# Thermal Study of Valve Regulated Lead Acid Batteries and Electronics Chamber Used in Stand-Alone Street Lighting Applications

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**Abstract:** This paper presents a study on the heat generation of Valve-Regulated Lead Acid (VRLA) batteries used in certain off-grid street-lighting applications from PoleCo, a Halifax based company. One goal of the project was to produce validated COMSOL models of the enclosure that holds these VRLA batteries. This model can then be used to investigate methods of reducing the temperature of the batteries based on environmental conditions. In order to provide this validation, COMSOL models of experiments were built and the results were compared to the associated experimental data. For models involving heat conduction in solids, the COMSOL models provided very accurate results. For models incorporating natural convection and the influence of additional electrical components, producing accurate COMSOL models proved more challenging.

**Keywords:** Heat Generation, Battery Thermal Management, Conduction, Natural Convection.

## 1. Introduction

PoleCo is a Halifax, Nova Scotia based company that designs and supplies grid-independent street lighting systems. These street lights derive all of their power from renewable sources using small wind turbines, solar panels, or a combination of the two. In order to store the power, each street light has on-board rechargeable Valve Regulated Lead Acid (VRLA) batteries. These batteries store power generated, for example, by the solar panel during the day so that the streetlight can reliably draw power all night. The batteries are selected for their durability and long cycle lives, so that they can operate continuously for long durations in the field. Replacing these batteries is expensive both because of their unit cost, and also the expense of sending repair crews into the remote off-grid locations where the streetlights are usually installed. Hence, PoleCo has great interest in methods for prolonging the lifetime of the batteries.

One area where the VRLA batteries are particularly vulnerable is temperature management. In general, when a lead acid battery receives a float charge at a temperature 10°C above its intended operating temperature, the battery's life will be cut in half [1]. This temperature effect is especially troublesome for the PoleCo streetlights, because many of them are installed in locations with very high daytime ambient temperatures, such as Jamaica and Qatar. In addition, the batteries themselves generate some heat due to the effects of internal resistance to current flow as well as the electrolyte chemistry within the cells [1].

In order to develop a better understanding of the heat generation characteristics of their street-lighting system, PoleCo is collaborating with the Lab of Applied Multiphase Thermal Engineering (LAMTE) at Dalhousie University. Over the course of this project, experiments on the VRLA batteries and associated equipment have been performed. One phase of this project is to also create and validate numerical models of the experiments using COMSOL Multiphysics 4.4. This will lead to the next stage of the project, using the validated numerical models of the system to test methods of mitigating the heat gain in that system, such as through solar shielding or active cooling via fans.

This paper will present a brief summary of the experimental work carried out during this project, and then describe in detail the COMSOL models designed to simulate the experiments. The results of these simulations will be compared with the associated experiments both to validate the models and to test the accuracy of calculations aimed at predicting temperature rise of the batteries.

## 2. Use of COMSOL Multiphysics

### 2.1 Insulated Battery Experiment

#### 2.1.1 Geometry and Materials

The first experiments performed on the battery were designed to measure its temperature gain when charged at different rates. The experimental setup involved one VRLA battery enclosed in a tight-fitting box made from half-inch RSI-0.5 extruded polystyrene (XPS). The battery was charged with a bench-top DC power supply set to 14.5 V and various charging currents. The temperature of the battery was measured with fourteen adhesive T-type thermocouples arranged along the surface of the polypropylene casing.

In COMSOL, this experiment was modeled as two blocks, one representing the battery and the other representing the insulation, as shown in Fig. 1. The battery domain is 287 mm tall, 342 mm long, and 172 mm wide. The insulation block is subdivided into six panels to make it easier to mesh. This geometry is extremely simplified, and does not include any of the surface features of the battery such as handholds and electrical terminals, as seen in Fig. 2. In addition, the internal geometries of the cells that make up the battery were not included in the COMSOL model.

The thermophysical properties of the materials used in this simulation are defined by the values in Table 1.

**Table 1: Material Properties used in COMSOL Simulation**

| Material | Insulation | Battery |
|---|---|---|
| Thermal Conductivity (W/m·K) | 0.0254 | 34 |
| Density (kg/m$^3$) | 21 [2] | 2841 |
| Heat Capacity (J/kg·K) | 1500 [3,4] | 862.3 |

The density of the battery was calculated from direct measurement of its mass and volume. The heat capacity and thermal conductivity were calculated using a weighted average of the materials inside the battery, taken from the material data safety sheet [5].

In addition, the battery domain has fourteen boundary point probes arranged along its surface to record the temperature. These point probes are placed in locations that match the positions of the thermocouples used in the experiments to measure the battery temperature, as seen in Fig. 3. The purpose of these probes is to provide a convenient method for comparing the temperature data from the COMSOL simulation with the temperature data collected experimentally.

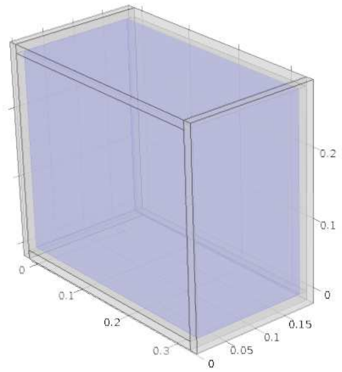

**Figure 1**. COMSOL Geometry of Insulated Battery.

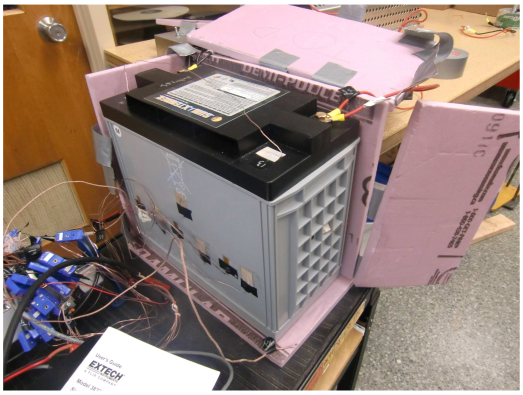

**Figure 2**. Photo of Insulated Battery with Associated Experimental Equipment.

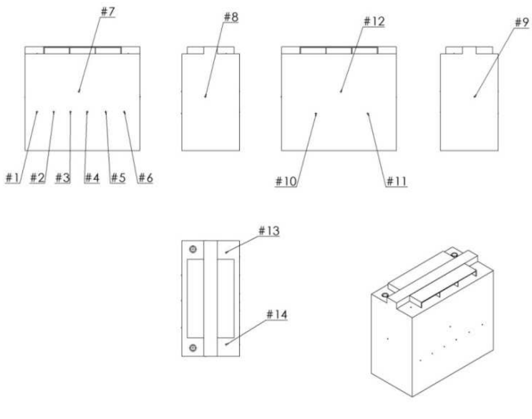


**Figure 3**. Schematic of Thermocouple Positions on Battery.

### 2.1.2 Governing Equations and Boundary Conditions

The Heat Transfer in Solids module is applied to all the domains. The initial temperature of the battery and insulation domains is set to a representative value from the charge experiment that is to be validated. For example, in Charge Experiment #5 (CE #5) the initial temperature was 22.2°C. The faces of the insulation not facing the ground are given boundary conditions appropriate for natural convection and radiation to ambient conditions at 22.2°C; the bottom surface in contact with the workbench is fixed at 22.2°C.

The battery domain is assigned as a heat source with power defined by a function specific to the experiment. The heat generation due to internal resistance inside the battery is given by Eq. (1) [6]:

$$P_{OV} = IDV \quad (1)$$

where $P_{OV}$ is the heat generated (W), $I$ is the current flowing through the battery (A), and $DV$ is the over-voltage (V). Over-voltage is the difference between the open circuit voltage of the battery before charging begins and the measured voltage at the battery terminals during charging. The values of $I$ and $DV$ for an experiment can be determined from measured values and are presented in Fig. 4.

The data presented in Fig. 4 is then simplified into a series of linear functions that are plotted in a piecewise fashion and set as a uniform power generation for the battery domain.

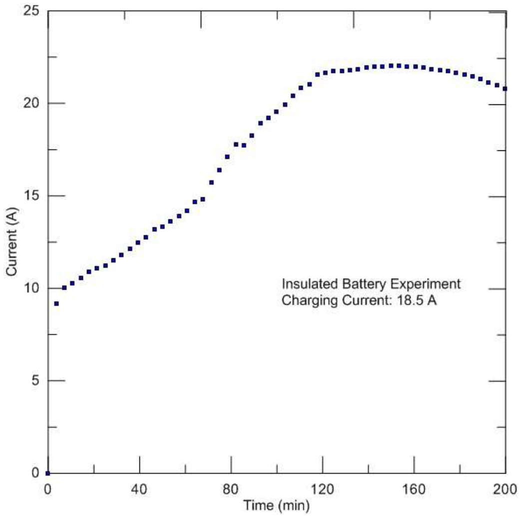


**Figure 4**. Power Associated with Over Voltage for Charge Experiment #5.

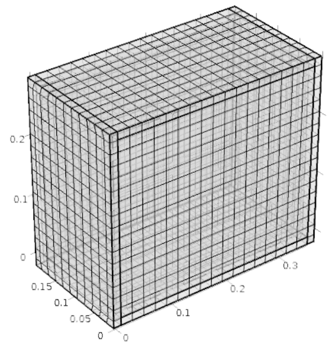

**Figure 5**. View of Meshed Geometry.

### 2.1.3 Meshing and Mesh Analysis

As the model geometry is formed from rectangular elements, it was possible to mesh it using swept tetragonals, as shown in Fig. 5. Tetragonal mesh elements were chosen to improve the convergence characteristics of the model, as well as save computational power by limiting the number of elements.

In order to determine the appropriate size of the tetragonal elements, a simple mesh analysis was performed. The simulation was run with mesh sizes corresponding to eight of the predefined settings in COMSOL. The temperature reading from boundary point probe #1 at the final time step was recorded for each run. Figure 6 presents that temperature as a function of the mesh size.

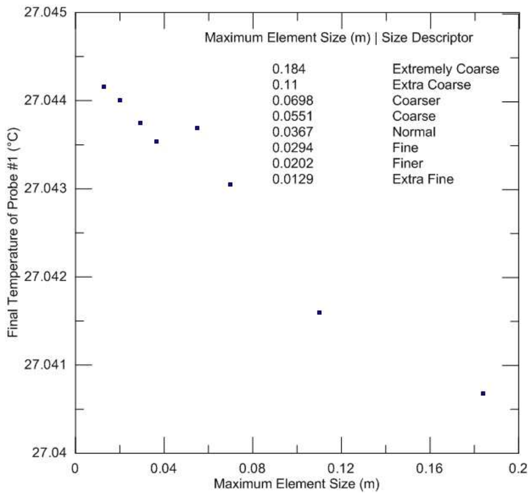


**Figure 6**. Comparison of Probe #1 Temperatures for Varying Mesh Sizes.

Overall, the difference in temperature between the finest and coarsest settings used is less than 0.004 °C. In addition, the difference between the Normal mesh setting and the finer meshes is extremely small compared to the differences between the coarser settings. Based on the trend presented in Fig. 6, the Normal predefined mesh setting was used. The complete mesh has 3553 elements. At this mesh size, the simulation is able to complete in less than 5 minutes.

### 2.2 PoleCo Enclosure Experiment
#### 2.2.1 Geometry and Materials

When the VRLA batteries are in use on a PoleCo lighting installation, they are held within an 18 inch square aluminum enclosure at the top of the light-post. Later experiments performed on the battery focused on how heat moved around within this enclosure, as shown by the experimental setup in Fig. 7.

The air cavities within this chamber are large enough that convective currents are expected to have a noticeable effect on the temperature of the batteries. There is a 40 mm gap between the batteries and a 65 mm gap between the enclosure walls and the batteries on the four sides. There is 150 mm of space above the two batteries. The charge controller has a 128 mm square base and is 73 mm tall. To better isolate the effects of these air currents, the exterior of the enclosure was completely wrapped in polystyrene insulation, similar to the insulated battery experiment.

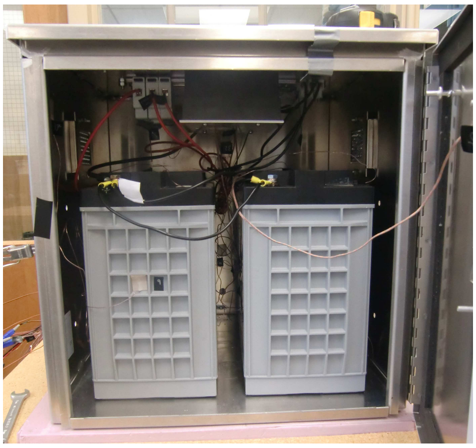

**Figure 7**. Photo of Batteries and Charge Controller within PoleCo Enclosure.

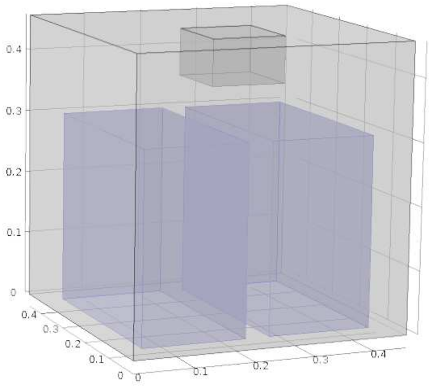

**Figure 8**. View of COMSOL Model of PoleCo Enclosure Experiment.

To model the flow of heat through solids and fluids, as well as natural convection effects, the Conjugate Heat Transfer with Laminar Flow physics was used. This model is defined by four domains; the aluminum box, the air inside the box, the two batteries, and the charge controller, as shown in Fig. 8. Of these, the box and the air use the standard material properties from the COMSOL library. The batteries use the same material properties as the ones in the model of the insulated battery experiment.

Investigation of the charge controller, however, showed that it needed to be treated with special attention. In a street-light installation, the charge controller modulates the current and voltage characteristics of the electrical energy from the solar panel. The purpose of this modulation is to ensure that the battery is always being charged at the highest possible power regardless of the position of the sun. As a result of this operation, the electronic circuitry within the charge controller generates a noticeable amount of heat. For the purposes of validating numerical models of the experiment, the charge controller has been modeled as a mass with a predefined temperature, set to match the experimental results from charge experiment #15 (CE #15). CE #15 was the first charge experiment performed in the insulated PoleCo enclosure.

For this simulation, the batteries are acting as heat sinks for the charge controller, in addition to generating heat themselves. As heat is flowing into the battery from an external source, it is important that the battery domain in this model accurately represents the internal structure of the actual battery. In the top section of the battery, for example, there is an air gap that contains gasses released by the battery during operation. This air gap acts as an insulator, slowing heat flow from the roof of the battery downwards. For the purposes of modeling, this gap was estimated to be 50 mm tall.

### 2.2.2 Boundary Conditions and Governing Equations

Similar to the insulated battery experiment, the batteries are defined as uniform masses, with the exception of the 50 mm air gap on the top surface. The heat generation is given by a function taken from experimental data. The addition of a fluid domain automatically defines wall domains on the interior of the enclosure and on the surfaces of the batteries and charge controller. All air flow is due to the natural convection, thus slowly flowing in a laminar manner with no slip condition at the walls. The outside faces of the box are thermally insulated, representing the polystyrene. A buoyancy force is included in the model as a volumetric force given by:

$$F_Z = -g*(rho-rho\_ref) \quad (2)$$

Where *g* is the gravitational constant, *rho* is the density of the air, and *rho_ref* is the density of air at 1 atm and 25 °C.

### 2.2.2 Meshing

Figure 9 shows the mesh used for this model, which was also a swept tetragonal due to the rectangular nature of the geometry. Several parametric surfaces were used to divide up the geometry in order to facilitate this. The mesh shown below has 5760 elements, and the simulation completes in a time of 30 to 40 minutes.

## 3. Experimental Results

### 3.1 Insulated Battery Experiment

This simulation is designed to be compared with an experiment than ran for 200 minutes. Thus, the transient solver was used to generate all the results. Figure 10 below shows the results from a simulation using the conditions associated with charge experiment #5 (14.5 V, 18.5 A) at the 200 minute mark.  The results of the probe comparisons can be seen in the Fig. 11.

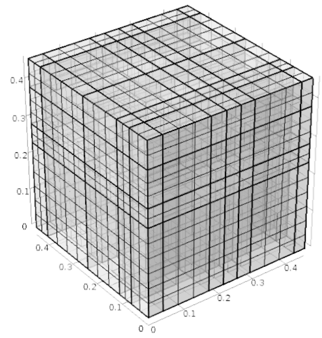

**Figure 9.** Meshed Geometry for PoleCo Enclosure Model

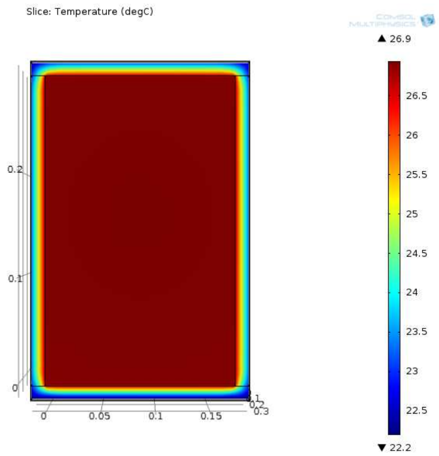


**Figure 10**. Temperature Plot of Battery Cross Section

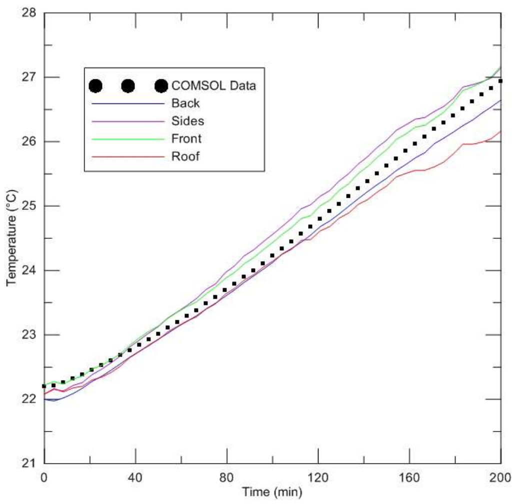


**Figure 11**. Comparison of Temperature Data from COMSOL Probes with Experimental Data from Charge Experiment #5

Because the battery was represented by a single uniform domain, there is only a negligible difference in the temperature readings between boundary point probes. Hence they are all represented by a single line. By the end of the simulation the difference between the experimental data and the probe data from the COMSOL model is relatively small. The majority of the thermocouple temperatures are within 0.5°C of the simulated results, while the rest are within 1°C. Note that the standard tolerance of the type-T thermocouples used for the experiment is 0.5 °C [7].

The close match between the COMSOL simulation and the experimental results suggests that using the over voltage measurements is a reasonably accurate method of calculating heat gain in the battery.

### 3.2 PoleCo Enclosure Experiment

Figure 12 shows a series of cross sections of the solution provided by the COMSOL model at the end of a 500 minute transient simulation.

In this solution, every element within the enclosure is at approximately the same temperature, slightly warmer near the ceiling by about 0.6 °C. At this point in the simulation the air has developed stratified layers due to the effects of natural convection.

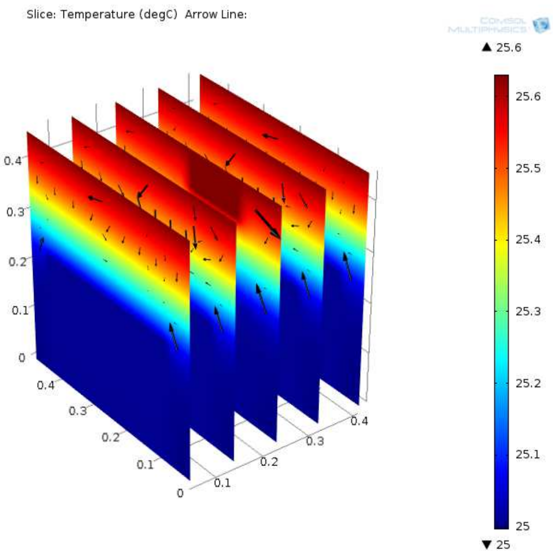


**Figure 12**. Temperature Plot of Enclosure at Various Cross Sections

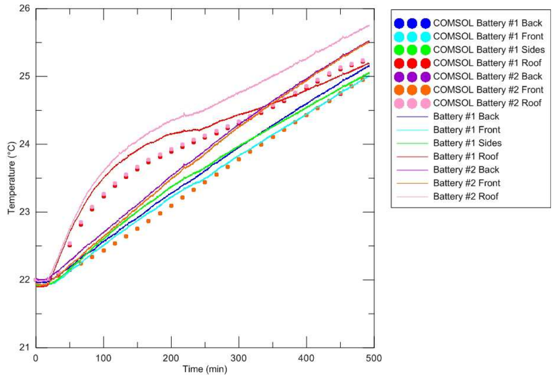


**Figure 13**. Comparison of Battery Temperature Data from COMSOL Probes with Experimental Data from Charge Experiment #15

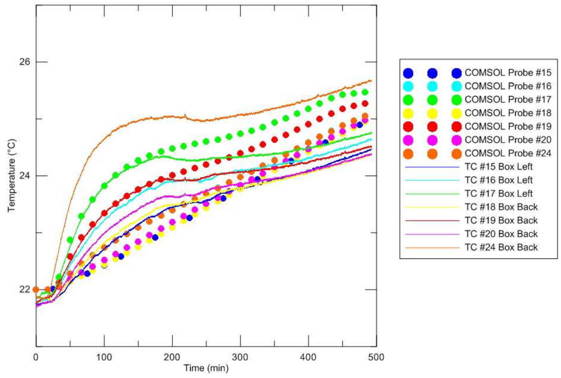


**Figure 14**. Comparison of Enclosure Temperature Data from COMSOL Probes with Experimental Data from Charge Experiment #15

Figure 13 shows a comparison between the data collected from the COMSOL probes on the battery domains and the experimental results. Overall the temperature trend seen in the experiment is matched by the simulation, although the temperatures are slightly under predicted. Notably, however, the addition of the air gap on the top of the battery helps capture the sharp rise in temperature seen on the roof of the battery. Note that radiation heat transfer within the enclosure was not simulated at this time.

Figure 14 shows the results from the COMSOL probes associated with the enclosure, compared with experimental data. The trend shown by the COMSOL probes does not match the experimental results precisely, although the magnitudes of the temperatures are very close. It is likely that modeling the internal structure of the battery more accurately would result in a simulation that more closely matches the experimental data.

## 4. Conclusions

For the purposes of producing useful numerical models of the PoleCo battery enclosure system, two types of COMSOL models were constructed based on experimental setups.

The first type of model simulated experiments performed on a single battery wrapped in insulation. In this model the system was simplified greatly, essentially breaking it down to a single uniform mass with certain material properties. By applying heat generation equations based on the over voltage applied to the battery, it was possible to simulate numerical results that were comparable to observed temperature changes from experiments. In this manner, the use of COMSOL helped to confirm that for the purposes of heat generation, the battery could be treated as a very simple object.

The second type of model was designed to mimic an experimental setup involving two batteries inside a small box, along with a charge controller. Unlike the previous model, it was important to accurately model the interior structure of the battery so that the transfer of heat through it from an external source would be modeled correctly. The results from this model approximately match the experimental results, and could be refined further in the future to provide better results.

Overall the COMSOL models helped show that using over voltage as a measure of the heat generated within the lead-acid battery during charging was a valid assumption.

## 5. References


1. D. Berndt, Valve-regulated Lead-acid Batteries, *Journal of Power Sources*, **100**, 29-46 (2001)

2. ASTM Standard C578-14, "Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation", 2014, www.astm.org

3. K. T. Yucel, C. Basyigit, C. Ozel, Thermal Insulation Properties of Expanded Polystyrene as Construction and Insulation Materials, *15th Symposium in Thermophysical Properties*, pp. 54-66 (2003)

4. H. Winterling, N. Sonntag, *Kunststoffe International*, **10**, pp. 18-21 (2011)

5. Concorde, *Concorde Battery Valve Regulated Lead Acid Battery*, [MSDS], (2014), Retrieved from: http://www.sunxtender.com/otherpdf/vrbatts_msds.pdf

6. H. Giess, Investigation of Thermal Phenomena in VRLA/AGM Stationary Lead/Acid Batteries with a Thermal Video Imaging System, *Journal of Power Sources*, **67**, 49-59 (1997)

7. ASTM Standard E230, "Standard Specification and Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples", 2012, www.astm.org


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