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Modeling thermal management of lithium-ion PNGV batteries

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Abstract

Batteries were designed with the aid of a computer modeling program to study the requirements of the thermal control system for meeting the goals set by the Partnership for a New Generation of Vehicles (PNGV). The battery designs were based upon the lithium-ion cell composition designated Gen-2 in the US Department of Energy Advanced Technology Development Program. The worst-case cooling requirement that would occur during prolonged aggressive driving was estimated to be 250 W or about 5 W per cell for a 48-cell battery. Rapid heating of the battery from a very low startup temperature is more difficult than cooling during driving. A dielectric transformer fluid is superior to air for both heating and cooling the battery. A dedicated refrigeration system for cooling the battery coolant would be helpful in maintaining low temperature during driving. The use of ample insulation would effectively slow the battery temperature rise when parking the vehicle in warm weather. Operating the battery at 10 °C during the first several years when the battery has excess power would extend the battery life.

Keywords: Lithium-ion; Battery modeling; Thermal modeling; Lumped-parameter model; PNGV Battery; Hybrid electric vehicle

1. Introduction

The control of temperature for a battery in a hybrid electric vehicle (HEV) is not difficult under most conditions. If extremes in the weather temperature are avoided and the battery is not frequently pressed to perform near its performance limits, the battery may give many years of useful service. For HEVs to be sufficiently attractive to garner a significant fraction of the vehicle market, however, the Partnership for a New Generation of Vehicles (PNGV) has set several difficult standards for the operation of hybrid vehicles that indirectly set a high standard for the battery thermal control system. The PNGV was established by the US Government and the US Council for Automotive Research (USCAR) in 1993 to develop new fuel-efficient automobiles.

A companion paper [1] to this paper discusses modeling of lithium-ion battery performance for the PNGV HEV application. In that paper, five batteries are designed for a power-assist HEV with varying ratios of the voltage at full power to that at full regenerative braking power. The spreadsheet program for the performance modeling in that paper [1] also has sheets on thermal modeling, which is a source for this paper. The goals for the PNGV batteries, Table 1, are from the PNGV Test Manual [2].

2. Battery design

The batteries designed for this study are based upon the lithium-ion system being studied by the US Department of Energy (DOE) in the Advanced Technology Development (ADT) Program. The compositions of the materials in this system have been designated Gen-2 and consist of a positive electrode material of $LiNi_{0.8}Al_{0.05}Co_{0.15}O_2$ (8% PVDF binder, 4% SFG-6 graphite, 4% carbon black) and a negative electrode of MAG-10 graphite (8% PVDF binder) with an electrolyte of 1.2 M $LiPF_6$ in EC:EMC (3:7) and 25-mm-thick PE Celgard separators. Quallion, LLC fabricated 165 cells of the 18650 size with electrodes of this composition for testing at Argonne National Laboratory, Idaho National Laboratory, and Sandia National Laboratory. In the tests at Argonne [1], the area-specific impedances were determined for charge and discharge in hybrid pulse power characterization (HPPC) tests [2] and values were determined for the lumped-parameter battery model [3]. The input parameters for the spreadsheet program for designing the batteries were based on the results obtained in the tests of the 18650 cells and for the same cell compositions and layer thicknesses as in those test cells [1].

The battery design study was conducted using a spreadsheet program that designs five batteries simultaneously with cells of the configuration shown in Fig. 1. The cell design for these batteries is based on winding the electrodes and separators around a core consisting of a polymer sleeve

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Table 1
PNGV energy storage system performance goals

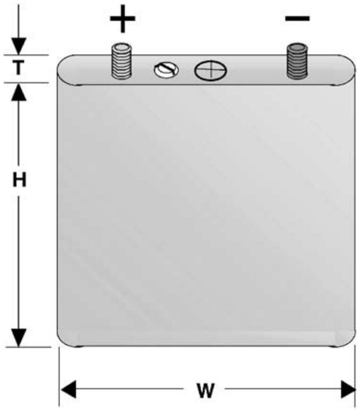
Characteristics	Units	Power assist	Dual mode
Pulse discharge power	kW	25 (18 s)	45 (12 s)
Peak regenerative pulse power	kW	30 (2 s)	35 (10 s)
		Min 50 Wh over 10 s regenerative total	97 Wh pulse
Total available energy (over DOD range where power goals are met)	kWh	0.3 (at C/1 rate)	1.5 (at 6 kW constant power)
Minimum round-trip energy efficiency	%	90	88
Cold cranking power at −30 °C (three 2 s pulses, 10 s resets between)	kW	5	5
Cycle-life, for specified SOC increments	Cycles	300,000	3750
		Power assist cycles (7.5 MWh)	Dual mode cycles (22.5 MWh)
Calendar life	Years	15	15
Maximum weight	kg	40	100
Maximum volume	l	32	75 (at 165-mm max height)
Operating voltage limits (note: maximum current is limited to 217 A at any power level)	Vdc	Max $\leq$ 440, min $\geq$ (0.55 $\times$ V_{max})	Max $\leq$ 440, min $\geq$ (0.5 $\times$ V_{max})
Maximum allowable self-discharge rate	Wh per day	50	50
Temperature range			
Equipment operation	°C	−30 to +52	−46 to +66
Equipment survival		−30 to +52	−46 to +66

0.5 mm thick and 4 mm across. The input parameters for the five batteries were identical except that the number of cell windings in the cells was increased for each succeeding battery to study the effect of this variable on the dimensions, weight, and performance of the batteries. The area of the cell electrodes and the capacity of the cells varied with the number of cell windings. The net effect of increasing the number of cell windings on the battery power density and the ratio of the voltage at full power to that at full regeneration power is shown in Fig. 2. A module was designed that contains 12 cells in series connection (Fig. 3). Spacers provide a 1-mm-wide flow space between the cells. The batteries were designed to consist of four modules (48 cells total in series connection) with sufficient space for connections and flow passages and 12-mm-thick exterior insulated walls with 1-mm-thick aluminum sheet on the inside and outside surfaces.

Greater detail on the cell and battery design and the electrical performance calculated for these batteries is provided in [1]. The thermal performances of these batteries, the main topic of this paper, were calculated on a separate sheet of the same spreadsheet. Some of the parameters for the first, third, and fifth of these batteries are shown in Table 2.

3. Thermal design

The goals set by PNGV (Table 1) directly and indirectly affect the thermal management system for the battery. Whereas the battery must be capable of delivering 25 kW of power during normal driving, only 5 kW is needed for a cold start at −30 °C. It follows that the battery must be heated rapidly from −30 °C to a temperature at which it can



Dimensions, mm

	Unit 1	Unit 3	Unit 5
Thickness	15	19	24
Width	100	100	100
Height	110	110	110

Fig. 1. Flat-wound lithium-ion cell design.

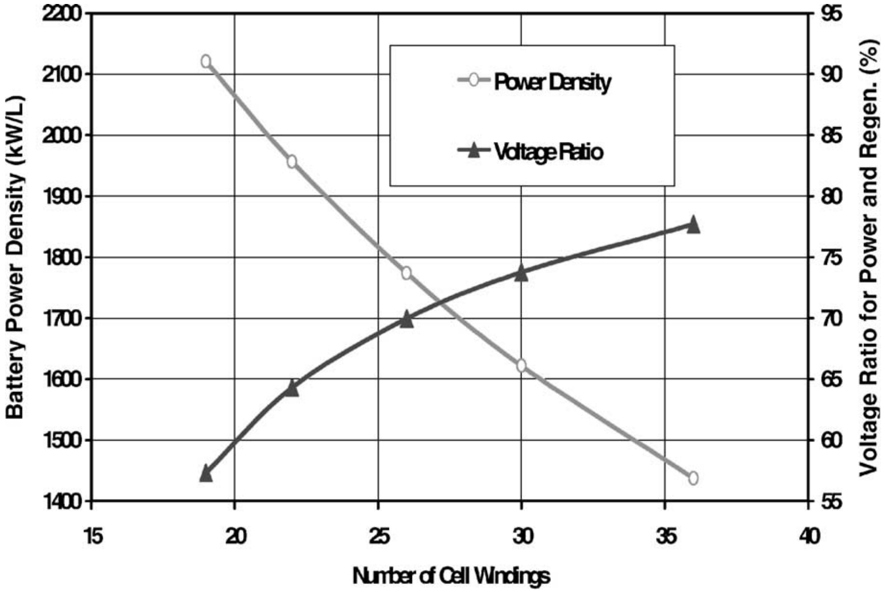


Fig. 2. Effect of number of cell windings on battery power density and ratio of battery voltages for full discharge power and regeneration power, using Gen-2 lithium-ion flat-wound cells, 100 mm cell width, 110 mm cell height.

deliver the full rated power. At the other end of the temperature range, the battery must be maintained <52 °C while it is being operated. As a result, if air is used as the coolant in warm climates, the temperature rise of the air flowing through the battery and the temperature difference between the air coolant and the center of the cells must be small. If the battery temperature is allowed to rise to as high as 66 °C while the vehicle is in standby (Table 1), it would be difficult to cool it to 52 °C before starting the vehicle or soon thereafter. It may be easier to prevent the battery temperature from rising above the maximum operating temperature of 52 °C even during standby. Finally, the goal of a calendar life of 15 years for the battery may indirectly impose even stricter temperature control standards than those specifically listed as PNGV goals.

3.1. Modeling of cell cooling

Many factors affect the ease and the effectiveness of cooling the battery cells. These include the rate of heat generation, the shape of the cell, the type of coolant, the flow rate of the coolant, and the thickness of the flow passages.

In a vehicle simulation study [4] using Battery 3 of this study, the heat generation rate was low for either the moderate driving conditions of the Federal Urban Driving Schedule (FUDS) or the Highway Fuel Economy Test

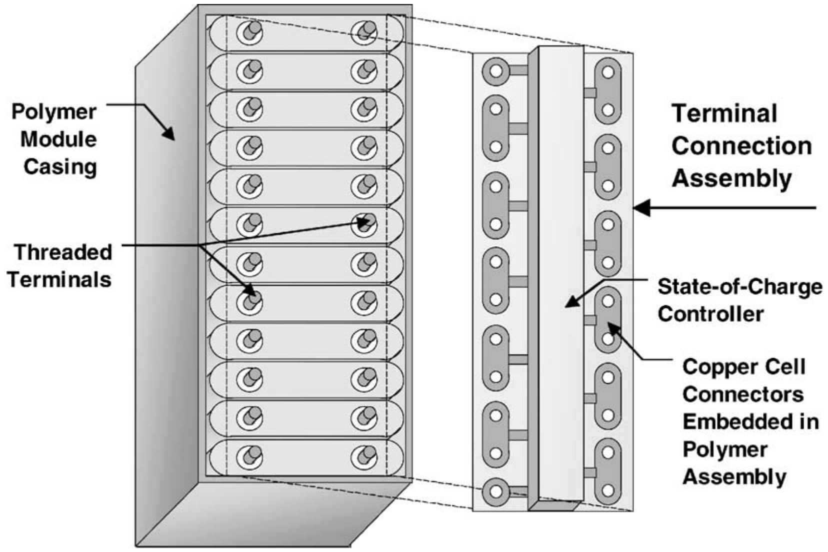


Fig. 3. Twelve-cell lithium-ion battery module for hybrid electric vehicle.

Table 2
Batteries of flat-wound, Gen-2 lithium-ion cells designed for power-assist HEV, dielectric coolant

Cell parameters	Battery 1	Battery 3	Battery 5
Electrode thicknesses (μm)			
Negative electrode	35	35	35
Positive electrode	35	35	35
Number of cell windings	19	26	36
Height (mm)	110	110	110
Width (mm)	100	100	100
Thickness (mm)	15	19	24
ASI for 18 s power pulse (Ω cm^2)	28.6	28.5	28.7
Initial power (W)	685	683	682
Initial capacity (Ah)	8.1	11.0	15.1
Battery_parameters			
Number of cells	48	48	48
Number of modules	4	4	4
Cooling fluid	Silicone	Silicone	Silicone
Power margin to allow for degradation (%)	30	30	30
Rated discharge power (kW)	25	25	25
Rated regeneration power (kW)	30	30	30
Minimum discharge voltage (V)	118	139	151
Maximum charge voltage (V)	205	199	194
Available energy (Wh)	300	300	300
Available capacity, % of rated capacity	21.2	15.6	11.4
Values for lumped-parameter model (new battery)			
Ohmic resistance (48 cells) (Ω)			
Electrodes and separators	0.106	0.078	0.057
Cell current collection	0.007	0.006	0.005
Battery connectors	0.005	0.005	0.005
Total Ohmic resistance	0.118	0.089	0.067
Polarization resistance (Ω)	0.138	0.101	0.074
Polarization time constant (τ) (s)	27	27	27
Length (mm)	428	512	631
Width (mm)	238	238	238
Height (mm)	151	151	151
Volume (l)	15	18	23
Weight (kg)	24	29	36
Initial power density (kW/l)	2.12	1.77	1.44

(HWFET) cycle, because the battery currents were low. The battery thermal control system, however, must be designed for the most difficult cooling conditions that are likely to occur. A representative cycle for those conditions is the HWFET cycle with speeds multiplied by a factor of 1.3. The multiplier raises the average speed to 62.7 mph and the top speed to 77.9 mph. The acceleration rates and the distance traveled on the cycle are increased accordingly. In a separate vehicle simulation study [4], the performance of Battery 3 (Fig. 1 and Table 2) was simulated on the HWFET cycle with the speeds multiplied by 1.3. It was found that the average heat generation rate over the cycle was 249 W for the 48-cell battery or about 5 W per cell. With a constant cooling rate, the battery temperature varied from the initial temperature by a maximum of only 0.7 °C, because of the effect of the heat capacity of the battery. This variation would have been enhanced slightly if entropic heating and cooling had been considered. However, the final state of charge of the battery was almost the same as the initial state of charge and varied from that during the driving cycle by a maximum of only 6.4%. We concluded that the cooling requirement for Battery 3 in this study could be based on the average heat generation rate of 5 W per cell, which was about that determined for the enhanced HWFET cycle.

Of the five battery designs in this study (three of which are listed in Table 2), only Battery 3 was tested in the simulation studies of [4] referred to above. The other batteries are designed to operate over different voltage ranges, have different impedances and, thus, would have different heat generation rates under similar driving conditions. The average I^2R heating effect within the battery would be nearly directly proportional to the battery impedance without taking into account the differing currents: the effect of the voltage variation from the open circuit voltage on discharging is offset by a similar effect in the opposite direction on charging. Accordingly, the following relationship was applied for estimating the maximum heat generation rate (q) required for the cells in the five batteries of this study:

$$q = \frac{R}{R_0} q_0 \tag{1}$$

where R is calculated impedance of battery at end of a 2 s pulse impedance, R_0 the impedance of the reference battery (Battery 3), q_0 the maximum heat generation rate calculated for the reference battery cell (5 W).

The impedance after a 2 s pulse was applied because 2 s is representative of the average length of the pulses on a driving cycle. (If the impedances for 18 s pulses were applied consistently, the results would be changed only slightly.) The maximum heating rates for the batteries are given in Table 3 and plotted on the upper curve in Fig. 4.

Two methods of cooling the battery were considered in this study: air cooling and cooling with a silicone transformer fluid designed for high temperature duty such as Dow Corning 651 Transformer Fluid. A comparison of cooling with these fluids is shown in the lower two curves of Fig. 4 and in Table 3. The flow is within the laminar range for both air and the transformer fluid, and thus, the Nusselt number for flow between the cells is 8.235 [5]. The air coolant is less effective than the liquid coolant in removing heat from the cell surface.

It is of interest to note the effect that the number of cell windings has on the ease of cell cooling. Increasing the number of cell windings for a cell of a set power rating increases the active area and the ratio of the voltage at full discharge power to that at full regeneration power (Fig. 2). For a larger number of windings (higher voltage ratio) the cell is operated closer to the open-circuit voltage on both charge and discharge, and thus, less heat is generated (Fig. 4). However, this effect is compensated for by the thick winding, which results in a longer path for heat dissipation from the cell. As a result, there is little difference in the temperature rise for the center of the cell above the

Table 3
Cooling of batteries designed with flat-wound, Gen-2 lithium-ion cells

	Unit 1	Unit 3	Unit 5
Cell dimensions (mm)			
Height	110	110	110
Width	100	100	100
Thickness	15	19	24
Number of cells per battery	48	48	48
Battery impedance for 2 s pulse discharge (Ω)	0.127	0.095	0.072
Maximum heat generation rate (W/battery)	319	240	181
Coolant temperature rise across cell (°C)	1.0	1.0	1.0
Air coolant	4.0	4.0	4.0
Silicone transformer fluid	1.0	1.0	1.0
Coolant flow rate per cell (g/min)			
Air coolant	100	75	57
Silicone transformer fluid	191	143	108
Coolant channel thickness (mm)	1.0	1.0	1.0
Pressure drop in coolant system, bar through			
Passages between cells			
Air coolant	0.0028	0.0021	0.0016
Silicone transformer fluid	0.016	0.012	0.009
Balance of system for transformer fluid	0.10	0.10	0.10
Power to motor for pumping transformer fluid (W)	1.5	1.1	0.8
Power to blower for circulating air (W)	87	60	42
Temperature rise above coolant temperature (°C)			
Silicone transformer fluid			
To surface of cell	0.6	0.5	0.4
To center of cell	2.5	2.5	2.6
Air coolant			
To surface of cell	3.4	2.7	2.2
To center of cell	5.3	4.7	4.4

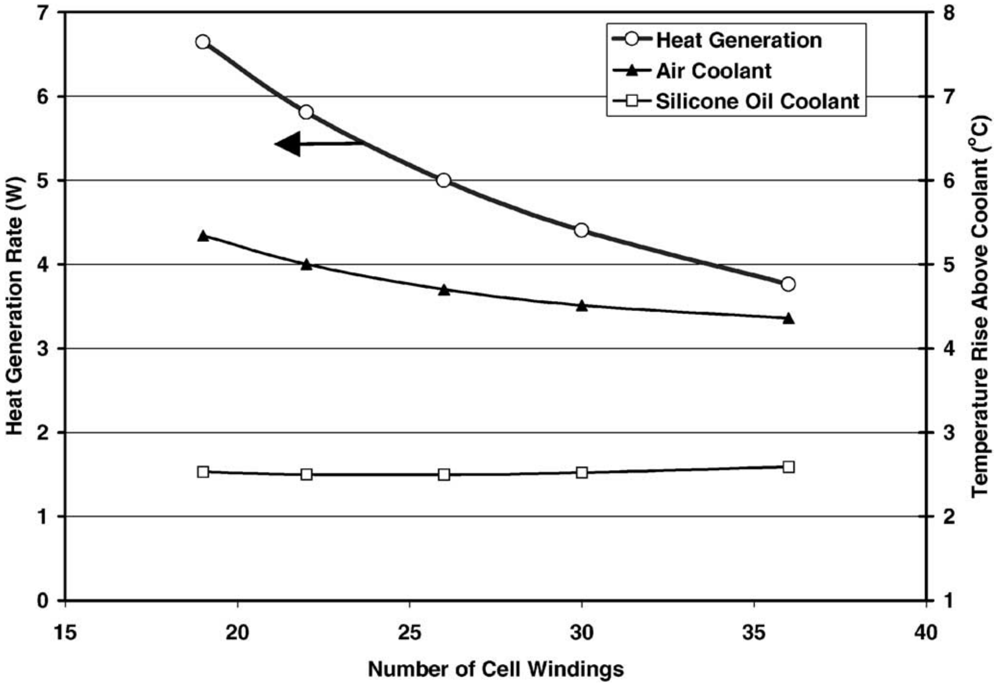


Fig. 4. The effect of the number of windings around the cell core and the heat generation rate and the temperature rise at the cell center above that of the coolant.

coolant temperature for cells cooled by the transformer fluid (Table 3 and Fig. 4). For air-cooled cells, however, the temperature gradient across the coolant is great and proportional to the heat generation rate so that lower heat generation rates result in lower temperatures at the center of the cell.

The pressure drop for flow between the cells was calculated for laminar flow between infinite plates and found to be acceptably low for the transformer fluid (Table 3). The pressure drop for air coolant was even lower, but nevertheless, the air blower requires high power because of the large volume of air being pumped. Other disadvantages in cooling with air compared to the transformer fluid include the need for larger cross-sections in the flow passages for the supply and exit manifolds, a larger temperature rise across the cells, and the need for parallel air flow channels to all modules. These measures are necessary to reduce the pressure drop through the system and limit the power to the circulating blower. Recirculation of most of the air (with the addition of a relatively small rate of cool fresh air) is necessary at low ambient temperatures because the average cell temperature will be within 2–5 °C of the coolant air inlet temperature. Because of the large air manifold passages needed for the high cooling rate required for the aggressive driving conditions set for this study, the modules and the battery would be somewhat larger if cooled by air than if cooled by transformer fluid. The design of the air-cooled system was not completed and the dimensions given in Table 2 are for batteries cooled with transformer fluid.

3.2. Refrigeration of coolant

Liquid coolant must be cooled by ambient air, which introduces an additional temperature step between the ambient air and the battery. Cooling the liquid coolant by refrigeration may solve this problem. One approach would be to add a heat exchanger to the existing air conditioning system. But that system is greatly oversized for cooling the battery (2–3 t or 7–10 kW versus the needed 0.25 kW) and battery cooling would require its use in the spring and fall when it would otherwise not be operated. A more practical solution is a dedicated refrigeration system with an output of only 250 W and a compressor driven by a 75–100 W motor, about the size required for the recirculation blower on an air cooled system (Table 3). Because of its small capacity, it is believed that a dedicated refrigeration system would not be expensive and it simplifies the control of the coolant temperature during vehicle operation. Additional advantages are noted below.

3.3. Battery temperature during standby

A problem that must be addressed is how to prevent the battery temperature from rising too high when the vehicle is parked on a hot day and the temperature under the hood may reach 50 °C or higher. If the battery temperature were to approach the maximum temperature for battery survival of 66 °C (Table 1), it would be difficult to reduce the temperature to the acceptable temperature for operation, 52 °C, in a reasonable time. A dedicated refrigeration system makes possible the operation of the battery well below ambient temperature during warm summer months and solves the problem of maintaining a moderate battery temperature when the vehicle is parked in sun on a warm day. The rate at which Battery 3 will increase in temperature without battery cooling from an initial temperature of 10 °C when the vehicle is idle is illustrated in Fig. 5. For this case, the battery insulation is 10 mm thick with a thermal conductivity of 0.026 W/(m °C). The battery would warm to 50% of the difference between the ambient temperature and the initial battery temperature in about 7 h. If the thickness of the insulation were increased to 20 mm to slow the

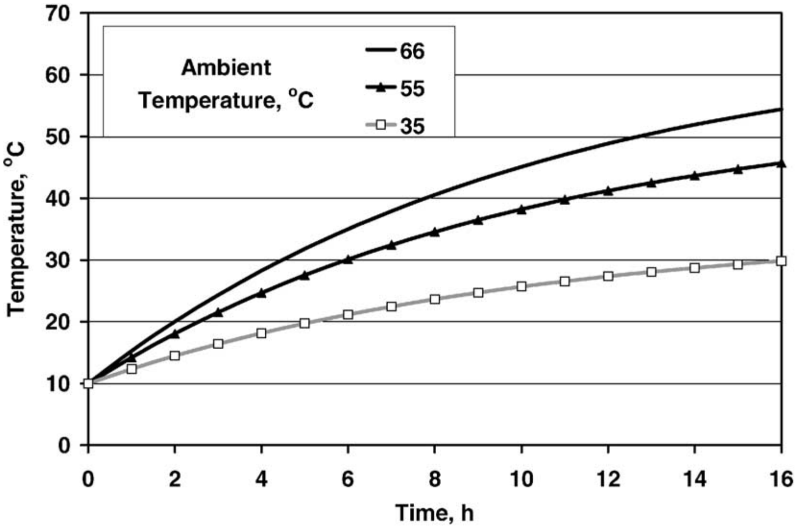


Fig. 5. Temperature rise for 25 kW battery during standby without cooling; initial temperature: 10 °C; insulation: 10 mm thick, 0.026 W/(m °C).

temperature rise, the weight of the battery would increase by only 1.4%, but the volume would increase by 28%.

It is apparent that if the battery is operated at a temperature well below ambient and insulated with only 10 mm of insulation, it will remain safely cool for many hours (until sunset) while parked in the sun on a hot day.

3.4. Heating the battery after a cold start

As noted above, the battery must be heated rapidly after a cold startup at −30 °C, where it need only provide 5 kW of power, to a temperature where it can deliver near full power of 25 kW. To increase the temperature of Battery 3 by 20 °C, would require 225 Wh of heat or about 3.4 kW delivered for 4 min. It is apparent that the battery cannot heat itself that rapidly with I^2R heating. Electric heaters within the battery and powered by the battery and the engine and its generator should be considered.

Another way to deliver the heat may be by heating the battery coolant by means of heat exchange with the engine coolant. There would be a delay in the initiating of heating as the engine gradually warms up. Also, the temperature change in the fluid as it flows through the battery would be much larger than for the normal cooling condition and it may be necessary to increase the size of the coolant passages and the flow rate to mitigate this effect.

Heating the battery after a cold start is difficult to accomplish with low-cost approaches, so every effort should be made to slow the rate of heat loss. Increasing the insulation thickness to 20 mm, as was suggested for slowing the rate of temperature increase while parking in the summer time, also appears to have merit for winter operations.

3.5. Extending battery life

The goal of a calendar life of 15 years for the battery may indirectly impose even stricter temperature control standards than those specifically listed as PNGV goals. For all batteries, deleterious processes accelerate as the temperature increases. A battery system that otherwise meets all of the goals for the PNGV application may be aided in meeting the full lifetime requirement by the use of a thermal control system that imposes stricter temperature control than that specifically called for by the PNGV table of goals.

One means of extending battery life with thermal control is to operate the battery at 10 °C during the first several years of battery life. The batteries in this study should easily achieve the power goals during that period of low temperature operation because they are designed with 30% excess power to allow for decreasing power capability with aging [1]. Implementation of this strategy requires the use of a dedicated refrigeration system.

Maintaining the battery well below the PNGV maximum temperature targets even during parking of the vehicle will also extend battery life. The use of extra insulation and low operating temperatures help to accomplish this strategy.

3.6. Advantages of silicone transformer fluid over air as a battery coolant

In general, liquids are more effective heat transfer media than air. For this application, the volumetric heat capacity of air is low requiring a high air circulation rate for adequate heat removal. The high flow rate requires large flow passages and a high power requirement for the blower. These objections are even more serious for rapid heat-up from a cold start, which requires much higher heat transport rates than cooling. Also, the conductivity of air is only about 20% that of the transformer fluid, resulting in a proportionately lower heat transfer rate for laminar flow at the same temperature differential or a higher cell wall temperature. Additionally, the transformer fluid, which does not support combustion, appears to be a safer heat transfer medium than air.

The use of a silicone transformer fluid may lead to a reduction in the cost of battery cell construction. Water is insoluble in this fluid and, thus, its use might make practical crimped cell closures that are sealed with a polymer. Such seals are probably impractical for use with air as a coolant because water diffusion from the air across the seal would limit the life of the cell to less than the 15-year target.

4. Conclusions

Thermal management goals, set for HEV batteries by the PNGV, are necessary if these vehicles are to meet the needs of owners in the wide variety of climates in the United States. The goals are especially challenging under the aggressive driving conditions to which many vehicles are occasionally subjected. Specific conclusions concerning the means of thermal control to meet this challenge include the following:

- Silicone transformer fluid would be a heat transfer medium superior to air for both heating and cooling the battery. Air is less effective because of its low conductivity and low heat capacity per unit volume, which results in a large temperature rise for the air and high power demand for the circulating blower.
- Rapid heating of the battery from very low temperatures is more difficult than cooling the battery to dissipate the heat generated during driving. Rapid heating might be accomplished with electric heaters within the battery or by heating the battery coolant with heat transferred from the engine coolant. Rapid heating would be especially difficult with air as the heat transfer medium.
- For cooling the battery, a dedicated refrigeration system appears to be practical because the cooling requirement is very low (about 250 W), and thus, the unit may be inexpensive.
- Extra insulation in the battery case (20 mm thickness rather than the 10 mm thickness used in most of this study) would be effective in slowing the heating process in warm weather when the vehicle is parked and slowing the cooling process in very cold weather.

- Operating the battery at 10 °C during the first several years will extend the battery life. A dedicated refrigeration system makes this practical and the battery would not suffer any power loss, because it must be designed with an initial excess of power to allow for degradation with aging.

Acknowledgements

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