BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

ARTICLE

A Simplified Analytical Method for Assessing Fluid Mixing Homogeneity in Flow Battery Storage Tanks

Dabin Mi [1], Qiang Guo [2], Jiang Wei [2], Lihui Sui [2], Yaze Wang [2], Tianhao Wang [2*]

[1] Hebei Construction & Investment Group Co., Ltd., Shijiazhuang 050011, China

[2] Hebei Vansheng Technology Co., Ltd., Shijiazhuang 050011, China

ABSTRACT

The electrolyte storage tank, as a key component in the vanadium redox flow battery (VRFB) system, directly influences the battery's operational performance and the accuracy of state-of-charge (SOC) estimation through the mixing homogeneity of the internal electrolyte. To address the challenge in engineering applications of rapidly evaluating mixing processes in storage tanks, this paper proposes a simplified analytical method for assessing fluid mixing homogeneity in VRFB tanks. The proposed method is a computational fluid dynamics (CFD)-based methodology that combines an internal flow-field simulation with monitoring of outlet parameters. It provides a qualitative and semi-quantitative analysis of the tank's overall mixing performance by comparing the simulated inlet electrolyte scalar concentration curve with the theoretical response curve under ideal, complete-mixing conditions. The research focuses on a multi-inlet conical-bottom self-mixing tank, and a traditional cylindrical flat-bottom tank was used for comparison, with their internal flow fields and mixing mechanisms analyzed using simulation software. The simulation results suggest that the flow streamlines within the conical-bottom self-mixing tank are more uniformly distributed, and its outlet response curve more closely matches the theoretical complete-mixing curve, indicating superior mixing homogeneity compared with the conventional structure. The simulation results were further confirmed by experiments using scaled-down physical models, and the experimentally measured characteristics of the conductivity distributions were in good agreement with the numerical inferences. The paper demonstrates that the suggested approach has the following strengths: simplified modelling, low computational cost,

*CORRESPONDING AUTHOR:

Tianhao Wang, Hebei Vansheng Technology Co., Ltd., Shijiazhuang 050011, China; Email: wth1116@alumin.sjtu.edu.cn

ARTICLE INFO

Received: 6 March 2026 | Revised: 30 April 2026 | Accepted: 21 May 2026 | Published Online: 12 August 2026

DOI: https://doi.org/10.30564/jees.v8i8.13363

CITATION

Mi, D., Guo, Q., Wei, J., et al., 2026. A Simplified Analytical Method for Assessing Fluid Mixing Homogeneity in Flow Battery Storage Tanks. Journal of Environmental & Earth Sciences. 8(8): 320–330. DOI: https://doi.org/10.30564/jees.v8i8.13363

intuitive criteria, and utility as a guide for structural design optimisation of VRFB tanks and for system-level modelling.
Keywords: Vanadium Redox Flow Battery; Storage Tank; Mixing Homogeneity; Computational Fluid Dynamics; Outlet Monitoring

1. Introduction

Vanadium redox flow batteries (VRFBs) have gained significant attention as a potential technology for large-scale stationary energy storage applications due to their inherent safety, long lifetime, modularity and separable power and energy capabilities [1–3]. The key difference between VRFBs and traditional batteries, in which energy is stored in solid electrodes, is that VRFBs store energy in liquid electrolytes containing vanadium ions in different oxidation states. The electrolytes flow between the storage tanks and cell stacks upon charging and discharging. This design allows energy storage capacity to be primarily increased by increasing the volume of the electrolytes, while power is primarily determined by the size and number of the cell stacks. These features enable VRFBs to be well integrated with renewable energy sources, used for load shifting or microgrid storage, and other applications where long-term, dependable energy storage is essential [4–8].

The storage tanks of a VRFB system are usually considered as reservoirs for the positive and negative electrolytes. But their hydraulic and mixing properties can play an important role in the performance of the battery system. In operation, the electrolyte continuously flows in and out of the tanks, with varying concentrations and state of charge (SOC). To achieve optimal performance, the electrolyte should mix quickly and thoroughly with the tank contents so that the concentration, SOC, and other physical properties are uniform throughout the tank. In such cases, the storage tank can be treated as a well-mixed reservoir in system models, and measurements of the electrolyte state at representative points (e.g., the outlet) can serve as an average representation.

However, in engineering practice, achieving perfect mixing is challenging. The flow inside a storage tank is significantly influenced by the tank shape, tank bottom, inlet/outlet location, flow velocity, and optional flow devices. If the structure is not well-designed, several undesirable flow features, such as short-circuiting, dead zones, preferential flow paths, and poor circulation, may arise. Short-circuiting occurs when a portion of the electrolyte flow reaches the outlet quickly without interacting with the rest of the electrolyte. On the other hand, stagnant zones are created by weak mixing in certain regions of the tank, where the electrolyte is not part of the circulation. These two effects reduce the effective mixing volume, leading to spatial non-uniformity in electrolyte concentration and SOC.

This non-uniformity is not only a local fluid-dynamic problem but may also affect the overall system. SOC estimation is an important aspect of VRFB energy management and control. Typical SOC estimation approaches assume that the electrolyte flowing through (or monitored at) a point in the tank is representative of the tank's average condition. However, if the tank is not well mixed, this is not the case. The outlet electrolyte concentration or another SOC-related signal may not be representative of the average electrolyte concentration in the tank, leading to inaccurate estimates of battery capacity, charge-discharge control, safety margins, and efficiency. So, enhancing and testing tank mixing is a valuable, yet under-recognized, part of VRFB system design [5].

Previous work on VRFB tanks and electrolyte mixing has delivered useful insights via experiments, theory, computational fluid dynamics (CFD) and system models. Experimental methods can experimentally demonstrate the concentration distribution and mixing performance, particularly with tracers, conductivity measurements or optical techniques. But experiments can be time-consuming and expensive, especially if various tank shapes, inlet arrangements, or operating modes are involved. It's even more challenging in full-scale experiments due to the high cost and complexity of VRFB electrolytes. Alternatively, high-precision numerical models can capture complex fluid flow and species transport patterns but typically need detailed model geometry, fine meshes, extensive parameter tuning, and time-consuming calculations. The inclusion of electrochemical reactions, multi-component transport, heat transport, and pump loop dynamics adds complexity. These methods are useful for in-depth research but could be potentially less efficient for

engineering screening and preliminary design of VRFB structures [9,10].

There is, therefore, a need for an efficient, intuitive, and simple method to assess the mixing effectiveness of VRFB storage tanks that does not rely on fully coupled electrochemical or highly resolved concentration-field models. During engineering design, designers may want to rapidly evaluate multiple tank designs and determine whether a particular design is likely to provide satisfactory mixing. In this case, a method that provides a relative indication of the mixing character might be preferred to a complex model that is difficult to implement and understand. The key question is to find an evaluation method that is simple to apply in design but also representative of the actual mixing patterns within the tank.

To address this problem, this paper presents a simple analytical method to evaluate the homogeneity of fluid mixing in VRFB tanks. The proposed method is unique in that it combines flow-field simulation inside the tank with outlet monitoring. Rather than conducting detailed spatial concentration analysis within the tank, the new method will assess the overall mixing effectiveness by examining the temporal response of a scalar concentration at the tank outlet. This simulated response is compared to a theoretical response curve for complete mixing. The outlet is the junction between the tank and the external circulation loop, and its concentration history is a direct consequence of the combined effect of the flow structure, residence time distribution and mixing. This approach reduces the difficult task of assessing three-dimensional mixing in the tank to a more practical comparison between the simulated and theoretical outlet response [11,12].

The ideal complete-mixing curve is a physically realistic comparison. If the tank is a fully mixed volume, the concentration of the incoming electrolyte at the outlet should follow the theoretical dilution or replacement curve as a function of tank volume and the incoming electrolyte flow rate. Any departure from the ideal curve suggests that mixing is incomplete. If the simulated curve closely matches the theoretical curve, it can be assumed that the incoming electrolyte is quickly distributed throughout the tank and then flushed out through the outlet. On the other hand, significant deviation suggests a lack of mixing, lagging in the participation of some fluid volumes, or a nonuniform residence time distribution. Moreover, the position of the simulated curve relative to the ideal curve may indicate the main flow mechanism. For instance, a response curve that is faster than the ideal curve may indicate short-cutting; a slower response may imply that the incoming fluid is not well dispersed or that some parts of the tank are not well mixed [13].

The outlet-response-based index is a useful criterion because it does not require specifying many sample points in the tank or detailed concentration variance across the entire tank volume. It is also a convenient and intuitive criterion for evaluating multiple tank designs under identical operating conditions. In this study, the approach is used to compare the performance of two typical tank designs: a multi-inlet self-mixing conical bottom tank and a conventional cylindrical flat bottom tank. Both tanks have equal volumes and inlet and outlet sizes, enabling the study of how tank geometry and flow configuration affect mixing. The steady-state simulations are conducted to investigate streamline patterns and identify potential stagnant zones or flow channels. Next, dynamic simulations are conducted to obtain the temporal outlet scalar concentration and to compare the results with the theoretical continuous stirred-tank reactor (CSTR) curve [14,15].

Another significant contribution of this study is the combination of numerical simulation with small-scale experiments. We use scaled physical models of the tanks to verify the findings of the simplified CFD approach with experiments using deionised water and a sodium chloride solution as the tracer. Concentration is measured at several locations by measuring conductivity. Experimental measurements show good agreement with the simulation results: the self-mixing tank with a conical bottom exhibits a more uniform conductivity distribution and approaches ideal mixing characteristics, whereas the conventional flat-bottom tank shows greater concentration variations and more pronounced non-uniform mixing. This supports the proposed simple method as a quick assessment method [16–19].

This study is thus novel in two ways. First, it proposes a new engineering-based method for evaluating mixing performance by combining computational fluid dynamics flow-field visualisation and outlet response curve monitoring, as an alternative to complex concentration-field modelling. Second, it shows that the method can evaluate the mixing performance of various VRFB tank designs and reveals the merit of a multi-inlet conical-bottom design for self-mixing.

It has more complicated streamlines, fewer dead volumes and dominant flow channels, and a more desirable outlet concentration response (approaching the ideal complete-mixing response) than conventional flat-bottom tanks [3,5,20–22].

In conclusion, this study provides a simple, inexpensive and intuitive method of analysing the mixing uniformity of electrolyte tanks in VRFB. This approach can be used in the preliminary design stage, tank geometry optimisation, and system modelling. The connection between tank structure, flow patterns, outlet response, and experimental results provides a practical means to guide VRFB tank-structure design and to improve the effectiveness of SOC estimation and system operation.

2. Analysis of Fluid Mixing inside Storage Tanks

Mixing in a storage tank is a typical internal flow problem, primarily controlled by forced convection and assisted by diffusion. During the charging and discharging process of a vanadium redox flow battery (VRFB), the electrolyte flows back and forth between the storage tank and the stack. When an electrolyte with a different state of charge is added to the tank, it mixes with the previously stored electrolyte, creating concentration gradients in both time and space. If the electrolyte can be quickly mixed with the existing electrolyte in the tank, then the concentration and SOC distribution will be more uniform. On the other hand, if the flow field is poorly structured, some areas may have a slow circulation, resulting in poor mixing [23,24].

In real storage tanks, mixing is strongly influenced by tank structure and operating conditions, such as tank size, bottom structure, inlet and outlet locations and velocities, and the fluid flow path. Ideally, a tank should help distribute incoming electrolyte throughout the tank volume and allow adequate mixing between the two. But inappropriately designed tanks can produce dominant flow channels, short-circuiting, or stagnant zones. Dominant flow channels minimise mixing between the incoming electrolyte and the liquid volume. Short-circuiting is when some of the flow reaches the outlet prematurely. Dead zones are areas where flow is slow, and the electrolyte is not involved. These create a smaller mixing volume and local variations in electrolyte concentration and SOC.

For VRFB, mixing within the storage tank may have impacts beyond local mixing. Because the electrolyte properties often used for SOC estimation and control (e.g., at the outlet and/or in the circulation loop) may not represent the averaged electrolyte condition in the tank in the case of non-uniform tank concentration. This can affect the accuracy of SOC measurement, battery capacity, and charge/discharge control. Hence, the homogeneity of tank mixing needs to be assessed for both hydraulic system design and battery system control [25].

Currently, tank-mixing homogeneity can be studied using experiments, high-fidelity numerical simulations or electrochemistry-flow models. Experimental approaches are straightforward and can be used to directly observe concentration distribution, but they are typically time-consuming and expensive, particularly when multiple tank designs are to be evaluated. Detailed numerical models can predict the velocity field and concentration distribution, but they require complex modelling, fine meshing, and high computational costs. Models that couple species transport and electrochemical reactions are even more challenging.

Thus, for design purposes, a more representative and simplified analysis approach is desirable. This method should simplify modelling while still describing the tank's overall mixing characteristics. By capturing essential flow features and the measurable outlet response, mixing homogeneity can be assessed qualitatively and semi-quantitatively, providing valuable insights for the rapid screening and design of VRFB storage tanks [4,5,7,26,27].

3. Method for Analyzing Mixing Homogeneity in Storage Tanks

3.1. Analysis Concept

For ideal mixing, the electrolyte's physical and chemical properties should be uniformly distributed throughout the storage tank. This is reflected in the time-varying behaviour of the physical parameters at the outlet, which gradually approaches a stationary state. Based on this hypothesis, this paper offers a simplified approach. This new methodology does not directly calculate the internal concentration field distribution in the tank; instead, it targets the tank's overall flow behaviour. Rather, it employs an approach of "internal flow

field simulation + outlet parameter monitoring". The overall mixing efficiency is reflected in the temporal characteristics of the parameters at the tank outlet[28].

3.2. Numerical Model Setup

3D models of the storage tanks were developed in 3D CAD software (**Figure 1**). Appropriate simplifications were made based on the real engineering structures. Although the overall geometry (such as the inlet/outlet positions and the major tank body structure) was preserved, some local details that have little influence on the flow pattern were neglected. Model 1 is a multi-inlet, conical-bottom, self-mixing tank, while Model 2 is a conventional cylindrical tank. The two models have the same tank capacity and inlet/outlet sizes.

(**a**) (**b**)

Figure 1. Three-dimensional schematic diagrams of the simplified storage tank models: (**a**) Conical-bottom self-mixing tank; (**b**) Traditional flat-bottom tank.

The models of both tanks were built using simulation software. A stationary simulation was conducted to study the flow field within the tank, while a dynamic simulation was conducted to track the electrolyte composition at the outlet. The electrolyte in the models was assumed to be incompressible and Newtonian. Reactions and heat transfer were ignored, and only the hydrodynamics were considered. A pressure-based solver was used to solve the governing equations, such as the continuity and momentum equations. The standard k-ε turbulence model was chosen to model.

3.3. Boundary Conditions and Monitoring Methods

The tank inlet and outlet were modelled as velocity and pressure outlets, respectively, in the numerical simulations. To assess the flow field characteristics, the steady-state simulation results were used to generate streamline distribution maps for the entire tank. A well-designed flow field, indicating a lower risk of creating mixing dead zones, is characterised by continuous, evenly distributed streamlines throughout the tank, with no dominant streamline. On the other hand, the existence of large mixing dead zones or short-circuiting flows is implied.

Mixing homogeneity was evaluated by placing a monitoring surface at the outlet cross-section. The temporal change in the scalar concentration (inlet electrolyte concentration) was monitored on this surface. In the meantime, the concentration change curve for complete mixing was determined. The difference between the simulated and theoretical curves reveals the degree of mixing completeness; the smaller the difference, the more complete the mixing. The curve's relative location can also indicate flow behaviours. A simulated curve positioned below the theoretical curve indicates the accumulation of the inlet electrolyte in the region of the inlet. On the other hand, if the simulated curve is above the theoretical curve, the existence of short-circuiting flow is observed. The theoretical curve can be calculated using Equation (1). While this criterion does not explicitly represent the spatial distribution, it captures relative differences in mixing efficiency among different structures (or operating conditions)[29,30].

$$\eta(t) = 1 - e^{-\frac{Q}{V}t} \tag{1}$$

where:

$\eta(t)$: theoretical scalar concentration of the inlet electrolyte on the monitoring surface at time t;

Q: volumetric flow rate of the inlet electrolyte (unit: mm^3/s);

V: internal volume of the storage tank (unit: mm^3);

t: flow time elapsed from the initial state.

The specific parameters for the steady-state simulation setup are provided in **Table 1**, and those for the transient simulation are detailed in **Table 2**.

Table 1. Steady-state simulation parameters.

Item	Value
Solver Mode	Steady-State
Gravity	x: 0, y: 0, z: −9.81 m/s^2
Electrolyte Density	1,320 kg/m^3
Dynamic Viscosity of Electrolyte	0.005 Pa·s
Viscous Model	Standard k–ε
Inlet Boundary Condition	Velocity Inlet
Inlet Flow Rate	66.5 cm^3/s
Outlet Boundary Condition	Pressure Outlet
Outlet Gauge Pressure	0 Pa
Solution Algorithm	SIMPLE
Number of Iterations	10,000

Table 2. Transient simulation parameters.

Item	Value
Solver Mode	Transient
Gravity	x: 0, y: 0, z: −9.81 m/s^2
Electrolyte Density	1,320 kg/m^3
Dynamic Viscosity of Electrolyte	0.005 Pa·s
Viscous Model	Standard k–ε
Mixture Settings	Species Transport
Mixture Method	Ideal Gas Mixing
Inlet Boundary Condition	Velocity Inlet
Inlet Flow Rate	66.5 cm^3/s
Outlet Boundary Condition	Pressure Outlet
Outlet Gauge Pressure	0 Pa
Solution Algorithm	SIMPLE
Number of Time Steps	10,000
Maximum Iterations per Time Step	20
Time Step Size	0.05 s

4. Simulation Results and Analysis

4.1. Analysis of Flow Field Characteristics inside Storage Tanks

The numerical simulation results revealed that the internal flow is strongly influenced by the inlet/outlet configuration, tank shape, and the presence of flow guides. The streamlines in the multi-inlet conical-bottom tank model are presented in **Figure 2a**. Closed streamlines from inlets to the outlet are generated in the tank. The streamlines are uniformly distributed within the tank, and many quickly spread out after entering the main tank. There are no well-defined flow bundles or short-circuits. This indicates that the flow entering the tank uniformly disturbs the fluid throughout the tank and maintains a gentle circulation, which is beneficial for electrolyte mixing [31].

However, the streamline patterns within the conventional cylindrical tank are shown in **Figure 2b**. A strong dominant flow channel is generated along the inlet direction. Streamlines tend to concentrate on the wall opposite the inlet/outlet and form vortices, while the region near the wall of the inlet/outlet side has many fewer streamlines, and no streamlines near the inlet. This suggests an unequal distribution of the flow field. The electrolyte in the region distant from the inlet/outlet is well mixed, while the electrolyte near the inlet/outlet is not well mixed and is even stagnant. As a result, mixing is uneven and incomplete, which may result in short-circuiting.

4.2. Analysis of Outlet Monitoring Results

In the transient analysis, the fluid properties of the incoming electrolyte from the inlet (the active stream) and the existing electrolyte originally within the tank (the passive fluid) were set to be identical. Statistical analysis of the scalar concentration of the inlet electrolyte at the monitoring surface yielded the mass fraction-time curve at the outlet, revealing differences in parameter stabilization characteristics under different tank structural designs.

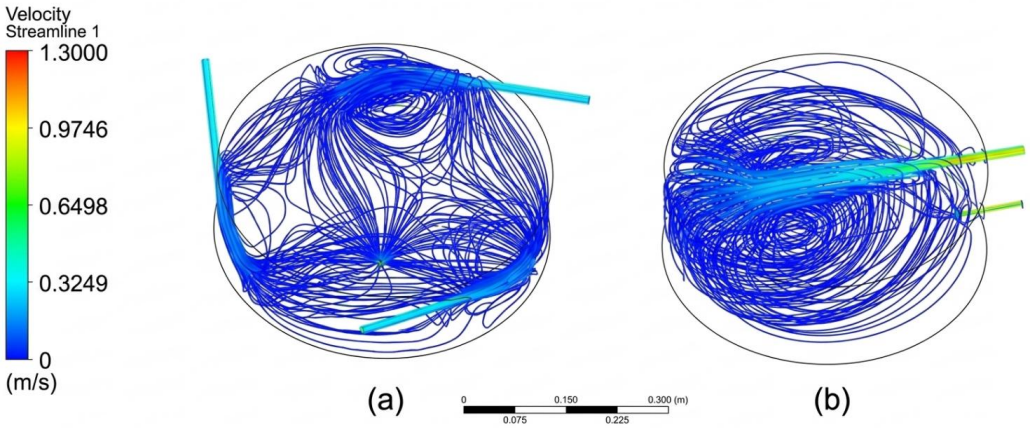


Figure 2. Streamline distribution diagrams inside the storage tank models: (**a**) Conical-bottom self-mixing tank; (**b**) Traditional flat-bottom tank.

The theoretical curve and the simulation curves for the two tank models are shown in **Figure 3**. According to the calculation, under the condition of perfect mixing within the tank, the theoretical scalar concentration of the inlet electrolyte at the outlet monitoring surface would reach 50% after 168 s of flow. The relative positions of the simulation curves to the theoretical curve were used to determine whether short-circuiting flow was present. Although different, both simulation curves lie below the theoretical curve, indicating that while the degree of mixing homogeneity differs between the two tanks, neither exhibits short-circuiting flow.

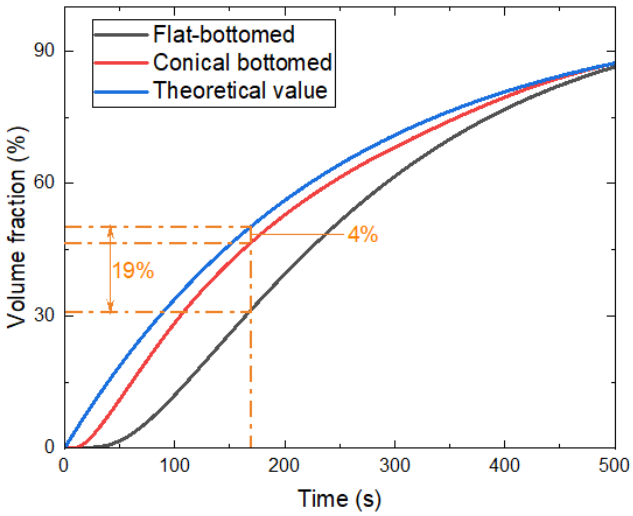


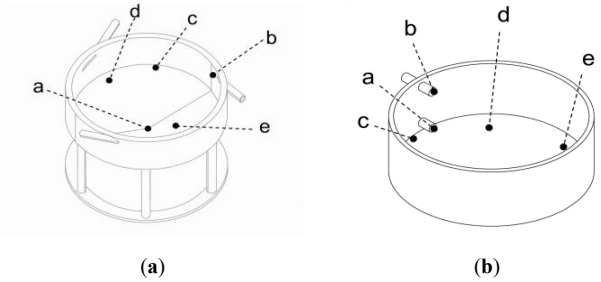
Figure 3. Variation of the scalar concentration of the inlet electrolyte at the outlet monitoring surface with time.

The profiles of the simulation curves and the scalar concentration at 168 s were used to compare mixing homogeneity. The simulation curve for the conical-bottom tank closely matches the theoretical curve throughout the simulation. At the 168-s time mark, the absolute deviation between the simulation and theoretical curves is approximately 4%, indicating good mixing homogeneity in the conical-bottom tank. On the other hand, the simulation curve for the flat-bottom tank has a long initial period, which leads to a large difference between the simulation and theoretical curves in the first half of the simulation. It reaches a maximum of about 19% at 168 s. After that, it decreases due to the replacement of the tank electrolyte. This suggests that the flat-bottom tank has a worse mixing performance [6].

5. Experimental Verification

5.1. Experimental Apparatus and Condition Setup

To validate the effectiveness of the simulation results, corresponding physical experiments were designed in this study. The experimental setup is illustrated in **Figure 4**, where scaled models of the two storage tanks were fabricated using 3D printing technology. A peristaltic pump was employed to control the inflow and outflow rates, ensuring equal volumes of liquid entered and exited the tank per unit time.



(**a**) (**b**)

Figure 4. Schematic diagrams of sampling point distributions: (**a**) Conical-bottom self-mixing tank; (**b**) Traditional flat-bottom tank.
Note: Sampling point a is located at the tank outlet; point b is at one of the inlets; point c is at the junction between the tank bottom and side wall; point d is on the tank bottom surface; and point e is at an arbitrary location within the internal tank volume.

To reduce experimental complexity and cost, deionized water was used to simulate the original electrolyte within the tank, and a saturated sodium chloride solution was used to simulate the inlet electrolyte. A small amount of potassium permanganate was added to the latter as a tracer. During the injection process, a measured quantity of the saturated sodium chloride solution was introduced into the tank filled with deionised water, simulating electrolyte mixing at different states of charge.

After injection, a pipette was used to collect samples from multiple representative locations within the tank, as detailed in **Figure 5**. The conductivity of the mixture at every sampling point was measured. The concentration (determined by conductivity) at different points was compared with the theoretical concentration based on perfect mixing in the tank. The discrepancies and their variances were calculated to assess the homogeneity of mixing within both structures. Finally, by comparing the experimentally measured mixing non-uniformity with the differences observed between the simulation and theoretical curves, the validity of the numerical simulation results was verified.

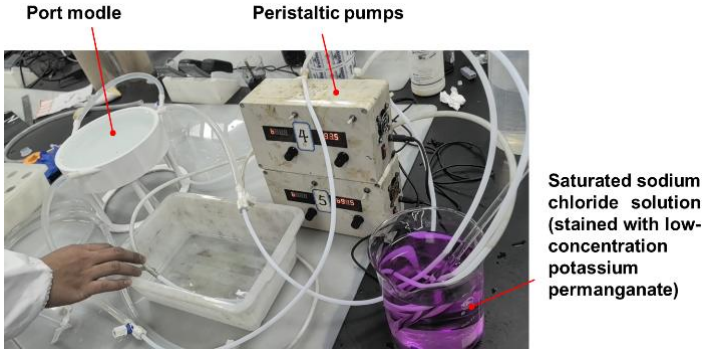


Figure 5. Test system diagram.

5.2. Analysis of Experimental Results

The experimental results are shown in **Figure 6**. It can be observed that the measured conductivity values at various sampling points for the conical-bottom self-mixing tank are relatively close to the theoretical value, with a variance of only 6.4. This indicates good mixing homogeneity inside this structure. In contrast, the conductivity values for the traditional flat-bottom tank deviate significantly from the theoretical value, with a minimum discrepancy of 20 μS/cm and a variance as high as 1,420.16, far exceeding those of the conical-bottom structure. This demonstrates non-uniform mixing and the presence of flow dead zones within the traditional tank. Therefore, the experimental results effectively validate the simulation conclusions and concurrently demonstrate the feasibility of the simplified analysis method proposed in this study[5,19].

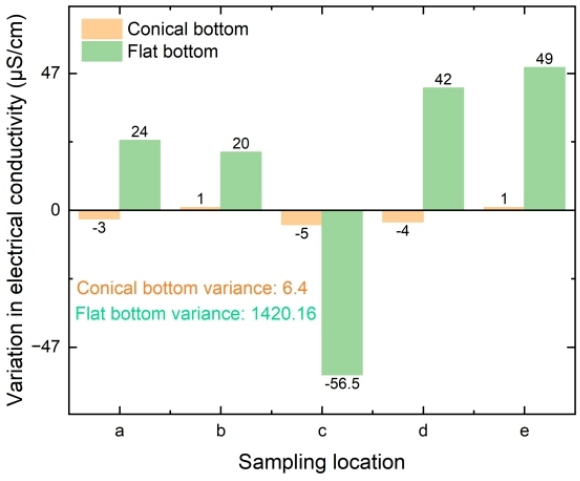


Figure 6. Deviation of the measured conductivity at each sampling point from that of the theoretically ideal mixed solution.

6. Conclusion

This study proposed a simplified analytical method for evaluating fluid mixing homogeneity in vanadium redox flow battery (VRFB) storage tanks and applied it to compare a multi-inlet conical-bottom self-mixing tank with a traditional cylindrical flat-bottom tank. The method was developed to meet the need for a practical engineering tool that can assess tank mixing performance without relying on complex electrochemical coupling or full-field concentration analysis.

The given approach was developed based on the principles of internal flow field simulation and outlet parameter monitoring. The tank was simplified while retaining the major geometric characteristics that influence flow behaviour, such as the tank body, inlet arrangement, and outlet position. The external streamline distribution has been studied with steady-state simulations, and the internal streamline distribution and the scalar concentration of the inlet electrolyte at the outlet have been monitored with transient simulations. A hypothetical complete-mixing curve was implemented as the benchmark. The qualitative and semi-quantitative judgement of the overall mixing performance of the different tanks, based on comparing the simulated outlet concentration response with this ideal curve, was possible. A smaller deviation of the theoretical curve indicated increased homogeneity in mixing, whereas the position of the simulated curve relative to the theoretical curve helped detect potential short-circuiting or inadequate exchange.

Results of numerical simulations indicated noticeable differences between the two tank structures. The multi-inlet conical-bottom self-mixing tank produced more dispersed, continuous streamlines that occupied most of the tank volume, indicating effective circulation and reduced stagnant areas. Conversely, the old-fashioned flat-bottom tank exhibited a more discontinuous flow field, with a dominant flow direction and sparsely spaced streamlines, indicating weaker fluid exchange and potential dead zones. This trend was further confirmed by the transient outlet monitoring results. At ideal complete mixing, it should take 168 s for 50% of the inlet electrolyte to reach the outlet. At this point, the conical-bottom tank exhibited a deviation of approximately 4% from the theoretical value, indicating good mixing homogeneity. In comparison, the flat-bottom tank exhibited a considerably larger deviation of about 19, indicating much poorer mixing performance.

Scaled physical experiments were conducted to test the simulation's conclusions. The original and incoming electrolytes were represented by deionised water and saturated sodium chloride solution, respectively, and conductivity was recorded at various representative sampling points. The conical-bottom tank had conductivity values very close to the theoretical value for fully mixed conditions, with a variance of 6.4. Conversely, the conventional flat-bottom tank exhibited significantly larger concentration differentials, with a variance of 1,420.16. These experimental findings were in close agreement with the numerical results and demonstrated that the conical-bottom self-mixing structure provides more uniform mixing.

All in all, the outlet-response-based approach suggested is quite intuitive, easy to work with and understand, and computationally inexpensive. It can also differentiate the mixing performance of various tank structures and be used for quick engineering evaluation, structural optimisation, and system-level analysis of VRFB storage tanks.

Author Contributions

Conceptualization, Y.W.; methodology, T.W.; investigation, D.M., Q.G., L.S., Y.W. and T.W.; resources, L.S.; writing—original draft preparation, D.M., Q.G., Y.W. and T.W.; writing—review and editing, Y.W. and T.W.; validation, Y.W. and T.W.; formal analysis, Y.W.; data curation, Y.W. and T.W.; supervision, J.W. and T.W.; project administration, D.M., Q.G., L.S. and T.W.; funding acquisition, Q.G. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the S&T Program of Hebei (Grant number: 23284403Z).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Barzigar, A., Ebadati, E., Mujumdar, A.S., et al., 2025. A comprehensive review of vanadium redox flow batteries: Principles, benefits, and applications. Next Research. 2(4), 100767. DOI: https://doi.org/10.1016/j.nexres.2025.100767

[2] Godiwala, S., Wei, L., Bao, J., et al., 2025. Economic model predictive control of vanadium redox flow batteries for power arbitrage. Journal of Energy Storage. 137, 118567. DOI: https://doi.org/10.1016/j.est.2025.118567

[3] Hassan, F.M., Theeb, M.A., 2020. Effect of diffuser height on thermocline in stratified chilled water storage tank. Journal of Applied Fluid Mechanics. 14(2), 429–438.

[4] Hsiao, Y.-S., Huang, J.-H., Lin, H.-Y., et al., 2025. Recovery of V_2O_5 from spent catalysts and its application in vanadium electrolytes for vanadium redox flow batteries. Journal of Energy Storage. 116, 115990. DOI: https://doi.org/10.1016/j.est.2025.115990

[5] Prieto-Díaz, P.A., Trovò, A., Marini, G., et al., 2024. Experiment-supported survey of inefficient electrolyte mixing and capacity loss in vanadium flow battery tanks. Chemical Engineering Journal. 492, 152137. DOI: https://doi.org/10.1016/j.cej.2024.152137

[6] Prieto-Díaz, P.A., Maurice, A.A., Vera, M., 2025. Electrolyte mixing in vanadium flow battery tanks: Effects on capacity utilization. Chemical Engineering Journal. 525, 170162. DOI: https://doi.org/10.1016/j.cej.2025.170162

[7] Prieto-Díaz, P.A., Ibáñez, S.E., Vera, M., 2023. Fluid dynamics of mixing in the tanks of small vanadium redox flow batteries: Insights from order-of-magnitude estimates and transient two-dimensional simulations. International Journal of Heat and Mass Transfer. 216, 124567. DOI: https://doi.org/10.1016/j.ijheatmasstransfer.2023.124567

[8] Li, Y., Sun, L., Cao, L., et al., 2021. Dynamic model based membrane permeability estimation for online SOC imbalances monitoring of vanadium redox flow batteries. Journal of Energy Storage. 39, 102688. DOI: https://doi.org/10.1016/j.est.2021.102688

[9] Aparicio-Mauricio, G., Rodríguez, F.A., Pijpers, J.J.H., et al., 2020. CFD modeling of residence time distribution and experimental validation in a redox flow battery using free and porous flow. Journal of Energy Storage. 29, 101337. DOI: https://doi.org/10.1016/j.est.2020.101337

[10] Trovò, A., Prieto-Díaz, P.A., Zatta, N., et al., 2024. Early investigations on electrolyte mixing issues in large flow battery tanks. Batteries. 10(4), 133. DOI: https://doi.org/10.3390/batteries10040133

[11] Huang, Z., Mu, A., Wu, L., et al., 2022. Comprehensive analysis of critical issues in all-vanadium redox flow battery. ACS Sustainable Chemistry & Engineering. 10(24), 7786–7810.

[12] Huang, Z., Mu, A., 2021. Numerical research on a novel flow field design for vanadium redox flow batteries in microgrid. International Journal of Energy Research. 45(10), 14579–14591. DOI: https://doi.org/10.1002/er.6710

[13] Hasyim, M.R., Ma, D., Rajagopalan, R., et al., 2017. Prediction of charge-discharge and impedance characteristics of electric double-layer capacitors using porous electrode theory. Journal of the Electrochemical Society. 164(13), A2899–A2913. DOI: https://doi.org/10.1149/2.0051713jes

[14] Suo, L., Ren, J., Zhao, Z., et al., 2020. Study on the nonlinear dynamics of continuous stirred tank reactors. Processes. 8(11), 1436. DOI: https://doi.org/10.3390/pr8111436

[15] Ochoa-Tapia, J.A., Hernandez-Rodriguez, R., Alvarez-Ramirez, J., 2025. Effect of the residence time distribution on the dynamical behavior of isothermal continuous stirred tank reactors: A nonlocal modeling approach. Industrial & Engineering Chemistry Research. 64(12), 6433–6444.

[16] Crowther, J., Dandy, G., 2012. Model comparisons for tracer experiments at a clear water storage tank. Australasian Journal of Water Resources. 15(2), 145–156.

[17] Angeloudis, A., 2014. Numerical and experimental modelling of flow and kinetic processes in serpentine disinfection tanks [PhD Thesis]. Cardiff University: Cardiff, UK.

[18] Poonoosamy, J., Kosakowski, G., Van Loon, L.R., et al., 2015. Dissolution–precipitation processes in tank experiments for testing numerical models for reactive transport calculations: Experiments and modelling. Journal of Contaminant Hydrology. 177–178, 1–17. DOI: https://doi.org/10.1016/j.jconhyd.2015.02.007

[19] Tafarojnoruz, A., Loprieno, P., Fiorini Morosini, A., et al., 2025. CFD-based hydraulic performance improvement of a chlorine contact tank: The case study of a southern Italy plant. Fluids. 10(12), 328. DOI: https://doi.org/10.3390/fluids10120328

[20] Minke, C., Kunz, U., Turek, T., 2017. Techno-economic assessment of novel vanadium redox flow batteries with large-area cells. Journal of Power Sources. 361, 105–114. DOI: https://doi.org/10.1016/j.jpowsour.2017.06.066

[21] Liu, Y., Jiang, W., Zeng, Q., et al., 2025. Adaptive estimation of SOC and capacity of iron-chromium redox flow battery based on improved parameter identification and unscented Kalman filtering. Journal of Energy Storage. 120, 116482. DOI: https://doi.org/10.1016/j.est.2025.116482

[22] You, Y., Ji, X., Liu, Q., et al., 2025. Enhanced SOC estimation for lithium-ion batteries via ultrasonic paths fusion and spatio-temporal neural network. Journal of Energy Storage. 135, 118295. DOI: https://doi.org/10.1016/j.est.2025.118295

[23] Schofield, K., Musilek, P., 2022. Charge and Capacity Tracking in Vanadium Redox Flow Battery Systems. Clean Technologies. 4(3), 607–618. DOI: https://doi.org/10.3390/cleantechnol4030037

[24] Gundlapalli, R., Jayanti, S., 2021. Case studies of operational failures of vanadium redox flow battery stacks, diagnoses and remedial actions. Journal of Energy Storage. 33, 102078. DOI: https://doi.org/10.1016/j.est.2020.102078

[25] Díaz, P.Á.P., 2024. On the role of the electrolyte mixing inside the tanks of vanadium redox flow batteries [PhD Thesis]. Universidad Carlos III de Madrid: Madrid, Spain.

[26] Saha, S., Mamun, M.A.H., Hossain, M.Z., et al., 2008. Mixed convection in an enclosure with different inlet and exit configurations. Journal of Applied Fluid Mechanics. 1(1), 78–93.

[27] Ren, Y., Lv, B., Ran, Z., 2025. Application of computational fluid dynamics—Optimized biomimetic microchannel liquid-cooled plates in battery thermal management systems. Journal of Applied Fluid Mechanics. 19(2), 61–75. DOI: https://doi.org/10.47176/jafm.19.2.3810

[28] Krowne, C.M., 2024. Physics, electrochemistry, chemistry, and electronics of the vanadium redox flow battery by analyzing all the governing equations. Physical Chemistry Chemical Physics. 26(4), 2823–2862. DOI: https://doi.org/10.1039/D3CP04223E

[29] Bird, R.B., Stewart, W.E., Lightfoot, E.N., 2002. Transport Phenomena, 2nd ed. Wiley: New York, NY, USA.

[30] Cussler, E.L., 2009. Diffusion: Mass Transfer in Fluid Systems, 3rd ed. Cambridge University Press: Cambridge, UK. DOI: https://doi.org/10.1017/CBO9780511805134

[31] Rafefi, A.R., 2020. Development of thin film electrical resistance sensors for in situ monitoring of top of the line corrosion [PhD Thesis]. The University of Manchester: Manchester, UK.