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Review on Battery Thermal Management System for Electric Vehicles

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Abstract-The lithium-ion batteries are widely used for electric vehicles due to high energy density and long cycle life. Since the performance and life of lithium-ion batteries are very sensitive to temperature, it is important to maintain the proper temperature range. In this context, an effective battery thermal management system solution is discussed in this paper. This paper reviews the heat generation phenomena and critical thermal issues of lithium-ion batteries. Then various battery thermal management system studies are comprehensively reviewed and categorized according to thermal cycle options. The battery thermal management system with a vapor compression cycle includes cabin air cooling, second-loop liquid cooling and direct refrigerant two-phase cooling. The battery thermal management system without vapor compression cycle includes phase change material cooling, heat pipe cooling and thermoelectric element cooling. Each battery thermal management system is reviewed in terms of the maximum temperature and maximum temperature difference of the batteries and an effective BTMS that complements the disadvantages of each system is discussed. Lastly, a novel battery thermal management system is proposed to provide an effective thermal management solution for the high energy density lithium-ion batteries.

Index Terms-Battery thermal management Lithium-ion battery Vapor compression cycle Next generation battery

1. INTRODUTION

Interest on electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) has significantly increased, as environmental regulations on greenhouse gas (GHG) emission have been strengthened. The fundamental challenge for EVs is to find an appropriate energy storage system that can support high mileage, fast charging and high-performance driving. Recently, rechargeable lithium-ion (Li-ion) batteries are regarded as the most suitable energy storage device for EVs because of their higher energy density, higher specific power, lighter weight, lower self-discharge rates, higher recyclability and longer cycle life than other rechargeable batteries such as lead-acid, nickel–cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) batteries. They also have the advantage of no memory effect.
Pesaran (2002) and Pesaran et al. (2013) suggested that the operating temperature range should be kept between 15°C and35°C and the maximumtemperature difference (ΔTmax) from module to module should be below 5°C to avoid adverse effects of Li-ion batteries. Then they briefly reviewed and classified BTMSac cording to the heat transfer mediums: air, liquid and phase change material (PCM). Especially, they focused on BTMS using PCM and in vestigated the thermo-mechanical behaviors and heat transfer enhancement of the PCM to apply properly in BTMS. They also conducted a comprehensive trade-off analysis of BTMS following analysis of Cosley and Garcia (2004). Later, Pan et al. (2016) reviewed in more detail on the way to improve the low thermal conductivity of PCM. similar to Rao and Wang (2011), they reviewed BTMS by classifying them as air, liquid, PCM, heat pipe and combinations of them according to heat transfer mediums.

2. BATTERY THERMAL MANAGEMENT SYSTEM

2.1. Thermalmodelandissues

The battery is the most important part of EVs, repeating a number of charge and discharge cycles in an external environment during its lifespan. Li-ion batteries' performance is closely related to temperature, so it is important to understand how heat is generated inside the battery . Heat generation inside the Li-ion batteries is a com plex process that requires an understanding of how the rate of electro chemical reaction changes with time and temperature and how current f lows in the battery. According to Thomas and Newman (2003), Li-ion cells are known to generate heat by the reversible entropy, resistive dissipation, relaxation of the concentration gradient of the cell and chemical reaction. Simply, heat generation of the battery is pre sented by Gu et al.
Q, I, U and V respectively represent the heat generation rate, the electric current passing the cell, the open-circuit voltage and the cell voltage of the Li-ion batteries. The first term on the right side of the equation is about the resistance loss in the cell and the second term is related to the reversible entropic heat in the electrochemical reaction.In the above mentioned studies, Li-ion batteries generally generate three types of heat during charging and discharging activation irreversible heat due to the electrochemical reaction polarization joule heating causing ohmicloses andreversible reaction heat due to entropy change during chargeanddischarge. The battery capacity decreases because the active material inside the battery is converted to an inactive phase and battery power is reduced because of the increase in impedance. battery capacity decreases as the cycle repeats when the temperature Is above or below the proper operating temperature. .Thermal runaway is a phenomenon that can lead to destructive consequences such as rapid temperature rise, gas generation and even battery explosion as the process of temperature increase is accelerated. .In addition to the problem of temperature non-uniformity and rapid rise, energy and power cap abilities of Li-ion battery significantly decrease when operating at low temperatures .The causes of performance reduction of Li-ion batteries at low temperature s are generally known as solid electrolyte interface film, surface charge transfer impedance and lithium solid diffusion in electrodes
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2.2. Phase change material cooling system

ThePCMisamaterialthataccumulatesoremitsheatbyusingaprocessofchangingfromonestatetoanotheratacertaintemperature.Thishasbeenwidelyusedinmanyindustriessuchascivilandenergyengineeringbecauseitcanabsorborreleaselargeamountsofheatthroughphasechangeprocesseswithoutenergyconsumption.Inrecentyears,astheenergydensityandloadofbatterieshaveincreased,BTMShasbeenusingapowerfulcoolingsystemthatusesmanychannelsofliquidcoolingloops.However,suchasystemhasdisadvantagesthatthecomplexityofthesystemincreasesandthepowerconsumptionofthecompressorincreases.OnewaytomitigatethesedisadvantagesisthePCMcoolingsystem,.thecellsaredirectlyattachedtothePCM,whichisgenerallyasolidmaterialblockmachinedormoldedsothatthecellscanbeinserted.TherearealsotwoplatesonthetopandbottomorrightandleftsidesofthePCMtoreleasetheheatabsorbedbythePCM.Whenthebatteryischargedordischarged,heatisgeneratedinthecells,andthisheatistransferredtothePCM,whichisindirectcontactwiththecellsduetotheconductionphenomenondependingonthetemperaturedifference.PCMfirstabsorbsheatassensibleheat,andthenabsorbsalargeamountoflatentheatuntiltheendofthephasechangeprocessataconstanttemperaturewhenitfinallyreachesthemeltingpointasthetemperaturegraduallyrises.Thismeansthatitcancopewiththedrasticthermalloadofthebatterywithoutabnormaltemperaturerisingandsignificanttemperatureunevenness.However,whenonlyPCMisusedasBTMS,itisdifficulttooperatecontinuouslyifthePCMiscompletelymeltedduetohotweatherorcontinuouscharge/dischargecyclesofthebattery.Therefore,additionalcoolingsystemsthatreleasetheheatofthePCMtotheoutsideareessentialandveryimportant.AlthoughincreasingthePCMmasshasthebenefitofdelayingthephasechangecompletiontime,itwillnotbeabletoreduceenergyconsumption,whichisimportantforusingPCM,becauseitincreasestheweightandreducesEVperformance.So,theappropriatePCMmassmustbedetermined.AnotherimportantfactortobeconsideredintheapplicationofPCMtoBTMSistoselecttheappropriatePCM.TheproperPCMshouldhavecharacteristicsofhighlatentheat,highheatcapacity,highthermalconductivityandphasechangetemperaturewithintheoperatingrangeofthebattery.Moreover,thePCMshouldbechemicallystableandnontoxicwithlowornosub-coolingeffectinthefreezingprocess.Comprehensively,paraffinisconsideredthemostsuitablematerial,butithasafataldisadvantageofhavingalowthermalconductivitysimilartomostPCM's.Thismeansthatitisslowtorespondtohighdemandapplications.Therefore,therehavebeenmanystudiestoimprovethethermalconductivityofPCMwithoutsignificantlyaffectingthegoodcharacteristics.TherearethreemethodsforimprovingthethermalconductivityofPCM:addingthermallyconductivematerialsuchascarbon-nanopowder,addingmetalfins,addingporousmaterialsuchasanexpandedgraphitematrix(EGM).StudiesonthesemethodswerereviewedindetailbyPanetal.(2016).Despiteeffortstoimprovethelowthermalconductivityproblem,PCMisstil ldifficulttoapplytoautomotiveBTMSduetoproblemssuchasleakage,poormechanicalpropertiesandlowsurfaceheattransferbetweenthePCMandtheexternalenvironment.

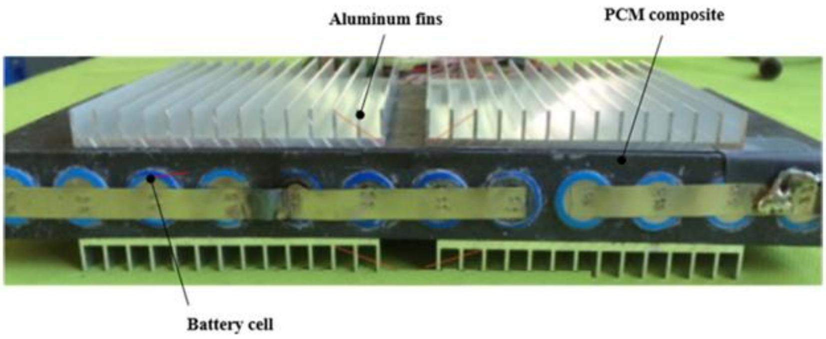


Fig 2.2. Schematic diagram of the BTMS consisting of LDPE/EG/paraffin composite PCM with batterycells and aluminum fins

2.3 Heat pipe cooling system

The PCM cooling system mentioned above was able to lower the temperature of the battery without consuming energy due to the use of latent heat, but due to its low conductivity which results in inadequate temperature gradients and longtime response, it has difficulties to apply to BTMS. There have been many efforts to improve the thermal con ductivity of many PCMs, but volume changes during the re-solidification process are difficult to manage. As a way to overcome these dis advantages, thermal management of the battery using a heat pipe may be a promising alternative. A heat pipe is a device that can operate spontaneously without external pumped power and transport large amounts of heat energy at considerable distances with high speeds utilizing phase-change heat transfer even at very small temperature differences. It also has features such as compact structure, flexible geometry, long lifetime and low maintenance, so that this has used in many industries for efficient thermal management . However, the heat pipe is not yet applied to the main purpose of actual EVs BTMS because of their low capacity and efficiency and small contact area. The structure of the heat pipe consists of only an airtight container and a working f luid. In detail, it is composed of an evaporator section, an adiabatic section and a condenser section. The evaporator section is attached to a heat source that needs cooling. The working fluid in a heat pipe evaporates by absorbing heat from the heat source and then moved to the condenser section through the adiabatic section due to the difference in internal pressure of the container. In the condenser section, the working f luid condenses through external heat exchange. After that, it has be come liquid and moves back to the evaporator section by the capillary force of the wick. There are various kinds of methods in which the working fluid returns from the condenser section to the evaporator section depending on the driving force. This series of processes can be repeated without external energy consumption. a schematic diagram of the heat pipe cooling system. Heat pipes are usually complex in shape, but in this figure, flat heat pipes are re presented for simplicity. The heat pipes contact with the battery cells in order to cool the heat of the cells by conductive heat transfer.

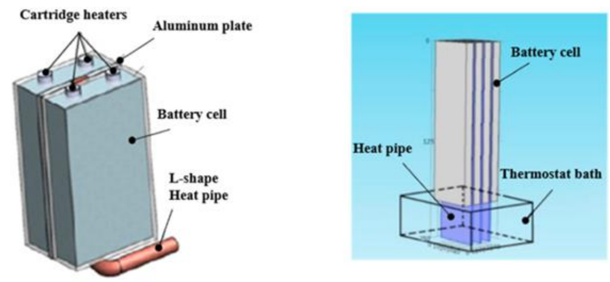


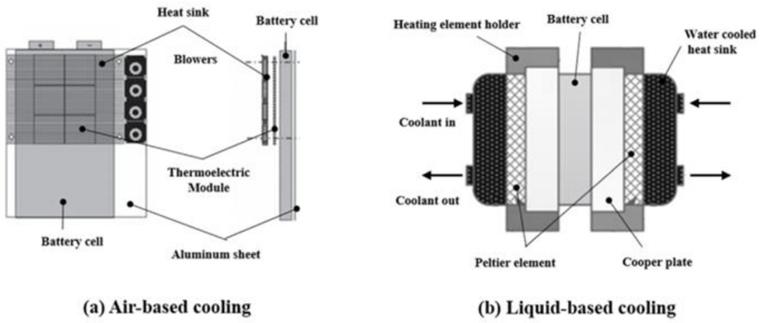
Fig 2.3 Schematic diagrams of heat pipe cooling system

2.3 .Thermoelectric element cooling system

Research and development of thermoelectric element over the past decade has received much attention due to their potential applications in environmentally friendly energy and energy management. Thermoelectric element applications can be divided into two different groups. One is the thermoelectric generator (TEG) based on the Seebeck effect to convert heat into electricity to use waste heat as an energy source. The other the thermoelectric cooler (TEC) based on the Peltier effect to convert electricity into thermal energy to provide cooling and heating for a variety of items. TEC is already used in the field of automotive applications such as the climate control of EVs and the cooling and heating of luxury automobile seats. Therefore, it can also be applied to BTMS. TEC consists of a matrix of p-type and n-type semiconductors alternately between two thin ceramic wafers and uses the Peltier effect to create a heat flux between the junction of two different types of conductors by passing the current through the circuit consisting of the matrices . A simpli f ied schematic of the thermoelectric element cooling system using TEC is shown in Fig. 2(g). The top side of the TEC (cold end) is attached to the battery and the bottom side (hot end) is connected to the cooling plate through which a heat transfer medium such as air or liquid flows. When TEC is supplied with direct current (DC) from the power supply system, heat generated from the battery is transferred from top side to the bottom side, so that the top side gets colder and the battery cools down. The system can also heat the battery by reversing the direction of the DC to the TEC. Thus the thermoelectric element cooling system can control the temperature of the battery to an appropriate level by ad justing the direction and amount of the supplied DC. This system ty pically has the advantages of compact size and moderate weight, low maintenance effort, wide operating temperature range, high reliability, no mechanical moving parts, noiseless and long life. Despite the 206 Applied Thermal Engineering 149 (2019) 192–212 J. Kim et al. advantages mentioned above, due to the low efficiency of the Peltier process, realistic application and research on automotive BTMS are not actively pursued.

A few studies on this system have been categorized and reviewed according to the fluid flowing through the cooling plate attached to the hot end. Studies using air as a fluid are as follows. Alaoui (2013) pro posed BTMS using TEC combined with forced air cooling. which shows one cell unit in a 48-cell battery-cell thermal management system, they mounted six TEC modules coupled with the extruded heat sink on the surface of a 60Ah Li-ion pouch cell and screwed the cell onto the aluminum plate for mechanical support. In addition, they constructed four blowers next to the heat sink to discharge heat from the battery to the outside. Their proposed BTMS was evaluated for the energy consumption to maintain the proper temperature of the battery and coefficient of performance (COP) under 3C constant discharge current conditions and US06 drive cycle conditions. According to the research results, the proposed BTMS consumed 919 Wh to reduce the pack temperature from 57.6°C (temperature when there is no BTMS) to 46.8°C under 3C discharge conditions and 317 Whinthe drive cycle condition to lower 8.82°C at the temperature without BTMS. In addition, the COP is about 0.9 for the constant cur rent test and about 1.2 for the drive cycle. Esfahanian et al. (2013) have proposed a new way to improve air-cooled thermal management with the help of thermoelectric because air-cooled cooling does not effectively cool the battery at high discharge rates and under abusive con ditions such as high operating temperatures or ambient temperatures . They proposed a system that was numerically analyzed using a three-dimensional CFD model. Simulation results show that under high charge/discharge rate and ambient temperature above 40°C, the bat tery temperature can be kept below 35°C and the cell temperature difference below about 6°C. On the other hand, studies using liquids to cool the hot end of TEC are as follows. Liu et al. (2014) proposed a new BTMSusing TEC combined with liquid cooling .

They developed a thermal model of a Li-ion battery and TEC and calibrated the model through experiments. In the proposed BTMS, the cold end of the TEC is attached to the battery cells to absorb their heat, and the hot end is attached to the water jacket to transfer heat. They firstly developed a thermal model of TEC and battery, then analyzed the cooling performance of the proposed system applied to the battery pack consisting of eight cells with 100Ah capacity. Simulation results at 1C discharge conditions showed that the TEC cooling allowed the battery tempera ture to remain below 40°C and the average temperature difference between battery cells was less than 1°C. These results are much better than cooling without TEC. However, the TEC has a small contact area between the batteries, which increases the uneven temperature in the battery cell. To overcome these problems, they argued that it can be overcome by inserting a high conductivity material between the TEC. Troxler et al. (2014) studied the effect of artificially induced tempera ture gradient on cell performance . They used TEC to induce and maintain the temperature gradient of the Li-ion battery at isothermal and non-isothermal conditions,



not battery cooling. However, their experimental setup shows how to apply the TEC to cool the battery. One side of the TEC is in contact with the copper plate to increase the contact area with the battery cell and the other side is attached to the heat sink through which the cooling water flows to discharge the heat transmitted by the copper plate.

Fig 2.3. Schematic diagrams of thermoelectric elements cooling

3. Conclusion

Although BTMS without the VCC is not widely applied to actual EVs, it still has a great potential in terms of energy consumption andthermal performance. The PCM cooling systems are capable of absorbing a large amount of battery heat at the same temperature in a phase change process with little or no energy consumption. However, this system has problems in coping with the low thermal conductivity of PCM, continuous battery heat load after completion of phase change of PCM, leakage of PCM, volume change and inhomogeneity of the whole module in repeated melting/solidifying processes. The heat pipe cooling system can transfer heat more efficiently due to the higher thermal conductivity of the heat pipe than general PCM, but it is reto combine with a cooling plate because of the limited contactarea with the battery.Thermoelectric element cooling system can control the temperature of the battery precisely by controlling the amountanddirectionofthecurrentintheTEC.However,sinceitsefficiencyisverypoor,in-depthstudieshavenotbeenconductedyet.AsaresultofreviewingvariousBTMS,itwasfoundthatthecomparisonofeachsystemwasnotdirectlycomparableduetothedifferenceoftype,capacity,andoperatingconditionsofthetestedbatteries.However,theadvantagesanddisadvantagesofeachsystemwereidentified.Therefore,inordertodevelopamoreeffectiveBTMS,itiscrucialtoselectanappropriateBTMSdependingonthepurposeoftheEVandcombiningvarioussystemstocompensateforthedisadvantages.Inthefuture,thermalloadoftheEVbatteriesisexpectedtoincreaseduetotheincreasedenergydensityofthebattery.Therefore,theBTMSwillbedevelopedtointegrateseveralBTMSoptions,suchasthedirecttwo-phaserefrigerantcoolingwiththePCM,heatpipeandthermoelectricsystems.

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