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On-board monitoring of 2-D spatially-resolved temperatures in cylindrical lithium-ion batteries: Part I. Low-order thermal modelling

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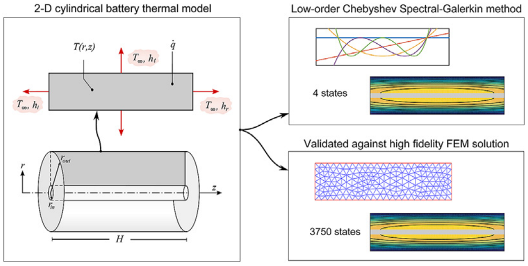
HIGHLIGHTS

- Derivation and validation of low-order 2-D thermal model for cylindrical cells.
- Efficient numerical implementation based on Chebyshev spectral-Galerkin method.
- Includes anisotropic heat conduction and inhomogeneous convection boundary conditions.
- Applicable to various battery cooling configurations, such as side or end cooling.
- Suitable for use in a state-estimator with surface temperature or EIS measurements.

GRAPHICAL ABSTRACT



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ABSTRACT

Estimating the temperature distribution within Li-ion batteries during operation is critical for safety and control purposes. Although existing control-oriented thermal models - such as thermal equivalent circuits (TEC) - are computationally efficient, they only predict average temperatures, and are unable to predict the spatially resolved temperature distribution throughout the cell. We present a low-order 2D thermal model of a cylindrical battery based on a Chebyshev spectral-Galerkin (SG) method, capable of predicting the full temperature distribution with a similar efficiency to a TEC. The model accounts for transient heat generation, anisotropic heat conduction, and non-homogeneous convection boundary conditions. The accuracy of the model is validated through comparison with finite element simulations, which show that the 2-D temperature field (r, z) of a large format (64 mm diameter) cell can be accurately modelled with as few as 4 states. Furthermore, the performance of the model for a range of Biot numbers is investigated via frequency analysis. For larger cells or highly transient thermal dynamics, the model order can be increased for improved accuracy. The incorporation of this model in a state estimation scheme with experimental validation against thermocouple measurements is presented in the companion contribution (Part II).

1. Introduction

Lithium-ion batteries generate heat due to electrochemical processes, which results in internal temperature gradients during operation. In a typical usage scenario, such as a standard vehicle

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drive cycle, cells may experience temperature differences between surface and core of 20 °C or more [1]; and during a rapid overheating event this discrepancy can be as large as 40–50 °C [2]. High battery temperatures could trigger thermal runaway resulting in fires, venting and electrolyte leakage. While such incidents are rare [3], consequences include costly recalls and potential endangerment of human life. Consequently, transient thermal modelling of batteries during operation is an essential requirement for battery management systems to ensure safe and optimal performance.

In this study, we present and validate a low-order thermal model of a cylindrical battery cell, capable of capturing 2-D thermal dynamics. The model is based on the spectral-Galerkin method, achieving high accuracy with minimal computational requirements, making it suitable for online applications. The remainder of this paper is organised as follows. In Section 2, the alternative numerical methods for low-order thermal modelling are discussed. In Section 3, a gentle introduction to Galerkin-spectral methods is provided by means of a toy problem - a 1-D heat equation in Cartesian coordinates. In Section 4, the full 2-D thermal model is presented; and in Section 5, the results of the model are validated through comparison with high fidelity Finite Element (FE) simulations. Matlab code to simulate the presented model is available online.[1]

2. Low-order thermal modelling

Lumped parameter thermal equivalent circuit (TEC) models are perhaps the most popular approach for efficient thermal modelling. These methods have been used extensively for low-order and control-oriented modelling of battery cells and packs [1,4–10]. Their main advantage is that they are simple to implement. However, they are unable to predict the full temperature field throughout the domain of interest; their outputs merely consist of nodal values representing average temperatures. This is a particular limitation when comparison with temperature measurements at discrete locations is necessary for state or parameter estimation. Moreover, since the parameters of the model have no physical meaning, they require parameterization using experimental data for any given set of parameters and operating conditions. On the other hand, TEC models with parameters that can be directly calculated from physical properties have been used extensively in thermal modelling of electric machines and other applications [11–13]. However, these are known to have poor performance for large Biot numbers, whilst increasing the number of elements to improve accuracy comes at the expense of increased computational complexity [14,15].

Physics based models instead solve the underlying diffusion partial differential equation (PDE) governing the heat transfer. They are generally applicable to a broad range of problems, and can predict the full temperature field throughout the domain of interest. Several studies have presented 2-D or 3-D thermal simulations of battery cells [16–19]. However, the solution is typically obtained using computationally intensive numerical methods such as Finite Difference Methods (FDM) or Finite Element Methods (FEM), and so their potential for application in control systems is limited. Analytical solutions have also been developed [20,21], however these are inappropriate for on-line applications since time domain solutions rely on computationally intensive integral transforms.

To reduce the computational burden of physics based models, low order approaches have been proposed using techniques such as balanced truncation [22,23] and polynomial approximation (PA) [24–27]. However, these methods are only suited to 1-D problems involving infinite or semi-infinite domains, or symmetric boundary conditions [28]. This may be acceptable for cases in which thermal gradients arise predominantly in one direction, such as in air cooling of small form factor (e.g. 18650 or 26650) cylindrical cells. However, large form factor cells have a greater propensity for thermal gradients in multiple directions. Recent studies have used 45 Ah cylindrical cells with a diameter of 64 mm and height of 198 mm [29]. Such dimensions give rise to much larger Biot numbers and hence more significant thermal gradients. Moreover, certain cooling configurations, such as end cooling via cooling plates, are more likely to give rise to axial variations. These systems also introduce additional complexities, such as the potential for each surface of the cell to be in contact with a different cooling fluid with a different free stream temperature and/or convection coefficient. Fig. 1a shows a case with forced convection via a liquid coolant at the base of the cell and natural convection to the air at the other surfaces. Fig. 1b shows another scenario in which unequal cooling of multiple cells can result in 2-D thermal dynamics as heat is transferred axially through the tabs from one cell to a neighbouring cell. Consequently, there is a clear need for low-order thermal models capable of capturing 2-D thermal dynamics.

Spectral methods are an alternative numerical method for solving PDEs, in which the spatial discretization is carried out using global rather than local approximating functions [30,31]. In general, FDM and FEM methods are suitable for complex geometries, whereas spectral methods provide greater computational efficiency at the expense of model flexibility and the assumption of a smooth solution. Spectral methods are a type of weighted residual method - a group of approximation techniques in which the solution errors are minimized in a certain way - and they are classified according to the minimization technique employed. The most common techniques are spectral-collocation and spectral-Galerkin. In a collocation method, the solution is obtained by interpolating an approximating function at a set of domain nodes, whereas in a Galerkin method, the solution is obtained by forcing the residual of an integral multiplied by a test function to zero.

Spectral methods have been used in previous studies for low-order battery modelling [32–35], and recently they have even been applied to 2-dimensional problems [36]. However, to the authors' knowledge, no study has applied a Galerkin method to 2-D battery thermal problems. This is perhaps due to the complexity of accounting for non-homogeneous boundary conditions, in particular convection boundary conditions, using a Galerkin method. One of the advantages of the Galerkin method is that the basis functions implicitly satisfy the boundary conditions, and so it possible to have very low order models with satisfactory accuracy.

In this paper, we present a 2-D model of a cylindrical cell based on a Chebyshev spectral-Galerkin (SG) method. The model accounts for transient heat generation, anisotropic heat conduction,

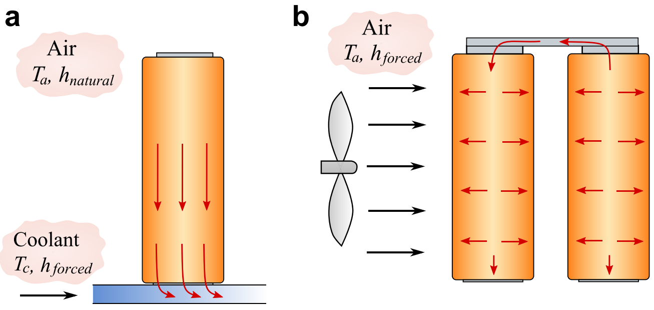

Fig. 1. Battery cooling configurations resulting in 2-D thermal dynamics: (a) Plate cooling, (b) unequal cooling with intercell heat transfer.

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[1] www.github.com/robert-richardson/Spectral-Thermal-Model-2D.