 g. Variations in cathode airflow had only a minor influence on freeze-start performance. Overall, the study demonstrates that combining an aggressive but controlled freeze preparation with low-voltage potentiostatic heat-up provides the most robust and efficient freeze-start strategy for automotive PEM fuel cell stacks under severe winter conditions.

Keywords PEM fuel cell, Freeze start, Automotive size, FCEV

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1 Introduction

Reaching net-zero greenhouse gas emissions by 2050 is one of the major challenges of the ongoing energy transition and requires substantial changes in both the energy and transportation sectors. Numerous studies have investigated potential transition pathways and technology portfolios to achieve this target [1, 2]. For road transportation, scenarios range from highly electrified systems to more diversified technology mixes. In many medium- and high-electrification scenarios, fuel cell electric vehicles (FCEVs) complement battery electric vehicles (BEVs), particularly in applications where long driving ranges, rapid refueling, or high energy demand are required [3]. Consequently, FCEVs are increasingly regarded as a key zero-emission technology for both light-duty and heavy-duty mobility, supporting the transition towards a climate-neutral transport sector. Vehicles used for road transportation are exposed to harsh environmental conditions. Ensuring reliable functionality and startability under all climatic conditions is essential. These requirements are particularly relevant for fuel cell electric vehicles (FCEVs), which are increasingly offered as a zero-emission alternative for both light and heavy-duty vehicles by several OEMs [4–6].

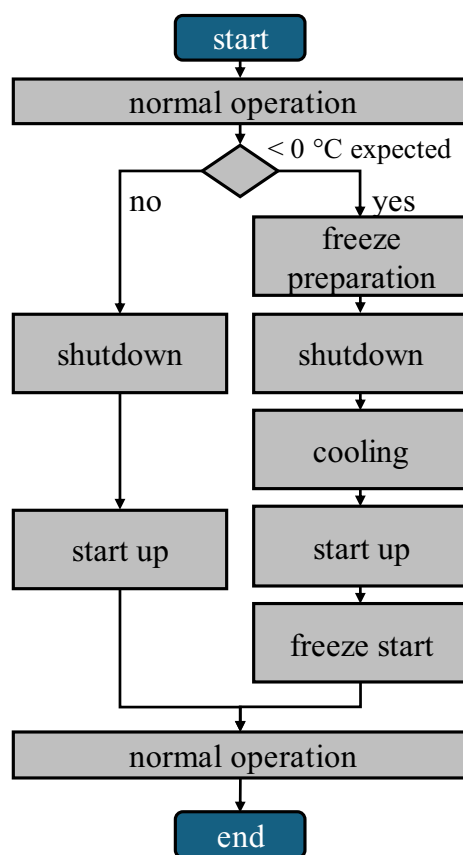


Fig. 1 Schematic procedure for a freeze start compared with a normal start

In FCEVs, the primary power converter is the hydrogen fuel cell. Inside the fuel cell, hydrogen reacts with ambient air in a proton exchange membrane (PEM) fuel cell, producing water, heat, and electrical power. The reaction occurs at the cathode (air) side, where water is generated at the catalyst layer. Most of this water is expelled through excess airflow, but diffusion also occurs through the membrane into the anode (hydrogen) compartment, and electro-osmotic drag transports water from the anode to the cathode side [7]. As a result, liquid water and moisture are present throughout the entire system. This creates a particular challenge for FCEVs operating in winter conditions.

The relevance of freeze-start capability varies considerably across regions. While it is of minor importance in warm climates, it becomes a critical customer requirement in countries that experience frequent and prolonged sub-zero temperatures during winter. Takahashi et al. predicted 1,241 freeze start events over a service life of 15 years for a Toyota Mirai operated in Canada [8]. Furthermore, when an FCEV is parked, the fuel cell stack can cool down to the ambient temperature after approximately 14 h of parking time [9]. This indicates that freeze starts are particularly relevant in light-duty applications, where long parking periods are common, and must therefore be reliably managed in cold-climate countries. The U.S. Department of Energy (DoE) requires that fuel cells can start unassisted at temperatures as low as -30°C , and they aim for the system to reach 50% of its rated power within 30 s after the start request at -20°C [10]. This requires high heat up rates, as the typical stable operating temperature lays between 60 and 80°C [11].

To enable starts at temperatures below 0°C , specific measures are required both immediately after operation and during the subsequent start-up process. The sequence of these measures is illustrated schematically in Fig. 1. The diagram begins with normal operation of the fuel cell system. If sub-zero temperatures are not expected, a conventional shutdown procedure is sufficient. For the next start, a standard start-up procedure, consisting of supplying the cells with the required reactants, is adequate. However, if temperatures below 0°C are anticipated, a drying procedure of the fuel cell stack is necessary. Many studies have prepared fuel cells for freezing by implementing a drying phase immediately after stopping the operation [8, 12, 13]. The purpose of this drying phase is to remove excess water from the bipolar plates (BPP), gas diffusion layer (GDL), catalyst layer (CL), and membrane. Throughout this study, the drying phase is named freeze preparation. This helps to prevent ice formation during cooling and facilitates water absorption by the membrane during the freeze start [12]. The water content of the membrane is directly related to its proton conductivity. Lower water content results in

higher membrane resistance. Proton conductivity, and thus membrane resistance, can be measured using the high-frequency resistance (HFR), which is typically the impedance at 1000 kHz [14]. Therefore, the progress of drying can be monitored in real-time through HFR measurements. The drying process is performed using ambient intake air and fresh hydrogen. Excessive drying can lead to reduced startability due to increased protonic resistance [15], as well as cause mechanical stress on the membrane and catalyst support [16]. Conversely, insufficient drying may result in failed starts caused by reactant blockages and hence accelerate degradation due to local [17] or global fuel starvations [18].

If the stack temperature is below 0 °C, a dedicated freeze-start procedure is required to heat the stack before it can be returned to normal operation. During this phase, the fuel cell must generate sufficient heat to thaw the frozen components while simultaneously limiting water accumulation that could lead to ice blockages [19–22]. Similarly, the transition from 0 °C to the targeted operating temperature must be managed carefully to avoid local flooding within the system [12]. Local flooding on the anode side causing hydrogen starvation, in particular, can lead to degradation of the cathode catalyst layer, negatively impacting further fuel cell performance [17]. Global flooding of a cell can lead to a cell reversal and carbon corrosion on the anode catalyst layer [23].

Ishikawa et al. found out that the water in the catalyst layers can be in a supercooled state above –15 °C [24]. This was confirmed by Tabe et al. [20]. This indicates that freeze starts at lower temperatures than –15 °C can show different behavior.

The method of drying is believed to influence the reliability of freeze starts and the durability of the cells. An

even distribution of drying throughout the cells is necessary. In this study, the influence of the flow rates of anode and cathode during the drying phase and the HFR-threshold, when the drying phase is finished, on the startability and durability is investigated.

Various strategies for freeze start are discussed in several studies. Some researchers and companies demonstrate the feasibility of heating the fuel cell stack solely through the heat generated during the start process [8, 25]. Conversely, the use of external heaters is also considered in research and industry [25, 26]. However, external heaters require additional installation space and consume vehicle power and energy, which are limited in road transport vehicles. Consequently, this study focuses exclusively on freeze start strategies that do not rely on external heaters. A brief overview of research in the field of freeze starts is given in Table 1.

Despite extensive research on freeze-start phenomena, most experimental investigations have either been conducted on small laboratory-scale cells or on full fuel cell systems with limited access to local stack behavior. Furthermore, many short-stack studies do not reproduce the vehicle-relevant thermal boundary conditions that govern the balance between heat generation, water production, and ice formation during practical freeze starts. As a result, the transferability of existing findings to automotive fuel cell systems remains limited.

Therefore, this study presents a novel experimental methodology and the corresponding results for investigating the interaction between freeze preparation and freeze-start procedures on a short-stack level under vehicle-relevant heat-up conditions. Achieving realistic heat-up behavior is particularly important for evaluating the

Table 1 Summary of previous studies

Scale	Heating Concept	Research Focus	Key Findings
Single cell (4–50 cm ²)	Internal heating	Freeze mechanisms	Supercooled water exists below 0 °C and ice formation occurs in the catalyst layer [24, 20, 21, 22]. Reliable freeze start investigations require active areas of at least 50 cm ² [27]. Mechanisms of global hydrogen starvation were investigated [23, 28].
Single cell (4–50 cm ²)	Internal heating	Parameter studies	Increased membrane drying improves startability and water uptake capacity [19, 29]. The influence of membrane thickness, microporous layer (MPL) properties, current density, and start temperature has been studied [19, 29, 30].
Automotive stack	External heating	Freeze phenomena	Significant current-density and mass-transport inhomogeneities occur during freeze start [31]. Residual water can accelerate catalyst-layer degradation [32].
Automotive stack	External heating	Heating concepts	Catalytic heating has been demonstrated as a feasible heating concept [33]. Different heating approaches, including end-plate, coolant, and air heating, have been compared [34, 35].
Short stack – automotive	Internal heating	Start strategy optimization	Freeze-start performance is strongly influenced by drying extent and operating conditions [13, 36]. Local HFR measurements and current-density distributions have been used for model validation [12]. Durability under repeated freeze-start cycling has been assessed [8, 13].
Fuel cell system	Internal heating	System-level studies	System-level studies identified thermal mass and stack voltage as critical parameters for freeze-start performance and demonstration of feasibility [37]. Accelerated stress tests for freeze-start durability have been proposed [8].

balance between heat generation and water production during freeze start operation.

2 Experiment

Throughout the study, a short stack of 10 cells with an active area of 285 cm^2 each was used. The membrane electrode assembly (MEA), commercially available from Johnson Matthey, had a Pt loading of 0.05 mgPt/cm^2 on the anode and 0.4 mgPt/cm^2 on the cathode, with a membrane thickness of $15 \text{ }\mu\text{m}$. The stainless-steel bipolar plates (BPP) from DANA Reinz Dichtungs GmbH feature a straight flow field, with the cathode and anode arranged in counterflow. The cells are mounted in a cell holder supplied by Tandem Technologies Ltd. The required contact pressure for the stack is provided by a pneumatic compression system.

The experiments were conducted on a Horiba FuelCon big short stack test bench (S005-LT), which is specifically equipped with an additional cooling circuit to simulate

the thermal behavior expected in a vehicle. This setup allows active cooling of the stack down to $-18 \text{ }^\circ\text{C}$.

The additional coolant circuit consists of a small circuit (red) that includes a coolant pump, a flow meter, a three-way valve (1), and two temperature sensors at coolant inlet and outlet of the stack. This small circuit connects to the big circuit (green), as shown in Fig. 2. Cooling for the big circuit is supplied by a water-water heat exchanger controlled by an external thermostat. The coolant used in the additional cooling circuit was BASF Glysantin® FC G20-00/50, with a density of 1.065 g/cm^3 at $20 \text{ }^\circ\text{C}$. The coolant volume of the small circuit was 170 mL . In addition to the coolant, the current collectors and the coolant pump contributed to the overall thermal mass of the system.

The position of the three-way valve #1 regulates the mixture of cold and warm water, thus controlling the temperature at the stack inlet. When the temperature is below the setpoint, the coolant circulates only in the small circuit. When the temperature is above the

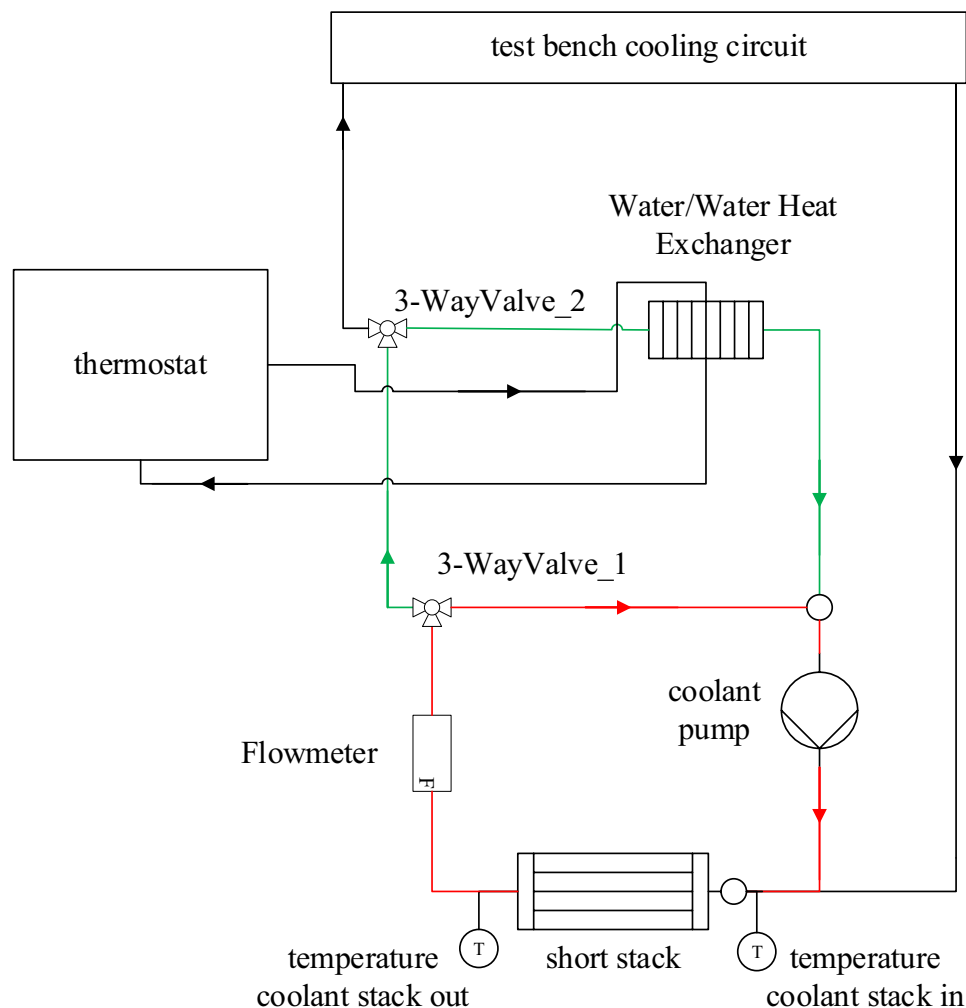


Fig. 2 Simplified piping and instrumentation diagram (P&ID) of the additional coolant circuit

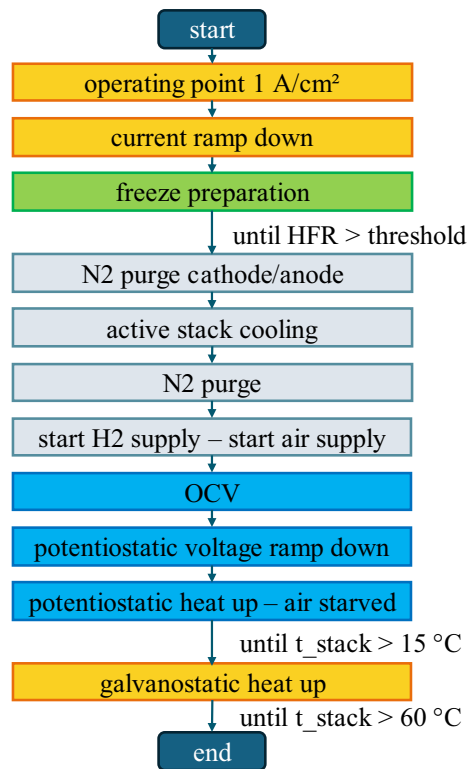


Fig. 3 Flowchart of the test sequence for freeze start on short stack

setpoint, cold coolant is mixed into the circuit, so that the temperature can be held. This regulation is made by a proportional–integral–derivative (PID) controller with typical anti-windup measures. Both the piping and the stack are insulated to minimize heat input from the environment.

Pure hydrogen and compressed dry air are supplied by the test bench. Pressure, temperature (heating) and humidity of the gases can be conditioned by the test bench.

The test sequence for the study is shown in Fig. 3. The start point for each test is an operating point at a current density of 1 A/cm² at 65 °C at the coolant outlet. The stoichiometry at the anode is 1.5 and at the cathode 2.0. The gases are humidified to a dewpoint of 46 °C. The pressure at the outlet is 1.5 bara at the anode and 1.0 bara at the cathode. This operating point is maintained for 5 min, which is assumed to be sufficient to achieve reproducible starting conditions before beginning the freeze preparation. The current is then ramped down stepwise to 0.01 A/cm², while the flows are adjusted stoichiometrically until the minimum flow rates of the mass flow controllers are reached. Once the anode backpressure is reduced to 1.0 bara at the outlet, humidification of the gases is switched off, and the desired flow rates for freeze preparation are set. The stack's HFR is monitored throughout the test. During the drying phase, the membrane water content decreases, causing the HFR to

Table 2 Summary of mass flows and times for freeze preparation

Study	Cathode Area [cm ²]	Cells [-]	Cathode Flow Density [g s ⁻¹ cm ⁻²]	Anode Flow Density [g s ⁻¹ cm ⁻²]	Du-ration [s]
Liu et al. [38]	298	360	6.11×10^{-4}	Not relevant. Fuel cell system (FCS)	480
Takahashi et al. [12]	273	20	2.84×10^{-4}	3.05×10^{-6}	40
Liphardt et al. [13]	Several hundred cm ²	20	$\sim 6.68 \times 10^{-4}$	$\sim 2.31 \times 10^{-5}$	30
This work	285	10	4.14– 8.32×10^{-4}	2.46×10^{-5}	38*

*38 s as average to reach 600 mOhm*cm²/cell

increase. A summary of the values compared to previous studies is given in Table 2. When the desired threshold is reached, hydrogen and air are switched off, and a brief nitrogen purge (5 Nl/min for 30 s) is applied to both compartments. This purge is necessary to avoid air diffusion into the anode compartment. Active cooling of the stack with a rate of 6 K/min then begins until the new target starting temperature is reached.

The desired temperature was maintained for 25 min to ensure a homogeneous temperature distribution throughout the stack. Preliminary measurements indicated that temperature differences between the monitored stack locations became negligible after approximately 25 min, and longer holding times did not provide any measurable benefit. A brief N₂/N₂ purge is performed to prevent air/air starts which might damage the electrodes, and to avoid introducing additional degradation mechanisms to this study. Hydrogen is then supplied to the anode, and a pressure of 1.5 bara is set at the anode outlet. An anode pressure of 1.5 bara was selected as it lies at the lower end of the typical operating range and is expected to support water removal from the stack by increasing the hydrogen volumetric flow rate.

Following this, the air supply is started, and the OCV phase begins. The cathode airflow is set to 0.75 g/s, corresponding to a current of approximately 105 A at a cathode stoichiometry of $\lambda = 2$. The stack voltage is then gradually reduced stepwise to the desired level. At the selected airflow, potentiostatic operation at lower stack voltages can result in higher currents and slight cathode air starvation. This reduces the electrical efficiency of the fuel cell and consequently increases heat generation, thereby supporting rapid stack warm-up during the freeze-start process. The influence of the cathode airflow rate is investigated separately in the subsequent parameter variation study.

The hydrogen flow is stoichiometrically adjusted ($\lambda = 1.5$) to prevent hydrogen starvation. Once the stack

outlet temperature exceeds 15 °C, the freeze start can be considered complete, since ice formation is no longer expected and stable galvanostatic operation can be established. Initially, the cathode air flow is controlled with a stoichiometry of 2.5 to minimize the risk of flooding, while the current is ramped up to 1 A/cm². The stack is heated up internally to 60 °C, as this temperature is within the typical operating range of automotive PEM fuel cells and allows stable humidified operation.

As the temperature increases, the air stoichiometry is gradually reduced stepwise to 2.0. Once the heat-up phase is complete, the current is set to 0, humidification is switched on, and the current is ramped back up to 1 A/cm² to reach the humidified operating point.

The study began with a parameter variation to identify a reliable set of parameters for freeze starts down to -18 °C. Each temperature was tested 3 times with the freeze start procedure FS3. The flow rates on the cathode, as well as the threshold of the HFR, were varied. A summary of the tested variations is given in Table 3. The schematic process is given in Fig. 4.

Using the best-performing parameter set for freeze preparation, different freeze start strategies were tested

Table 3 Variation of Freeze Preparation (FP)

Name	Anode Flow [g/s]	Cathode Flow [g/s]	HFR threshold [$\Omega \cdot \text{cm}^2/\text{cell}$]
FP1	0.07	1.18	0.20
FP2	0.07	2.37	0.20
FP3	0.07	1.94	0.25
FP4	0.07	1.94	0.40
FP5	0.07	2.37	0.60

3 times. The required stack voltage during the potentiostatic heat-up phase was varied. To adjust the resulting current, the air flow was also varied. The effects of these changes on the heat-up rate and reliability were investigated. The parameters are listed in Tables 3 and 4.

3 Results and discussion

The following section is divided into two parts. First, the influence of freeze preparation parameters on the minimum achievable start temperature is investigated. Based on the identified optimal preparation strategy, different freeze-start operating strategies are subsequently evaluated with respect to heating rate, water production, and electrical performance.

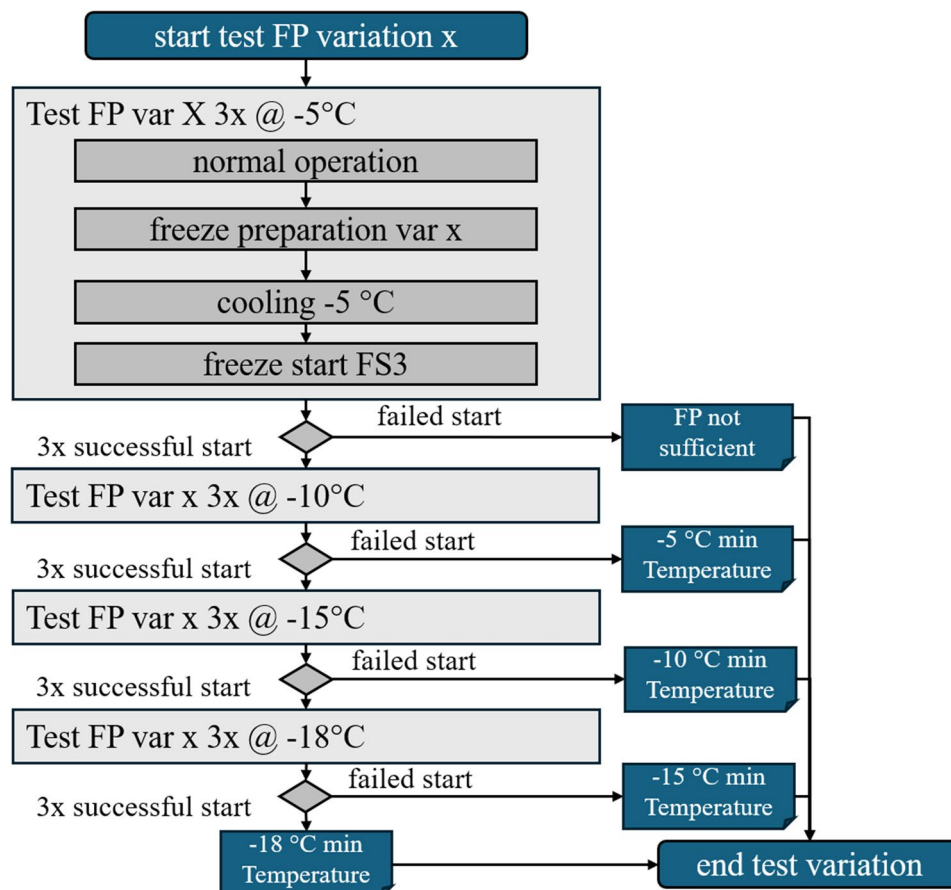


Fig. 4 Schematic overview of the test procedure

Table 4 Overview of the experimentally tested freeze start strategies

Name	Anode Stoichiometry [-]	Cathode Flow [g/s]	Stack Voltage [V]
FS1–5.25 V	1.5	0.75	5.25
FS2–4.75 V – low flow	1.5	0.65	4.75
FS3–4.75 V	1.5	0.75	4.75
FS4–4.75 V – high flow	1.5	0.85	4.75
FS5–4.25 V	1.5	0.75	4.25
FS6–3.75 V	1.5	0.75	3.75
FS7–3.25 V	1.5	0.75	3.25
FS8–2.75 V	1.5	0.75	2.75

3.1 Freeze preparation

Five different variations of the freeze preparation were tested. The parameters for these variations can be found in Table 3. For each variation, freeze starts were performed from -5°C down to the lowest possible temperature in 5°C steps. In this study, a freeze start was considered failed if the cell voltage dropped below -0.1 V . A negative cell voltage is the result of a cell reversal caused by global hydrogen starvation [23]. For the sake of long-term reliability, this should be avoided. A cell voltage of less than 0 V may already indicate cell reversal. To prevent misinterpretations due to minor measurement errors, the threshold value was set to -0.1 V .

An entire experiment following the test sequence shown in Fig. 3 is illustrated in Fig. 5. The test sequence begins at an operating point of 1 A/cm^2 , with a stack coolant outlet temperature of 65°C and gas humidification at a dew point of 46°C for both anode and cathode (red dashed Line 1). After holding for approximately 10 min, the current and flow are ramped down stepwise (Line 2). The humidification of the gases is then switched off, and freeze preparation begins at Line 3. Afterwards, the cell is flushed with N_2/N_2 . Once the flushing is complete, active cooling of the stack starts. It can be observed that there is no significant temperature difference between the coolant stack inlet and outlet until -15°C is reached. The inlet temperature remains around -18°C , while the outlet temperature stays near -15°C and gradually approaches -18°C after a prolonged holding time. Once the cooling phase is finished, a brief N_2/N_2 flushing is performed (Line 4). An increase in cell voltages can be observed because residual oxygen in the cathode and hydrogen in the anode pipes reach the catalyst layer when the N_2/N_2 flushing begins.

After the flushing, hydrogen is supplied to the anode, followed by air to the cathode, and the OCV phase starts (Line 5). The stack voltage is gradually reduced in potentiostatic mode until the desired average stack voltage for the freeze start variation is reached (Line 5.1).

This phase ends when the coolant stack outlet temperature rises above 15°C (Line 5.2). The load control mode is then switched to galvanostatic mode, and the air flow is regulated to maintain a stoichiometry of 2.5.

The stack voltage increases immediately, and the current and flows are ramped up until 1 A/cm^2 is reached. At each current step, the weakest cell voltage is monitored. The next higher current step is set once the minimum cell voltage exceeds a defined threshold. This current is held until the coolant stack outlet temperature rises above 59°C (Line 6).

Then, the current is switched off, and the gas humidification is activated to 46°C . Finally, the current is ramped back up to 1 A/cm^2 , reaching the operating point.

The parameter variations FP1, FP2, and FP3 have HFR thresholds of 0.2 and $0.25\text{ }\Omega\cdot\text{cm}^2/\text{cell}$, with a minimum possible start temperature of -10°C according to the definition of a failed start due to cell voltages lower than -0.1 V . In contrast, higher HFR thresholds allowed for lower starting temperatures: FP4 down to -15°C and FP5 down to -18°C .

The minimum possible start temperature is defined as the temperature at which a freeze start can occur without negative cell voltages (less than -0.1 V).

Figure 6 displays example measurement data from a failed freeze start. After a brief OCV phase, the stack voltage is reduced stepwise to the desired value of 4.75 V . In this start, Cell 1 was the weakest cell, with its voltage dropping to -0.1 V . As a result, the test safety procedure stopped the potentiostatic mode.

According to the literature, a negative cell voltage indicates cell reversal. This phenomenon occurs when the gas flow to the anode of a cell is globally blocked. To maintain the current, alternative reactions take place, with the oxygen evolution reaction (OER) and carbon oxidation reaction (COR) considered the most likely [17].

Similar behavior was observed for freeze preparation variants FP2, FP3, and FP4 during start attempts at temperatures below the minimum possible start temperature. Variants FP1 and FP2 share the same anode flow and HFR threshold but differ in cathode flow during the drying phase. Increasing the cathode flow did not result in a lower minimum possible start temperature.

One possible explanation for this observation is the HFR-threshold-based control of the drying process. In both variants, the target average HFR was reached. This suggests that a sufficiently homogeneous drying distribution was achieved in both cases, such that increasing the cathode flow rate while maintaining the same HFR threshold did not affect the minimum achievable start temperature.

Similarly, a slight increase in the HFR threshold to $0.25\text{ }\Omega\cdot\text{cm}^2/\text{cell}$ did not result in a measurable improvement in the minimum achievable start temperature. However,

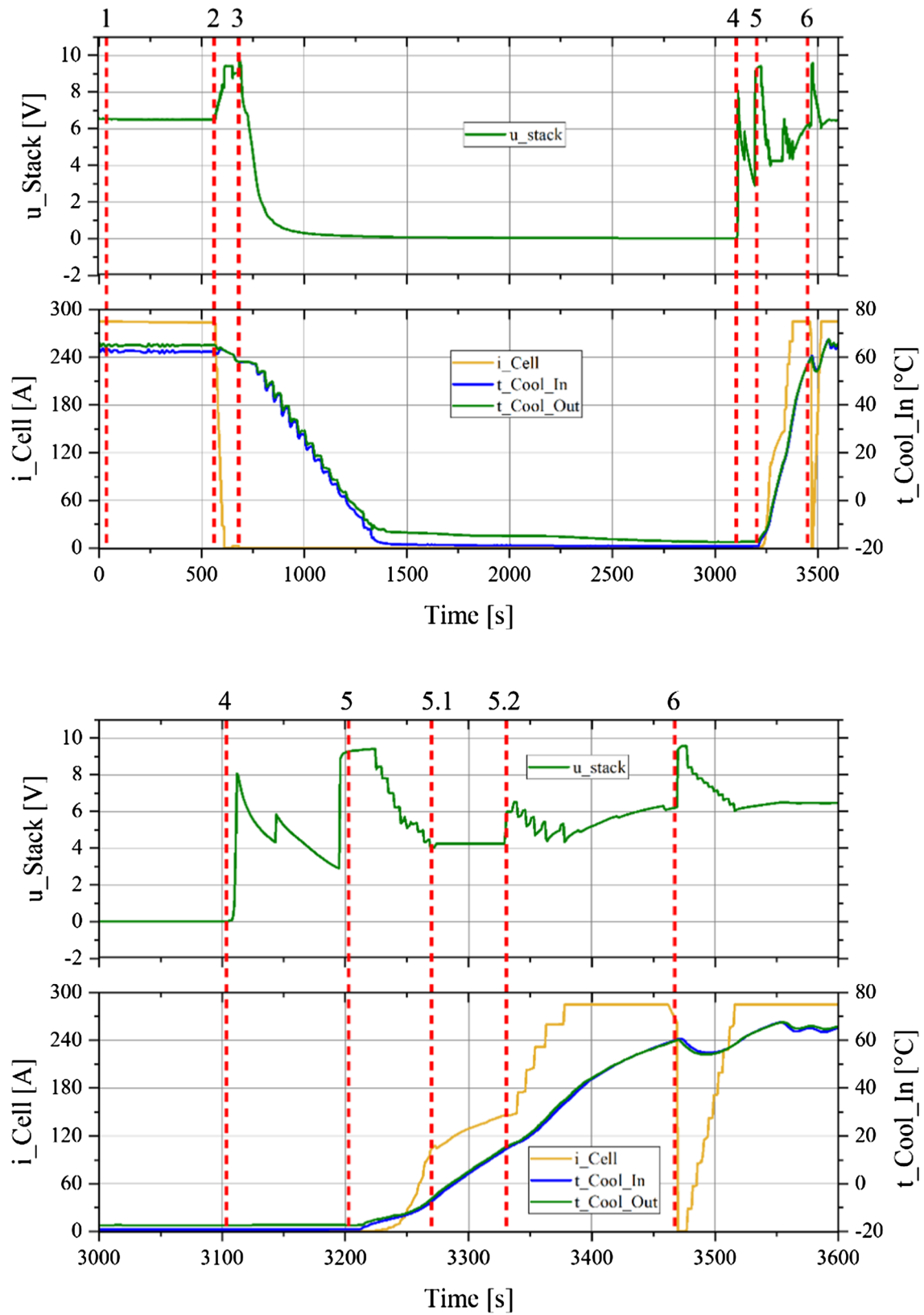


Fig. 5 Measurement data of a freeze start from -18°C (up: whole test sequence, down: zoomed into freeze start)

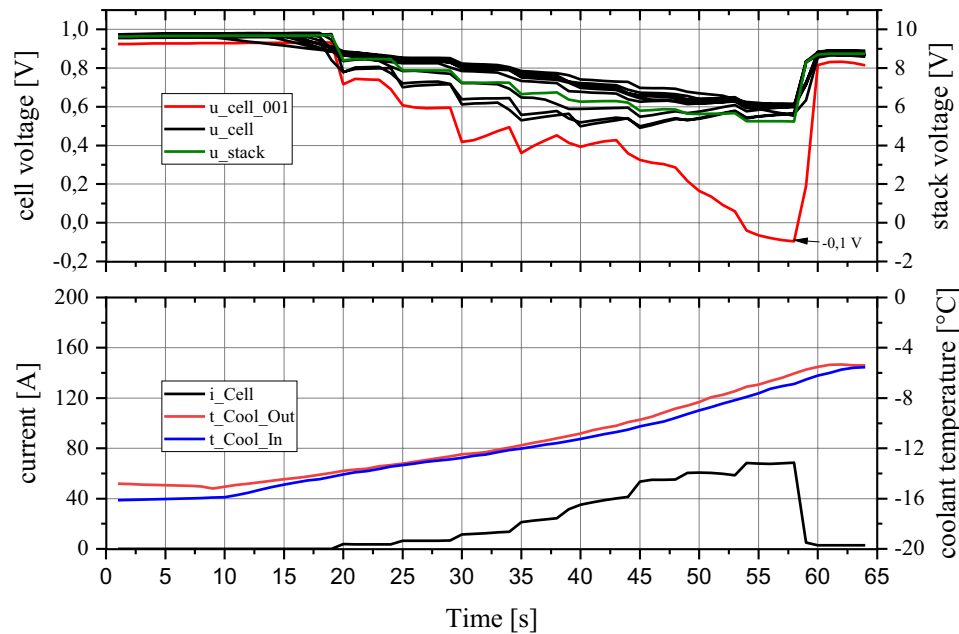


Fig. 6 Measurement data of a “failed” freeze start from -15°C with the freeze prep variation FP1

the temperature intervals investigated in this study were relatively large (from -10°C to -15°C). As a result, small improvements in freeze-start capability may not have been captured by the chosen test matrix.

An increase in the HFR threshold results in a lower minimum possible startup temperature. The FP4 variant, with an HFR threshold of $0.40\ \Omega\cdot\text{cm}^2/\text{cell}$, resulted in a modest improvement, lowering the minimum achievable start temperature to -15°C . Using the FP5 variant with $0.6\ \Omega\cdot\text{cm}^2/\text{cell}$, the stack can be started at -18°C without negative cell voltages. The minimum cell voltage during a successful freeze start was $0.108\ \text{V}$, with cell number 8 being the weakest (see Fig. 7). A higher HFR threshold after the drying phase leads to lower membrane water content. The membrane can absorb more of the produced water, resulting in less water being transported to the bipolar plate channels. Consequently, the likelihood of ice formation in the GDL, CL, or channels is reduced when the membrane absorbs a greater amount of water. This result is consistent with the studies performed on smaller cell sizes during isothermal tests [19, 29]. The flow rates and drying durations applied during the freeze preparation phase are of a similar order of magnitude to those reported by Liphardt et al. [13] and Takahashi et al. [8] see Table 2.

During the measurement, the HFR value decreases slightly during the freeze start. At the beginning of the freeze start, the measurement device was unable to measure accurately, resulting in an offset value. The decline in HFR can mainly be attributed to two factors: an increase in stack temperature and an increase in membrane water

content. An empirical modeling approach describing this behavior was published by Springer et al. [39].

The variation in cell voltages following potentiostatic operation remains significant and only begins to converge once the operating temperature reaches approximately 60°C . This suggests that a uniform supply to the cells has not yet been established during this phase (between Line 5.2 and 6 in Fig. 5). The primary cause is poor water removal during potentiostatic operation. Reduced mass flow at the cathode lowers the stack’s electrical efficiency, resulting in increased water volume within the cells and localized flooding.

3.2 Freeze start strategy

Once a functional freeze preparation method had been identified, the parameters for the freeze start strategy were varied. In this study, only potentiostatic tests were conducted for heating up to 15°C . The initial configuration was the FS3 cold-start strategy. In this case, the cathode flow was $0.75\ \text{g/s}$, and the stack voltage was set to $4.75\ \text{V}$. To investigate these values, the stack voltage was varied, and a small variation in the mass flow rate at the cathode was also introduced. The exact values can be found in Table 2. The anode stoichiometry was 1.5 for all variations. The various freeze start strategies were carried out four times. To compare these strategies, the following indicators were used: the heating rate during operating point of the variation in K s^{-1} , the average water production in g s^{-1} , the overall water production including the voltage ramp in g and the average electric power during the operating point in W (Fig. 8).

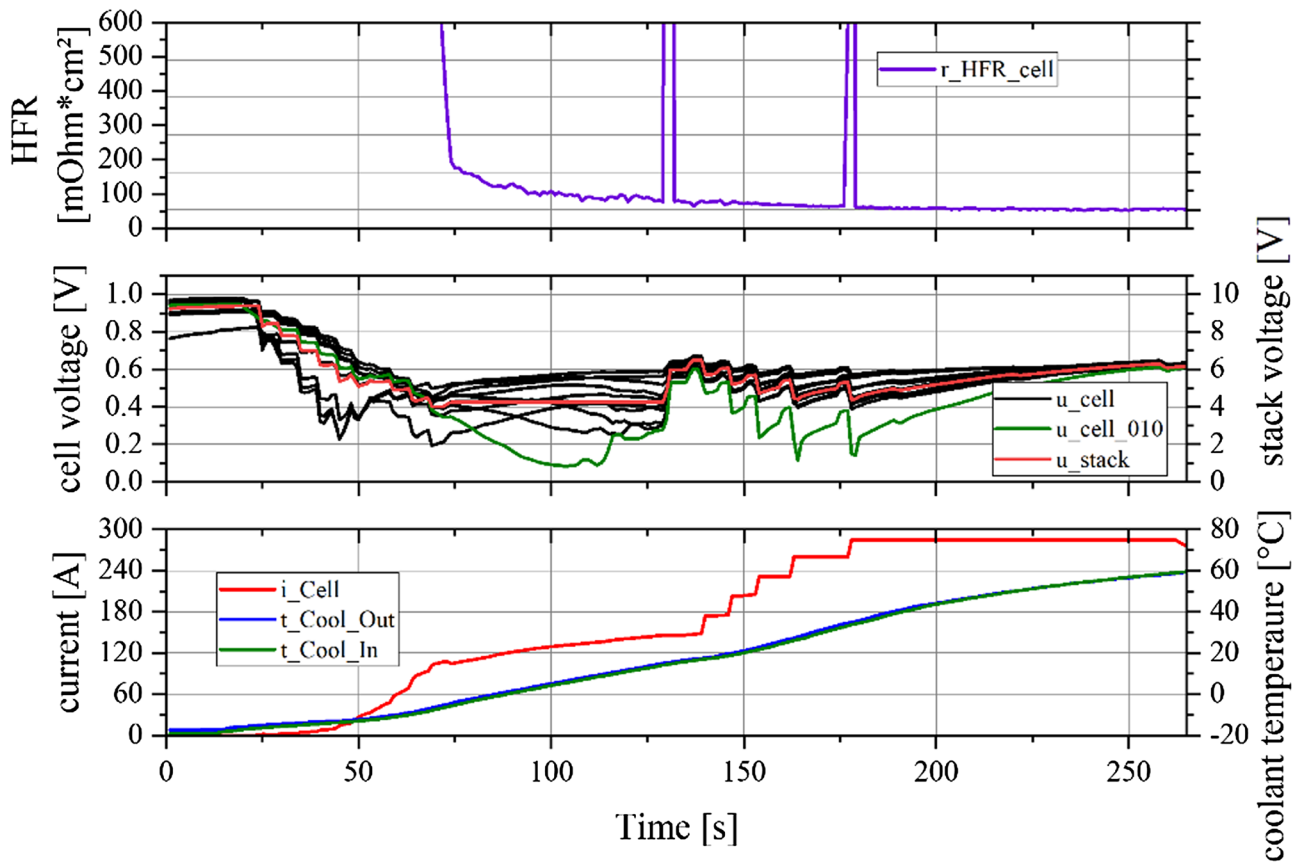


Fig. 7 Measurement data of a “successful” freeze start from $-18\text{ }^{\circ}\text{C}$ with the freeze prep variation FP5

3.2.1 Variation of the mass flow

The cathode mass flow rate was varied by $\pm 0.10\text{ g s}^{-1}$ around the baseline value of 0.75 g s^{-1} (FS3). The resulting heat-up rates ranged from 0.26 K s^{-1} for FS2 to 0.30 K s^{-1} for FS4, while FS3 achieved an intermediate value of 0.28 K s^{-1} (Fig. 8a).

The average water production rate increased slightly with increasing air flow, ranging from 0.13 g s^{-1} for FS2 to 0.16 g s^{-1} for FS4. Despite the higher instantaneous water production, the total water production remained within a relatively narrow range between 9.75 g and 10.60 g (Fig. 8c).

A more pronounced influence was observed for electrical power output. Increasing the cathode flow rate led to higher stack currents and therefore higher electrical power, which increased from 672 W for FS2 to 807 W for FS4, with FS3 again exhibiting intermediate behavior (Fig. 8e).

Overall, the investigated variation in cathode flow rate had only a moderate effect on freeze-start performance. Higher air flow slightly increased the heating rate, water production rate, and electrical power output.

3.2.2 Variation of the stack voltage

In this variation, the target 10-cell stack voltage ranged between 5.25 V and 2.75 V . The heating rate was 0.26 K s^{-1} for FS1 at 5.25 V and 0.32 K s^{-1} for FS8 at 2.75 V (Fig. 8b). Generally, the heating rate increases monotonically as the stack voltage decreases. The average water production rate ranged from 0.13 g s^{-1} for FS1 to 0.19 g s^{-1} for FS8 (Fig. 8d). During potentiostatic operation, the stack voltage is controlled by the stack current; achieving a lower stack voltage requires a higher current, which results in increased water production rate. However, the overall water production—from the start until the temperature reached $15\text{ }^{\circ}\text{C}$ —was lowest for FS8 at 8.8 g , compared to 10.3 g for FS1. The water production rate is higher for FS8 than for FS1. Due to the lower electrical efficiency in FS8, the heating rate is higher, and thus the total time required for defrosting is shorter. The resulting cumulative water production is therefore also lower in this case.

The highest electric power was recorded for FS3 at 752 W , while the lowest was for FS8 at 547 W (Fig. 8f).

A clear trend is observed for the heating rate as well as the average water production rate and total water production. The increase in heating rate with decreasing stack voltage can be explained by a decline in electrical

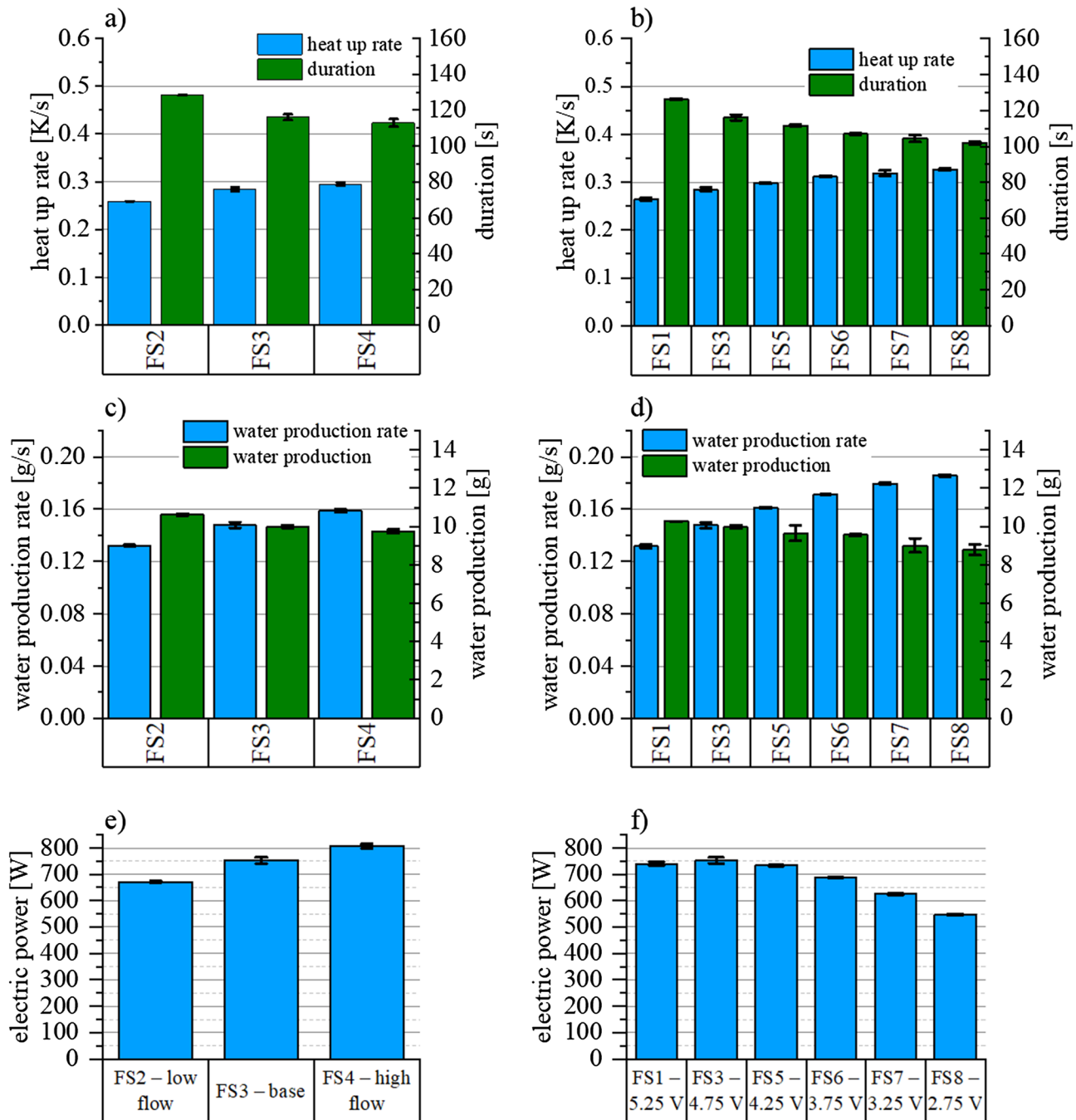


Fig. 8 Results of the characteristic parameters to describe the freeze start strategy

efficiency. A system-level parameter study identified a similar relationship between stack voltage and heat-up rate, although it remains unclear whether oxygen starvation was deliberately employed as part of the start strategy [37].

Additionally, the stack current must increase to achieve a lower stack voltage, assuming the cathode mass flow remains constant. Higher stack current leads to increased average water production rate.

To achieve high heat-up rates, selecting a low stack voltage is most effective. However, this results in both low overall water production and reduced average electric power. The membrane's capacity to absorb water is limited. Therefore, the goal should be to keep total water production as low as possible during the startup process. This reduces the amount of water that needs to be transported from the MEA to the bipolar plate channels, where it could potentially freeze and cause blockages.

4 Conclusion

The experimental setup described here enables simulation of heating conditions to come close to those inside a vehicle. The heating rates closely match those derived from vehicle data by an accelerated stress test (AST) for a full-size stack (FSS) on an FCS [9].

This study experimentally investigated freeze start strategies for automotive-sized PEM fuel cell short stacks, emphasizing the balance between startability, durability, and practical applicability without relying on external heaters. An adapted cooling circuit provided realistic thermal boundary conditions comparable to those in fuel cell electric vehicles, enabling evaluation of freeze starts down to $-18\text{ }^{\circ}\text{C}$.

The results clearly demonstrate that the freeze preparation strategy is the primary factor determining the minimum achievable start temperature. Among the parameters studied, the high-frequency resistance (HFR) threshold at the end of the drying phase had the most significant impact on startability. Low HFR thresholds ($0.20\text{--}0.25\text{ }\Omega\cdot\text{cm}^2/\text{cell}$) resulted in unreliable starts below $-10\text{ }^{\circ}\text{C}$, regardless of the cathode flow rate. In contrast, increasing the HFR threshold substantially improved freeze start robustness. The FP5 preparation strategy (HFR = $0.60\text{ }\Omega\cdot\text{cm}^2/\text{cell}$) enabled reliable starts at $-18\text{ }^{\circ}\text{C}$ without negative cell voltages, making it the best-performing freeze preparation in this study. The poorest performance was observed for FP1–FP3, which consistently failed below $-10\text{ }^{\circ}\text{C}$ due to cell reversal caused by reactant starvation.

These findings confirm that a sufficiently dried membrane can temporarily absorb a significant portion of the product water generated during cold start, thereby reducing ice formation in catalyst layers, gas diffusion layers, and flow channels. However, drying must be homogeneous across the stack, as unavoidable cell-to-cell flow maldistribution—due to manufacturing tolerances—can lead to local under- or oversupply and premature failure.

For the freeze start (heat-up) strategy, potentiostatic operation proved effective for controlled heating of the frozen stack. Varying the cathode mass flow rate within a narrow range had only minor effects on heating rate, water production, and electrical power. In contrast, stack voltage during potentiostatic operation strongly influenced freeze start performance. Lower stack voltages led to higher currents, increased heating rates, and lower total water production until $15\text{ }^{\circ}\text{C}$ was reached. Among the tested strategies, FS8 (2.75 V) achieved the highest heating rate and lowest total water production, making it the most thermally efficient strategy, albeit with reduced electrical power output. Conversely, FS1 (5.25 V) had the lowest heating rate and highest water production, representing the least favorable freeze start strategy.

Although lower stack voltages reduce available electrical power during the initial freeze start phase, previous vehicle-level analyses indicate that power demand immediately after startup is low, making this trade-off acceptable for real-world FCEV operation [9]. Nevertheless, once the stack temperature exceeds $15\text{ }^{\circ}\text{C}$ and the mode switches to galvanostatic control, careful current ramp-up and increased cathode stoichiometry remain essential to prevent local flooding, hydrogen starvation, and carbon corrosion.

The present study is subject to several limitations. The experiments were conducted on a 10-cell short stack and therefore cannot fully capture all thermal, flow distribution, and control effects occurring in full-size automotive fuel cell systems. Furthermore, the investigated parameter space was limited to selected freeze-preparation and freeze-start operating conditions, and durability effects were assessed indirectly through startability criteria and voltage behavior rather than through long-term degradation testing.

Future work should extend the developed methodology towards freeze-start operation at temperatures down to $-30\text{ }^{\circ}\text{C}$ in order to address automotive target requirements under severe winter conditions. In addition, the transferability of the presented short-stack methodology should be validated against an FCS to assess the comparability of freeze-start behavior, heat-up characteristics, and durability-related effects across different system scales.

Overall, this work demonstrates that combining an aggressive but well-controlled freeze preparation (high HFR threshold) with low-voltage potentiostatic heat-up offers the most robust and efficient freeze start performance. The methodology presented provides a practical and transferable framework for evaluating freeze start durability and supports the development of reliable cold start strategies for automotive fuel cell systems operating under severe winter conditions.

Abbreviations

AST	Accelerated stress test
BPP	Bipolar plate
CL	Catalyst layer
DoE	Department of Energy
FCEV	Fuel cell electric vehicle
FCS	Fuel cell system
FP	Freeze preparation
FS	Freeze start
FSS	Full-size stack
GDL	Gas diffusion layer
HFR	High-frequency resistance
MEA	Membrane electrode assembly
MPL	Microporous layer
OCV	Open-circuit voltage
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
PID	Proportional–integral–derivative
P&ID	Piping and instrumentation diagram

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Author contributions

M.S. set up the experiment and wrote the main manuscript text. A.A. and R.E. supervised the work and reviewed the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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