A Foster Network Thermal Model for HEV/EV Battery Modeling

Xiao Hu, Shaohua Lin, Scott Stanton, and Wenyu Lian

***Abstract*—Battery thermal management for high-power applications such as electrical/hybrid vehicles is crucial. Modeling is an indispensable tool to help engineers design better battery cooling systems. An accurate battery thermal model using a Foster network is proposed. The parameters in the Foster network, including capacitance and resistance, are extracted from computational fluid dynamics (CFD) results. The Foster network model is then shown to provide equivalent results as those from CFD under transient heat dissipation inputs. The model can be readily coupled with a battery electrical circuit model to form a complete battery system circuit model capable of predicting accurate battery temperature and the impact of temperature on battery electrical transient performance.**

***Index Terms*—ANSYS, battery electrical circuit model, battery thermal management, computational fluid dynamics (CFD), electric vehicle (EV), FLUENT, hybrid EV (HEV), linear and time invariant (LTI), SIMPLORER.**

I. Introduction

RECENTLY, many mathematical models for batteries have been proposed due to the emerging battery applications, particularly for electrical/hybrid vehicles. These models range from the more detailed electrochemistry models [1]–[3] to the system-level electrical circuit models [4]–[6]. While the electrochemistry models are excellent tools for studying and optimizing a single battery cell performance, electrical circuit models have gained popularity among system-level design engineers due to the ease of use of these circuit models and their capability of representing the state of charge, I–V characteristics, and dynamic behavior of a battery system. When it comes to the impact of temperature on battery performance, these electrical models can be divided into two categories. Battery models [4] for low-power applications, in general, do not consider the thermal effect on the battery performance because it is usually negligible. On the other hand, for high-power applications such as electrical/hybrid vehicles, thermal network models [5], [6] have been used to predict the temperature to couple with electrical models to include the impact of temperature on battery performance. This type of models typically uses the concept of thermal capacitance and thermal resistance. In order to obtain accurate results, the number of those elements used in the thermal network model needs to be large, and the network is thus complex. Moreover, the process to obtain the accurate numerical values for those elements is tedious. With a reduced number of elements, in which typically one node for each battery cell is adopted [5], the model does not provide sufficient accuracy.

In this paper, an accurate battery thermal model using a Foster network is proposed. In such a Foster network model, a number of capacitors and resistors are also used. However, they do not have the same meaning as that of the thermal capacitors and thermal resistors used in the thermal network model. Instead, they are used to represent the transfer function of the battery thermal system. Due to the different natures of those elements, the way the RCs are connected and the way to extract the numerical values for the RCs are entirely different. In the thermal network approach, the RCs are connected corresponding to the physical arrangement of the battery cells, and their numerical values are extracted through physical argument, calculation, or testing. For the Foster network, however, the RC connection is fixed regardless of the physical arrangement of the battery cells. Moreover, the numerical values for the elements are exacted through matching the step responses of the Foster network to those of the battery system either calculated by using computational fluid dynamics (CFD) or obtained by testing. In order to have a good thermal network representation, one needs a good understanding of the thermal system at hand and sound engineering judgment; the Foster network approach, on the other hand, has a more straightforward and systematic way of implementation. It will be shown that the Foster network gives equivalent solution as CFD under certain assumptions. Moreover, it would give identical solution as the testing if step responses of the battery system are from the testing rather than from CFD if the same assumptions are satisfied. Not only are the results from the Foster network very accurate but also the simulation time using the Foster network model is comparable to that using the traditional thermal network model, instead of hours that a CFD model could require. Moreover, the Foster network thermal model can be readily coupled with temperature-dependent battery electrical models to replace the simple thermal network model to provide more accurate results without the sacrifice of calculation time. The Foster network approach has been used for electronics cooling [7], [8] for some time. However, this method is first introduced here for battery cooling.

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This paper is organized as follows. Section II describes the linear and time invariant (LTI) representation of a battery thermal system. This section lays the foundation for the method. Section III represents a single battery cell system using a Foster network model just to introduce the method. In Section IV, a battery module of six battery cells is represented by a matrix of Foster networks. Moreover, a battery module consisting of 16 cells from General Motors (GM) is also presented. Section V uses the Foster network approach for a nonlinear battery cooling example. Section VI introduces a complete battery model, which couples the electrical model and the Foster network thermal model. Finally, Section VII is the conclusion.

II. LTI Representation of Battery Thermal System

In using the Foster network method, the thermal problem is treated like a system. A system is an entity that processes a set of input signals (or simply called inputs) and yields another set of output signals (or simply called outputs) [9]. In this paper, signals are functions of time. Any electrical circuit, including the Foster network used here, can be viewed as a system. Current at different locations can be viewed as the input signals, and voltage at different locations can be viewed as the output signals. For the thermal problem at hand, the inputs are the power dissipated by the battery cells, and the outputs are the temperature at user-specified locations.

When a system is LTI, the system has very nice features. First of all, such a system is completely characterized by its impulse response. For a single input and a single output LTI system, the output under the condition of initial rest is equal to the input convolved with the impulse response [10]. Second of all, if two LTI systems have the same impulse or step response, the two systems behave identically in that the outputs of the two systems under the condition of initial rest are the same provided that the inputs to the two systems are the same. This feature allows us to use the Foster network, which is an LTI system, to represent the thermal system, which also turns out to be an LTI system under certain conditions. Therefore, instead of solving the partial differential equations for the battery thermal behavior, a Foster network can be used to represent the battery system without any loss of accuracy. A Foster network, governed by ordinary differential equations, can be solved easily and quickly in any circuit simulator.

To introduce this method, a single battery cell system is used first for simplicity. Then, a battery module with six battery cells and a battery module with sixteen cells from GM are used to illustrate the use of this method for more complex systems.

III. Single Battery Cell Foster Network Model

In this section, the simplest system, a system with a single input and a single output, is discussed. A single battery cell cooling system is such an example. Fig. 1 shows such a single cell battery cooling system simulated in FLUENT, a CFD code in ANSYS simulation tool suite. The CFD model has one flow inlet on the left and one pressure outlet on the right. A battery cell is in the middle of the domain. Convection heat transfer

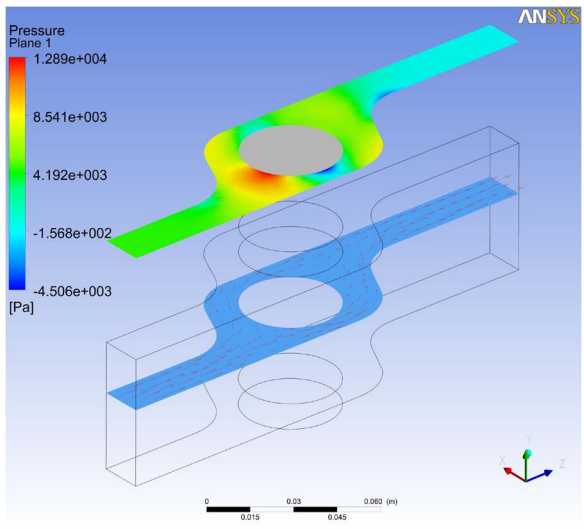

Fig. 1. Single cell battery cooling system.

takes the heat generated by the battery cell away. Therefore, this is a standard conjugate heat transfer problem in CFD.

For such a system, the power dissipated as a function of time to the battery cell is used as the input, and the volume-averaged temperature of the battery cell as a function of time is used as the output. Such a system becomes an LTI system under constant flow rate, constant density, constant specific heat, constant transport properties, and linear boundary conditions. Temperature and heat flux boundary conditions are linear, and radiation boundary condition is an example of nonlinear boundary conditions. Constant density and constant properties are excellent assumptions for water cooling battery systems. For air cooling battery systems, it is still a good assumption under the range of temperature variation considered. In Section V, a test will be conducted to compare results from the Foster network and those from a full nonlinear CFD model with nonconstant properties. The results will confirm that acceptable accuracy is obtained. For the same reason as that of the temperature range considered, radiation can be ignored. Frozen velocity fields can be satisfied under constant pump speed. For different pump speeds and, thus, different velocity fields, a separate set of Foster network is needed. To discuss different pump speeds is not included in this paper. For this paper, a constant pump speed is assumed.

For such an LTI battery thermal system, the system can be completely characterized by its impulse response, which, in this case, is the history of temperature increase of the battery cell given a unit amount of heat source to the battery cell applied at a time of zero. The impulse response is obtained by performing a CFD calculation. Fig. 2 shows a typical impulse response of such a system.

Subsequently, the system response under transient input is simply the convolution of the impulse response and the input, given by the following equation:

$$y(t) = \int_0^t x(\tau)h(t-\tau)d\tau \tag{1}$$

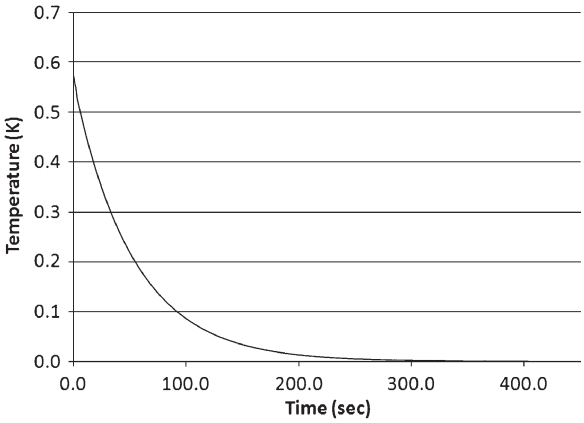

Fig. 2. Typical impulse response curve.

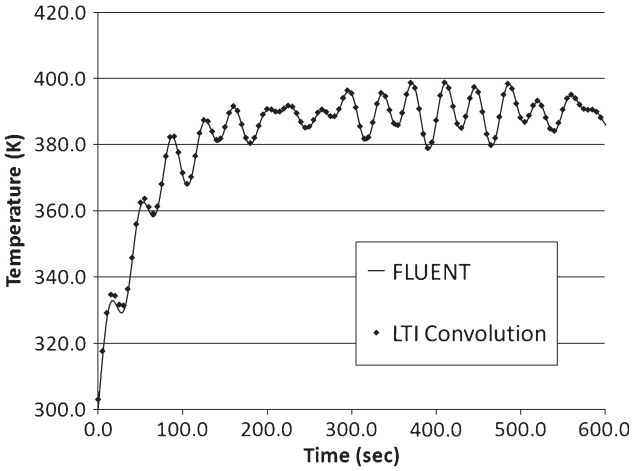

Fig. 3. Comparison between CFD and convolution results.

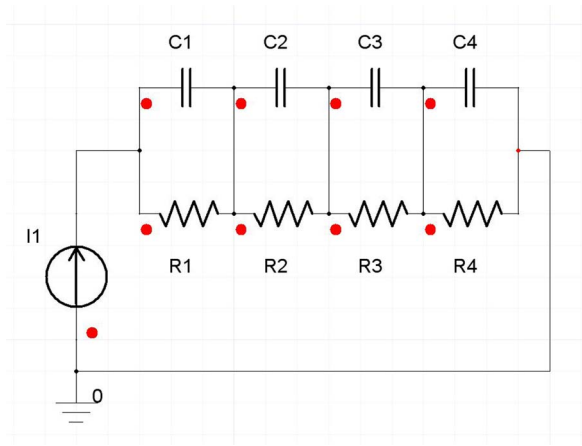

Fig. 4. Typical Foster network.

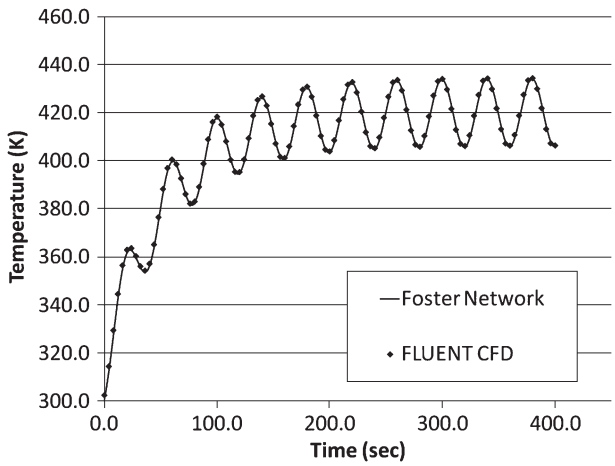

Fig. 5. Comparison between CFD and Foster network results.

where y represents the output, the temperature here; x represents the input, the power dissipated here; and h represents the impulse response. A short notation commonly used for convolution is

$$y(t) = x(t) * h(t). \tag{2}$$

Note that the Laplace transform of the aforementioned equation changes the convolution calculation to a multiplication calculation. Moreover, the Laplace transform of the impulse response is commonly known as the transfer function.

Fig. 3 shows the comparison of temperature history under an arbitrary input using FLUENT CFD and convolution. The results confirmed that FLUENT calculation using full CFD and convolution gives identical solution and thus verifies that impulse response completely characterizes the system behavior. The benefit of using convolution is time saving. While CFD calculation of such a single cell system can take minutes or even a couple of hours, depending on the size of the mesh, convolution takes less than 1 min.

Even though convolution is easy and fast for single input and single output systems, for systems with multiple inputs and outputs, convolution calculation can still be time consuming granted that it is still much faster than CFD calculation. A Foster network approach maintains the benefit of accuracy but runs even faster than convolution. A Foster network approach has the additional benefit of coupling easily with a battery electrical circuit model.

As mentioned earlier, if two LTI systems have the same step response, the two LTI systems are equivalent. A Foster network, being an electrical circuit network, is an LTI system and thus will be equivalent to the battery thermal system provided that its step response can be curve fitted to be the same as that of the battery thermal system. The curve fitting can be achieved by changing its resistance and capacitance values using a nonlinear least squares method. A typical Foster network is shown in Fig. 4. Note that it has a fixed topology in that only the number of rungs or RC pairs and values of the RCs will change regardless of the actually thermal system that it represents.

Once the curve fitting is finished, the Foster network is equivalent to the original battery thermal system and thus can be used to predict the battery transient performance under transient inputs without loss of accuracy. The current measured at point A in the Foster network in Fig. 4 becomes the power dissipation input, and the voltage measured at the same point A from the Foster network in Fig. 4 becomes the temperature output. Fig. 5 shows the comparison between Foster network results and FLUENT results under a sinusoidal input. Identical results are obtained using the Foster network and the FLUENT full

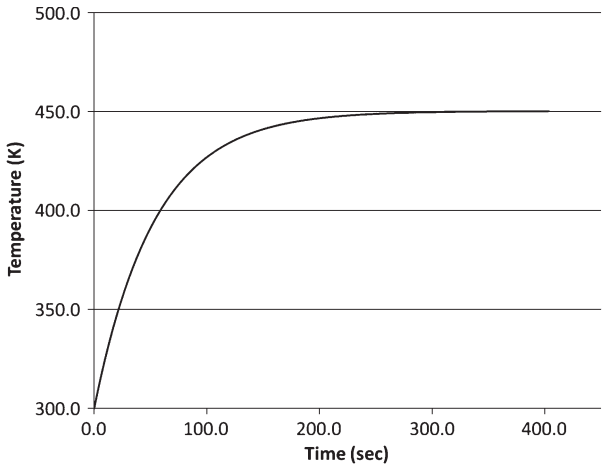

Fig. 6. Typical step response of self-heating.

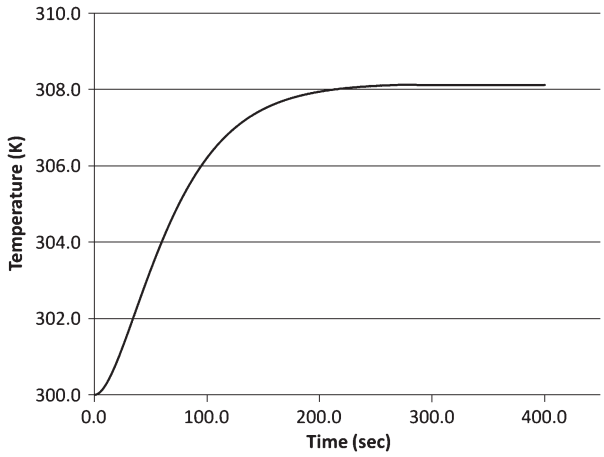

Fig. 7. Typical step response of cross-heating.

CFD method, confirming that the Foster network can be used to represent the original battery thermal system.

At this moment, it is worth mentioning the curve-fitting process. While curve-fitting self-heating step response is quite straightforward, to curve fit cross-heating needs some special attention. This is because the shape of the step response for self-heating is different from that for cross-heating. The step response of a typical battery thermal system is shown in Figs. 6 and 7 for self-heating and cross-heating, respectively. Note that the self-heat curve has a positive slope at the start of the curve, but the cross-heating curve typically has a slope close to zero at the start of the curve. The step response of a Foster network can be shown to be the following:

$$V = I \cdot \sum_{i=1}^{m} R_i \cdot \left(1 - e^{-t/\tau_i}\right) \tag{3}$$

where m is the number of rungs or RC pairs and parameters R_i and τ_i will need to be determined through curve fitting the transient step response of the thermal system. A typical step response from a Foster network will not give a slope close to zero as required by cross-heating curves and thus will not allow us to match the step response of cross-heating from the thermal system. However, if one allows for negative values for R, the resistance, the curve fit would work just fine. Even though negative values for R pose no difficulty mathematically, it gives problems to circuit simulators. However, this difficulty can be overcome by using positive values for R but subtracting the voltage contribution from that part of the RC circuit. In this way, the Foster network itself has no negative values for R, but rather, it has a part with negative voltage contribution. Curve fitting was done manually for the examples demonstrated here. However, using the software Simplorer 8.1 offered by ANSYS, the curve fitting process is done automatically.

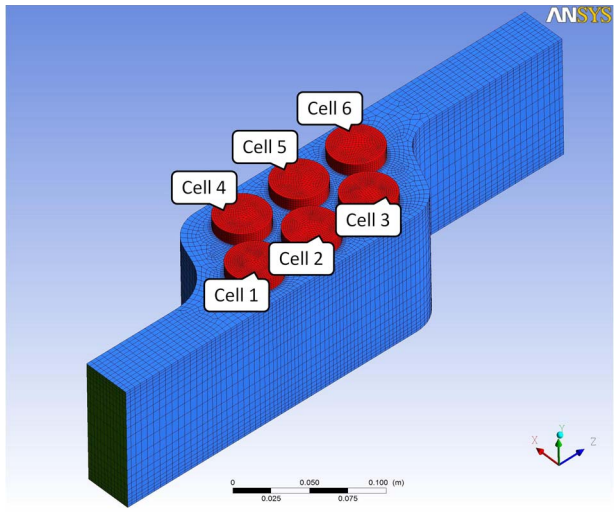

Fig. 8. Battery system with six battery cells.

The aforementioned discussion also reveals a limitation of using the Foster network to represent an LTI system. While a Foster network can curve fit fine for the current thermal system, it has rather simple step response curves and thus cannot be used as a general method to represent LTI systems with complex step response curves. In that case, the more general convolution method is always valid.

IV. Foster Network for a Battery Module

For battery modules with multiple cells, superposition can be used to predict thermal performance since the system is linear. Therefore, the output (temperature) of a battery cell is a sum of the contribution from the inputs (power dissipated) of all battery cells. The following equation is a mathematical statement of superposition:

$$\begin{bmatrix} y_1(t) \\ y_2(t) \\ \vdots \\ y_n(t) \end{bmatrix} = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1m}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2m}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{n1}(t) & h_{n2}(t) & \cdots & h_{nm}(t) \end{bmatrix} * \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_m(t) \end{bmatrix} \tag{4}$$

where y_i represents the output, the volume-averaged temperature at the ith battery cell; x_i represents the input, the power dissipated at the ith battery cell; $*$ here denotes convolution as indicated in (2); and h_{ij} in the matrix represents the impulse response of the jth input on the ith output. Similar to the single cell system, the impulse response matrix completely characterizes the behavior of the system. In order to determine impulse

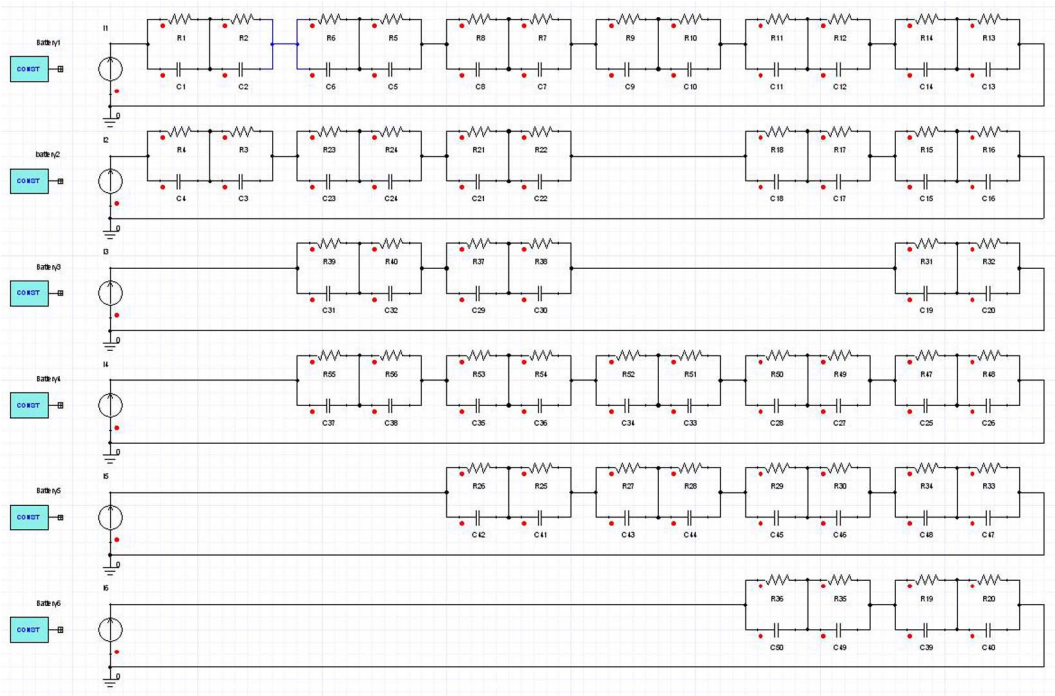

Fig. 9. Foster network model for the six-cell system.

response matrix h_{ij}, one needs to turn on one battery cell at a time. For example, one can turn on battery cell number j only; then, the history of temperature increase at battery cell number i becomes the h_{ij} if the input to battery cell number j is a unit impulse.

Even though the test cases so far use battery cells as heating sources and use the same battery cells for temperature measurement, this is not necessary. One could also have other heating sources and other temperature measurement points. For instance, one could add bus bar heating as another heating source and perhaps measure the battery housing temperature at some points. In that sense, the impulse response matrix in (4) does not need to be square.

In passing, we note that, if one is only interested in the steady-state performance of temperature, namely, all x and y in (4) are constant and all h_{ij}'s are simply the area under the corresponding impulse response curve and thus are also constants, then convolution becomes multiplication. Under such simplified conditions, very intuitive physical meaning for h_{ij} exits. A jth column of the h matrix tells the temperature pattern for all battery cells under the single power input of j. An ith row, on the other hand, tells the contribution from different heat sources on the ith battery cell. It is also worth mentioning that one can accurately calculate the power dissipation inputs by measuring temperature outputs and then use the least squares approximate solution for power. This calculation is possible if the columns of h_{ij} are independent and the number of outputs is more than that of the inputs. The requirement of having more outputs than inputs reduces the impact of measurement noise on the calculation.

Rather than using convolution, a Foster network runs even faster as discussed earlier. For a multiple input/output system, each step response needs to be curve fitted to generate a Foster network. Therefore, for a six-battery-cell system, as shown in Fig. 8, a Foster network matrix containing a total of 36 elements, each of which is a Foster network, is needed in principle. In practice, however, this number can be reduced since some of the cross-heating is not very effective and thus can be ignored. Fig. 9 shows the Foster network for this system. Due to the size of the matrix, it is hard to tell the details in this figure. However, the main point of this figure is to emphasize that this is a matrix of 6×6. Moreover, each element in the matrix is a Foster network of the form shown in Fig. 4 but with only two pairs of RCs. Furthermore, some of the cross-heating elements are missing because the thermal contribution from that Foster network is negligible. Fig. 10 shows the comparison between FLUENT CFD results and Foster network results for three arbitrarily chosen battery cells under a rather arbitrary set of inputs. While the Foster network gives identical solution as FLUENT CFD, the solution time is less than half a minute, and FLUENT full CFD calculation takes approximately half an hour. Moreover, both runs are under a Windows XP laptop.

As a final example, a battery module with 16 cells from GM under a given power dissipation profile is simulated using both the full CFD in FLUENT and Foster network in Simplorer 8.1. Figs. 11 and 12 show the geometry of the battery system and its full CFD solution, respectively. Fig. 13 shows the comparison of cell temperature histories between full CFD results and the Foster network results for three arbitrarily chosen battery cells. It can be seen that results from the Foster network match exactly those from full CFD calculation. The CFD model used here has more than two million computational control volumes and requires a run time of approximately 2 h on one single CPU, while the Foster network simulation can be finished in less than 1 min. Moreover, both runs are under a Windows XP laptop.

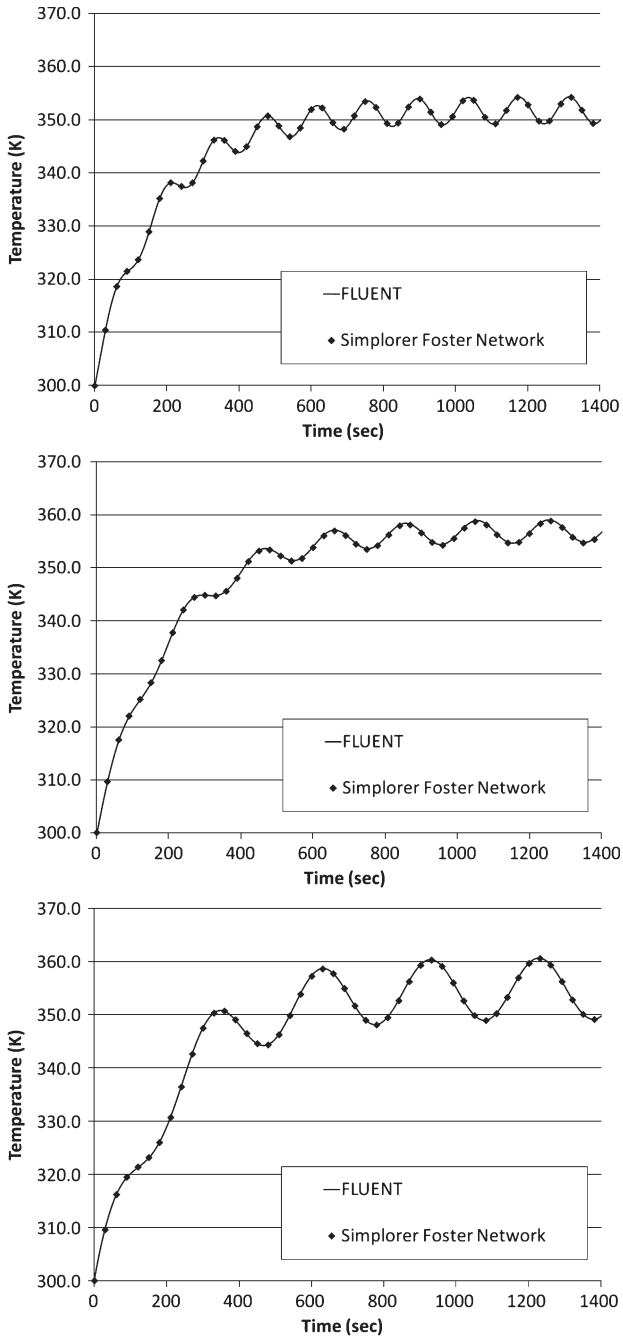

Fig. 10. Comparison between FLUENT results and Foster network results for three battery cells.

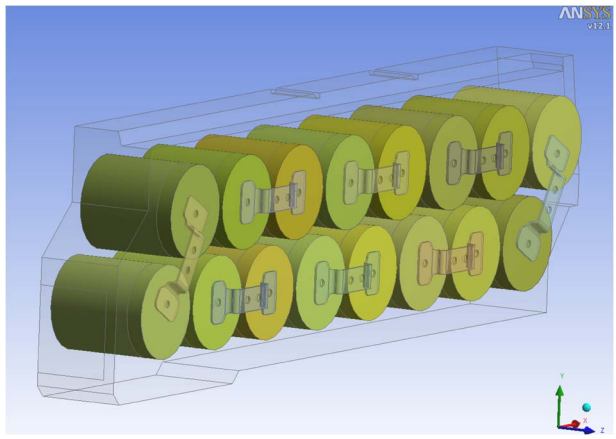

Fig. 11. GM battery module with 16 cells.

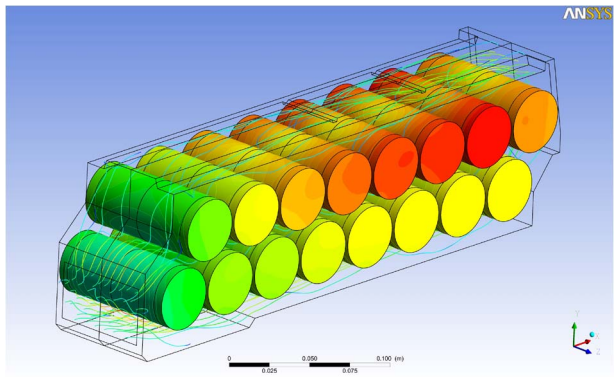

Fig. 12. CFD solution for the 16-battery-cell GM module.

It may have been apparent during the discussion, but it is worthwhile to reiterate how many CFD runs are necessary to characterize a battery thermal system. The answer depends on how many independent heat sources are used to heat up the battery system. In the six-battery-cell case shown in Fig. 8, it is assumed that each battery cell is heated independently (having separate current going through them) and thus six CFD runs are needed. This is a very general approach and typically not necessary as battery cells within each module are typically connected in serial. The 16-cell GM example shown in Fig. 11 confirms such serial connection. If the battery cells in a module are connected in serial, there is only one independent heat source for that module, and thus, only one CFD run is necessary to generate all step responses needed. Therefore, for the 16-cell example, only one single CFD run is performed to characterize the battery thermal system.

Note that the heat sources typically are both functions of space and time. However, when the Biot number for the battery cells is relatively small, it is a good approximation to use spatially uniform heat source distribution rather than the actual spatially nonuniform heat source distribution as done in all test cases in this paper. However, in such an approximation, it is not necessary to use the Foster network method. If spatially nonuniform heat source is desired, one has to make sure to use such a distribution when generating the step response curves.

V. Foster Network for a Nonlinear Example

For the Foster network to give the same results as the CFD model, the system represented by the CFD model needs to be LTI. Real battery thermal systems are not LTI since the governing equations for battery thermal systems are the Navier–Stokes equations, which are notoriously nonlinear. It is interesting to compare the results from the Foster network with those from a full nonlinear FLUENT CFD model. For testing, the same battery module with six battery cells is used. A CFD simulation, which satisfies both linearity and time invariance requirement,

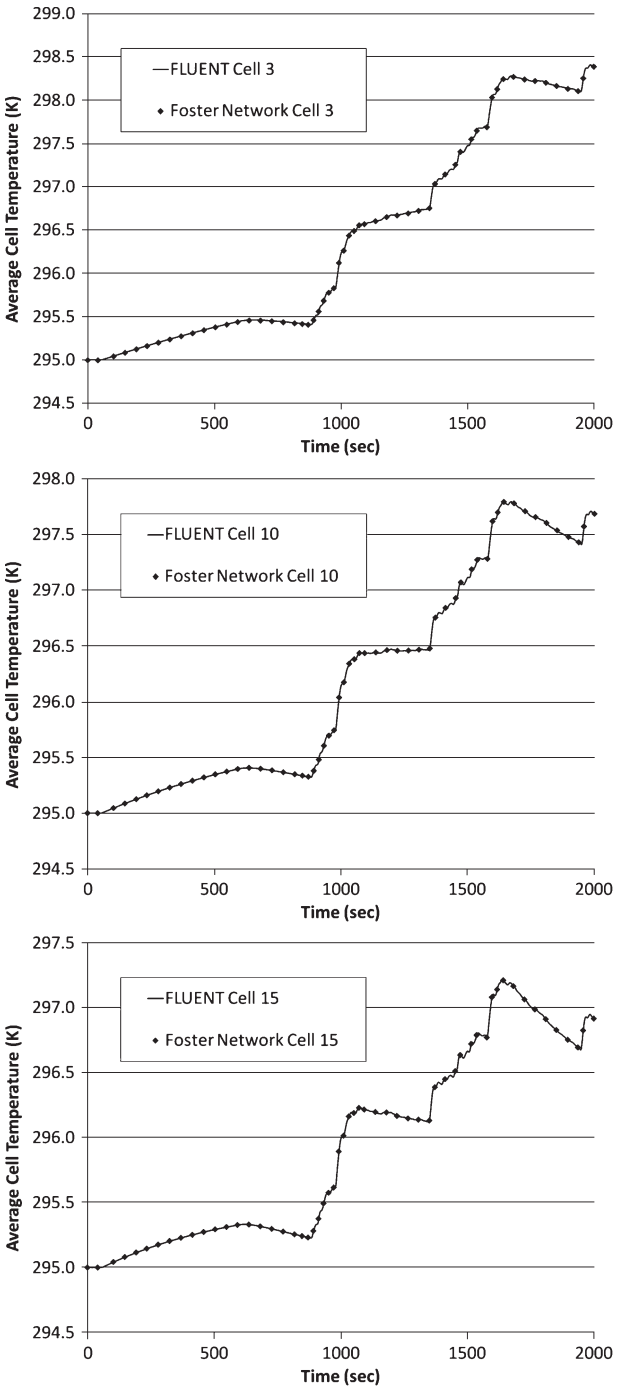

Fig. 13. Comparison of FLUENT CFD results with Foster network results.

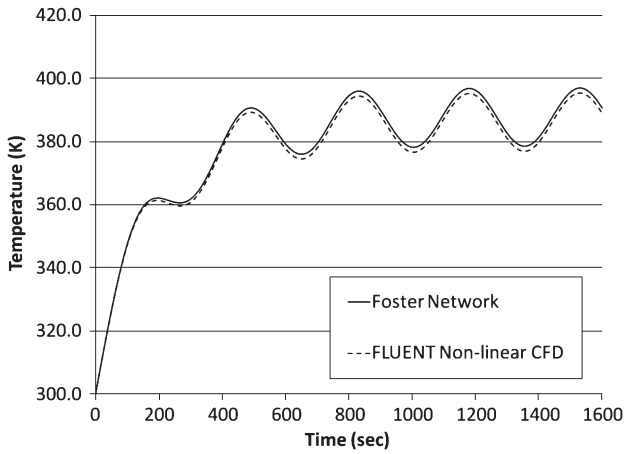

Fig. 14. Comparison of Foster network model with FLUENT nonlinear CFD model.

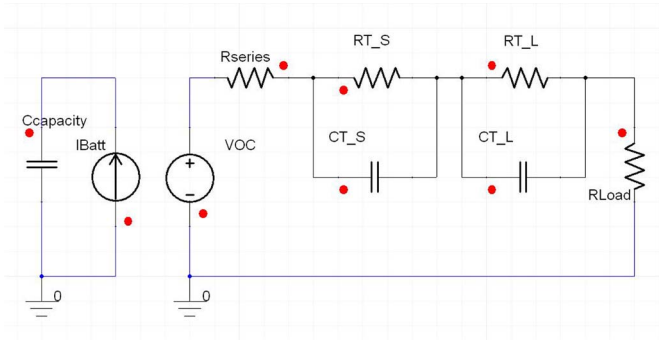

Fig. 15. Electrical circuit model for a battery cell.

was performed to generate the needed step response curves for the Foster network model. A Foster network model is then created based on those step response curves. Results from the Foster network model are then compared with those from a *new* CFD model using the same flow rate but with ideal gas law for density- and temperature-dependent properties. Fig. 14 shows the comparison for cell one under sinusoidal power dissipation input. Cell one was chosen here arbitrarily, and all cells exhibit similar behavior. The comparison is no longer as perfect as shown in Fig. 10 or 13 since the Foster network model is no longer equivalent to the *new* CFD model which has nonlinearity effects due to nonconstant density- and temperature-dependent properties. However, it can be calculated from Fig. 14 that the maximum error due to nonlinearity is approximately 2% when the battery cell temperature increases by approximately 90 K. A maximum error of 2% could be quite acceptable considering that most battery thermal applications do not even have a temperature increase of 90 K, and thus, smaller error will be involved using the Foster network approach.

Note that, if results from the Foster network method are accepted for nonlinear problems, the time saving by using the Foster network method is even larger. For the CFD model shown in Figs. 8 and 12, only the energy equation is solved, and the Foster network method is already about one to two orders of magnitude faster. A full CFD model with nonlinear effects is another one or two orders of magnitude slower because the full CFD model for a nonlinear problem solves the complete set of Navier–Stokes equations rather than only the energy equation. The number of equations solved in such a nonlinear CFD problem is seven rather than one, the time step used for such a nonlinear model has to be reduced for the same accuracy, and the number of iterations needed per time step is more due to nonlinearity. Therefore, a Foster network model is expected to be three to four orders of magnitude faster than the corresponding full nonlinear CFD model. For the simple test case here, the full CFD model runs for approximately 8 h on one CPU while the Foster network model runs only for approximately 10 s, a speed-up factor of approximately 30 000.

VI. Complete Battery Circuit Model

Battery electrical circuit models are used to predict and optimize battery run time and circuit performance. Many battery circuit models have been proposed in the literature. A circuit model by Chen and Rincon-Mora [4] is shown in Fig. 15. These models need to be coupled with a battery thermal model if temperature impact on the battery performance is desired. The battery thermal model used is typically the traditional thermal network model. Such a thermal model is not very accurate since it uses only one or a couple of resistors and capacitors to represent each battery cell and it typically uses one constant heat transfer coefficient for each battery cell. To make this type of model more accurate, more nodes or parameters are needed, but more parameters would make such type of models more complex to calibrate. The proposed Foster network here can be used to replace the traditional thermal network with increased accuracy without loss of performance. It is worth to mention, however, that the traditional thermal network does not need to assume linearity and time invariance and thus it is a more general approach. However, as demonstrated in this paper, battery thermal simulations can satisfy those assumptions pretty well and thus can benefit from the less general but much more accurate Foster network approach.

VII. Conclusion

Battery cooling systems can be represented by a matrix of Foster networks. This is possible because battery cooling systems can be considered to be an LTI system. The Foster network, being an LTI system, can thus be used to represent the battery cooling LTI system. It was shown that the Foster network approach gives equivalent solution as the CFD and it obtains results in less than half a minute compared with hours of run time from CFD. However, CFD or testing is still needed to generate the step responses for the battery system, which are required to calibrate the Foster network model. The Foster network is also shown to be able to replace the traditional thermal network model to couple with battery electrical models. The Foster network approach is much more accurate than the traditional thermal network approach without loss of performance.

A preliminary study shows that the nonlinearity associated with nonconstant properties gives a maximum error of approximately 2% when the battery cell temperature increases by approximately 90 K. With smaller temperature increase, the error associated with the Foster network approach is expected to be even smaller.

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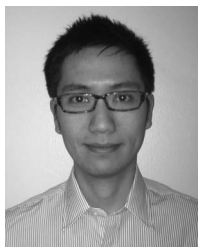

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