2021-01-0761 Published 06 Apr 2021

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Validation of a Lumped Electro-Thermal Model of a 14S1P Battery Module with 3D CFD Results

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Citation: Champhekar, O., Hu, X., and Wakale, A., "Validation of a Lumped Electro-Thermal Model of a 14S1P Battery Module with 3D CFD Results," SAE Technical Paper 2021-01-0761, 2021, doi:10.4271/2021-01-0761.

Abstract

A lumped electro-thermal model for a battery module with 14 cells in series (14S1P), and with a cooling channel, is created by two-way coupling of an equivalent circuit model (ECM) and a linear time-invariant (LTI) method based thermal reduced order model (ROM). To create the ROM, a step response data in the form of temperature versus time curve is required. This data is obtained by running a transient full three-dimensional (3D) computational fluid dynamics (CFD) analysis for the full module. The thermal ROM accounts for the effect of the heat generated by the active cells, the joule heat generated in tabs and connectors, and the coolant inlet temperature. To create an ECM, data from hybrid pulse power characterization (HPPC) test is used. Such a lumped electro-thermal model for a battery module can run faster than a 3D CFD analysis and can be easily integrated in a system level model. A 3D electro-thermal conjugate heat transfer (CHT) CFD analysis of a battery has high accuracy and fidelity, but it can be difficult to implement in a system level simulation. Hence, it is important to establish the accuracy of the lumped model by comparing with the 3D CFD results. Results from the lumped model are compared with the results from a 3D CFD simulation for a drive cycle. The lumped model results are within 1.6% of the CFD results. Also, the lumped model runs in a few seconds for a complete drive cycle making it a suitable model for a system level simulation.

Introduction

To combat the problem of climate change, regulations all over the world are pushing the auto industry to reduce the tailpipe emissions and reduce the generation of greenhouse gases (GHG) like CO_2. Over the last few years, battery electric vehicles (BEV) have been gaining popularity because of their high efficiency and zero GHG generation. These BEV's typically consist of battery packs containing several modules. Each module is made of several cells arranged in a series and/or parallel combination and may also have a cooling circuit to regulate temperature of the cells. Cells generate heat as current flows through them causing a rise in the temperature. Typical operating temperature range of such cells in the packs should be around -10 ºC to 50 ºC. Beyond this temperature range, the battery may undergo degradation resulting in a loss of performance [1]. To keep the cell temperature within desirable range, many battery packs use a cooling channel in the design to regulate the temperatures inside the pack. This makes the thermal management of battery packs one of the most important aspects of a pack design. Numerical simulations tools like CFD play an important role in designing such thermal management systems.

Simulation of a battery pack or a module is a multi-physics problem. The cell level simulation involves solving the electrical or electrochemistry part while the module level simulation involves running a CHT analysis in conjunction with the electrical part. A model-based approach can be very effective in understanding the behavior of such a complex multi-physics problem [2].

A battery cell can be simulated using physics based electro-chemical models. A commonly used electrochemistry model for li-ion batteries is the Newman electrochemistry model first proposed by Doyle, Fuller, and Newman [3,4,5]. This model has been widely used in simulating the electro-chemical behavior of battery cells [6,7]. Such a physics-based model requires mesh resolution at electrode level. Hence, this approach can get impractical when simulating a battery pack, since a battery pack is several orders of magnitude larger than an electrode.

To make the pack level simulation practical, the current-voltage (I-V) dynamics of a battery cell can be modeled using an ECM [8,9]. An example of such an ECM is a circuit with two parallel resistor-capacitor pairs, a series resistance, and a source voltage. To use this ECM, it is important to identify the correct values of these 6 parameters. This can be done by curve fitting the data generated from the HPPC test [10]. The ECM parameters can be a function of temperature and SOC. For each combination of temperature and SOC level, one HPPC test curve is required.

Thermal simulation of battery modules involves simulating a CHT problem. High fidelity results can be achieved by running a full transient 3D CFD simulation [11,12]. The CFD results can give a good insight into the temperature distribution in the entire battery module. However, in a system level simulation, using a 3D CFD simulation can be impractical because of long simulation times. Instead, a thermal network model can be created and applied at a system level [13,14]. Such a model typically consists of thermal resistances

FIGURE 22 Comparison of heat loss of cell 7 for lumped versus CFD results.

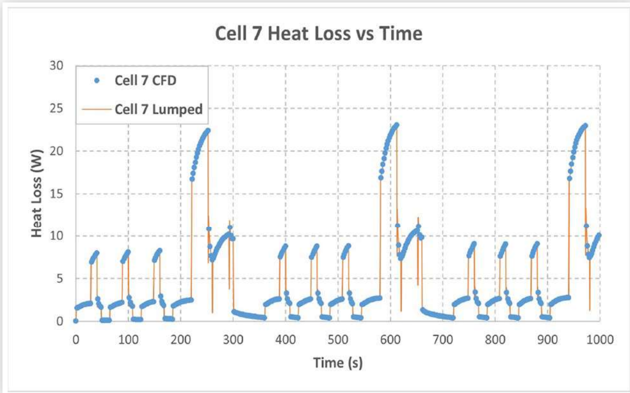


FIGURE 23 Comparison of cell 1 average temperature for lumped versus CFD results.

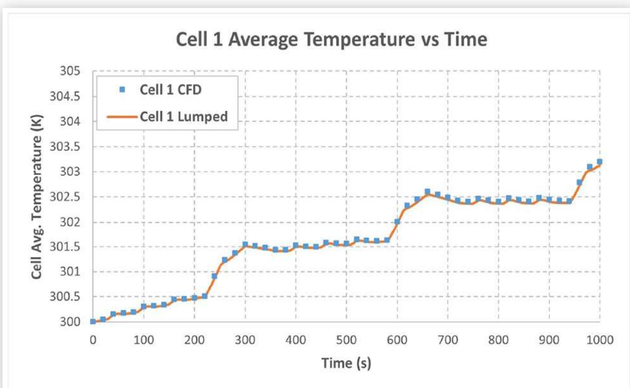
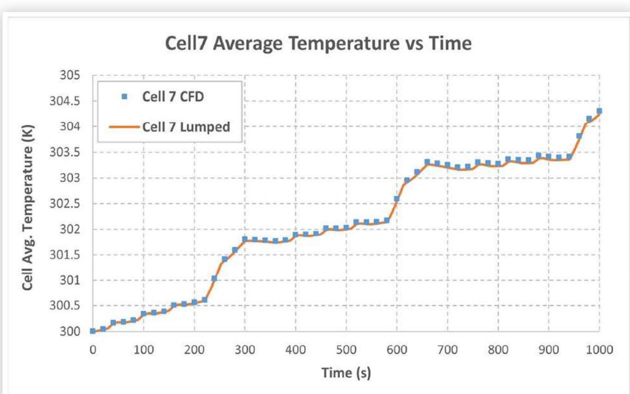


FIGURE 24 Comparison of cell 7 average temperature for lumped versus CFD results.



of the jumps in the heat source values. Despite these intricacies, the lumped ECM-ROM model can capture the results accurately.

The 2-norm difference is less than 1.6 % for any cell. Table 2 shows the comparison of the temperatures after 1000 seconds for all the 14 cells and the 2-norm difference %.

TABLE 2 Comparison of average temperature for all cells after 1000 seconds.

	CFD	Lumped	2-norm difference %
Cell 1	303.20	303.13	1.51
Cell 2	303.37	303.31	1.47
Cell 3	304.03	303.98	1.47
Cell 4	304.08	304.03	1.49
Cell 5	304.25	304.19	1.41
Cell 6	304.26	304.2	1.38
Cell 7	304.30	304.24	1.28
Cell 8	304.30	304.25	1.29
Cell 9	304.31	304.26	1.38
Cell 10	304.31	304.25	1.39
Cell 11	304.23	304.18	1.44
Cell 12	304.21	304.16	1.43
Cell 13	303.95	303.88	1.47
Cell 14	303.87	303.81	1.52

Conclusions

A detailed comparison of results from a lumped coupled electro-thermal model of a 14S1P battery module is done with 3D CFD results. The lumped model is built by coupling the ECM with LTI ROM for the entire module. The ECM is generated using results from HPPC test data at 3 different temperature levels and 13 different SOC levels. The LTI ROM is created using step response results generated from CFD simulation. The LTI ROM consists of 3 inputs and 14 outputs. A complex drive cycle profile is used as input and the simulation is run for 1000 seconds of physical time. The electrical and thermal behavior predicted by the ECM-ROM lumped model is able to closely match with the 3D CFD results. The average temperatures for the cells predicted by the lumped model is withing 1.6% of the CFD results. The 3D CFD simulation takes 36 hours on a 64-core machine, whereas the lumped model takes less than 10 seconds on a laptop using only one core. This means that the lumped model can predict results faster than real time. Hence, this lumped model could be a very good model to use for system level simulations, and battery management system simulations.

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Abbreviations

CFD - computational fluid dynamics
14S1P - 14 series 1 parallel
RC - resistance capacitance
CHT - conjugate heat transfer
ECM - equivalent circuit model
LTI - linear time invariant
ROM - reduced order model
SOC - state of charge
BEV - battery electric vehicles
GHG - greenhouse gases
I-V - current-voltage