

Transition-Metal-Modified Graphite Felt Cathodes for Energy-Efficient Vanadium Electrolyte Production

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Introduction

Vanadium redox flow batteries (VRFBs) are promising for large-scale and long-duration energy storage, but the cost and energy demand associated with vanadium electrolyte production remain important barriers to wider deployment. Electrochemical preparation of vanadium electrolyte from V_2O_5 provides a potentially scalable route, but the cathodic reduction process is accompanied by substantial polarization and competing hydrogen evolution, resulting in increased electricity consumption.

Here, we investigate transition-metal-modified graphite felt (GF) as a low-cost cathode strategy for improving the electrochemical production of vanadium electrolyte. Four transition metals (Fe, Co, Ni and Mn) were introduced onto graphite felt using a solution-based modification and thermal treatment approach. Their surface morphology and elemental distribution were compared, followed by systematic evaluation under identical vanadium electrolyte production conditions.

Method

Electrode preparation

Commercial graphite felt was pretreated by concentrated H_2SO_4 followed by washing, drying and thermal treatment. Fe-, Co-, Ni- and Mn-containing precursor solutions were subsequently used to modify the pretreated GF through solution impregnation. The modified felts were dried and calcined in air to obtain transition-metal-modified GF electrodes.

Electrochemical vanadium electrolyte production

The modified GF electrodes were evaluated for the electrochemical reduction of V_2O_5 under identical electrolyte composition, electrode area, current density and cell configuration. Cell voltage was continuously recorded during electrolysis, while vanadium oxidation-state evolution and energy consumption were determined at different stages of the process.

Performance metrics

- Electrolysis performance: cell voltage-time profile.
- Vanadium reduction: average vanadium oxidation state as a function of electrolysis time.
- Energy efficiency: specific energy consumption per mole of vanadium produced.

Results

Scanning electron microscope (SEM) characterisation

Transition-metal-containing surface features were observed on the graphite fibres, with distinct morphologies and elemental distributions among the four modified electrodes.

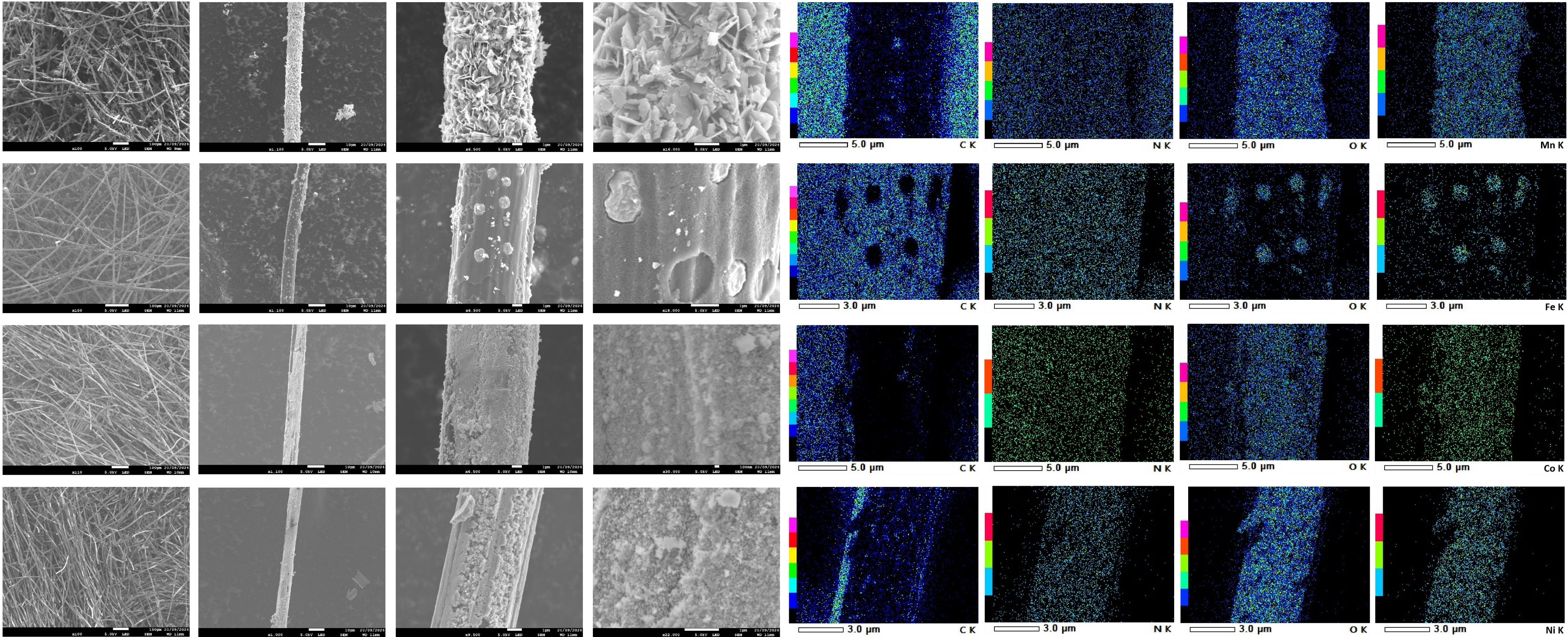


Figure 1. Morphological and elemental characterization of transition-metal-modified graphite felt electrodes. SEM images at progressively higher magnifications showing the morphology of the graphite fibres and the deposited metal-containing species for (a) Fe-GF, (b) Co-GF, (c) Ni-GF and (d) Mn-GF. Corresponding EDS elemental maps show the spatial distribution of C, O, N and the respective transition metal across the modified graphite felt surfaces.

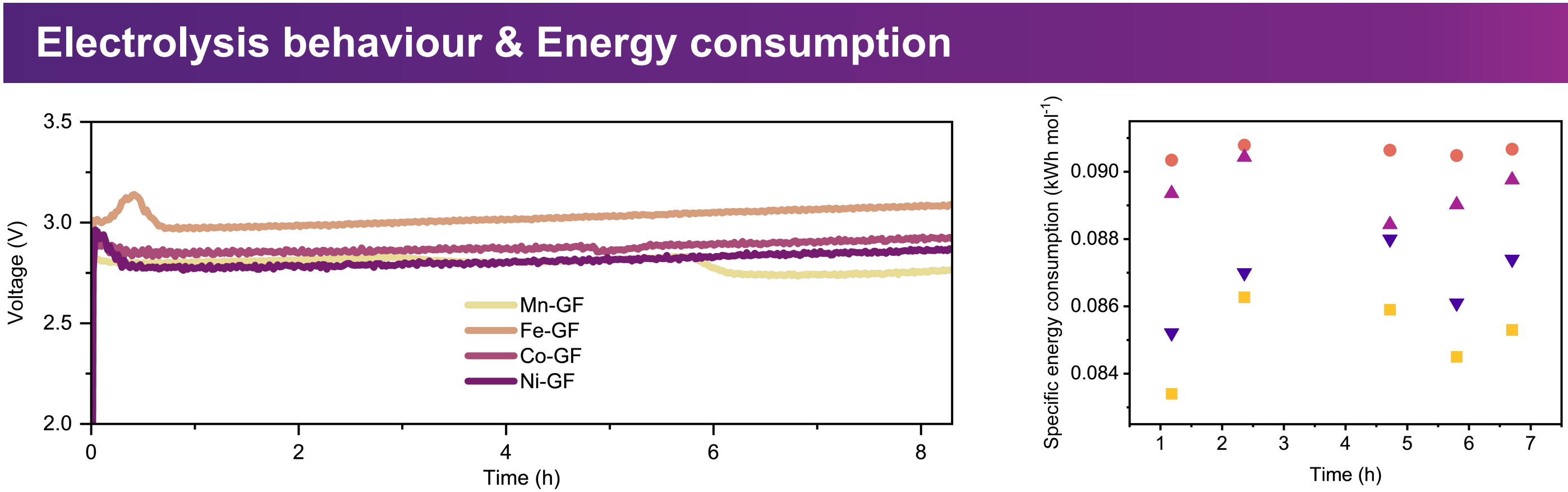


Figure 2. Electrolysis voltage profiles of transition-metal-modified graphite felt cathodes during V_2O_5 -based vanadium electrolyte production.

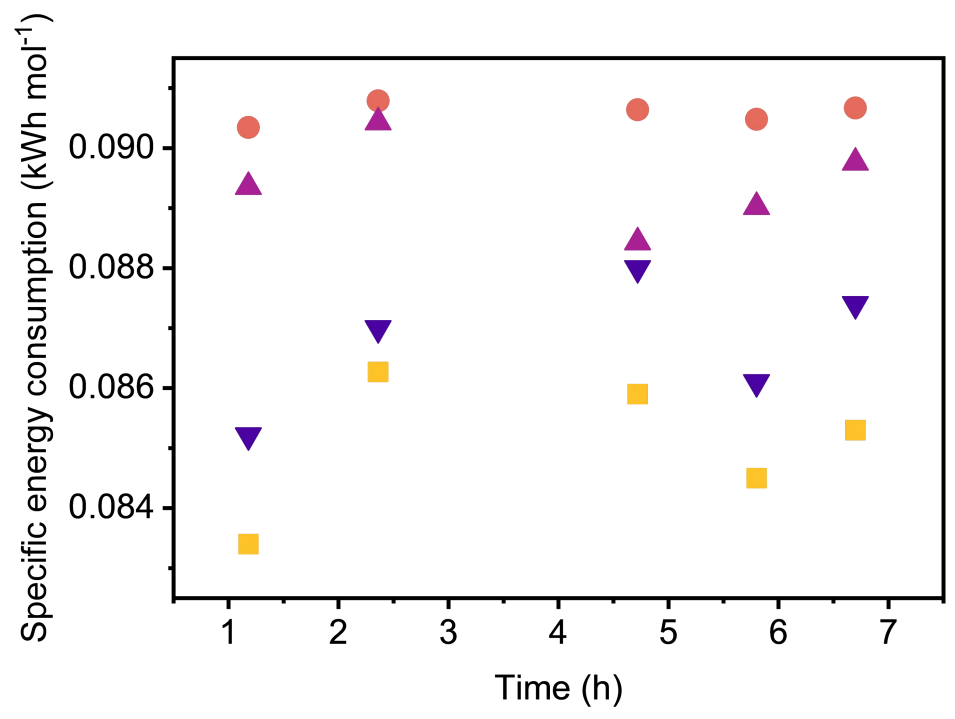


Figure 3. Specific energy consumption during electrochemical vanadium electrolyte production.

Cell voltage as a function of electrolysis time for Fe-GF, Co-GF, Ni-GF and Mn-GF under identical electrolyte composition, electrode configuration and applied current density. The voltage profiles reveal distinct electrochemical behaviour among the transition-metal-modified cathodes during vanadium electrolyte production.

Specific energy consumption normalized to the amount of vanadium processed, at different stages of electrolysis for Fe-GF, Co-GF, Ni-GF and Mn-GF. The comparison highlights the influence of transition-metal modification on the electricity demand associated with vanadium reduction.

Conclusions

- Fe-, Co-, Ni- and Mn-modified graphite felt electrodes were successfully prepared and evaluated under identical vanadium electrolyte production conditions.
- SEM and EDS confirmed distinct surface morphologies and elemental distributions associated with the different transition-metal modifications.
- The modified electrodes exhibited different electrolysis voltage profiles and vanadium reduction behaviours, demonstrating that cathode composition strongly influences the electrochemical production process.
- The evolution of vanadium oxidation state and specific energy consumption provides a basis for identifying promising transition-metal-modified cathodes for further optimization.
- Ongoing work will focus on optimizing metal loading and electrode preparation conditions, investigating long-term stability and metal leaching, and establishing the relationship between electrode properties, vanadium reduction kinetics and energy consumption.