Simulation Battery Cooling System for Small Scale Electric Vehicle (Light EV)

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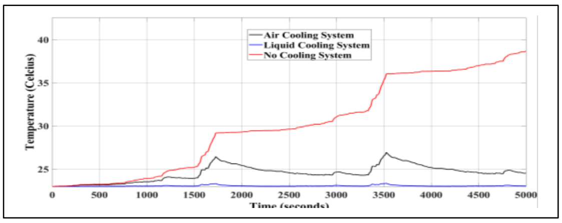
Graphical Abstract



Abstract

The Battery Thermal Management System (BTMS) has widely used for Electric Vehicle (EV) as cooling system to reduce high temperature occurred from batteries source during discharge and charge process. Since the performance and cycle life of batterie is very sensitive to temperature, it is important to maintain the proper temperature range in order to avoid the thermal issues and improve the performance. Therefore, the purpose of this project is to study the effectiveness of different type of cooling system for small scale Electric Vehicle (EV). The study is conducted by using two main types of cooling system available which is air and liquid cooling. In order to evaluate the effectiveness of those cooling system, an analysis is conducted by developing an EV model using MATLAB/Simulink software and simulated at different speed of the vehicle from the few driving cycle that commonly used in researcher paper.

Keywords

Battery Thermal Management System (BTMS); liquid cooling; air cooling; MATLAB/Simulink; Electric Vehicle.

Introduction

As Electric Vehicle (EV) has become a promising alternative for sustainable and cleaner energy emission in transportation, but their effective potential in real world driving conditions strongly depends on the performance of their battery source [1]. However, it can affect the performance and cycle life with the temperature and dynamic characteristic of the batteries [2]. Therefore, implementation of Battery Thermal Management System (BTMS) become important as the cooling system for the battery. The most common BTMS that provided in EV nowadays is air, liquid, and Phase Change Material (PCM) where those cooling system has pros and cons of their implementation in BTMS. However, the PCM cooling system are not compatibility to simulate by using 1-D MATLAB/Simulink due to complexity of working operation itself. In additional, Lithium-ion battery are most popular and widely used in EV industry since the battery have high energy density and long cycle life [3].

Other than that, EV is a vehicle that uses pure electricity to power all systems by generate a large amount of heat and cause temperature rise during discharge and charge process. Besides that, the process only works between certain temperature extremes and in EV, Li-ion battery cannot be used without any BTMS due to their reliability, safety and performance that can cause the battery overheats or non-uniform temperature distribution in the battery pack that might cause blowout or malfunction where the risk can cause life- threatening safety issues.

Therefore, this project mainly aims to study of the effectiveness of different type of cooling system for small scale Electric Vehicle (EV). The analysis was conducted by developing an EV model in MATLAB/Simulink based on the theory of operation of EV and all components has been developed separately and validated by using information gathered based on the experiment and project that have been done by other researchers. However, the model developed only concentrated to battery component due to insufficient time, complexity and high precision for development of EV model. MODEL DEVELOPMENT

MODEL DEVELOPMENT

To develop an EV model in MATLAB/Simulink, there are four primarily block models based on the theory of operation of EV. Besides that, the analytical calculation is necessary to obtain intuitive performance results of the implemented vehicle model [4]. Below are listed the four block models:

a) Vehicle dynamic Model (with the specification vehicle)
b) Transmission (included with DC motor, motor controller and other related components)
c) Battery model (Lithium-ion, Pouch cell type)
d) BTMS (for each type cooling system).

Modelling Vehicle dynamic Model

For the vehicle performance modelling, the first step is producing an equation for required 'traction force' as the force propelling vehicle forward that transmitted to the ground by the drive wheels. To propel a vehicle with a mass 'm_v', at a velocity 'V' and up a slope of angle 'θ', the tractive effort has to accomplish the following [5]:

- Overcome the aerodynamic drag
- Overcome the rolling resistance
- Provide the force needed to overcome the component of vehicle's weight over a slope
- Accelerate and deceleration the vehicle, if the velocity is not constant.

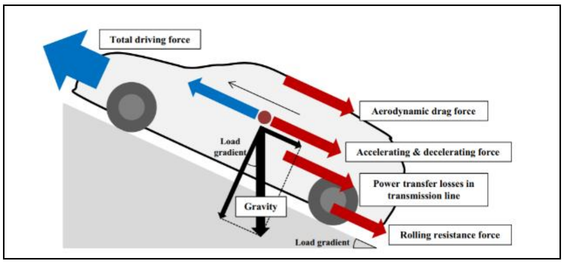


Figure 1: Schematic representation of the forces acting on a vehicle in motion

Table 1: Specification of Toyota C+pod (X)

Grade		G	X
Vehicle category (Road Transport Vehicle Act)	Minivehicle	Ultra-compact mobility (type approval)	
Length x Width x Height	(mm)	2,490 x 1,290 x 1,550	
Wheelbase	(mm)	1,780	
Track	(mm)	Fr: 1,105 / Rr: 1,095	
Minimum ground clearance	(mm)	145	
Vehicle weight	(kg)	690	670
Minimum turning radius	(m)	3.9	
Capacity	(seats)	2	

Table 1 showed that schematic diagram of forces acting during traction force occurred within the parameter that involved in calculation. Then, Figure 2 presented the specifications of EV model that used in the parameter of vehicle dynamic model where the parameters was decided based on the specification small scale EV that available in market which is Toyota C+pod.

Aerodynamic Drag Force

The force is created due the resistance or friction of air toward vehicle body during driving. This aerodynamic drag force is calculated as follow:

$$F_a = \frac{1}{2}.\rho.A.C_d.V^2 \qquad (1)$$

The value of ρ is come from air density and the value are dependent on temperature, altitude and humidity but the most cases are used 1.25 kg.m^{-3} and it can be reasonable value for this case. From Figure 2, the frontal area, A was calculated using simple equation and obtain 1.7 m^2 for small scale EV and the value drag coefficient, C_d is 0.29 based on typical small-scale EV and lastly the velocity of vehicle can be determined from the driving cycle input.

Tire Rolling Resistance

The resistance due to friction of the vehicle's tire on the road during driving which known as tire rolling resistance. The force is calculated as the follow:

$$F_r = \mu r.m_v.g \tag{2}$$

In this case, the coefficient of rolling resistance, μ_r is 0.012 as typical value for a radial ply tire type. Mass, m is 830 kg as the total weight for the vehicle, passengers and driver by assume the capacity allowed in EV model is 2 peoples with average weight 70 kg. The acceleration of gravity is 9.81 m/s^2 as standard value that been used for most cases and value velocity, V are from the driving cycle.

Hill Climbing Force

The resistance of the vehicle moving on a sloping road. The gradient resistance appears due to the component of gravity. So, the equation of hill climbing force is:

$$F_g = \mathrm{m_v.g.\sin\theta} \tag{3}$$

Where the value of θ as the slope or gradient of hill to drive vehicle up is 0 by assuming the simulation was run on the flat road surface. Other's parameters can determine with calculation.

Inertia Force

The inertia force is needed to encounter inertia resistance during acceleration and deceleration the vehicle calculated as follow:

$$F_{acc} = \mathrm{m_v.a} \tag{4}$$

Acceleration value, a can determine by using simple physical law formula which is by differentiate the different value of velocity, V respect to time travel and it can be done through the application of MATLAB/Simulink that has been programmed. Then, the value of F_{acc} can obtained by multiple by mass of vehicle, m which is 830 kg.

Traction Force and Power demand

The traction force, Ft can be obtained by sum of all force acting by using the equation follow:

$$F_t = F_a + F_r + F_g + F_{acc} \tag{5}$$

From the traction force result, power demand can be calculated by multiply the traction force with velocity vehicle as the equation follow:

$$P_t = F_t.V \tag{6}$$

Modelling Transmission

In this part, the transmission model was developed with simple calculation and the model also was included with the motor controller, electric motor and others related components. However, to build a high precision model that function as a real EV will takes lot of time and require high level knowledge of MATLAB/Simulink model. So, as the main propose of the project is to study the effect of cooling battery system, the model are concentrated more toward battery model.

Modelling Battery Model

This model is used to build battery model that can evaluate the performance of battery such as battery current, voltage, and state of charge (SOC) by using the power demand from the vehicle dynamic and transmission based on the driving cycle that involved. Below is the specification of battery that used in the model:

Table 2: The specification of battery model

Main drive battery	Type		Lithium-ion battery
	Capacity	(Ah)	51
	Total voltage	(V)	177.6
	Total power	(kWh)	9.06

The battery model was build based on the same EV model which is Toyota C+pod as shown in Table 2 and from the battery characteristic and the specifications, a mathematical modelling need to been done in order to obtain the value of battery's performance in battery block model such as voltage, state of charge (SOC), current and so on.

State of Charge (SOC)

State of charge (SOC) is the level of charge of an electric battery relative to its capacity, C and also depending on battery initial SOC condition, SOC_{init} which has been assumed as 90% considered for fully battery state of charge for this case and below is the equation to calculate the SOC of battery model:

$$SOC = SOC_{init} - \int \frac{I_{battery}}{C_{usable}}\, dt \tag{7}$$

Battery Current

The battery current can be calculated from the terminal power [5] and for this case the power, P (Watt) is the power requirement from the vehicle dynamic model through the transmission. The current can be calculated as follow:

$$I_{battery} = \frac{P}{V_{battery}} \tag{8}$$

Usable of Battery Capacity

In real life, the usable of battery capacity will decrease due to the increasing charge or discharge cycle number, discharge current. and storage-time (self-discharge) where the effect was known as the capacity fading effect, CCF. However, in this case, the value of CCF is 1 as the battery of model used is new which no storage time and there are no cycle life losses. Next, the value of C_{init} is 51 Ah as the capacity of battery based on the Table 2. Below are the equations for calculate the value of usable capacity, C_{usable} in (Ah) and the CCF:

$$C_{usable} = 3600. C_{init}. CCF \tag{9}$$

Where:

$$\text{CCF} = 1 - (\text{Calendar life losses} + \text{Cycle life losses}) \tag{10}$$

Battery Open Circuit Voltage

From the value of SOC, the battery open circuit voltage, V_{voc} was determined in order to find the real output voltage of the battery model by using the equation below:

$$Vvoc = (66.235). SOC7 - (242.73). SOC6 + (364.5). SOC5 - (291). SOC4 + (134.7). SOC3 - (37.016). SOC2 + 6.4517. SOC + 2.9007 \tag{11}$$

Battery Output Voltage

The real battery output voltage, $V_{battery}$ can calculated by using this equation below:

$$Vbattery = Vvoc - Ibattery. R + \Delta E(T) \tag{12}$$

Where the value of parameter V_{voc} and $I_{battery}$ can obtained by using previous equation which is (9) and (6). However, the value R is represented as the internal resistance battery that assumed as approximately constant over 25% to 100% SOC application [6]. Normally, Li-ion battery typically work in range between 2.5 to 1 $m\Omega$ based on a high-fidelity electrochemical model [7]. Therefore, the value that considered in this model 0.001 ohm. For temperature correction of potential, $\Delta E(T)$ is used to compensate for the variation of equilibrium potential that is induced by temperature changes can be referred in Figure 2 below as the ambient temperature in this case.

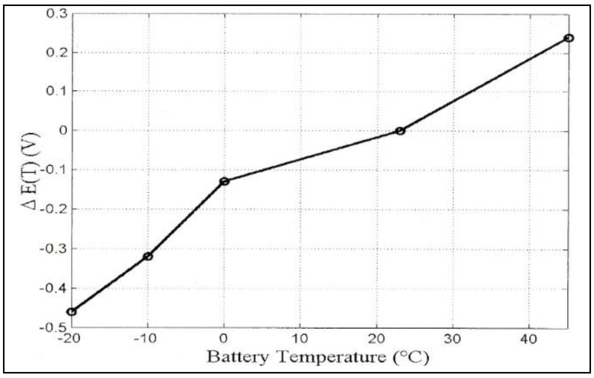


Figure 2: Temperature dependent potential correction term

Modelling Battery Thermal Management System (BTMS)

For the BTMS block model is used to find the thermal management of the Li-ion battery that used during driving in EV. So, there are two types used in BTMS block model which is air cooling system and liquid cooling system where at this part the model capable to evaluate the performance of battery in term of temperature rise, battery temperature and energy consumption.

Heat Generation

For this case, the heat generation can be modelled by using the power losses from the battery due to internal resistance and electrochemical reaction [7]. However, power loss from electrochemical reaction was neglected due complexity implementation and also less important compare to the power loss from internal resistance in heat generation [8,9]. The power loss due to internal resistance is calculated as follow:

$$P_{loss} = I^2. R \tag{13}$$

Where the power loss is depending on battery current based on the power demand and battery voltage that obtained from the losses of capacity usable due to temperature effect. Then, the energy generated, Q calculated from the power loss by using this equation:

$$Q = \int P_{loss} dt \tag{14}$$

While in adiabatic system, all energy source can express into heat energy by using this following equation:

$$Q = m.C_p.\Delta T \qquad (15)$$

From the equation, the temperature change can be obtained in term of ΔT where the m represented as mass of battery cell involved and C_p is specific heat capacity for the material that be used in the cooling system. Both values of C_p can be determined by using material properties table from the internet based on the ambient temperature in Kelvin unit [10].

Heat Transfer (Cooling System)

Cooling process is the process for heat transfer to the surrounding by using particular of material and also known as convection process. So, the heat transfer can be calculated by using simple thermodynamic equation which is:

$$Q_t = A.h.(T_{battery} - T_{surrounding}) \qquad (16)$$

While A is the area surface of battery that contacted with the material during convection process and h is convective heat transfer coefficient that calculated by using equation below:

$$h = Nu.\lambda.\left(\frac{1}{L}\right) \qquad (17)$$

Where Nusselt number, Nu can be calculated by using Reynold number, Re and Prandtl Number, Pr that been expressed for flat plat in uniform surface temperature as the Table 3 below [11]:

Table 3: Nusselt number for external convection on flat plate

External convection for uniform surface temperature, T	Nusselt number, Nu
Laminar flat plate	$Nu = 0.332.\,Pr^{1/3}.\,Re^{1/2}$
Turbulent flat plate	$Nu = 0.037.\,Re^{4/5}.\,Pr^{1/3}$

With Reynolds number, Re calculated by the equation follow:

$$Re = \rho.V.L.\frac{1}{\mu} \qquad (18)$$

And Prandtl number, Pr is calculated by using this:

$$Pr = \mu.C_p.\frac{1}{\lambda} \qquad (19)$$

Where the value Cp is for thermal capacity and the value of μ and λ for dynamic viscosity and thermal conductivity respectively was calculated as the Table 4 shown:

Table 4: Polynomial equations for air and liquid material properties [12,13,14,15]

Material	Equation of C_p ($J.\,kg^{-1}K^{-1}$), μ (Pa. s) and λ ($W.\,m^{-1}K^{-1}$)
Air [12]	$Cp = (1.9327x\,10^{-10}).T^4 - (7.9999x\,10^{-7}).T^3 + (1.1407x\,10^{-3}).T^2 - (4.4890x\,10^{-1}).T + 1.0575x\,10^3$
Liquid [13]	$Cp = (4.14964x\,10^{-6}).T^{2.5} - (0.00011535353).T^2 + (0.0012992528).T^{1.5} - (0.0056181625).T + 4.2174356$
Air [14]	$\mu = 4.9 \times 10^{-8}.\,T + 3.6656 \times 10^{-6}$
Liquid [13]	$\mu = 1/(557.82468 + 19.408782.T + 0.1360459.T^2 - 3.1160832 \times 10^{-4}.T^3)$
Air [15]	$\lambda = 1.5207 \times 10^{-11}.T^3 - 4.857 \times 10^{-8}.T^2 + 1.0184 \times 10^{-4}.T - 3.9333 \times 10^4$
Liquid [13]	$\lambda = -0.0009412945.T^{0.5} - 1.5154918 \times 10^{-6}.T^2 - 0.00012516934.T^{1.5} + 0.0026363895.T + 05650285$

Working Principle

The Figure 3 below shown that the working principle and overall layout of MATLAB/Simulink for simulation of cooling battery system for small EV to evaluate the performance of battery source at various speed driving. The Figure 4 shows that the general parameters used in the simulation.

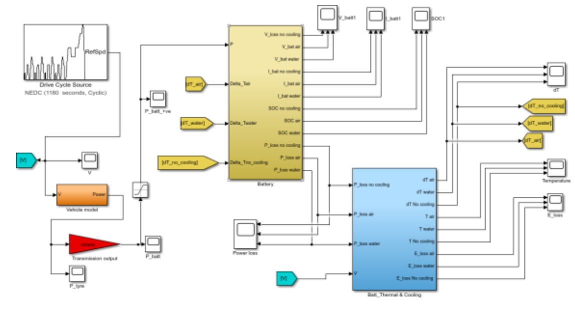
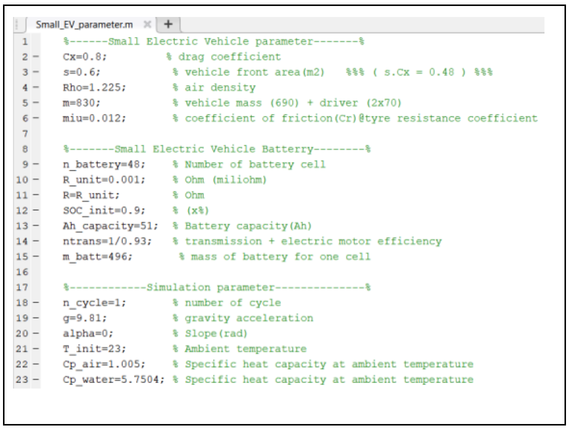


Figure 3: The working principle of EV and complete layout MATLAB/Simulink model



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%------Small Electric Vehicle parameter-------%
Cx=0.8;          % drag coefficient
s=0.6;            % vehicle front area(m2)   %%% ( s.Cx = 0.48 ) %%%
Rho=1.225;        % air density
m=830;            % vehicle mass (690) + driver (2x70)
miu=0.012;        % coefficient of friction(Cr)@tyre resistance coefficient

%-------Small Electric Vehicle Batterry--------%
n_battery=48;     % Number of battery cell
R_unit=0.001;     % Ohm (miliohm)
R=R_unit;         % Ohm
SOC_init=0.9;     % (x%)
Ah_capacity=51;   % Battery capacity(Ah)
ntrans=1/0.93;    % transmission + electric motor efficiency
m_batt=496;        % mass of battery for one cell

%------------Simulation parameter--------------%
n_cycle=1;        % number of cycle
g=9.81;           % gravity acceleration
alpha=0;          % Slope(rad)
T_init=23;        % Ambient temperature
Cp_air=1.005;     % Specific heat capacity at ambient temperature
Cp_water=5.7504; % Specific heat capacity at ambient temperature
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Figure 4: General parameter of simulation model

RESULTS AND DISCUSSION

New European Driving Cycle (NEDC)

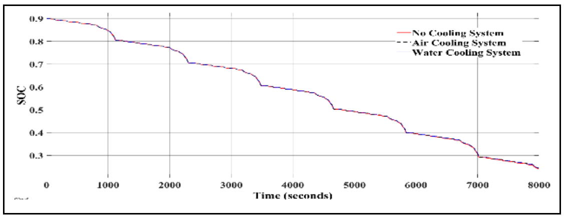

Figure 5: SOC of battery under NEDC analysis

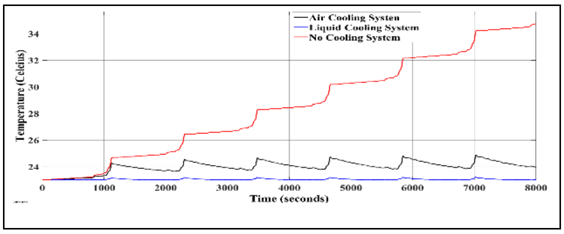

Figure 6: Battery temperature of different cooling system (NEDC)

By implementing the parameter from the Figure 5 in the model using NEDC driving cycle, it shows that the cycle number that can be achieved by the vehicle battery is 7 cycles as shown in Figure 5 where all the SOC under different cooling are slightly different for each other and the simulation was stopped at 8000 seconds due to the SOC reach at minimum point which 25% to prevent the damage occurred in the battery. For, Figure 6, the result show that the liquid cooling system is gentler in term of temperature rise during driving compare to air cooling system. The maximum temperature for each cooling system is 24.66 °C for the air-cooling system followed by 23.14°C for the liquid cooling system and for no cooling indicated 35.27 °C.

Worldwide harmonized Light-duty vehicles Test Cycle (WLTC) class 3

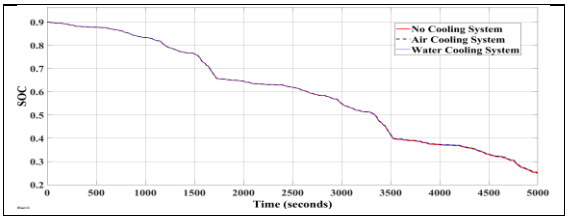

Figure 7: SOC of battery under WLTC analysis

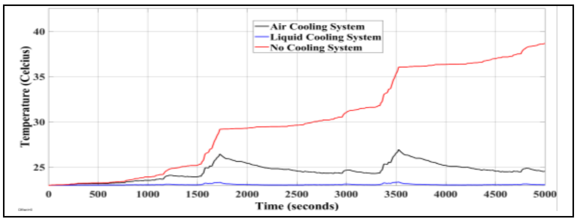

Figure 8: Battery temperature of different cooling system (WLTC)

Based on WLTC performance analysis, the Figure 7 shows that the cycle number that needs to reach minimum SOC value is approximately 3 cycles compare to NEDC analysis which is 7 cycle and the time stopped simulation at 5000 seconds. This is happened due to the WLTC class 3 has lot of discharge and charge process or accelerate and decelerate process during driving in 1 complete cycle. Therefore, the SOC for WLTC consume more power to move the vehicle and decrease the time operation compare NEDC. For, Figure 8, the result show that the liquid cooling system is the lowest for temperature rise during driving with maximum temperature 23.3°C compare to air cooling system with maximum temperature 26.3°C. Lastly, followed by no cooling system with maximum temperature 37.38°C.

Highway Fuel Economy Driving Schedule (HWFET)

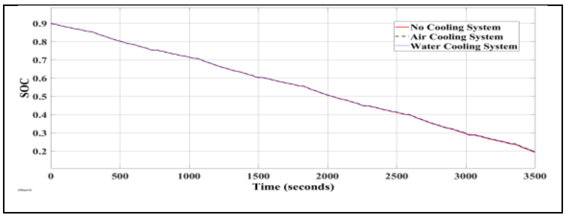

Figure 9: SOC of battery under HWFET analysis

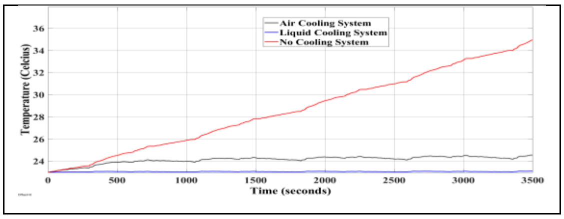

Figure 10: Battery temperature of different cooling system (HWFET)

For HWFET the time for SOC reach 25% from initial SOC, 90% is approximately 3500 second, the main reason why the HWFET has the lowest period for the SOC reach the minimum point compare to others driving cycle even though the time travel for WLTC that higher than HWFET is because of the speed travel under HWFET has higher average compare to WLTC which cause the SOC under HWFET drain more power from the battery. Therefore, HWFET only take about 4 to 5 cycles only for the SOC reach the minimum point as the Figure 9 illustrated. The result for HWFET almost have same pattern with other result from NEDC and WLTC load where the maximum temperature rising for liquid cooling system is 23.09℃ followed by air cooling system 24.4

℃ and 35.93℃ for the no cooling system as the Figure 10.

CONCLUSION

Modelling Vehicle dynamic Model

In this study, step-by-step analytical calculation of Electric Vehicle (EV) was presented in this paper. Based on the analytical calculation, EV was modeled in MATLAB®/Simulink® software. From the simulation result, the effectiveness of liquid cooling system is higher compare to air cooling system where liquid cooling system has more controlled the temperature rise which good in control of working temperature range for the LI-ion battery. In addition, this study found that the effect of charge and discharge of battery has impact the battery to produce more heat rejection as situation of under WLTC driving cycle. Besides that, SOC of battery can be affected by the speed traveling due high power drained by EV as the situation on HWFET where the high average speed causes the time period SOC reach minimum limit shorter compare to others driving cycle. Lastly, the result of the simulation obtained is close proximately with others researcher finding about cooling system in BTMS..

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REFERENCES

[1] *Mastanamma, Y., and M. Aruna Bharathi., 2017 "Electric Vehicle Mathematical Modelling and Simulation Using Matlab-Simulink", IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), 12.4, pp. 47-53*

[2] *Y. Muratoğlu and A. Alkaya, 2017 "Dynamic Modeling of Lithium-Ion Battery with Temperature Effect", European Journal of Technic, vol. 7, no. 1, pp. 1-7*

[3] *Soylu, S. 2011 "Electric vehicles: modelling and simulations", BoD–Book on Demand*

[4] *Larminie J., Lowry J. 2003 "Electric Vehicle Technology Explained", 1st edition, John Wiley & Sons Ltd, West Sussex, England*

[5] *Guzzella, L., & Sciarretta, A. 2005 "Vehicle propulsion systems–introduction to modeling and optimization", 2nd edition, Springer*

[6] *L. Zheng, L. Zhang, J. Zhu, G. Wang and J. Jiang, 2016 "Co-estimation of state-of-charge, capacity and resistance for lithium-ion batteries based on a high-fidelity electrochemical model", Applied Energy, vol. 180, pp. 424-434*

[7] *Bhide, S., & Shim, T. 2009 "Development of improved Li-ion battery model incorporating thermal and rate factor effects", IEEE Vehicle Power and Propulsion Conference, pp.544-550*

[8] *Gao, L., Liu, S., & Dougal, R. A. 2002 "Dynamic lithium-ion battery model for system simulation", IEEE transactions on components and packaging technologies, 25(3), 495- 505*

[9] *Fang, W., Kwon, O. J., & Wang, C. 2010 "Electrochemical–thermal modeling of automotive Li-ion batteries and experimental validation using a three-electrode cell", International journal of energy research, 34(2), 107-115*

[10] *"Engineering ToolBox", Engineeringtoolbox.com, 2021. [Online]. Available: https://www.engineeringtoolbox.com/. [Accessed: 19- Aug- 2021*

[11] *AME 60634: Intermediate heat transfer. (n.d.). https://www3.nd.edu/~powers/ame.60634/index1.html*

[12] *Patanwar, P., & Shukla, S. K. 2012 "Parametric studies of a hybrid desiccant cooling system", Int J Energy Eng, 2, 253-8*

[13] *C. POPIEL and J. WOJTKOWIAK, 1998 "Simple Formulas for Thermophysical Properties of Liquid Water for Heat Transfer Calculations (from 0°C to 150°C)", Heat Transfer Engineering, vol. 19, no. 3, pp. 87-101*

[14] Wikimedia Foundation. “Temperature dependence of viscosity”, Wikipedia.https://en.wikipedia.org/wiki/Temperature_dependence_of_viscosity.

[15] Guest. (n.d.). Thermal conductivity of air vs. temperature plot. pdfhall.com.https://pdfhall.com/queue/thermal-conductivity-of-air-vs-temperature plot_5b6b6fda097c47eb248b4614.html