Revealing the Performance Enhancement of Oxygenated Carbonaceous Materials for Vanadium Redox Flow Batteries: Functional Groups or Specific Surface Area?

Lin Zeng, Tianshou Zhao,* and Lei Wei

It is widely recognized that the oxygenated carbonaceous materials improve the performance of vanadium redox flow batteries (VRFBs). However, whether the enhanced vanadium redox reactions are due to the existence of grafted oxygen-containing functional groups (OCFGs) or the enlarged specific surface areas (SSAs) during the course of surface treatments is still under dispute. To determine which factor is indeed responsible for the enhanced redox reactions, a set amount of OCFGs is intentionally grafted on the model carbon electrode without modifying the surface area using an alkaline-mediated hydrothermal treatment. Experimental results, using the peak potential separation and the activation energy as electroactivity descriptors in the three-electrode cell, demonstrate that OCFGs promote the V(II)/V(III) redox reaction, while exhibiting a minute catalytic effect on the V(IV)/V(V) redox reaction. The superior electroactivity is also testified by a flow battery test, in which the energy efficiency as well as the charge/discharge capacity of VRFBs with hydrothermally treated samples is significantly higher than those of VRFBs with the pristine one. Through these experiments, it is verified that OCFGs contribute to the electroactivity promotion for carbon electrodes rather than the enhanced SSA. The findings can guide the effort to design high-performing carbonaceous electrodes for VRFBs.

1. Introduction

Redox flow batteries (RFBs) as energy storage devices have gained increasing attention to address the intermittency and distribution of renewable energies, such as wind energy and solar energy.[1] Among these RFBs, vanadium redox flow batteries (VRFBs) employing the same vanadium element in four different oxidative states have been widely investigated and gradually commercialized for the large-scale stationary applications.[2] One of the significant merits of VRFBs is the high flexibility in configuration and operation. That is, the energy storage and power generation are decoupled such that the energy capacity depends on the amount and composition of electrolyte stored in the reservoir while the power generation is determined by the electrochemical activity of the porous electrode.[3]

The porous electrode is the key component to provide the electrochemical reaction sites and transport the species, including the ions and the generated/consumed electrons.[4] Currently, the carbonaceous materials, including graphite felts,[5] carbon papers,[6] and carbon cloths,[7] have been extensively studied as the electrode in VRFBs as a result of their high electrical conductivity, excellent chemical stability, and mechanical properties. However, these pristine carbon materials are plagued by the low electrochemical activity and bad compatibility with the liquid electrolyte, thereby leading to a low energy efficiency for VRFBs. Consequently, these carbon electrodes were subjected to surface treatments before being employed as electrodes.[8] Currently, several categories of surface treatment procedures, such as thermal treatment,[9] chemical etching,[6c,7a,10] and electrochemical treatment,[11] have been widely applied for the carbon electrodes.

The performance of carbon electrodes after surface treatments can be influenced by the following aspects. First, the carbon surface will be plentifully grafted with the oxygen-containing functional groups (OCFGs), which enable to enhance the absorption of vanadium ions on the carbon surface. It was demonstrated that there was a direct relationship between the electrochemical activity and the amount of hydroxyl groups grafted on the surface of carbon fiber.[12] Second, these treatments will rough the carbon surface of electrodes, thereby increasing the surface area. The roughed surface area can provide fast electron channels for the redox reaction. In addition, the surface tension of carbon materials will be modified to allow the accessibility of liquid electrolyte, which will facilitate the heterogeneous electrocatalysis between the vanadium ions and carbon electrodes.

Although these influences of surface treatments on vanadium redox reaction were well demonstrated in the previous literature,[7a,11] there are yet some different opinions proposed by other researchers recently. Melke et al.[9] reported that the
amount of OCFGs was less necessary for the electrochemical activity while sp² carbon content on the surface played the role of activity improvement. The authors also claimed that OCFGs only got the carbon surface wet for vanadium redox reaction happened. Cao et al. [14] studied the influence of various surface pretreatments on the electrochemical activity and concluded that the specific surface area was contributed to the activity enhancement while OCFGs had a reverse effect on the vanadium redox reaction. Meanwhile, Taylor et al. [15] also reported a similar result, which showed that there was no correlation between vanadium redox activity and the amount of OCFGs. Recently, Fink et al. [16] also analyzed the effect of OCFGs on the kinetic activity of vanadium ions by electrochemical impedance spectroscopy; it was shown that OCFGs enhanced the V(III)/V(II) redox reaction while impeded the V(IV)/V(V) redox reaction.

Our literature review indicates the vanadium redox reactions are significantly sensitive to surface composition and surface area of carbon electrodes. Due to the harsh preparation process reported in the previous literature, the surface composition and surface area were simultaneously changed during the course of pretreatment. In this situation, it is difficult to implement the activity analysis as a result of the complex and uncontrollable surface for carbon electrodes. Therefore, there are different opinions, even the opposite views, to interpret the role of OCFGs on the vanadium redox reactions.

To address the issues aforementioned, in this work, we chose a typical carbon cloth (CC) as the model electrode, and hydrothermally treated by alkaline solutions. Compared to the previous alkaline activation methods that simultaneously changed the surface area and surface composition, [17] the specific surface area of carbon cloth after the treatment was almost unchanged after the hydrothermal treatment. Therefore, we can separately analyze the effect of OCFGs on the vanadium redox reactions.

To address the issues aforementioned, in this work, we chose a typical carbon cloth (CC) as the model electrode, and hydrothermally treated by alkaline solutions. Compared to the previous alkaline activation methods that simultaneously changed the surface area and surface composition, [17] the specific surface area of carbon cloth after the treatment was almost unchanged after the hydrothermal treatment. Therefore, we can separately analyze the effect of OCFGs on the vanadium redox reactions. More importantly, the amount of OCFGs was gradually augmented on the carbon cloth surface, which made the electrochemical activity analysis that affected by OCFGs realistic. The surface properties, including the amount of OCFGs, the category of OCFGs, and the graphitization degree, were comprehensively analyzed. Meanwhile, the electrochemical activities for the V(IV)/V(V) reaction and the V(III)/V(II) reaction were determined by electrochemical tests, respectively. Finally, we verified the performance and the long-term stability in a single-cell VRFB.

2. Results and Discussion

2.1. Characterization of Treated Carbon Cloth

The surface morphology of carbon cloth before and after the hydrothermal treatment was determined by field emission scanning electron microscopy (FESEM). As shown in Figure 1a, it is seen that the carbon cloth is comprised of woven carbon fibers with the average diameters of 9 (±3) µm. Although there are some grooves on the surface of pristine carbon fibers, the morphologies of the carbon fibers were yet almost unchanged after the alkaline hydrothermal treatment (Figure 1b–e). A high-resolution FESEM image of CC-12M is presented in Figure 1f, from which it is still observed that the alkaline-mediated hydrothermal treatment has an indistinguishable effect on the carbon fiber surface, which indicates that the alkaline treatment is a mildness process. The energy-dispersive X-ray (EDX) mapping analysis was performed to detect the oxygen distribution on the carbon fiber surface, as shown in Figure S1 (Supporting Information). The oxygen signal is evenly distributed across the entire carbon fiber, suggesting a uniform distribution of the oxygen on the carbon fiber surface.

Raman measurement was performed to analyze the influence of alkaline hydrothermal treatment on the microstructure for the carbon cloth. As illustrated in Figure 2a, the laser beam was focused on the surface of individual carbon fiber. To make sure of the data reproducibility, 15 randomly selected carbon fibers were evaluated for each sample. In a typical Raman spectrum (Figure 2b), the carbon cloth exhibits two strong peaks, centering at around 1350 and 1587 cm⁻¹, which are derived from the structural imperfections created by the grafted OCFGs (D band) and the first-order scattering of E2g mode (G band), respectively. [18] The laser beam of Raman has a penetration depth of about 50 nm for graphitic materials. [19] However, the influence of laser
penetration on all the carbon fibers is the same. Meanwhile, all the Raman spectra are scanned three times, and each spectrum is almost overlapped, indicating the effect of the laser on the surface state is limited. As all the surface of carbon fibers are modified by the alkaline-mediated hydrothermal treatment, any changes in the Raman spectra of the alkaline-treated samples are attributed to the modification of the surface during the treatment. Hence, the intensity ratio between the D band and G band \((I_D/I_G)\) can be used to indicate the surface defects derived from the grafted OCFGs.\(^{[18b,20]}\) All the \(I_D/I_G\) ratios for all samples are presented in Figure 2c,d, from which it is seen that the \(I_D/I_G\) ratio is gradually shifted from 0.70 to 0.95. The augment of \(I_D/I_G\) ratio with the increased treatment strength indicates that higher KOH concentration introduced copious of functional groups on the carbon fiber surface. Meanwhile, the G-band position slightly shifts to a higher frequency (blue-shift), which indicates the Raman-inactive nonzero phonon density of states above the G band become active as a result of phonon confinement caused by the defects created.\(^{[21]}\)

X-ray photoelectron spectroscopy (XPS) surface analysis was further performed to identify the amount and composition of OCFGs on the carbon fiber surface. The high-resolution O 1s XPS spectra with the peak position at around 532.0 eV for all samples are presented in Figure 3a, from which it is clearly observed that OCFGs with increased content are incorporated on the surface of carbon fibers since the intensity of O 1s spectrum is gradually augmented. The oxygen content was then quantitatively determined (Figure 3b; Figure S2, Supporting Information). The oxygen doping level is very sensitive to the alkaline concentration, such that it is increased from 5.95% to 12.08% when the alkaline concentration increases from 6 to 12 m. It is interesting that the surface of pristine CC also contains a little amount (0.78%) of OCFGs, suggesting the existence of a trace amount of oxygen-containing impurities. The high-resolution C 1s XPS spectra are then analyzed to reveal the categories of OCFGs. A typical high-resolution C 1s XPS spectrum (CC-10M) is illustrated in Figure 3c, in which the C 1s spectrum is fitted by convoluting four peaks, that is, C—C peak (284.3 eV), C—OH peak (286.0 eV), C==O peak (287.1 eV), and COOH peak (290.5 eV).\(^{[12a,22]}\) The respective percentage of the OCFGs is plotted in Figure 3d. The proportions of hydroxyl type (C—OH) functional groups as well as carbonyl type (C==O) functional groups are simultaneously increased when the treatment process becomes harsh. But the percentage of carboxyl type (COOH) functional groups is almost unchanged (around 8%). It was demonstrated that the hydroxyl-type functional groups were beneficial to the activity promotion for vanadium redox reaction.\(^{[23]}\) We will analyze the influence of OCFGs on vanadium redox reactions in the following section.

Even though the mechanism for the alkaline oxygenation of OCFGs on carbon fiber surface is unclear, the following aspects should be considered. The KOH with high concentration will react with the carbon, thereby introducing the OCFGs on the carbon fiber surface. This kind of reaction, i.e., carbon oxidation by KOH activating, has been proved in the literature as reported before.\(^{[24]}\) On the other hand, due to the high graphitization degree of carbon cloth, this type of reaction will only take place at the surface, which will not largely augment the specific surface area, as observed by FESEM.
2.2. Accessible Surface Area

The accessible surface area (ASA) was measured by cyclic voltammetry in 3 m H₂SO₄. The cyclic voltammograms and the corresponding capacitances calculated are presented in Figure 4. Normally, the current is generated by charging of the electrochemical double layer and redox reaction of the functional groups on the carbon surface. The quinone/hydroquinone redox reaction with the oxidation potential of +0.55 V and reduction potential of +0.38 V was reported in the previous literature[22b,25] and used to determine the surface area of carbon.[24] We also calculated the capacitance (C_p) with the following equation

\[
C_p = \frac{\int i \, dV}{v \cdot \Delta E}
\]

where \(i\) is the current, \(V\) is the voltage, \(v\) is the sweep rate (20 mV s⁻¹), and \(\Delta E\) is the voltage window (0.6 V).[26]

---

Figure 3. XPS survey spectra of a) O 1s and b) the oxygen content for all samples. c) The typical XPS survey spectra of C 1s (CC-10M) and d) the fitting percentage of functional groups.

Figure 4. a) Cyclic voltammograms in 3 m H₂SO₄ (nitrogen-saturated) for carbon cloth samples. b) Capacitances calculated from enclosed area of cyclic voltammogram.
Although the capacitance is almost linearly increased as shown in Figure 4b, it is yet clearly observed that the currents generated from the electrochemical double layer are almost unchanged for all the carbon cloth samples when compared the alkaline treated samples with the pristine one. The currents contributed by the redox peaks, centering at 0.55 V for oxidation and 0.38 V for reduction, are gradually augmented with the increased amount of grafted functional groups in the samples. These results further demonstrate that the surface area of carbon cloths was almost unchanged, while the surface of carbon fiber was grafted with considerable OCFGs. The ASA measurement is in agreement with the FESEM observation and XPS analysis. Hence, the carbon cloths with a controllable amount of OCFGs on the surface and an insignificant modification of surface area were well prepared.

2.3. Electrochemical Activity Analysis

The electrochemical activity analysis was implemented by cyclic voltammetry (CV) measurement. Figure 5a depicts the CV curves for different electrodes obtained with a scan rate of 5 mV s\(^{-1}\) in 0.1 M V (IV) +3 M H\(_2\)SO\(_4\). It is clearly exhibited that the CV curves obtained on the treated CC samples are almost overlapped with the one obtained on the pristine one, implying that the grafted OCFGs have an insignificant influence on the V(IV)/V(V) redox reaction. The peak potential separation (\(\Delta E_P\)) as an indicator of electrochemical activity in the three-electrode cell is then calculated, as presented in Figure 5b. When the CCs are hydrothermally treated by alkaline solution, the \(\Delta E_P\) ranges from 118 to 98 mV, which is close to the value for the pristine one (\(\Delta E_P = 115\) mV). With a high content of OCFGs in the CC-12M, the onset potential for the V(IV)/V(V) redox reaction is even slightly positively shifted, which is indicative of the inverse effect of OCFGs on the V(IV)/V(V) redox reaction. These results are in line with the reports published in the previous literature\(^{[16,27]}\). However, it should be noted that a detrimental effect of OCFGs on the V(IV)/V(V) redox reaction was not observed in our experiment. This is due to the oxygen content levels obtained here are lower than the values reported previously\(^{[16,27]}\).

CV curves at different temperatures are compared in Figure 5c, in which the onset potential of the V(IV) oxidation is slightly positive-shifted with elevated temperatures due to the enhanced redox kinetics. The improved in activity is ascribed to not only the increased diffusion coefficient of vanadium ions in the electrolyte, but also the accelerated reaction rate of electrodes. Since the electrolyte is fixed (0.1 M V (IV) +3 M H\(_2\)SO\(_4\)), the contribution of the OCFGs on these electrodes toward the reaction kinetics can be quantified. The potential-dependent activation energy, related to the reaction barrier, can be calculated for these electrodes based on Arrhenius equation.

\[
\Delta E_p = \frac{\Delta E_p}{T} = \frac{1}{T} \ln \frac{[\text{H}_2\text{SO}_4]}{[\text{H}_2\text{SO}_4]_0} + \frac{A}{R T} \ln \eta
\]

where \(\Delta E_p\) is the peak potential separation, \(T\) is the temperature in Kelvin, \(A\) is the Arrhenius pre-exponential factor, \(R\) is the gas constant, and \(\eta\) is the overpotential.

Figure 5. a) Cyclic voltammograms of carbon cloths in 0.1 M V (IV) +3 M H\(_2\)SO\(_4\) (nitrogen-saturated) at 25 °C. The scan rate was 5 mV s\(^{-1}\). b) The relationship of peak potential separation (\(\Delta E_p\)) with the oxygen content. c) Cyclic voltammograms of CC-10M in 0.1 M V (IV) +3 M H\(_2\)SO\(_4\) (nitrogen-saturated) at different temperatures. The scan rate was 5 mV s\(^{-1}\). d) The activation energy of different carbon cloths at \(\eta = 100\) mV.
\[ \int = i_0 \exp \left( -\frac{E_a}{RT} \right) \]  

where \( \int \) is the measured current, \( E_a \) is the apparent activation energy, \( R \) is the gas constant, and \( T \) is the temperature in kelvin. The \( E_a \) at an overpotential (\( \eta \)) of 100 mV was calculated. It is shown that the values of \( E_a \) on the alkaline-treated samples is almost the same with the pristine CC (Figure 5d), which verifies that the kinetics of V(IV) to V(V) on the surface of alkaline-treated samples are not modified significantly. The analysis further confirms the OCFGs exhibit a minute catalytic effect on the V(IV)/V(V) redox reaction.

Meanwhile, the electrochemical activity toward the V(II)/V(III) redox reaction was measured in 0.1 M V (III) +3 M H\(_2\)SO\(_4\). Contrary to the limited effect of OCFGs on the V(IV)/V(V) redox reaction, the cathodic peaks (V(III) reduction) obtained on the treated CC samples significantly shift positively while the anodic peaks (V(II) oxidation) on the treated CC samples shift negatively when compared to the pristine sample, as exhibited in Figure 6a. The peak potentials of V(III) reduction are summarized in Figure S3 (Supporting Information). Obviously, a positive shift of the peak potential has been observed with an increase in the OCFG content up to 9.1 wt%, and beyond this composition, the decrease in the peak potential has been found. Meanwhile, the \( \Delta E_p \) for V(II)/V(III) redox reaction was measured, as presented in Figure 6b. The \( \Delta E_p \) for CC-0 is 433 mV while \( \Delta E_p \) significantly reduces from 262 mV for CC-6M to 156 mV for CC-10M. Although the \( \Delta E_p \) increases to 266 mV for CC-12M, while this value is still largely lower than that of CC-0. Except for the CC-12M, the \( \Delta E_p \) is almost linearly reduced with an increase in oxygen content. This result demonstrates that the OCFGs have an excellent electrocatalytic activity toward the V(II)/V(III) redox reaction on the surface of carbon fibers.

Similarly, CV curves of the V(II)/V(III) redox reaction at different temperatures are also compared in Figure 6c, from which it is observed that the kinetics are largely enhanced at elevated temperatures in spite of the accompanied hydrogen evolution reaction. Hence, the scan potential was limited –0.60 V versus Ag/AgCl at elevated temperatures. The activation energy at \( \eta = 100 \) mV is subsequently calculated (Figure 6d). Contrary to the V(IV)/V(V) redox reaction, the \( E_a \) values on the alkaline-treated samples are substantially reduced compared to the pristine sample. For instance, the \( E_a \) on CC-10M is 28.56 kJ mol\(^{-1}\), which is only about 57% of the \( E_a \) on the pristine one (49.54 kJ mol\(^{-1}\)). The significantly reduced \( E_a \) implies that the V(II)/V(III) redox reaction on these alkaline-treated samples is accelerated by the grafted functional groups. However, it should be worth noted that the \( E_a \) values of the V(II)/V(III) redox reaction are much larger than those of the V(IV)/V(V) redox reaction, particularly on the sample with lower content of OCFGs. The result further clarifies the importance of OCFGs toward the V(II)/V(III) redox reaction.

Hence, all the results demonstrated here show that the OCFGs have a significant effect on the negative redox reaction, while showing a minute catalytic effect on the positive redox reaction. However, the treatment intensity should be carefully controlled.
controlled since the grafting of abundant OCFGs will reduce the graphitization degree of carbon, thereby deteriorating the electrical conductivity of carbon. This can be proved by the performance of CC-10M that possesses considerable OCFGs. These results are in accordance with the results reported in the previous literature\cite{14–16}. It is worth mentioning that we choose carbon cloth as the model electrode, instead of the glassy carbon electrode, which makes the results practical for real application. Meanwhile, the carbon cloths possess a controllable amount of OCFGs on the surface and an insignificant modification of surface area, which can effectively separate the influence of OCFGs on the vanadium redox reaction from the effect of surface area.

2.4. Flow Battery Performance

The performance was evaluated in VRFBs respectively assembled with different as-prepared electrodes at room temperature under otherwise identical membrane preparations and operating conditions. First, we measured the polarization curves and the associated power-density curves, which have been employed to fast evaluate the performance of flow batteries recently\cite{6a,28}. A charging current of 100 mA cm\(^{-2}\) was applied to charge the VRFBs and polarization curves were measured at 50% state of charge with a potential range from 1.7 to 0.5 V. As presented in Figure 7a, the polarization overpotential of VRFBs with CC-0 is obviously larger than those of VRFBs with alkaline treated samples, particularly at the low current density range, i.e., the activation region. The behavior evidently demonstrates that there is a largely kinetic polarization on the pristine sample. However, the cell voltages almost linearly increase with the current densities on the alkaline treated samples, which is indicative of ohmic polarization process in the entire current range. The reduced activation loss is beneficial for the performance gain, which promotes the power density of VRFBs with CC-10M to 889 mW cm\(^{-2}\), compared to 674 mW cm\(^{-2}\) in the VRFBs with the pristine one. The behavior evidently demonstrates that the OCFGs can significantly catalyze the vanadium redox reactions.

We also measured the charge–discharge voltage profiles under a constant-current mode with a current density range from 100 to 400 mA cm\(^{-2}\). As presented in Figure 7b, all the charge potentials for alkaline treated samples are lower than that of CC-0 while the discharge potentials for alkaline treated samples are higher than that of CC-0, implying the redox reaction on the alkaline treated samples endures much lower polarization during the battery operation. Hence, an augmented discharge/charge capacity can be achieved in the same testing condition, as demonstrated in Figure 7c. At a current density of 100 mA cm\(^{-2}\), the discharge capacity of VRFBs with CC-10M is boosted to 12.5 Ah L\(^{-1}\), which is 22% higher than that of VRFBs with CC-0 (10.3 Ah L\(^{-1}\)). Meanwhile, the energy efficiencies (EEs) for VRFBs under different current densities were then calculated to evaluate the energy conversion efficiency. It is seen from Figure 7d that all the

---

**Figure 7.** a) Polarization curves and power-density curves of VRFB with different electrodes. The state of charge is 50%. b) Charge–discharge curves of VRFBs with various electrodes at a current density of 100 mA cm\(^{-2}\). c) The specific discharge capacity of VRFBs as a function of cycle number at different current densities. d) Energy efficiencies of VRFBs with various electrodes at different current densities.
VRFBs with the alkaline treated samples exhibit higher EEs than that of the pristine sample under the measured current range. More importantly, the EE for VRFBs with CC-10M reaches 85.0%, which is 10% higher than that of VRFB with CC-0 at the current density of 100 mA cm\(^{-2}\). Although the EEs for CC-12M reduce to some extent, the EEs are still significantly higher than that of CC-0 at 100 mA cm\(^{-2}\) (83.2% vs 75.5%). Combined with the CV analysis, it is concluded that the performance enhancement is absolutely ascribed to the grafted OCFGs, on which the vanadium redox reactions, particularly, the V(II)/V(III) redox reaction, are well electrochemically catalyzed.

Since CC-10M exhibits the superior cell performance, it was chosen to perform a cycling test to identify the chemical stability of the electrodes. The VRFB with CC-10M as the electrode was cycled at a current density of 100 mA cm\(^{-2}\) for 400 cycles. For a comprehensive comparison, a VRFB with the pristine carbon cloth as the electrode was also cycled in the same conditions. As presented in Figure 8, the CEs for CC-10M and CC-0 are almost identical during the entire test, while the EEs and voltage efficiencies (VEs) for CC-10M are considerably higher than that of CC-0. More importantly, after 400 cycles, the EE for CC-10M remains at 82.7% with a decay rate of 0.0031% per cycle. We also observe the EE for CC-0 is slightly reduced with a decay rate of 0.0030% per cycle. The similar decay rate indicates that the grafted functional groups, instead of the specific surface area, are contributed to the electroactivity promotion for carbon electrodes. The findings can be applied to guide the development of carbon electrodes to achieve superior cell performance in the future.

3. Conclusion

In summary, we intentionally grafted the OCFGs on the model carbon electrode, i.e., carbon cloth, without modifying the surface area by an alkaline-mediated hydrothermal treatment. Therefore, we analyzed the effect of OCFGs on the electrocatalytic activity toward vanadium redox reactions. Our results demonstrated that the OCFGs had a significant catalytic effect on the V(II)/V(III) redox reaction, while showing an insignificant effect on the V(IV)/V(V) redox reaction. The electroactivity promotion for the V(II)/V(III) redox reaction was derived from the reduction of the peak potential separation, thereby reducing the energy barrier for redox reactions. Therefore, when the OCFGs was optimized to 9.1 wt%, the carbon cloth sample (CC-10M) exhibited a minimum peak potential separation and a lowest charge transfer resistance for the V(II)/V(III) redox reaction. Meanwhile, the VRFBs with CC-10M gained an energy efficiency of 85.0%, which was 10% higher than VRFBs with CC-0 at a current density of 100 mA cm\(^{-2}\). The CC-10M was also demonstrated with a superior chemical stability in a cycling test. Therefore, we verified that the grafted functional groups, instead of the specific surface area, were contributed to the electroactivity promotion for carbon electrodes.

Figure 8. Cycling performance of VRFBs assembled with CC-0 and CC-10M at a current density of 100 mA cm\(^{-2}\), respectively.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. 16213414).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

flow batteries, functional groups, oxygenated carbonaceous materials, specific surface area, vanadium redox reactions

Received: October 4, 2017  
Revised: October 25, 2017  
Published online: [1] a) B. Dunn, H. Kamath, J.-M. Tarascon, Science 2011, 334, 928;  