Thermal Effects on Non-Rechargeable Li-ion Batteries due to Temperature Changes

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***Abstract*– Li-ion batteries currently are the most used power source of different electric and electronics systems. Several works study the temperature effect on rechargeable batteries' performance, but there are limited experimental results of non-rechargeable batteries. This paper presents the thermal effects on non-rechargeable Li-ion battery CR2 model, exposing them to different temperatures to compare it with the manufacturer's data. The result of this research shows that thermal shock and extreme temperature decrease discharge time or operation voltage which impact their performance.**

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I. Introduction

At present lead-acid, nickel-metal hydride (NiMH), and lithium-ion (Li-ion) have been the choices for commercial applications. Different factors are considered in the selection of battery, but the more important factors are energy capacity (Ah), energy density (Wh/kg), power density (W/kg), longevity, cost, safety, and voltage per cell. Lithium-ion type of battery is considered to be one of the most promising technology for modern applications due to its highest power density on a per-unit of volume and weight basis of commercial batteries.

In [1] various technologies and application considerations are presented. The study includes the characteristics of different type of rechargeable batteries, electrical models, and criteria for battery selection.

Due to the constant change of temperature that batteries may experience during operation, recent studies are focused on temperature effect on battery performance. Studies based its experiments on different batteries capacities and typically are interested in two of the more promising commercial applications areas: batteries used on mobile applications and electric vehicle technology [2-4]. However, although almost all the investigations base their studies on rechargeable Li-ion batteries, information about temperature effects on non-rechargeable Li-ion batteries for low power applications are not available. Basically, the only information available for a customer is the limited data sheet provided by manufacturers, which do not specify under what conditions the tests were made to determine the ideal operating temperature range. Also, no report or study shows a comparison of several non-rechargeable CR2 Li-ion battery models that bring a customer useful information to determine the best battery brand for their specific application or design working under some special temperature conditions.

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Previous research activities focused on the generation of models to incorporate thermal and rate factors effects to allow dynamic simulations and virtual prototyping of Li-ion battery-powered systems using engineering simulation packages such as Matlab, VTB, AMESim, CADENCE, among others [5-7].

This research is focused on the study of the thermal effects on non- rechargeable CR2 Li-ion batteries typically used in low power commercial applications, exposed to different temperatures. Results of this research give a scientific evidence of thermal effect due to temperatures changes that are present in cities and could affect the batteries performance typically used as power source for commercial products. Experimental results were compared with simulations performed in PowerSim (PSIM).

II. Experimental procedure

In order to determine how CR2 Lithium-Ion batteries are affected by temperature changes, a specific procedure was implemented to perform the study.

A. Experimental Setup

PLA printing filament, which is an environmentally friendly polymer, was selected to making the enclosures using an Afinia 3D printer (see Figure 1).

Fig. 1 Afinia 3d Printer and set of tests enclosures

To produce certain temperature conditions, two heating chambers were built (see Figure 2). The desired temperature was adjusted by a universal temperature controller F/C SSR thermostat temperature Controller Output using a programmable digital adjustor PID with a power supply of 90-260V AC, 60Hz. The temperature controller adjusted the pulsed-power of two light bulbs of 250W to reach the desired temperature. The actual temperature inside was measured using a thermocouple K-type.

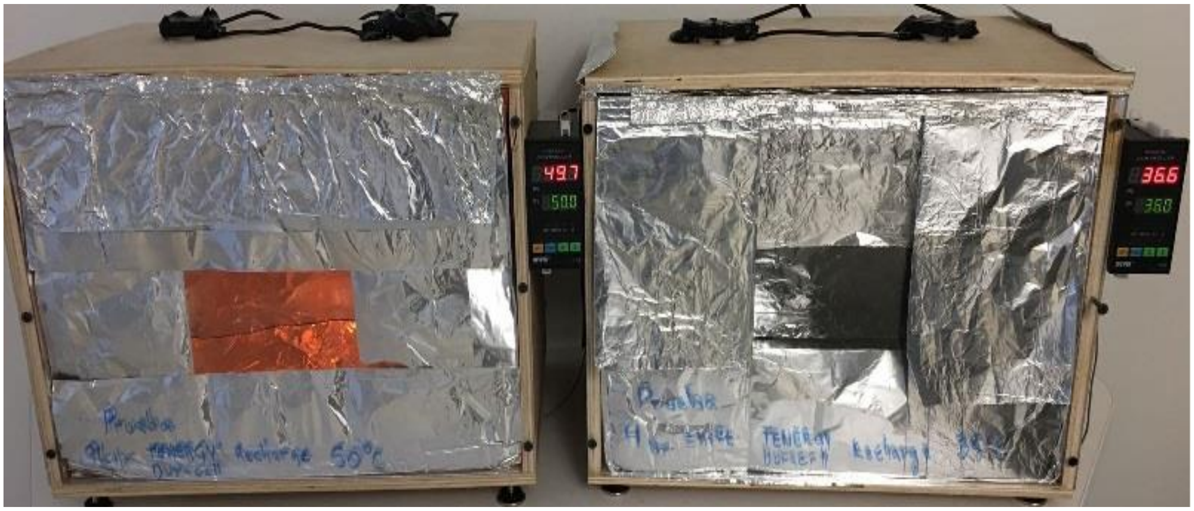


Fig. 2 Heating Chambers.

A refrigerator was used to reach 0°C while digital thermometer with a range of -40°C to 71°C was configured to ensure correct temperature condition. To begin the discharging process, a circuit board with a fixed load resistance of 280Ω (surface mount) was connected in parallel with the battery which makes it easy to calculate the current extracted from the battery, power delivered, and the expected time of discharge.

B. Batteries

3V CR2 Li-ion non-rechargeable batteries were used during this research. This battery model is commonly used in low power commercial application such as digital cameras and photographic equipment, flashlights and Remote Control (RC) car toys, due to their size and capacity. In USA different brands are available in department stores and pharmacies, but some of the more common are: Duracell, Nuon, and Tenergy.

Figure 3 shows the circuit board used to discharge the batteries and two battery's brands: Duracell and Tenergy. Board is inserted inside the enclosure mentioned before.

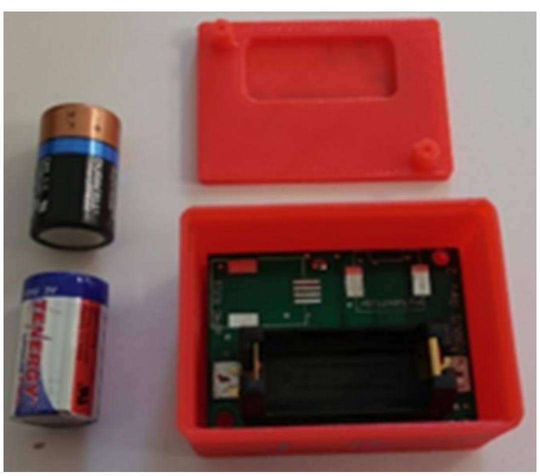


Fig. 3 CR2 Li-ion Battery with the circuit board.

A summary of main information available in datasheets of these batteries is shown in Table I. Three batteries have the same nominal voltage and similar capacity and operating temperature range. Nuon battery is 46% heavier than the other two batteries.

TABLE I. Parameters available in batteries' datasheet

Battery	**Capacity (mAh)**	**Nominal Voltage (V)**	**Operating Temp. (°C)**	**Average Weight (g)**
Duracell	780	3.0	-20 to 75	11
Nuon	780	3.0	-20 to 60	16
Tenergy	750	3.0	-20 to 60	11

C. Temperature Changes

Four test scenarios were created to expose the batteries to the following temperatures:

- Constant temperature of 25°C (room temperature)
- Constant temperature of 50°C (high temperature).
- Constant temperature of 0°C (low temperature).
- Temperature changes from 0°C to 35°C (thermal shock – T.S.) using the following temperature profile: 0°C (10am – 2pm), 25°C (2pm – 6pm), 36°C (6pm – 10pm), and 25°C (10pm – 10am).

Three different tests were made for each battery brand selected and the average calculated value was plotted to study discharge behavior and how is affected by different conditions that can lead to poor or good battery performance. The number of batteries readings were four per day (every four hours from 10am to 10pm).

D. Simulations

Different engineering simulations packages are available to perform studies in all the engineering fields. PowerSim was selected because it is commonly used in the field of power electronics and motor drive and can be used to simulate any electronic circuit.

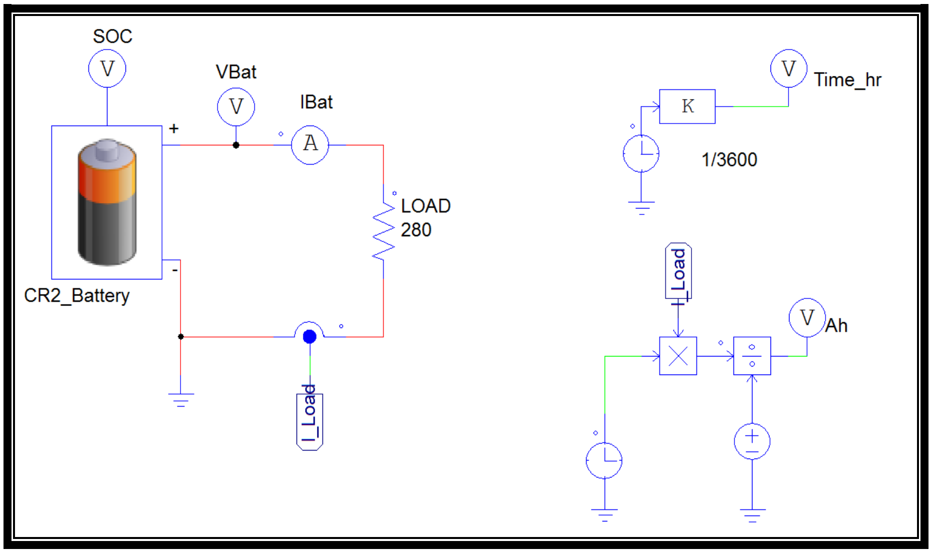


Fig. 4 Simulation in PSIM

III. RESULTS

Figure 4 shows a model created in PowerSim that was used to compare experimental results with manufacturer parameters. Model was compose using a standard battery modified to include CR2 parameters, measurement elements to acquire voltage and current in the whole system, a load with the same value used during experimentation, and conversion units blocks.

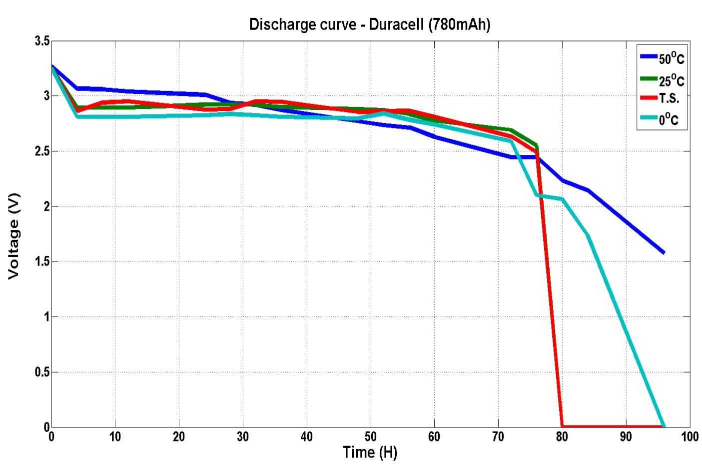
A simulation sampling time of 10 seconds and a room temperature (25°C) were selected to run the simulations for each CR2 brand studied. Temperature changes cannot be included but with room temperature condition the reliability of the results obtained experimentally can be validated.

A. Non-rechargeable CR2 Duracell Battery

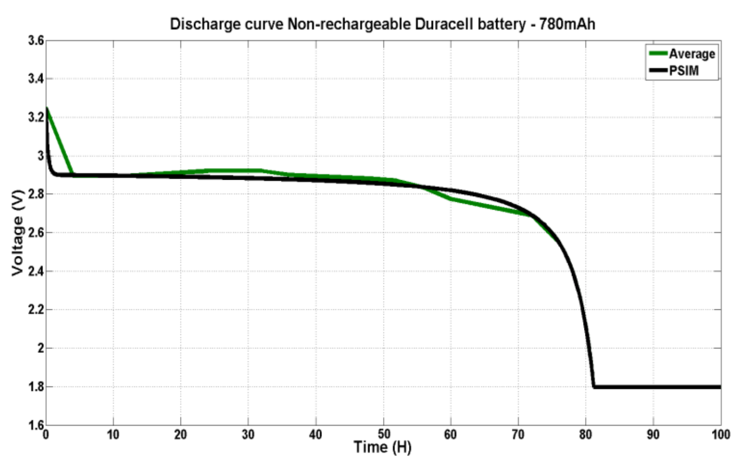
Figure 5(a) shows average values for the 4 test scenarios created while plots of results obtained at 25°C between experiments and simulations performed in PSIM using datasheet's parameters are shown in Figure 5(b).

Results presented in Figure 5(a) show that Duracell batteries have a constant voltage value in almost all their operating time at room temperature. When the battery is exposed to extreme temperature (0ºC or 50ºC), its operating voltage is lower than operating at room temperature, and a bigger ripple is however presented as well, the discharge time is approximately 20% more than at room temperature. On the other hand, when exposed to thermal shock scenario, the battery has a similar behavior as operating at room temperature.

A maximum measurement error of 1.5% can be estimated from results presented in Figure 5(b). This is due to the accuracy of the measurement element, load resistance tolerance, and estimation of some battery parameters.



(a)



(b)

Fig. 5 Non-rechargeable CR2 Duracell Li-ion battery plot for: (a) average values for different temperature tests; (b) simulation in PSIM at 25°C

B. Non-rechargeable CR2 Nuon Battery

Figure 6(a) shows average values results for the 4 test scenarios created while plots of results obtained at 25°C between experiments and simulations performed in PSIM using datasheet's parameters are shown in Figure 6(b).

Results presented in Figure 6(a) shows that Nuon batteries have small oscillations on operating voltage at room temperatures during 60% of their operational time. After that, their operating voltage decrease at a significant rate until fully discharge. When the battery was exposed to extreme temperature or thermal shock scenarios, the battery was not able to maintain a constant voltage which can generates an undesired voltage on the load.

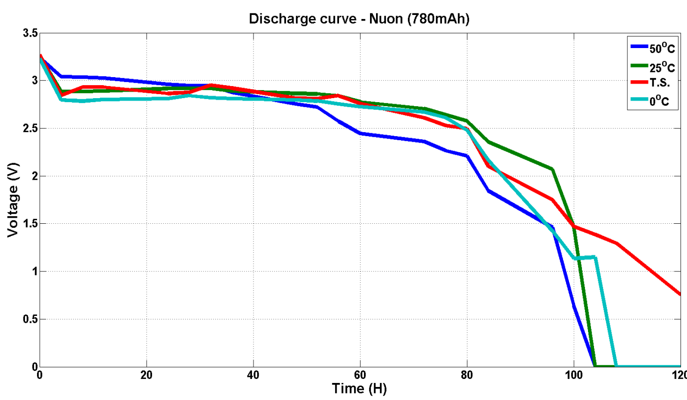
From results presented in Figure 6(b), a maximum measurement error of 7% can be observed at 84 hours of discharge when the battery had a 15% of its total capacity.

C. Non-rechargeable CR2 Tenergy Battery

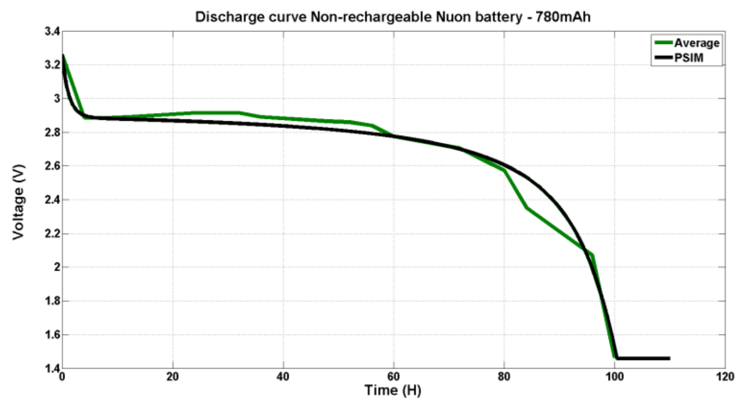
Figure 7(a) shows average values results for the 4 test scenarios created while plots of results obtained at 25°C between experiments and simulations performed in PSIM using datasheet's parameters are shown in Figure 6(b).

A high impact on the capacity of Tenergy battery operating at high temperatures was identified according with results presented in Figure 7(a). This explains the ripple on operating voltage when battery is operating under thermal shock scenario. However, operating voltage is constant in almost the whole range of operation. Discharge time is similar in all cases, except at 50°C.

From results presented in Figure 7(b), a maximum measurement error of 3.7% can be observed at first 20 hours of discharge time.

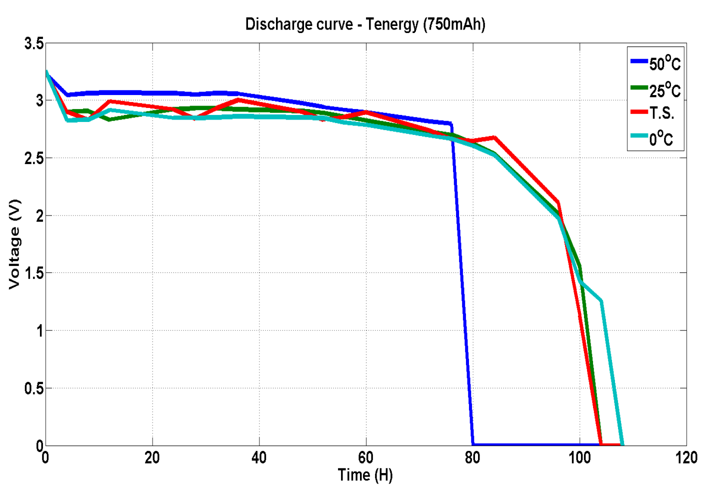


(a)

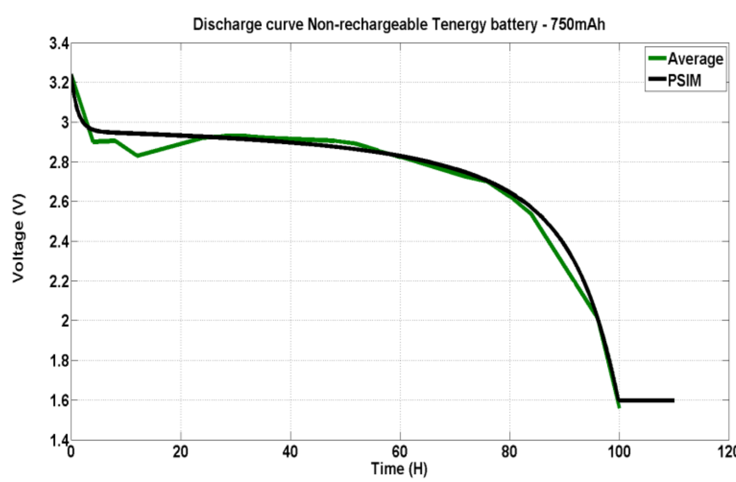


(b)

Fig. 6 Non-rechargeable CR2 Nuon Li-ion battery plot for: (a) average values for different temperature tests; (b) simulation in PSIM at 25°C



(a)



(b)

Fig. 7 Non-rechargeable CR2 Tenergy Li-ion battery plot for: (a) average values for different temperature tests; (b) simulation in PSIM at 25°C

D. Climate in the USA

The National Oceanic and Atmospheric Administration (NOAA) is an agency within the Department of Commerce that provide citizens, planners, emergency managers and other decision makers with reliable information about weather forecasts, severe storm warnings, and climate monitoring [8]. This information is continuously updated, and it is available for free on its website and can be downloaded by anyone to be processed in the most convenient way possible.

In particular, climate information is available from 1895 to present and can be segregated by states, regions, and country which include all 48 states. Average temperature, maximum or minimum temperature, precipitation, among others, can be used as a parameter to obtain specific information.

According with data collected from last decade (2006 - 2016) by NOAA, the annual average temperature of all US States varies from 0°C to 24°C during all months of the year as presented in Figure 8. Lower temperatures are identified at winter season (December to February), the highest temperature at summer season (June - August) while the medium temperature at spring (March - May) and fall (September - November) seasons.

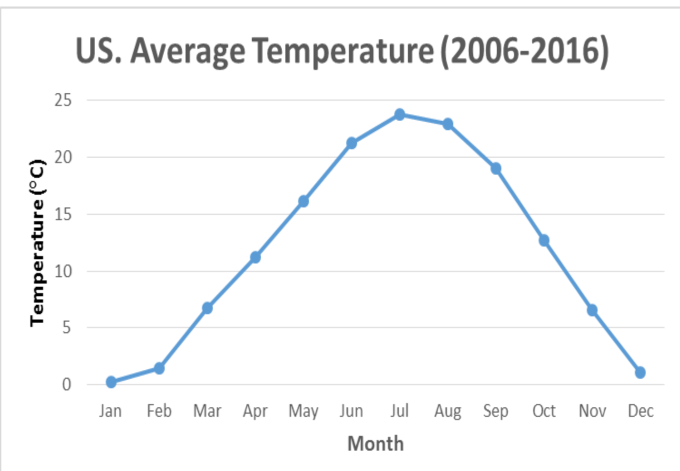


Fig. 8 Annual average temperature by month of all US. States from 2006 to 2016

To simplify the analysis, United States can be divided into four regions: Eastern, Southern, Central, and Western. To obtain critical temperature values from all data collected, four months were selected to represent critical values for each season: January (winter), April (spring), July (summer), and October (fall). Maximum, minimum, and average values of temperature by region for each selected month are summarized in Table II. Same term period was used (January 2006 – December 2016).

TABLE II. Average temperature by region from 2006 to 2016

Month	Region	Max. Value	Min. Value	Average
January	Eastern	4	- 6.33	- 1.17
	Southern	13.39	- 0.12	6.67
	Central	0.5	- 10.78	- 5.17
	Western	6.28	- 4.78	0.73
April	Eastern	17.5	4.17	10.84
	Southern	24.67	9.95	17.33
	Central	15.22	1.56	8.39
	Western	16	1.78	8.89
July	Eastern	28.89	17	22.95
	Southern	33.28	20.78	27
	Central	29.33	15.56	22.4
	Western	30.73	14	22.39
October	Eastern	18.17	6.45	12.34
	Southern	27.17	10.73	17.95
	Central	16.5	3.33	9.95
	Western	18.06	4.17	11.12

Results demonstrate that the lowest temperatures occur in the Eastern and Central regions during the winter season, while the highest temperatures occur in the summer season in the Southern and Western regions. On the other hand, significant temperature variations occur in all regions in the spring and fall seasons.

IV. CONCLUSIONS

This research presents the behavior of non-rechargeable CR2 Li-ion batteries operating at different temperature conditions and supplying a constant load. Results show a good behavior of Tenergy brand working at different temperature. Therefore it is recommended for most regions of the USA as a power source for low power applications. On high temperatures regions, their operation time will be approximately 20% less than the other regions.

Nuon battery has been recommended in applications where temperature is controlled due to their performance is decreased when it is operating under temperature changes. Duracell battery has acceptable behavior to sudden changes in temperature, making it a good choice for the central and western regions of the country, especially when seasonal changes are nearing.

This project serves as the starting point for obtaining models of non-rechargeable Li-ion batteries in which changes in temperature could be included and then generate power converters that allow the extension of the battery life.

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REFERENCES

[1] A. Chen and P. Sen, "Advancement in Battery Technology: A state of the art review," *IEEE Industry applications society annual meeting,* Portland, 2016.

[2] J. Leuchter and P. Bauer, "Capacity of power-batteries versus temperature", *IEEE European Conference on Power Electronics and Applications,* Geneva, 2015.

[3] H. Song, J. Jeong, B. Lee, D. Shin, B. Kim, T. Kim, and H. Heo. Bauer, "Experimental study on the effects of pre-heating a battery in a low-temperature environment", *IEEE Vehicle Power and Propulsion Conference,* Seoul, 2012.

[4] P. Keil, M. Englberger, and A. Jossen, "Hybrid Energy Storage Systems for Electric Vehicles: An Experimental Analysis of Performance Improvements at Subzero Temperatures", *IEEE Trans. on Vehicular Technology*, vol. 65, No. 3, pp. 998-1006, March 2016.

[5] Y. Tan, J. Mao, and K. Tseng, "Modelling of battery temperature effect on electrical characteristics of Li-ion battery in hybrid electric vehicle", *IEEE International Conference on Power Electronics and Drive System,* Singapore, 2011.

[6] S. Bhide and T. Shim, "Development of improved Li-ion battery model incorporating thermal and rate factor effects", *IEEE Vehicle Power and Propulsion Conference*, Dearborn, 2009.

[7] L. Gao, S. Liu, and R. Dougal, "Dynamic Lithium-Ion Battery Model for System Simulation", *IEEE Trans. on Components and Packaging Technologies*, vol. 25, No. 3, pp. 495-505, September 2002.

[8] NOAA, Climate. Available in: https://www.ncdc.noaa.gov/cag/. Date of last access: February 16th, 2017.