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Mitigation of Heat Dissipation in Ultracapacitor

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Abstract: **-**The main purpose of this study is to investigate the performance of ultracapacitors in energy intensive applications.This paper details the experimental analysis done for variouscombinations of material components used in ultracapacitors and its effect on major performance parameters. The paper describes the software simulation done to analyze the thermalconductivity behavior of the ultracapacitor. In the presented work,it is found that the polythene separator separating the two electrodes of the ultracapacitor and engulfing the ultracapacitor module is one of the weakest links in heat transfer. Synthesizedmaterialsused for substitutingpolythene separator will surely have optimized heat dissipation. The work done is one of its kind wherein experimental analysis and software simulationshave been carried out to complement the outcomes.

Keywords*: Ultracapacitor,Electrode,Electrolyte,MATLAB,Thermal*.

1. Introduction

In recent years, ultracapacitors have been improved upon their characteristics and have come up as a successful alternative tobatteries in many sectors. Although the energy storage capacity of batteries is10-100 times more than that of ultracapacitors, ultracapacitors overcome theadvantages offered by batteriesin many practical applications. Ultracapacitorsare being used as a power booster in many applications [1], even though they lag on parameters such as potential window [2]. Ultracapacitorscombined with batteries have made remarkable improvements in the automobile industry [3]. The faster charge and discharge characteristics of ultracapacitor makes its use suitable in typical impulse current generator applications [4- 6].

Numerous research papers elaborate the ultracapacitorbehavior and need of additional extensive research on ultracapacitors [7-9]. Various alternatives are being used for electrode materialsnamely, carbide derived carbons, zeolite– templated carbons etc. [10].Sustainable development objectives have resulted in increased use of biomass-based materials in the preparation of electrodes of ultracapacitors [11-12]. The electrode-electrolyte double layer formed in the ultracapacitor enhance storage capacity [13-16]. Various charge storage volumes with different electrolytes are the result of electrochemical reactions [16-24]. There is a need to predict the temperature rise of each of the layer in ultracapacitor to address the issue of heat dissipation. The major drawback associated with the use of ultracapacitors is that they heat up during operation. Since an ultracapacitor is a pulse current device, the thermal aspects are usually neglected.

2. Objectives

In this paper an attempt has been made to study the effect of heat through various materials that are used to construct an ultracapacitor using MATLAB and COMSOL simulations. The simulation shall help visualize how each layer of the ultracapacitor is heated and devise an easy or difficult path for heat to dissipate.Thermal runaway can be avoided by such study. This is one of the major research gap identified and is addressed in this research work. With this objective, the research paper is framed into subsequent parts. The following section on Methods elaborates the electrode materials, separators and packaging materials used in the construction of ultracapacitors. Part 3 comprises of parameters of ultracapacitor under consideration.It is followed by their analysisin MATLAB and COMSOLalong with the results obtained in part 3 and part 4. It is followed by concluding remarks.

3. Methods

Materials in Ultracapacitors

Manufacturing of the ultracapacitor primarily involves making use of activated carbon simply because of its inexpensive value, highexterior volume, electrode manufacturing methodologies and availability. Storage capacity of ultracapacitor is greatly influenced by the interface that occurs because of double layer formations between the electrode and electrolyte. Consequently, capacitance primarily hangs on the Specific Surface Area (SSA) available for electrolyte ions, it is referred to as available SSA. Specimens of the electrode making carbon materialsare carbide derived carbon, zeolite-templated carbon, onion like carbon nanotubes, graphene etc.

Nearly all ultracapacitors use activated carbon for electrode preparation. It inherits substantial surface area, inexpensive value, larger pores and favorable electrical characteristics. Activated carbon can be made by physical and chemical procedure from carbonous materials. In this research work, VULCAN XC-72R, NORIT, PICA and YP50 are verified for parametric mismatch assessmentThe SEM image of Vulcan XC-72R hypothesizes about its structure, that the prime particle is clustered and curvilinear in shape. In view of the nonstop development of technology, single walled carbon nanotubes and multi walled carbon nanotubesare an important metamorphosis. CNTs (Carbon nanotubes) are known for their peculiar pore composition, good thermic and mechanical firmness with exemplary electrical characteristics.Carbon-fiber-reinforced polymer also called graphene has gained its acceptability now days. Metal oxides are blended with activated carbon to lessen the internal resistance of the device.Manganese dioxide stands as the predominant metal oxide extensively utilized in the fabrication of ultracapacitors. Throughout this research endeavor, the terms 'manganese dioxide' and 'metal oxide' have been employed interchangeably to denote the active material employed in the construction of ultracapacitors. They display large specific capacitance and small resistance which make them highly sought after. Normally, transition metal oxides are more appropriate for ultracapacitor constructions. Manganese dioxide possesses good chemical and physical characteristics which finds extensive usage in the construction of ultracapacitors. It has high SSA. It is inexpensive and present in abundance. It not only is inexpensive and habitat friendly, but also has superior capacitive performance in numerous electrolytes. Other oxides like ruthenium, tinetc. have limitations in terms of their characteristicsor commercialization. Scientists have put in their continuous efforts to replace the polythene separators in view of their deteriorating effects on the environment. Various materials like paper, PBI, PVC, AGM etc. have been tried by researchers with limited success. Polythene is porous and has got non-decaying characteristics making it practical for its use in ultracapacitors Current collector is a major constituent of the ultracapacitor electrode. It is desirable to have the current collector as permeable as possible. Till date aluminum and stainless steel are the most usedcurrent collector materials either in the form of a foil or a wire mesh.

Parameters affecting heat dissipation

This paper helps in finding out the issues in characteristics of the materials used in the ultracapacitor by simulation approach. Thermal conductivity and particle size are most critical parameters in heat dissipation in ultracapacitor. Theoretical analysis of these two parameters is presented in this section.

Thermal Conductivity

The performance of the ultracapacitor is heavily dependent on the volume of effective heat transfer. It decides the life of the ultracapacitor to a large extent. Ultracapacitors draw a large amount of current because of which their components get heated. It is desirable to pass on this heat effectively to the neighboring component so as to use theultracapacitor efficiently over its design life. Materials used in ultracapacitor; their thermal conductivity are specified in Table 1.

Table.1 Thermal Conductivities(W/m*K) of normally used materials in ultracapacitor.

Packaging Materials	Separator materials	Electrode materials	Current Collector materials
0.09-0.63	0.2-0.5	0.5-0.7	200-210

Table 1 describes that the current collector thermal conductivity is comparatively much better than that of the electrode materials as well as separator. It is obvious that the thermal conductivities of respective materials shall fall in the range for faster conduction of heat otherwise it will contribute to the destruction of the ultracapacitor. It is essential to have research in this direction from the perspective of material engineering. The separator having improved thermal conductivity will be a path breaking solution.

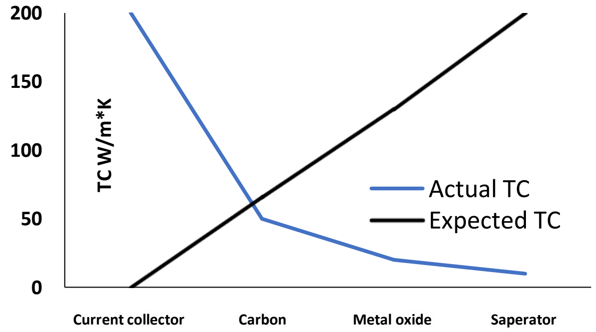

Figure.1 Mismatch of thermal conductivity

Figure 1 is thegraphical representation of mismatch of thermal conductivity for generally used materials in ultracapacitor and expected thermal conductivity(TC)variation. The thermal conductivities of ultracapacitormaterials do not fall under identical range. For high performance of ultracapacitor, the heat transfer rate shall be as gradual as possible however the graph cannot be parallel to the reference horizontal axis because the rate of heat transfer reduces when heat transfer advances from one material to another.

Particle Size

It is essential to have the pore size and particle size in the same range. The better the electrolyte molecules or ion size matches with the pore size of the electrodes the more effective charge accumulation takes place. It leads to the enhanced value of the capacitance. It is expected that, the linking of electrode particles with the electrolyte particles to a greater extent leads to enhanced heat flow in the ultracapacitor.Materials used in ultracapacitor, their particle and pore size are given in Table 2. Figure 2 illustrates the relative position of the materials with regard to ultracapacitor. Each material has its derived particle size that influences the thermal stability of the overall ultracapacitor structure.

Table.2 Particle Size (um) of generally used materialsin ultracapacitor

Electrolyte materials	Electrode materials		Separator Materials
	Vulcan XC-72R	**Metal Oxide**	
0.03-0.2	0.02-0.05	0.057	50-60

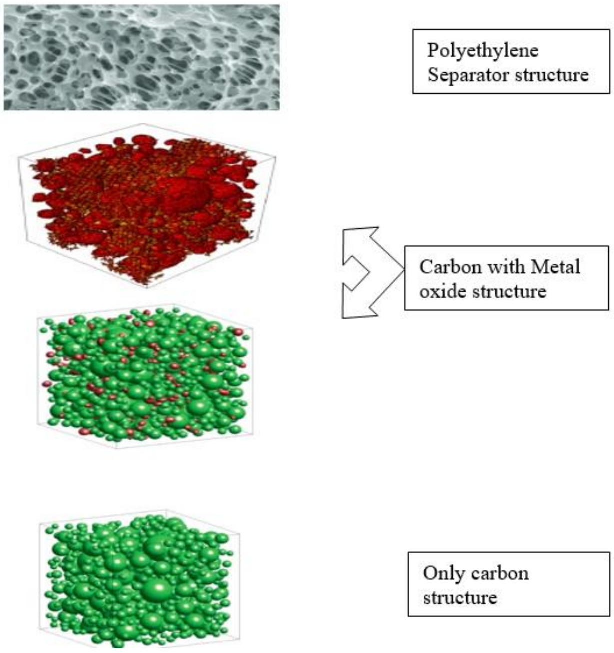

Figure.2 Possible particle interface among electrode material and separator in Ultracapacitor.

Analysis of heat dissipation using MATLAB

Various parameters of ultracapacitors like dimensions of electrode, porosity, material type, material density, thermal conductivity, heat capacity, electrical conductivity etc. are used as input parameters and temperature rise at each layer is considered as output parameter. MATLAB did permit plotting of major functional parameter i.e., temperature rise of each layer for various combinations of electrode materials, separator materials and electrolytes. Figures3, 4 and 5 show the graphical user interface after inserting the input values required. These figures show the temperature at various layers with various carbon and metal oxides. Some interesting facts were uncovered after running the simulation. Heat flow depends on various factors like particle size mismatch, thermal conductivity etc. This kind of simulation can be extended for analysis of other electrical energy storage devices like battery, capacitor and fuel cell. Ultracapacitor is a pulse current device and will be used in every battery operated and fuel cell based vehicle in the coming decades.Hence, this simulation can help researchers decide the exact material characteristics required for ultracapacitorconstruction to prevent thermal runaway. It will automatically increase the life cycle of the device. This simulation is the first of its kind and is the main contribution of the research work presented in this paper.

Analysis of heat dissipation using COMSOL

In the realm of ultracapacitor research, a comprehensive analysis of critical parameters, including electrode dimensions, porosity, material properties and their impact on temperature rise within the device, has been undertaken. This section employs COMSOL Multiphysics as the simulation platform, extending the capabilities for in-depth exploration.The simulation process entails the systematic variation of these input parameters, yielding temperature rise profiles across different layers within the ultracapacitor. Figures 6, 7, and 8 illustrate the user interface in COMSOL after input parameterization, showcasing temperature distributions for a diverse range of electrode materials, separator materials, and electrolytes.Noteworthy insights have emerged from this extended simulation endeavor. The analysis elucidates that heat flow within the ultracapacitor system is intricately influenced by factors such as thermal conductivity among others, unveiling the complex interplay of these variables. Furthermore, the significance of this research extends beyond ultracapacitors alone. While the focus has been on this pulse current device, the methodology presented here holds the potential for broader applications encompassing the analysis of various electrical energy storage devices, including batteries, capacitors, and fuel cells.Considering the imminent integration of ultracapacitors into the realm of electric vehicles, our simulation findings bear profound implications. The ability to determine precise material specifications for ultracapacitor construction, mitigating the risk of thermal runaway, and enhancing the overall lifecycle of these power devices, is a pivotal contribution of this research. One significant revelation from the investigations is the identification of the polyethylene separator as the primary factor limiting heat dissipation within ultracapacitors. This discovery underscores the critical role played by the separator material in thermal management. As depicted in Figure 9, a three-dimensional representation of the ultracapacitor subjected to the same parameters as those studied in the previous MATLAB analysis is presented. Notably, despite variations in electrode materials, the volume of the ultracapacitor module remains relatively constant at approximately 0.18 cm^3. Consequently, the observed temperature drops across different scenarios are of minor significance, hovering at around 1% across all cases.

4. Results

Result of heat dissipation using MATLAB

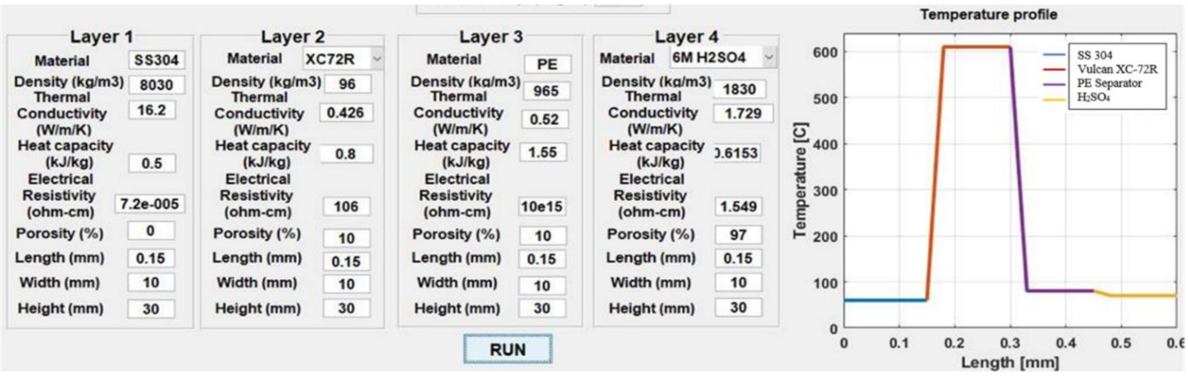

Figure.3 Temperature variation in the ultracapacitor with Activated Carbon as electrode material

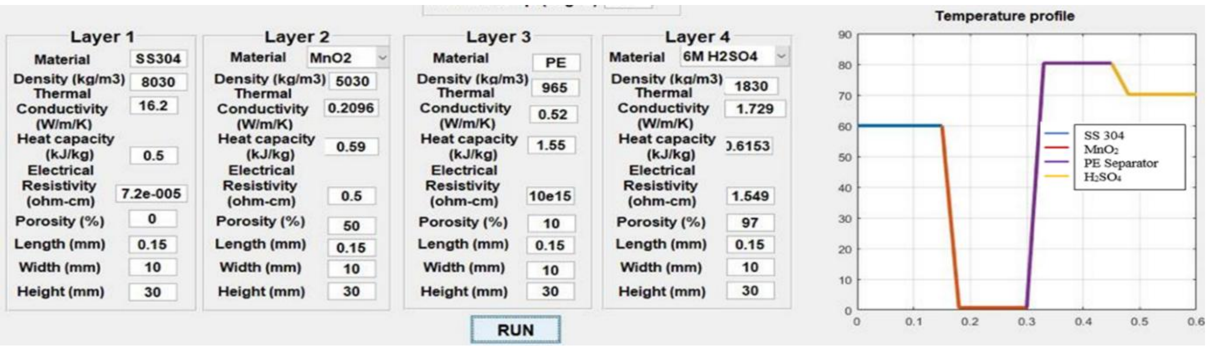

Figure.4 Temperature variation in the ultracapacitor with metal oxide as electrode material.

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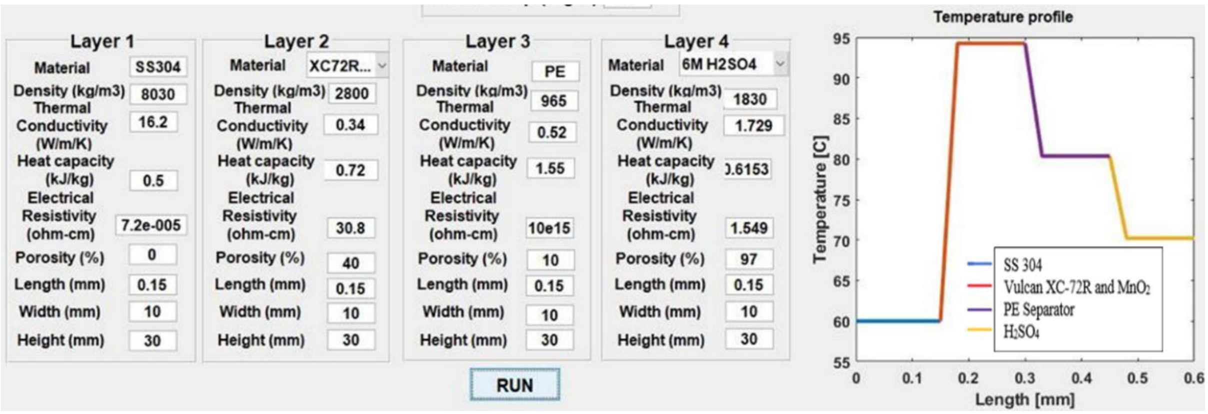

Figure.5 Temperature variation in the ultracapacitor with activated carbon and metal oxide as electrode material.

Figure3 describes the temperature variation in the ultracapacitor with Activated Carbon as electrode material. Temperature of current collector, electrode material, electrolyte, and separator are in simulation can be observed. Maximum temperature reached is 600 degree Celsius. Figure 4 describes the temperature variation in the ultracapacitor with metal oxide as electrode material. Temperature of current collector, electrode material, electrolyte, and separator are in simulation can be observed. Maximum temperature reached is 80 degree Celsius. Metal oxide helps in quick dissipation of heat. Figure 5 describes the temperature variation in the ultracapacitor with metal oxide and activates carbon as electrode material. Temperature of current collector, electrode material, electrolyte, and separator are in simulation can be observed. Maximum temperature reached is 95 degree Celsius. Metal oxide helps in quick dissipation of heat is the major finding from this simulation work.

Result of heat dissipation using COMSOL

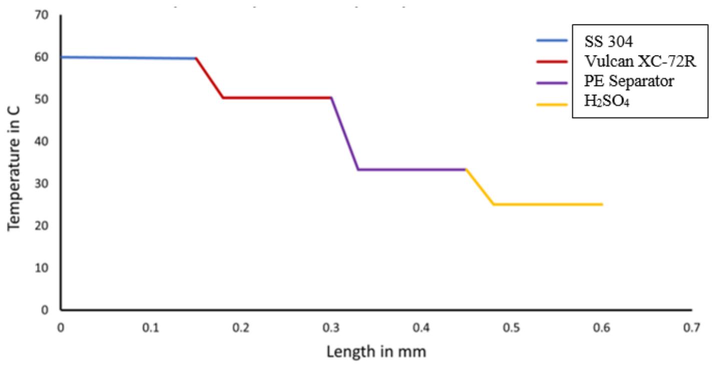

Figure 6 Temperature variation in the ultracapacitor with Activated Carbon as electrode material in COMSOL

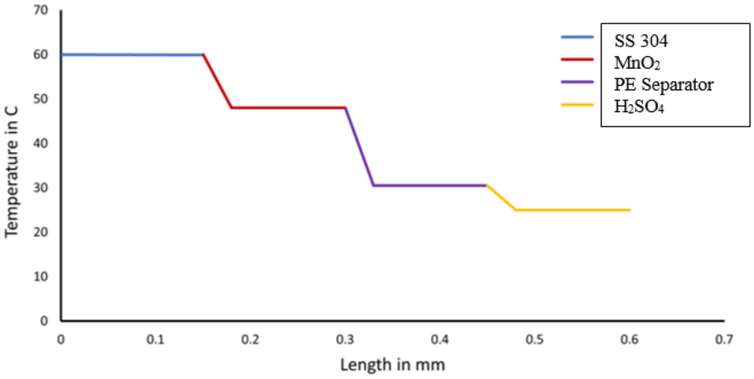

Figure 7 Temperature variations in the ultracapacitor with metal oxide as electrode materialin COMSOL.

Figure 9 offers a visual representation of the thermal analysis within the ultracapacitor, illustrating the temperature variations which are not possible in MATLAB simulation. This simulation does not give temperature variation at each layer in gradian form as it considers average temp variation within the module. It underscores the stability of thermal performance within the compact volume of the ultracapacitor. It also shows a significant temperature drop at the PE separator layer which is not clearly coming out in MATLAB simulation.

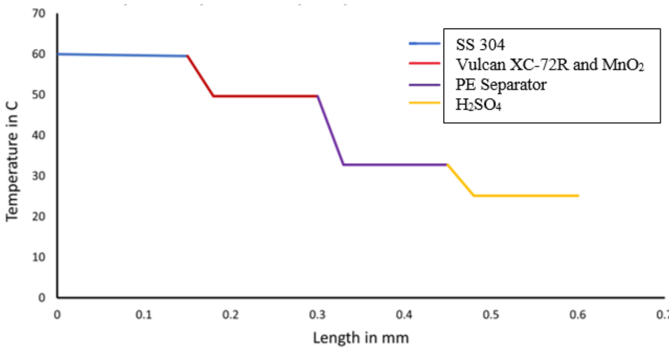

Figure. 8 Temperature variations in the ultracapacitor with activated carbon and metal oxide as electrode material in COMSOL

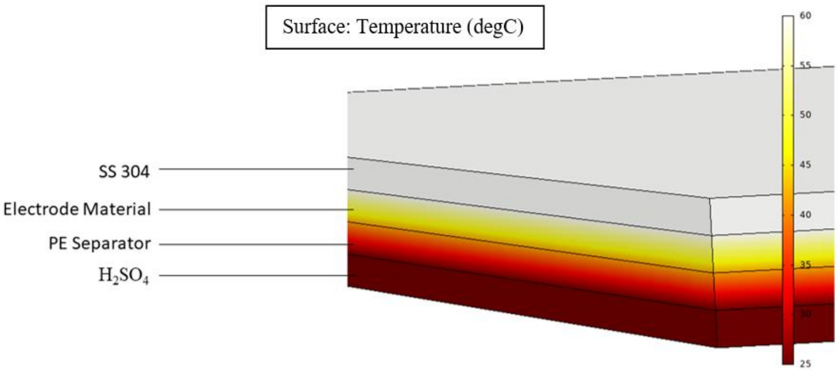

Figure 9: Thermal analysis of ultracapacitor Module

5. Discussion

As observed, the thermal conductivity of the materials used in ultracapacitor is yet to ensure free passage of heat transfer. MATLAB simulation has come out with importance of metal oxide in heat transfer. In general metal oxides are added for additional charge storage to improve capacitance and it also reduces the internal resistance. However, MATLAB simulation has demonstrated additional role of heat transfer by metal oxides in electrode material. As per COMSOL simulation one requires separator with good thermal conductivity to minimize thermal runaway of the device. Mainly the separator is the weakest link in heat transfer. Exploring separator materials with optimum thermal conductivity will have far reaching effects on the performance of the ultracapacitor regarding heat transfer. Use of synthesized materials as separator will pave the way forultracapacitor with optimized functioning. MATLAB simulation gives internal temperature rise in the graphical form where as COMSOL givens three dimensional visualization of the device which thermal imaging camera also may not able to detect or present. COMSOL cannot pick internal temperature shoots which has been clearly picked up by MATLAB simulation.

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