Noble Evaporative Battery Thermal Management System for EVs/HEVs

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Abstract

EVs battery voltage changes significantly to meet the power demands while the car is in acceleration. Battery pack needs to generate a high output within a very short time to meet the power demand of the car at the time of momentary peak load. These peak load periods generate powerful electrical currents, causing significant warming of the Li-ion cells due to internal resistance causes internal cells damage. $LiFePO_4$ batteries, however, can be used efficiently only within a desired operating temperature in the range 25 to 35^{0}C. The battery operating temperature of 40°C and above, the battery life span is reduced. The rationale of this study is to develop an innovative evaporative battery thermal management system to control the battery temperature in the desired range in order to increase the battery life span and to improve the battery performance. Evaporative battery thermal management system for EV and HEV has been developed from this study with estimating the total cooling loads and thermal behavior of the cells of battery. Experimental results shows that the developed thermal management system able to keep battery temperature in the range of 25 to 35^{0}C both in charging and discharging.The performance of EV with EC-BThMS has been compared with the EVs with air cooling battery thermal management systems. The EV with EC-BThMS can save 17.69% more energy than the EV with AC-BThM 1 and 23% than the EV with AC-BThMS 2. Furthermore, Based on the performance result our developed EC-BThMS it could be concluded that the the presented EC-BThMS would be able to increase the battery life span by 31% and overall EV performance about by 15%.

Keywords
Thermal Management System, EV, $LiFePO_4$ battery, Evaporative Cooling; Thermal sensor and relay; Energy saving.

1. Introduction

Electrical Vehicle (EV) needs to be equipped with high power battery pack for traction, where the DC link voltage needs to change significantly according to load conditions. EV's electrical motor converts batteries energy into tractive energy. Batteries energy is developed with discharging the current by keeping the voltage constant. To charge and discharge the battery quickly whilst optimizing battery using requires perfect control of the battery temperature. To avoid premature aging of the temperature-sensitive lithium-ion cells, the Li-ion batteries need to be cooled. Hence, significant importance has been placed on thermal management of Li-ion battery cells to achieve the desired life span. There are different approaches for the management of temperature of Li-ion batteries such as air cooling and liquid cooling. Heat control and management is one of the most important issues in the lithium-ion batteries at high temperature or high charge/discharge rate will lower charge/discharge efficiency and lower the battery life, or even cause safety problem reported by [Xiangzhe and Hongbin (2005), Bernardi et al. (2005), Benjer et al. (2009), Wang et al.(2009), Chen and Evans (1994)]. Forgez *et al.*(2010) has studied on the thermal characteristics of a cylindrical LiFePO4/graphite Li-ion battery and developed a lumped thermal model based on experimentally achieved parameters. Dominko et al.(2005), Alhalaj et al. (2000), Kim and Kim (2007), Gao et al.(2011), Wong et al. (2010), Duan and Naterer (2010), and Thomas (2009) were studied on electrochemistry and structures of LiFePO4 material. They have reported that the Li-ion battery capacity drops seriously under low temperature. It drops about 17-22% when the battery cells temperature is -20^{0}C. The internal impedance is almost be constant when the temperature is 25^{0}C or up, but it will increase as the temperature drops. The internal impedance can reach 25% more when the temperature drops from 25^{0}C to -20^{0}C . Heat starts discharging between 40-72^{0}C and it will be more than 5 times when the temperature reaches 80-119^{0}C which leads to the decomposing of the solid electrolyte interface membrane. The anode material starts decomposing and reacting with the electrolyte under a higher temperature of about 172^{0}C . Furthermore, the researcher Pesaran (2001) reported that Li-ion battery performs better at temperature range of 50-60^{0}C, the battery life cycle would get shorter at temperature more than 60^{0}C. Sabbah *et al.*,(2008) and Kizilel *et al.*, (2009) were studied on air-cooling battery thermal management system. They reported that air cooling system is not a proper thermal management system to keep the temperature of the cell in the desirable operating range without expending significant fan power.

2. Mathematical Modeling

The heat generated into the battery cells during discharging/charging process due to: (i) electrochemical reaction, (ii) electric resistance inside the cell, and (iii) polarization resistance as energy is required for the diffusion and movement of atoms in the battery reaction reported by [Krüger et al (2009) and Bergveld (2001)]. The foregoing information includes generation factors; however, the magnitude of heat generated depends to a great extent on the chemistry type, state of charge/discharge profile and temperature of the cells. Total heat generated (Q_{gen}) inside a battery cell due to electrochemical reactions can be expressed by using the equation of Krüger et al (2009):

$$\dot{Q}_{gen} = \left(\frac{T_m \Lambda S_i}{nF}(i) + i^2 R_{tol}\right) \quad with\,\Delta S = \int_{T_\alpha}^{T_{bat}} \frac{C_p}{T} dT = C_P Ln \frac{T_{bat}}{T_\alpha} \tag{1}$$

Therefore, the equation (1) can be rewrite as,

$$\dot{Q}_{gen} = \left(i^2 R_{tot} + \frac{T_i}{nF} C_p i Ln\left(\frac{T_{bat}}{T_i}\right)\right) \tag{2}$$

with $nF = \dfrac{Q_T}{0.278(m_b)}(M_R)$

where, Q_T is the total capacity of the battery, n is the number of mole, M_R is the molar mass of the $LiFePO_4$ in C/mol, m_b is the total mass of the battery in kg. Molar mass of the $LiFePO_4$ is calculated as 157.76 g/mole by using the atomic weight of Li 6.99 g, Fe 55.85 g, P 30.97 g and O_4 64 g.

Total resistance (R_{tot}) of the battery pack is calculated as

$$R_{tol} = R_1 + R_2 + R_3 + \ldots\ldots\ldots\ldots + R_{13} = \sum_1^{13} n_m R_i \;;\; R_1 = R_2 \ldots\ldots = R_{13} \tag{3}$$

where, i is the current flow, F is the Faraday constant (9.64122×10^4 C.mol^{-1}) [Iqbal Hossain, 2003], T_{batt} is the battery temperature, ΔS donates the entropy change due to the changing of current and R is the total resistance of the battery. Convection heat transfer occurs from the surface of the battery modules to the coolant due motion of fluid (refrigerant) within the boundary layer of the modules and the heat removal can be expressed by the following equation:

$$Q_{conv} = hA_s(T_{bat} - T_\alpha) \tag{4}$$

where, h is termed the convection heat transfer coefficient, A_s is the area of the modules' surface, and T_∞ is the temperature of the cooling medium .While radiation heat transfer occurs between surfaces due to the emission and absorption of electromagnetic wave. Radiation heat transfer is complex when many surfaces at different temperatures are involved; however in the limit that a single surface at the temperature T_s interacts with surroundings at temperature T_∞ then the radiation heat transfer from the surface can be calculated according to Bergveld (2001)]:

$$Q_{rad} = A_s \sigma \varepsilon \left(T^4{}_{bat} - T^4{}_\alpha\right) \tag{5}$$

where σ is the Stefan-Boltzmann constant (5.67x10^{-8} W.m^{-2}.K^{-4}), and ε is the emissivity of the battery module's surface. Thus, energy outflow is due to convection and net radiation from the surface can be expressed as follows:

$$Q_{out} = \left(hA_s(T_{bat} - T_\alpha) + \frac{kA_s}{d}(T_m - T_a) \; + A_s \sigma \varepsilon \left(T_{bat}{}^4 - T_\alpha{}^4\right)\right) \tag{6}$$

From the First Law of Thermodynamics, the amount of energy stored in a control volume must equal the amount of energy that enters the control volume plus the energy generated within the control volume, minus the amount of energy that leaves the control volume. Thus, this statement can be written as;

$$Q_{st} = Q_{in} + Q_{gen} - Q_{out} \tag{7}$$

where, Q_{st} is the rate of energy increment stored within the battery cell, Q_{in} is the rate of energy transfer into the cell, Q_{out} is the rate of energy transfer out of the cell and Q_{gen} is the rate of energy generation.

It is assumed that there is no heat energy transfer ($Q_{in} = 0$) from cell to cell. Therefore, the overall energy balance on a battery module can be expressed as:

$$Q_{st} = Q_{gen} - Q_{out}$$

$$Q_{st} = \left(\frac{T_{bat} \Delta S_i}{nF} (\Delta i) + i^2 R \right) - \left(hA_s (T_{bat} - T_\alpha) + A_s \sigma \varepsilon \left(T^4{}_{bat} - T^4{}_\alpha \right) \right) \tag{8}$$

The changes in energy storage due to temperature change over time t can be expressed as:

$$Q_{st} = \frac{dU_t}{dt} = \frac{d}{dt}\left(\rho V c_p T \right) \tag{9}$$

where, Q_{st} is the internal thermal energy of the battery module, V is the volume of the module, ρ is the mass density and c_p is the specific heat capacity. The above overall energy equation used to calculate the average battery temperature T_{batt} over time can then be written as:

$$\frac{d}{dt}\left(\rho V c_p T \right) = \left(\frac{T_{bat} \Delta S_i}{nF} (i) + i^2 R \right) - \left(hA_s (T_{bat} - T_\alpha) + A_s \sigma \varepsilon \left(T^4{}_{bat} - T^4{}_\alpha \right) \right) \tag{10}$$

Therefore, by replacing the volume of the module (V) and the mass density of the battery module (ρ) by the mass of the battery (m_b) into the equation (10), the overall energy equation used to calculate the battery temperature T_{batt} can be expressed as follows:

$$\frac{dT_{bat(r)}}{dt} = \frac{1}{m_b C_p} \left[\left(\frac{T_{bat} \Delta S_i}{nF} (i) + i^2 R \right) - \left(hA_s (T_{bat} - T_\alpha) \right) \right] \tag{11}$$

Equation (11) can be written as;

$$T_{bat(r)} = T_{bat(initial)} + \frac{\Delta t}{m_b C_p} \left[\left(\frac{T_{bat} \Delta S_i}{nF} (i) + i^2 R \right) - \left(hA_s (T_{bat} - T_\alpha) \right) \right] \tag{12}$$

where Δt is the is the variation of battery temperature in degree Celsius. Power requirement of the vehicle is estimated by considering the vehicle dynamic on the different road conditions. A total power (P) need for the vehicle to propel on the road is calculated by using the equation:

$$P = \frac{\left[f_r W + \frac{\rho_a}{2} C_D A_f V^2 + W \sin\theta \right]}{1000} (V) \tag{13}$$

The vehicle is operated with induction motor which draws power from the battery pack to meet the load demands during startup, acceleration, coasting and cruising. A 96.5 volt rating motor is used for the propelling the car. The drawing current (I) of the motor can be estimated as,

$$I = \frac{\left[f_r W + \frac{\rho_a}{2} C_D A_f V^2 + W \sin\theta \right]}{1000 \times V_b \times \eta_m} (V) \tag{14}$$

where, V is the vehicle speed in km/h and V_b is the motor rating voltage in Volts and η_m is the motor efficiency.

3. Heat Generation into the Battery

The heat generated into the cells in both charging and discharging of the battery for electrochemical reactions with changing entropy and resistive heating with changing current. Figure 1 shows the heat generated into the cells during discharging without using the cooling system. For the vehicle speed of 120 $km.h^{-1}$, the heat would generate into the cells 900 W on 0% grade and 2420 W on 3.67% grade. While, for the vehicle speed of 60$km.h^{-1}$, the heat would generate into the cells 160 W on 0% grade and 380 W on 3.67% grade. The current for the corresponding heat, 160 W is 38 amp, 380 W is 90 amp, 900 W is 220 amp, and 2420 W is 335 amp. Figure 4 shows the battery temperature for 38 amp is 28^{0}C, 90 amp is in the range of 28-45^{0}C, 220 amp is in the range of 35 -95^{0}C; 335 amp is in the range of 48 -185^{0}C if the vehicle is powered by 84.6kWH battery pack. It is noted that the battery able to discharge current maximum 460 amp for 30 sec at 25^{0}C only. In real practice none of the vehicle power system is designed for the operation of 10 to 30 sec. Therefore, it is important to develop an effective battery cooling thermal management system to power the vehicle for longer time. Li-ion batteries can be used effectively within a certain temperature range: 20 to 40^{o}C. The operation of $LiFePO_4$ batteries at high temperature causes the battery cells to degrade rapidly and the performance and capacities are adversely affected. Heat generation of battery for different battery cycle has been shown in Figure 2.

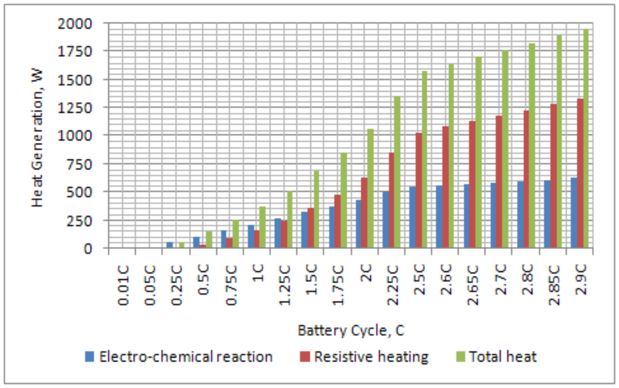


Figure 1 : Heat generation for the electrochemical reaction and resistive heating

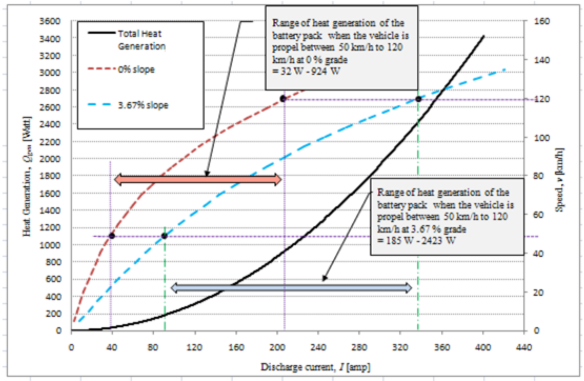
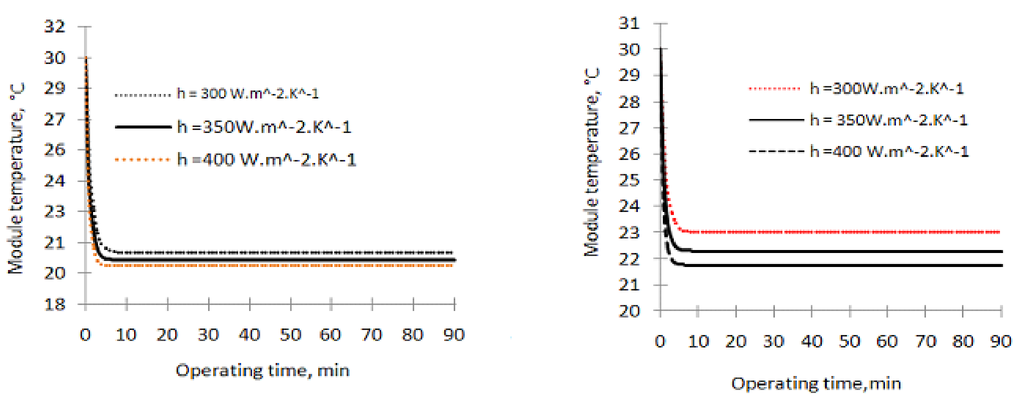


Figure 2: Battery cells heat generated without cooling

4. Performance of the Evaporative System: Theoretically

The on-board condition for a battery pack is very abominable. It works at fluctuant charging/discharging current to meet the vehicle dynamic load such as startup, acceleration, coasting, and etc. The temperature gets higher than static working condition. Synchronously, the interior heat transmission is worse than that of the surface, heat concentrate in the interior and the battery pack thermal field is asymmetric. As a consequent, the variety of each cell's internal impedance, capacity and voltage get higher. Heat generations of the battery's module are considered as 100 W, 200 W and 300 W while, the heat transfer coefficient (h) for the thermal management system are considered as 300, 350 and 400 W.m^{-2}.K^{-1} for the simulation of the evaporative thermal management system. Figure 3 for the heat generation of 100 W and 20 minutes vehicle operation, the result shows that the module temperature decrease gradually from 30°C to 20.2^{0}C, 30^{0}C to 20.5^{0}C and 30^{0}C to 20.8^{0}C for the h value of 400 W.m^{-2}.K^{-1}, 350 W.m^{-2}.K^{-1} and 300 W.m^{-2}.K^{-1}, respectively. Figure 3(b) for heat generation of 200 W and 20 minutes operation, the result shows that the module temperature will increase from 30°C to 24°C, 30°C to 25 ^{0}C and 30°C to 26^{0}C for the h value of 400 W.m^{-2}.K^{-1}, 350 W.m^{-2}.K^{-1} and 300 W.m^{-2}.K^{-1}, respectively.



(a) Q=100 W (b) Q=200

Figure 3: Evaporative battery thermal management system

4. Evaporative System Development

Figure 4 is our developed evaporative cooling system for an electrical vehicle's battery pack of 84.6 kWh. The shell of the battery cooling thermal management system is made with aluminum alloy with the density of 1636 $kg.m^{-3}$, specific heat capacity (C_p) of 1.377 $kJ.kg^{-1}.K^{-1}$, and heat conductivity (k) of 0.427 $W.m^{-1}.K^{-1}$. Our developed cooling system is automatically operated with the response of the thermocouples. It starts when the internal battery module temprature is more than 40^0C and stop until the temperature goes down to 25^0C. While, the evaporator or cooling duct is fabricated by using copper for its excellent thermal conductivity of 394$W.m^{-1}.K^{-1}$ and non-magnetic properties which is considered for our evaporative cooling duct for rapid heat transfer and to maintain the battery temperature in the range of 25 – 40^0C.

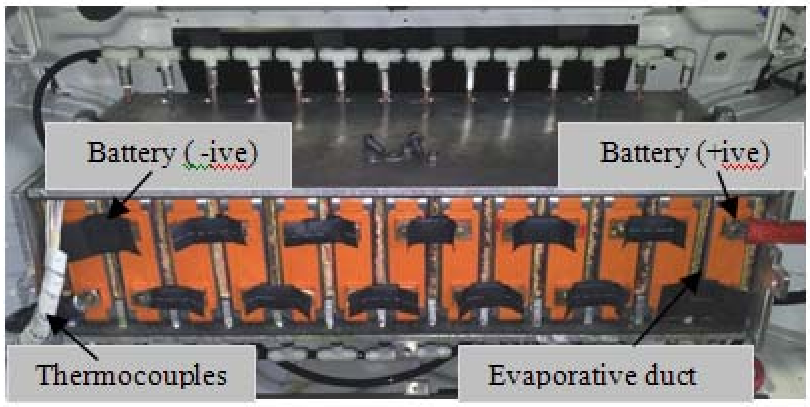
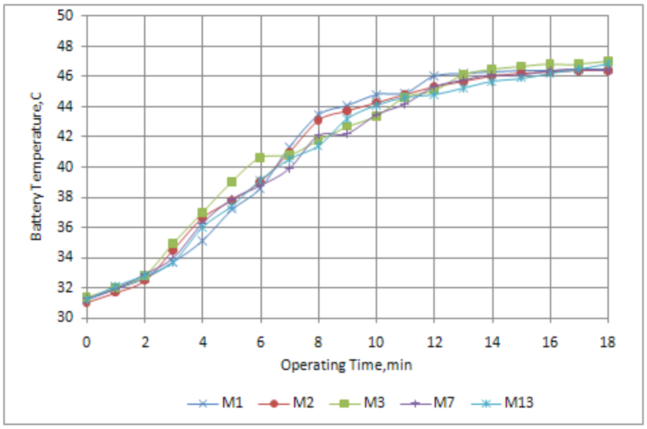


Figure 4: Evaporative Cooling System

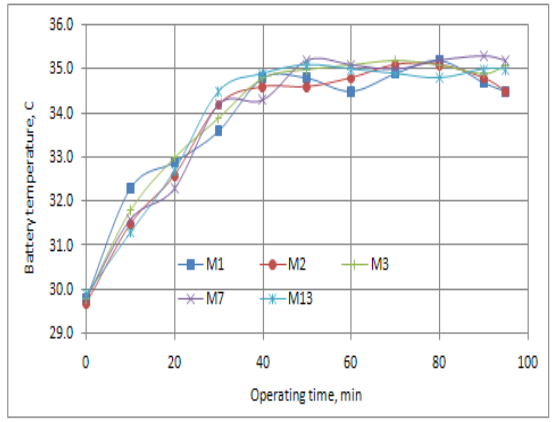
The evaporative duct is provided with an intake port located at the bottom of each module and an exit port at the top. The intake port is used to deliver the low pressure liquid refrigerant to the inside of the evaporative duct and exit port is used to suck the heated refrigerant from the evaporative duct. This cooling system cools the battery pack by a direct refrigerant-based evaporative cooling. Heat generated from the battery is absorbed by the evaporating refrigerant inside the cooling duct and then dissipate heat to the surrounding air at the condenser. This process turns the refrigerant from low pressure liquid to low pressure vapor. The evaporator or cooling duct is connected in parallel to the main refrigerant circuit. The most common working fluid for refrigeration 'R134a' is used as the medium of heat transfer. The liquid regrigerant in the evaporative ducts absorb heat from the modules and keep the temperature of the battery modules in the desired range of 25 to 40^0C.

5. Performance of the Evaporative System - Experimentally

Three different cooling systems vehicle has been tested on the Sepang F1 circuit of Malaysia as shown in Figure 5, for identifying the vehicle performance and energy efficiency. The developed EV's was evaporative cooling battery thermal management system (EV EC-BThMS) and others two electric vehicles (EVs) were air cooling battery thermal management system (AC-BThMS 1 and AC-BThMS 2). The air cooling system has been made of AC-BThMS 1 with 8 fans of each 20 W and AC-BThMS 2 with 12 fans of each 20 W.



(a) Travelling distance 11.4 km with speed 120km/h



(b) Traveling distance 69km with speed 60km/h

Figure 5: Battery temperature of the EV with EC-BThMS

Performance Investigation of EVs has been conducted by operating in three different modes: ¼ mile acceleration; 11.4 km distance traveling with maximum speed of 120 km/h; and farthest distance with maximum distance of 60 km/h. For the farthest distance operation vehicle was ran until the battery voltage cut-off of 78 volts. The EV of evaporative cooling system was able to travel ¼ mile in 22 sec, 11.4 km travel in 17 min, and maximum distance travel 69 km with maximum speed of 60 km/h. Figs.5 show the evaporative cooling thermal management system performance. Fig. 5(a) indicates that the temperature of the module increases with increasing the discharge battery current to meet the speed of the test EV 120 km/h. The battery temperature spike to maximum 47^{0}C for discharging current of 120 amp. Fig. 5(b) shows that the battery temperature increases with increasing the battery discharge current to reach the test EV speed of 60 km/h with discharging maximum current of 80 amp. The cooling system was not activated as the temperature was less than 40^{0}C. The energy efficient of this developed electric vehicle evaporative cooling battery thermal management system (EV EC-BThMS) has been compared with two other electric vehicles (EVs) of air cooling battery thermal management system (AC-BThMS 1 and AC-BThMS 2). Table 1indicates that the EV with EC-BThMS can save 17.69% more energy than the EV with AC-BThM 1 and 23% than the EV with AC-BThMS 2. This is because the potentiality of the EC-BThMS which was able to maintain the temperature in the range of 25-40^{0}C. The result of Table 2 shows that the EV with EC-BThMS can save 25% more time than the EV with AC-BThM 1 and 23% than the EV with AC-BThMS 2 for the ¼ mile acceleration; 20.21% more time than the EV with AC-BThM 1 and 21.28% than the EV with AC-BThMS 2 for the 11.4 km distance travelling.

Table 1: Performance of the evaporative cooling over air cooling battery thermal management system of EV

EV Type	Performance Measurement Mode				
	¼ Mile Acceleration (sec)	Two laps (11.4 km) traveling time, (min)	Max. Velocity (within 2 laps) (km/h)	Farthest Distance (km)	Energy saving of developed EV over tested EV (%)
EV with EC-BThMS	22	17:15	119	68.62	-
EV with AC-BThMS 1	51	26:51	119	59.94	17.69
EV with AC-BThMS 2	25	26:19	91	57.75	23%

6. Conclusion

The main role of a battery cooling system is to ensure that the battery temperature can be controlled and maintained within a certain range, thereby improving the battery performance and lifetime of use. Two-phase evaporative cooling for the battery cooling system of EVs and HEVs should be more widely researched in the near future as the use of two-phase material (refrigerant) as a heat transfer medium is very effective in maintaining the battery temperature whether during charging or discharging condition, because of its higher heat transfer coefficient. In the battery cooling system using liquid (either coolant or refrigerant) as a medium of heat transfer, the most important matter that needs to be stressed or paid attention is to ensure no leakage from the system, whereby any leakage from the system can cause electric short circuit, and in severe case will lead to a car fire.

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Biography

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