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WHITE PAPERS

Measurement of Overpotentials and Liquid Potentials in Flow Batteries

Flow Rates and Pressure Drop in Tubes and Redox Flow Units

Heat Transfer Performance of Redox Flow Temperature Control Units with Single-Pass and Continuous Flow Heat Exchange

Carried out by the Redox-Flow team

Published in 2025

Simplicity, flexibility, quality.

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Measurement Of Overpotentials And Liquid Potentials In Flow Batteries

Introduction

Flow battery R&D is much driven by optimisation of electrodes and flow cell geometry. In a standard lab type flow battery setup, it is only the electrical current and cell potential that is measured. Although these two parameters alone determine the overall performance, it is from an R&D perspective desired to understand which parts and components that contributes to the overall energy losses. This white paper focuses on the experimental possibilities for mapping these losses out.

Note that this white paper only applies for reversible electrochemical systems, like flow batteries. For irreversible electrochemical systems like water electrolysis other methods are needed.

Definition of energy levels

Fig. 1 below is a general representation of the energy levels in a flow battery (or any other reversible electrochemical flow system). In the figure the blue scale represents absolute energy levels with respect to e.g. SHE. On the absolute scale the abbreviations are:

- ε_{CC-} and ε_{CC+} : The potential on the negative and positive side current collectors
- ε– and ε+ : The (redox) potential of the liquid on the negative and positive side – note that it is variable and depends on the state-of-charge and is described by the Nernst equation
- ε_{ref} : The potential of (a) reference electrode(s) in the setup

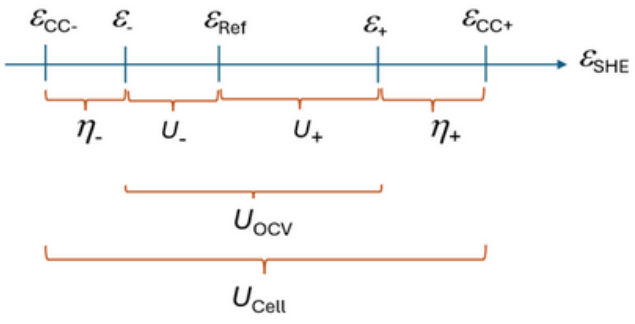


Figure 1. Energy levels in flow batteries.

While the upper (blue) potentials are absolute energy levels, the lower (orange) parts show the measurable voltages. Here

- η_- and η_+: The overpotentials for the charging (discharging) the negative and positive side liquids
- U_- and U_+: Measured potentials with respect to a reference electrode to determine the liquid (redox) potentials of the negative (ε_-) and positive side (ε_+)
- U_{OCV}: Potential measured in an OCV cell
- U_{cell}: The potential measured on the electrochemical cell by battery tester or potentiostat

The overpotentials and the electrolyte redox potentials are the most important parameters for mapping out internal resistive losses. There are multiple ways for a total mapping out of η_-,η_+ , ε_- and ε_+ and and only two are outlined below.

Setup with reference electrodes and OCV cell

Fig. 2 shows a generic representation of how the energy levels are completely mapped out by use of reference electrodes. The red lines depict the hydraulic circuit, while blue lines are potential measurements and the black part are units in the hydraulic circuit. This includes bottles, pumps, reference electrodes, flow through electrode holders, OCV cell and flow battery cell.

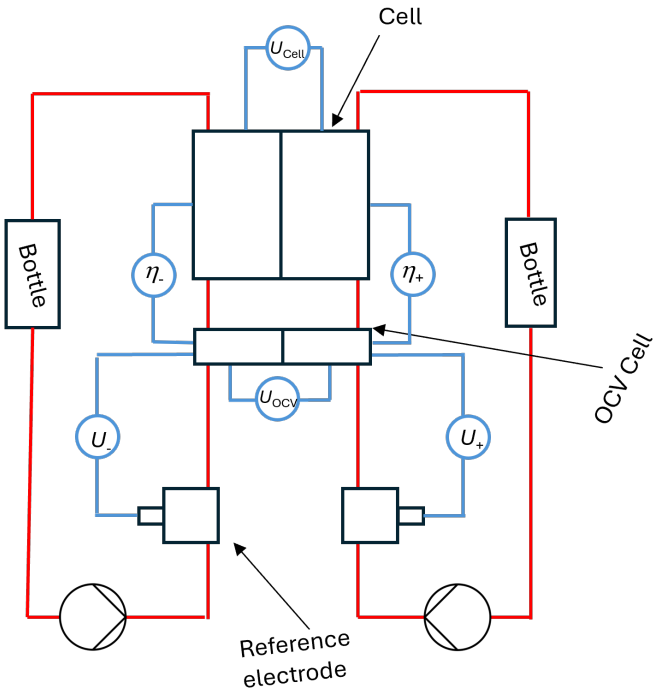


Figure 2. Schematic representation of a setup with reference electrodes.

The voltage difference between the negative side of the OCV cell and the current collectors on the flow cell measures the negative side overpotential (η_-) and vice versa for the positive side overpotential (η_+). I.e. the difference between the applied potential to the current collector and the potential of the solution. The voltages U_- and U_+ measured between the reference electrodes and the OCV cell can be related to the redox potentials of the solutions (ε_- and ε_+). Depending on the sign definitions and the electrical connections, $U_- = \pm\varepsilon_- \pm \varepsilon_{\mathrm{ref}}$ and $U_+ = \pm\varepsilon_+ \pm \varepsilon_{\mathrm{ref}}$, where is the standard potential of the reference electrode.

An experimental setup based on a 12A/5V tester, a S-cell with 25 cm² active area, with AV Carb (G475) thermally treated carbon felt electrodes and Fumatech FS930 electrode was assembled in a circuit similar to the one in fig. 2. Reference electrodes (double junction calomel) were inserted into Redox-Flow.com flow through electrode holders. The OCV cell was mounted with a FS930 membrane.

The reference electrodes were calibrated against a pristine V3/4+ solution and values around 0.19 V were consistently measured over time. In all tests standard 1.6 M vanadium solutions were used for tests and ambient temperatures were in the range 22-24°C.

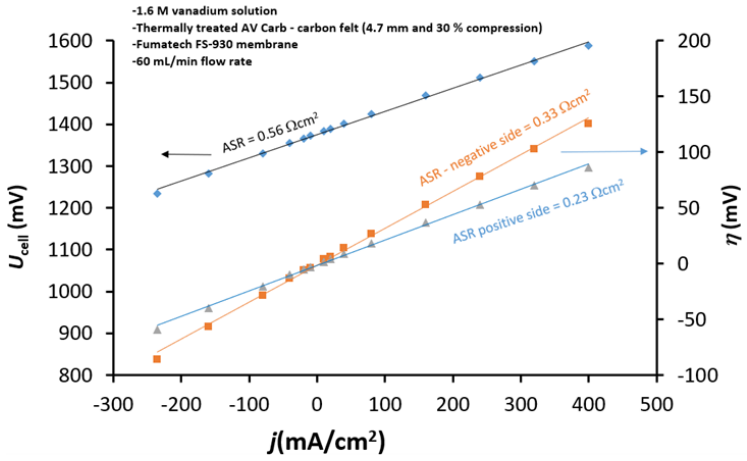


Figure 3. Polarisation curve and overpotentials for both negative and postive side. Note that the reference electrodes are not used in this experiment.

Fig. 3, shows the polarisation curve measured at 50% State-of-charge (SOC). Here a very low internal area specific resistance (ASR) of 0.56 Ωcm² was found. From the overpotential measurements the contributions were found to be higher for the negative side (0.33 Ωcm²) compared to the that of positive side (0.23 Ωcm²), and is in agreement with scientific literature. It can also be seen that the two half-cell ASRs add up to the total value. In the figure both overpotentials are defined as positive on charging and negative on discharging, other sign conventions can be used and defined from Fig. 1.

To further demonstrate the capabilities of the setup, Fig. 4 shows the first initial (pre) charging to full 100% SOC for a vanadium flow battery with 8 A (320 mA/cm²). The top graph shows the cell potential, OCV and redox potentials of the negative and positive side with respect to $V^{\frac{3}{4}+}$ ($\varepsilon_- = \pm U_- \pm \varepsilon_{\mathrm{ref}}$, where $\pm$ refers to sign definitions and electric wiring). The capacity of the battery is about 2787 mAh and it is seen that both ε and ε+ remain low but increasing with capacity until approximately 1400 mAh where both increases suddenly due to the initial pre-charging is finished and the electrolyte gets into the in 0 % SOC. After this and ε_- and ε_+ increases until maximum SOC is reached.

Also U_{OCV} is measured from the OCV cell and shown in the figure, alternatively it could also be constructed from the measured redox potential ($U_{\mathrm{OCV}} = \varepsilon_+ - \varepsilon_-$). A comparison show that they are within 5-10 mV of each other, this discrepancy is primarily attributed shunt currents (see below). In the range where the precharging is about to finish the difference is larger. This discrepancy is attributed to the short charging time (25 min), relatively low flow rate and different time constants for the units. i.e. due to the double junction (high resistance) of the calomel electrodes it is expected that they are reacting a little slower than the OCV (low resistance). The consequence is that the system is not in equilibrium. A slower charging and higher flow rate would give more consistent results.

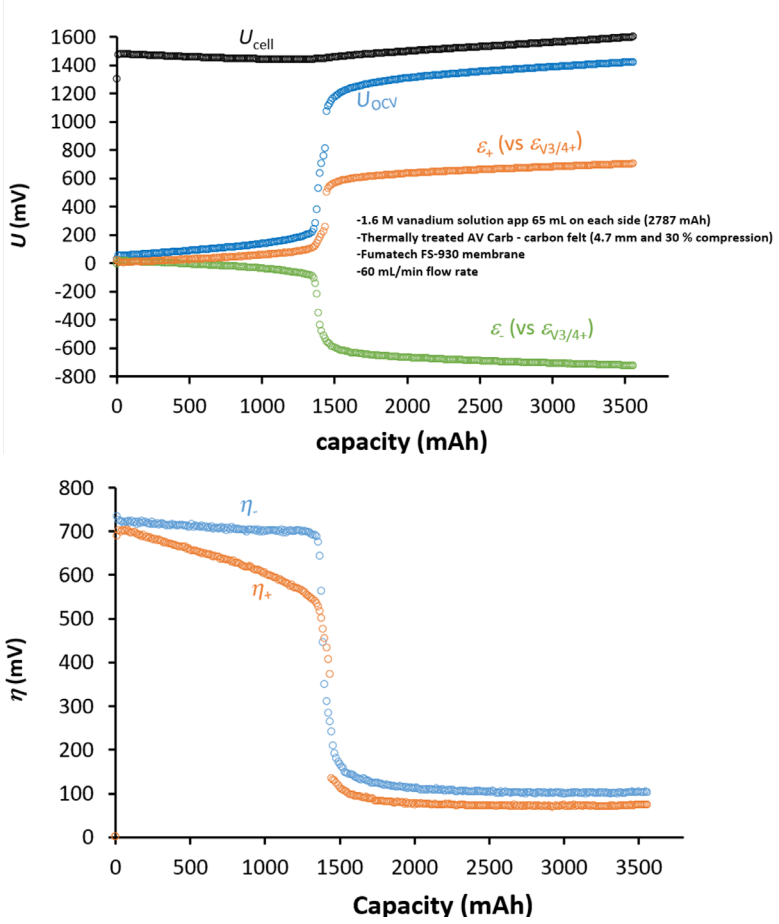


Figure 4. First initial (pre) charging of a vanadium flow battery with full mapping of all energy levels in one single experiment.

Lower graphs in fig. 4, shows the negative and positive side overpotentials. Here it is seen that there is a significant overpotential associated with the pre-charging of the electrolyte. However, once the electrolyte reaches 0 % SOC and onwards, the overpotentials drops to about 80-120 mV.

Setup with OCV cell with internal reference

Redox-Flow.com has developed a unique OCV cell that enables addition of a central chamber to the OCV cell. This central chamber can be used as an 'internal' reference electrode in the OCV cell and replace the reference electrodes used in the other setup.

Schematic figure below shows the setup. Again, red and blue lines refer to the electric and hydraulic circuit respectively, while the black parts are units in the circuit.

As in the previous setup, the overpotentials (η_- and η_+) are measured directly between the outer chambers of the OCV cell and electrochemical flow cell. While the redox potentials (ε_- and ε_+) are measured with respect to the redox solution in the central chamber through the voltages U_- and U_+.

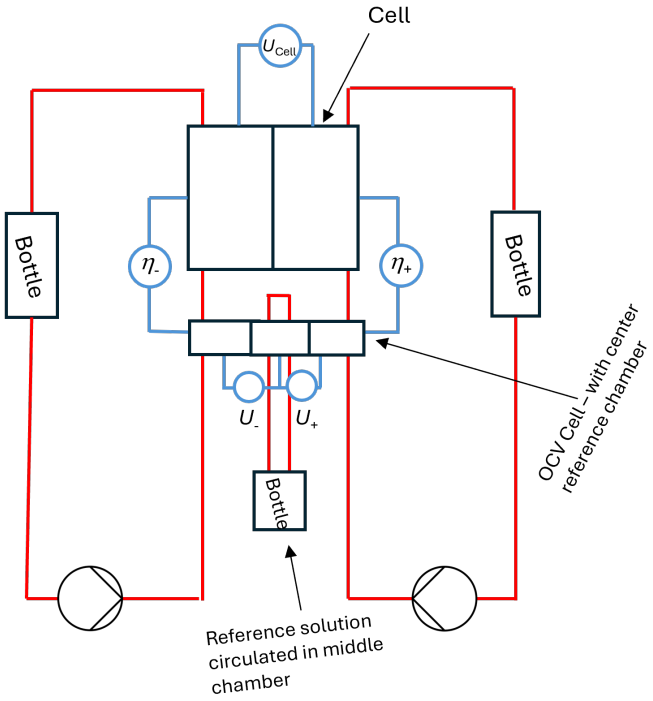


Figure 5. Schematic representation of a setup with an OCV cell with internal reference.

The central chamber reference solution is circulated from an external third bottle. If the reference solution is not circulated the reference solution may 'drift' as the membranes are not fully permselective, whereby the reference potential changes with time. There can be specific chemistries, membranes or short experimental times where circulation is not necessary, however, Redox-Flow.com recommends as default to use circulation if this option is used.

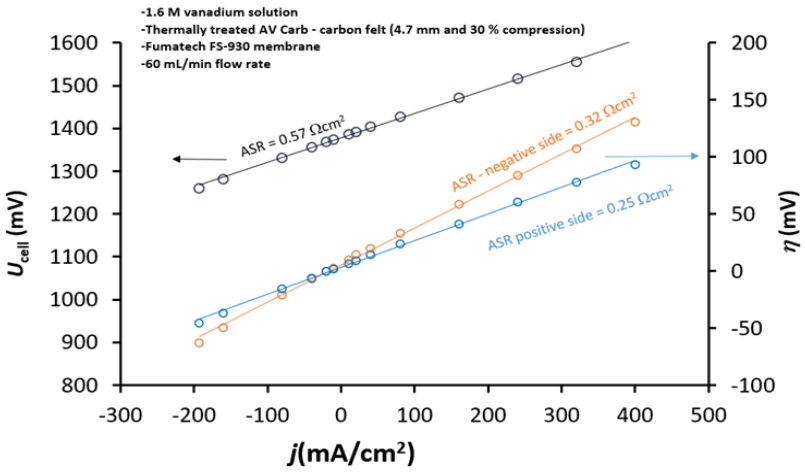


Figure 6. Polarisation curve and overpotentials for both negative and positive side. Note that the reference electrodes are not used in this experiment

Fig. 6 shows the polarisation curve at 50 % SOC and an ASR of 0.57 Ωcm² is found and within experimental uncertainty of the 0.56 Ωcm² found in the normal OCV setup. Also the ASRs for the negative (0.32 Ωcm²) and positive (0.25 Ωcm²) are very close to the ones found in the previous test. This not only underlines the robustness of the method, but also that both setups are suitable for measurement of overpotentials.

To demonstrate the capabilities of the setup, Fig. 7 (similar to Fig.4) shows the first initial (pre) charging to full 100% SOC for a vanadium flow battery with 3 A (120 mA/cm²). The central reference chamber of the OCV cell is circulated with pristine $V^{\frac{3}{4}+}$ vanadium solution at a rate of 60 ml/min (same solution as used in the flow battery cell). The top graph shows the cell potential, OCV and redox potentials of the negative and positive side. Since the reference solution is $V^{\frac{3}{4}+}$ no conversion/calibration of the voltage measurement is needed. Overall, the trend is the same as for the setup with reference electrodes and demonstrates the functionality of the OCV cell with reference chamber.

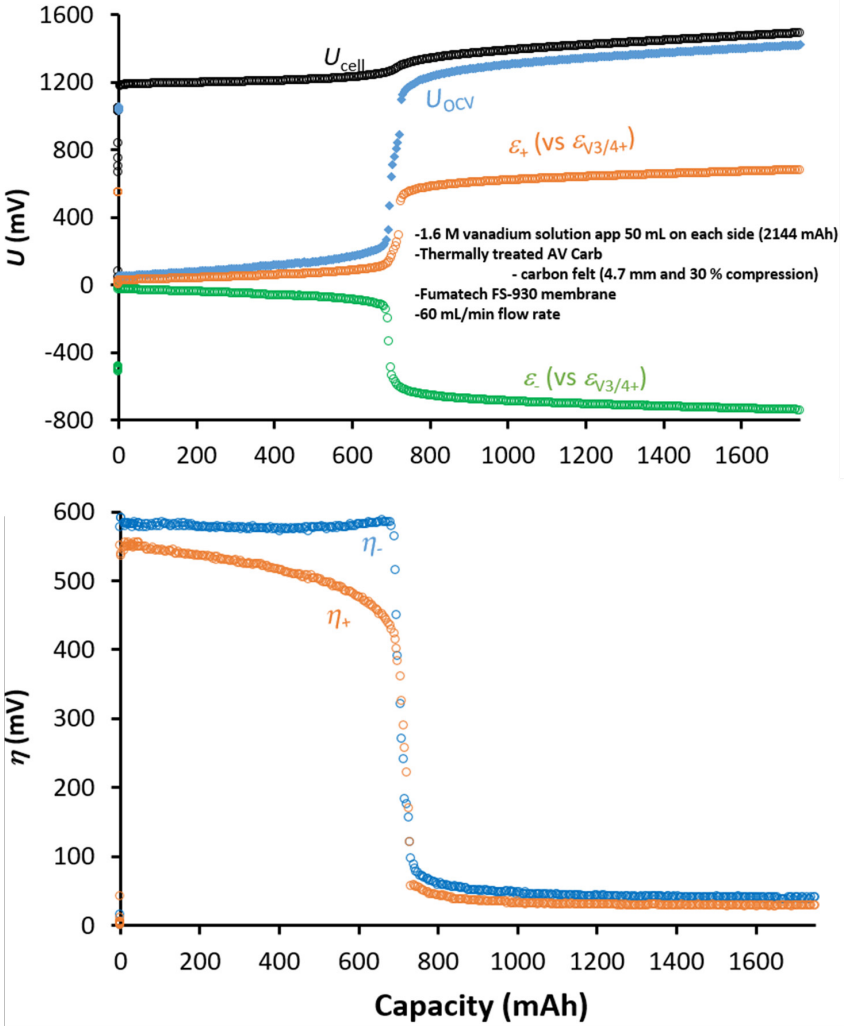


Figure 7. First initial (pre) charging of vanadium flow battery with full mapping of all energy levels in one single experiment.

Cycling data and hydraulic shunt

To further demonstrate some of the potential R&D applications, a battery cycling test was conducted on the setup with the OCV cell with internal reference. Here the cycling parameters were 3A constant current charging/discharging to 1.6 V and 0.8 V, followed by constant voltage charging/discharging down to 0.3 A.

Fig. 8 shows the charge/discharge capacity vs the cycle number. As can be seen the capacity retention drops quite fast as the battery is cycled. This mechanism behind the capacity is quite complex but mainly determined by cross-over of vanadium from one to the other side, whereby the other side becomes the capacity limiting factor. To balance out this cross-over and volume changes in the two bottles, the bottles are in many cases connected with a tube/hydraulic shunt. This is switched on after cycle 21. Here it is seen that the capacity is somewhat restored in the subsequent cycles (some of the electrolyte also becomes inactive in the syringe used in the shunt, explaining partly the missing capacity).

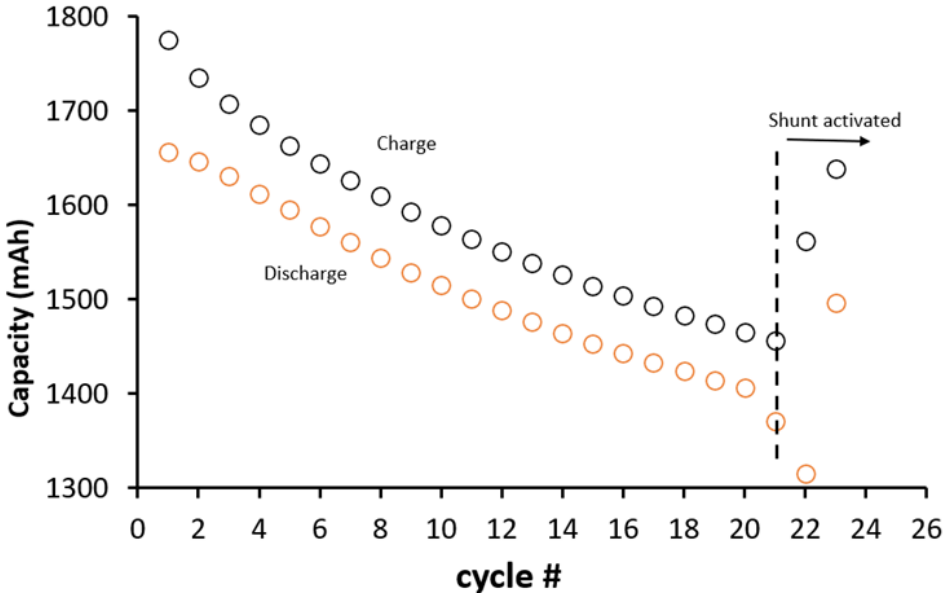


Figure 8. Charge/discharge capacity vs cycle number. First cycle that includes pre charging is not included. After cycle 21 shunt between the two bottles is activated.

The understanding of the capacity fade can be improved by measuring the liquid redox potentials of the solutions with OCV cell with internal reference as shown in fig. 9. From the liquid potentials on the negative side it is seen that they have a sharper decrease on discharge as it approaches 0% SOC (and sharper increase on charging) compared to that on the positive side. This is a clear indication that the negative side, is the capacity limiting side and that vanadium ions are transferred to the positive side during repeated cycling. Once the hydraulic shunt is opened, these cross-over effects are mitigated and capacity is (somewhat) restored.

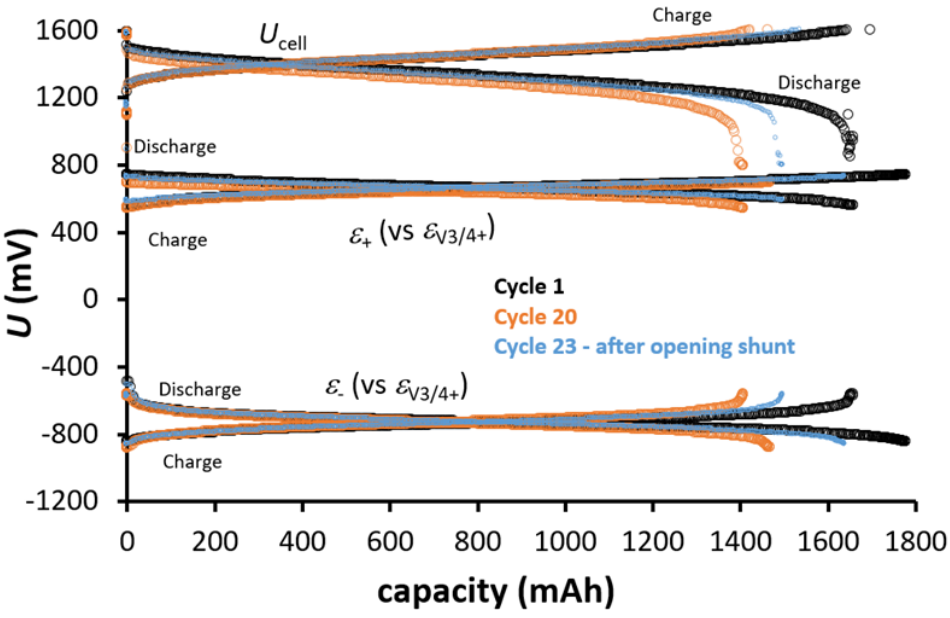


Figure 9. U_{cell}, ε_- and ε_+ for cycle 1, 20 and 23 on charge and discharge.

Shunt Currents

It has been reported that shunt currents through the OCV cell can affect the overpotential measurements. To investigate the magnitude of this effect, an experiment where both the 'OCV cell with internal reference' and reference electrodes were inserted into the same experimental setup. It was charged to a specific value and left resting until all potential measurements were stable. Then 8 A (pulse) charging was applied, and all potentials were monitored as function of time. Results are shown in fig. 10. The top graph shows the over-potential measurements and as expected a sharp increase is seen when the current is applied, and the voltage change is considered as being the overpotential.

It is expected that $\varepsilon_- + \varepsilon_+$ should remain constant (no change of SOC within seconds of the charging). If this is not the case, it can be seen from $U_{cell} = \varepsilon_- + \varepsilon_+ + \eta_- + \eta_+$ (fig. 1) that this would lead to an error in the overpotential ($\eta_- + \eta_+$) measurement. As can be seen from the middle graph in fig. 10, the potential change of ε_- and ε_+ is about 1-1.5 mV and the error on the overpotential 80-120 mV (top graph) is only of the order 1 % and not as high as reported elsewhere in literature. It is anticipated that the low impact is due to the low internal resistance of the Redox-Flow.com OCV cell. The tube length (1/16'' ID) from cell to OCV cell is total about 20 cm and results in approximate 0.06 mA shunt current through the OCV cell. It is anticipated that the OCV cell with internal reference chamber has a very low internal resistance of about 10 Ω, which would result in a potential loss of about 0.5 mV and in relative agreement with the value of about 1 mV.

As a last point, the lower graph shows the response of the calomel electrodes. Here a larger potential change of about 5 mV is seen. This potential change does not as such affect the overpotential measurement but will lead to error in the liquid potentials. This error should not be compared directly to the overpotentials measurement, but to the relative change over a full SOC, which is of the order 200 mV. In this case it is still relatively small, but there can be specific experiments where this error is unacceptable and here it is recommended to use a blocking sheet (PTFE) inside the OCV cell that is supplied with the OCV cell. The blocking sheet isolates the two sides of the OCV cell and prevents shunt current, hereby it no longer works as an OCV cell, but can only be used for overpotential measurements.

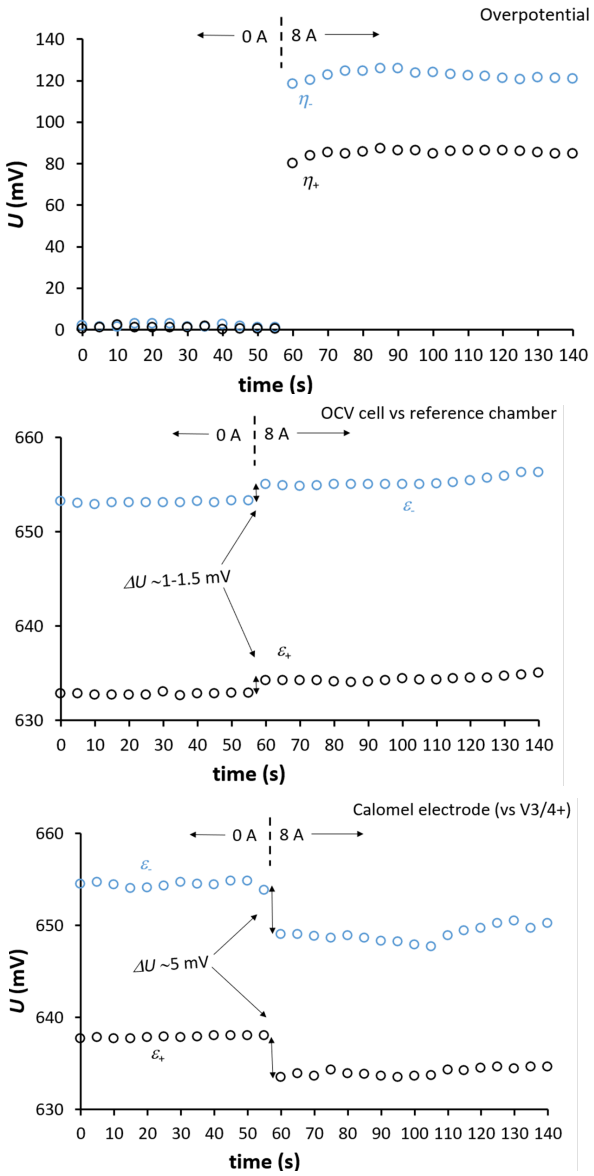


Figure 10. Direct current pulse experiment to monitor effect on voltages.

Internal resistance of electrochemical devices and measurement of voltage signals

The voltage from the OCV cell and reference electrodes in the experiments above have been measured with the AUX unit that can be supplied together with the battery testers sold by Redox-Flow.com. When measuring on electrochemical devices/sensors it is important to understand the magnitude of the internal resistance of the device. I.e. the internal resistance of the OCV cell is in the range 5-50Ω depending on configuration, membrane and chemistry. The double junction calomel electrode has an internal resistance of about 3-8 kΩ. Internal resistances below 10-30 kΩ are 'considered' as low and can be measured by standard voltmeters (that typically have internal resistances > 100 kΩ).

Nonetheless, it is paramount that the voltage measurement device is bipolar. I.e. the voltage measurement device cannot share a common 0/zero for measuring multiple potentials.

Besides this, in some cases it can be considered to include galvanic isolation between the electrochemical device and voltage measurement unit. If there is a voltage bias between the experimental setup and the measurement unit, this can lead to galvanic/electrical currents between the electrochemical sensor and measurement unit, this will quickly deteriorate the electrochemical sensors and give false readings. Alternatively, this can also be mitigated by grounding all devices in the setup that is connected to grid power to the same ground, connecting all devices to the same ground connection can minimise/remove voltage biases. Also, for many other good reasons grid powered devices in the same experimental setup should always be connected to the same ground.

Considerations and recommendations

Choosing the right experimental setup for mapping out energy levels and potentials can be done in many ways. However, in many applications it is not necessary to make a full mapping and is there redundancy is the measurements. Table below summarises some of the considerations for the experimental setup.

What kind of measurement is needed?	**OCV only? Overpotentials? Electrolyte redox potential – for one side only or both sides?**
Shunt currents through OCV cell	It is easy to measure through a direct current pulse measurement. How accurate does the measurement need to be? Consider tube lengths and placement of units. If there is a hydraulic shunt between electrolyte bottles (only for vanadium flow battery systems), what impact can that have on shunt currents.
Time delays in the electrochemical and hydraulic system	As the units (reference electrode, OCV, flow battery cell) comes in series there can be some delay in the response depending on dead volumes, flow rates and electrical current. I.e. higher flow rates and lower electrical currents will mitigate this.
Measure before / after electrochemical cell	Whether to measure before or after the flow battery cell, depends on the specific aim of the test. For standard tests like the ones in this note, we recommend measuring before.
Electrical measurements	Both the OCV cell and the double junction reference electrodes of redox-flow.com are ‘low impendance’ and the voltage can be measured directly on standard voltmeters and data loggers. However, the voltage must be measured in a bipolar manner (i.e. no common 0 between several independent voltage measurements).
Reference electrodes	In most redox-flow batteries the electrolyte concentrations are so high that a large osmotic pressure difference is built up between electrolyte in flow battery and reference electrode. This will result of pollution/deterioration of the reference electrodes. So always use double junction reference electrodes.

Finally, the table below shows some of the advantages/disadvantages between using a setup with an OCV cell with internal reference or reference electrodes. Redox-Flow.com does not promote one over the other, we have developed the OCV cell with internal reference because we are 'electrochemical nerds', so consider the internal reference as a research tool.

	Advantages	Disadvantages
Reference electrodes with standard OCV cell	• Well described in literature • Shunt currents can be blocked in OCV cell	• Calibration of reference electrodes • Drifting of reference electrodes over prolonged testing time
OCV cell with internal reference	• Only need one unit for a full mapping • Hydraulic circuit becomes very simple – few connections and fittings • The internal reference option/middle chamber is included as an option with the Redox-Flow.com OCV cell • Potentially no calibration of 'reference solution' – depending on chemistry	• The reference electrolyte must be circulated in the central chamber (can relatively easy be done with peristaltic pumps, if an additional pump head can be added to the pump) • There are limited number of reference electrolyte solutions avaible. For vanadium flow batteries V3/4+ solutions can be used. For neutral/alkaline Ferro/Ferri-cyanide solutions can be used, but may not be compatible with the flow battery chemistry) • Shunt currents – If the OCV cell with internal reference is used for mapeing out all potentials, there will be shunt currents through the OCV cell. This can destroy accuracy of the measurements.

References and suggested reading

In connection with this note, it is suggested to read the following papers to get an overall understanding of the methodology and theory.

1. Gonzalez, G., & Peljo, P. (2025). Experimental Set-Up for Measurement of Half-Cell- and Over-Potentials of Flow Batteries During Operation. Batteries & Supercaps, 8(2), e202400394.
2. Langner, J., Melke, J., Ehrenberg, H., & Roth, C. (2014). Determination of overpotentials in all vanadium redox flow batteries. ECS Transactions, 58(37), 1.

Flow Rates and Pressure Drop in Tubes and Redox Flow Units

Introduction

Understanding and managing pressure losses in tubing and electrochemical units is essential for ensuring optimal performance and reproducibility in electrochemical flow systems. We are often asked about best practices and design considerations regarding pressure drop. While the final configuration must be tailored to your specific application, this whitepaper provides guidance and insight to support more informed decision-making.

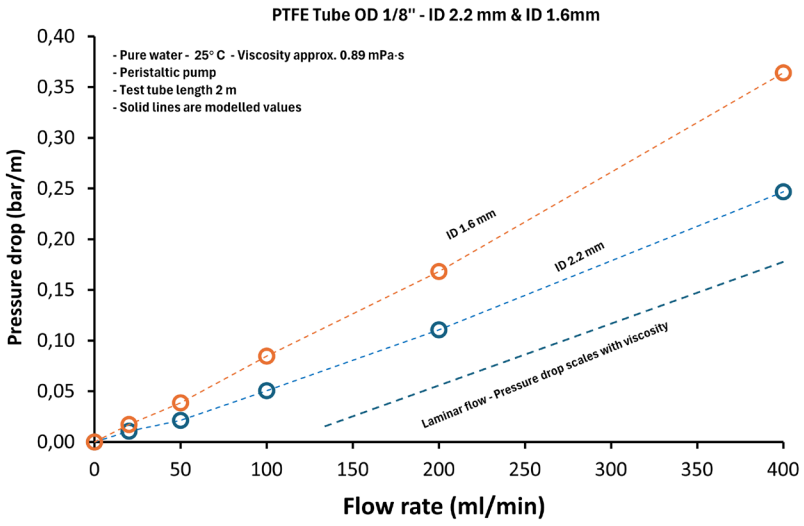
Tubes

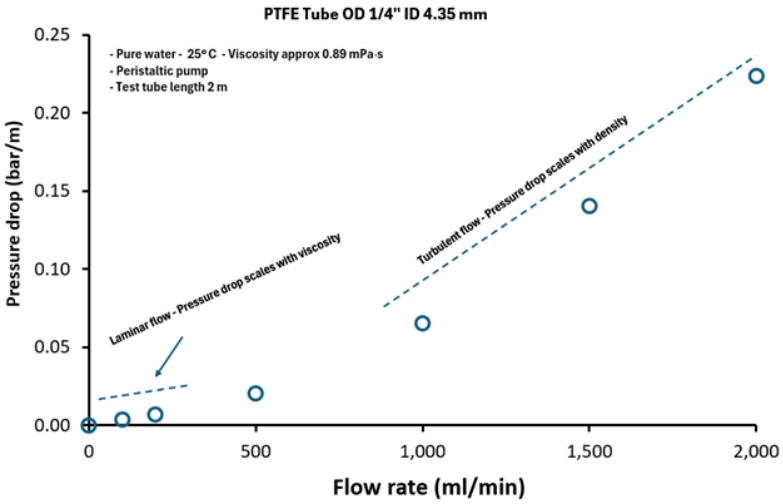
At Redox-Flow.com, we offer three standard tubing sizes, listed with their outer (OD) and inner diameters (ID):

- 1/8'' OD – 1/16'' (1.6 mm) ID
- 1/8'' OD – 2.2 mm ID
- 1/4'' OD – 4.35 mm ID

The pressure drop per meter of tubing is shown in the graphs below as a function of flow rate. These measurements were taken using pure water at room temperature. However, it is important to note that pressure loss is influenced by:

- Fluid viscosity (large dependence on temperature),
- Fluid density (small dependence on temperature, but large dependence on dissolved salt/chemicals)
- Flow regime (laminar vs. turbulent)





Flow Regimes and Pressure Drop

The pressure loss depends on the viscosity (temperature) and density of the fluid and whether it is in laminar or turbulent flow range. For laminar flow range, the pressure drop is proportional to the viscosity, turbulent flow range the pressure drop is proportional to the density of the fluid.

To estimate pressure drop for a given setup, determine whether the flow is laminar or turbulent using the Reynolds number (Re):

$$Re = \frac{\rho Q D}{\mu A}$$

Where ρ is the density of the liquid, Q is the flow rate and D is the diameter of the tube, μ is the dynamic viscosity of the liquid and A is the cross-sectional area of the tube.

Guideline values:

- Re < 2300 $\longrightarrow$ laminar flow
- Re > 2900 $\longrightarrow$ turbulent flow

Then scale with either density or viscosity of the liquid according to the graphs.

Depending on the tubing length and application, Redox-Flow.com recommends keeping pressure losses below 0.1–0.2 bar/m.

Electrochemical cells

Redox-Flow.com electrochemical cell types (A, S, and X) are designed to minimize pressure drop at the hydraulic inlet and outlet. However, the total pressure drop depends entirely/significantly on the electrodes used. Here Redox-Flow.com general recommendations are:

- For thin electrodes (<1 mm thickness): Use current collectors with interdigitated flow fields to improve distribution and reduce pressure drop.
- For thicker electrodes (>1 mm thickness): Current collectors with flat flow fields can be used, although performance heavily depends on the intrinsic hydraulic resistance of the electrode material.

Redox-Flow.com also provides tools and units that allow direct measurement of the hydraulic resistance of different electrodes to support empirical testing and optimization.

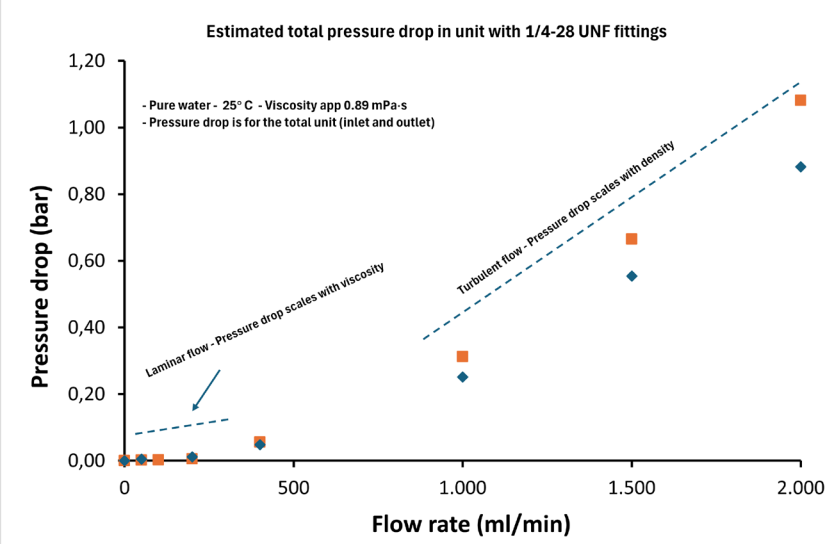
Inline/electrochemical units

This section applies to inline units using ¼-28 UNF fittings (commonly known as IDEX fittings for 1/8'' OD tubing).

We offer a variety of inline units for integration of:

- Reference electrodes
- Pressure sensors
- UV/VIS detectors
- And more

In these units, pressure drop is largely governed by the fitting and related orifice restrictions. The accompanying graph illustrates pressure losses for two representative units. As observed, pressure loss increases substantially beyond 400 mL/min. For applications requiring flow rates > 500 mL/min, we recommend reaching out to Redox-Flow.com to discuss customized solutions.



Heat Transfer Performance Of Redox Flow Temperature Control Units With Single-Pass And Continous Flow Heat Exchange

Introduction

Understanding and quantifying heat transfer in compact flow systems is essential for optimizing performance and reproducibility in thermal management and process design. This study focuses on evaluating the efficiency of two types of Redox Flow temperature control units under varying flow conditions: 1) a single-pass plate heat exchange operated using the single flow control unit, and 2) a continuous flow heat exchange operated using the double flow control unit. While the ideal configuration and performance depend on the specific application, the following work provides practical data, analysis, and guidance to support more informed design and operation of small-scale liquid heating systems.

The temperature control units

The Redox Flow heating & cooling units can be used for controlling the temperature of liquids and electrochemical cells - including flow batteries and electrolysers. To the best of our knowledge, similar products cannot be found by any other companies in the field.

Controlling temperature of cells and liquids for flow batteries, electrolysers and other electrochemical flow cells is challenging. One of the most widely used solutions is to place the cell and liquid bottles inside a heating chamber. While Redox-Flow has recommended this solution before (and still does, when it is viable), it comes with several limitations and shortcomings:

- Most commercial heating chambers do not come with feed-through holes for electrical wires to the cell and must be drilled manually
- For high temperature operation, the pump must be placed outside the heating chamber and can result in long hydraulic connections
- In heating/cooling chambers the space is limited and setting up experiments becomes tedious and time consuming
- Chambers with both heating and cooling are in general very costly
- Due to limited thermal conductance through bottles and cells, the time for reaching the set point temperature can be long (> 1-2 hours)

The solution developed by Redox-Flow.com comes in three different configurations that are based on the same components and can be interchanged depending on the purchased option (upgrading is always possible). All options include a PEEK flow body and metal block, shown in the pictures below. The PEEK body contains one (variant 1) or two separate (variant 2) flow chambers for heating/cooling one or two independent liquids, respectively. The liquids in the experimental setup are circulated through the PEEK flow body and placed against a metal heating/cooling plate, whereby heat is transferred to or from the liquids in the PEEK flow body. The metal plate is separated from the liquids in the experimental setup by a thin PTFE sheet, whereby corrosive/oxidative solutions can also be heated without corroding the metal plate. At the time of the studies, the material of the heating block was aluminium.

The aluminium block can be 1) heated by placing it on a heating plate, or 2) heated or cooled using heat cartridges for liquids and thermometers.

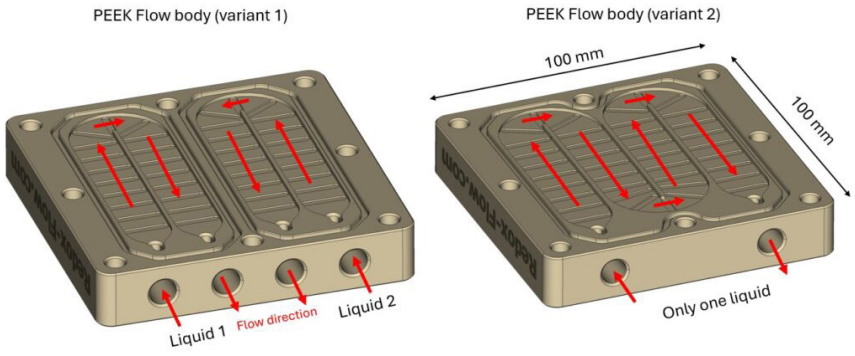


Figure 1

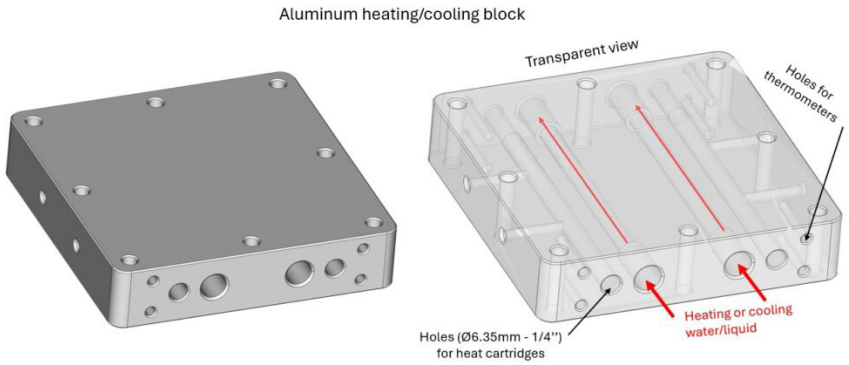


Figure 2

There are three options for the heating/cooling unit. For all products, the temperature can be controlled by circulating heating/cooling liquids through the metal block or by using a heat cartridge in the metal block. In two of the products, the temperature can also be controlled by placing the unit on a heating plate.

Study 1: Single-Pass Heat Exchange Using The Single-Flow Temperature Control Unit

Experimental setup

The experiment was performed using a peristaltic pump, a Redox Flow single-flow temperature control unit with an aluminum plate, a temperature-controlled heater, and two digital thermometers. Water was used as the working fluid and passed once through the control unit (non-recirculating flow).

The heater temperature was set to 80 °C, 100 °C, and 120 °C, while the flow rate was varied at 4, 8, 12, and 20 mL/min. The inlet fluid temperature (T_F) was maintained at approximately 20 °C throughout the experiments.

The following temperatures were recorded:

- T_F : temperature control unit liquid inlet temperature
- T_E : temperature control unit liquid outlet temperature
- T_A : temperature of the aluminum plate

These measurements were also used to calculate the overall heat-transfer coefficients (U) and to evaluate the efficiency of the single-flow temperature control unit under different operating conditions.

Results

Three graphs were prepared to illustrate the relationship between the outlet temperature (T_E) and the flow rate for each heater setting. Each graph corresponds to one of the tested heater temperatures of 80 °C, 100 °C, and 120 °C, and shows how the outlet temperature decreases as the flow rate increases. This trend reflects the reduced residence time of the water in contact with the heated surface at higher flow rates.

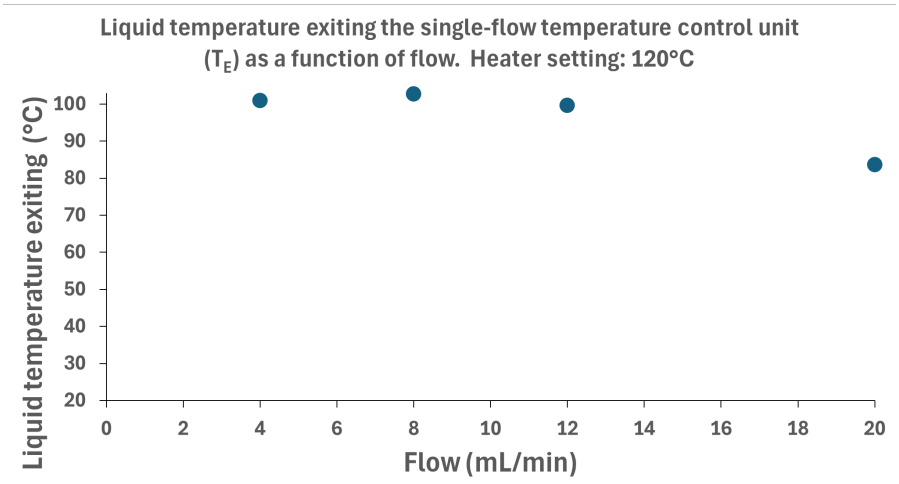


Figure 3

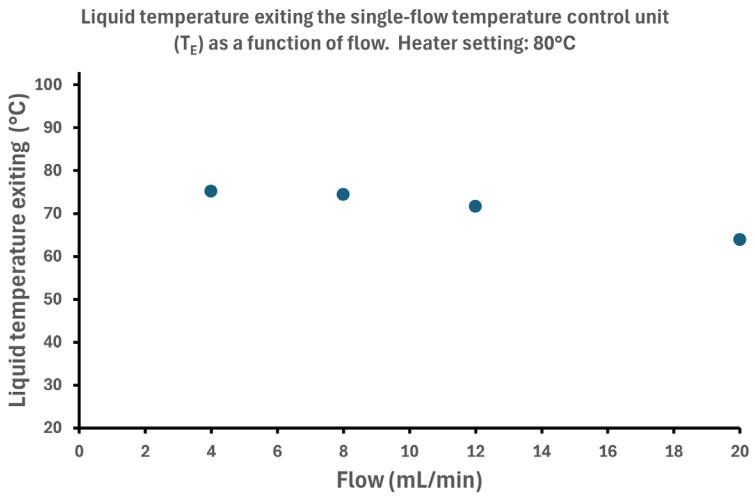


Figure 4

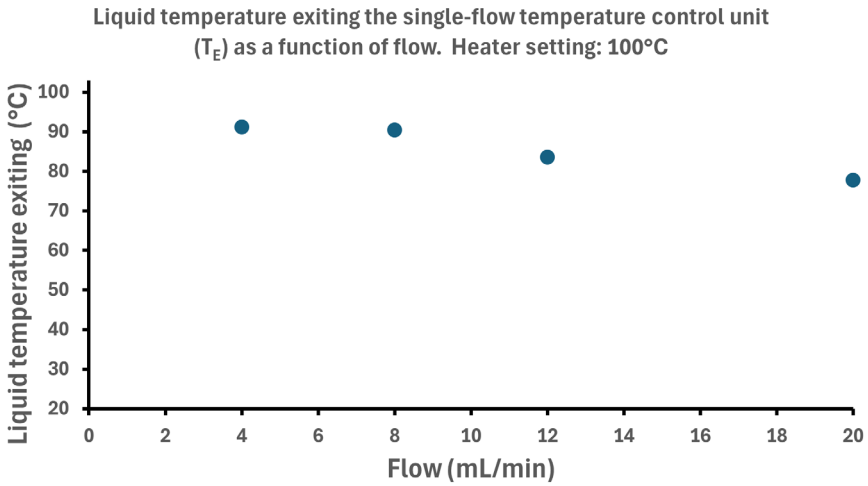


Figure 5

The graph below shows the heat transfer coefficient between the aluminum block and the liquid at three different heater settings. The coefficients can be used for estimating the heat transfer power between the unit and the liquid.

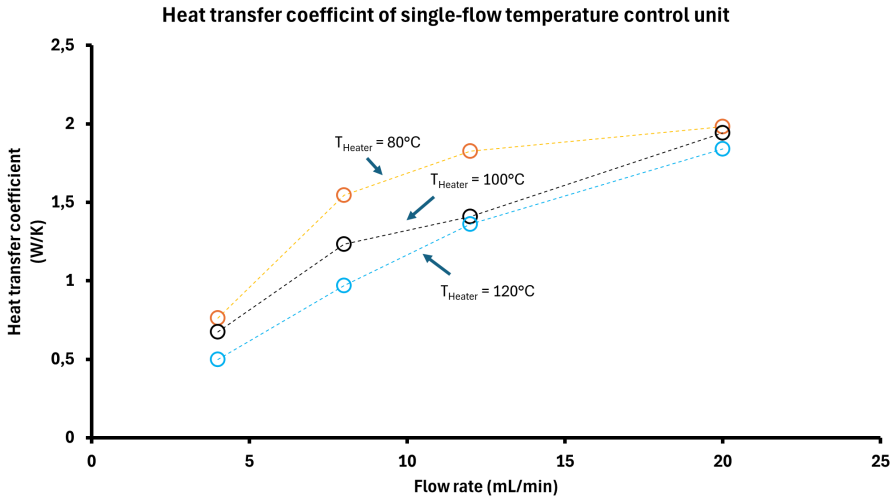


Figure 5

Calculating exiting liquid temperature from the results

The exiting liquid temperature (T_E) can be estimated using the empirical formulas below. These equations relate (T_E) to the flow rate at different heater setpoints (80 °C, 100 °C, and 120 °C). These models are valid for flow rates between 4 and 20 mL/min. Extrapolation beyond this range may result in unreliable predictions.

Formula 1

At the heater setting of 80°C:

$$T_E = -0.0348\big(\text{Flow rate}\big)^2 + 0.1201\big(\text{Flow rate}\big) + 75.383$$

Formula 2

At the heater setting of 100°C:

$$T_E = -0.0038\big(\text{Flow rate}\big)^2 - 0.8115\big(\text{Flow rate}\big) + 95.225$$

Formula 3

At the heater setting of 120°C:

$$T_E = -0.1166\big(\text{Flow rate}\big)^2 + 1.7069\big(\text{Flow rate}\big) + 96.166$$

Example Calculation

To determine the flow rate required to achieve an exiting liquid temperature of 80 °C at a heater setting of 100 °C, use Formula 2:

$$80 = -0.0038\big(\text{Flow rate}\big)^2 - 0.8115\big(\text{Flow rate}\big) + 95.225$$

Thus, at a heater setting of 100 °C, a flow rate of approximately 17,35 mL/min results in an exiting liquid temperature of 80 °C.

Study 2: Continuous Flow Heat Exchange Using The Double Flow Temperature Control Unit

Experimental setup

The experiment was performed using a peristaltic pump, a double-flow temperature control unit with an aluminum plate, a temperature-controlled heater, and two digital thermometers. Water was used as the working fluid and passed continuously through the temperature control unit (recirculating flow).

Figure 5

Results

Heat Transfer Coefficient

Graph below shows the heat transfer coefficient between the aluminum block and the liquid. It is measured by heating about 500 mL of water in a bottle (without an electro-chemical cell) by placing the heating unit on a heating plate where the aluminum block temperature is fixed and the temperature in the bottle is monitored.

The heat transfer coefficient is in the range 1 W/K to 5 W/K and dependent on the flow rate. We term the coefficient 'apparent' as it does not strictly follow the definition of the 'overall heat transfer coefficients'. Nonetheless, the coefficients can be used for estimating the heat transfer power between the unit and the liquid. I.e., if there is a 40 K temperature difference between the aluminum block and the liquid and the flow rate is 100 mL/min, it can be expected that 100 W of heat is transferred.

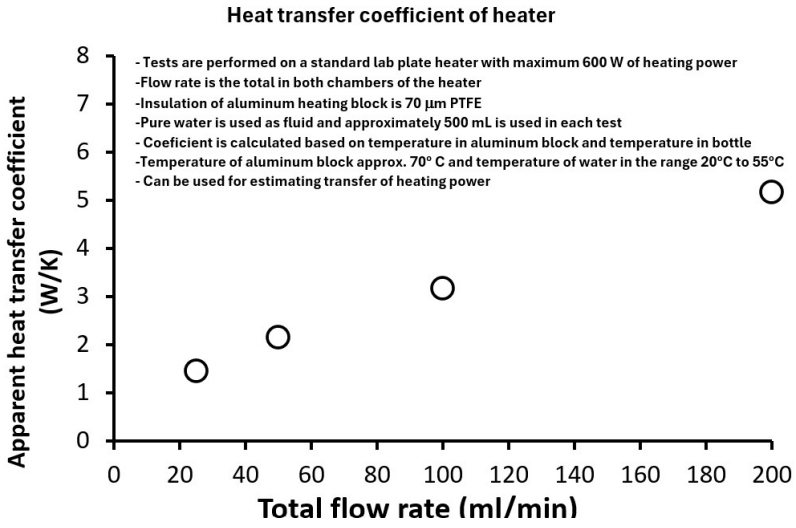


Figure 6

Bottle Heating

Graph below shows a configuration where the unit is placed on a heating plate and connected to a pump and a bottle with 500 mL of water (i.e., an electrochemical cell is not included in the circuit). The heating plate has a maximum of 600 W heating power and PID control, where the input for the control is an external thermometer, which in this case is placed in a bottle. In addition to this thermometer, one is also placed inside the aluminum block. In this test, the water temperature set-point in the bottle was set at 75°C. It is seen that the water reaches 75°C within 15 minutes and stability is reached within about 35 minutes. Better control strategies can shorten time before stability.

Figure 5

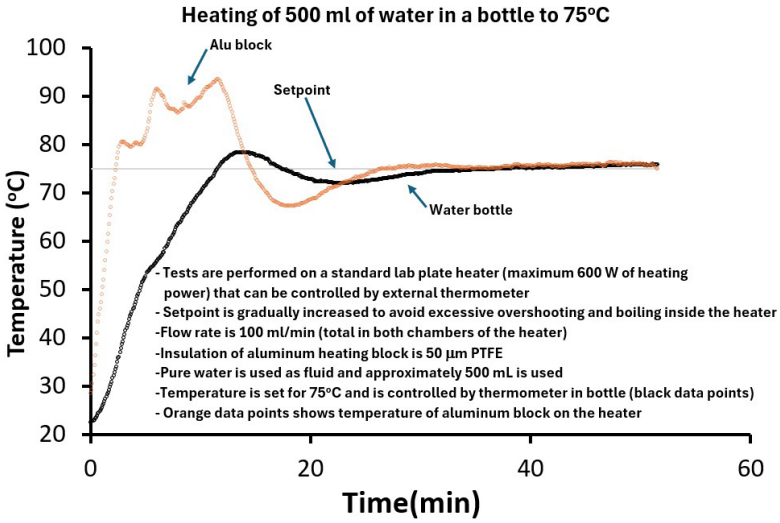


Figure 7

Cell & Bottle Heating

Graph below shows a configuration where the unit is placed on a heating plate and connected to a pump. The heating unit is placed after the pump and followed by an electrochemical cell and a bottle. The total water volume is 500 mL. The heating plate has a maximum of 600 W heating power and PID control, where the input for the control is an external thermometer. In this case, the control thermometer is placed inside the cell (close to the current collector). Temperature stability is reached within about 35-45 minutes. More aggressive temperature control strategies where temperature over shooting is allowed will decrease time to reach the temperature set-point.

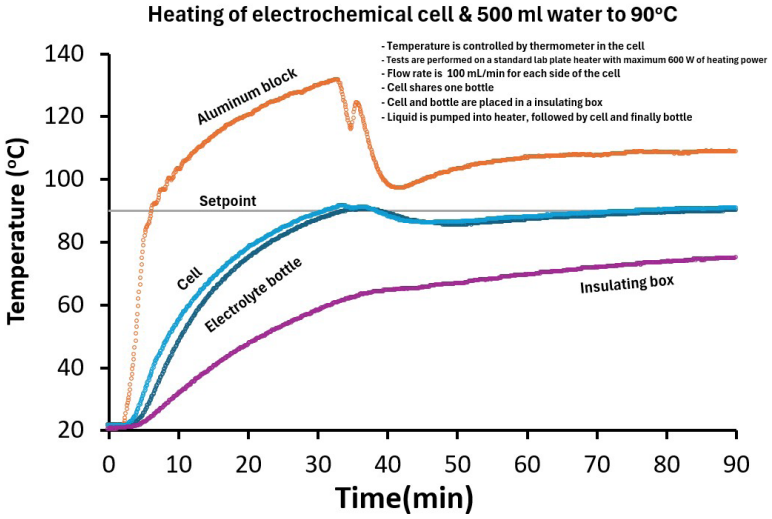


Figure 8

Feel free to contact us if you have any questions!

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