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Review

Thermal modeling and heat management of supercapacitor modules for vehicle applications

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ABSTRACT

Temperature has a huge influence on supercapacitor cells and modules ageing. Consequently, thermal management is a key issue concerning lifetime and performance of supercapacitor modules. This paper presents thermal modeling and heat management of supercapacitor modules for vehicle applications. The thermal model developed is based on thermal-electric analogy and allows the determination of supercapacitor temperature. Relying on this model, heat management in supercapacitor modules was studied for vehicle applications. Thus, the modules were submitted to real life driving cycles and the evolution of temperatures of supercapacitors was estimated according to electrical demands. The simulation results show that the hotspot is located in the middle of supercapacitors module and that a forced airflow cooling system is necessary.

Contents

1. Introduction

Heat production in supercapacitor is related exclusively to Joule losses. The supercapacitors support currents up to 400 A or more depending on cell capacitance and used technology. The repetitive charge and discharge cycles of the supercapacitor cause a significant warming even though the equivalent series resistance value is around the mΩ according to the capacitance. Several authors showed that the supercapacitor ESR varies according to the temperature [1–3]. In [4] the authors have studied the effect of the temperature and the voltage on the supercapacitors ageing. They have established a model which allows analyzing self-accelerating degradation effects caused by elevated voltages and temperatures. In the reference [5] the authors have studied and modeled the temperature effect on the supercapacitor self discharge.

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Nomenclature

cp specific heat capacity ($J\,kg^{-1}\,{}^\circ C^{-1}$)
C supercapacitor capacitance (F)
C_{th} thermal capacitance ($J^\circ\,C^{-1}$)
$C_{th\text{-}i}$ thermal capacitance of the layer number i ($J^\circ\,C^{-1}$)
$C_{insulating\text{-}layer}$ thermal capacitance of the insulating layer ($J^\circ\,C^{-1}$)
$C_{metal\text{-}case}$ thermal capacitance of the metal case ($J^\circ\,C^{-1}$)
dr elementary thickness (m)
dR_{th} elementary thermal resistance (Ω)
EIS electrochemical impedance spectroscopy
ESR supercapacitor equivalent series resistance (Ω)
ES energy storage
EVs electric vehicles
f frequency (Hz)
FCVs fuel cell vehicles
G electrical conductance (Ω^{-1})
G_{th} thermal conductance T_{mea}
h convection heat transfer coefficient ($W\,m^{-2}\,{}^\circ C^{-1}$)
HyHEELS hybrid high energy electrical storage
HEVs hybrid electric vehicles
I current flux (A)
$I(t)$ RMS current value (A)
$\mathrm{Im}(z)$ imaginary component of the supercapacitor impedance response
J current flux density ($A\,m^{-2}$)
L hollow cylinder length (m)
n number of layers of supercapacitor
$P(t)$ total power dissipated by Joule effect (W)
R hollow cylinder inner radius (m)
$R_{electric}$ electrical resistance (Ω)
R_s hollow cylinder outer radius (m)
$\mathrm{Re}(z)$ real component of the supercapacitor impedance response
$R_{convection}$ convection heat transfer resistance (Ω) or (${}^\circ C\,W^{-1}$)
R_{th} thermal resistance (${}^\circ C\,W^{-1}$)
$R_{th\text{-}i}$ thermal resistance of the layer number i (${}^\circ C\,W^{-1}$)
$R_{insulating\text{-}layer}$ thermal resistance of the insulating layer (${}^\circ C\,W^{-1}$)
$R_{metal\text{-}case}$ thermal resistance of the metal case (${}^\circ C\,W^{-1}$)
S_{sc} heat exchange surface of the supercapacitor (m_2)
T hollow cylinder inner surface temperature (°C)
T_a ambient temperature (°C)
$T_{Hi\text{-}mea}$ measured temperatures (°C)
$T_{Hi\text{-}sin}$ simulated temperatures (°C)
T_{mea} measured temperature (°C)
T_{min} minimum temperature (°C)
T_{max} maximum temperature (°C)
T_s hollow cylinder outer surface temperature (°C)
T_{sin} simulated temperature (°C)
ΔT temperature difference (°C)
ΔV potential difference (V)

Greek letters
Φ heat flux (W)
φ heat flux density ($W\,m^{-2}$)
λ thermal conductivity ($W\,m^{-1}\,{}^\circ C^{-1}$)
μ density ($Kg\,m^{-3}$)
σ electrical conductivity $T_{Hi\text{-}sin}$
τ system time constant (s)

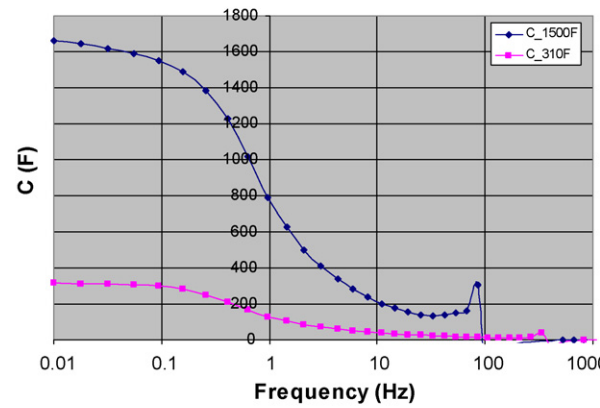

Fig. 1. BCAP1500F and BCAP310F capacitance as function of frequency with a bias voltage respectively of 2.7 V and 2.5 V and a temperature of 20 °C.

This rise in temperature can have the following consequences:

- The deterioration of the supercapacitor characteristics, especially ESR, self discharge and lifetime [4,5], which affect its reliability and its electrical performance.
- The pressure inside the supercapacitor is increased.
- A premature aging of metal contacts, in fact the repetitive heating and significant temperatures can deteriorate rapidly the terminal connections of the supercapacitor.
- The evaporation of the electrolyte and hence the destruction of the supercapacitor if the temperature exceeds 81.6 °C the boiling point of the electrolyte.

Therefore, it is important to know and understand the heat behavior of supercapacitor cells and modules. This leads to an estimation of the space-time evolution of the temperature.

This paper deals with the thermal modeling of supercapacitors and heat management in supercapacitor modules. The originality of this work is based on the integration of thermocouples located inside the supercapacitor during its manufacturing by Maxwell technologies. Cooling systems were also studied for supercapacitor modules subjected to a driving cycle.

2. Supercapacitor electric characterization

The Maxwell BCAP310F and BCAP1500F supercapacitors used in this study are based on activated carbon technology and organic electrolyte. These devices were characterized using the electrochemical impedance spectroscopy (EIS). This allows the determination of the supercapacitor real and imaginary components of the impedance response. It assumed that the supercapacitor capacitance C and the series resistance (ESR) are deduced from the experimental results respectively:

$$C = \frac{-1}{2\pi Im(z) f} \quad (1)$$

$$ESR = Re(z) \quad (2)$$

where $\mathrm{Im}(z)$ and $\mathrm{Re}(z)$ are respectively the imaginary part and the real part of the supercapacitor impedance and f is the frequency.

Figs. 1 and 2 represent the BCAP310F and the BCAP1500F capacitance and ESR as a function of frequency. At low frequency, the capacitance is maximum, for example at 10 mHz the capacitance value is in order of 1660 F for the BCAP1500F and 315 F for the BCAP310F. At 50 mHz the ESR value is in order of 1 mΩ for BCAP1500F and 5.2 mΩ for BCAP310F. The BCAP310F ESR is relatively high because this device was fabricated, by Maxwell technologies, especially for these thermal tests; it is including four thermocouples type K inside.

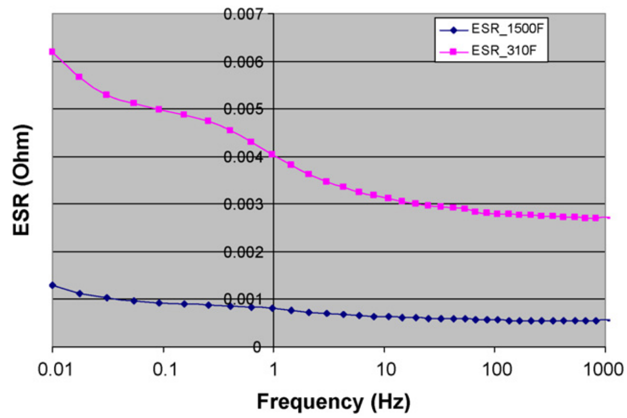

Fig. 2. BCAP1500F and BCAP310F series resistance as function of frequency with a bias voltage respectively of 2.7 V and 2.5 V and a temperature of 20 °C.

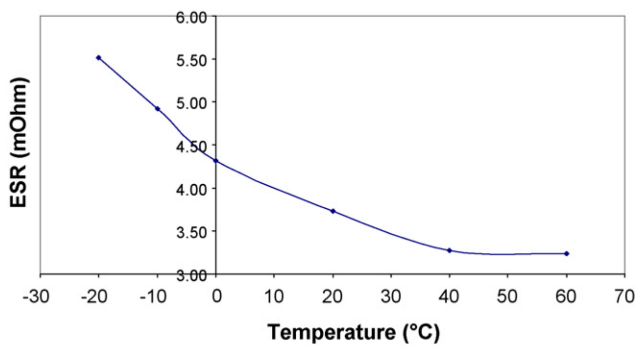

Fig. 3. BCAP310F equivalent series resistance as function of temperature.

The BCAP1500F capacitance and ESR were calculated in DC state. *ESR* and *C* are respectively about 1.07 mΩ and 1525 F.

For supercapacitor thermal behavior, the device was characterized by using the EIS for different temperature. Fig. 3 represents the Maxwell BCAP0310F ESR variations according to the temperature. The ESR increases at negative temperature values. The ESR variation is higher for negative temperature than for positive one. This is due to the fact that the electrolyte's ionic resistance is strongly influenced by the temperature. Above 0 °C ESR varies slowly with the temperature. Below 0 °C the temperature dependence is stronger. Higher ESR is due to the increase of the electrolyte's viscosity at low temperatures limiting ionic transport speed which increases the resistance of the electrolyte.

In the case of the capacitance, the experimental results show that the capacitance is lower at negative temperature as shown in Fig. 4. For example, at *f* = 10 mHz there is no variation of the capacitance with temperature. At 100 mHz, *C* = 335 F at −20 °C whereas *C* = 361 F at 20 °C. At negative temperature, the supercapacitor capacitance decreases with temperature.

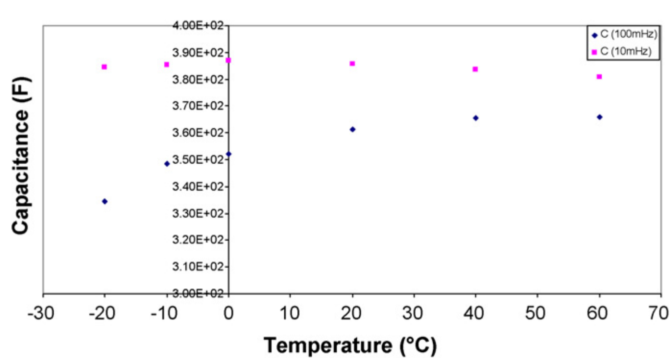

Fig. 4. BCAP310F capacitance evolution according to the temperature for 10 mHz and 100mHz.

In conclusion, it is clear that the supercapacitor electric performances and lifetime depend on the temperature.

3. Thermal modeling of supercapacitors

In order to establish a thermal model of a supercapacitor cell, it is important to expose its geometric structure. The structure of a basic cell is cylindrical. The technology achievement is identical to that used for conventional capacitors. Thus, there is a basic multilayer that consists of a positive electrode and a negative electrode of activated carbon. They are electrically isolated with a separator placed between them. The ensemble forms a layer which is rolled several times and then placed in a metal case and impregnated with an organic electrolyte. The two electrodes are metalized and connected to the outside (+) and (−) terminal connections of supercapacitor.

Refs. [6–9] present thermal modeling of supercapacitors. Different methods are used, heat equation resolution, electric-thermal analogy. The models developed allow the determination of supercapacitor temperature.

As it described before, the structure is cylindrical geometry. Theoretical study and experimental results show that the temperatures of a layer are uniform; however the temperature of each layer is different. Thus, the thermal modeling can be studied by calculating the total thermal resistance and capacitance of the supercapacitor.

3.1. Theoretical recall

Consider a hollow cylinder with an inner radius R, an outer radius R_s, a length L, thermal conductivity λ, specific heat capacity cp and density μ. The inner surface is maintained at a temperature T and the outer surface at temperature T_s.

The elementary thermal resistance and thermal capacitance of an elementary thickness dr is expressed by:

$$dR_{th} = \frac{1}{\lambda}\frac{dr}{2\pi rL} \tag{3}$$

$$dC_{th} = \mu cp 2\pi Lrdr \tag{4}$$

Therefore, the total resistance and capacitance are given by:

$$R_{th} = \frac{1}{2\pi\lambda L}\int_{R}^{R_s}\frac{dr}{r} = \frac{1}{2\pi\lambda L}\ln\left(\frac{R_s}{R}\right) \tag{5}$$

$$C_{th} = \mu cp\pi L({R_s}^2 - R^2) \tag{6}$$

3.2. Case of a supercapacitor

In order to calculate the total thermal resistance R_{th} and thermal capacitance C_{th} of the supercapacitor, each layer in the supercapacitor is modeled by its thermal resistance $R_{th\text{-}i}$ and its thermal capacitance $C_{th\text{-}i}$. R_{th} and C_{th} are given by:

$$R_{th} = R_{insulating\_layer} + R_{metal\_case} + \sum_{i=1}^{n} R_{th\_i} \tag{7}$$

$$C_{th} = C_{insulating\_layer} + C_{metal\_case} + \sum_{i=1}^{n} C_{th\_i} \tag{8}$$

Where: $R_{metal\text{-}case}$, $R_{insulating\text{-}layer}$, $C_{metal\text{-}case}$ and $C_{insulating\text{-}layer}$ are the thermal resistance and thermal capacitance of the metal case and insulating layer and n is the number of layers.

Table 1
Thermal-electrical equivalences.

Thermal parameters	Electrical parameters
Thermal conductivity (λ) (W m^{-1} °C^{-1})	Electrical conductivity (σ) (Ω^{-1} m^{-1})
Temperature difference (ΔT) (°C)	Potential difference (ΔV) (V)
Heat flux density (φ) (W m^{-2})	Current flux density (J) (A m^{-2})
Thermal resistance (R_{th}) (°C W^{-1})	Electrical resistance ($R_{electric}$) (Ω)
Thermal conductance (G_{th}) (W °C^{-1})	Electrical conductance (G) (Ω^{-1})
Heat flux (Φ) (W)	Current flux (I) (A)
Thermal capacitance (C_{th}) (J °C^{-1})	Electrical capacitance (C) (F)

Based on this analysis, a Matlab/Simulink® simulation model was developed in order to calculate the R_{th} and C_{th} of a supercapacitor cell. Calculated values were compared to experimental values and the simulation model was validated. This application permits to calculate the evolution of the temperature in each layer of the supercapacitor cell.

The thermal modeling of a supercapacitor is done using the thermal-electric analogy. Table 1 shows the equivalences between thermal and electrical parameters.

Fig. 5 shows the thermal-electric model of the supercapacitor. The conduction heat transfer mode is the most important within a supercapacitor. The other two modes of heat transfer (radiation and convection) are neglected. However the convection heat transfer mode between ambient air and the outer surface of the supercapacitor is taken into account. The thermal model gives the evaluation of the temperature of the supercapacitor depending on the electrical power, the ambient temperature and the convective heat transfer coefficient.

The total power dissipated in the supercapacitor is given by:

$$P(t) = ESR \times I^2(t) \tag{9}$$

Where: ESR is the equivalent series resistance of the supercapacitor and $I(t)$ is the RMS current value passing through it.

The resistance $R_{convection}$ represents the heat transfer between the surface of the supercapacitor and the ambient air. Its value depends on the convective heat transfer coefficient h and the heat exchange surface of the supercapacitor S_{sc}. This coefficient can be calculated by determining the system time constant τ.

$$\text{Where}: \tau = R_{convection} \times C_{th} \Rightarrow R_{convection} = \frac{\tau}{C_{th}} \tag{10}$$

$R_{convection}$ can also be calculated by:

$$R_{convection} = \frac{1}{hS_{sc}} \tag{11}$$

For an optimal design of the supercapacitor and its cooling system in case of supercapacitor modules, it is advantageous to know the spatial and temporal evolution of temperature. A special 310 F supercapacitor cell, with four thermocouples placed inside was developed in order to validate the thermal model. The model was also validated for a 1500 F cell.

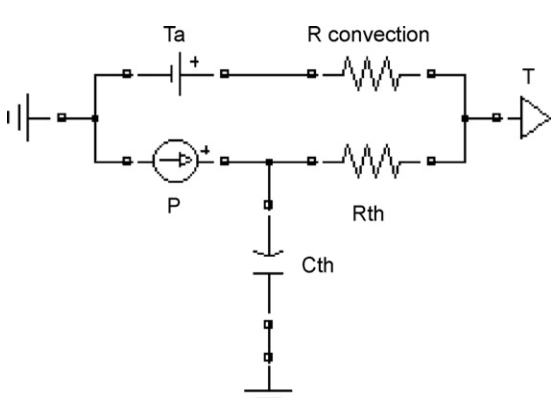

Fig. 5. Thermal-electric model of the supercapacitor.

Table 2
Parameters values of 310 F and 1500 F supercapacitor cells.

Parameters	310 F	1500 F
T_a	22.5 (°C)	17.5 (°C)
$R_{convection}$	11 (°C/W)	3.5 (°C/W)
R_{th}	6.5 (°C/W)	4.2 (°C/W)
C_{th}	44 (J/°C)	268 (J/°C)

Table 2 shows the parameters values used in the model for a 310 F and 1500 F supercapacitor cells.

As explained previously, $R_{convection}$ depends on the convective heat transfer coefficient h (here natural convection) and the heat exchange surface of the supercapacitor S_{sc}. It is normal that $R_{convection}$ is smaller in case of the 1500 F cell because $R_{convection}$ and the heat exchange surface are inversely proportional, and the outer surface of the 1500 F is bigger than the 310 F one.

In order to study the condition of repetitive and extreme stress, repetitive charge and discharge cycles between (1.25 V and 2.5 V) and (1.35 V and 2.7 V) respectively with 30 A and 75 A constant currents are applied to the 310 F and 1500 F cells, respectively. The supercapacitors were suspended in the air to avoid any contact with other materials. The measurement is carried out with free convection.

Fig. 6 shows the measured temperatures $T_{Hi\text{-}mea}$ (i = 1, 2, 3, 4) and those obtained by simulation $T_{Hi\text{-}sim}$ for the 310 F cell. T_{H1}, T_{H2}, T_{H3} and T_{H4} represent the temperatures of the four thermocouples placed inside the BCAP310F supercapacitor. The four Thermocouples are placed at the middle of the axial position. In the radial position, the first thermocouple which is represented by the temperature T_{H1} is placed after three turns of jelly roll, the second thermocouple T_{H2} is placed after six turns of jelly roll, the third thermocouple T_{H3} is placed after nine turns of jelly roll and the fourth thermocouple T_{H4} is placed after 12 turns of jelly roll. The first phase represents the warming phase of the cell which is subjected to the charge and discharge cycles during around 40 min. Then, during the second phase the process is stopped and the temperature of the supercapacitor is decreased by natural convection to reach the ambient temperature which is about 22.5 °C.

Fig. 7 shows the evolution of the outside surface temperature of the 1500 F supercapacitor. The warming phase is about 133 min

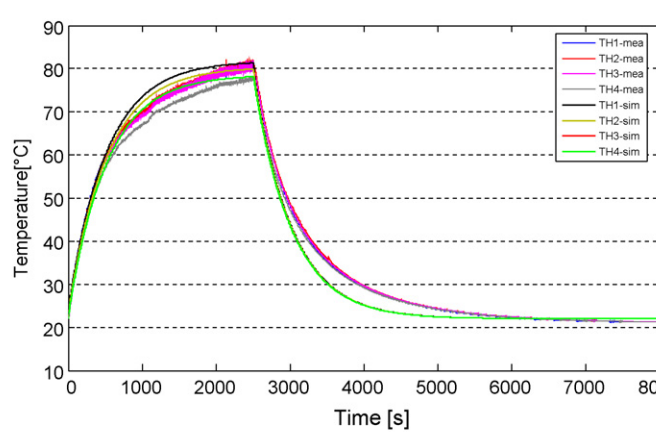

Fig. 6. Evolution of measured and simulated temperatures of 310 F cell as function of time. T_{H1}, T_{H2}, T_{H3} and T_{H4} represent the temperatures of the four thermocouples placed inside the BCAP310F supercapacitor. The four Thermocouples are placed at the middle of the axial position. In the radial position, T_{H1} is placed after 3 turns of jelly roll, T_{H2} is placed after 6 turns of jelly roll, T_{H3} is placed after 9 turns of jelly roll and T_{H4} is placed after 12 turns of jelly roll. .

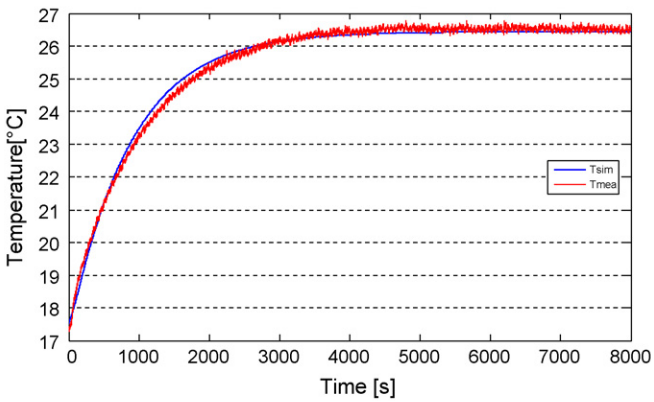

Fig. 7. Evolution of measured and simulated temperatures of 1500 F cell as function of time.

where the supercapacitor is charged and discharged at 75 A as constant current. The ambient temperature is around 17.5 °C.

These results show a good correlation between experimentation and simulation. Good agreements were obtained with 10 A and 20 A as a current value of charge and discharge cycles as well.

4. Thermal management of supercapacitor modules

Supercapacitor thermal management is important in order to optimize the performance and to reduce the life-cycle costs of advanced fuel cell, hybrid electric and electric vehicles (FCVs, HEVs, and EVs). Both, temperature and temperature uniformity significantly affect the performance and life of energy storage (ES) devices and vehicles. That is why the European project HyHEELS (hybrid high energy electrical storage) conducts research and development in the thermal management supercapacitors to optimize performance and extend life of the supercapacitors, the fuel cell and the whole power train of the vehicle. In fact, HyHEELS provides a supercapacitor energy storage system for the use in hybrid and fuel cell vehicles, which satisfies all properties necessary to make it an integrative component.

In order to study the thermal management of supercapacitor modules, it is interesting to study the influence of the configuration of the supercapacitor cells in the module. A simulation model in Matlab/Simulink® is developed to study by simulation the thermal management in supercapacitor modules. Each cell is modeled by a thermal-electric model. The convection heat transfer mode between cells is modeled by resistances. The convection from a cell is modeled by resistances which depend on the heat exchange surface and the convective heat transfer coefficient (the number of resistances is depends on the number of the neighboring cells). The convection between cells and air is also modeled by a voltage source which represents the ambient temperature, and a resistance which represents the convection heat transfer. The modeling takes into account the convective heat transfer coefficient which changes if the convection is natural or forced. Fig. 8 gives an idea about the thermal modeling of a six supercapacitors module and the heat transfer flows between the air and the cells and between the cells themselves.

Table 3
Characteristics of Maxwell 1500 F supercapacitor.

Parameters	Provided by Maxwell	Measured
Operating temperature range	−40 °C, +65 °C	–
Equivalent series resistance	ESR = 0.47 (mΩ)	ESR = 0.39 (mΩ)
Thermal resistance	R_{th} = 4.5 (°C/W)	R_{th} = 4.2 (°C/W)
Thermal capacitance	–	C_{th} = 268 (J/°C)

This simulation model makes it possible to dimension the supercapacitor cooling system, if it is necessary. This is in order to maintain the temperature of the module in the operating temperature range given by the manufacturer.

4.1. Simulation specifications

The supercapacitor used in the simulation is a BCAP 1500 Farad (Maxwell technology); its characteristics are shown in Table 3:

The module studied in this paper is composed of 20 cells of 1500 F. The cells are arranged into four rows of five supercapacitors each. The simulation was carried out using the simulation model presented previously. Each supercapacitor is represented by its thermal model. The manufacturer recommends an operating temperature range between −40 and 65 °C. The study of thermal management gives the evolution of the temperatures in different points of the module and determines if the module needs a cooling system. The simulation model permits also to size the cooling system when it is necessary. The simulation takes into account natural or forced convection and conduction heat transfer modes.

The application permits to subject the module to any power profile. For vehicle and transport application, it is interesting to study the evolution of the temperatures of supercapacitor modules when the module is subjected to a real life driving cycle. In this study the Scania and BMW driving cycles, respectively for heavy duty vehicle and for passenger car applications, are considered. The characteristics of each cycle are presented below.

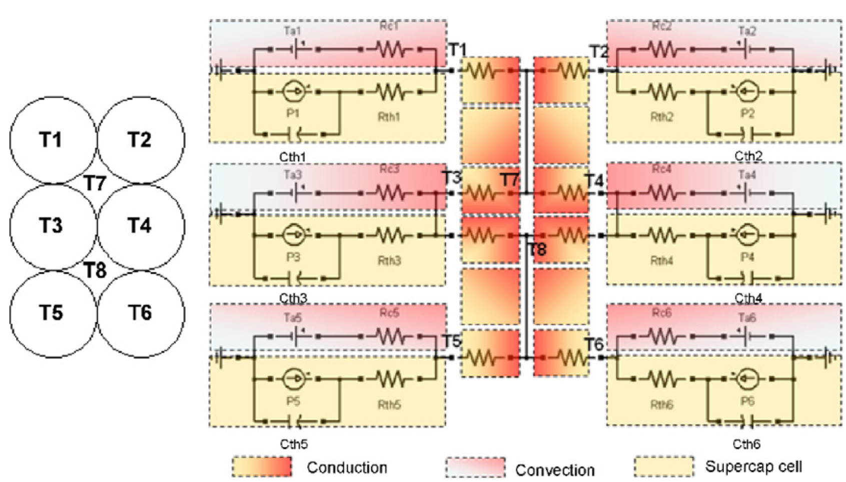

Fig. 8. Thermal-electric model of six supercapacitors module.

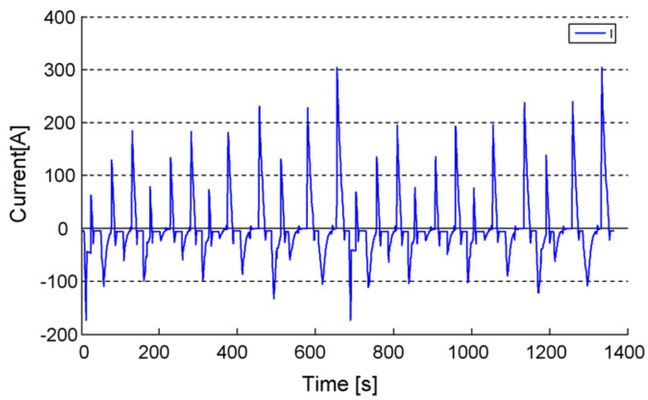

Fig. 9. Supercapacitors modules' current for Scania driving cycle as a function of time.

4.1.1. Scania heavy duty vehicle driving cycle characteristics:

The total time of the cycle is 22.766 min (1366 s). Fig. 9 shows the current of the supercapacitor modules during a cycle. The power losses in the supercapacitor modules depend on this current profile.

4.1.2. BMW passenger car driving cycle characteristics:

The total time of the cycle is 11.975 min (718.5 s). Fig. 10 shows the current of the supercapacitor modules during a cycle. The Joule effect in the supercapacitor modules is caused by this current profile.

4.2. Simulation results

The simulations are carried out for two different initial ambient temperatures which are 25 °C and 50 °C respectively, and for one and more cycles in order to get the steady states (Scania: 30 cycles = 11.383 h, BMW: 60 cycles = 11.975 h) with natural and assisted convection.

4.2.1. Scania heavy duty vehicle driving cycle

For one driving cycle, supercapacitors module does not require a cooling system. However, in practice supercapacitors module is used usually for more than one driving cycle.

Figs. 11 and 12 show the evolution of the maximum temperature of the supercapacitors module as a function of time with natural and assisted convection and with 25 °C and 50 °C as ambient temperatures, respectively. The maximum temperature of the supercapacitors module is located in the middle of the module. In natural convection, the temperature is higher than 65 °C, which means that the supercapacitors module requires a cooling system.

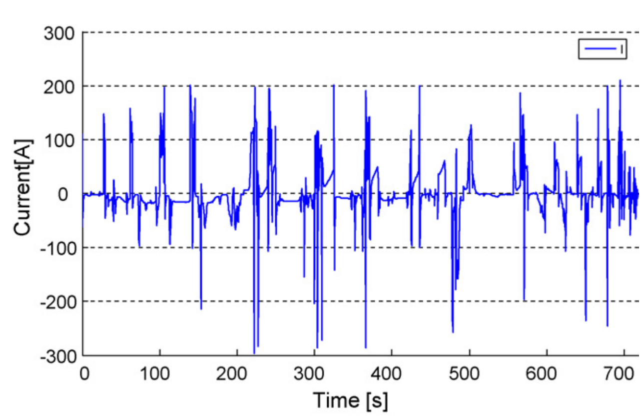

Fig. 10. Supercapacitors modules' current for the BMW driving cycle as a function of time.

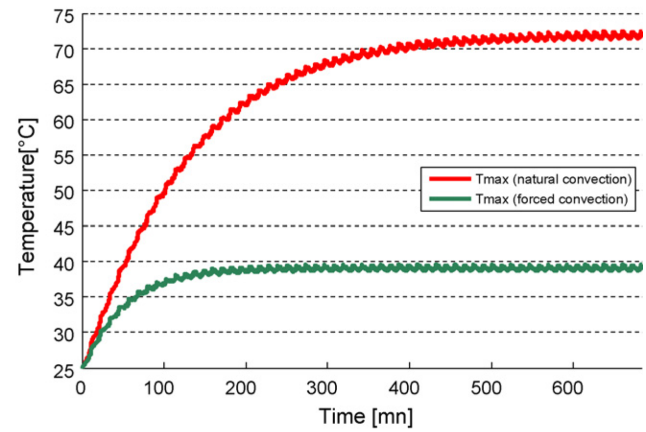

Fig. 11. Evolution of the maximum temperature in the module as function of time (30 cycles, ambient temperature $T_a = 25\,^{\circ}C$, natural and forced convection) with Scania driving cycle.

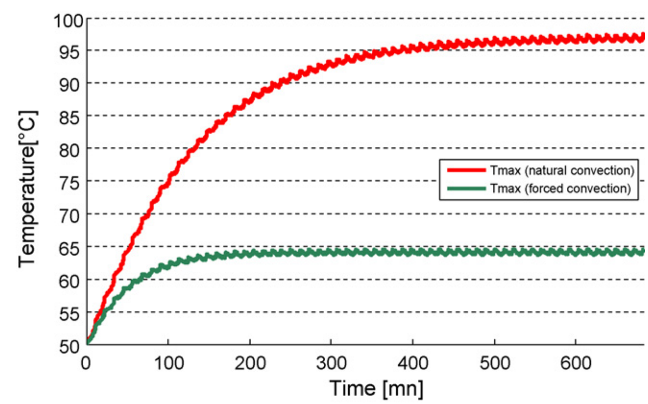

Fig. 12. Evolution of the maximum temperature in the module as function of time (30 cycles, ambient temperature $T_a = 50\,^{\circ}C$, natural and forced convection) with Scania driving cycle.

This last was introduced in the simulation by changing the convective heat transfer coefficient. In forced convection, it is clear that the temperatures are less than 65 °C.

4.2.2. BMW passenger car driving cycle

Fig. 13 shows the evolution of the maximum and minimum temperatures of the supercapacitors module as a function of time for

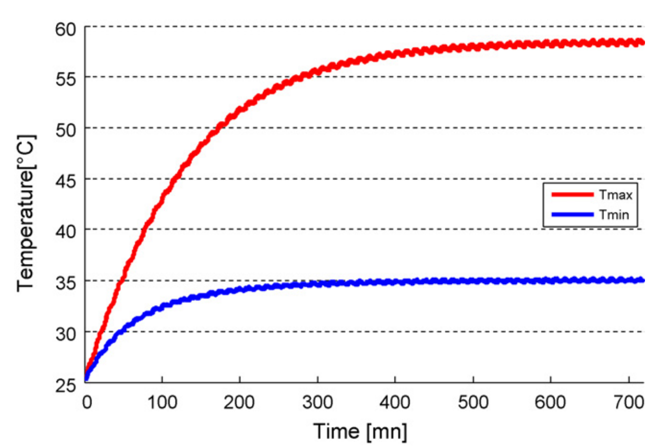

Fig. 13. Evolution of the minimum and maximum temperatures in the module as function of time (60 cycles, ambient temperature $T_a = 25\,^{\circ}C$, natural convection) with BMW driving cycle.

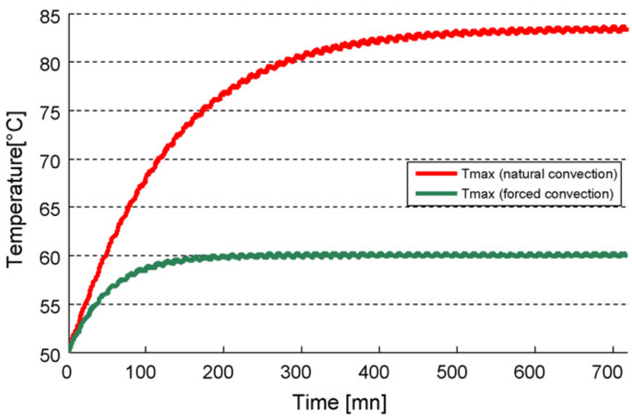

Fig. 14. Evolution of the maximum temperature in the module as function of time (60 cycles, ambient temperature $T_a = 50\,^\circ$C, natural and forced convection) with BMW driving cycle.

Table 4
Maximum and minimum temperatures in all cases.

Case	1 Cycle		30 Cycles		
	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{max} > 65 (°C)
Scania cycle					
T_a = 25 (°C)	29.21	32.21	39.42	**72.41**	After 10 cycles
T_a = 50 (°C)	54.21	57.21	**64.42**	**97.4**	After 2 cycles
T_a = 25 (°C) + Cooling			29.42	39.52	Never
T_a = 50 (°C) + Cooling			54.42	64.52	Never
	1 Cycle		60 Cycles		
	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} > 65 (°C)
BMW cycle					
T_a = 25 (°C)	26.7	27.75	35	58.5	Never
T_a = 50 (°C)	51.7	52.75	60	**83.5**	After 7 cycles
T_a = 50 (°C) + Cooling			53	60.25	Never

The bold values mean that the temperature is limit or higher than 65 °C.

60 cycles with natural convection and 25 °C as an ambient temperature. Fig. 14 shows the evolution of the maximum temperature of the supercapacitors module as a function of time with natural and assisted convection and with 50 °C as ambient temperature. In natural convection, the maximum temperature is higher than 65 °C; a cooling system was required, sized and verified as shown in Fig. 14.

4.2.3. Required cooling system:

In this application, the convective heat transfer coefficient h in natural convection is approximately 12 W m^{-2} °C^{-1}. For assisted or forced convection a higher convective coefficient is required which is about three times more than the natural one. This is equivalent to an air speed of 2.5 m s^{-1} approximately.

Table 4 recapitulates all the cases. In conclusion, for BWM driving cycle the supercapacitors module does not require a cooling system, if the ambient temperature is 25 °C. However, the cooling system is necessary when the ambient temperature is in order of 50 °C. For Scania heavy duty vehicle cycle, a cooling system is required because the module temperature exceeds the maximum temperature given by the manufacturer (65 °C).

5. Conclusion

In this paper, a supercapacitor thermal model is developed. This last is based on the thermal-electric analogy. Thermal resistance and thermal capacitance have been calculated for a cylindrical geometry. The model is validated using experimental results of the BCAP310F. This last is a special supercapacitor cell including four thermocouples inside manufactured by Maxwell technologies. The thermal model was adapted for BCAP1500F. Simulation and experimental results for BCAP1500F and BCAP310F are in good agreement. The thermal model developed in this paper was used for heat management of supercapacitor modules for Scania heavy duty vehicle driving cycle and for BMW passenger car driving cycle. The simulation results show that the hotspot is located in the middle of supercapacitors module. The cooling system of supercapacitors module depends on the power profile during the driving cycles, on the ambient temperature and on the convective heat transfer coefficient.

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