PACK LEVEL DESIGN OPTIMIZATION FOR ELECTRIC VEHICLE THERMAL MANAGEMENT SYSTEMS MINIMIZING STANDARD DEVIATION OF TEMPERATURE DISTRIBUTION

by

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Abstract

Green technologies have recently gained interest for many reasons. Economic factors in conjunction with an increased social desire to reduce our environmental impact on the Earth have created a desire for more environmentally friendly technologies, especially automotive technologies such as the electric car. While public interest in electric vehicles is growing, there are a number of challenges which must first be addressed before their widespread adoption is possible. Cost, longevity, and range are all important factors which need to be addressed for electric vehicles to compete directly with their gasoline counterparts. By more efficiently using the energy stored within the battery pack, some of these issues can be addressed.

This study focuses on the thermal management systems for electric vehicles and the application of design optimization in the early design phase considering the pack in its entirety. A liquid cooling system is considered for a current generation electric vehicle, with time dependent heat generation rates within the battery cells based on vehicle operating conditions. Identifying the most efficient distribution of cooling within the battery pack to achieve uniform temperature is the objective of optimization.

Simulations were performed on a complete battery pack model, featuring 288 battery cells and 144 cooling plates. Anisotropic material properties and non-uniform heat generation rates are included as well as energy demands based on a representative vehicle drive cycle. Results have shown that through design optimization, the standard deviation of temperature within the battery cells can be improved by as much as 80% when compared to a conventional design. The standard deviation of temperature saw improvement from an average of 0.2828 K for a conventional design to 0.05318 K after optimization.

These results are specific to the given battery pack construction, battery cell, and cooling type. The method of modeling and analysis can be extended to many battery geometries and cooling technologies in the future. Application of design optimization to the problem of thermal
management system design can yield significant improvements to battery pack thermal management, and thereby incrementally improve the efficiency of electrified vehicles.
Acknowledgements

I would like to thank my supervisor, Dr. Il-Yong Kim, for all of his helpful suggestions and guidance throughout this project. I have learned a great deal from working with him in my time at Queen’s University and cherish the experience greatly.

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My family and friends have been very supportive of me during graduate school, I would not have been able to accomplish so much without their support and guidance. Past and present members of the structural and multi-disciplinary systems design group with whom I have worked have also been an inspiration, source of ideas, and reality check when needed.

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List of Symbols

\( \dot{Q} \) = Heat generation rate (W)

\( I \) = Electric current (A)

\( R \) = Electrical resistance (Ω)

\( \dot{q} \) = Heat flow rate (W/m²)

\( k \) = Thermal conductivity (W/m K)

\( T \) = Temperature (K)

\( G_{\text{Cooling}} \) = Cooling plate heat conductance (W/K)

\( T_{\text{Avg}} \) = Battery cell average temperature (K)

\( T_{\text{in}} \) = Coolant inlet temperature (K)

\( KE \) = Kinetic energy (J)

\( m \) = Mass (kg)

\( v \) = Speed (m/s)

\( P_{\text{drag}} \) = Drag power loss (W)

\( \rho \) = Air density (kg/m³)

\( A \) = Vehicle frontal area (m²)

\( C_d \) = Vehicle coefficient of drag (unitless)

\( P \) = Electrical power (W)

\( V_{\text{Tot}} \) = Total voltage drop (V)

\( d \) = Design vector (unitless)

\( T_{\sigma} \) = Standard deviation of temperature (K)

\( T_i \) = Temperature of \( i \)-th element (K)

\( T_{\text{Avg}} \) = Average temperature (K)

\( HG_{\text{plate}} \) = Heat generation potential (unitless)
$HG_{\text{Total}} = \text{Total heat generation potential for entire plate (unitless)}$

$V_e = \text{Element volume (m}^3\text{)}$

$\Delta T = \text{Temperature difference (K)}$
1.1 Motivation

Rising oil prices and concerns for the long term sustainability of fossil fuel dependent industries have created an increased global interest in green technologies. This applies to many, if not all, industries, including the automotive sector. Consumer’s desire for increased efficiency in personal transportation stems from both economic concerns as well as the increased desire to reduce the global carbon footprint. These two consumer concerns have created a considerable desire within the automotive market for highly efficient, practical alternatives to the internal combustion (IC) engine powered vehicles which currently dominate the market.

To satisfy the desire for more green personal transportation options, auto makers have taken a number of steps: there has been a marked increase in attention to efficiency and fuel consumption in conventional IC vehicles, and there have been a number of new electric and hybrid electric (EV & HEV) vehicles introduced into the market. While these new technologies do address some of the environmental concerns, they are not yet matured to the point that the IC engine is and have a great potential for improvement.

There are a number of common concerns or drawbacks when considering EV/HEV vehicles in contrast to IC vehicles: the first and most commonly stated concern is in relation to the potential range of the vehicles. While most EV ranges are satisfactory for daily commutes, they limit the possibility for the vehicles to be used for longer trips. This is compounded by the second major concern, charging time. While many EVs can be charged in a few hours, this generally requires a dedicated high voltage charging station, which is not yet commonplace. When charging through conventional 110/220V power supplies charging can take more than 8 hours depending on the size of the battery. Another major concern for EV/HEVs is the cost and
lifetime of the vehicle. These stem mostly from the battery pack used in the vehicle. Currently batteries make up a significant portion of the cost of the vehicle. This is a considerable cost, especially when the battery pack has a finite lifetime before it requires replacement. Most EV/HEVs are designed for a battery lifecycle of 10 years, after which the battery pack will have deteriorated to the point where it must be replaced.

Many of these concerns can be addressed through improvements to battery pack technology. Extending the range and lifetime of the battery pack can be achieved by keeping the pack operating under optimum conditions as much as possible. Batteries are sensitive to temperature and can suffer permanent damage if operated at too high or too low a temperature. While in operation, current battery technologies generate a non-trivial amount of heat which must be removed and/or managed to maintain optimal conditions. Some battery chemistries are also susceptible to thermal runaway if temperatures become too high, which is a major safety concern. Improvements made to the thermal management systems of EV/HEV battery packs stand to improve range and effectiveness of the battery pack. There are a number of different approaches to battery thermal management, and robust design of the system will help alleviate many concerns for potential EV/HEV customers.

1.2 Objective

Desirable characteristics for EV battery packs are high energy density (J/m³) and high specific energy (J/kg). Due to this fact battery packs are generally constructed to be as compact as possible such that they take up the least amount of space and can be placed as low as possible in the vehicle. With a highly compact construction, usually taking the form of stacks of prismatic battery cells, heat generation within the battery cells needs to be regulated by a thermal management system. Two common approaches to thermal management are by i) air cooling and ii) liquid cooling. Liquid cooling is a highly customizable approach using coolant pumped through plates placed between battery cells to absorb and remove heat from the battery pack. A
common layout for liquid cooling systems is to place a cooling plate between every other battery cell, reducing the total number of cooling plates while still having each battery cell in direct contact with an element of the thermal management system.

Cooling plate performance is important in managing the temperature of the battery pack. A major concern is the average temperature of the battery cells, which must be maintained in a specific range to ensure efficient operation of the cells and minimize degradation. Another important aspect to consider is the temperature distribution within the battery cell and the battery pack. Large temperature fluctuations across a battery cell can damage the cell, reducing the overall effectiveness of the pack. Large variations in the temperature of battery cells within the pack will also lead to premature failure of a single cell (generally necessitating replacement of the entire battery pack) as well as a reduction in useful range for the vehicle.

This study will investigate an approach to pack level optimization of EV battery thermal management systems. All work is based on the current General Motors EV, the Chevy Volt. At the pack level the major concerns are the distribution of temperature within the battery cells and throughout the pack. Assuming the use of a liquid cooling system we will investigate the optimum distribution of cooling performance within the pack to achieve minimized temperature distributions.

The objectives of this study are therefore:

1. Construct a simplified model of the battery pack for optimization.
2. Apply time varying boundary conditions to simulations to simulate real world operating conditions.
3. Create an optimization routine for distribution of cooling potential within the battery pack.
4. Investigate temperature distributions with respect to time and location within the battery pack.
5. Demonstrate that design optimization can improve the performance of battery thermal management systems.

1.3 Contributions

Previous studies in the area of pack level design have modeled a number of different approaches to cooling and various operating conditions. Studies have also been conducted looking specifically at the performance of the cooling plates under a number of steady state operating conditions, with and without optimization. This study is the first to apply time-varying heat generation rates to an entire EV battery pack with design optimization. While previous studies into cooling plate performance have shown marked improvements in performance, they have also shown a high sensitivity to the applied boundary conditions. The results from this study show that the behavior of the cooling plates and the boundary conditions, such as heat flux into the plates, are dependent on one another. By modeling the battery pack under real world operating conditions, a representative set of boundary conditions can be found which are applicable to high fidelity modeling and optimization at the cell level.

This study demonstrates the potential improvement in temperature distribution through thermal management system design optimization. By identifying important considerations early in the design of a battery pack, a thermal management system which is specifically suited to the needs of a certain vehicle, set of operating conditions, or battery type is possible. This is achieved through not only modeling the cooling system but incorporating the battery cells, and a time dependent thermal simulation. Future work on both pack level and cell level design will be able to use these results to investigate and model new thermal management system designs.
Chapter 2

Literature Review

2.1 Climate Change

Climate change is a generally accepted truth in our world today. We have seen an average rise in global temperature of 0.74 K over the last 100 years [1] and do not expect this trend to diminish in the near future. Along with an increase in temperature, there are many associated effects observable in the environment. Increased ocean levels (1.7 to 3 mm per year) [1], glacial retreat [2], reduction in the polar ice caps [3], and abnormal weather events are some of the suspected results of global climate change. While there has been debate as to the cause and severity of these effects, the generally accepted cause is the massive increase in greenhouse gas (GHG) emissions over the course of the 20th century [1, 4, 5].

Greenhouse gases are a group of gases which when present in the atmosphere will facilitate the greenhouse effect and trap radiated heat from the sun in the terrestrial system by keeping the energy in the atmosphere instead of radiating back into space [6]. There are a number of gases which can contribute the greenhouse effect in our atmosphere, many of which are the result of human activity and are produced in industry in large quantities. Carbon dioxide (CO₂) is one of the most common and best known GHG’s. CO₂ is produced during the burning of fossil fuels, which is the primary source of its production. Land use is also important when considering CO₂ since deforestation/reforestation can have an impact on its levels. Methane (CH₄) is another GHG which is produced during agricultural activities, waste management, and energy use. Nitrous oxide (N₂O) is also produced during agricultural activities, primarily due to fertilizer use and also contributes to the greenhouse effect. Fluorinated gases (F-gases) are a group of gases including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur...
hexafluoride (SF₆), which are produced by industry and are used in refrigeration. Table 1 shows the contribution of each GHG to the total worldwide production in 2004 [1].

Table 1 - Contribution to Global Greenhouse Gas Emissions by Type [1]

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (Fossil Fuel Use)</td>
<td>57%</td>
</tr>
<tr>
<td>Carbon Dioxide (Deforestation, Biomass Decay, etc.)</td>
<td>17%</td>
</tr>
<tr>
<td>Carbon Dioxide (Other)</td>
<td>3%</td>
</tr>
<tr>
<td>Methane</td>
<td>14%</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>8%</td>
</tr>
<tr>
<td>F-gases</td>
<td>1%</td>
</tr>
</tbody>
</table>

Greenhouse gases are produced by a number of different industries and processes used by our society. The largest contributor to GHG emissions comes from energy production. Transportation also contributes a significant amount to the worldwide total. Table 2 shows the global distribution of GHG production by industry, also for 2004 [1].
Table 2 - Contribution to Global Greenhouse Gas Emissions by Industry [1]

<table>
<thead>
<tr>
<th>Industry</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Supply</td>
<td>26%</td>
</tr>
<tr>
<td>Industry</td>
<td>19%</td>
</tr>
<tr>
<td>Forestry</td>
<td>17%</td>
</tr>
<tr>
<td>Agriculture</td>
<td>14%</td>
</tr>
<tr>
<td>Transport</td>
<td>13%</td>
</tr>
<tr>
<td>Residential &amp; Commercial buildings</td>
<td>8%</td>
</tr>
<tr>
<td>Waste &amp; Wastewater</td>
<td>3%</td>
</tr>
</tbody>
</table>

The totals for GHG contributions and production by industry for the US is shown in Table 3 and Table 4 [7].

Table 3 - Contribution to US National Greenhouse Gas Emissions by Type [7]

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>84%</td>
</tr>
<tr>
<td>Methane</td>
<td>9%</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>5%</td>
</tr>
<tr>
<td>F-gases</td>
<td>2%</td>
</tr>
</tbody>
</table>
### Table 4 - Contribution to US National Greenhouse Gas Emissions by Industry [7]

<table>
<thead>
<tr>
<th>Industry</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Supply</td>
<td>33%</td>
</tr>
<tr>
<td>Industry</td>
<td>20%</td>
</tr>
<tr>
<td>Agriculture</td>
<td>8%</td>
</tr>
<tr>
<td>Transport</td>
<td>28%</td>
</tr>
<tr>
<td>Residential &amp; Commercial buildings</td>
<td>11%</td>
</tr>
</tbody>
</table>

It can be seen that the distributions are similar, but not identical to the worldwide totals. Of particular note is the increased contribution by transportation to the production of GHG’s in the US, contributing 28% of the total national level of 6,702 million metric tons of CO$_2$ equivalent [7].

Reducing the overall production of GHG’s has become central in the effort to mitigate the greenhouse effect and curb the increase in temperature seen over the last 100 years. Efforts are being made to ensure cleaner, more efficient industrial processes to reduce GHG production. While these efforts are possible in developed countries, there is continuous industrial and economic growth across the planet. Even with reductions in first world nations, the increased production in emerging markets (such as China) may still result in net increases of GHG emissions worldwide. The creation of new, clean technologies which can reduce or eliminate the production of GHG’s is sorely needed.

### 2.2 Social and Legislative Demand for Electric Vehicles

Beginning late in the 20$^{th}$ century and continuing until the present, there has been an increase in social awareness regarding climate change and environmental practices in general. People now better understand the effects of excessive energy consumption, especially the effect
of transportation on the environment. Degradation of air quality in large metropolitan cities is both an environmental and health concern [8]. In addition to environmental concerns, there is a growing concern about dependence on foreign oil to fuel national energy needs. Ever increasing oil (and gasoline) prices [9] are another concern for consumers when considering transportation options today. Coupled with the finite reserves of fossil fuels available for use [10], this has created uneasiness with respect to the absolute dependence of the transportation sector on oil production.

These economic and social considerations have created a growing market for low or zero emissions vehicles for personal transportation with sales of EVs doubling from 2011 to 2012 [11]. Options such as hybrid electric vehicles (HEVs) and fully battery electric vehicles (EVs) are gaining popularity both for their apparent economic benefit as well as their reduced impact on the environment. The total lifetime impact of HEV/EVs on the environment is yet to be seen [12], and depending on the source of the electric energy, HEC/EVs may not yet yield significant improvements over conventional IC vehicles. Regardless of the end environmental impact of HEV/EVs, they are attractive to consumers due to their low emissions on road and perceived environmental impact. This has created a desire for EV technology and has facilitated research and development in the field.

The production of low/zero emissions vehicles is not only driven by the social and consumer demand for increased efficiency in the transportation sector. Currently there are a set of government mandated regulations requiring auto makers in the US to reduce their average fleet-wide emissions by 2025, known as Corporate Average Fuel Economy (CAFE) [13]. CAFE regulations require automakers to reduce emissions by setting a minimum average fuel economy for passenger and light duty trucks. Fuel economy is to be increased incrementally each year until 2025. Table 5 shows the fuel economy targets for different classes of vehicles for 2025.
Table 5 - CAFE Standards for Cars and Light Duty Trucks in 2025 [13]

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>CAFE Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPG</td>
</tr>
<tr>
<td>Small Car</td>
<td>61</td>
</tr>
<tr>
<td>Large Car</td>
<td>46</td>
</tr>
<tr>
<td>Small Light Duty Truck</td>
<td>50</td>
</tr>
<tr>
<td>Large Light Duty Truck</td>
<td>30</td>
</tr>
</tbody>
</table>

With harsh penalties for automakers that do not satisfy the CAFE regulations, significant effort is being put into increased efficiency for all car and light duty truck designs in the near future. Since CAFE regulations apply to the average fuel economy for a given brand’s model range, the introduction of low/zero emissions vehicles such as HEV and EVs will greatly aid in reducing the average for the range.

The combination of desire on the part of the consumer and the need for automakers to produce more energy-efficient vehicles have created an increased desire for electric vehicles. While there exist other technologies which may fill the role (fuel cells for example), electric vehicles are the most attractive and viable option for the time being.

2.3 Electric Vehicles

Electric vehicles have been in existence for over 100 years. These early versions of the electric car were used as personal cars, vans, taxis, delivery vehicles, and buses. The electric vehicles of the early 20th century were an attractive alternative to the hand-started, noisy, and smelly IC engine alternative [14]. With improvements to the IC engine, the electric vehicle lost popularity due to the ease of operation and improved reliability of fossil fuel powered vehicles. Today we have seen a resurgence of electric vehicles in the personal transportation market. One of the earliest well known examples of an electric car was the General Motors EV1, produced
from 1996 to 1999. It was the first mass-produced fully electric vehicle produced by a major automaker and served to demonstrate the possibilities electric drive vehicles could offer. The EV1 initially used lead-acid batteries, with a curb weight of 3,086 pounds. The available range for these models was 96 km, with a battery pack capacity of 16.5 kWh. By the time the EV1 was discontinued, it had shifted to nickel metal hydride batteries, reducing the curb weight to 2,908 pounds. The range of the newer generation vehicles was increased to 257 km, with a capacity of 26.4 kWh [15].

More recent additions to the electric vehicle market include the well-known Tesla Roadster (2008-2012) and model S (2012-present). These are produced by electric car manufacturer Tesla Motors located in California, USA. The Tesla Roadster was one of the first performance based electric vehicles, showing that electric drive vehicles need not be only designed for economy but can achieve levels of performance on par with those of IC engine vehicles. The Model S is a new model, designed to compete in the luxury sedan market. Both of these vehicles have been successful in demonstrating the potential of electric drive vehicles to replace conventional IC offerings in the future. The Roadster has a range of 393 km, a curb weight of 2,723 pounds, and a battery capacity of 53 kWh [16]. The Model S has a range of 426 km, curb weight of 4,647 pounds, and a capacity of 85 kWh [17, 18]. Both models produced by Tesla Motors are fully electric vehicles, requiring plug-in recharging, which utilize lithium ion battery packs.

Nissan has produced a fully electric vehicle for the personal transportation market as well, the Nissan Leaf. The Leaf is a compact 5-door hatchback intended for daily commuting which is currently in production (2010-present). It features a range of 121 km, curb weight of 3,291 pounds, and battery capacity of 24 kWh [19, 20]. The Leaf uses lithium ion battery cells and is notable due to the fact that it uses air-cooling in its thermal management system.
General Motors has produced a plug-in electric vehicle with range extension, known as the Chevrolet Volt (2010-present). The Volt is intended to be used as a purely electric vehicle, with the capability to generate electricity on board using a gasoline powered generator. Due to this fact it is promoted as an electric vehicle with range extension, as opposed to a hybrid-electric vehicle. In purely electric drive mode, the Volt features a range of 61 km, has a curb weight of 3,781 pounds, and a battery capacity of 16.5 kWh [21]. The Volt was designed to be able to bridge the gap between purely electric vehicles and IC engine vehicles in that it is not limited in total range (it can be operated continuously on gasoline power for extended trips) but can still be used as a purely electric vehicle for everyday use, being recharged between uses.

In the last decade there have been a number of hybrid-electric vehicle offerings from many automakers. These include both new vehicle designs (such as the Toyota Prius) as well as many hybrid versions of IC engine models. Hybrid offerings are available from a large number of large automakers including but not limited to: Toyota, Honda, Mazda, Hyundai, BMW, Mercedes, Porsche, Volkswagen, Ford, Chevrolet, and Dodge. In addition to the proliferation of hybrid-electric vehicles being introduced into the market, there have been a number of concept cars produced not for commercial success but to showcase the potential of both individual automakers and electric vehicle technology in general. These are not limited to maximum efficiency commuter vehicles but extend into the realm of performance as well. Many of the latest versions of so called “supercars” produced by the likes Ferrari, McLaren, and Porsche feature hybrid power plants used to boost the available power by over 150 HP [22, 23, 24].

It can be seen that electrified vehicles have moved into the mainstream and no longer occupy such a small niche market as they traditionally have. This increase in public interest and potential for commercial success have made the design and development of electric drive systems an important consideration in the automotive market. Electrified vehicles have a number of
unique considerations which must be taken into account to ensure a desirable and useful end product. There are 3 major types of electric drive vehicles, discussed below.

2.3.1 Internal Combustion Hybrid Electric Vehicles

Internal Combustion hybrid electric vehicles use predominantly the power of the IC engine to propel the vehicle. The electric drive system is present to supplement the power provided by the IC engine and reduce the overall fuel consumption of the vehicle. The electric drive system is also used during braking maneuvers to help decelerate the vehicle. During these deceleration events, the energy storage system is charged, or energy is harvested during these events. After the vehicle is slowed down the energy is then spent on acceleration to increase speed. This approach allows for the energy usually spent on braking to be recouped. The braking energy is conventionally lost to heat in the braking system. By reusing braking energy the overall dependence on the IC engine is diminished and fuel economy is increased.

Hybrid electric vehicles will see numerous charge/discharge events during every trip. As such there is less need for the energy storage system to be able to store large amounts of energy. The primary consideration for hybrids is the ability of the storage system to quickly store the energy from braking, and quickly discharge that same energy when the vehicle accelerates again. The storage system must also be able to handle a very high number of charge/discharge cycles before degrading. These considerations mean that smaller battery packs or super-capacitors are well suited for use in hybrid electric vehicles [25].

2.3.2 Purely Electric Vehicles

Purely electric vehicles use only electric power for all of the vehicle systems. This includes both locomotion as well as all ancillaries such as GPS, radio, and climate control. Similar to hybrid electrics, they may also utilize regenerative braking to minimize the amount of energy lost during deceleration.
Since purely electric vehicles (or, battery electric vehicles: BEVs) have only the battery as a source of energy, it must be large enough to provide all of the energy for a round trip of daily use. This means the battery pack is generally quite large and heavy in order to store the required amount of energy. The large mass fraction of the vehicle devoted to the battery pack becomes one of the limiting factors in the range of the vehicle. As the energy is depleted from the pack, the mass does not decrease and must still be accelerated and decelerated regardless of the state of charge (SOC) [26]. While the batteries used in BEVs are required to store a much higher total amount of energy, they differ in requirements from those seen in HEVs. One of the primary differences is that they will see far fewer charge/discharge cycles over time. Each driving event represents only one discharge cycle as opposed to the many seen in HEVs. The other major difference is in the required rate of energy delivery [27]. The larger BEV packs still need to deliver enough power to propel the vehicle; they are however much larger and the individual strain on each battery cell in lower. The types of batteries used then do not need to be able to handle such large spikes of charge and discharge rate that are seen in HEV operation. These considerations mean that battery packs with high specific energy (W/kg) are best suited for use in BEVs. A large depth of discharge (DOD) is also advantageous in purely electric vehicles. Useful DOD represents the amount of energy which may be used by the vehicle without depleting the battery to the point that permanent damage might occur: typically on the order of 80% but varies based on battery chemistry [28].

2.3.3 Electric Vehicles with Range Extension

EVs with range extension are essentially the same a purely electric BEVs with the addition of an onboard IC engine. Most commonly the IC engine is used to power a generator which directly powers the electric traction motors, with excess energy being used to charge the battery pack. The IC engine may be connected to the drive wheels through a conventional transmission; this adds extra mass and complexity to the vehicle though. Utilizing the onboard IC
engine as an electrical generator has the added benefit of allowing it to operate at its most
efficient RPM continuously while generating electricity, as opposed to being used to drive the
wheels directly as in a conventional IC vehicle.

Considerations for the battery pack follow those of BEVs in general. If the battery pack
used in a range extended vehicle is too large, it will greatly diminish the efficiency of operation
during use of the IC engine as the added weight will put a much greater strain on the power
generation system.

2.4 Electrified Vehicle Batteries

2.4.1 Battery Types

There are two major types of battery geometries used in current EVs. They are i)
cylindrical spiral wound cells and ii) pouch type battery cells. Both are similar in basic
construction but differ mainly in packaging. Both types of battery cells feature a negative anode
and positive cathode with a separator between them to ensure there is no direct contact between
the electrodes. They also have some form of electrolyte which fills the volume of the battery cell.
Dry cell batteries use an electrolyte paste which has only enough liquid to allow for current flow
where a wet cell battery has a fully liquid electrolyte. The electrolyte allows for ions to pass from
the anode to the cathode during discharge and vice versa during charging. Figure 1 shows the
basic construction of a single battery cell.
The major difference between cylindrical and pouch type batteries comes from their packaging. A pouch type cell is a large, flat cell, usually rectangular and very thin. This allows for a highly compact stacking of multiple cells and each cell features a large surface area for thermal transfer when heating or cooling is necessary. This is also a common battery construction for use in personal electronic devices as its form factor is applicable to compact handheld electronics. Cylindrical cells are essentially rolled up pouch type cells. This creates a compact single cell which has a large electrode surface area relative to volume of the battery cell. A common cylindrical lithium ion battery cell is the 18650 cell, used in many laptop battery packs and LED flashlights. The 18650 cell is also utilized in both the Tesla Roadster and Model S, with 6,831 cells in the Roadster and over 7,000 in the Model S [30]. Figure 2 highlights the similarities and differences between the two battery constructions.
In addition to battery form factor or shape, battery chemistry represents the other major defining characteristic of battery type. There have been a number of battery chemistries used in EVs and HEVs in the past. These include lead-acid, nickel-metal-hydride (NiMH), and lithium-ion (Li-ion) batteries.

Lead-acid batteries are very common and used in almost all vehicles on the road today as a part of the starting system. It is the battery chemistry of choice in many applications due to its low cost and technological maturity. Although lead-acid batteries have low specific energy and low energy density, they are able to produce a large instantaneous current, giving them good specific power. They are also cheap to produce, which makes them attractive in terms of initial investment as well as cost to replace.

Nickel-metal-hydride batteries are a further refinement of the nickel-cadmium battery chemistry. They feature much improved specific energy and energy density when compared to lead-acid batteries, and boast a high specific power as well. NiMH batteries suffer from a high...
self-discharge rate, which is the rate at which they lose energy when not in use, up to 20% on the first day and 4% each day afterward [32].

Lithium ion batteries are the most commonly used HEV/EV battery cell used today. Li-ion batteries have high specific energy, energy density, and specific power, and do not suffer from excessive self-discharge rates [33]. Li-ion batteries are susceptible to thermal runaway, which is an uncontrolled exothermic reaction that takes place once the battery cell reaches a certain temperature threshold. This is a serious safety concern since thermal runaway can result in fire or explosion.

Figure 3 shows a comparison of specific energy and energy density for many different battery chemistries. It can be seen that successive generations of battery technologies have seen a trend of increasing specific energy and energy density, with that trend expected to continue with new technologies such as lithium-air batteries.

![Figure 3 - Comparison between various battery cell chemistries showing the specific energy and energy density [34]](image-url)
2.4.2 Battery Considerations

There are many important considerations which need to be made when selecting a battery type and chemistry to use in HEV/EV applications. Cost must be addressed such that the vehicle is in the proper price range for its intended market to make it a desirable option for consumers. Total energy capacity must also be matched to the intended use for the vehicle. When considering battery chemistries, there will be different operating conditions depending on the type of vehicle the battery is intended for; as previously discussed, HEVs will need to be able to provide a large portion of their power very quickly, and also recharge quickly during braking. Purely electric vehicles need more total capacity but do not need to discharge completely as quickly. This creates a divergence between the two types of vehicles, HEVs with high charge/discharge rates and many charge cycles and EVs with higher capacity and fewer total charge cycles. Battery lifetime and depth of discharge are two more considerations which must be addressed and are dependent on one another. The more deeply discharged a battery, the fewer total cycles it can go through before degrading, making the balancing of DOD and intended lifetime important [35]. Most EVs have an intended battery pack life of at least 10 years, after which the pack must be replaced at significant cost.

2.4.3 Effect of Temperature

The temperature at which battery cells operate can have a significant effect on their performance and life. Hallaj et al. [36] have shown that the temperature, along with state of charge, and discharge rate are important factors for battery operation. The overall performance, current output and operating voltage [37], are dependent on the battery cell operating temperature. In the case of Li-ion batteries (which are the current choice for EVs), temperatures above and below the ideal operating temperature can have significant negative side effects. Operation of the battery cell below the ideal range can seriously damage the battery cell, shorten the life of the pack, and reduce the available energy [38]. This is due to changes in the chemical
reaction which produces the electric current used by the traction motors. As the operating
temperature drops below the ideal range the chemical reaction slows and is not able to produce
full voltage and power output. If temperatures become too high within a battery cell, the total
amount of energy available for discharge fall rapidly as for the low temperature case. Plating can
occur and will permanently reduce the energy storage and number of useful charge/discharge
cycles for a battery cell, reducing the effectiveness of the pack even when occurring in a single
cell [39]. Chacko and Yongmann [40] have shown that maintaining a battery temperature of 25
°C to 45 °C for Li-ion batteries allows for their most efficient operation. Once temperatures
reach the threshold for thermal runaway (in Li-ion batteries), destruction of the battery is
possible, with significant safety concerns for vehicle occupants.

With sensitivity to temperature which affects performance, storage capacity, and life of
the battery pack, thermal management is important in EV battery pack design. Reductions in
total available power can be on the order of 20% when temperatures are outside the working
range, and total number of charge/discharge cycles can be reduced by 75% [41]. During normal
operation of an EV battery pack, a positive heat generation is produced internally by the battery
cells. As such the cooling of battery packs becomes the primary concern of the thermal
management system.

2.5 Battery Cooling Systems

Battery thermal management systems, often referred to as cooling systems since their
primary function is to limit the temperature increase of the battery during use, are numerous and
must be suited to the type of battery and its intended use. These can range from a complete lack
of thermal management to actively controlled, powered systems with variable operation to suit
conditions. A well designed thermal management system will keep the battery pack within its
operating temperature window, which can increase the efficiency of the battery significantly. The
system should also maintain as constant as possible a temperature both within individual cells as
well as across the entire pack, assuming multiple cells are used. The most common approaches to battery thermal management in EVs are discussed below.

2.5.1 Passive Cooling vs. Active Cooling

Passive cooling systems include simplest, lowest energy usage thermal management systems. These can range from no thermal management whatsoever aside from the battery itself acting as a heat sink to more complex systems which limit the peak temperature of the battery.

For low power applications, a passive air-cooling system can be used, such as in electric scooters (2 wheeled) and mobility scooters (similar to electric wheelchairs). For applications where the duration of use or power consumption are low and the battery heat capacity is sufficient to absorb any heat generated during operation, a passive system will reduce complexity, weight, and cost.

More advanced passive systems can limit temperature spikes by using phase change materials (PCM). These are a class of material commonly made of a mixture of wax and graphite which can be designed to melt at a specifically defined temperature. The latent heat of phase change is large and will temporarily limit the temperature to the melting temperature. Upon cooling below the melting point the PCM will solidify and can repeat its function of temperature spike limitation. This approach is applicable when there are large spikes of charge/discharge and heat generation in a small battery pack, or one that is difficult to cool in other ways [42, 43]. Any type of passive cooling offers limited control over the temperature of the battery, or the distribution of temperature within the battery.

Active cooling systems are more complex and require power for their operation. Active cooling systems can utilize either air or a liquid as a cooling medium. Coolant is actively circulated over, or through, the battery pack absorbing heat and rejecting it to the environment. Active cooling systems are attractive when the battery packs have high heat generation rates as they are able to remove heat energy at a higher rate than typical passive cooling systems. They also offer a level of control which is not possible in passive cooling: the coolant temperature can
be changed using an air conditioning system, the coolant flow rate can be controlled, and the routing of the coolant can also be varied.

Active cooling systems do require power to operate, which can potentially reduce the total usable energy output of the battery pack for locomotion (in EVs) if the system is not scaled properly to the needs of the battery pack. Active cooling systems offer more control in terms of average pack temperatures and temperature distributions within the pack than passive systems. When efficiency is a major concern, this makes active cooling attractive as it allows the battery pack to operate near the optimal temperature much of the time. Maintaining a constant temperature throughout the pack is also a concern when efficiency and life are important and active cooling systems are able to achieve good uniformity.

2.5.2 Air Cooling vs. Liquid Cooling

Air cooling has been used for thermal management in a number of EVs. The Toyota Prius uses an air cooling system, as does the newer Nissan Leaf. Both vehicles utilize air conditioning to lower the air temperature enough for the system to be effective. Air cooling is attractive since it is light and simple in comparison to liquid cooling. The mass of the coolant is extremely low as it is a gas, and is readily available in the form of ambient air. If the environmental temperature is high, the air may have to be actively cooled, which can require additional energy from the battery pack. The Prius is able to negate some of this effect by using cabin air drawn from behind the back seats of the vehicle to cool the batteries, cooling both the passenger compartment and battery pack using the same cooling circuit. Air ducting can cause packaging problems in air cooled systems as there needs to be sufficiently large passages to supply the coolant to the pack, and remove it as well. If the air is passed over the battery cells in series, there can also be an undesirable temperature gradient along the coolant path due to the increase in temperature of the coolant [44]. Reversal of the air flow path can alleviate this problem in many cases [45]. Another added benefit to air cooled systems is the possibility of
cycling between active and passive operation. If the speed of the vehicle is sufficient to supply
air flow over the battery, no power is required for the system, reducing the load on the battery and
increasing range. If air cooling is used, it can also become impossible to seal the battery pack
from the environment, as ambient air is passed over the cells, contamination or blockages may
occur and require battery service to remedy.

Liquid cooling systems are commonly used in current generation EVs such as the Chevy Volt [21], Tesla Roadster, and Model S. These vehicles all have very compact battery packs
which are completely sealed from the environment, with only a liquid coolant inlet and outlet
which connects to a closed loop liquid circuit. Compact battery packs allow for packaging low in
the vehicle and improves the performance and handling of the vehicle. Liquid cooled systems are
more complex than air cooled systems, with more components (such as cooling plates) and need
to be completely sealed to avoid liquid leaking into the battery pack. The mass of the liquid
coolant and associated plumbing is also higher than that of an air system. Despite these
drawbacks, liquid cooling systems are highly compact and allow for a greater degree of control
over air cooled systems. By altering the geometry of the coolant passages in a battery pack, and
the routing of these passages, the absorption of heat by the coolant can be controlled to a high
degree. This allows for highly uniform temperature distributions within the pack and within each
cell if properly designed. As with an air based system, the coolant can reject heat to the
environment passively (through an air-liquid heat exchanger) or it can be actively cooled using an
onboard air conditioning system. The high degree of control of the distribution of heat absorption
within the pack and control over the total rate of heat absorption makes liquid cooling an
attractive option for high energy density battery packs with high heat generation rates.
Chapter 3

Methods

3.1 Problem Statement

3.1.1 Battery Pack Design

Temperature regulation within the battery packs of EVs has been identified as an important aspect relating to their safe and efficient operation. With the increasing energy density and reduced masses of EV battery packs, a thorough examination of thermal management systems is becoming an important aspect of battery pack design. When considering an EV battery pack, there are two distinct levels of design to consider: one being the small scale, or individual cell level design, and the other is the large scale, or pack level design. With liquid cooling having been identified as a highly desirable means of thermal regulation, this means the cell level design centers on the design of liquid cooling plates. High fidelity models can be created and have design optimization applied to determine optimum coolant channel geometry. The results of this optimization can achieve minimum temperature variance, minimum pressure drop (reducing pumping power required for the coolant), or minimum average temperature.

For pack level design, the goals are very similar: minimizing the average temperature of the pack, minimizing pumping losses, and reducing the variance of temperature within the pack. Since the battery pack features many individual battery cells, the considerations for temperature and variance of temperature need to be extended from one individual battery cell to include all battery cells within the pack. Real world use of EV battery packs is also not a steady state problem, with the battery pack seeing conditions of high, and low, discharge and heat generation. When considering cell level design, a high fidelity model is required to simulate the fluid flow and heat transfer characteristics between the plate and coolant. For the much larger battery pack, a more simple approach is required to allow for multiple function evaluations of the battery pack.
model, especially when considering a time dependent transient simulation. As such the
considerations at the pack level for thermal management also extend to include not only the
thermal conditions of multiple battery cells, but also how their behavior changes over time while
in use in-vehicle.

3.1.2 Objective Function

The major considerations for battery pack thermal performance are i) average
temperature of the battery pack and ii) temperature distribution both within the individual battery
cells and across the battery pack as a whole. When considering the average temperature of the
battery pack, the total amount of thermal energy removed from the battery pack is of primary
concern. In a liquid cooling system, the rate of energy removal from the battery pack is directly
related to the temperature difference between the pack as a whole and the coolant inlet
temperature. Previous results from cooling plate optimization show that the average battery pack
temperature and coolant temperature are closely linked, and lowering the average pack
temperature is easily achieved by lowering the coolant temperature. The temperature distribution
of the battery cells and battery pack are highly dependent on the performance of the cooling
system behavior beyond coolant inlet temperature.

In performing a transient thermal analysis on the battery pack as a whole, we can see both
the temperature distribution within the pack spatially (within a single cell and between cells), as
well as with respect to time. The objective function for optimization is then minimization of the
standard deviation of temperature for the battery pack. Since there is more than one dimension to
the problem (spatial distribution and distribution over time), the standard deviation of temperature
can have a number of meanings. Temperature distribution could be interpreted as the variability
of temperature at a single location over the time duration of the simulation, or as the variability at
a single point in time over a single, or multiple, battery cells. Initial exploration of the design
space has shown that the temperature within the battery pack is slow to change due to the large
thermal mass associated with the battery cells, which implies the primary concern will be maintaining a uniform temperature *spatially* within the battery pack rather than limiting the sudden increase in temperature during periods of high heat generation. Considering these preliminary results the spatial standard deviation of temperature has been identified as the objective function to be minimized. Since the simulation in question is time dependent the mean over time of the spatial standard deviation of temperature is the single value result used for optimization.

### 3.1.3 Boundary Conditions

There are many aspects which will affect the operating conditions and relevant boundary conditions for battery pack thermal simulation. The electrochemical processes occurring in the battery cells are complex and unique to the chemistry and style of battery cell under consideration. There are also complex fluid dynamics to consider in the liquid cooling plates themselves. Since this work is focused on the thermal performance and thermal management system of EV battery packs, mechanical properties such as stress and strain are ignored. This leaves positive and negative heat generation as the two types of loads on the battery pack. Positive heat generation comes from the battery cells themselves and is applied as a volumetric body load on the battery cells depending on the drive cycle and simulation time. The only other potential source of heat flow into the system is if the battery pack itself is cooler than the liquid coolant and it serves to heat the pack as opposed to cooling, which is not explored in this work.

Heat flow out of the system could come from a number of sources. Primarily the heat taken out of the battery pack will be through the thermal management system, which is considered here as a liquid cooling system, and rejected to the ambient environment. Heat could also escape the system through convection, conduction, or radiation to the surroundings (road, air, vehicle body). Thermal radiation is negligible at the temperatures seen in the simulation, and conduction from the battery pack to the vehicle is minimal due to the construction of the pack.
itself. The battery pack construction sees the battery cells and cooling system sealed within an enclosure for structural rigidity as well as safety. The battery enclosure is water-tight to allow for wet weather operation of the vehicle without the danger of high-voltage short circuits, which pose a danger to occupants as well as the electronics and components of the battery pack itself. Since the entire battery pack is sealed to the environment, there is no airflow in or out of the pack. The small volume of air contained within the pack does not contribute significantly to the overall pack cooling, especially once the temperature of the air is close to that of the pack. The effect of this small thermal mass is ignored.

As such the positive source of heat generation in the simulation comes from the internal heat generation in the battery cells, and the heat absorption comes only from the liquid cooling plates. The specifics of the positive and heat absorption are discussed more fully in the following sections on battery cell (3.2.3) and cooling plate (3.2.4) modeling.

### 3.2 Modeling

#### 3.2.1 EV Battery Pack

The battery pack used as a reference design in this work is that of the Chevy Volt. The Volt uses 288 lithium-ion pouch type battery cells, arranged into 3 major battery sections. Battery Sections 1, 2, and 3 have 90, 72, and 126 battery cells respectively. Figure 4 shows the physical layout of the Volt’s battery pack. The cells are arranged electrically in groups of 3 parallel cells to boost the current output of the pack. These 3 cell groupings are then connected in series to give a total of 96 groups of 3 cells. Total voltage output for the pack is 360 Volts, and a maximum current output of 400 Amps is possible for a duration of 30 seconds. The mass of the battery pack is roughly 190 kg, with a total battery cell mass of 140 kg.
The thermal management system utilized by the Volt is a liquid cooling system. There is a 2:1 ratio of battery cells to cooling plates, with one plate inserted between every other cell in the pack. Liquid coolant, comprising of a 50/50 water-glycol mixture (common automotive antifreeze), is pumped through the cooling plates, which are arranged in parallel such that the inlet temperature is constant throughout the entire pack. The coolant can reject heat to the environment through radiators mounted on the vehicle, or actively cooled using the onboard air conditioning system. During cold weather operation, the coolant can be heated to bring the pack temperature up into the working range.

Figure 4 - CAD model of the Chevy Volt battery pack.
3.2.2 Finite Element Modeling of Components

The finite element (FE) model representing the battery pack is created parametrically within the ANSYS APDL environment. The number of battery cells, their size and all physical properties are written to text files within MATLAB which are then read by ANSYS. Scalar parameters used in the simulation are listed in Appendix B for reference. Since the battery pack is made of a number of repeating segments, both as a whole and within each of the sections, the geometry creation is modular and loops though a small portion of geometry repeatedly to generate the battery pack in its entirety. This section describes geometry creation, meshing, and boundary condition application.

Figure 5 - Basic building block for the battery pack. Repeats to achieve the desired number of cells in a given battery section.
The smallest repeating portion of the battery pack is the combination of battery cell, cooling plate, battery cell, insulation (Figure 5). Using dimensions defined in MATLAB, volumes are created for each component, and each component is named “cellX” (for battery cells) or “plateX” (for cooling plates) where “X” is increased incrementally throughout the process. This process is looped through until the desired number of battery cells is reached for each battery section, completing the geometry for the entire pack. Meshing is then performed by selecting the edges corresponding to the defined dimensions and applying the specified mesh density. Each component is meshed such that there are 8 elements in width (x-direction), 10 elements in height (y-direction), and 3 elements in thickness (z-direction). Each volume is meshed using a hexahedral element, Solid70, which is a thermal element having no structural properties. The final meshed model, which contains a total of 138,960 elements, is shown below in Figure 6.
Boundary condition applications are specified for each component (battery cells and cooling plates) individually, by referencing their local coordinate system. This allows the boundary condition to be the same numerically, varying only in which local origin the spatial values are in reference to. Specifics of the boundary conditions for the battery cells and cooling plates are discussed in their respective section below, 3.2.3 and 3.2.4.

3.2.3 Battery Cells

The battery cells used in the Chevrolet Volt are lithium-ion, pouch type battery cells. Each cell generates a nominal 3.75 Volts of electric potential and can output as much as 4.17
Amps of current [21]. They are laminar in construction, featuring multiple layers including a positive cathode made of aluminum, a negative anode made of nickel plated copper [46], as well as a separator to prevent direct contact of the cathode and anode. Due to this layered construction, they feature highly anisotropic thermal conductivity and cannot be represented by a standard material in the ANSYS simulation environment. Maleki et al. [47] performed a detailed study on similar Li-ion type battery cells investigating their thermal conductivities both in-plane and cross-plane. The specific battery cells tested by Maleki et al. [47] were not identical to those used in the Volt, but were a cylindrical cell commonly used in laptops as well as in Tesla EVs, called 18650 cells. Although cylindrical cells feature fundamentally different thermal conduction behavior, their results are applicable none the less. Cylindrical type cells are essentially “rolled up” pouch type cells and Maleki’s work was performed on the 18650 form cells after they had been unrolled. Their results are shown in Table 6.

Table 6 - Physical properties of a Lithium-ion battery cell for cross-plane and in-plane behavior. Results obtained from a Sony 18650 cell. [47]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-Plane</td>
<td></td>
</tr>
<tr>
<td>Heat Capacity (J/kg K)</td>
<td>1280</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m K)</td>
<td>3.4</td>
</tr>
<tr>
<td>In-Plane</td>
<td></td>
</tr>
<tr>
<td>Heat Capacity (J/kg K)</td>
<td>1278</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m K)</td>
<td>28.05</td>
</tr>
</tbody>
</table>

It can be seen that the difference in thermal conductivity from in-plane to cross-plane is nearly an order of magnitude, which cannot be ignored. This is an important aspect in battery cell modeling since any heat which must be conducted through the cell will spread out in the plane of
the cell much more quickly than it conducts through it. While the battery cell itself features a number of distinct layers and is made up of a number of different materials, the material properties used in the simulation are uniform throughout the cell, although anisotropic.

Heat generation in battery cells comes from two major sources. The first is joule (or resistive) heating. This is the direct result of current passing through the cathode and anode, generating heat due to the electrical resistance. Equation 1 shows the relationship between current and energy dissipation

**Equation 1 – Resistive heating equation**

$$\dot{Q} \propto I^2 R$$

where $\dot{Q}$ represents heating in W, $I$ is current in A, and $R$ is resistance in Ω. Figure 7 shows how the current flow through a pouch type battery cell is distributed. Since all of the current produced must pass through the electrode tabs, the current, and therefore the effects of Joule heating, are highest in that region. Due to the non-linear relationship between current and heat generation, the amount of resistive heating generated at any one location within the battery cell is not a straightforward calculation, especially since the resistance will change with temperature and the current distribution will also then be altered. To accurately determine the level of Joule heating within the cathode and anode, a detailed mapping of the current density within each electrode is required.
Figure 7 - Typical current flow through pouch type battery electrodes. Current density diminishes towards the lower edge of the pictured electrodes. Maximum current density is seen in the tabs.

The second source of heat generation within a battery cell comes from the electrochemical reaction which generates the electric potential within the cell. Many researchers have created approaches by which an analytical model of a battery’s current density and electrochemical process may be solved [48, 49, 50]. While these methods are powerful tools and potentially helpful, they feature a level of detail beyond the current scope of this work. Kim et al. [50] performed both theoretical modeling of a pouch type battery cell’s heat generation and experimental validation of their model. These results show the distribution of heat generation within a comparable battery cell to that of the Chevy Volt and have been used to determine the heat generation profile used in this work. Kim et al. [50] performed a number of tests on an LG
Chem pouch type lithium-ion battery cell, and using a thermal imaging camera captured the temperature profiles for each load at each time interval. The tests performed are shown in Table 7. Note that 1C discharge will completely discharge the battery once in an hour, 3C will discharge the capacity of the battery 3 times in an hour.

Table 7 - Testing conditions for heat generation in LG Chem Li-ion battery cell. The cell begins testing at the specified initial temperature. Readings are taken at each of the 3 times for all 3 initial temperatures for each discharge rate, resulting in a total of 9 tests. [50]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Times (min)</td>
<td>1  6   11</td>
</tr>
<tr>
<td>Initial Temperatures (°C)</td>
<td>15  25  45</td>
</tr>
<tr>
<td>Discharge Rates (C)</td>
<td>1    3   5</td>
</tr>
</tbody>
</table>

The results for the test featuring the highest discharge rate (5C) at the earliest time (1min) at an initial temperature of 25 °C were used in this study, as they would most accurately represent the heat generation profile of the battery before the temperature distribution equalized throughout the cell. The results are shown in Figure 8.
Figure 8 – Surface heat generation profile for a pouch type Li-ion battery. Results show only the distribution across the face of the cell. [50]

The results shown in Figure 8 are non-dimensional and show only the relative temperatures (and assumed heat generation rates) locally within the battery cell. Kim et al. [50] have shown that the heat generation at the bottom edge of the type of battery cell seen in the Chevy Volt has a very low local heat generation rate, due to minimal current density in that location. As such the heat generation distribution within the plates has been set to a minimum value of 1 in that location, with a maximum of 6 near the electrode tabs.

The method described above was used to determine the heat generation profile of the two outermost faces of the battery cell heat generation. Since each battery cell is represented by 3 thickness-wise (z-directional) layers of 8 by 10 elements in-plane (x- and y-direction), the central layer also needs to have a heat generation profile defined. For the central layer of elements, the heat generation distribution was created by averaging the two adjacent elements from the two outer faces. In this way the central slice of elements in each battery cell features a heat generation profile which is the average of the two outer faces. The heat generation profile for all
three slices of an individual battery cell can be seen in Figure 9, along with an isometric view of an entire battery cell.

![Figure 9 - Battery cell 3D heat generation profile. The rates are taken from t = 320s in the simulation.](image)

With the distribution of the internal heat generation defined qualitatively in 3-dimensions, only the total amount of heat generated, or the volumetric heat generation rate, is left to be defined. This is discussed in section 3.2.7.
3.2.4 Cooling Plates

The cooling plates are thin constructions made from stamped aluminum. The thickness (i.e. z-directional dimension) of a cooling plate is 1 mm. Although they do contain liquid coolant, the ratio of coolant to plate volume of the Volt is not explicitly known. The physical properties of 6061 aluminum are used in the cooling plate modeling, as shown in Table 8.

Table 8 - Cooling plate material properties. Bulk properties for 6061 aluminum were used.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m3)</td>
<td>2700</td>
</tr>
<tr>
<td>Heat Capacity (J/kg K)</td>
<td>896</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m K)</td>
<td>167</td>
</tr>
</tbody>
</table>

Heat generation/absorption within the cooling plates is due to the difference in temperature between the liquid coolant and the cooling plate itself. Without directly simulating the fluid flow and heat transfer occurring within each cooling plate, we must represent the effects using a less computationally intensive method. The cooling plates currently used in the Chevy Volt have a 0.75mm thick channel through which the coolant flows in the plate. The finite element model of a cooling plate in this study has 3 thickness-wise (i.e. z-directional) layers of 8 by 10 elements in-plane (x- and y-direction). The two exterior layers have a thickness of 0.125 mm each, and the central layer has a thickness of 0.75 mm. The negative heat generation within the cooling plates is then modeled as a volumetric negative heat generation within the center “slice (or layer)” of elements of each cooling plate. The arrows in Figure 10 indicate these central layers of cooling plate finite elements. This means that any heat removed from the pack must first flow into the center of the cooling plates before it is absorbed and removed from the system, analogous to the real world behavior of the liquid cooled plates.
Figure 10 - Location of applied cooling plate boundary conditions. Note that cooling plates and insulation spacers appear the same due to equal mesh definition.

The amount of heat removed by each element in the cooling plates is dependent on its location within the plate as well as the temperature of the element. Since the heat is being absorbed by the coolant, the behavior of the cooling plates must be such that no heat absorption occurs when the elements are at the same temperature of the coolant. Negative heat generation must occur when the elements are above the coolant temperature, and positive heat generation must occur when the elements are below the coolant temperature. This necessitates the definition of a coolant inlet reference temperature, which has been set to 300 K. The coolant inlet
temperature was set using results from previous research [51, 52, 53] such that the results from cell level (or cooling plate level) optimization work done within Dr. Il Yong Kim’s group would be applicable. Using data produced using the cell level modeling techniques, a heat generation rate dependent on temperature was found. A combinatorial data set simulated cooling plate behavior using CFD (computational fluid dynamics), while using various boundary conditions listed in Table 9.

Table 9 - Range of parameters for combinatorial simulation of liquid cooling plate operating conditions. All possible combinations were simulated.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelengths (#)</td>
<td>1, 2, 2.5, 3</td>
</tr>
<tr>
<td>Channel Width (mm)</td>
<td>5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30</td>
</tr>
<tr>
<td>Channel Amplitude (mm)</td>
<td>20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70</td>
</tr>
<tr>
<td>Heat Flux (W)</td>
<td>6.4, 11.2, 16, 20.8</td>
</tr>
<tr>
<td>Coolant Temperature (K)</td>
<td>280, 300, 320, 340</td>
</tr>
<tr>
<td>Coolant Flow (kg/s)</td>
<td>0.0005, 0.001, 0.002</td>
</tr>
</tbody>
</table>

Using the results for simulations featuring a coolant inlet temperature of 300 K and 4 different heat generation rates, a relationship between average plate temperature and heat absorption was found to be (-5 W/K). All of the combinatorial simulations used were converged, steady state simulations. More information on the set of combinatorial simulations is available in Appendix A. The behavior of the cooling plate’s temperature dependent heat generation rate is based on Fourier’s Law of thermal conduction. The law, stated in Equation 2, says that the flow of heat is dependent on the temperature gradient within a body. For the liquid cooling plates, this corresponds to the flow of heat from the battery cells and cooling plate aluminum into the liquid coolant. While the actual process is complex due to the use of liquid coolant, we have simplified it into a linear relationship since no direct simulation of fluid flow occurs in this study.
Equation 2 – Fourier’s Law describing heat conduction as a function of temperature gradient.

\[ \vec{q} = -k \nabla T \]

where \( \vec{q} \) is heat flow in W/m\(^2\), \( k \) is the thermal conductivity of the material in W/m*K, and \( T \) is the temperature in K.

This linear relationship between average cooling plate temperature and (negative) heat generation within the plates is reinforced by the results of the combinatorial simulations in Appendix A. Figure 11 shows the relationship between average cell temperature and heat flux into the cell level simulation.

**Figure 11** - Plot showing the relationship between cell average temperature and heat flux for cell level simulation with a coolant inlet temperature of 300 K. Geometries A-D are representative of designs near the optimum result for minimized cell average temperature.

Here a number of steady state simulations were run where the heat flux into the cooling plate was varied. The average temperature of the cell/plate interface was used as the reference temperature. This allowed for a relationship between heat flow through the cooling plate and average temperature to be established.
The total “power” of strength of the cooling plates is the final issue to address. Recognizing that the relationship between temperature and (negative) heat generation is linear in our work, we can make some useful approximations regarding the behavior of cooling plates with different cooling distributions. Since one major goal in this work (and in EV battery design in general) is to maintain uniform battery cell and pack temperature, we assume a uniform temperature throughout the battery cells and cooling plates. If the temperature is uniform and the relationship between temperature and heat absorption is linear, it becomes possible to sum over all elements in the cooling plate FE model featuring heat generation boundary conditions and maintain a constant, total-plate rate of heat generation. An example calculation is shown in 3.2.5. The end result is that even though the distribution of cooling performance in the plates will be changed, the overall level of cooling potential will remain relatively unchanged, where the cooling potential is defined as:

**Equation 3 - Equation for cooling plate heat performance as a function of heat flow, plate temperature, and coolant inlet temperature.**

\[
G_{cooling} = \frac{\dot{Q}}{(T_{P\,Avg} - T_{C\,in})}
\]

where \(G_{cooling}\) is the cooling plate heat conductance in W/K, \(\dot{Q}\) is heat flow in W, \(T_{P\,Avg}\) is the cooling plate average temperature in K, and \(T_{C\,in}\) is the coolant inlet temperature in K.

### 3.2.5 Cooling Plate Design Variables

During the optimization of the cooling plate heat absorption distribution there would ideally be no variation in the total amount of heat absorbed for different distributions. This allows for a direct comparison of the distributions. There is then a necessity for some control over the total cooling potential in each plate. If the level of cooling potential were allowed to vary (non-dimensionally) from 1-10 for each design vector cooling plates with all design vectors set at 10 would absorb considerably more heat than those set all to 1.
If an initial assumption of complete temperature uniformity throughout the battery pack is made, hand calculations can show that summing the temperature dependent heat absorption rate over all of the elements in the cooling plate will yield the same total heat absorption rate. With small temperature variations within the battery cells and cooling plates, this assumption is close to the actual operating conditions. Shown below in Figure 12, we can see two cooling plates, one with a constant set of design variables (set at 5) and a plate with a linearly decreasing set of design variables ranging from 10 (at the top of the plate) to 1 (at the bottom of the plate). In this example, the cooling power has been arbitrarily set to (-100) W/K, the element volume at 0.1 m³, and the temperature difference between the plate and coolant at 2 K.

<table>
<thead>
<tr>
<th>Height element number</th>
<th>Uniform Distribution</th>
<th>Non-Uniform Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>non-dimensional cooling (1-10)</td>
<td>row sum</td>
</tr>
<tr>
<td>10</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>5 5 5 5 5 5 5 5 5</td>
<td>40</td>
</tr>
<tr>
<td>width element number</td>
<td>1 2 3 4 5 6 7 8</td>
<td>400</td>
</tr>
<tr>
<td>plate-total sum</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>plate-total sum</td>
<td>440</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 12 – Example cooling plate heat absorption distributions.**

Figure 13 shows the total amount of heat absorbed by each element in the cooling plate. This is calculated using Equation 4 for each element:

**Equation 4 - Normalized heat absorption rate for a single element.**

$$
\dot{Q} = \left( \frac{H_G \text{plate}}{H_G \text{Total}} \right) V_e \Delta T \ G_{\text{cooling}}
$$
where $\dot{Q}$ is the heat absorption rate in W, $HG_{\text{plate}}$ is the non-dimensional heat absorption rate (the design variable, 1-10), $V_e$ is the volume of the element in m$^3$, $\Delta T$ is the temperature difference between the plate and the coolant in K, and $G_{\text{Cooling}}$ is the cooling plate heat conductance in W/K.

Table 10 - Physical properties for styrofoam insulation spacers. Values are typical of commercially available household insulation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>width element number</td>
<td>1 2 3 4 5 6 7 8</td>
</tr>
<tr>
<td>plate-total sum (W)</td>
<td>-20</td>
</tr>
<tr>
<td>height element number</td>
<td>1 2 3 4 5 6 7 8</td>
</tr>
<tr>
<td>row sum</td>
<td>1 2 3 4 5 6 7 8</td>
</tr>
<tr>
<td>Uniform Distribution</td>
<td>Heat absorbed in each element (W)</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>10</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>9</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>8</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>7</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>6</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>5</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>4</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>3</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>2</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
<tr>
<td>1</td>
<td>-0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -0.25 -2</td>
</tr>
</tbody>
</table>

**Figure 13** – Example heat absorption rates for individual elements in cooling plates.

When the heat absorption is summed over all elements the total amount of heat removed from the system is equal for both cases (In this case 20 W).

By normalizing the amount of heat absorbed by the plate with the total sum of the design variables a constant rate of heat removal can be maintained for cooling plates with different distributions of their cooling potential.

### 3.2.6 Insulation

The insulation spacers used in this work were modeled as a regular commercially available styrofoam insulation. The material properties used in the simulation are shown in Table 10. The insulation spacers are used primarily to ease manufacture and do not see a large heat flux, as they are situated between battery cells which conduct their heat away from the insulation towards the cooling plates (see Figure 5).
Density (kg/m³)  30
Heat Capacity (J/kg K)  1450
Thermal Conductivity (W/m K)  0.033

3.2.7 Pack Level Modeling Considerations

Normal operating conditions for EVs are not generally steady state in nature. Frequent changes in speed with both high and low discharge rates from the battery pack are expected during everyday use. Due to this fact the simulation should represent these conditions when investigating the optimum approach to cooling the battery pack. The Environmental Protection Agency (EPA) has defined a number of standardized tests used to compare fuel economy and test vehicle operation characteristics. These range from slow speed driving with frequent stops, representing city driving, to constant high speed driving, representing highway driving. We have chosen to use the US06 drive cycle which is commonly in use to test fuel economy for road vehicles. Figure 14 shows a plot of the US06 drive cycle’s speed as a function of time. The total time elapsed during a US06 cycle is 600 seconds (10 minutes). This speed profile contains both low speed urban driving as well as constant high speed operation seen on highways, and is a good representation of everyday commuting use. The drive cycle is defined at intervals of 1 second, giving a good resolution of speeds used in calculations for the simulation.
The US06 drive cycle is used in simulation to determine the load on the EV battery pack, and calculate the heat generation at each 1 second interval. This is done using the physical characteristics for the Chevy Volt shown in Table 11 along with the US06 speed profile. Using the vehicle mass and change in speed over each 1 second interval, the change in kinetic energy is calculated using Equation 5.

**Equation 5 – Equation for change in kinetic energy due to a change in speed**

\[
\Delta KE = \frac{1}{2} m (v_{i+1}^2 - v_i^2)
\]
where $\Delta KE$ is the change in kinetic energy in J, $m$ is vehicle mass in kg, and $v_i$ is the speed at the current time step in m/s. The resultant value for $\Delta KE$ is the total amount of kinetic energy which needs to be spent over the current time step. Air drag must also be accounted for to determine the power requirements for operation at a constant speed, which will have no change in kinetic energy. Using the values in Table 11 air drag is calculated using Equation 6.

**Equation 6 - Relationship for power lost to aerodynamic drag.**

$$P_{drag} = \frac{1}{2} \rho v^3 A C_d$$

where $P_{drag}$ is the power loss to drag in W, $\rho$ is air density in kg/m$^3$, $v$ is vehicle speed in m/s, $A$ is the frontal area of the vehicle in m$^2$, and $C_d$ is the vehicle drag coefficient (dimensionless). Using the change in kinetic energy along with the power required to overcome aerodynamic drag, the total energy requirements are found at 1 second intervals for the duration of the simulation.

There was no consideration made for the rate of change of aerodynamic losses as the time interval is very short at 1 second.

This value for required power must then be related to a heat generation rate within the battery cells. Using properties shown in Table 12 for the battery pack, maximum voltage and current levels along with Equation 7 gives us a theoretical maximum power delivery from the battery pack.
Table 12 - Chevy Volt battery pack electrical performance information [46]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pack Voltage (V)</td>
<td>360</td>
</tr>
<tr>
<td>Pack Peak Current (A)</td>
<td>400</td>
</tr>
<tr>
<td>Peak Power Output (J)</td>
<td>144000</td>
</tr>
<tr>
<td>Total Cell Count (N/A)</td>
<td>288</td>
</tr>
<tr>
<td>Parallel Cells in Cell Group (N/A)</td>
<td>3</td>
</tr>
<tr>
<td>Total Cell Groups in Series (N/A)</td>
<td>96</td>
</tr>
<tr>
<td>Maximum Current per Cell (A)</td>
<td>133.3</td>
</tr>
<tr>
<td>Cell Maximum Heat Generation (W)</td>
<td>20.8</td>
</tr>
</tbody>
</table>

Equation 7 - Electrical power relationship between voltage drop and current flow.

\[ P = I V_{tot} \]

where \( P \) is power in W, \( I \) is current in A, and \( V_{tot} \) is total voltage in V. Applying an assumed motor efficiency of 0.9 [56], the fraction of total power requirement is calculated for each time step. Using data provided by GM Canada for the heat generation levels in typical battery cells, a value of 20.8 Watts per cell is used as the maximum discharge current. Using a linear relationship between battery cell power output and heat generation, the total heat generation rate for a single cell is defined at each time step.

For work previously performed within our research group a uniform heat generation of 500 W/m² (16.0 W total) was used to simulate the maximum heat generation rate for a single battery cell, with this information provided by GM Canada. GM has since published a paper which models the Volt battery pack under time dependent operating conditions [21]. This simulation uses the US06 drive cycle for the Chevy Volt and shows the heat generated over said
drive cycle, as a running average of the heat generated over 120 seconds. Comparing the heat generated using 500 W/m$^2$ to the published work done by GM revealed this value to be low. Increasing the heat generation at maximum output to 650 W/m$^2$ was in much better agreement with GM’s published results and was used in this work as opposed to the previous value of 500 W/m$^2$. Where 500 W/m$^2$ corresponds to 16.0 W of heat generation, 650 W/m$^2$ corresponds to 20.8 W of heat generation at maximum output.

With the spatial heat generation profile discussed in Section 3.2.3 and the total amount of heat generated within a cell, the final step in battery cell heat generation is the creation of a 4-dimensional heat generation boundary condition for the battery cells. The heat generation rate is then dependent on 3 spatial dimensions (x, y, and z) as well as varying in time. The battery cell heat generation profile is summed over the volume of 240 elements (8 by 10 by 3 in x-, y-, z-directions, respectively) in the FE model. This gives the total amount of heat generation for the entire cell which can be scaled to obtain the desired total heat generation rate at any time during the simulation. The profile is normalized to a total heat generation rate of 1 Watt then scaled up to the desired rate for each time step. The result is a time varying volumetric heat generation rate for each time step in the simulation, which varies spatially within the battery cells.

The final pack level consideration for simulation is the coolant flow distribution through the cooling plates. The layout of the cooling system is shown in Figure 15. The cooling plates, having one or multiple channels each, are arranged in parallel within the pack. It is expected that the last cooling plates in the circuit (Battery Section 3) will see a lower flow rate than the cooling plates situated nearer the inlet (Battery Section 1).
Figure 15 - Layout of Chevy Volt cooling system. Coolant enters the Inlet Header, passes through the cooling plates (in parallel) and exits through the Outlet Header. The number of cooling plates in each section has been reduced for clarity.

Without performing CFD on the flow regime, determining the amount of flow through each plate is difficult, especially since at this point in the cooling system design, detailed plate design has not yet been completed. Considering these facts the flow rate through the plates is approximated using data provided by GM Canada, and results published by Jayaraman et al. [21] which modeled the Chevy Volt coolant flow. Jayaraman et al. [21] found that the flow rate is consistent within each battery section, and drops from the first to the second section, as well as from the second to the third section. These drops in flow rate are on the order of 10% of volumetric flow rate. Table 13 shows their results for CFD simulation of flow through the pack.
Table 13 - Flow Distribution in the Chevy Volt through each battery section. [21]

<table>
<thead>
<tr>
<th>Battery Pack Section</th>
<th>Flow Rate (m3/s)</th>
<th>Relative to Section 1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>1.22E-06</td>
<td>100%</td>
</tr>
<tr>
<td>Section 2</td>
<td>1.16E-06</td>
<td>94.93%</td>
</tr>
<tr>
<td>Section 3</td>
<td>1.11E-06</td>
<td>90.69%</td>
</tr>
</tbody>
</table>

The results show that the flow rate can be assumed to be constant within each battery section. The reduction in flow rate from battery section to battery section was determined to result in a roughly 10% reduction in cooling potential from one battery section to the next. These results were obtained using the combinatorial data on cooling plate behavior in Appendix A.

3.3 Simulation & Optimization

The simulation being evaluated in this work is a time dependent, linear thermal simulation performed using the ANSYS simulation environment. Using the parameters and approaches described in the preceding sections, a model of an EV battery pack is solved to determine the distribution of temperatures within the battery pack. Each simulation, or function evaluation during optimization, is run from within MATLAB, which serves to pre-process variables, create boundary conditions, and perform post-processing evaluations of results. Figure 16 shows an flow chart of the simulation process, including what software performs which functions, and what is passed between MATLAB and ANSYS.
Figure 16 - Simulation flow chart.

The design variables used for optimization control the behavior of the cooling plates, specifically the spatial distribution of heat absorption in the plate. Each battery section was optimized independently and the results combined into a single model once complete to reduce the simulation time. Although there are 80 elements in each cooling plate which can actively remove heat from the plate, the number of design variables was reduced to 20 to reduce the number of function evaluations needed for each optimization iteration. Figure 17 shows how the 80 elements were grouped into a total of 20 design variables per cooling plate. The cooling plate
behavior in each battery section was constant, meaning for the entire model the total number of design variables was 60.

Figure 17 - Design variables for cooling plate heat absorption. A total of 80 finite elements of the central layer are grouped into 20 design variables.

The FE model of each cooling plate features 8 elements in width (x-direction), 10 elements in height (y-direction), and 3 elements in thickness (z-direction). With only the central slice of elements having (negative) heat generation boundary conditions applied, they become the design domain for optimization. Figure 17 shows all 3 layers of elements for a single cooling plate, with total numbered rows and columns for the central slice. The central slice has the elements whose behavior is defined by the design variables numbered from 1 to 20, each of which consists of a group of 4 elements. Each cell grouping is 2 elements wide by 2 elements high.

For each battery section the objective function used was the standard deviation of temperature within one battery cell in the center of the battery section, meaning for a battery
section with 90 cells the 45\textsuperscript{th} cell was used. With the current model there is almost no difference in behavior between cells within a single battery section due to the symmetry of the design.

There are exactly 2 battery cells per cooling plate with insulation separating these groupings. The physical asymmetry in the model is seen at the ends of each battery section. This arises from the fact that the insulation on each end face is the same dimensions as those used internally in the pack, meaning any heating or cooling it experiences is due to only 1 battery cell, as opposed to 2 cells which all others are in contact with. The low heat capacity and poor thermal conductivity of the insulation mean this has a limited effect on the temperature distribution throughout individual battery sections. The objective function was evaluated as described by Equation 8:

**Equation 8 - Optimization statement**

Minimize \( T_\sigma(d) \)

Subject to \( 1 \leq HG_{\text{plate}}(d) \leq 10 \)

Where \( T_\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (T_i - T_{avg})^2} \)

\( T_{avg} = \frac{1}{N} \sum_{i=1}^{N} T_i \)

where \( d \) is the design vector; \( T_i \) is the temperature of the \( i \)-th element of an individual battery cell in K; \( N \) is the total number of elements of an individual battery cell; \( T_\sigma \) is the standard deviation of temperature in K; \( T_{avg} \) is the average temperature of the cell in K; and \( HG_{\text{plate}} \) is the cooling potential at a location within the cooling plate which is unitless.
Chapter 4

Results

4.1 Baseline Design Results

4.1.1 Baseline Design

The design used to base the improvements made during optimization will be referred to as the baseline design. This design represents a conventional approach to designing a thermal management system for an EV, such as the Chevy Volt. As with previous initial work done within Dr. Il Yong Kim’s group [51-53], the baseline design assumes a constant rate of heat flux into the cooling plates from the battery cells over the contact area. This assumption leads to the definition of the cooling plate boundary conditions such that the cooling performance is constant throughout the cooling plate model. This means that all 20 design variables in the baseline design are set arbitrarily to 5 (in a possible range of 1-10). The actual value used is irrelevant since the total cooling potential of the plates is explicitly defined and the design variables only change the distribution. As long as all 20 design variables are equal, the performance of the plates will be the same.

The baseline design results feature no design optimization and are used to demonstrate the improvements made through optimization techniques. The simulation duration is 600 seconds of driving, with the previously described methods applied to calculate heat generation within the battery cells as well as the cooling plates.

4.1.2 Baseline Average Temperature

After simulating the behavior of the model over the full 600 second duration of the US06 drive cycle, the average temperatures of each cell in the battery pack (288 total cells) can be seen as a function of time. The average temperatures of cells within each battery section (1, 2, and 3)
are very consistent; the results are for a representative cell taken from the middle of each battery section. Figure 18 shows the average temperature profiles for the 3 battery sections over time.

![Cell 45, 126, 225 Average Temperature](image)

**Figure 18 - Average cell temperature for representative cells in Battery Sections 1, 2, and 3.**

One of the questions this work aimed to answer was whether the temperature change with respect to time or with respect to position within the battery pack was more important. Previously simulations have been based on steady state conditions with heat generation rates representative of the battery cell at a maximum discharge rate. This heat generation rate of 20.8 Watts per cell represents the worst case scenario for the battery pack operating conditions; it is not indicative of the real world operation of the vehicle and battery pack.

We can see that the temperature changes very little over the course of the simulation with an average cell temperature of 301 K, a maximum temperature of 301.3 K, and a minimum temperature of 300.8 K. This falls well within the ideal working range of current battery technology. The spread of temperature between each battery section was no more than 0.1 K, with a maximum difference between sections 1 and 3 of 0.2 K. Due to the large thermal mass of
the battery pack, spikes in temperature relative to time are not great, indicating that limitation of temperature change over time is not critically important.

4.1.3 Baseline Standard Deviation of Temperature

The temperature distribution within the battery cells as well as between battery cells throughout the pack have been identified as important considerations when designing a pack thermal management system. The results in Section 4.1.2 show that the spread of temperature between cells is less than 0.2 K over the pack for the baseline design. Figure 19 shows the standard deviation of temperature within the same 3 representative cells over the course of the simulation.

![Figure 19 - Standard deviation of temperature within cells from Battery Sections 1 (blue), 2 (green), and 3 (red) for the baseline design.](image)

Here we can see that the standard deviation of temperature within the 3 sections is highly consistent. This is not an unexpected result since the only difference in the cooling plate performance between the three battery sections is the total cooling potential. This indicates that a more powerful cooling plate may achieve a lower standard deviation of temperature; however,
this effect appears slight. Figure 20 shows the mean, maximum and minimum temperatures for the same 3 representative cells.

**Figure 20 - Minimum, maximum, and average cell temperature for cells in Battery Sections 1, 2, and 3.**
The maximum difference in temperature within the cells can reach nearly 1.5 K during high discharge, high heat generation time periods. These periods of maximum temperature difference correspond to those times where the standard deviation of temperature is greatest (see Figure 19) as would be expected. Looking at the results shown in Figure 20, we can see that the minimum temperature within a given battery cell in any battery section varies a small amount over time. This minimum temperature occurs at the bottom edge of the battery cell where heat generation is at a minimum. The maximum temperature seen within a battery cell changes much more dramatically with time in comparison to the minimum temperature. The maximum occurs near the top edge of the battery cell, near the terminals, as expected. Figure 21 shows the temperature contours of a central cell in Battery Section 1 during periods of high and low standard deviation of temperature.

Figure 21 – Battery cell temperature distribution at a) t = 320s and b) t = 500s. a) corresponds to a high standard deviation of temperature and b) corresponds to a low standard deviation of temperature.
4.1.4 Baseline Heat Flux Profile

Previous work by Jarrett and Kim [52] showed that the heat flux profile boundary condition has a great effect on the optimal design results for cell level cooling plate design. We are then interested in finding the optimum profile of heat flux from the battery cells into the cooling plates at the pack level such that the results can be applied to the high fidelity cell level models considering more complex effects such as fluid flow. Figure 22 shows the heat flux contours of a battery cell at a central location within Battery Section 1, again during periods of high and low standard deviation of temperature. The period at which the largest standard deviation of temperature is seen (t = 320s) is also a time period during which the largest heat generation rate is experienced.

![Figure 22 - Battery heat flux distribution at a) t = 320s and b) t = 500s. a) corresponds to a high standard deviation of temperature and b) corresponds to a low standard deviation of temperature.](image)

60
How the heat flux from the battery cells into the cooling plates varies with time also warrants consideration. Figure 23 shows the heat flux rates at 3 vertical locations along the center line of a battery cell within Battery Section 1. It can be seen that the periods of high temperature and high heat generation correspond to those periods of highest heat flux from the battery cell into the cooling plate.

Figure 23 - Heat flux rates from a battery cell into the adjacent cooling plate for 3 vertical locations along the center line of the cooling plate, battery cell interface. Results are for cell45 in Battery Section 1. Cell45 is the middle battery cell in the first section.

4.1.5 Discussion of Baseline Design Results

The results shown in the preceding sections represent a baseline for comparison with optimized results shown in the following section. The baseline results show an acceptable distribution of temperature within the cells as well as across the pack. The spread of both average cell temperatures and standard deviation of temperatures within individual cells over time are not
large, indicating that the distribution of temperatures spatially within the battery pack show the most potential for improvement in this pack model.

4.2 Results for Optimized Standard Deviation of Temperature

The results shown in this section correspond to the results of design optimization on all 3 battery sections. Each battery section was evaluated and optimized independently to reduce the total number of design variables and time requirements for each optimization iteration. The initial function evaluation in each case corresponded to the baseline result as it was used as the starting point for optimization. After design optimization was performed on each battery section, the 3 results were combined and evaluated together in a complete pack model.

Each function evaluation takes roughly 2.5 hours, with the total number of function evaluations per iteration totaling 21. The actual computing time varies slightly between battery sections as the total number of battery cells is not equal, with 90 cells in battery section 1, 72 in battery section 2, and 126 in battery section 3. This computing time is associated with a high end desktop PC, using an Intel i7 CPU running at 2.67GHz with 12 GB of RAM.

4.2.1 Optimized Average Temperature

The average temperature of a central representative cell in each battery section is shown in Figure 24.
Figure 24 - Average cell temperature for representative cells in Battery Sections 1 (blue), 2 (green), and 3 (red).

The average temperature of the pack is 301 K, the maximum average temperature is 301.25 K, and the minimum average temperature is 300.8 K. These results are very similar to the baseline design.

4.2.2 Optimized Standard Deviation of Temperature

Standard deviation of temperature, or temperature distribution, is one of the major considerations in battery pack performance and is the objective function for minimization in this work. Figure 25 shows the standard deviation of temperature within representative central battery cells in each section.
Figure 25 - Standard deviation of temperature within cells from Battery Sections 1 (blue), 2 (green), and 3 (red) for the optimized design.

Standard deviation of temperature within a single cell peaks at 0.125 K for the optimized design. The behavior of standard deviation of temperature between the 3 battery sections is also very similar. Figure 26 shows the mean, maximum, and minimum temperatures seen within central cells for each battery section.
Figure 26 - Minimum, maximum, and average cell temperature for cells in battery sections 1, 2, and 3.
Here again we can see very similar behavior between the 3 battery sections as with the baseline design. The maximum temperature seen in Battery Section 1 is 301.4 K, and the minimum in Battery Section 1 is 300.65 K. The largest difference between minimum and maximum temperature seen at any one time is 0.7 K, experienced at roughly 320 seconds, corresponding to the period of highest discharge, and heat generation rate. As with the baseline design, the highest temperature occurs near the top edge of the cell near the electrode tabs. The minimum temperatures occur at the bottom edge where the heat generation rate is lowest.

The temperature distribution of a central Battery Section 1 cell is shown in Figure 27 at times of high and low standard deviation as for the baseline design.

![Figure 27 - Battery cell temperature distribution at a) t = 320s and b) t = 500s. a) corresponds to a high standard deviation of temperature and b) corresponds to a low standard deviation of temperature.](image-url)
4.2.3 Optimized Heat Flux Profile

The profile of heat flux from a central battery cell within Battery Section 1 into the adjacent cooling plate is shown in Figure 28 during the periods of high and low standard deviation of temperature.

Figure 28 - Battery heat flux distribution at a) $t = 320s$ and b) $t = 500s$. a) corresponds to a high standard deviation of temperature and b) corresponds to a low standard deviation of temperature.

The heat flux from battery cells into cooling plates over time is shown in Figure 29 for 3 vertical locations along the center line of the cooling plate, as with the baseline design.
Figure 29 - Heat flux rates from a battery cell into the adjacent cooling plate for 3 vertical locations along the center line of the cooling plate, battery cell interface. Results are for cell45 in Battery Section 1. Cell45 is the middle cell in the first section.

4.3 Comparison of Results

In this section, results for both the baseline and optimized designs have been formatted for comparison. Initially the values for average temperature are compared in Figure 30. In this figure we can see that the qualitative behavior of both designs is nearly identical. The quantitative temperatures are also in very close agreement. This is the expected result since the total cooling potential was set to be equal for both designs. The fact that the average temperatures for both designs agree so closely further reinforces the assumptions made in 3.2.5 for constant cooling performance. A distinct improvement in average pack temperature was not expected since the objective function was the standard deviation of temperature. It can be seen
that there is a slight decrease (less than 0.025 K) in average temperature for the optimized design though. This is a result of the cooling potential within the plates being more effectively used than in the baseline design; a greater (negative) heat generation rate is spatially located where there is more heat generated and a greater need for heat absorption.

Figure 30 - Comparison of average temperature between a) baseline and b) optimized designs.

Comparison of the standard deviation of temperature is of particular interest for this work as it was the objective to be minimized, and a significant improved should be made. Figure 31 shows the standard deviation of temperature for the designs. The improvement through design optimization is obvious when the plots are compared on the same scale. A peak standard deviation of 0.42 K for the baseline design compared to a peak of 0.13 K for the optimized design.
Figure 31 - Comparison of standard deviation of temperature between a) baseline and b) optimized designs.

Figure 32 compares the mean, minimum and maximum temperatures for a central cell in each battery section. Here improvement in spatial temperature distribution through a single cell is evident as well. While the minimum cell temperature is increased, it has moved closer to the mean, and allowed for the redistribution of cooling potential within the plates. This allows for more heat to be absorbed from the top of the cell, lowering the maximum temperature and yielding an improved temperature distribution.
Figure 32 - Comparison of mean, maximum, and minimum cell temperatures for battery sections 1, 2, and 3 between a) baseline and b) optimized designs.

Figure 33 compares the temperature distributions visually at 320 seconds into the simulation for a single cell in battery section 1, corresponding to the highest standard deviations of temperature, and highest heat generation rates.
Figure 33 - Comparison between a) baseline and b) optimized design at $t = 320s$ showing the distribution of temperature within a central cell in Battery Section 1.

The tighter distribution of temperatures can be seen in this figure for the optimized design. Figure 34 compares the temperature distributions for the entire pack between both designs, with the same trend being visible.
Figure 34 - Comparison of temperature across the battery pack between the a) baseline and b) optimized design. The figure represents the temperature distribution at t = 320 sec.

The heat flux profile between battery cells and the cooling plates is one of the key results which will be applicable to cell level design in future work. Figure 35 compares the heat flux profiles visually, again at 320 seconds into the simulation.
Figure 35 - Comparison of perpendicular heat flux between the a) baseline and b) optimized design at $t = 320$ sec.

Figure 35 shows that there is a lower transfer of heat from the battery cell to the cooling plate near the bottom edge, and an increase at the top edge. This agrees with the previous observations in that the optimization has created a cooling potential distribution within the plates which more effectively removes thermal energy from the cells to achieve a uniform temperature distribution. Figure 35 shows similar qualitative distributions between the two designs, but with a more pronounced gradient of heat flux from top to bottom for the optimized design. By determining the most effective distribution of cooling potential within the cooling plates and applying this ideal boundary condition during cell level design optimization, a design more specifically suited to a particular battery pack can be achieved.
Chapter 5

Conclusions

5.1 Summary of Results

This work was undertaken to investigate the effectiveness of pack level optimization on electric vehicle thermal management systems. Improving the temperature distribution was identified as a key goal in thermal management system design and was therefore selected as an objective function for design optimization. The results are broken down into the following 5 sections.

5.1.1 Construct a simplified model of the battery pack for optimization

With a battery pack consisting of anywhere from a few hundred to thousands of battery cells, it is not practical to include the level of detail in a pack level model as has been included in previous optimization work done at the cell level. With such a large number of components to be modeled, along with the fluid dynamics which generally needs to be considered for thermal management systems, a high fidelity model becomes impractical for design optimization. We have succeeded in creating a much simpler, representative model of the battery pack, without the explicit need for computational fluid dynamics to model the performance of a thermal management system. Inclusion of the battery cells themselves, as well as realistic heat generation boundary conditions and material properties were required to achieve an accurate model of the battery pack as a whole. Creating a pack level model which is suited to design optimization required that the model be relatively simple to solve. It also needed to be parametric such that any design features which may be identified as being important in achieving the design goals can be easily altered by the optimization routine.

The model created in this work solves each sub-step of the simulation in under 10 seconds for a 288 battery cell and 144 cooling plate design. This has allowed it to be used for
pack level optimization. The model does not directly model physical design features of the cooling plates themselves (e.g. coolant passages), but is a proxy representation such that the optimum solution for the pack level design can be identified as early in the design phase as possible.

5.1.2 Apply time varying boundary conditions to simulations to simulate real world operating conditions

Simulating the performance of the battery pack over a representative operational cycle was identified as another important aspect of pack level analysis. While a steady state approach is applicable to cell level design which incorporates fluid dynamics, it does not fully capture the behavior of the system. By using actual or estimated values for the physical properties of a vehicle, a more realistic simulation was possible. It was found that while the maximum heat generation rate of the Chevy Volt was 20.8 Watts, this heat generation rate was never actually achieved during operation over a US06 drive cycle. While this maximum rate of heat generation is certainly possible within the battery pack, it is not by any means a representative operating condition for the battery cells or the cooling plates. By applying an energy balance equation at each simulation sub-step, a much better representation of time-averaged operating conditions was found which can be applied to more detailed simulations if steady state simulation is used.

5.1.3 Create an optimization routine for distribution of cooling potential within the battery pack

A gradient based optimization routine was created to improve the distribution of heat absorption within the cooling plates. This was achieved by setting the temperature dependent heat absorption rate of the cooling plate elements as the design variable for optimization. Altering the design variables changed the spatial distribution of cooling potential within the plate to minimize the objective function, which in this study was the standard deviation of temperature within the battery cells.
While the optimization does not define or create any physical geometries for cooling plate design, it serves to give a system level performance target for the cooling plates. This will serve to reduce total design time by identifying the design goals for the cooling plates at the cell level prior to specific plate design. Identifying the ideal heat absorption profile and the total amount of heat which is necessary to be removed will provide a more complete set of boundary conditions for cell level optimization.

5.1.4 Investigate temperature distributions with respect to time and location within the battery pack

By simulating the battery pack thermal behavior over the US06 drive cycle the distribution of temperature was found across the cells in the pack as well as over time. This allowed us to see how the temperature changed during a typical daily driving event. Results have shown that the temperature does not change drastically over time, due to the large thermal mass of the battery cells in the pack. The large mass of the battery cells (on the order of 140 kg [21]) is slow to heat up even during periods of aggressive heat generation cause by rapid acceleration. The distribution of temperature within the pack is highly uniform due to the pack construction. The battery pack modeled was based on the Chevy Volt, which features many repeating elements built up to produce a pack with 3 major battery sections with a total of 288 cells.

5.1.5 Demonstrate that design optimization can improve the performance of battery thermal management systems

The simulation showed that there is significant room for improvement in achieving a uniform temperature distribution within the individual battery cells. Compared to the baseline design, an optimized design was able to reduce the standard deviation of temperature within the cells from a maximum of 0.42 K in the baseline design to 0.13 K in the optimized design. The average standard deviation of temperature was reduced from 0.2828 K in the baseline to 0.05318 K in the optimized design as well.
This has shown that through the application of design optimization to the pack level, performance of the thermal management system improvements to the system are not only possible but can make a considerable difference. The spread of temperature within the cells was reduced from 1.5 K to 0.7 K from the baseline design to the optimized design.

5.2 Limitations of Work

While the modeling and simulation was successful in showing that the application of design optimization can yield appreciable improvements to the problem of pack level thermal management design, there are currently a number of limitations to the approach.

Due to the way in which information is passed between MATLAB and ANSYS, there is no possibility for the results of the simulation to change the boundary conditions or other parameters of the simulation. One exception to this is in the behavior of the cooling plates, which are dependent on the temperature of the cooling plates. This limitation means that it is impossible to vary the heat generation within the battery cells as a function of temperature. An estimation of the state of charge of the battery pack is also not possible. These issues arise due to the battery cell dependence on temperature to accurately predict energy consumption along with other operating parameters. Without a feedback route for the results of each sub-step of the simulation to be related back to MATLAB for further processing, the heat generation of the battery cells cannot be dependent on the cell temperature. Another limitation due to the simulation structure is a lack of ability to predict the range of the vehicle. If passing the energy usage between the solver (ANSYS) and the optimization program (MATLAB) was possible, a real time estimation of state of charge and range would be possible.

With each cooling plate having 80 finite elements, there exists the possibility for having 80 distinct design variables in the optimization for each battery section. Even though the model is quite simple, the number of simulation sub-steps per function evaluation (600) combined with
the number of design variables (20 per battery section, totaling 60 for the entire pack), the number
of function evaluations, and time required meant it was not feasible to use all 80 possible design
variables. Increasing the resolution of the design variables within the cooling plates will yield a
more accurate mapping of the heat flux from the battery cells into the cooling plates, which can
be used in cell level work.

5.3 Future Work

Moving forward there are a number of possible improvements which can be built on to
the results of this work. Incorporating a theoretical model of battery internal heat generation
based on current draw, temperature, and state-of-charge would yield a more accurate heat
generation rate and distribution within the battery cells. This would also serve to unbalance the
temperature distribution within the battery pack as higher internal temperatures in the battery
cells can lead to increased heat generation rates. Having as accurate as possible a representation
of the internal heat generation in the battery cells is of vital importance in obtaining accurate
results from optimization.

In addition to incorporating a theoretical battery model, incorporating a predictive model
for coolant flow through the pack would be advantageous. Early in the design phase where this
work would be performed, the cooling plates themselves will not have a finalized design. Simple
modeling along with previous experience could be used to create an acceptable range of coolant
flow rates through the plates based on the required heat absorption rates. This would allow for a
more accurate representation of the total cooling potential of plates in the different battery
sections.

The results of this work, primarily the heat flux profile between battery cell and cooling
plate, can be immediately applied to cell level cooling plate design optimization. These results
show a much more detailed distribution of heat flux than has previously been used at the cell
level. It has been shown that the cell level design is highly sensitive to boundary conditions, including heat flux profile.

5.4 Conclusions

Electric vehicles face a number of challenges before they can be fully embraced as a replacement for the IC engine vehicle for personal transportation. The most pressing concerns are those associated with cost, longevity, and available range. As EV technology matures, we can expect these concerns to lessen as the cost, lifetime, and range of EVs increases. This maturation will come from a number of sources: increased and streamlined production methods for batteries will help alleviate cost concerns. The concerns for lifetime and range of EVs will need to be addressed through increased efficiency in battery technology, of which thermal management plays an important role.

This work demonstrates the possibility of improvements in temperature management through the use of design optimization in thermal management systems. As newer battery technologies are introduced, such as Lithium-air batteries, there will also be increases in the energy density and specific energy of battery packs. As the mass of battery packs is decreased and the energy storage levels are increased, thermal management will play an increasingly important role. With battery temperature playing a fundamental role in efficiency and safety of EVs, the foundation for new approaches to thermal management system design need to be continually developed. The approach outlined here is applicable in the early design stage to highlight potential problem areas (temperature spikes, distribution of temperature between cells, or distribution of temperature within cells) in thermal management system architecture.

Through the application of design optimization to thermal management systems, the refinement and development of EV technology can be fundamentally improved. A more complete picture of heat generation rates, and flow within the battery pack will highlight important design considerations for the next generation of EVs.
References


[53] B. Banks, “Numerical design optimization for thermal and pressure behavior of multiple curved channel cooling plates in electric-vehicle battery cooling systems” Master’s thesis for Master’s Degree, Queen’s University.


Appendix A

Combinatorial Data Simulations

A set of simulations using the cell level modeling and analysis techniques developed by previous students in Dr. Il Yong Kim’s group were performed to explore the design space of the cooling plates. These simulations were performed by Benjamin Banks during his Master’s thesis research on cell level design optimization. A range of operational variables were established such that the effect of changing the coolant inlet temperature, coolant flow rate, heat generation rate of the battery cells, and channel geometry could be investigated. Table 14 shows the range of inputs used for this work.

Table 14 - Combinatorial data range of variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range of Values</th>
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<tr>
<td>Wavelengths (#)</td>
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<tr>
<td>Channel Width (mm)</td>
<td>5</td>
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<tr>
<td>Channel Amplitude (mm)</td>
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<tr>
<td>Heat Flux (W)</td>
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<tr>
<td>Coolant Temperature (K)</td>
<td>280</td>
</tr>
<tr>
<td>Coolant Flow (kg/s)</td>
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</table>

This set of variables was run in every possible combination, yielding a total of 23,232 possible configurations. Of these 21,072 were able to converge on a solution and produce a useful result. Of the remainder most failed simulations were due to mesh failure at the extremes of the geometry variables. Figure 36 shows how the cell level simulation was performed. Direct simulation of coolant flow using CFD was performed in a steady state simulation with a specified heat flux through the face of the cooling plate in contact with a battery cell. Figure 37 shows the geometry of the channels used in the combinatorial data set, two curved channels whose amplitude, width and number of wavelengths could be altered.
The results of these simulations considered the temperature of the surface of the cooling plate which is in contact with the battery cell (which has a heat flux boundary condition applied to it) as the battery cell temperature. The outputs of each simulation were; Average temperature (K), standard deviation of temperature (K), fluid pressure drop through the cooling plate (Pa), and...
outlet coolant temperature (K). With this data it is possible to investigate the correlation between some operating conditions such as cell temperature and heat flux under various operating conditions. Although these simulations are steady state, and their results are utilized in a transient simulation, the results are still applicable. These results demonstrate the possible range of performance which can reasonably be expected from cooling plates in conditions which could occur in the actual battery pack.

With so many available data points to consider the results were narrowed down to a smaller range of geometries. A set of data which spans the optimum solution found during Ben’s research which had few simulation failures was used to produce the results shown in this work. The range of geometry variables is shown in Table 15. For each of these 12 geometries the coolant inlet temperature was 300 K, and the inlet flow rate was 0.001 kg/s (as used in cell level optimization). Heat fluxes of 6.4 W, 11.2 W, 16.0 W, and 20.8W were all used. There were 4 results for each of the 12 geometries, under the operating conditions used for cell level optimization but with a number of heat fluxes.

Table 15 - Combinatorial geometries used for data analysis.

<table>
<thead>
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<th>geometry number</th>
<th>Wavelengths (#)</th>
<th>Width (mm)</th>
<th>Amplitude (mm)</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>7.5</td>
<td>30.0</td>
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</table>
One important result which was necessary for this work was knowledge of the relationship between cell temperature and heat flux. Since these simulations are all steady state the applied heat flux into the cooling plate is equal to the heat flow out of the plate due to the increased temperature of the coolant flowing out of the plate. Figure 38 shows the relationship between cell temperature and heat flux for 4 of the 12 geometries; 1, 4, 8, and 12. The relationship is highly linear in the region shown, which supports the assumption that the temperature dependence of the heat absorption rate used in this study is linear. If we consider all of the available results which were performed in the combinatorial simulations the most effective geometries were able to achieve a cooling plate thermal conductance \(G_{\text{Cooling}}\) close to 5 W/K. Under the assumption that whatever specific cooling plate geometry is used will be optimized based on the results of this work, we have used this result for \(G_{\text{Cooling}}\) as a representative cooling plate performance.

![Cell Average Temperature vs Heat Flux for Selected Cooling Plate Geometries](image)

Figure 38 - Combinatorial data select results showing the relationship between cell temperature and heat flux rate.
Another important aspect of the cell level design which affects the pack level performance is the effect of flow rate on cooling plate performance. With flow rates decreasing from one battery section to another there is a need to represent this in the pack level simulation. The specific drop in flow from one battery section to another is highly dependent on the cooling plate design itself, since the flow through cooling plates is in parallel through the battery pack. This means that the higher the pressure drop through a single cooling plate the more uniform the flow distribution in the pack will be, but the more energy will be required to pump the coolant through the cooling channels. Without a specific plate design it is impossible to accurately represent the flow distribution at the pack level, especially since each successive optimization iteration will change the behavior of the cooling plates. Figure 39 shows the relationship between coolant flow rate and cell average temperature for geometry 12, as defined above, for all 4 heat flux rates. The effect is more pronounced at higher heat fluxes, and is nonlinear in all cases. Cooling performance is improved with higher flow rates since the coolant moves more quickly within the channels and maintains a lower temperature further into the channels. The range of coolant flow rates selected for the combinatorial data was double (0.002 kg/s) and half (0.0005 kg/s) of that used in previous cell level optimization, which corresponds roughly to that seen in the Chevy Volt. We know from the work by Jayaraman et al. [21] that the flow rate decreases roughly 10% from battery section 1 to battery section 3 in the Volt battery pack. The combinatorial data points set at half and double the nominal flow rate are too large a step to obtain more specific local behavior near 0.001 kg/s flow rate, as such the reduction in cooling plate thermal conductance was set at a 10% reduction per battery section. This allows for investigation of the effects of reduced cooling potential on the average cell temperature as well as the optimized cooling distribution in the plate.
Figure 39 - Cell average temperature dependence on flow rate for geometry 12 from the combinatorial simulation data set.
Appendix B

Scalar Parameters

\%number of battery cells in each section
sec1_cells=90;
sec2_cells=72;
sec3_cells=126;

\%gaps between the sections
sec12_gap=0.05; \% [m]
sec23_gap=0.05; \% [m]

\%meshing and model parameters
widthdiv=8; \% number of elements in width [-]
heightdiv=10; \% number of elements in height [-]
thickdiv=3; \% number of elements in thickness [-]
pcthick=0.0005; \% thickness of the coolant channel in the plate [m]

\%cell parameters
cthick=0.00635; \% cell thickness [m]
chigh=0.200; \% cell height [m]
cwide=0.160; \% cell width [m]
ckxx=3.4; \% cell thermal conductivity in x-(through) [W/(m*K)]
ckyy=24.0; \% cell thermal conductivity in y-(height) [W/(m*K)]
ckzz=24.0; \% cell thermal conductivity in z-(width) [W/(m*K)]
cc=800; \% cell specific heat capacity [J/(kg*K)]
cdens=1845; \% cell density [kg/m^3]
c_matnum=1; \% cell material number for ANSYS [-]

\%plate parameters
pthick=0.001; \% plate thickness [m]
pratio=-(2*pthick/(pthick-pcthick))-2); \% [-]
pcdist1=(pthick-pcthick)/4; \% distance from co-ord system to centre of first element [m]
pcdist2=pthick/2; \% distance from co-ord system to centre of middle element [m]
pcdist3=pthick-pcdist1; \% distance from co-ord system to centre of last element [m]
phigh=chigh; \% plate height [m]
pwide=cwide; \% plate width [m]
pkxx=167; \% plate thermal conductivity in x-(through) [W/(m*K)]
pkyy=167; \% plate thermal conductivity in y-(height) [W/(m*K)]
pkzz=167; \% plate thermal conductivity in z-(width) [W/(m*K)]
p=896; \% plate specific heat capacity [J/(kg*K)]
pdens=2700; \% plate density [kg/m^3]
p_matnum=2; \% plate material number for ANSYS [-]

\%insulation parameters
ithick=0.001; \% insulation thickness [m]
ihigh=chigh; \% insulation height [m]
iwide=cwide; \% insulation width [m]
iki=kxx; \% insulation thermal conductivity in x-(through) [W/(m*K)]
ikiy=kyy; \% insulation thermal conductivity in y-(height) [W/(m*K)]
ikiw=ikzz; \% insulation thermal conductivity in z-(width) [W/(m*K)]
ici=1450; \% insulation specific heat capacity [J/(kg*K)]
idens=30; \% insulation density [kg/m^3]
i_matnum=3; \% insulation material number for ANSYS [-]

\%origin of section 1
sec1_x0=0;
sec1_y0=0;
sec1_z0=0;

%origin of section 2
sec2_x0=sec12_gap+(cthick*sec1_cells)+(pthick*sec1_cells/2)+(ithick*((sec1_cells/2)+1));
sec2_y0=0;
sec2_z0=0;

%origin of section 3
sec3_x0=sec2_x0+sec23_gap+cwide+...
   (cthick*sec2_cells)+(pthick*sec2_cells/2)+(ithick*((sec2_cells/2)+1));
sec3_y0=0;
sec3_z0=(cwide/2)-(((cthick*sec3_cells)+(pthick*sec3_cells/2)+(ithick*((sec3_cells/2)+1)))/2);