



Research Article

<https://doi.org/10.1631/jzus.A2400544>

Study of the effect of flow frames on the performance of a 10 kW/40 kWh vanadium redox flow battery using a multi-scale model

Junhong LIN¹, Zihao MA², Shaojun LIU^{1✉}, Hao SONG^{1✉}, Guoneng LI³, Weihong WU¹, Chenghang ZHENG¹, Xiang GAO^{1✉}

¹State Key Laboratory of Clean Energy Utilization, State Environmental Protection Center for Coal-Fired Air Pollution Control, Zhejiang University, Hangzhou 310027, China

²Shanghai Electric Group Co., Ltd., Shanghai 200336, China

³Department of Energy and Environment System Engineering, Zhejiang University of Science and Technology, Hangzhou 310023, China

Abstract: The cell structure in vanadium redox flow batteries (VRFBs) critically impacts battery efficiency. Therefore, in this study, we evaluate the effect of different flow frames on VRFB cell performance and system efficiency. This is accomplished through a multi-scale model combining a 3D model of the cell and an equivalent circuit model (ECM) of the stack. The results reveal that during the discharge process, increasing the flow rate can boost the discharge voltage, but also leads to higher pumping power consumption. Moreover, the pressure drop of the cell decreases as the number of flow frame channels increases. Due to improved reactant concentration distribution, the five-channel flow frame has a higher discharge voltage than other configurations at low reactant concentrations, even exceeding that of the 20-channel flow frame. The flow frame and flow rate were optimized for a 10 kW/40 kWh VRFB with a genetic algorithm approach. Using a five-channel flow frame, a peak discharge efficiency of 93.70% was obtained at a flow rate of 960 mL/min. The results of this study may aid future design of kilowatt-scale VRFBs.

Key words: Flow frames; Vanadium redox flow battery (VRFB); Multi-scale model; Genetic algorithm; Battery efficiency

1 Introduction

With the rapid growth of clean energy sources such as solar and wind power, energy storage technologies such as lithium-ion (Guo F et al., 2023; Park et al., 2023; Guo SS et al., 2025) and flow batteries (Zerrahn and Schill, 2017; Albertus et al., 2020; Lu et al., 2024) are receiving increasing attention. In addition to the benefits of long-duration energy storage and recyclability, flow batteries are intrinsically safer than lithium-ion batteries due to the non-flammable aqueous electrolyte used. The flow field design critically affects the performance of flow batteries. For vanadium flow batteries, elaborate electrolyte channels are typically carved in the electrodes (Bhattarai et al., 2019; Yang et al., 2022)

or bipolar plates (Zheng et al., 2016; Zeng et al., 2019); specially designed flow frames are also used to regulate the flow field. The configuration of such channels has been extensively investigated. For instance, Ali et al. (2022) compared the performance of serpentine and interdigitated channels, showing that 2 mm serpentine flow channels resulted in higher cell voltage and more uniform V^{2+} concentration in the negative electrode. However, serpentine flow channels also resulted in higher pump power consumption. Thus, Lu et al. (2021) optimized the discharge power and system efficiency of serpentine flow channels, demonstrating that power and system efficiency reached 16.73 W and 87.8%, respectively; these values were 2.85 W and 3.7% higher than the conventional approach, respectively. Sharma and Kumar (2021) also improved serpentine channels with two new designs: split serpentine and split-merged serpentine channels. Their experiments demonstrated better electrolyte distribution in the split serpentine channel. Additionally, Gundlapalli and Jayanti (2021) proposed a flip-flop directional split serpentine flow field, which demonstrated excellent

✉ Shaojun LIU, phoenix205@zju.edu.cn
Hao SONG, sh13082858628@vip.163.com
Xiang GAO, xgao1@zju.edu.cn

Shaojun LIU, <https://orcid.org/0000-0003-0976-5707>

Received Nov. 23, 2024; Revision accepted Apr. 7, 2025;
Crosschecked Dec. 5, 2025

© Zhejiang University Press 2026

distribution and quick evacuation of product species. Their novel channel configuration ensures scaling from 900 to 2200 cm² of active cell area.

Designing cells with a large active area is becoming more common in industrial practice, but has not been extensively studied (de León et al., 2006; Sun et al., 2019). A large active area can effectively reduce the number of cells in the stack, which is more conducive to the application of vanadium redox flow battery (VRFB) (Sun et al., 2019). Several cells can be connected to form a stack, enabling kilowatt-scale VRFB systems. In such systems, channels carved in the flow frames (instead of bipolar plates) are extensively employed to reduce material costs (Kim et al., 2013; Guarnieri et al., 2018; Delgado et al., 2022). However, this usually leads to kilowatt-scale VRFBs having lower energy efficiency compared to batteries employing laboratory-scale equipment (Kapoor and Verma, 2022).

Only a few studies have investigated the effect of flow frames and achieved kilowatt-scale VRFBs. For example, Kim et al. (2013) demonstrated a flow frame design in a 1 kW/1 kWh VRFB, with the average energy efficiency reaching 82% at a low current density of 80 mA/cm². Guarnieri et al. (2018) tested a 9 kW/26 kWh VRFB with 40 cells, in which the flow frames followed an equal path length design.

In a typical cell, good electrochemical performance is always accompanied by an increased pressure drop. However, the conventional equivalent circuit model (ECM) for VRFBs (Delgado et al., 2022; Zhao et al., 2023) is unable to calculate this pressure drop. It also cannot represent the dynamics of cell voltage during battery operation. For this reason, we propose a multi-scale model that combines a 3D model of the cell and an ECM of the stack. Using this model, the effect of different flow frames on the performance of a 10 kW/40 kWh VRFB is investigated. Varying structures are compared in terms of VRFB system efficiency and cell performance.

2 Numerical modeling

2.1 VRFB description

As shown in Fig. 1, the studied VRFB consists of an electrical stack, two electrolyte storage tanks, two pumps, and several connecting pipes. I_L is the total current of the stack. The stack is comprised of multiple

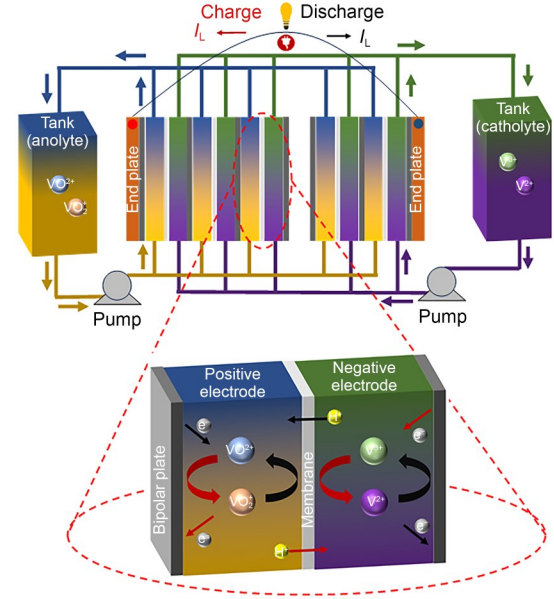


Fig. 1 Schematic diagram of the VRFB

cells connected in series. A cell consists of two porous electrodes and an ion exchange membrane between them. Two tanks are used to store the anolyte and catholyte, respectively. During operation, electrolyte is pumped into the porous electrode, and electrochemical reactions take place. The positive and negative electrode reactions are described by Eqs. (1) and (2), respectively.



The state of charge (S_c) is used to describe the relative amount of vanadium ions with different valences, in both the porous electrodes and the tanks. It is defined by Eq. (3):

$$S_c = \frac{c_{\text{V}^{2+}}}{c_{\text{total}}} = \frac{c_{\text{V}^{5+}}}{c_{\text{total}}}, \quad (3)$$

where $c_{\text{V}^{2+}}$ and $c_{\text{V}^{5+}}$ are the molar concentrations of V^{2+} and VO_2^+ , respectively; c_{total} is the total vanadium ion concentration in a given electrolyte.

2.2 Description of the VRFB cell

In this work, a 3D VRFB cell was constructed. The VRFB cell consists of porous electrodes, current collectors, a proton exchange membrane, bipolar plates, and flow frames, as shown in Fig. 2. Flow channels

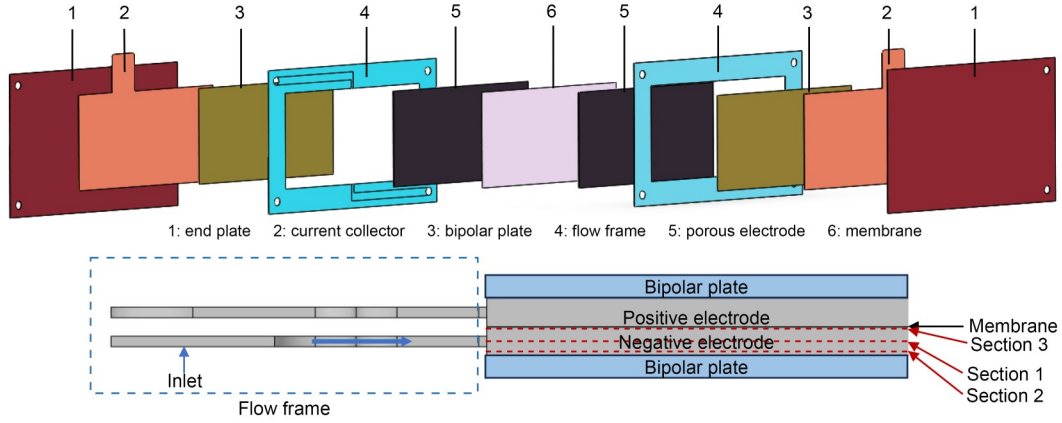


Fig. 2 Schematic diagram of the components used in a VRFB cell. Sections 1–3 refer to the three cross-sections selected from the negative porous electrode. Sections 2 and 3 are located at the bipolar plate and membrane, respectively; section 1 is located at the midplane between them

were carved into the flow frame to provide a steady electrolyte supply. Three flow frames with different numbers of channels were compared in terms of flow field and electrochemical performance. The 3D model enables detailed analysis of cell performance and can act as a reference for design optimization. In the assembly and sealing of the cells, the channel depth in the flow frames will be lower than the thickness of the electrodes. The width of the channels and the position of the inlet were kept consistent for the three flow frames. The geometric parameters of the VRFB cell are listed in Table 1.

Table 1 Geometric parameters of the VRFB cell

Parameter	Value
Cell height (mm)	300
Cell width (mm)	600
Channel depth (mm)	1.3
Electrode thickness (mm)	3.5
Membrane thickness (μm)	50

2.3 Governing equations

2.3.1 Fluid flow in the frames and electrodes

The flow of electrolyte is described by the Navier–Stokes equation (Eqs. (4) and (5)):

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u}, \quad (4)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (5)$$

where ρ is the electrolyte density; $\mathbf{u}$ is the velocity of the electrolyte; p is the pressure of the liquid; μ is the dynamic viscosity of the electrolyte.

The flow of electrolyte in a porous electrode is described by Darcy's law (Eq. (6)):

$$\mathbf{u} = -\frac{K}{\mu} \nabla p, \quad (6)$$

where K is the permeability of the porous electrode. This permeability can be described by the Kozeny–Carman equation (Eq. (7)):

$$K = \frac{d_f^2 \varepsilon^3}{K_{ck} (1 - \varepsilon)^2}, \quad (7)$$

where d_f is the carbon fiber diameter; K_{ck} is the Kozeny–Carman constant; ε is the electrode porosity.

2.3.2 Ions in the electrodes

The ions in the positive and negative electrodes are mainly comprised of vanadium ions (V^{2+} , V^{3+} , VO^{2+} , and VO_2^+) and ion products from sulfuric acid (H^+ , HSO_4^- , and SO_4^{2-}). Each ion obeys the following conservation equation:

$$\frac{\partial}{\partial t}(\varepsilon c_j) + \nabla \cdot (-D_j^{\text{eff}} \nabla c_j - z_j \kappa_j F c_j \nabla \varphi_j + \mathbf{u} c_j) = -S_j, \quad (8)$$

where t is the time; j is a particular ion; c_j is the molar concentration of the ion j ; D_j^{eff} is the effective diffusion coefficient of the ion j in the porous electrode; z_j and κ_j are the charge number and the ionic mobility of the ion j , respectively; F is the Faraday constant; φ_j is the ionic potential in the electrodes; S_j is the source term of the ion.

Electrolyte solutions are electrically neutral, so:

$$\sum_j z_j c_j = 0. \quad (9)$$

The diffusion of ions in VRFBs occurs in porous electrodes, which differs from behavior in free space. The ideal ion diffusion coefficients are corrected with the Bruggeman equation (Eq. (10)):

$$D_j^{\text{eff}} = \varepsilon^{1.5} D_j, \quad (10)$$

where D_j denotes the diffusion coefficient of the ion j in free space.

The source term describes how ion concentrations change in the electrolyte due to electrochemical reactions or the dissociation of sulfuric acid, as shown in Table 2 (i is the current density).

Table 2 Source terms of the conservation equation

Source term, S_j	Description	
	Positive electrode	Negative electrode
Source term of V^{2+} , $S_{V^{2+}}$	—	$\nabla \cdot \frac{i}{F}$
Source term of V^{3+} , $S_{V^{3+}}$	—	$-\nabla \cdot \frac{i}{F}$
Source term of VO^{2+} , $S_{VO^{2+}}$	$\nabla \cdot \frac{i}{F}$	—
Source term of VO^{3+} , $S_{VO^{3+}}$	$-\nabla \cdot \frac{i}{F}$	—
Source term of H^+ , S_{H^+}	$-S_{H^+}$	$-2\nabla \cdot \frac{i}{F} - S_{H^+}$
Source term of HSO_4^- , $S_{HSO_4^-}$	$S_{HSO_4^-}$	$S_{HSO_4^-}$

2.3.3 Transport in the membrane

In a proton exchange membrane, it is assumed that H^+ are the only mobile ions. The current conservation equation can be expressed by Eq. (11):

$$N_{H^+} = -\frac{\sigma_{\text{mem}}}{F} \nabla \phi_{\text{mem}}, \quad (11)$$

where N_{H^+} is the flux density vector of H^+ ; σ_{mem} is the membrane conductivity; ϕ_{mem} is the membrane potential.

2.3.4 Electrochemical kinetics

The Butler–Volmer model was used to describe the relationship between current density and overpotential during the electrochemical reactions (Eqs. (12) and (13)):

$$J_1 = A_s F k_1 (c_{V^{4+}})^{(1-\alpha_1)} (c_{V^{5+}})^{\alpha_1} \left[\frac{c_{V^{4+}}^s}{c_{V^{4+}}} \exp\left(\frac{(1-\alpha_1)F\eta_1}{R_g T}\right) - \frac{c_{V^{5+}}^s}{c_{V^{5+}}} \exp\left(-\frac{\alpha_1 F \eta_1}{R_g T}\right) \right], \quad (12)$$

$$J_2 = A_s F k_2 (c_{V^{2+}})^{(1-\alpha_2)} (c_{V^{3+}})^{\alpha_2} \left[\frac{c_{V^{2+}}^s}{c_{V^{2+}}} \exp\left(\frac{(1-\alpha_2)F\eta_2}{R_g T}\right) - \frac{c_{V^{3+}}^s}{c_{V^{3+}}} \exp\left(-\frac{\alpha_2 F \eta_2}{R_g T}\right) \right], \quad (13)$$

where J_1 and J_2 are the transfer current densities of the positive and negative electrodes, respectively; A_s is the specific surface area of the electrode; k_1 and k_2 are the positive and negative reaction rate constants, respectively; α_1 and α_2 are the positive and negative charge transfer coefficients, respectively; $c_{V^{3+}}$ and $c_{V^{4+}}$ are the molar concentrations of V^{3+} and VO^{2+} , respectively; $c_{V^{2+}}^s$, $c_{V^{3+}}^s$, $c_{V^{4+}}^s$, and $c_{V^{5+}}^s$ are the molar concentrations of V^{2+} , V^{3+} , VO^{2+} , and VO^{3+} ions at the liquid–solid interface within the porous region, respectively; R_g is the universal gas constant; T is the temperature; η_1 and η_2 are the activation overpotentials of the positive and negative reactions, respectively. η_1 and η_2 are defined by Eqs. (14) and (15), respectively:

$$\eta_1 = \phi_s - \phi_l - E_1, \quad (14)$$

$$\eta_2 = \phi_s - \phi_l - E_2, \quad (15)$$

where ϕ_s is the electrode potential; ϕ_l is the electrolyte potential; E_1 and E_2 are the standard equilibrium potentials for positive and negative redox reactions, respectively. E_1 and E_2 are expressed by the Nernst equations (Eqs. (16) and (17)):

$$E_1 = E_1^0 + \frac{R_g T}{F} \ln \left(\frac{c_{V^{5+}} c_{H^+}^2}{c_{V^{4+}}} \right), \quad (16)$$

$$E_2 = E_2^0 + \frac{R_g T}{F} \ln \left(\frac{c_{V^{3+}}}{c_{V^{2+}}} \right), \quad (17)$$

where E_1^0 and E_2^0 are the positive and negative standard potentials, respectively; c_{H^+} is the molar concentration of H^+ .

The cell voltage E_{cell} is calculated by Eq. (18):

$$E_{\text{cell}} = E_1^0 - E_2^0 + \frac{R_g T}{F} \ln \left(\frac{c_{V^{2+}} c_{V^{5+}} c_{H^+}^2}{c_{V^{3+}} + c_{V^{4+}}} \right) - \eta_1 - \eta_2 - IR_{\text{cell}}, \quad (18)$$

where I is the discharge current of the cell; R_{cell} is the resistance of the cell.

2.4 Model parameters

Tables 3 and 4 list the relevant parameters used in the 3D model of the VRFB cell.

2.5 Boundary conditions

The structure of the flow frame has a critical impact on the performance of the VRFB cells. In this study, the VRFB performance was tested for three different flow frames, as illustrated in Fig. 3. The walls of both the flow frames and the porous electrodes were assumed to satisfy no-slip boundary conditions. The positive and negative electrolyte flow rates were kept equal and ranged from 240–1080 mL/min. The mass flow inlet and outlet pressure boundary conditions were defined for the flow frames. The current density used in the discharge simulation was 105 mA/cm². The system temperature was held at 293.15 K. The equations governing the 3D numerical model of the cell were solved using COMSOL Multiphysics® software.

2.6 Mesh independence analysis

Effective mesh division can improve the computational efficiency and accuracy of simulations. The 3D model of the VRFB was therefore investigated for mesh independence. The model was mainly divided into tetrahedral meshes, and the mesh was refined in corners and areas of complex flow, as shown in Fig. 4. To verify the independence between the simulation results and the number of meshes, four different mesh numbers were selected for comparative simulations. The mesh number increased proportionally from 1.15×10^6 to 1.22×10^7 , with the obtained results shown in Fig. 5. Considering both the computational cost and accuracy, a mesh number over 6.20×10^6 was used for future comparison and discussion. We also compared structured and unstructured meshes to validate the effectiveness

Table 3 Model parameters of the VRFB cell

Parameter	Value	Reference
c_{total} (mol/m ³)	1700	—
H ⁺ initial concentration, $c_{\text{H}^+}^0$ (mol/m ³)	4000	—
HSO ₄ ⁻ initial concentration, $c_{\text{HSO}_4^-}^0$ (mol/m ³)	4000	—
V ²⁺ diffusion coefficient, $D_{\text{V}^{2+}}$ (m ² /s)	2.400×10^{-10}	(Lee et al., 2019)
V ³⁺ diffusion coefficient, $D_{\text{V}^{3+}}$ (m ² /s)	2.400×10^{-10}	(Lee et al., 2019)
VO ²⁺ diffusion coefficient, $D_{\text{VO}^{2+}}$ (m ² /s)	3.900×10^{-10}	(Lee et al., 2019)
VO ₂ ⁺ diffusion coefficient, $D_{\text{VO}_2^+}$ (m ² /s)	3.900×10^{-10}	(Lee et al., 2019)
H ⁺ diffusion coefficient, D_{H^+} (m ² /s)	9.312×10^{-9}	(Lee et al., 2019)
SO ₄ ²⁻ diffusion coefficient, $D_{\text{SO}_4^{2-}}$ (m ² /s)	1.065×10^{-9}	(Lee et al., 2019)
HSO ₄ ⁻ diffusion coefficient, $D_{\text{HSO}_4^-}$ (m ² /s)	1.330×10^{-9}	(Lee et al., 2019)
R_g (J/(mol·K))	8.3145	—
F (C/mol)	96485	—
S_c	0.8	—
K_{ck}	9	—
ρ (kg/m ³)	1354	(Lee et al., 2019)
μ (Pa·s)	4.928×10^{-3}	(Lee et al., 2019)
A_s (m ⁻¹)	1.62×10^4	(Lee et al., 2019)
d_f (m)	1.76×10^{-5}	(Yuan et al., 2020)
Electrode conductivity, σ_{ed} (S/m)	1000	(Lee et al., 2019)
ε	0.90	—

Table 4 Parameters used in the simulation

Parameter	Value	Reference
k_1 (m/s)	6.8×10^{-7}	(Lee et al., 2019)
k_2 (m/s)	1.7×10^{-7}	(Lee et al., 2019)
α_1	0.55	(Lee et al., 2019)
α_2	0.45	(Lee et al., 2019)
E_1^0 (V)	1.004	(Lee et al., 2019)
E_2^0 (V)	-0.255	(Lee et al., 2019)

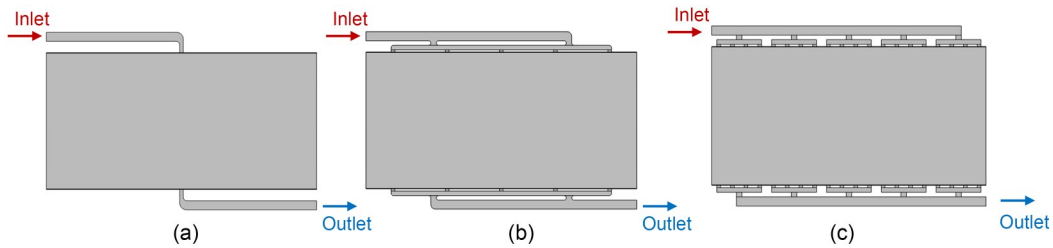


Fig. 3 Flow frame designs for the numerical simulation: (a) channel 1; (b) channel 5; (c) channel 20



Fig. 4 Mesh refinement in corners and areas of complex flow

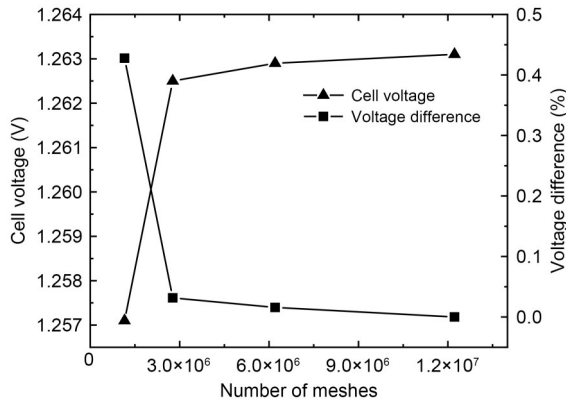


Fig. 5 Mesh independence analysis

of unstructured meshes in this context. Fig. S1 of the electronic supplementary materials (ESM) shows the structured meshes for channel 1, and Fig. S2 of the ESM compares the results of structured and unstructured meshes. Both methods produce essentially the same results, showing that unstructured meshes can flexibly and accurately treat complex geometries.

2.7 Multi-scale model of the VRFB

In the ECM of the VRFB, each cell is simplified to consist of a series-connected internal resistance and a controlled voltage source, where the internal resistance (R_{int}) is comprised of the component resistance and the contact resistance between components. The voltage of the controlled source is obtained by linear interpolation of the cell model simulation results under different operating conditions. The resistances of the porous electrodes and the proton exchange membrane are calculated in the cell model, so R_{int} represents only the resistance of the bipolar plate between the cells. The ECM uses the Simscape block in MATLAB software to construct a circuit model with parallel and series ohmic resistors connected to controlled voltage sources (represented as cells of the VRFB) and a constant current source (used to simulate constant current discharge).

Shunt currents are generated by the flow of electrolytes in the stack manifolds, which form paths between individual cells connected in series. The paths can be simplified to equivalent resistances in the ECM. These resistances R are calculated using Eq. (19):

$$R = \frac{l}{\sigma A}, \quad (19)$$

where l is the effective length; σ is the electrical conductivity; A is the cross-sectional area. R consists of four parts: $R_{pc,j}$, $R_{nc,j}$, $R_{pm,j}$, and $R_{nm,j}$ ($j=1, 2, \dots, 40$), which denote equivalent resistances of the electrolyte of the j th cell in the positive channel, the negative channel, the positive manifold, and the negative manifold, respectively. The electrical conductivity σ depends on the S_c of the solution in each cell (Trovò et al., 2019):

$$\sigma_n = S_c \sigma_{V^{2+}} + (1 - S_c) \sigma_{V^{3+}}, \quad (20)$$

$$\sigma_p = S_c \sigma_{V^{5+}} + (1 - S_c) \sigma_{V^{4+}}, \quad (21)$$

where σ_n and σ_p are the catholyte and anolyte conductivities, respectively; $\sigma_{V^{2+}}$, $\sigma_{V^{3+}}$, $\sigma_{V^{4+}}$, and $\sigma_{V^{5+}}$ are the solution conductivities of V^{2+} , V^{3+} , VO^{2+} , and VO_2^+ , respectively.

Additionally, species are exchanged between the stack and the tank during battery operation. The mass balance of the VRFB model is based on the following assumptions: (1) the electrolyte is completely mixed in the pipe, stack, and tank; (2) the charge loss during battery operation is caused only by the shunt current, and the transport of species across the membrane is not considered; (3) electrolyte parameters, such as density, viscosity, and mobility, remain constant during battery operation; (4) flow rate differences between cells are not considered.

The ion concentration in the tanks is determined by the flow rate and the ion concentration at the stack outlet. The concentration in the tanks is calculated using Eq. (22) (Han et al., 2024):

$$\frac{dc_n^{\text{tank}}}{dt} = \frac{Q}{V_{\text{tank}}} (c_n^{\text{stack}} - c_n^{\text{tank}}), \quad (22)$$

where c_n^{tank} ($n=2, 3, 4, 5$) is the concentration of the n -valent vanadium ion in the tank; Q is the flow rate of the stack; V_{tank} is the volume of electrolyte in the positive/negative tank; c_n^{stack} is the concentration of the n -valent vanadium ion at the outlet of the stack.

The concentration in the cell is controlled by both the flow rate and the electrochemical reaction. Moreover, it is assumed that the concentration distribution in the cell varies linearly, which is expressed by Eqs. (23)–(25):

$$\frac{dc_n^{\text{cellave},j}}{dt} = \frac{Q}{MV_{\text{cell}}} (c_n^{\text{tank}} - c_n^{\text{cellout},j}) \pm \frac{I_j}{zFV_{\text{cell}}}, \quad (23)$$

$$c_n^{\text{cellave},j} = \frac{c_n^{\text{cellin},j} + c_n^{\text{cellout},j}}{2}, \quad (24)$$

$$c_n^{\text{stack}} = \frac{\sum_{j=1}^M c_n^{\text{cell},j}}{M}, \quad (25)$$

where $c_n^{\text{cellave},j}$ is the average concentration of the n -valent ($n=2, 3, 4, 5$) vanadium ion within the j th cell; $c_n^{\text{cellout},j}$, $c_n^{\text{cellin},j}$, and $c_n^{\text{cell},j}$ are the concentrations of the n -valent vanadium ion at the inlet, outlet, and the entire cell within the j th cell, respectively; M is the number of cells ($M=40$); V_{cell} is the volume of electrolyte in the cell; z is the unit activity coefficient; I_j is the charge/discharge current that flows through the j th cell ($I_j > 0$ for charging and $I_j < 0$ for discharging). The sign of the value is determined by the species. When n equals 2 or 5, the value is positive; when n equals 3 or 4, the value is negative.

Therefore, the multi-scale model of the VRFB is shown in Fig. 6. The parameters used in the multi-scale model are shown in Table 5. The currents and voltages in the circuit are calculated using Kirchhoff's law.

3 Results and discussion

A major goal of this study is to analyze how the flow frame affects the VRFB performance. A properly distributed flow field in the porous electrodes of a VRFB cell can improve the battery performance. Hence,

battery performance across different flow field distributions was investigated in terms of discharge voltage, velocity, pressure drop, and vanadium ion concentration. Finally, the effect of flow frame on system efficiency was analyzed using the multi-scale model of the VRFB. Given that mass transfer and electrochemical reactions in the positive and negative electrodes are essentially similar, only the negative electrode was used for comparative analysis.

3.1 Model validation

To validate the accuracy of the cell model, the discharge data from a single cell with an electrode size of 600 mm×300 mm was tested. The initial and final vanadium ion concentrations were quantified by potentiometric titration to determine the corresponding state of charge S_c . Constant current density discharge tests were conducted on the single cell experimental platform (Fig. 7). During the experiment, the electrolyte flow rate was set to 1080 mL/min, and the applied current density was 105 mA/cm², which is consistent with the conditions in the numerical simulation. The VRFB discharge cutoff voltage was set to 1.1 V.

Fig. 8 compares the simulation and experiment results for the discharge voltage at different S_c values. The results indicate that the numerical model accurately reflects the behavior of the battery during discharge. In the low S_c region, the discrepancy between the numerical results and the experimental results is more obvious. This is because the cell discharge voltage decreased rapidly at the end of discharge, which increased the error in estimating the reactant concentration during the discharge process.

3.2 Velocity and pressure drop

The velocity distributions within the electrodes are significantly influenced by the configuration of the

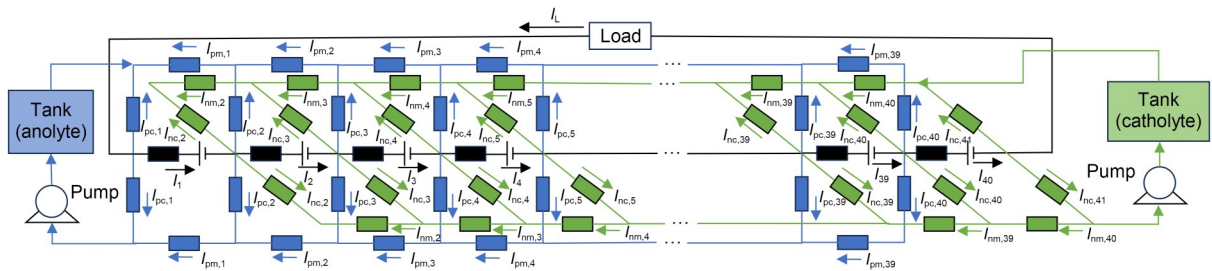
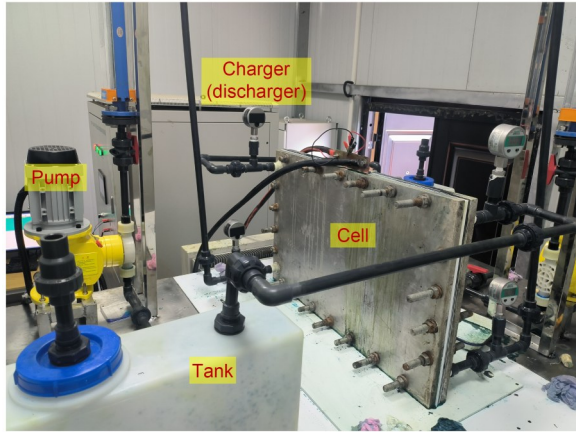
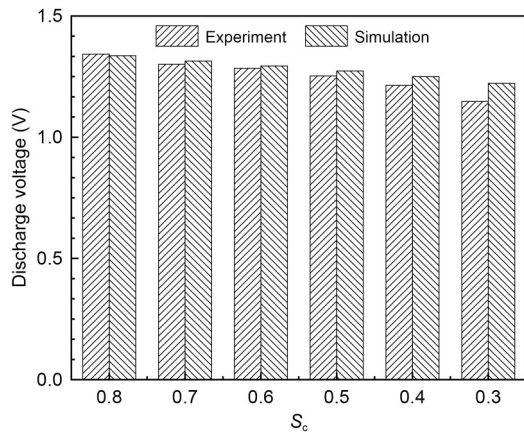


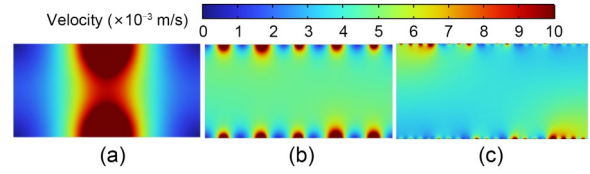
Fig. 6 Multi-scale model of a VRFB with 40 cells. I_j ($j=1, 2, \dots, 40$) is the current through the internal resistance of the j th cell; $I_{pm,j}$ and $I_{pc,j}$ are the currents in the positive manifold and positive channel of the j th cell, respectively; $I_{nm,j+1}$ and $I_{nc,j+1}$ are the currents in the negative manifold and negative channel of the $(j+1)$ th cell, respectively

Table 5 Parameters used in the multi-scale model of the VRFB

Parameter	Value	Reference
R_{int} (Ω)	1.6×10^{-7}	—
$\sigma_{V^{2+}}$ (S/m)	27.5	(Moro et al., 2017)
$\sigma_{V^{3+}}$ (S/m)	17.5	(Moro et al., 2017)
$\sigma_{V^{4+}}$ (S/m)	27.7	(Moro et al., 2017)
$\sigma_{V^{5+}}$ (S/m)	41.3	(Moro et al., 2017)
V_{tank} (m^3)	0.75	—
V_{cell} (m^3)	0.00063	—
Manifold length, l_m (m)	0.008	—
Manifold area, A_m (m^2)	4.91×10^{-4}	—
I_L (A)	189	—
Pump efficiency, ψ_{pump}	0.9	(Ali et al., 2020)

**Fig. 7** Test platform for a cell of the VRFB**Fig. 8** Comparison of the simulation and experiment results

flow frames, as illustrated in Fig. 9. A large area of high values is clearly observed for channel 1, which is located in the middle of the electrode. In contrast, high

**Fig. 9** Distribution of velocity (section 1) at the negative electrode for all three flow frames ($Q=600$ mL/min): (a) channel 1; (b) channel 5; (c) channel 20. References to color refer to the online version of this figure

value areas for channels 5 and 20 are only located near the top and bottom of the electrode.

Fig. 10 depicts the effect of flow rate on velocity distribution. Over section 1, velocities along a red line, which is offset 30 mm from the top of the electrode (line 1), were chosen for comparison. As expected, velocity differences increase with increasing flow rates for all flow frames. Interestingly, the number of velocity peaks is the same as the number of channels for channels 1 and 5, coinciding with the velocity contour shown in Fig. 9. As channel numbers continue to increase, velocity peaks transform into velocity plateaus at channel 20. A similar phenomenon can be observed along other lines, as evidenced by the velocity changes along lines 150 mm (line 2) and 270 mm (line 3) offset from the top of the electrode. Meanwhile, the velocity fluctuates relatively gently along line 2. This is mainly due to the significant resistance exerted on the fluid by the porous electrode. According to Darcy's law, the higher the fluid velocity, the greater the resistance it encounters. This causes the fluid in regions with higher velocity to diffuse towards adjacent regions, leading to a more uniform velocity distribution. Additionally, we assessed velocity fluctuations by dividing the standard deviation σ_u of the velocity by its mean value u_{ave} . Along lines 1 and 3, channels 5 and 20 show similar values. But along line 2, channel 5 has a more uniform velocity than channel 20, implying a more even distribution of concentration.

Another key performance parameter for the cell is the pressure drop, which affects the amount of pump consumption during battery operation. An excessive pressure drop will reduce the system efficiency during the charge/discharge cycle and necessitate stronger mechanical properties for the components, which may increase manufacturing costs. Fig. 11 presents a comparison of the pressure drops of different flow frames with flow rates ranging from 240–1080 mL/min. An approximate positive linear relationship between pressure

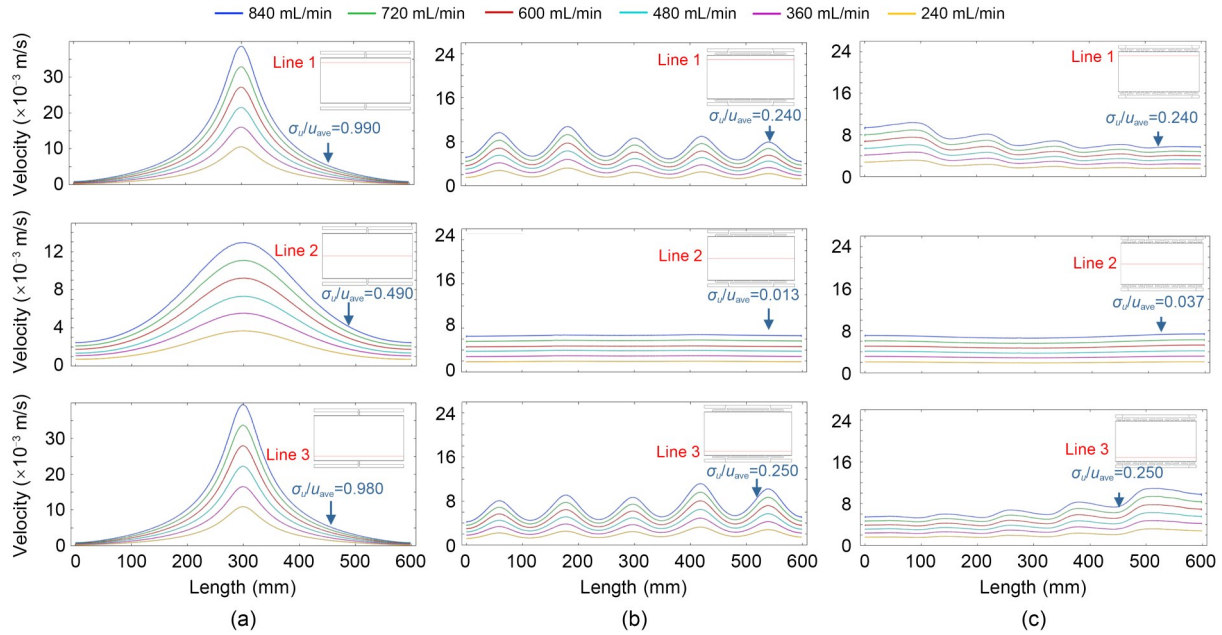


Fig. 10 Effect of flow rate on velocity distribution along the red line for different flow frames (section 1): (a) channel 1; (b) channel 5; (c) channel 20. References to color refer to the online version of this figure

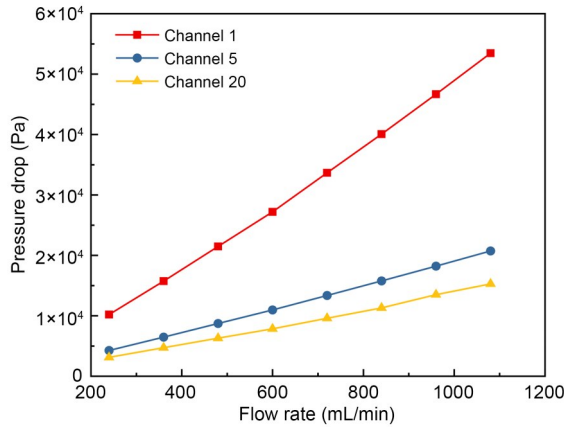


Fig. 11 Pressure drop for different flow frames across various electrolyte flow rates

drop and flow rate can be observed. The pressure drop for channel 1 reaches 5.3×10^4 Pa at a flow rate of 1080 mL/min, while the pressure drops for channels 5 and 20 are relatively low. This may be because Darcy's law governs fluid flow in porous electrodes. The pressure drop in the electrodes is further illustrated in Fig. S3 of the ESM. A high value for channel 1 is obvious, and channels 5 and 20 have almost the same values. Note that the pressure drop of channel 5 is higher than that of channel 20, implying that the differences in the flow frames are responsible for this effect. Indeed, channel 20 has a shorter electrolyte path

in its flow frame compared to channel 5, as shown in Fig. S4 of the ESM.

3.3 Discharge voltage and V^{2+} concentration distribution

Discharge voltage is an important factor in evaluating battery performance. Therefore, we compare the discharge voltage for the three flow frames across different flow rates. In the numerical simulations, the S_c is kept between 0.2 and 0.8, and the discharge current density is set at 105 mA/cm². The cutoff voltage was set to 1.1 V. The flow rates of catholyte and anolyte were equivalent and were increased from 240 to 1080 mL/min. The discharge voltages of batteries with different flow frames across varying flow rates and S_c values are shown in Fig. 12. With an increasing flow rate, the discharge voltages of all three flow frames rise. This is because the higher flow rate can increase the concentrations of reactants in the electrodes. However, when the reactant concentrations become sufficient, this effect becomes weaker; therefore, the voltage difference between the three flow frames decreases. Thus, the electrolyte flow rate is the main factor influencing the discharge process of the VRFB. Channel 5 has a higher discharge voltage than channels 1 and 20, especially at low flow rates and S_c values. Interestingly, this contrasts with the speculation that more channels

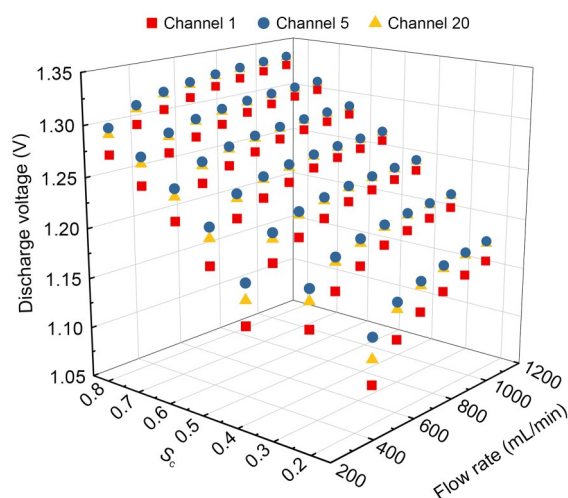


Fig. 12 Discharge voltages for the three flow frames at varying flow rates and S_e values

would lead to a more even distribution of velocity and a higher discharge voltage.

We aim to explain this phenomenon by investigating the reactant concentration distribution in the negative electrode. In Fig. 13, the concentration distributions of V^{2+} in sections 1–3 are shown when the flow rate is 360 mL/min, and the S_e is 0.3. Compared to channels 5 and 20, channel 1 shows a large low-concentration

region of V^{2+} , which would significantly hinder battery performance. For channels 5 and 20, the V^{2+} concentration distributions are similar, with obvious high values near the diagonal lines. This phenomenon can be explained by the direction of the pressure gradient in the porous electrode. As depicted in Fig. S5 of the ESM, the pressure is high near the inlet and low near the outlet; this pressure gradient causes the fluid to flow from the inlet towards the outlet. Accordingly, V^{2+} ions are transported along with the fluid and follow the trend of the diagonal line.

To evaluate the reactant concentrations, total values were calculated and are shown in Fig. 13. The values over different sections follow the same order, that is, channel 5 > channel 20 > channel 1. Moreover, this trend persists with increasing flow rates, as shown in Fig. S6 of the ESM. The superior value for channel 5 may be a consequence of the more uniform velocity distribution. As mentioned above, along different lines for channel 5, the velocity fluctuation values (σ_u/u_{ave}) are 0.240, 0.013, and 0.250, which are always lower than their counterparts in channel 20. Thus, the unique design of channel 5 promotes a higher reactant concentration within the electrode, leading to lower concentration polarization and higher discharge voltage.

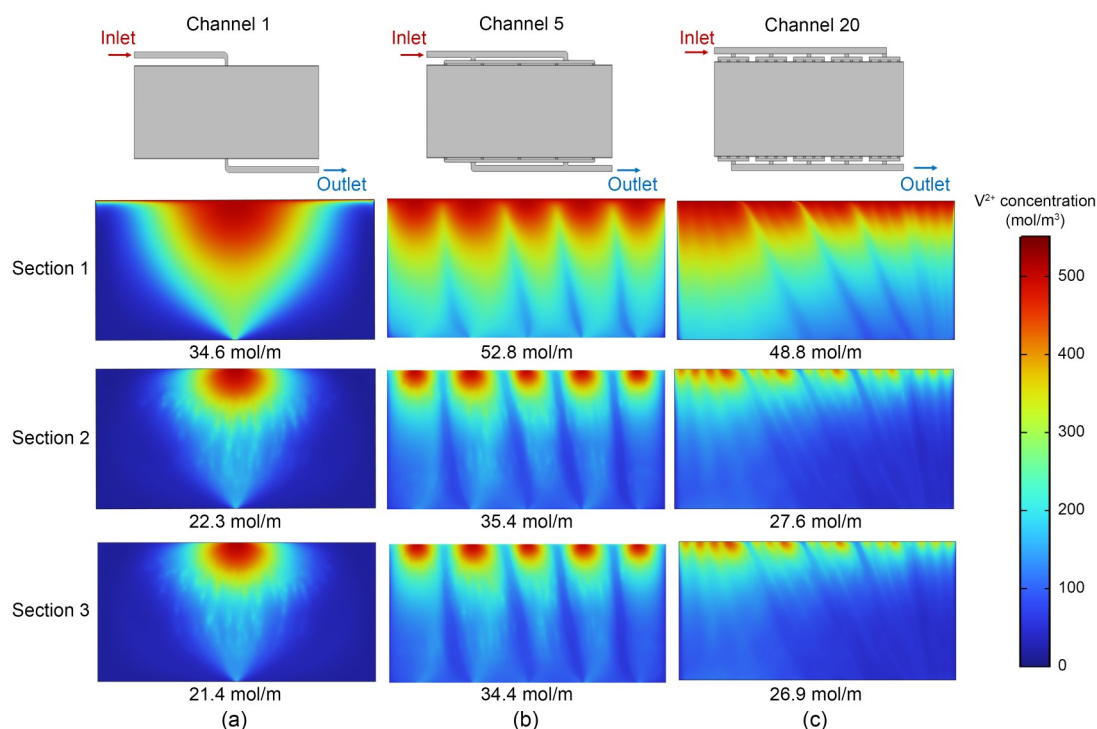


Fig. 13 V^{2+} concentration distribution and total values at different sections: (a) channel 1; (b) channel 5; (c) channel 20. References to color refer to the online version of this figure

3.4 Impact of flow frame on system efficiency

Efficiency is a crucial parameter for evaluating the performance of a battery system. In the operation of a VRFB, increasing the electrolyte flow rate can enhance the stack voltage, but it also leads to higher pump power consumption. Therefore, the selected flow rate needs to balance the electrochemical reaction and the pump power consumption. We use the system efficiency to comprehensively assess the impact of flow rate on these two aspects. To ascertain the optimal power efficiency using different cell structures, a 10 kW/40 kWh VRFB model with 40 cells was built. Then, the pump power consumption P_{pump} of the entire stack and the power loss P_{loss} due to overpotential were investigated. The VRFB system efficiency ψ_{power} was calculated as follows:

$$\psi_{\text{power}} = \frac{P_{\text{net}}}{P_{\text{total}}} = 1 - \frac{P_{\text{loss}} + P_{\text{pump}}}{P_{\text{total}}}, \quad (26)$$

$$P_{\text{loss}} = \sum_{j=1}^M I_j A (\eta_{p,j} + \eta_{n,j}) + P_R, \quad (27)$$

$$P_{\text{pump}} = \frac{2(\Delta P_{\text{cell}} + \Delta P_G)Q}{\psi_{\text{pump}}}, \quad (28)$$

where P_{net} is the output power; P_{total} is the total input power; $\eta_{p,j}$ and $\eta_{n,j}$ are the activation overpotentials of the positive and negative reactions in the j th cell, respectively; P_R is the stack ohmic power loss; ΔP_{cell} is the pressure drop in the cell; ΔP_G is the gravitational potential difference between the tank and the stack that needs to be overcome.

The system efficiency of each flow frame at varying flow rates can be obtained from the VRFB model, as shown in Fig. 14. As the flow rate increases, the system efficiency of each flow frame gradually rises, and the gap between the efficiency of channels 5 and 20 gradually disappears. After the flow rate reaches 960 mL/min, increasing the flow rate has little effect on the system efficiency. A peak efficiency of 93.51% was observed at the electrolyte flow rate of 1080 mL/min for channels 5 and 20.

From the ECM model, it was ascertained that an important parameter affecting the efficiency of the stack is the resistance of each cell. Among these resistances, R_{pm} and R_{nm} (equivalent resistances of the electrolyte in the positive manifold and negative manifold, respectively) are determined by the thickness of the porous electrodes and bipolar plates; unfortunately, these are

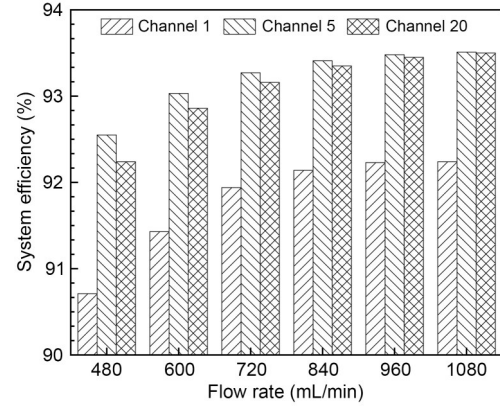


Fig. 14 System efficiency for various flow frames at varying flow rates

difficult to change. R_{pc} and R_{nc} (equivalent resistances of the electrolyte in the positive channel and negative channel, respectively) can be increased by extending the lengths of the inlet/outlet pipes and shrinking the pipe cross-section in the cell, so as to reduce the shunt current. However, this also increases the pressure drop as well as the pump power consumption of the stack. Therefore, we decide to use the genetic algorithm to optimize the parameters, such as pipe length and cross-section width. Table 6 lists the optimization parameter ranges, and more detailed information on the genetic algorithm workflow can be found in Fig. S10 of the ESM. The upper limit of the flow rate is based on the pump's rated power, while the lower limit is set such that the system can operate normally without damaging the electrolyte. The maximum values for pipe length and cross-section width are constrained by the manufacturing precision. Our minimization objective (or objective function) is the VRFB's system loss efficiency in the discharging process.

Table 6 Optimization parameters and ranges

Parameter	Range
Pipe length of the positive side, L_p (m)	0–3
Pipe length of the negative side, L_n (m)	0–3
Pipe cross-section width of the positive side, W_p (mm)	10–60
Pipe cross-section width of the negative side, W_n (mm)	10–60
Q (mL/min)	360–1080

The optimal solutions obtained are shown in Table 7. Each solution includes the optimal sizes and the corresponding system efficiency of the discharge

Table 7 Optimization results

Channel	L_n (m)	L_p (m)	W_n (mm)	W_p (mm)	Q (mL/min)	ψ_{power} (%)
1	1.263	1.708	58	59	1080	92.65
5	1.555	1.697	60	52	960	93.70
20	1.141	1.709	45	53	977	93.63

process. The highest efficiency of 93.70% was observed for channel 5 at an electrolyte flow rate of 960 mL/min.

4 Conclusions

The performances of three different flow frames in a VRFB were evaluated at both the cell and stack levels. To analyze the flow field and species concentration distribution at the cell level, a 3D model of the VRFB cells was developed. With this model, the cell performance was compared across different flow rates and S_c values, investigating factors such as pressure drop, velocity, vanadium ion concentration distribution, and discharge voltage. The results showed that the pressure drop of the cell decreases gradually with increasing number of channels in the flow frame. The cell with a five-channel flow frame was superior to the other configurations at low reactant concentration. We also found that despite a high flow rate enabling satisfactory discharge voltage, it also causes extra pump power consumption. Next, we proposed an ECM of the stack to simulate the operation of the battery. The system efficiency of the discharge process was used to evaluate different cell structures. The voltage differences between cells and the conductivity of the electrolyte generate shunt currents within the stack and piping system, which lead to energy losses and reduced system efficiency. The cell parameters affecting the shunt current in the discharge process were therefore optimized using a genetic algorithm. The final optimized configuration, using a five-channel flow frame, achieved a maximum system efficiency of 93.70% at a flow rate of 960 mL/min.

Acknowledgments

This work is supported by the “Pioneer” and “Leading Goose” R&D Program of Zhejiang Province (No. 2024C03116), China and the National Natural Science Foundation of China (Nos. 42341208 and 52206119).

Author contributions

Junhong LIN, Zihao MA, Guoneng LI, Weihong WU, and Chenghang ZHENG performed the experiment. Hao SONG and Xiang GAO conceived the idea and designed the research. Junhong LIN and Shaojun LIU analyzed the data and wrote the manuscript. All authors contributed to the discussion of the manuscript.

Conflict of interest

Junhong LIN, Zihao MA, Shaojun LIU, Hao SONG, Guoneng LI, Weihong WU, Chenghang ZHENG, and Xiang GAO declare that they have no conflict of interest.

References

- Albertus P, Manser JS, Litzelman S, 2020. Long-duration electricity storage applications, economics, and technologies. *Joule*, 4(1):21-32.
<https://doi.org/10.1016/j.joule.2019.11.009>
- Ali E, Kwon H, Kim J, et al., 2020. Numerical study on serpentine design flow channel configurations for vanadium redox flow batteries. *Journal of Energy Storage*, 32:101802.
<https://doi.org/10.1016/j.est.2020.101802>
- Ali E, Kim J, Park H, 2022. Numerical analysis of modified channel widths of serpentine and interdigitated channels for the discharge performance of vanadium redox flow batteries. *Journal of Energy Storage*, 53:105099.
<https://doi.org/10.1016/j.est.2022.105099>
- Bhattarai A, Wai N, Schweiss R, et al., 2019. Vanadium redox flow battery with slotted porous electrodes and automatic rebalancing demonstrated on a 1 kW system level. *Applied Energy*, 236:437-43.
<https://doi.org/10.1016/j.apenergy.2018.12.001>
- de León CP, Frías-Ferrer A, González-García J, et al., 2006. Redox flow cells for energy conversion. *Journal of Power Sources*, 160(1):716-732.
<https://doi.org/10.1016/j.jpowsour.2006.02.095>
- Delgado NM, Monteiro R, Cruz J, et al., 2022. Shunt currents in vanadium redox flow batteries—a parametric and optimization study. *Electrochimica Acta*, 403:139667.
<https://doi.org/10.1016/j.electacta.2021.139667>
- Guarnieri M, Trovò A, D’Anzi A, et al., 2018. Developing vanadium redox flow technology on a 9-kW 26-kWh industrial scale test facility: design review and early experiments. *Applied Energy*, 230:1425-1434.
<https://doi.org/10.1016/j.apenergy.2018.09.021>
- Gundlapalli R, Jayanti S, 2021. Effective splitting of serpentine flow field for applications in large-scale flow batteries. *Journal of Power Sources*, 487:229409.
<https://doi.org/10.1016/j.jpowsour.2020.229409>
- Guo F, Wu XW, Liu LL, et al., 2023. Prediction of remaining useful life and state of health of lithium batteries based on time series feature and savitzky-golay filter combined with gated recurrent unit neural network. *Energy*, 270:126880.
<https://doi.org/10.1016/j.energy.2023.126880>
- Guo SS, Li XP, Zhang ZH, et al., 2025. Advancements in lithium

- solid polymer batteries: surface modification, in-situ/operando characterization, and simulation methodologies. *Energy Materials*, 5:500041.
<https://doi.org/10.20517/energymater.2024.214>
- Han A, Huang QS, Zhang QN, et al., 2024. Effect of flow rate control modes on a vanadium redox flow battery based on a numerical model. *Korean Journal of Chemical Engineering*, 41(6):1703-1714.
<https://doi.org/10.1007/s11814-024-00152-y>
- Kapoor M, Verma A, 2022. Technical benchmarking and challenges of kilowatt scale vanadium redox flow battery. *WIREs Energy and Environment*, 11(5):e439.
<https://doi.org/10.1002/wene.439>
- Kim S, Thomsen E, Xia GG, et al., 2013. 1 kW/1 kWh advanced vanadium redox flow battery utilizing mixed acid electrolytes. *Journal of Power Sources*, 237:300-309.
<https://doi.org/10.1016/j.jpowsour.2013.02.045>
- Lee J, Kim J, Park H, 2019. Numerical simulation of the power-based efficiency in vanadium redox flow battery with different serpentine channel size. *International Journal of Hydrogen Energy*, 44(56):29483-29492.
<https://doi.org/10.1016/j.ijhydene.2019.05.013>
- Lu MY, Jiao YH, Tang XY, et al., 2021. Blocked serpentine flow field with enhanced species transport and improved flow distribution for vanadium redox flow battery. *Journal of Energy Storage*, 35:102284.
<https://doi.org/10.1016/j.est.2021.102284>
- Lu Y, Shao Z, Lu H, 2024. Quantification of anthropogenic heat and simulation of its effects on environment and climate: a comprehensive review. *Renewable and Sustainable Energy Reviews*, 204:114802.
<https://doi.org/10.1016/j.rser.2024.114802>
- Moro F, Trovò A, Bortolin S, et al., 2017. An alternative low-loss stack topology for vanadium redox flow battery: comparative assessment. *Journal of Power Sources*, 340:229-241.
<https://doi.org/10.1016/j.jpowsour.2016.11.042>
- Park S, Chaudhary R, Han SA, et al., 2023. Ionic conductivity and mechanical properties of the solid electrolyte interphase in lithium metal batteries. *Energy Materials*, 3:300005.
<https://doi.org/10.20517/energymater.2022.65>
- Sharma H, Kumar M, 2021. Enhancing power density of a vanadium redox flow battery using modified serpentine channels. *Journal of Power Sources*, 494:229753.
<https://doi.org/10.1016/j.jpowsour.2021.229753>
- Sun J, Zheng ML, Yang ZS, et al., 2019. Flow field design pathways from lab-scale toward large-scale flow batteries. *Energy*, 173:637-646.
<https://doi.org/10.1016/j.energy.2019.02.107>
- Trovò A, Marini G, Sutto A, et al., 2019. Standby thermal model of a vanadium redox flow battery stack with crossover and shunt-current effects. *Applied Energy*, 240:893-906.
<https://doi.org/10.1016/j.apenergy.2019.02.067>
- Yang F, Qu DW, Chai YW, et al., 2022. Development of three-dimensional model for the analysis of the mass transport in vanadium redox flow batteries. *International Journal of Hydrogen Energy*, 47(64):27358-27373.
<https://doi.org/10.1016/j.ijhydene.2022.06.091>
- Yuan CG, Xing F, Zheng Q, et al., 2020. Factor analysis of the uniformity of the transfer current density in vanadium flow battery by an improved three-dimensional transient model. *Energy*, 194:116839.
<https://doi.org/10.1016/j.energy.2019.116839>
- Zeng YK, Li FH, Lu F, et al., 2019. A hierarchical interdigitated flow field design for scale-up of high-performance redox flow batteries. *Applied Energy*, 238:435-441.
<https://doi.org/10.1016/j.apenergy.2019.01.107>
- Zerrahn A, Schill WP, 2017. Long-run power storage requirements for high shares of renewables: review and a new model. *Renewable and Sustainable Energy Reviews*, 79:1518-1534.
<https://doi.org/10.1016/j.rser.2016.11.098>
- Zhao XB, Kim YB, Jung S, 2023. Shunt current analysis of vanadium redox flow battery system with multi-stack connections. *Journal of Energy Storage*, 73:109233.
<https://doi.org/10.1016/j.est.2023.109233>
- Zheng Q, Xing F, Li XF, et al., 2016. Flow field design and optimization based on the mass transport polarization regulation in a flow-through type vanadium flow battery. *Journal of Power Sources*, 324:402-411.
<https://doi.org/10.1016/j.jpowsour.2016.05.110>

Electronic supplementary materials

Figs. S1–S10