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DESIGN OF AN ELECTRIC VEHICLE BATTERY COOLING SYSTEM WITH ECONOMIC CONSIDERATIONS USING GENETIC ALGORITHM

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ABSTRACT

Electric vehicles, with their numerous advantages, are a promising alternative to traditional vehicles. However, they are still plagued with high battery replacement costs due to short battery lifespan. As temperature is a key factor in this, battery cooling systems are widely explored solutions, but their associated costs remain to be considered. Hence, this study designs a cooling system for an electric vehicle battery considering the capital, operating, maintenance, and associated battery replacement costs of the system. The net present costs of two design choices, an active air-cooled and passive PCM-cooled one, are minimized using a genetic algorithm, paired with a system simulation covering the electrical, thermal and aging behavior of the battery. Two cases are also explored – operation under a drive cycle and under discharge at 3C, representing routine and extreme use. It is determined that for routine use, having no cooling is still the most economical choice, and that for extreme use, PCM cooling is the most advantageous option, both in terms of temperature reduction and cost.

Keywords: Electric vehicle, battery cooling system, optimization, genetic algorithm

NOMENCLATURE

Symbols

C_{cool}	Capital cost of cooling system
C_{batt}	Capital cost of battery pack
C_{op}	Total operating (electricity) costs
$kWh_{trac,life}$	Total lifetime energy used for traction

1. INTRODUCTION

Electric vehicles (EVs) are a leading alternative to traditional vehicles given their environmental, economic, and technical advantages. They have been found to be the most beneficial among alternative technologies in terms of overall costs, health and non-health benefits, and greenhouse gas savings [1].

One of the main challenges hindering the market penetration of EVs is the costs associated with short battery life, i.e. the rapid loss of battery capacity [2]. Elevated battery temperatures due to heat generation during operation [2] have been found to be one of the most significant contributors to battery capacity loss [3].

Given this, battery cooling systems are often necessary to maintain acceptable battery temperatures and prolong battery life. There has been a significant amount of research into battery cooling systems, especially into the three main cooling media – air, liquid, and phase change material (PCM) [4].

Extending battery life can greatly decrease the cost of ownership of an electric vehicle [5], but a battery cooling system entails added capital cost, and even operating costs for systems with active components like fans and pumps [6]. Therefore, in designing a battery cooling system, it is important to account not only for the battery temperature, as the vast majority of previous studies have, but also for the various associated costs.

This study therefore aims to design a battery cooling system to prolong the life of an electric vehicle battery and minimize overall costs. To achieve this, existing

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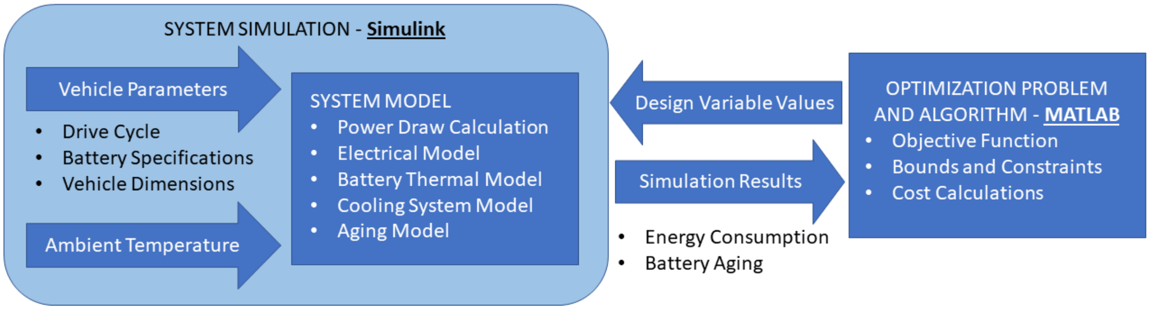

Fig 1 Overview of Simulation and Optimization

battery and cooling system models are linked to form a system simulation. The parameters of an electric vehicle, and environmental factors are then used as input to the simulation, whose results are used in the optimization of cooling system designs. Given that active and passive cooling systems each have advantages and disadvantages in terms of cost and performance, two types of cooling systems – an air-cooled and a PCM system – are considered. The optimized designs are then compared, and the more suitable is selected.

As shown in [7], the intensity of use, i.e. the drive cycle and current draw, directly influence the heat generation and cooling requirement of the battery. To see its influence on the cooling system design, optimization is performed under a drive cycle and discharge at 3C, representing routine and extreme use.

2. MATERIALS AND METHODS

The system simulation in this study is patterned after [8]. A notable departure from the simulation in [8] is the use of a single day of operation to represent the vehicle's use instead of an entire year. Another is the assumption of a zero rest period for the vehicle. These simplifications take advantage of the continuous, repetitive pattern of operation of the vehicle to decrease the simulation time.

The electric vehicle for which the cooling system is designed in this study is a typical electric jeepney operating in the Philippines, whose specifications are given in [9]. The jeepney operates under the Phase 2 Diesel Jeepney Drive Cycle developed in [10], and the ambient temperatures on a typical summer day in Manila, Philippines [11].

As seen in Fig 1, the design variable values generated in MATLAB, along with the vehicle specifications and ambient temperature are used as inputs to the system model, implemented in Simulink, which simulates the charging and discharging of the battery of the electric jeepney for 24 hours. The resulting energy consumption and battery aging data are then returned to MATLAB, where they are used in the calculation of the objective function. The algorithm repeats this until an optimal value is found. This procedure is implemented for both the air-cooled and PCM designs, for both the routine and extreme operation cases.

3. THEORY AND CALCULATION

3.1 *Air-cooled System*

Forced air cooling is a simple and cheap, yet effective method of regulating battery temperature [4]. The design selected for this study blows cool air crosswise over 18650 $LiFePO_4$ cylindrical cells, similar to [8]. As the typical electric jeepney has no air-conditioning system, a standalone vapor compression system for the cooling air is included in the design. A simple on-off control strategy with upper and lower set point temperatures is used for the fans [8].

3.2 *PCM-cooled System*

Given that a significant drawback of air-cooled systems is the large parasitic energy consumption of the fans [12], passive cooling systems – PCM in particular, are widely explored alternatives. PCM capitalizes on its large latent heat of fusion and suitable melting point to absorb a large amount of the heat generated by batteries without the need for energy-consuming components. Plain PCM is often enhanced with various other materials to improve its thermal conductivity and other properties [13].

Octadecane embedded with aluminum foam is used as the PCM in the alternative design [14]. Octadecane has a melting range of 28 to 30°C, which is well within the range of ambient temperatures to which the battery is exposed.

3.3 *Optimization Problem*

The general objective function for the design of the air-cooled and PCM cooling systems is given by (1).

$$\min {}^{C}/_{kWh} = \frac{C_{cool} + C_{batt} + C_{op}}{kWh_{trac,life}} \tag{1}$$

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Table 1 Objective Function Values

Jeepney Drive Cycle			
	Baseline	Air	PCM
C/kWh ($/kWh)	0.7050	0.7016	0.7248
Percent Difference (%)	--	0.48	-2.81
Total Net Present Cost ($)	16,535	16,536	17,106
Lifetime Energy Spent on Traction (kWh)	23,454	23,570	23,601
Discharge at 3C			
	Baseline	Air	PCM
C/kWh ($/kWh)	0.9650	9.8164	0.8339
Percent Difference (%)	--	-917.24	13.59
Total Net Present Cost ($)	17,246	18,126	19,555
Lifetime Energy Spent on Traction (kWh)	17,872	1,847	23,450

The capital cost of the cooling system for the air-cooled system covers the cost of the fans and of the vapor compression system used to cool the air. For the PCM system, it covers the cost of the octadecane and of the aluminum foam. The operating or electricity cost covers the lifetime cost of charging the battery. All costs are present values.

The influence of the parasitic energy consumption of the air-cooled system is reflected in the use of traction energy as the denominator. It follows that the higher the energy consumption of the cooling system is, the lower the amount of lifetime energy used for traction is.

For the air-cooled system, the optimization variables are: the inlet air velocity, the cooling capacity of the vapor compression system, and the upper and lower set point temperatures. For the PCM-cooled system, the optimization variable is the thickness of PCM surrounding each cell.

3.4 Genetic Algorithm

Genetic Algorithm (GA), which is patterned after biological evolution, is selected to solve the optimization problem given its robustness, ability to solve nonlinear problems, ability to handle dynamic components [15], and relative ease of implementation in MATLAB.

Table 2 Optimal Cooling System Design Values

Air		
	Drive Cycle	3C Discharge
Inlet Air Velocity (m/s)	0.10	3.72
Vapor Compression System Cooling Capacity (W)	0	0
Upper Set Point (Switch ON) (°C)	27	35
Lower Set Point (Switch OFF) (°C)	15	35
PCM		
	Drive Cycle	3C Discharge
PCM thickness around battery (mm)	1.0	5.5

4. RESULTS AND DISCUSSION

Table 1 presents the objective function values for the air-cooled and PCM-cooled designs, along with that for the uncooled case for both routine and extreme use. It can be seen that the air-cooled design yields negligible savings, and the PCM-cooled design even entails greater cost per kWh. The negative effect of the PCM on the cost can be attributed to its extremely high price, reflected by its higher net present cost in spite of the minimum amount of PCM selected by the algorithm, as seen in Table 2. Given these, it is recommended to maintain the absence of a cooling system under routine operation.

As for discharge at 3C, it is highly notable that the cost per kWh of the air-cooled system is 917.24% higher than the baseline. This can be attributed to the high energy consumption of the fans, as indicated by the significantly lower energy available for traction. The results clearly indicate that the best option for extreme operation is the PCM-cooled system. Although the high investment cost remains, the available energy significantly increases, yielding cost per kWh savings of 13.59%.

Table 2 shows the optimal cooling system design values determined by the genetic algorithm. For the air-cooled systems, it can be seen that no standalone vapor compression cooling is allotted, given its extremely high price.

For air cooling under the jeepney drive cycle, it can be seen that aside from having no standalone cooling, the inlet air velocity is set to the lower limit. This indicated that the temperatures reached by the battery do not exceed ambient temperatures enough to require ambient air to be blown.

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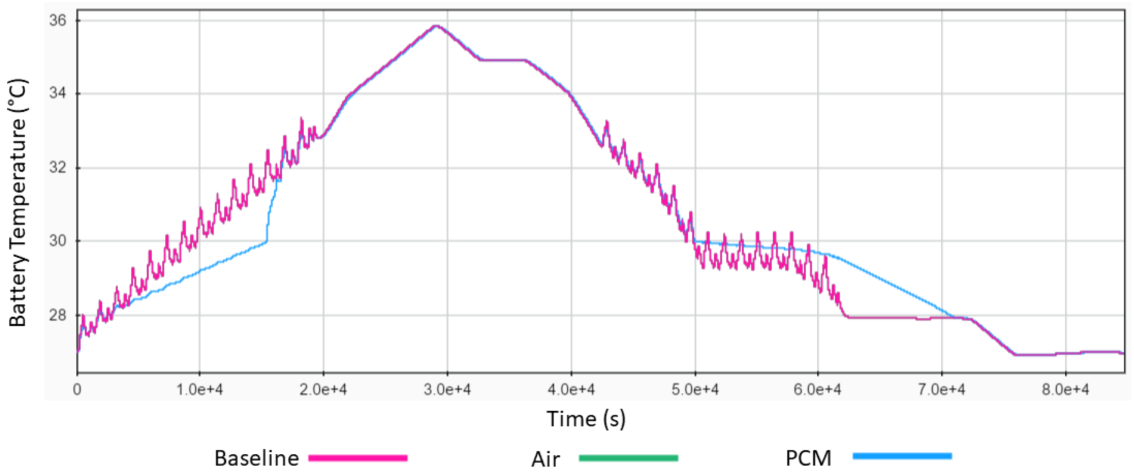

Fig 2 Battery Temperatures for Jeepney Drive Cycle

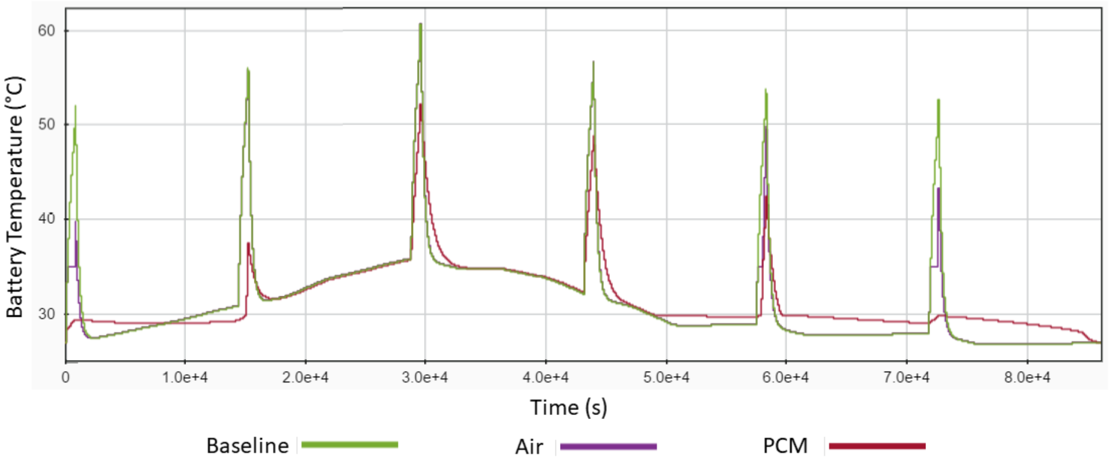

Fig 3 Battery Temperatures for Discharge at 3C

For air cooling under discharge at 3C, it is notable that the set points are at the upper limit, indicating the high cost of fan energy consumption, even at a moderate inlet velocity of 3.72 m/s.

The dependency of the effectiveness of the sensible and latent heat capacity of PCM on the amount of heat generation is indicated by the difference in PCM thickness for the two operation cases. While the lower limit is selected for the drive cycle, some PCM is allotted for the 3C discharge case.

Figs 2 and 3 show the battery temperatures throughout the day of operation for the drive cycle and 3C discharge cases. It can be seen in Fig 2 that the baseline and air cases have virtually the same temperature curve given the absence of standalone cooling and the minimal fan speed used.

Fig 2 also shows the behavior of PCM during routine operation. Being a significant addition to the pack thermal mass, it keeps it at low temperatures longer when the ambient temperature is increasing, and also keeps it at high temperatures longer when the ambient temperature is decreasing. In addition, the much higher heat capacity during PCM melting is seen in the lagging temperature change at the melting temperature range.

It can be seen in Fig 3 that for all cases, temperatures beyond the acceptable 35 °C are reached. Comparing the temperature curves of the air- and PCM-cooled systems, it can be seen that in spite of the high energy allotment for active cooling, PCM cooling is still more effective at keeping the temperatures low. PCM can be seen to be more effective at reducing temperature peaks, indicating the effectiveness of the high heat capacity of PCM at extreme temperatures.

5. CONCLUSION

The electrical, thermal, and aging behavior of the battery of a typical electric jeepney were simulated, given its parameters and the ambient temperature. The simulation was linked to a genetic algorithm to optimize two cooling system design choices – an active air-cooled system and a passive PCM-cooled one. Designs were optimized for a drive cycle and discharge at 3C, representing routine and extreme operation.

The results show that for routine operation, a cooling system yields no significant economic advantage, and that for extreme operation, PCM is the more effective cooling medium, especially given the high operating cost of the fans of the air-cooled system.

The economic approach to the design process can be extended to other cooling system types, especially liquid-cooled systems, another widely researched active cooling system. It is also recommended that CFD simulations be explored for more detailed design and analysis of the cooling systems. To add detail and accuracy to the costing of the cooling systems, it is also recommended that cost functions be developed for auxiliary components like casing and ducting. Lastly, further work can include sensitivity analyses of the optimization results to ambient temperature, capital and operating costs, and future battery costs.

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