SHORT COMMUNICATION

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Dynamic and precise temperature control unit for PEMFC single-cell testing

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Abstract

The performance and durability of polymer electrolyte membrane (PEM) fuel cells is sensitive to the operating temperature. In order to optimize the operation strategy of PEM fuel cells, it is essential to perform various stress tests within wide temperature ranges. Nevertheless, not all types of stress tests can be performed on the standard single-cells. For the low-temperature tests, an additional cooling device is needed, which is associated with high costs and long testing times. In this work, two high power temperature control units were developed. With the small-size ($50 \, cm^2$) and automotive-size ($285 \, cm^2$) designs, the PEM fuel cell tests at temperatures well below $0°C$ are possible with the temperature change rates of $80 \, K \, min^{-1}$. In addition to the high dynamics, the automotive design allows to set the temperature gradients over the active surface area. This offers the possibility to simulate different alteration effects, which can occur during normal operation and increases the comparability between the fuel cell single-cells and stacks.

KEYWORDS
Peltier element tempered single-cell, PEM fuel cells, PEMFC operation at low-temperature

1 | INTRODUCTION

With the turnaround in energy policy, alternative energy carriers for the transport sector, such as hydrogen, seems to be more and more attractive.[1] In 2015, the transport sector was responsible for 19% of the global final energy demand worldwide.[2] The energy conversion using polymer electrolyte membrane (PEM) fuel cells have the potential to reduce the pollutant emissions and to minimize the dependency on fossil fuels.[3] However, to be competitive with conventional combustion engines, significant improvements in cost and durability are required.[4,5] With regard to the durability, the operating temperature of PEM fuel cells plays a decisive role. Fuel cell electric vehicles must be able to operate in a wide temperature range, such as at temperatures well below the freezing point of water. Here, especially the start-up from low temperatures, such as $-20°C$, poses a challenge for the long-term stability of the PEM fuel cells.[6-8] At the other end of the temperature range, an interest in high temperature PEM fuel cells operating at temperatures between 120 and 200°C rapidly grows in order to achieve high efficiency.[9,10] However, experiments outside the standard temperature range in real applications are expensive and very time consuming. For these reasons, such tests are often performed at single-cell level

in the test bench environment. Therefore, single-cell test equipment must be able to reproduce such conditions. Usually a water-cooled cell hardware is used for the simulation of environmental conditions. With this type of temperature control, however, only temperature ranges from 0°C to slightly above 100°C are possible. Other coolants extend the temperature range but induce a new contamination source.[11] For investigations at temperatures below 0°C, special measurement setups such as environmental chambers[12,13] or/and additional cooling units[14] are required. However, durability tests in the environmental chambers are expensive, very time-consuming and it is questionable whether there is even comparability with the real applications. A decisive point here is the uneven temperature distribution on the PEMFC surface, either during start-up at low temperatures or during normal operation. In the case of start-up, when starting at low temperatures, an uneven temperature distribution occurs during the heating process.[14,15] This temperature distribution as well as the heating rate depends strongly on the output power and the thermal mass of the fuel cell. During normal operation, uneven temperature distributions can also occur at higher current densities, leading to reduced performance and degradation.[16,17] All conventional temperature control methods lack the ability to simulate temperature gradients on the surface of a PEMFC single cell. This and the previously mentioned critical aspects finally led to the search for a new way to control the temperature of a PEMFC single cell. With the help of electro thermal transducers, the so-called Peltier elements, temperatures outside the normal operating range, such as below freezing point and well above boiling point of water, can be easily reached.[18-20]

In this work, we introduce two dynamic single-cell designs (small-size of 50 cm² and automotive-size of 285 cm²) in which, the temperature is controlled by high power Peltier elements. With this method, the comparability between the single-cells and fuel cell stacks is increased. Various tests such as local hot spots, temperature gradients and approximation of the heating process for a single-cell within a fuel cell system during the cold start-up can be performed. This method of controlling the cell temperature represents a low-cost and space-saving way to expand the scope of single-cell tests and to perform various stress tests, such as low-temperature cycles without the help of an additional cooling device.

2 | EXPERIMENTAL SETUP

2.1 | Small size PET single-cell 50 cm²

The Peltier element tempered (PET) single-cell design with an active surface area of 50 cm² significantly differs from a usual water-cooled single-cell and can, therefore, be used in a small-size commercial test bench. The main difference is the type of temperature control and the additional PE temperature control unit, which contains a 24 V DC power supply and a MOSFET-based power electronics unit. Figure 1(A) shows the measurement setup with the PET single-cell, which
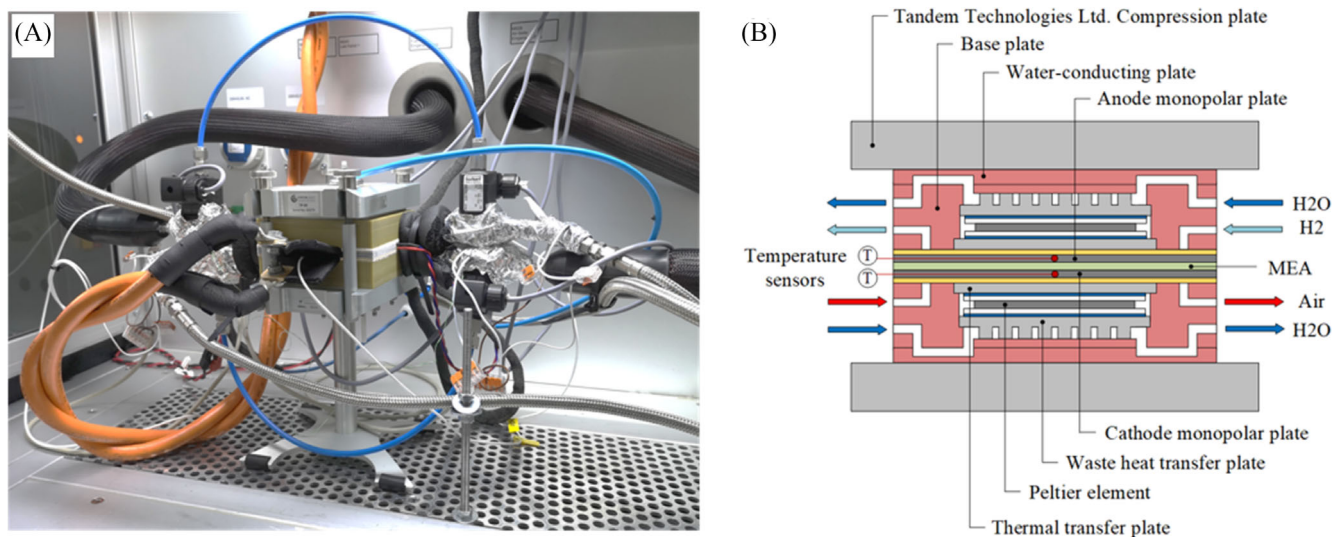

FIGURE 1   (A) A photo of the measurement setup with the Peltier element tempered (PET) single-cell, which is tempered to an active surface temperature of −20°C. (B) Detailed technical cross-section of the PET single-cell

is tempered to an active surface temperature of −20°C. As with the previous design (presented in our previous work[21]), the cell consists of two decoupled tempering units, of which the temperature can be adjusted separately. The main advantage of the proposed approach is the new material, the more compact and optimized cell design and the more powerful core with two high powered Peltier elements with a total thermal power of ~480 W (2 × 240 W). With this, both the dynamics and the working range could be increased considerably, as discussed later. For better understanding of the PET single-cell, a detailed technical cross-section is shown in Figure 1(B). Each core of the tempering units consists of a Peltier element, which requires good thermal isolation of the cold and the hot ceramic substrates from the environment. For this purpose, the tempering unit consists of four main parts: the base plate (BP), the water-conducting plate (WCP), the thermal transfer plate (TTP) and the waste heat transfer plate (WHTP). Both the WCP and the BP are made of amorphous polyimide Ultem® (Type 2300). The main advantage of this material is the low thermal conduction of 0.22 W m^{-1} K^{-1}, the high hardness and the coefficient of linear expansion, which is comparable to aluminum (~30.0 vs. 20.0 *10^{-6} K^{-1}).[22,23] Due to the comparable coefficient of linear expansion, the materials expand similarly within the given operation temperature range. For this purpose, the metallic TTP is built directly into the BP, which leads to an evenly flat tempering surface and a low mass of the temperature active parts. The lower amount of aluminum in the cell results in a better isolation of the temperature-stressed parts, such as the metallic WHTP and the metallic TTP. Another advantage of the polyimide is the approved temperature range between −30 and ~180°C as well as the good resistance to acids. Therefore, the temperature range described above can be easily reached on the active surface, which enormously expands the scope of the single-cell tests.

2.2 | Automotive size PET single-cell 285 cm^2

Similar to the 50 cm^2 PET single-cell, an automotive size PET single-cell with an active area of 285 cm^2 has been also developed. Besides the size, the main difference between these two single-cell types is the number of Peltier elements. While only two elements are used to control the temperature of the small cell, the anode and cathode of the PET single-cell of 285 cm^2 are equipped with 32 Peltier elements each with a total thermal power of 2 × 1280 W. Each element has its own temperature control loop consisting of a temperature sensor (PT1000) and power electronics. By contrast to the small cell, the high number of elements makes it possible to display temperature distributions with 64 different measuring points across the active area. This allows to simulate different disturbance effects from cell stacks, such as gradients caused by water cooling, in order to investigate the resulting cell behavior. Its standard setup is shown in Figure 2(A). Similar to the PET single-cell 50 cm^2, the design of the PET single-cell 285 cm^2 is based on the aluminum and Ultem® (Type 2300) materials. A detailed technical cross-section is shown in Figure 2(C). Depending on the requirements, a thermally conductive or thermally insulating behavior with almost identical thermal expansion is achieved in the individual layers, maximizing the overall efficiency and dynamics of the hardware. The thermal power for tempering the fuel cell is transferred to the active surface via the TTP. On the opposite side, the WHTP with integrated cooling fins ensures rapid transfer of the thermal losses to the water cooling system. Both plates are made of aluminum to achieve high thermal conductivity. By contrast, both the BP and the WCP are made of Ultem® (Type 2300) and thus thermally insulate the hardware from the environment. To connect the individual Peltier elements and the corresponding temperature sensors, each side of the hardware is equipped with two printed circuit boards (PCBs). Using a cable set, the PCBs are connected to a control cabinet containing the power electronics for the Peltier elements and the evaluation electronics for the temperature sensors. The switch cabinet is supplied with the three-phase current. The electrical power for the Peltier elements is provided by two power supply units, which convert the main voltage into 12 V DC. The inside of the control cabinet is shown in Figure 2(B).

3 | RESULTS AND DISCUSSION

With the new hardware concepts described in the previous sections, several tests were conducted in order to find the key working parameters. The small-size PET single-cell is consistently operable in the temperature range from −30 to 180°C, and the automotive-size PET single-cell is designed for the temperatures between −25 and 125°C. The lower limiting factor is the waste-heat removal of both tempering units, which depends on the test bench coolant circuit. The upper limit is given by the material and sensor limitations. This is a significant improvement compared with the commercially available
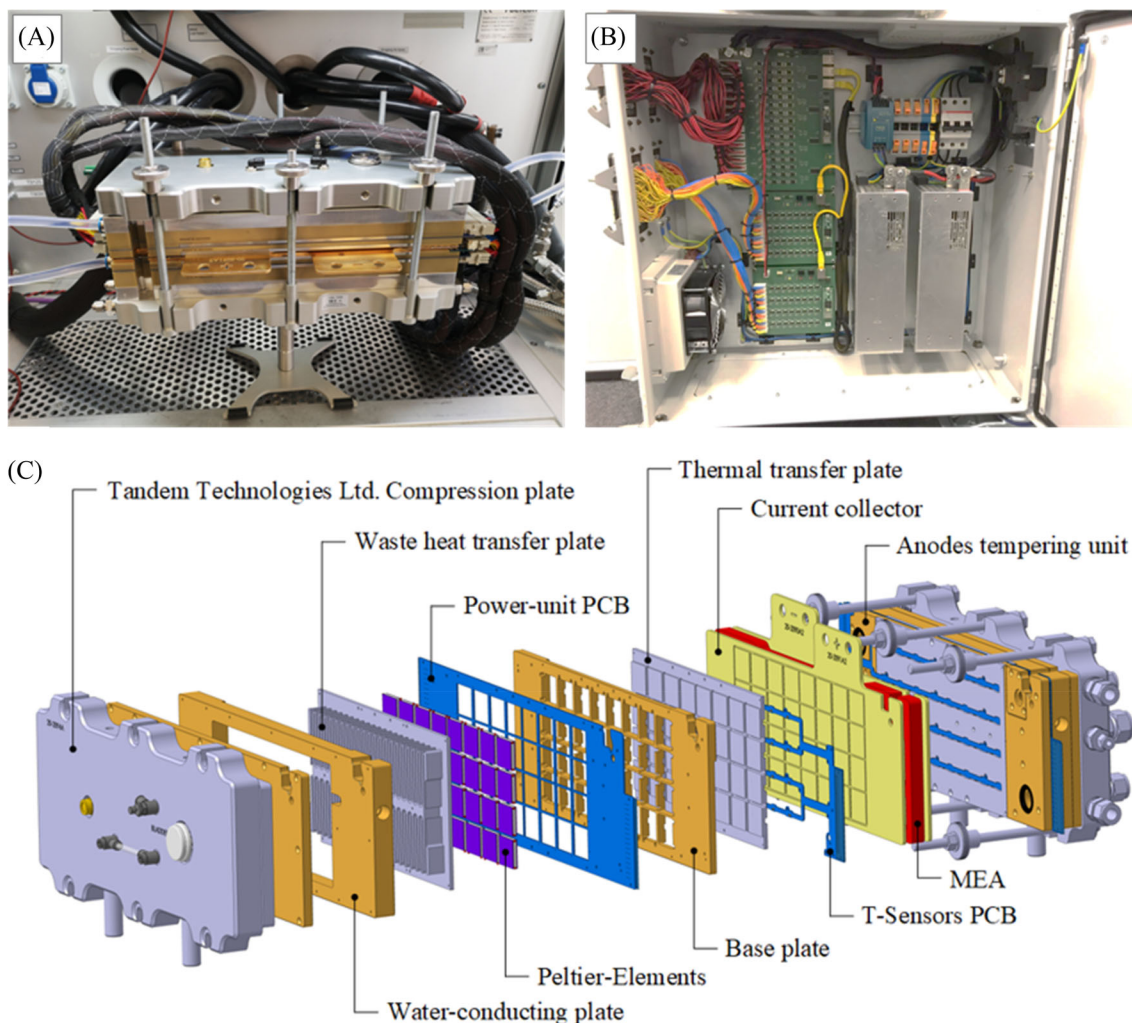
FIGURE 2 (A) A photo of the standard measurement setup with the automotive size Peltier element tempered (PET) single-cell. (B) The control cabinet for the control and power supply of the 32/32 temperature units. (C) Computer-aided design view of the automotive PET single-cell, with the assembled anode and cathode in exploded view

water-cooled cells ranging between 35 and 95°C. With both concepts, a maximal heating/cooling rate of 80 K min^{-1} at temperatures close to ambient temperature can be achieved. With increasing temperature difference to the ambient temperature the maximum rate decreases according to Newton's law of cooling. However, even at elevated temperatures around 80°C, the rate of 20 K min^{-1} can be maintained. Calculated according to IEC 60068-3-6 for the climate chambers,[24] this equals to a temperature change rate of 24 K min^{-1} for heating and 17 Kmin^{-1} for cooling. Currently, the commercial climate chambers achieve temperature change rates of 3–4.5 K min^{-1} for heating and 2–4.5 K min^{-1} for cooling.[25,26] A typical low-temperature cycle from −10 to 80°C and back can be carried out in less than 10 min with the proposed design. On the other hand, a low-temperature cycle from −20°C to an elevated temperature of 120°C takes less than 30 min. The PI-controller developed shows an accuracy of ±0.3°C in the whole temperature range from −25 to 125°C. An implemented ramp function provides an even temperature course (see Figure 3(A)). By contrast to the state-of-the-art cooling methods, the automotive-size cell with 64 autonomously controllable Peltier elements enables accurate temperature profiles within the cell. A temperature difference between the neighboring segments of up to 10°C is feasible (see Figure 4). It is therefore possible to simulate several scenarios of a fuel cell stack under operation. Possibilities include temperature gradients in plane of the cell due to different stack and cooling designs, temperature gradients across the cell between anode and cathode (see Figure 3(B)) accounting for different heat management concepts and simulating local hot-spots (see Figure 3(C)).
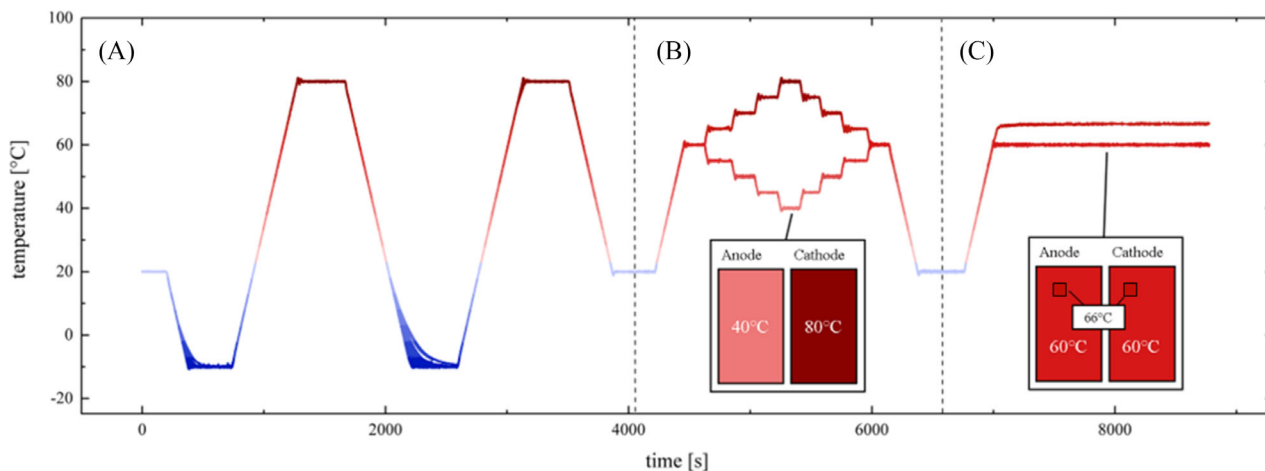
FIGURE 3 Temperature profiles of all 64 temperature sensors while performing cycles between −10 and 80°C in ramp mode (A), then spreading the anode and cathode temperature to a final temperature of 40/80°C (B) and finally setting a local hot-spot of 66°C versus 60°C cell temperature (C)
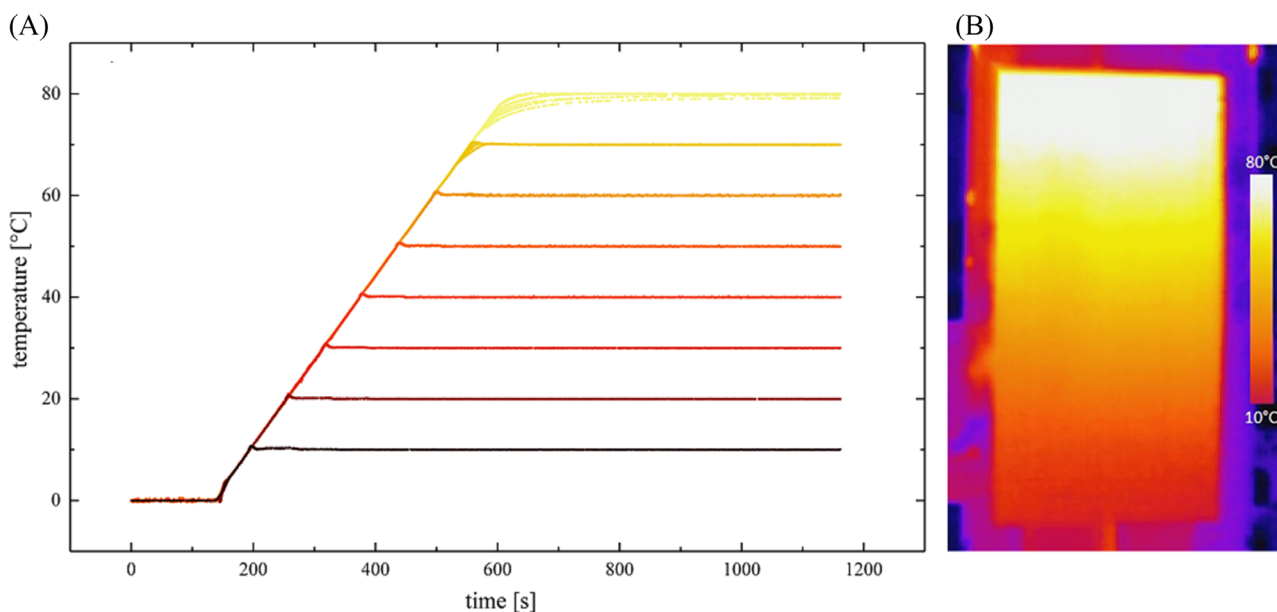

FIGURE 4 (A) Examples of temperature profiles of all 64 temperature sensors while setting a horizontal temperature gradient from 10 to 80°C in the ramp mode. (B) Image of the anodic current collector surface while applying a horizontal temperature gradient from 10 to 80°C. Taken with a thermal imaging camera

4 | CONCLUSIONS

In this work, we presented a dynamic and precise method for temperature control of PEM fuel cells over a wide operating range. Based on our previous work,[21] two single-cell designs (small-size 50 cm² and automotive-size 285 cm²) with high power tempering units were developed. The tempering units of the small design are tempered by two Peltier elements with a total thermal power of ∼480 W. In return, the units of the automotive design are tempered by 64 Peltier elements with autonomous temperature control loops consisting of temperature sensor and power electronics. With a total thermal power of ∼2.5 kW, temperature modification speeds of 80 K min⁻¹ and operating temperatures between −25 and 125°C can be achieved. Besides improved accuracy and dynamics, the automotive design enables temperature gradients in the longitudinal direction of up to 70°C. This allows to expand the scope for single-cell tests and represents a low-cost and

space-saving way to simulate different disturbance effects or to carry out low-temperature cycles without an additional cooling device.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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