Statistical Analysis On 1-Dimensional and 2-Dimensional Thermal Dissipation for Nickel Metal Hydride Battery System

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Abstract. Due to low environmental impact and rechargeable capability, the Nickel Metal Hydride battery has been considered to be one of the most promising candidate battery for electrical vehicle nowadays. The energy delivered by the Nickel Metal Hydride battery depends heavily on its discharge profile and generally it is intangible to tract the trend of the energydissipation that is stored in the battery for informative analysis. The thermal models were developed in 1-dimensional and 2-dimensional using Matlab and these models are capable of predicting the temperature distributions inside a cell. The simulated results were validated and verified with referred exact sources of experimental data using Minitab software. The result for 1-Dimensional showed that the correlations between experimental and predicted results for the time intervals 60 minutes, 90 minutes, and 114 minutes frompositive to negative electrode thermal dissipationdirection are34%, 83%, and 94% accordingly while for the 2-Dimensional the correlational results for the same above time intervals are44%, 93% and 95%. These correlationalresults between experimental and predicted clearly indicating the thermal behavior under natural convention can be well fitted after around 90 minutes durational time and 2-Dimensional model can predict the results more accurately compared to 1-Dimensional model. Based on the results obtained from simulations, it can be concluded that both 1-Dimensional and 2-Dimensional models can predict nearly similar thermal behavior under natural convention while 2-Dimensional model was used to predict thermal behavior under forced convention for better accuracy.

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INTRODUCTION

A Nickel Metal Hydride (Ni-MH) battery can be conceptually divided into two regions: a core region and a boundary region. The core region consists of a pair of electrodes (for single cell), a separator and electrolyte. The components of Ni-MH are harmless to the environment; moreover, the batteries can be recycled. The Ni-MH battery is safe to operate at high voltage and has distinct advantages, such as storing volumetric energy and power, long cycle life, wide operation temperature ranges, and a resistance to overcharge and discharge[1].

2-dimensional and non-isothermal model for a Ni-MH cell that was constructed on the planar electrode approximation due to the charge/discharge characteristics strongly depend on the cell temperature[2]. For simplicity, they are using a quasi-one dimensional model to describe the battery behavior and performance characteristics. Araki et al. [3], reported examine numerically and experimentally the thermal behavior of the Ni-MH cell during rapid charge and discharge cycles by a one dimensional model.

Heat dissipation in y-direction is examined by one directional model. Assume density, thermal conductivity and heat capacity of the electrode remain constant within temperature range, the one dimensional model can be written as[4]:

$$pC_p \frac{\partial T}{\partial t} = k_y \frac{\partial^2 T}{\partial y^2} + \frac{Q}{V} \quad (1)$$

Nevertheless, the heat dissipation in x-direction is also examined in order to yield more accurate results. The two dimensional model is written as [4]:

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$$\mathrm{pC_p}\ \frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \mathrm{k_x}\frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2} + \mathrm{k_y}\frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2} + \frac{\mathrm{Q}}{\mathrm{V}} \tag{2}$$

where k_x and k_y is the average heat capacity of cell, p is the average density, q is rate of total heat generation and V is the cell volume.

k_x and k_y is calculated based on the concept of equivalent electric resistance connected in a series or parallel form, when current pass through y-direction, k_y is series connected and is estimated according to following equation[4]:

$$k_y = \frac{L_y}{\sum \frac{L_{yi}}{k_i}} = \frac{L_y}{\frac{L_{yp}}{k_p} + \frac{L_{yn}}{k_n} + \frac{L_{ys}}{k_s}} \tag{3}$$

On the other hand, k_x which is parallel connected is estimated as:

$$k_x = \sum \frac{k_i L_{yi}}{L_y} = \frac{k_p L_{yp} + k_n L_{yn} + k_s L_{ys}}{L_y} \tag{4}$$

where k_i is calculated based on composite concept and can be written as:

$$k_i = k_{mi}(1-\varepsilon) + k_f(\varepsilon) \tag{5}$$

where k_{mi} is the conductivity of active materials, k_f is conductivity of electrolyte and ε is the porosity of the electrode.

Heat generated equation in is in unit kJ/h, since in this work, the time different is in seconds, hence we have to convert it to J/s, and heat generation per unit volume during charging without any sub reaction [5] is written as:

$$\mathrm{Q_c} = \left[0.547\mathrm{I_c} + 3.61{\mathrm{I_c}}^2\mathrm{R_t}\right] \times \frac{1000\left(\frac{\mathrm{J}}{\mathrm{kJ}}\right)}{3600\left(\frac{\mathrm{s}}{\mathrm{h}}\right)} \tag{6}$$

However, at the end of charging, sub reaction of the battery will start to occur and the heat generation per unit volume is written as:

$$Q_s = \left[5.334I_c + 3.61{I_c}^2R_t\right] \times \frac{1000\left(\frac{J}{kJ}\right)}{3600\left(\frac{s}{h}\right)} \tag{7}$$

The reaction when discharging is exothermic and the equation is as following:

$$Q_d = \left[-0.547I_d + 3.61{I_d}^2R_t\right] \times \frac{1000\left(\frac{J}{kJ}\right)}{3600\left(\frac{s}{h}\right)} \tag{8}$$

STATISTICAL MODEL VALIDATION

Assuming a constant heat transfer coefficient over the battery external surface, the boundary condition [6] can be written as follow:

$$-k_x\frac{\partial T}{\partial x} = \left[\frac{L_A}{k_A} + \frac{1}{h}\right]^{-1}(T - T_o) \tag{9}$$

at x = 0 and x = L_x, $0 < y < L_y$

$$-k_y \frac{\partial T}{\partial y} = \left[\frac{L_A}{k_A} + \frac{1}{h}\right]^{-1} (T - T_o) \quad (10)$$

at y = 0 and y = L_y, $0 < x < L_x$

where L_A denotes the thickness of wall, k_A represents thermal conductivity of wall. Eq. 9 and Eq. 10 are for 2-dimensional model while Eq. 9 only is for one-dimensional model.

In this study, the battery was kept at ambient temperature prior to charging and discharging. Table 1 and table 2 below shows the specific parameters uses in this study. Therefore, the initial condition can be written as:

$$T = T_o \quad (11)$$

at t = 0, $0 < x < L_x$, $0 < y < L_y$

TABLE (1). Cell specific parameters for thermal model

Parameter	Unit	Value	Source
Capacity of Cell	A-h	30	[4]
Length of nickel electrode,δ_{Ni}	mm	7.4	[4]
Length of MH electrode,δ_{MH}	mm	5.4	[4]
Length of separator,δ_{Sep}	mm	6.2	[4]
Thickness of the wall,L_A	mm	0.5	[4]
Porosity of nickel electrode,ε_{Ni}	-	0.22	[4]
Porosity of MH electrode,ε_{MH}	-	0.27	[4]
Porosity of Separator,ε_{Sep}	-	0.74	[4]

TABLE (2). Values of parameters for the baseline case in thermal model

Parameter	Unit	Value	Source
Average density, p	Kg/m^3	3250	[4]
Average heat capacity, C_p	J/kg-K	3200	[4]
Initial temperature,T_o	^oC	23.5	[4]
Thermal conductivity of structural material in nickel electrode,k_{Ni}	W/m.K	1.14	[4]
Thermal conductivity of structural material in MH electrode,k_{MH}	W/m.K	1.16	[4]
Thermal conductivity structural material in separator,k_{Sep}	W/m.K	0.22	[4]
Thermal conductivity of wall,k_A	W/m.K	468	[4]
Thermal conductivity of KOH,k_{KOH}	W/m.K	0.57	[4]

This model is validated by experimental results of from Wu et al. [4], the experimental results are listed in Table 3 (a), Table 3 (b), Table 3 (c), Table 3 (d), Table 3 (e) and Table 3 (f) below.

TABLE (3a). Temperature of battery along x-direction at 60 minutes

X, mm	Temperature, ℃
22.675	28.919
44.813	29.264
67.352	28.805

TABLE (3b). Temperature of battery along y-direction at 60 minutes

Y, mm	Temperature, ℃
3.2715	29.069
6.629	28.912
9.9949	29.263
13.351	29.033
16.709	28.948

TABLE (3c). Temperature of battery along x-direction at 90 minutes

X, mm	Temperature, ℃
22.755	31.547
45.331	32.256
67.877	32.017

TABLE (3d). Temperature of battery along y-direction at 90 minutes

Y, mm	Temperature, ℃
3.3227	31.978
6.5237	32.039
9.8874	32.245
13.407	32.233
16.602	31.930

TABLE (3e). Temperature of battery along x-direction at 114 minutes

X, mm	Temperature, ℃
22.553	38.702
45.577	40.066
67.653	38.513

TABLE (3f). Temperature of battery along y-direction at 114 minutes

Y, mm	Temperature, ℃
3.6068	39.032
6.822	39.893
10.026	40.100
13.376	39.579
16.730	39.203

RESULT AND DISCUSSION

Statistical models validation (T-Test) was done by using Minitab 16 software. The purpose of this model is to reconfirmation of the result data using simulated model compare with the result data from the previous experiment. Table 4 (a), 4 (b), and 4 (c) shows the comparison result between experimental and predicted data in x-direction at 60 minutes.

TABLE (4a). Comparison between predicted and experimental temperature of battery along x-direction at 60 minutes

X, mm	Experimental Temperature, ºC	Predicted Temperature 2D-Model, ºC
22.6748	28.919	29.218
44.8131	29.264	29.249
67.3521	28.805	29.157

TABLE (4b). Paired samples statistics in x-direction at 60 minutes

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Experimental Temperature	28.996	3	.2388	.1379
	Predicted Temperature 2D	29.208	3	.0468	.0270

TABLE (4c). Paired samples correlations in x-direction at 60 minutes

	N	Correlation	Sig.
Experimental Temperature & Predicted Temperature	3	.890	.301

From the result above, it can be shown that the significant p-value between experimental temperature and predicted temperature in x-direction at 60 minutes which is 0.301.This value did not indicate good correlational proximity because significant p-value should be below 0.05 to generate the good correlational proximity between

experimental temperature and predicted temperature. Hence, the correlation between these two is only about 89% which is not the expected significant result.

Table 4 (d) and 4 (e) below shows the comparison result between 60 minutes, 90 minutes, and 114 minutes in x-direction and y-direction.

TABLE (4d). Significant p-value results between time in x-direction and y-direction

Time	x-direction	y-direction (1D)	y-direction (2D)
60	0.301	0.577	0.463
90	0.251	0.083	0.020
114	0.024	0.018	0.014

TABLE (4e). Correlation results between time in x-direction and y-direction

Time	x-direction (%)	y-direction 1D (%)	y-direction 2D (%)
60	89.0	33.9	43.6
90	92.3	82.8	93.4
114	99.9	93.8	94.8

Based on the T-Test result shown in the table 4 (d) and 4 (e) above, it is showing the significant p-value results and correlation results between experimental temperature and predicted temperature in x-direction and y-direction for three different durational times. While as we observe the increment in the time duration relatively reduced the p-values and increased the correlational value to good proximity. From these results, it can be shown that the significant between experimental and predicted temperature for y-direction at 114 minutes has shownclosed proximity in the correlation between experimental and predicted result for both 1D and 2D. According to this comparison, the 1-dimensional model and 2-dimensional model tend to differ less in terms of temperature rise as the heat transfer coefficient at the external surface is decreased. In addition, comparing forced and natural convections indicates that the battery temperature is remarkably lower under forced convection than under natural convection. This discrepancy is ascribed to the fact that forced convection can sufficiently dissipate the generated heat. The 1-Dimensional model becomes less accurate than the 2-Dimensional model under forced convection.

CONCLUSION

The thermal model is simulated in 1-dimensional and 2-dimensional and capable to predict the temperature distribution within a cell, thus provide a cost effective tool to predict the thermal behavior of a battery. The simulation results are validated and verified by referred sources of experimental data and they are well correlated. Based on results obtained from simulations, the observed comparisons with experimental data are showing that 2-dimensional gives more accurate results than 1-dimensional model. However, 1-dimensional model is sufficient to predict the temperature distribution within the cell under natural convection. This is because the temperature gradient in the x-direction is not as pronounced as forced convection and can be neglected. The validation of the thermal curve profiling from experimental data have been compared with the extracted data from the literatures work with the simulation data. This is some of the best way to see whether the predicted results are matches with the experimental result and can give a confirmation that the battery system for Ni-MH can be predicted. It can be seen that the experiment data are distributed around the simulated curve.

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