Thermal Management System with Heatpipe for in Vehicle Electric Devices

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ABSTRACT A variety of electrical devices such as a lithium ion battery (hereinafter LIB) and etc. are implemented in the next generation vehicles such as the plug-in hybrid vehicle (hereinafter PHV), electric vehicle (hereinafter EV) and etc. for which we are expecting an important growth in the future.

This paper describes the results of examining the benefits obtained by applying the heatpipe system which has an excellent heat uniformity to the temperature management system for in-vehicle electronic devices to be mounted on these vehicles. It was found that with respect to the thermal management system for LIB, the heatpipe system has an excellent performance for the cooling and for the temperature uniformity. Although the volume is reduced by 88% in comparison to the air cooling system, if the 20 cells with ambient temperature of 35˚C and a heat amount of 3 W is cooled by the cooling source of 35˚C, the heatpipe system is able to suppress the highest cell temperature to 38.1˚C and the temperature difference between cells to 1.3˚C. Thus the excellent cooling performance and the temperature uniformity of the heatpipe system were confirmed. This paper also discusses the applicability of the heatpipe system to the cooling for other electric devices such as automotive inverters…etc.

1. INTRODUCTION

The further expansion of the eco-car which the motor is used as main or auxiliary power is foreseen in the future. In 2020, it is forecasted that at least, about 20% of the vehicle sales will be of these eco-cars that have the motor drive engine[1)]. In addition, the rate of not only the hybrid car (hereinafter HV) which was the leading this category, but also PHV which has a battery as main power source, EV and etc. will increase and in the same year, the sales will be of 2 M cars for each of the PHVs and the EVs. Many in-vehicle electric devices such as LIB, inverter and etc. are installed in these eco-cars, but the heat amount generated by each electric component is increasing because of the improvement of the vehicle performance. So it is predicted that the proposal for a cooling method that is efficient and saves the space is required. This paper will report the result of examining the implementation of the heatpipe system which has an excellent heat uniformity as a cooling technology for the in-vehicle electric devices such as LIB and inverters.

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2. THE CHARASTRISTICS OF LIB

2.1 The Problems at High Temperature

Because the vehicles with battery as the main power source have a low cost to drive and a low emission, it is expected that the number of sales will be expanding and they will be the main stream of the vehicles. But one of the hurdles for them to become popular is the distance that can be reached per individual charge. Currently, the distance that can be covered using only the battery charge is about 40-60 km in case of the PHV and 100-230 km in case of the EV (Except for some sport type vehicle) and it is much shorter in comparison to the 500 km of the typical Internal Combustion Engine (ICE) vehicle. In addition, it is estimated that in practice, the use of electrical equipment such as air conditioning and headlights, will reduce the actual travelling distance by 20-40% from the stated value. So the traveling distance is even shorter. Also, if the capacity of the battery is increased to cover a longer travelling distance, this distance will not increase proportionally because of the weight increase of the battery itself. Therefore, it is necessary to install the battery with a large charge capacity per unit volume and in the recent, the chances of these LIBs being mounted on these eco-cars are increasing.

However, since the charging capacity is reduced because of the storage in a fully charged state at high temperature and because of the repeated charging and discharging, the charging will be controlled to be completed below the fully charged state. In general, it is said that the used capacity range is about 50% in case of HV and 80% in case of PHV if the fully charged state is set as 100% and the completely discharged state is set as 0%.

Therefore, additional battery has to be installed in order to avoid the actual problems even if the charging capacity of the battery is reduced to some extent. So the situation is that the electric mileage will worsen and the living space will shrink.

On the other hand, the capacity degradation of LIB is due to the chemical reaction and it is stated that the degradation rate follows Arrhenius equation[2)]. This means that the battery life will be longer if the battery operating temperature is lowered or the heat generation during rapid charging is suppressed.

That is, if the battery temperature can be controlled appropriately, the capacity reduction due to the degradation can be suppressed while utilizing the battery up to a region close to the full charge and the number of the installed battery can be reduced.

2.2 The Problems at Low Temperature

Also, because the moving speed of Lithium ions is dropping and the battery cell reaction becomes harder at a low temperature well below 0˚C, a voltage drop will occur and the discharge capacity will be reduced in most of the LIB. Because this voltage drop will be considerable at high output (high current discharge), it can be the cause of the drop of the output (acceleration force) and/or maximum speed.

Therefore, it is necessary to heat the battery quickly at a low temperature and to take advantage of the originally available charge capacity.

3. ABOUT THE BATTERY TEMPERATURE MANAGEMENT SYSTEM

3.1 The Air Cooling System

Currently, the temperature management system in use in the LIB-based vehicles, especially for HV, is the air cooling system. This construction consists of LIB cells (unit battery) placed at a certain separation and they are placed in the case together with other equipment. There are the gaps between the case and the cells and by circulating the air into the gap (duct section), the air for temperature control flows through the gap between cells and exit on the opposite side. (Figure 1)

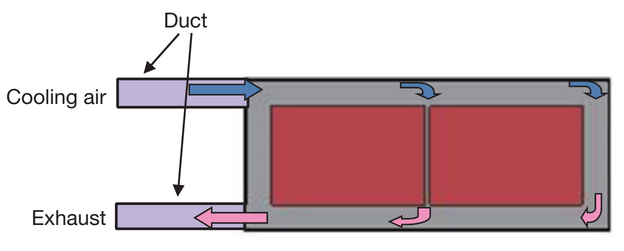

Figure 1 Schematic of a conventional air cooling system.

In this method, the main components required for the temperature management system are only the case for forming the duct and the fan for feeding the air. So it is very simple system. On the other hand, in case of the eco-cars such as PHV or EV that number of cells is large, the gaps in the duct and between cells are required and more spaces for circulating air are also required. It is stated that as mentioned earlier, for PHV and HV that can receive the economic efficiency by driving with only the electricity of the battery (hereinafter EV-drive), the longer EV-drive distance is required. On the other hand, because the mounting space is limited, it is necessary to minimize the volume for other than the battery cells as much as possible. Therefore, in the air cooling system, it is necessary to minimize the ducts and the gap between the cells as much as possible, but if it becomes too small, the impedance of air path will becomes large and a sufficient air flow won't be obtained. So the downsizing has a limitation.

3.2 The Heatpipe System

Currently, we are now considering the temperature management system with the heatpipe. The heatpipe is made by sealing the operating liquid into the container (vessel) and it is the device to transport the heat from the high temperature section to the low temperature section fast by removing the heat at the heat input section by the evaporation latent heat of the operating liquid and by releasing the heat at the cooling section when the vapor returns to the operating liquid. Also, in order to transport the operating liquid from the cooling section to the heat input section, the section called wick that generates capillary force is provided in the inner surface of the container and the cycle that the operating liquid is continuously supplied to the heat input section is formed. (Figure 2)

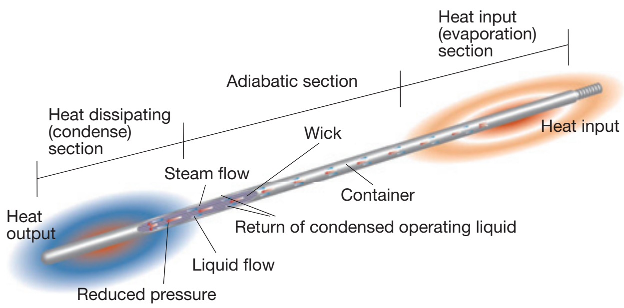

Figure 2 Schematic of heatpipe working.

Because the chemical reaction occurs depending on the combination of the operating liquid and the container and degrades the performance of the heatpipe, in general, their combination is fixed. The temperature management system proposed in this paper, the heatpipe with the combination of copper for the container and water for the operating liquids is used. Since water has a large specific heat, the amount of the heat transported by the same size of heatpipe is large so it contributes to the size reduction of the system.

If this heatpipe is thermally bonded to the side surface or the bottom surface of the rectangular cell that is the general shape in the LIB and is partially attached to the heating cooling source, it is possible to manage the cell temperature. Further, from the operation principle, the heatpipe has the function of not only simply transporting the heat, but also keeping the heat uniformity of the components that contact thermally. Therefore, for example, if many cells are attached to the same heatpipe, not only the temperature management can be done collectively, but also the uniformity of the heat between cells can be obtained. This time, in consideration of the assembling property, the case where the heatpipe system is attached to the bottom surface of the cell will be examined.

3.3 The Comparison of the Volume of the Air Cooling System and the Heatpipe Cooling System

For comparison of the air cooling system and the heatpipe system, the volume was examined in the following model.

In a cell size of W120 mm×H100 mm×D20 mm, assuming the battery pack that is made of a total cell numbers of 200 and one module of 20 cells, Type A, the duct thickness of 30 mm and the gap between cells of 3 mm and Type B, the duct thickness of 20 mm and the gap between cells of 2 mm, are examined. (Both of vertical gaps are 0 mm.) (Figure 3) Without considering the duct section other than the side surface of the cell, if the total volume of the cell and the duct of the cell side is calculated simply, it will be 80 L in case of Type A and 69 L in case of Type B.

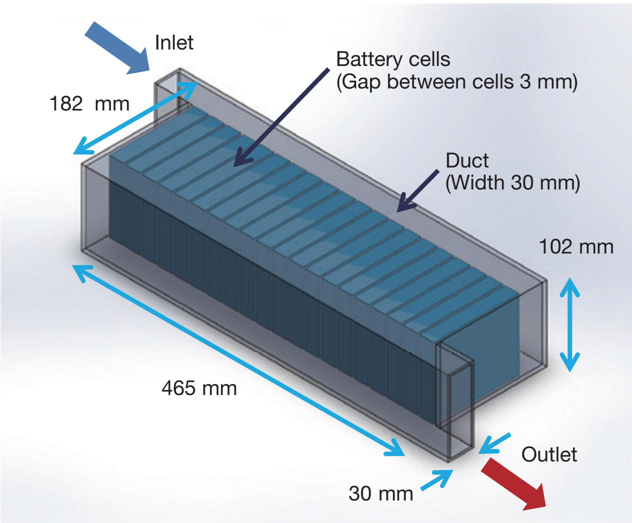

Figure 3 Schematic of air-cooling system for CAE. (Computer Aided Engineering)

Further, the occupation percentage of the volume of the duct and the gap between cells in the entire system is 40% and 30% respectively.

On the other hand, the heatpipe system has a configuration where the heatpipe with a diameter of 8 mm is flattened to 4 mm thickness, and then sandwiched by the aluminum plate of 2 mm thickness (Figure 4) and the cross sectional shape is 120 mm width and 8 mm thickness.

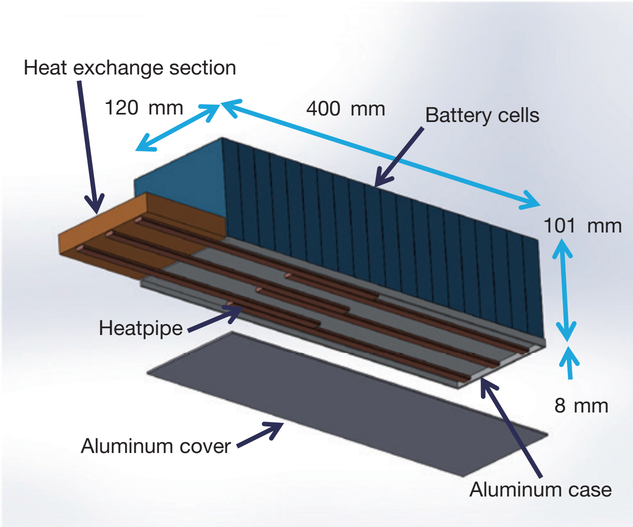

Figure4 Schematic of heatpipe system for CAE.

There is a section where some of the heatpipe are overlapped, but because the transferred heat capacity is reduced in inverse proportion to its length, the heat of the total system is transferred by providing the overlapped section as appropriate depending on the system configuration and by connecting the short heatpipes. (Figure 4)

For the heatpipe system, when the total volume of the section that contacts to the bottom of the cell and the cells is calculated in the same way, it was 53 L. The volume of the heatpipe system itself was only 4 L and the percentage of occupation in the total system was 7%. (Figure 5)

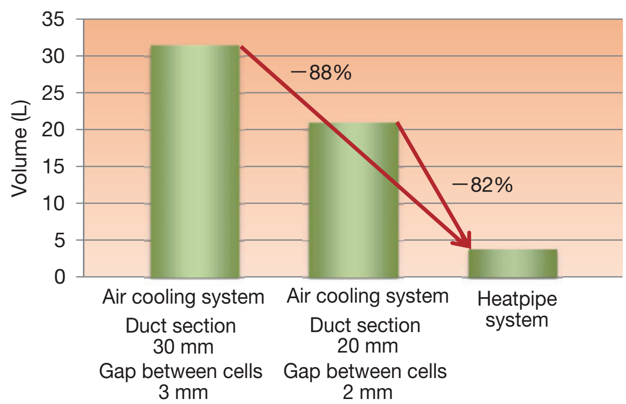

Figure 5 Volume comparison of each system.

3.4 The Comparison of the Cooling Performance

Next, the comparison of the cooling performance of the conventional air cooling system and the heatpipe system is explained.

The air cooling system is Type A and inlet and outlet of duct is placed in the opposite side of the cell module. (Figure 3)

Assuming that the air is circulated into these 10 modules by the large fan, the air flow rate is set to 0.6 m^3/min per one module.

On the other hand, in case of the heatpipe system, assuming that the temperature control is done by the refrigerant of an air conditioner or a water cooling pipe, the 100 mm block as the heat exchange section is provided and the heatpipe is modeled that the temperature of this section is controlled as a constant. It was assumed that the heat is transferred between the heatpipe system and the battery cells in the thermal sheet of 1 mm thickness (Thermal conductivity 1 W/mk).

At first, assuming the case that the cooling is required, the analysis condition is set. The ambient temperature, the air temperature of the cooling system and the temperature of the heat exchange section of the heatpipe system is set to 35˚C. In the case where the cell generates the heat of 3 W (an assumed condition for charging cycle), the thermal analysis confirmed the maximum cell temperature and the temperature difference between the cells in the module (the number of cell is 20.) for each.

Note that the distribution of temperature within the cells is not taken into consideration and the comparison is based on the average value of each cell, but the heat capacity is set to be same as the aluminum of the same volume.

Table 1 shows the results.

Table 1 The cooling performance comparison between air cooling system and heatpipe system.

	Max. temperature of cells (℃)	Temperature difference between cells (℃)
Air cooling system	44.6	5.4
Heatpipe system	38.1	1.3

In this way, temperature of the heatpipe system was lower by more than 6.5˚C compared to the one of the air cooling system and also the temperature difference between cells was 1.3˚C.

It further indicates that if there is a temperature difference, the extra energy is consumed because the other cells are cooled so much to cool the highest temperature cell to the predetermined temperature. Especially in the time of charging, the temperature of the cooling source has to be held to low temperature for relatively long time so from this point, it is seen that the heatpipe system is useful to improve the electricity mileage and the driving distance.

3.5 The Comparison of the Heating Performance

Next, the cases where the LIB is heated from a low temperature, in both systems, are compared.

The configuration of the cooling system is same as in paragraph 3.4 and the temperature of the entire system including cells is set to -10˚C. When the air with the temperature of 20˚C is circulating into this system at the rate of 0.6 m^3/min, the time when all the cell temperature reaches to 10˚C and the temperature difference between the cells at the time were confirmed by the thermal transit analysis.

On the other hand, the configuration of the heatpipe system is same as in paragraph 3.4 and in this case the temperature of the heat exchange section is set to 20˚C and the time when all cell temperature reaches to 10˚C and the temperature difference between cells at the time were confirmed by the same analysis as well.

The results are shown in Table 2.

Table 2 Elapsed time reached to 10 degree Celsius and temperature variation between battery cells.

	Elapsed time reached to 10℃ (sec.)	Temperature difference between cells (℃)
Air cooling system	2140	2.8
Heatpipe system	1010	6.0

In this way, the temperature difference between the cells was 2.8˚C in the case of the air cooling system and was 6˚C in the case of the heatpipe system. 2140 seconds were required to heat to 10˚C for all cells in the case of the air cooling system, but it can be seen that it was 1010 seconds (about the half of the air cooling system) in the case of the heatpipe system. Because the energy to control the temperature is consumed for only the time while heating, the temperature difference between the cells won't be an issue and the shortness of the heating time becomes essentially important.

Note that because water is used for the operating liquid, the heatpipe won't work when the system is stopped below freezing point. However, if the heatpipe size and the number of heatpipes were set appropriately, the operating liquid will melt from the heat input section even if the ambient temperature is below the freezing point and the melting portion will start the heatpipe operation again. Then gradually, the operating range will cover all of the heatpipe. In the end, the heat can be transfer to the terminal section of the heatpipe. This is the reason why the heatpipe heatsink with the operating liquid of water is used for such as railway where the ambient temperature is below the freezing point.

In addition, in this examination, the melting time is neglected because the occupation percentage of the operating liquid in the volume of the heatpipe is very little and it is estimated that there is small impact to the analysis results.

4. IN-VEHICLE ELECTRIC DEVICES

4.1 The Possibility of the Heatsink for the Inverter Element

Next, the applicability of the heatpipe heatsink for the cooling of the inverter element that generates a large amount of heat will be described.

4.2 The Heat Amount of Inverter and the Various Cooling Method

Currently, the output of the drive motor is around 20 kW for small HV car and around 100 kW for HV system of luxury car. In order to supply the electricity to this motor efficiently, the inverter circuit is used. The circuit of current inverter element is configured on the Si wafer and it is stated that the heat loss is about 5%.

Therefore, if the heat amount of the inverter predicted from these is summarized in each size of car, it is listed in Table 3.

Table 3 Assumed motor power heat loss of inverter.

Model	Size	Motor output (kW)	Calorific value of inverter (kW)
HV・PHV	Full	100	5.0
	Medium	60	3.0
	Compact	20	1.0
EV	Medium	80	4.0
	Compact	50	2.5

On the other hand, many combined elements are used by matching its output and it is stated that the heat density is around 30 W/cm^2. In the future, in the case of the highly heat resistant element such as SiC, it reaches the level of 100 W/cm^2. Also the heat per one element is around 200-300 W and the predetermined output is obtained using multiple elements. From the size of the heat amount and the heat density points of view, the air cooling using aluminum die-casting or extruded heatsink cannot achieve the cooling if the generated heat amount is not less than the value shown in the Table 3 or the heat density is not quite low. Therefore, currently the water cooling method is the common approach.

The water cooling system has a great benefit that can be used in the compartment (hood) where the ICE for HV, PHV and etc. is installed and the ambient temperature exceeds 100˚C. On the other hand, the piping is required and the manpower is needed for assembling. Also the weight of the system is heavy and in order to control the cooling temperature of the inverter element precisely, the electric water pump is needed and there is a disadvantage that electric power is consumed for other than the radiator fan.

For the vehicle where the temperature of engine compartment is not high such as EV, Fuel Cell Vehicle (FCV) and etc., the air cooling becomes possible if the heatsink becomes of high performance and therefore the weight reduction and the low electricity consumption will be possible. Also, even for the HV or PHV where engine is installed, if the inverter system can be moved from the engine compartment to the trunk space or the bottom floor, it can be installed at the location where the environmental temperature is relatively low and the air cooling will be possible. Also if the downsizing of ICE is proceeding, the air cooling of the ICE will become possible as before. So it is estimated that the air cooling of entire vehicle would not be impossible.

Heatpipe heatsink is already used for not only the cooling of the railway inverter, but also for the cooling of the inverter of high speed elevator or of CPU server. The heat amount for the railway inverter reaches several tens kW and the heat density of the CPU server sometimes reaches 60 kW/cm^2. But the air cooling by heatpipe heatsink is implemented for both cases. Therefore, for example, it is estimated that the air cooling can be done by installing the heatsink and the fan as shown in Figure 6 for the in-vehicle inverter.

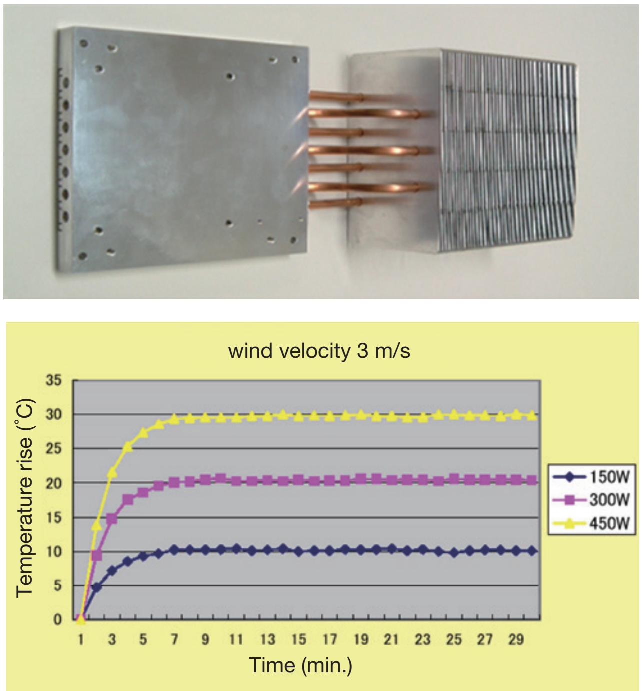

Figure 6 Heatpipe heatsink for inverter used for elevator and its performance.

4.3 The Cooling System for the Other In-Vehicle Electric Devices

For the cooling of the control unit of the in-vehicle electric devices such as the power control unit (PFU), the DC-DC converter, the electric power steering control unit (EPS) and etc., the aluminum die-casting and the extruded heatsink are being used.

Because of the processing limit, the fin with thickness of more than 0.6 mm is attached. On the other hand in case of such as the natural air cooling, the cooling efficiency of the fin itself won't change even if the thickness is thinner, for example 0.3 mm. So while maintaining the distance between the fins, the fin pitch can be narrow and more number of fins can be attached in the same volume. It leads to the weight reduction. In order to manufacture thin fins, it is better to use sheet metal processing plate and our company has the technology of the crimped fin (Figure 7) and the eco fin. By using these technologies, it is possible to achieve the light weight and the high performance of the control unit for the electric devices. At the same time it leads to the cost reduction.

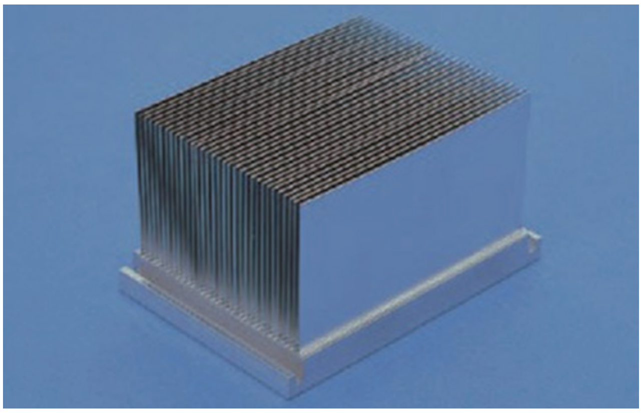

Figure 7 Crimped fin heatsink.

Furthermore, by embedding the heatpipe or installing it to the aluminum base, the thermal conductivity can be improved significantly and by defusing the local heat to the entire base, the highest temperature can be reduced.

In this way, by applying the heatsink that is combined well with sheet metal processing technology and heatpipe to various devices, the weight of the vehicle can be reduced and it leads to the improvement of the gas mileage or the electricity mileage.

5. CONCLUSION

In this paper, as an initiative of the cooling device proposed to the in-vehicle device of our company, the examples of the application of the heatpipe system to such components as LIB and etc. were introduced. By utilizing the heatpipe system to the temperature control device of the battery, the heating or cooling can be done more efficiently than the air cooling system. Also, by using the heatpipe heatsink, the air cooling system of the inverter can be realized. Further, by using the sheet metal processed heatsink for the cooling of in-vehicle electric devices or by installing the heatpipe on the base plate, the downsizing, weight reduction and cost reduction can be realized and it leads to the improvement of the gas mileage and the electricity mileage. We think that more cost reduction and more energy saving of eco-cars can be achieved by applying the heatpipe system.

We will continue to work on the research and development to extend the applicable range. It's to our pleasure if our technologies contribute to the earth environment even if only slightly.

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