

Intelligent Thermal Management of Li-ion Batteries via Temperature-Responsive Coolant Flow Control

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Abstract - A Battery Thermal Management system (BTMS) is responsible for cooling, heating, insulation, and ventilation of the battery pack to ensure safe, reliable, and long-lasting operation of the battery pack under controlled optimal conditions. Cold plates are one of the most popular active thermal control methods used in BTMS. Most cold plate-based cooling strategies use a constant coolant flow rate. A possible method to improve this could be a temperature-responsive coolant flow strategy. This paper focuses on the optimal control of coolant flow for an active hydraulic BTMS with mini-channel cooling plates. An appropriate cost function was formulated to optimise the coolant flow, capturing the trade-off between thermal degradation and pumping power. A software framework was created to obtain the optimal solution for flow rate as a function of time. The results obtained after optimisation showed that an optimal cooling strategy for high heat dissipation generally has three phases - i) increasing flow rate, ii) saturated flow rate, and iii) decreasing flow rate, which gives a lesser cost when compared to a constant flow rate.

Keywords: Optimal control, BTMS, electric vehicles, cold plate, thermal degradation

1. Introduction

Lithium-ion (Li-ion) batteries have become increasingly popular in recent years due to their long life span, low maintenance requirements, and high reliability in various devices, including laptops, smartphones, and electric vehicles (EVs). An important component integrated with most Li-ion battery packs in EVs is the Battery Thermal Management System (BTMS) [1]. A BTMS is responsible for cooling, heating, insulation and ventilation of the battery pack to ensure safe, reliable and long-lasting operation of the battery pack under controlled optimal conditions. Cold plates are one of the most popular active thermal control methods used in BTMS [2]. Most cold plate-based cooling strategies use a constant coolant flow rate. At lower system temperatures, the constant flow rate used is higher than the value required for maintaining the optimal temperature range of the batteries, resulting in higher pumping power. A possible method to improve this could be a temperature-responsive coolant flow strategy. This paper focuses on the optimal control of coolant flow for an active hydraulic BTMS with mini-channel cooling plates.

A serpentine channel-shaped, single inlet-outlet cold plate was chosen to analyse the coolant flow control strategy, as serpentine channels are one of the most commonly used cold plate geometries in the literature. An appropriate cost function was formulated to optimise the coolant flow, capturing the trade-off between thermal degradation and pumping power [3]. Two models, the Equilibrium Temperature model (ETM) and the Linear Thermal Degradation model (LTDM), have been proposed to model the thermal degradation costs of the batteries. ETM considers the equilibrium temperature during steady-state operation, such that the cost increases with increasing temperature. The ETM is useful for the steady state behaviour of the battery, which usually occurs under constant external power consumption. LTDM, on the other hand, focuses on linearly reducing battery thermal life when temperatures exceed a critical threshold, making it suitable for systems with fluctuating power consumption and transient behaviour.

A software framework was created to obtain the optimal solution for flow rate as a function of time. The continuous time setting was converted to a discrete-time setting to perform all operations numerically. A cascaded optimisation approach was utilised in which a close-to-optimum solution was obtained first, which was then used as the initial point for the next optimisation step in order to ensure a more efficient and fast convergence to the optimal solution, as the first-order optimality value reached closer to zero quicker. The software framework was made to support variable external power consumption, so the robustness of the cooling strategy to fluctuations in power drawn can also be seen.

2. Methodology

2.1. Design of the BTMS

A serpentine channel cold plate was considered as the thermal management system for the Li-ion battery. The design with an optimal number of turns considering the maximum temperature of the battery, thermal gradient and pumping power of the coolant was chosen for further analysis. The optimised serpentine cold plate design and its temperature contour are shown in Fig 1. The heat transfer coefficient and the pumping power trends were obtained for the chosen cold plate for different inlet flow rates. These values were considered for calculating the overall cost during the control optimisation.

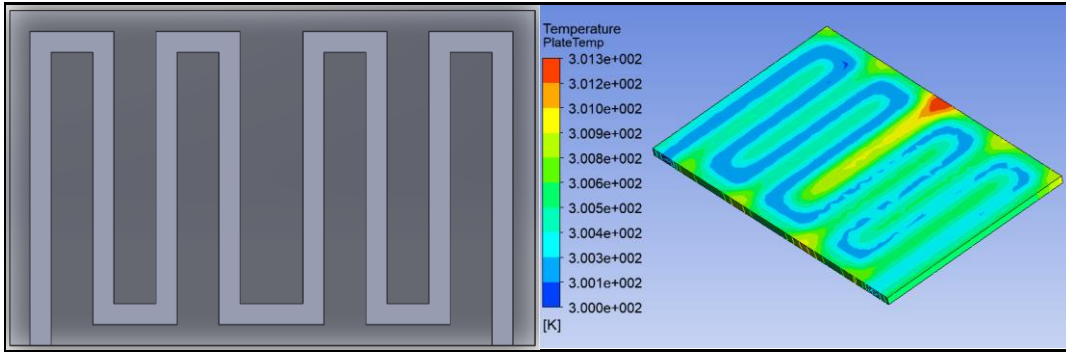


Fig. 1: Design and temperature contour of the optimised serpentine channel, respectively

2.2. Thermal degradation models

To optimise the coolant flow, an appropriate cost/objective function needs to be determined that accurately captures the trade-off between thermal degradation and pumping power. The effect of pumping power / pumping energy consumed to circulate the coolant can be easily incorporated since the monetary cost associated with pumping energy increases linearly. Mathematically, the average power consumed during the period of operation can be represented as follows:

$$E(\tau) = \frac{1}{\tau} \int_0^{\tau} Pow_p(t) dt \quad (1)$$

Incorporating the cost associated with thermal degradation is trickier and highly scenario-dependent. Various models can be used to incorporate the cost associated with thermal degradation. Some of them are as follows:

- 1) **Equilibrium temperature model** - In this model, the equilibrium temperature T_{eq} of the battery pack in steady-state operation is incorporated into the cost function along with the pumping energy consumed in such a way that as the equilibrium temperature increases, the cost increases.
- 2) **Linear thermal degradation model** - In this model, the battery thermal life $L(\tau)$ reduces linearly when the temperature exceeds a critical value. Mathematically,

$$L(\tau) = L_0 - \frac{1}{\tau} \int_0^{\tau} K(T)(T(t) - T_{crit}) dt \quad (2)$$

L_0 represents the initial battery life in the absence of any thermal degradation

$T(t)$ is the temperature of the battery at some time $0 \leq t \leq \tau$

T_{crit} is the critical temperature above which thermal degradation starts to occur

$K(T)$ is the thermal degradation coefficient, which represents the reduction in the lifetime of the battery when the battery temperature exceeds the critical temperature by 1 unit for a unit time duration, where $K(T) = 0$ when $T < T_{crit}$ and $K(T) = K_0$ when $T > T_{crit}$

The total thermal damage to the battery is represented by;

$$Dmg(\tau) = \frac{1}{\tau} \int_0^{\tau} K(T)(T(t) - T_{crit})dt \quad (3)$$

The equilibrium temperature model is useful for optimising the steady state behaviour of the battery, which usually occurs under constant external power consumption. However, if the external power consumption is varying or fluctuating due to external factors like noise, then the thermal degradation model is more suitable since it takes into account the transient behaviour of the battery. However, the equilibrium temperature model has the advantage of being computationally less complex as compared to the thermal degradation model.

2.3. Control optimisation

The decision variable(s) is the mass flow rate of the coolant as a function of time during the operation period of the battery, which is represented as $f(t)$ in a continuous time setting. In a discrete-time setting, $f(t)$ gets converted to an array/vector of flow rates, $f[1:N]$ where 1,2,3, ..., N represent the time instances. Thus, there would be N decision variables in total. The size of the time step depends on the characteristic time/time constant of the battery.

For a given external power consumption $Pow_{ext}(t)$ and a decided flow rate $f(t)$, the dynamics of the system are as follows:

$$D(t) = \frac{-(Pow_p(f(t)) + Pow_{ext}(t))}{R} + \left(\frac{Vol}{2R}\right)^2 \quad (4)$$

$$I_{drawn} = \left(\frac{Vol}{2R}\right) - \sqrt{D(t)} \quad (5)$$

$D(t)$ and I_{drawn} are calculated based on energy balance. It is assumed that the power from the battery is used by the pump $Pow_p(f(t))$ and for external use $Pow_{ext}(t)$, without any loss of energy and Vol represents the voltage of the battery during operation.

The temperature as a function of time can be determined on the basis of lumped-mass analysis

$$mC_p \frac{dT(t)}{dt} = I_{drawn}^2 R - h(f(t)) A (T(t) - T_{cool}) \quad (6)$$

$I_{drawn}^2 R$ represents the heat dissipated from the battery due to internal processes & $h(f(t)) A (T(t) - T_{cool})$ represents the heat absorbed by the coolant

R - effective resistance of the battery

A - surface area for for heat transfer to the coolant

T_{cool} - Temperature of the coolant, which is maintained constant during operation (the temperature maintenance aspect is incorporated in $Pow_p(f(t))$ using a suitable correction factor)

For constant flow rate, the equilibrium temperature T_{eq} can be obtained as:

$$T_{eq} = T_{cool} + \frac{I_{drawn}^2 R}{hA} \quad (7)$$

Based on the equilibrium temperature model, the cost function C can be defined as:

$$C_{eq-temp} = C_1(T_{eq} - T_{crit}) + C_2 E(\tau) \quad (8)$$

C_1 is the cost per unit increase in the equilibrium temperature above critical temperature and C_2 is the cost per unit increase in average pumping power consumed.

Based on the thermal degradation model, the cost function can be defined as:

$$C_{deg} = \frac{C_1}{L(\tau)} + C_2 E(\tau) \quad (9)$$

Thus, C_{deg} is the cost of operating the BTMS system per unit duration of service of the battery.

After choosing the appropriate cost function based on the context, the optimisation problem can be formulated in continuous time as follows:

Minimize C subject to the following constraints;

$$1) D(t) > 0, 0 \leq t \leq \tau$$

$$2) 0 \leq f(t) \leq f_{max}(t)$$

In discrete time, the optimisation problem can be formulated as follows -

Minimize C subject to the following constraints;

$$1) D[n] > 0, 1 \leq n \leq N$$

$$2) 0 \leq f[n] \leq f_{max}$$

3. Results & discussions

A software framework was created in MATLAB to obtain the optimal solution for flow rate as a function of time. The continuous time setting had to be converted to the discrete-time setting since all the operations needed to be performed numerically. Since the optimisation problem is non-linear, the solver used for obtaining the optimal solution was `fmincon`. A cascaded optimisation approach was utilised in which a close-to-optimum solution was obtained first, which was then used as the starting point for the next optimisation step. This made the process more efficient and led to faster convergence to the optimal solution as the first-order optimality value reached closer to zero quickly.

The results obtained below are based on the thermal degradation model for different external power consumption modes. The graph corresponding to uniform flow rate assumes that the flow rate cannot vary with time and the optimum value for constant flow rate is solved for. The graph for non-uniform flow rate relaxes the assumption used for uniform flow rate. This is done so as to compare the costs obtained in both cases. The cost in the case of a non-uniform flow rate should be lower than the uniform case since a uniform flow rate is technically a special case of a non-uniform flow rate.

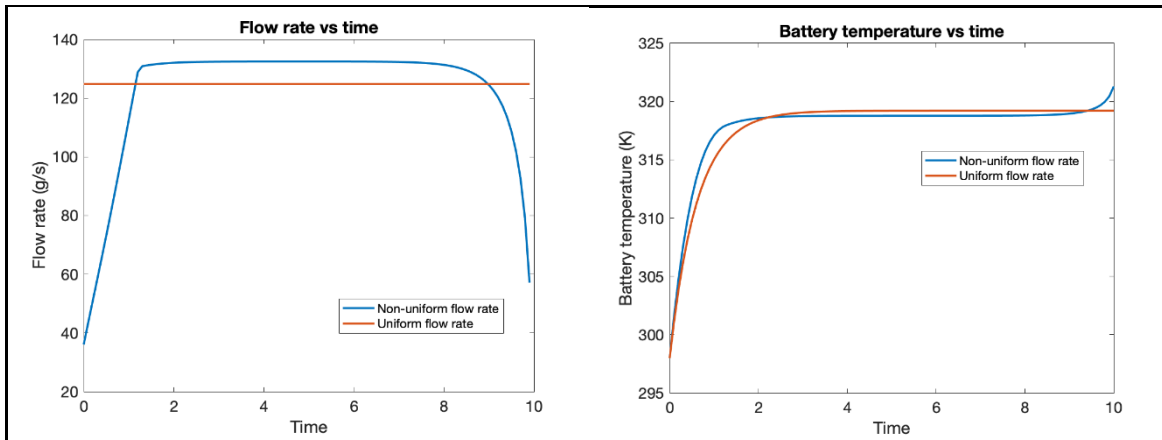


Fig. 2: Flow rate and Battery pack temperature for constant heat dissipation

The graphs above show the optimal flow rate (in g/s) and battery pack temperature (K) as a function of time (in units of battery time constant) for a constant external power consumption corresponding to a heat dissipation of 10 W / cell. This was done to observe the effect of thermal damage on the optimal solution more evidently, as the peak temperature reached is greater than ideal.

In general, the optimal cooling strategy for high constant heat dissipation has three phases - i) increasing flow rate, ii) saturated flow rate and iii) decreasing flow rate. Thus, the flow rate as a function of time takes the shape of an upside-down U. It has been observed that not only is the overall objective value reduced for non-uniform flow rate, but even the total thermal damage and pumping energy consumed are reduced by 1-5% for the operating duration.

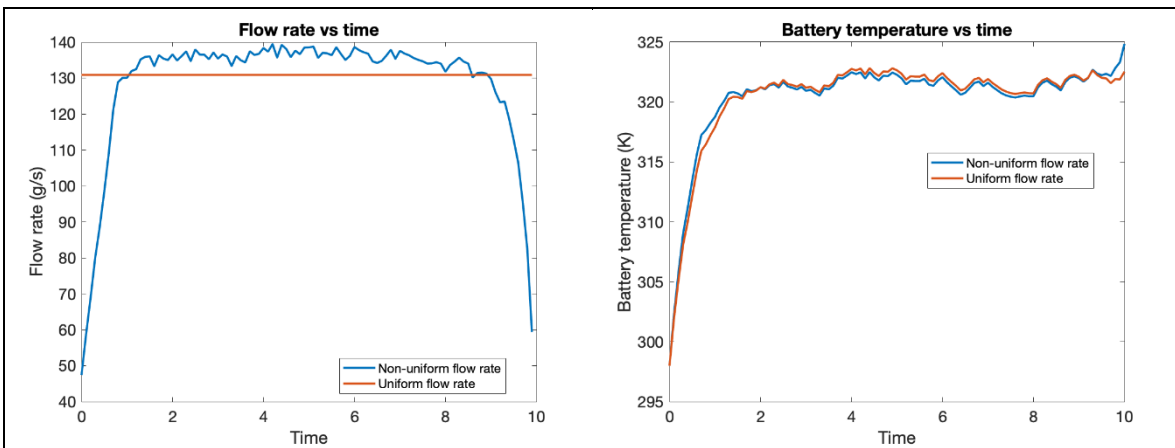


Fig. 3: Flow rate and Battery pack temperature for fluctuating heat dissipation

Our software framework also supports variable external power consumption, so the robustness of the cooling strategy to variation/fluctuations in external power drawn can be seen as well. The graphs above depict for the case of 10 W/cell subject to heat dissipation fluctuations. It is observed that the overall shape of the graph doesn't alter that much.

The graphs below depict the flow rate and battery temperature variation with time for linearly increasing power consumption (ramp power consumption) and sinusoidal power consumption respectively. For the ramp power consumption scenario, since steady state is not really achieved when constant flow rate is used, it is important to vary the flow rate during the period of operation so that temperature doesn't shoot up too much. It can be seen that for variable flow rate, the graph of temperature is close to what it would have been for steady state operation.

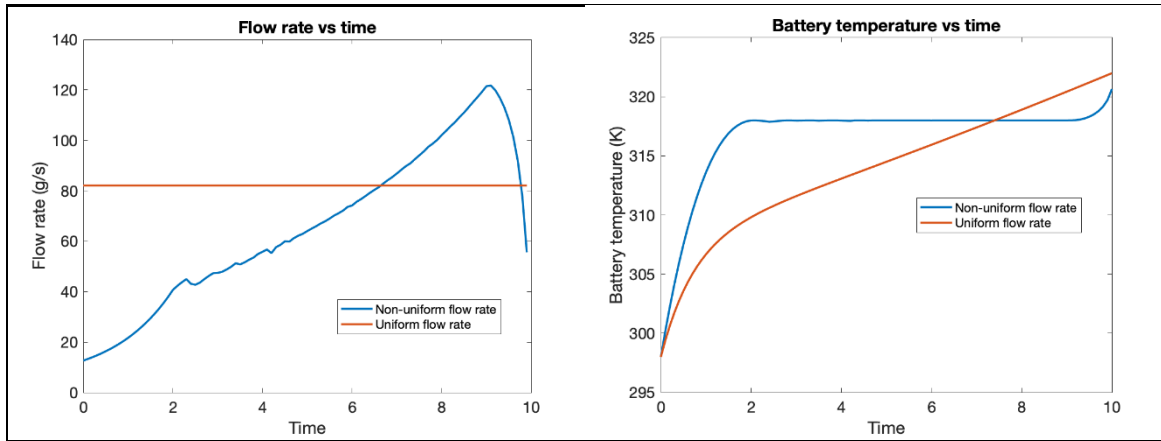


Fig. 4: Flow rate and Battery pack temperature for linearly increasing heat dissipation

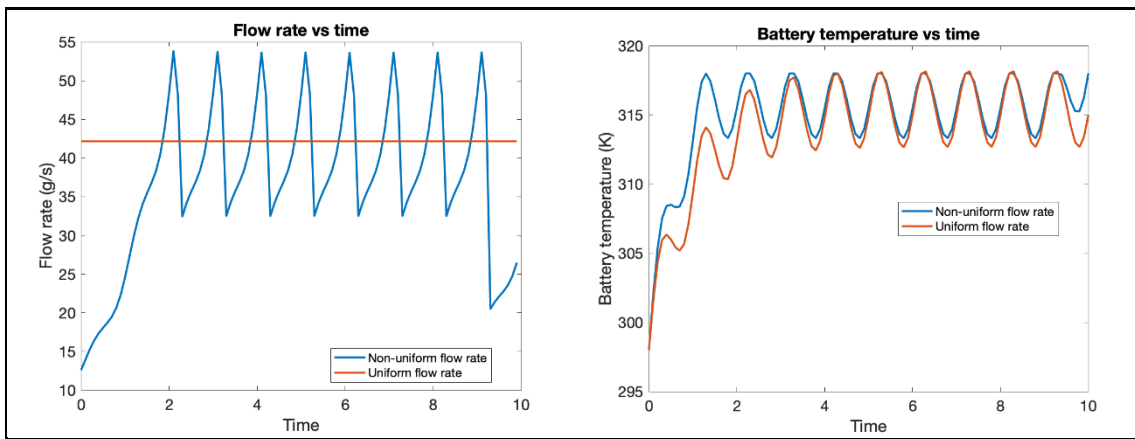


Fig. 5: Flow rate and Battery pack temperature for sinusoidal heat dissipation

4. Conclusion

Based on the results and the discussions, some of the conclusions that can be made are as follows:

1. In general, the optimal cooling strategy for high constant heat dissipation has three phases during the operating duration - i) increasing flow rate, ii) saturated flow rate and iii) decreasing flow rate. The optimal cooling strategy is not greatly altered even in the presence of fluctuations, which implies that the cooling strategy is robust to external disturbances
2. The equilibrium temperature model is useful for optimising the steady state behaviour of the battery, while the thermal degradation model is more suitable if the external power consumption is varying due to factors like noise.
3. Although we are able to obtain lower costs by varying the flow rate, the cost of the controller required to vary the flow rate properly has not been accounted for in this approach. Also, lumped analysis has been used for the dynamics of the system. Thus, it is unable to capture the effect of thermal gradients in the battery.
4. The requirement for computational power increases greatly as we try to increase the operating duration of the battery. Thus, the current optimal control framework cannot be used for very long operating durations

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