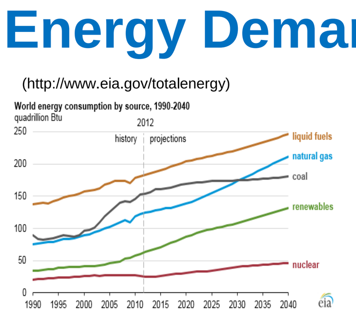
Alternative Designs to Harness Natural Convection in Flow Batteries

Md A. Ansari[1], S. Kumar[1]
1. Indian Institute of Science, Bangalore, Karnataka, India

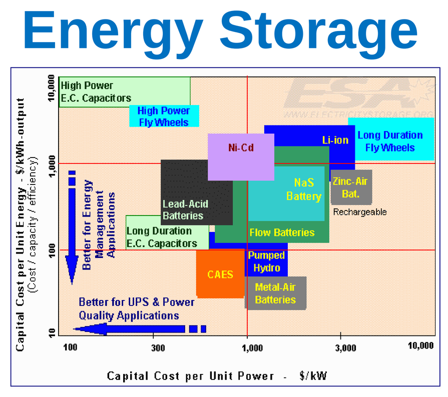
Abstract: The earlier work in our group has established that natural convection plays a dominant role in SLRFB. We used it to run a battery in which interestingly, the contents are agitated for brief spells when no current flows through it. The present work focuses on electrode configurations that harness the role of natural convection. In one such configuration, electrodes are positioned away from cell wall instead of keeping them flush with it, a practice followed in the previous configurations. The results are promising.

Introduction

Energy Demand


(http://www.eia.gov/totalenergy)

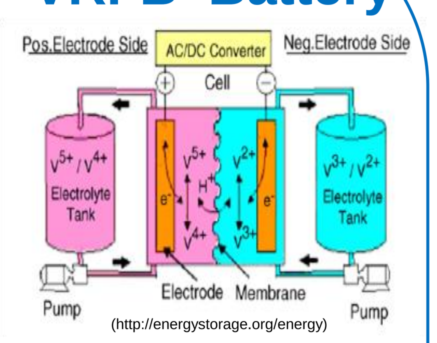
Energy Storage


(http://zebu.uoregon.edu/disted/ph162/l8)

Smart Grid/5MWh


(http://www.renewableenergyworld.com/)

VRFB Battery

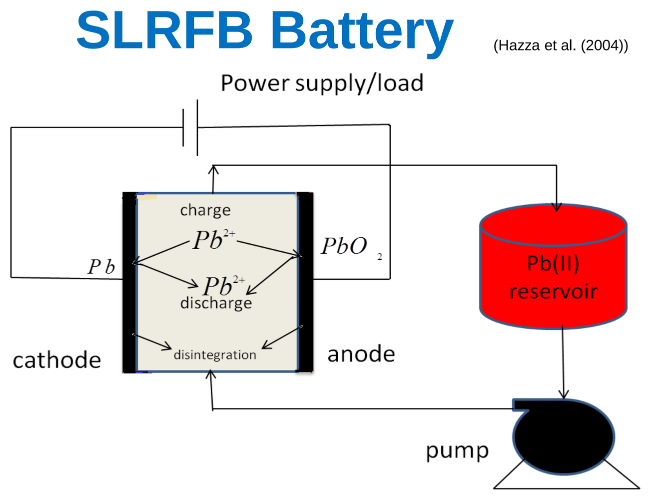


(http://energystorage.org/energy)

•Challenges: High cost of vanadium & periodic replacement of expensive membrane

SLRFB Battery

(Hazza et al. (2004))



•Challenge: Cycle Life

Cell Chemistry

•Cathode Reaction

$$Pb^{2+} + 2e^- \underset{discharge}{\overset{charge}{\rightleftharpoons}} Pb \qquad (E^0 = -0.13V / SHE)$$

• Anode Reaction

$$Pb^{2+} + 2H_2O \underset{discharge}{\overset{charge}{\rightleftharpoons}} PbO_2 + 4H^+ + 2e^- \qquad (E^0 = 1.56V / SHE)$$

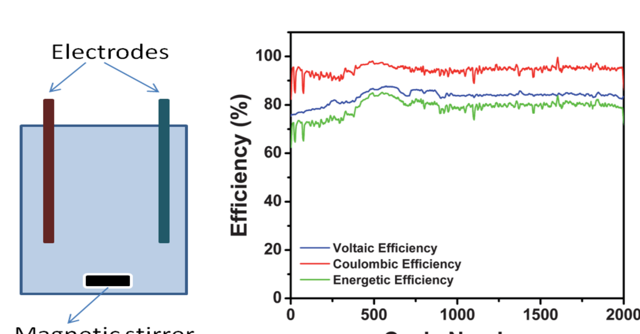
•Side Rxn

$$PbO + H_2O \underset{discharge}{\overset{charge}{\rightleftharpoons}} PbO_2 + 2H^+ + 2e^-$$

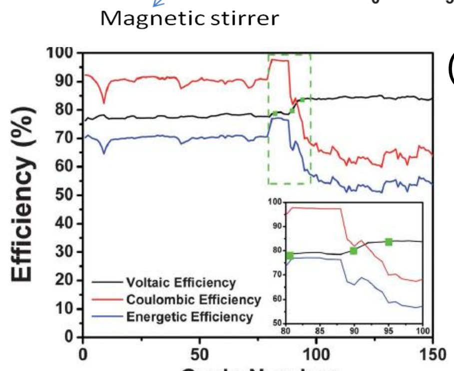
Previous Work

Beaker cell… Intense Agitation

(Verde et al., Energy Envi. Sci., 2013)



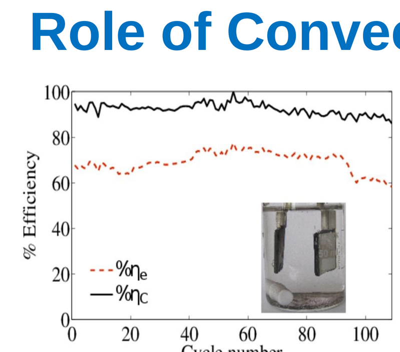
(b)Performance @ 700 rpm



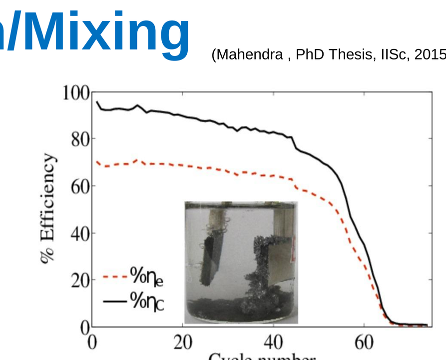
(a)Performance at 300 rpm

Design Experiments to Probe Role of Convection/Mixing

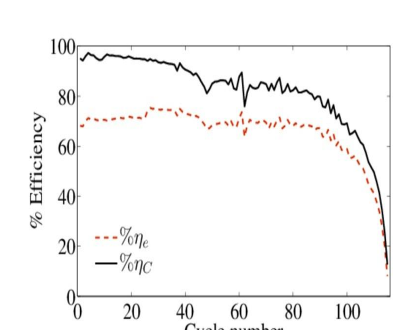
(Mahendra , PhD Thesis, IISc, 2015)



(a)Continuous mixing @ 700rpm

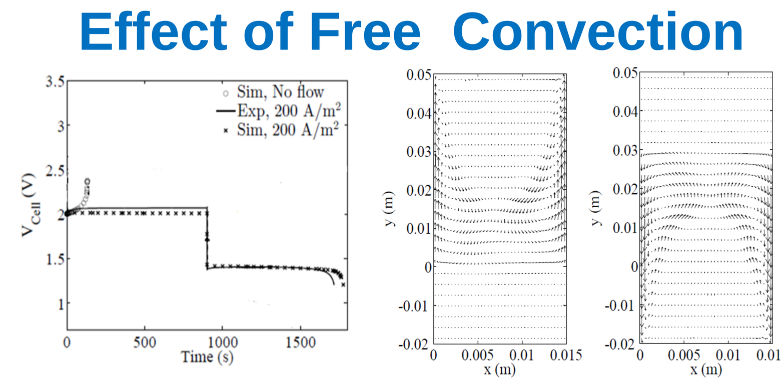


(b)No mixing



(c)Intermittent mixing @ 300rpm

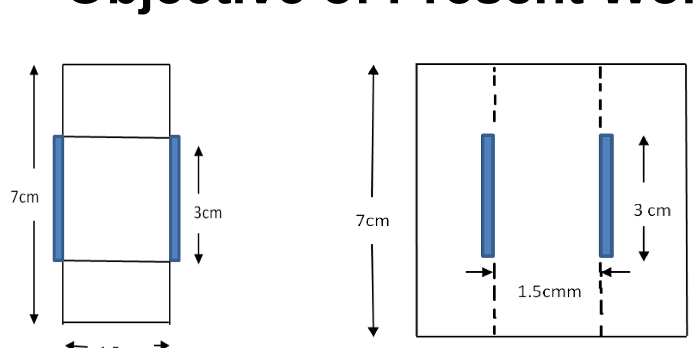
Effect of Free Convection



Cell Potential

Velocity Vector at 100s

Objective of Present Work



Standard cell

Lift cell

Initial & Boundary Conditions

Anode	Cathode
$2F\,(N_{Pb^{2+}}.n) = j_{PbO_2}$ $2F\,(N_{PbO_2}.n) = j_{PbO}$ $j_{PbO_2} + j_{PbO} = j_{an}$ $u = 0$	$2F\,(N_{Pb^{2+}}.n) = j_{Pb}$ $j.n = j_{ca} = j_{Pb}$ $u = 0$

Inlet	Outlet	Initial Cond.
$D_i \nabla c_i . n = 0$ $j.n = 0$	$D_i \nabla c_i . n = 0$ $j.n = 0$	$c_i = c_i^0$ $c^s_{PbO_2} = 0$ $c^s_{PbO} = 0$ $c^s_{Pb} = 0$

Computational Method:

Model Equations

[Newman & Alyea. Electrochemical system(2004)]

Mass Balance Eqn
$$\frac{\partial c_i}{\partial t} = -\nabla \cdot N_i$$

Nernst Planck Eqn
$$N_i = -D_i \nabla c_i - F z_i c_i u_{m_i} \nabla \phi + c_i u$$

Poisson Eqn
$$\nabla^2 \phi = -\frac{F}{\varepsilon} \sum_i z_i c_i$$

Charge Neutrality
$$\sum_i z_i c_i = 0$$

Charge Conservation
$$\nabla \cdot j = 0 \qquad j = F \sum_i z_i N_i$$

Navier Stokes Eqn
$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \mu \nabla^2 u + F \qquad \nabla \cdot u = 0$$

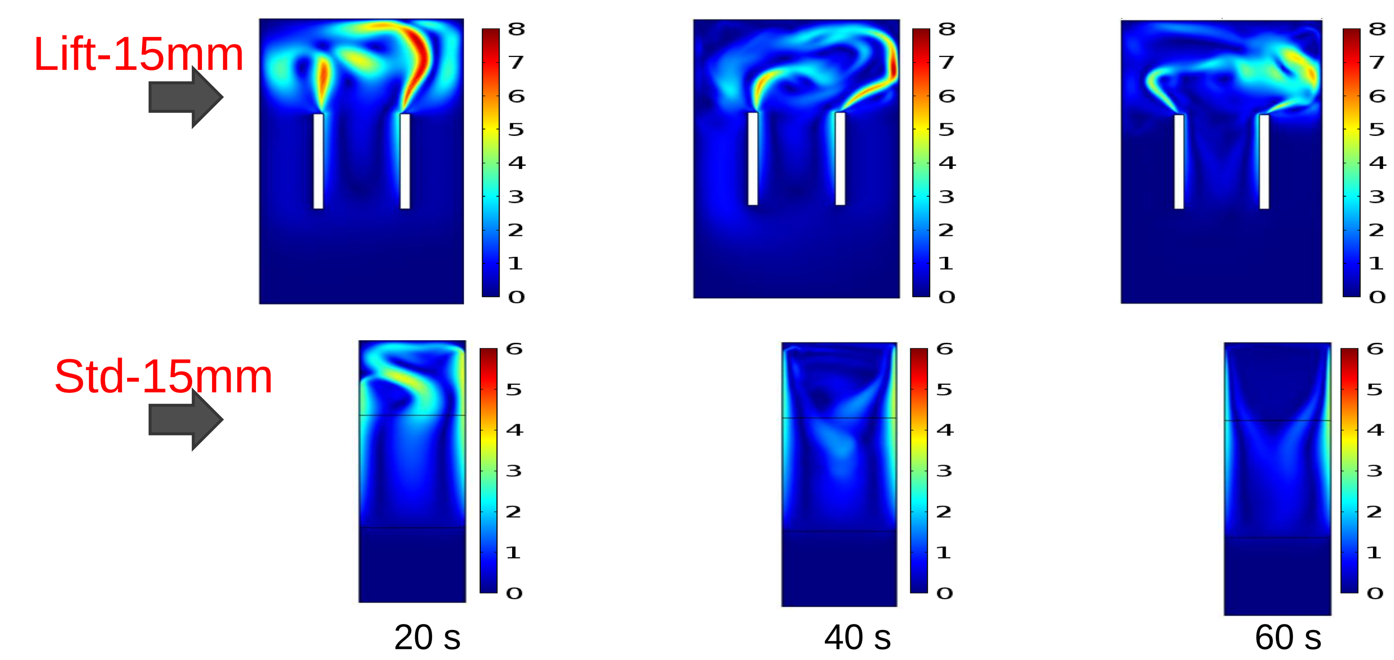
Buoyancy Force
$$F = \rho g \sum_i \beta_i (c_i^0 - c_i)$$

Coeff. of Expansion
$$\beta_i = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial c_i} \right)_{T, P, c_{j \neq i}}$$

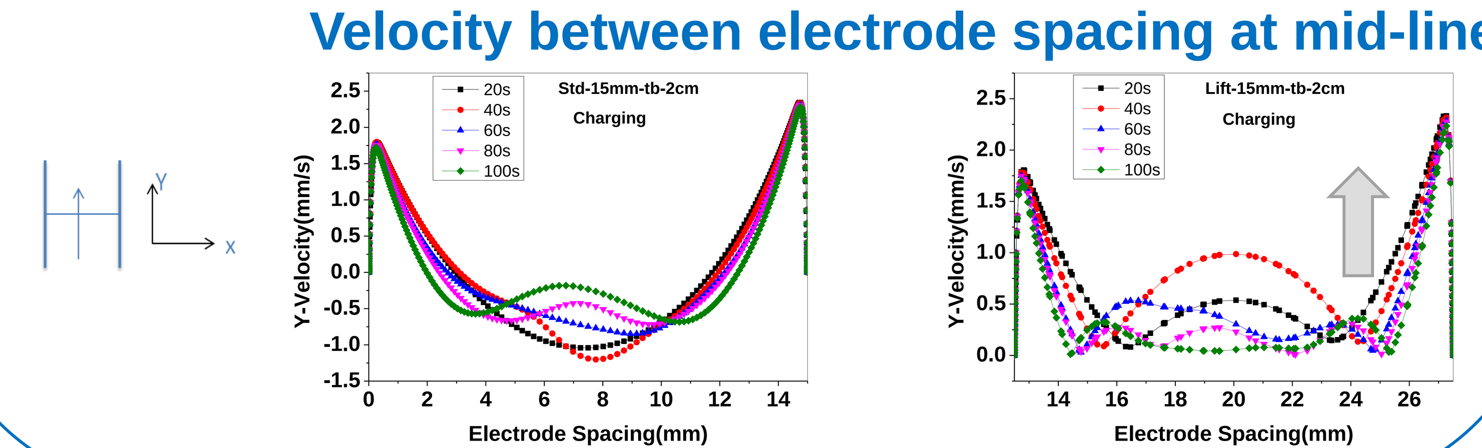
Cell Potential
$$V_{cell} = E_+ - E_- \pm \sum |\eta_\pm| \pm iR$$

Results

Velocity (mm/s): Free Convection Charging

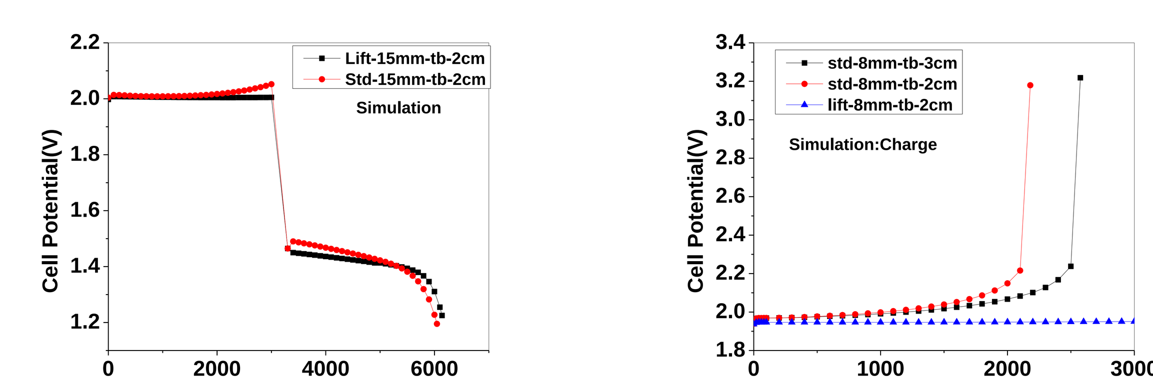


Velocity between electrode spacing at mid-line

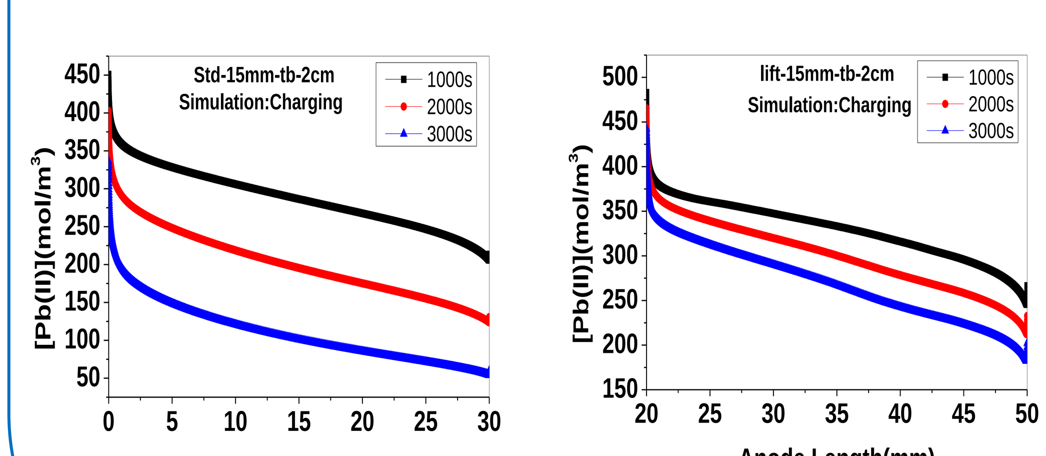


Results

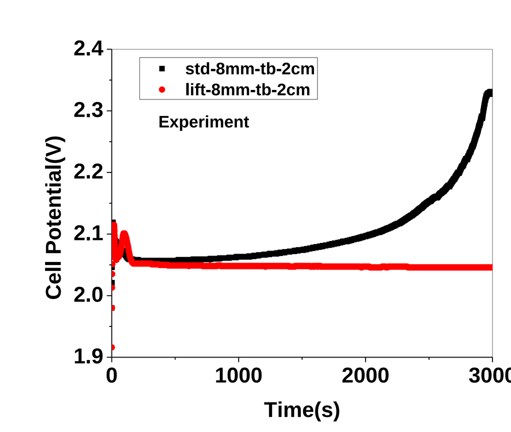
Effect of cell designs on performance



Concentration of Ions at Electrode



Experimental Verification



Conclusions

Alternative designs implemented are able to increase the battery performance. Model and experiment are in good agreement. The efforts are underway to explore new designs, such as slotted or grid type electrodes, as length scale in vertical direction impacts natural convection significantly.

References

[1]Hazza et al. A novel flow battery: A lead acid battery based on an electrolyte with soluble lead(II) Part I. Preliminary studies. Physical Chemistry Chemical Physics, 6(8), 1773-1778 (2004).
[2]Nandanwar, M. N. & Kumar, S. Modelling of Effect of Non-Uniform Current Density on the Performance of Soluble Lead Redox Flow Batteries. Journal of the Electrochemical Society, 161(10), A1602-A1610 (2014).
[3]Shah et al. A mathematical model for the soluble lead-acid flow battery. Journal of the Electrochemical Society, 157(5), A589-A599 (2010).
[4]Verde, et al. Achieving high efficiency and cyclability in inexpensive soluble lead flow batteries. Energy & Environmental Science, 6(5), 1573-1581, (2013).

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