Supplementary

Comparative Study of Kilowatt-Scale Vanadium Redox Flow Battery Stacks Designed with Serpentine Flow Fields and Split Manifolds

Ravendra Gundlapalli and Sreenivas Jayanti *

Department of Chemical Engineering and DST-Solar Energy Harnessing Center, IIT Madras, Chennai 60036, India; ravendra.gundlapalli@gmail.com
* Correspondence: sjayanti@iitm.ac.in; Tel.: +91-44 2257 4168

Supplementary Information

1. Equations for determining electrochemical parameters and pumping losses

If the pressure drop in a cell or stack is known, then the power consumed by the pump operation can be calculated from the following equation

$$P_{pump} = \frac{(\Delta P) \times Q}{\eta} \tag{1}$$

where ΔP = the cell pressure drop (Pa), Q = volumetric flow rate (m^3/s), η = efficiency of the pump (taken to be 75 %).

Electrochemical characteristics like capacity, round-trip efficiencies of coulombic, voltaic and energy for a life cycle, net energy efficiency, energy density and power density can be calculated using the following equations.

$$Capacity = \int_0^t I(t)dt \tag{2}$$

$$Coulombic\ efficiency = \frac{\int_0^{t_d} I(t)_{discharge} dt}{\int_0^{t_c} I(t)_{charge}\, dt} \tag{3}$$

$$Round - trip\ energy\ efficiency = \frac{\int_0^{t_d} E(t)_{discharge} I(t)_{discharge} dt}{\int_0^{t_c} E(t)_{charge}\, I(t)_{discharge} dt} \tag{4}$$

$$Voltaic\ efficiency = \frac{Energy\ efficiency}{Coulombic\ efficiency} \tag{5}$$

$E_{discharge}$ = discharge voltage of the cell (V)
$I_{discharrge}$ = discharge current of the cell (A)
dt = time interval between the measurements (s)
t_d = time of discharge (s) and t_c = time of charge (s)

$$Net\ energy\ consumed, W_c = \int_0^{t_c} I_c(t)E_c(t)dt + 2\int_0^{t_c} P_{pump}\,(t)dt$$

$$Net\ energy\ delivered, W_d = \int_0^{t_d} I_d(t)E_d(t)dt - 2\int_0^{t_d} P_{pump}\,(t)dt$$

$$Net\ energy\ efficiency = \frac{W_d}{W_c} \tag{6}$$

Table S1. Pump loss calculations for the stack 16 Cell—410 cm^2.

J (mA/cm^2)	SF	Flow rate (mL/min)	Pressure drop (Pa)	Power consumed (W)	Time for one cycle (h)	Energy consumed (Wh)	Charge energy (Wh)	Discharge energy (Wh)	EE (without pump loss)	EE (with pump loss)
60	4	1586	21231	1.80	0.67	1.20	225.40	171.20	75.95	75.42
60	5	1982	27305	2.89	0.77	2.23	245.30	191.10	77.90	77.00
60	7	2775	39468	5.84	0.93	5.42	298.40	235.00	78.75	76.94
60	9	3568	51631	9.82	1.03	10.09	329.00	262.40	79.76	76.69
75	4	1982	27305	2.89	0.48	1.38	194.40	141.70	72.89	72.18
75	5	2477	34897	4.61	0.59	2.73	241.10	180.30	74.78	73.65
75	7	3468	50097	9.27	0.71	6.54	285.20	220.20	77.21	74.92
75	9	4459	65297	15.53	0.73	11.35	293.90	228.10	77.61	73.75
90	4	2378	33378	4.23	0.36	1.54	178.80	127.50	71.31	70.45
90	5	2973	42505	6.74	0.45	3.00	216.80	158.80	73.25	71.86
90	7	4162	60741	13.48	0.55	7.40	267.20	201.50	75.41	72.64
90	9	5351	78978	22.54	0.59	13.23	286.40	215.10	75.10	70.49

J—current density, SF—Stoichiometric flow factor, EE—Energy efficiency.

Table S2. Electrochemical characteristics of the stack 16 Cell—410 cm^2.

J (mA/cm^2)	Flow rate (mL/min) or SF	Capacity (Ah/L)		Efficiency (%)			Energy density (Wh/L)
		Charge	Discharge	Columbic	Energy (without pump)	Voltaic	
60	1586/SF 4	16.9	16.4	97.16	75.95	78.17	21.40
60	1982/SF 5	19.5	19.0	97.13	77.90	80.21	23.89
60	2775/SF 7	23.7	22.5	95.18	78.75	82.74	29.38
60	3568/SF 9	26.3	24.9	94.82	79.76	84.11	32.80
75	1982/SF 4	15.1	14.7	97.09	72.89	75.08	17.71
75	2477/SF 5	18.7	18.2	97.01	74.78	77.09	22.54
75	3468/SF 7	22.4	21.6	96.34	77.21	80.15	27.53
75	4459/SF 9	23.2	22.3	96.37	77.61	80.53	28.51
90	2378/SF 4	13.8	13.4	97.67	71.31	73.01	15.94
90	2973/SF 5	16.9	16.4	97.04	73.25	75.48	19.85
90	4162/SF 7	20.8	20.2	96.93	75.41	77.80	25.19
90	5351/SF 9	22.3	21.5	96.59	75.10	77.75	26.89

Table S3. Electrochemical characteristics of the stack 8 cell—900 cm².

J (mA/cm²)	Flow rate (mL/min) or SF	Pressure drop (kPa)	Capacity (Ah)		Energy (Wh)			Efficiency (%)				Energy density (Wh/L)
			Charge	Discharge	Charge	Discharge	for pumping	Columbic	Energy (without pump)	Energy (with pump)	Voltaic	
45	2631/60 J SF 6	39.4	28.4	27.1	355.6	281.6	7.43	95.53	79.19	77.10	82.90	35.20
60		39.4	27.0	25.8	341.9	267.3	5.30	95.63	78.18	76.63	81.75	33.41
75		39.4	25.9	24.9	328.5	252.6	4.07	96.09	76.89	75.66	80.02	31.58
90		39.4	23.9	23.3	312.4	233.0	3.31	97.49	74.58	73.52	76.51	29.13
105		39.4	22.5	22.1	292.6	211.2	2.56	98.09	72.18	71.31	73.59	26.40
120		39.4	20.6	20.4	281.1	194.8	2.16	98.79	69.30	68.53	70.15	24.35
60	1754/SF 4	24.9	23.9	22.8	311.7	231.8	1.97	95.39	74.38	73.75	77.97	28.98
60	2192/SF 5	32.1	25.5	24.7	321.9	248.3	3.29	96.67	77.14	76.12	79.80	31.04
60	2631/SF 6	39.4	27.0	25.8	341.9	267.3	5.30	95.63	78.18	76.63	81.75	33.41
60	3069/SF 7	46.6	27.6	26.5	347.5	270.1	7.48	96.16	77.74	75.58	80.84	33.77
75	2192/SF 4	32.1	23.1	22.1	306.9	225.6	2.47	95.80	73.51	72.71	76.73	28.20
75	2740/SF 5	40.7	25.2	24.2	320.1	245.3	4.27	96.00	76.63	75.30	79.83	30.66
75	3288/SF 6	50.2	26.7	25.7	345.8	267.0	6.70	96.47	77.21	75.27	80.03	33.38

Table S4. Pump loss calculations for the stack 8 Cell—1500 cm².

J (mA/cm²)	SF	Flow rate (ml/min)	Pressure drop (Pa)	Power consumed (W)	Time for one cycle (h)	Energy consumed (Wh)	Charge energy (Wh)	Discharge energy (Wh)	EE (without pump loss)	EE (with pump loss)
45	SF 5 (J = 60)	3582	49069	9.37	0.83	7.75	340.60	277.00	81.33	79.05
60		3582	49069	9.37	0.58	5.44	320.60	250.90	78.26	76.56
75		3582	49069	9.37	0.43	4.07	307.10	231.80	75.48	74.16
90		3582	49069	9.37	0.34	3.18	283.50	206.30	72.77	71.65
105		3582	49069	9.37	0.26	2.47	266.70	186.60	69.97	69.04
120		3582	49069	9.37	0.20	1.90	242.80	165.00	67.96	67.17
60	2	1433	17993	1.38	0.48	0.66	281.00	197.80	70.39	70.16
60	3	2149	28347	3.25	0.54	1.76	306.10	232.30	75.89	75.32
60	4	2865	38701	5.91	0.58	3.45	332.00	264.00	79.52	78.48
60	5	3582	49069	9.37	0.59	5.56	338.21	266.27	78.73	77.09
75	2	1791	23170	2.21	0.35	0.78	261.58	186.54	71.31	71.02
75	3	2686	36112	5.17	0.40	2.09	288.80	218.90	75.80	75.07
75	4	3582	49069	9.37	0.43	4.02	313.80	239.10	76.20	74.91
90	2	2149	28347	3.25	0.27	0.88	234.30	170.80	72.90	72.52
90	3	3224	43892	7.55	0.33	2.45	282.80	209.30	74.01	73.14
90	4	4298	59423	13.62	0.35	4.83	301.56	226.57	75.13	73.53
120	2	2865	38701	5.91	0.16	0.94	189.10	125.10	66.16	65.66
120	3	4298	59423	13.62	0.20	2.78	249.10	169.10	67.88	66.77

Table S5. Electrochemical characteristics of the stack 8 cell - 1500 cm^2.

J (mA/cm^2)	Flow rate (ml/min) or SF	Capacity (Ah/L)		Efficiency (%)			Energy density (Wh/L)
		Charge	Discharge	Columbic	Energy (without pump)	Voltaic	
45	3582/60 J SF 5	28.6	27.1	94.80	81.33	85.79	34.63
60		26.7	25.5	95.80	78.59	82.04	31.99
75		24.8	24.0	96.80	75.48	77.98	28.98
90		23.3	22.5	96.38	72.77	75.50	25.79
105		21.0	20.5	97.78	69.97	71.55	23.33
120		18.5	18.1	98.18	67.96	69.21	20.63
60	1433/SF 2	22.3	20.9	93.89	70.39	74.97	24.73
60	2149/SF 3	24.8	23.8	95.89	77.11	80.42	30.66
60	2865/SF 4	26.9	25.6	95.09	79.52	83.62	33.00
60	3582/SF 5	27.3	26.1	95.62	78.73	82.34	33.28
75	1791/SF 2	20.2	19.3	95.67	71.31	74.54	23.32
75	2686/SF 3	23.2	22.2	95.48	75.80	79.39	27.36
75	3582/SF 4	24.5	23.7	96.70	76.20	78.80	29.89
90	2149/SF 2	18.5	18.0	97.35	71.67	73.63	21.35
90	3224/SF 3	22.3	21.6	97.12	74.01	76.20	26.16
90	4298/SF 4	24.2	23.6	97.52	75.13	77.04	28.32

2. OCV measurements for the Polarization tests:

The electrolyte was charged at a constant current density 60 mA/cm² with a pre-set voltage 1.8 times the number of cells in stack. After completing the charging at constant current density, it was then discharged with varying current densities in the range 20 mA/cm² to 200 mA/cm² with a step in current density 20 mA/cm² each lasted for 30 s. At the end of each such short-duration experiment, the open-circuit voltage (OCV) was measured for 60 s. Figure 1a shows the charging at constant current density followed by discharge at intervals of current densities. Figure 1b shows the broad vision of a few discharge curves where the OCV can be seen between the discharge curves which obtains a stable value within 60 s.

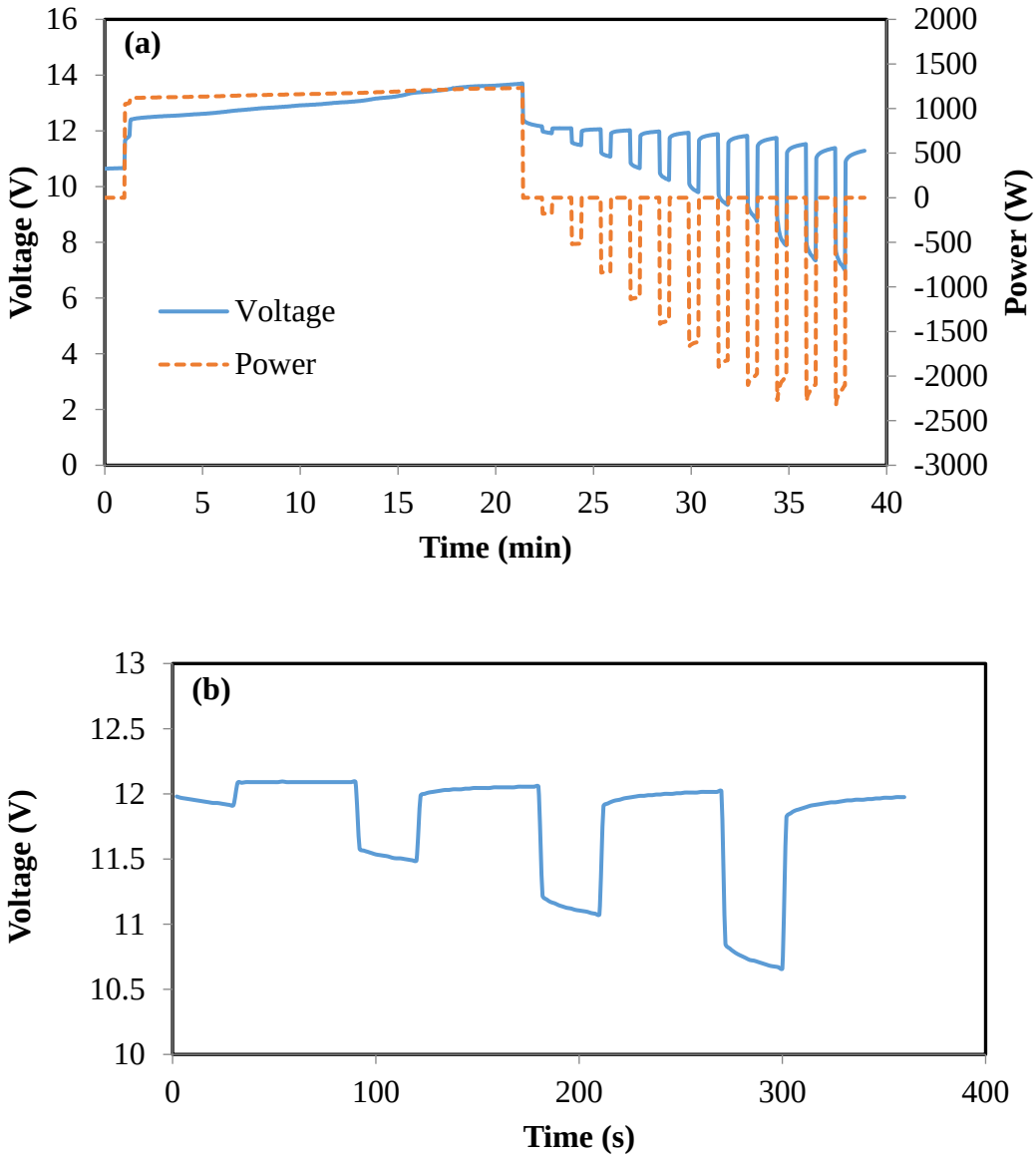

Figure S1. Polarization study of the stack 8 cell—1500 cm² (**a**) charging at constant current density of 60 mA/cm2 followed by discharge at intervals of current density and (**b**) broad visualization of the discharge curves with OCV measured between the discharge steps.