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Thermal regulation of satellites using adaptive polymeric materials

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Abstract

This paper focuses on the thermal performances of an adaptive radiator made of 16 electroemissive devices (EEDs) acting as electro-active materials for thermal control of satellites. EEDs are similar to an electrochemical cell where one electrode serves as active layer in the infrared and is made of a conducting polymer, the poly(3,4-ethylenedioxythiophene) (PEDOT), interpenetrated into a polyethylene oxide/nitrile butadiene rubber (PEO/NBR) solid gel electrolyte as supporting matrix. First, EEDs were placed in moderate vacuum (10⁻³ bars) to estimate their optical cyclability c.a. 4000 cycles in neutral and oxidized state. Then, an electro-emissive radiator (EER) assembled with 16 EEDs (total area of 80cm²) was tested under space vacuum conditions. "Hot" and "cold" operating cases of the satellite were simulated and ability of the radiator to control radiative exchanges between the satellite and its environment was estimated by comparison with the currently used optical solar reflector (OSR) radiators. In low emissivity state, the EER can slow down

the rejection of heat in a cold environment which is an interesting feature in terms of energy saving. Also when the EER is not directly exposed to the sun, it is able to reject the heat in the same way as the OSR radiator in a hot phase. By comparing the electrical consumption with a system operating with OSR, an energy saving in the order of 25% was demonstrated. Finally the EER exhibits bistability during many hours, *i.e.* memory effect once electrically switched into a given emissivity state, allowing to further reduce the electrical consumption.

1. Introduction: the challenges of the thermal control of satellites

An efficient thermal control of a spacecraft is a major issue that affects the performances and the longevity of the internal subsystems.[1-3] The temperature of satellite components (equipment, structure elements...) is set by the equilibrium between internal heat dissipation and external heat fluxes. For dissipating components such as the on-board system, the temperature must be maintained within a safe temperature range, generally within -30 °C and +90 °C. The common approach to configure the thermal control of satellites is to optimize, as a matter of priority, the hot environment. In this environment, the satellite is facing the maximal external solar flux and the thermal dissipation of the electronic components is at a maximum, leading to the most important thermal load. The current approach is to thermally insulate some sides of the satellite while allowing some dedicated areas to reject out the heat to space through radiative heat transfer. Radiative panels (i.e. radiators) are thus used. In the hot environment, these radiators are subject to two criteria: (i) a high infrared emissivity to reject as much as possible the heat towards space, and (ii) a low solar visible absorptivity to avoid high temperatures when the sun illuminates the surface of satellite. An excessive solar absorptivity and/or a low infrared emissivity (in hot case) would require more radiative surface leading to the modification of the satellite size and weight. Therefore, the ratio absorptivity/emissivity impacts directly the heat rejection capacity, the size of the satellite,

and thus its competitiveness on the market. Consequently, it is a critical parameter for satellites.

Currently, optical solar reflector (OSR) radiators, consisting in thin film coated quartz tiles, are directly applied onto the satellite radiative panels. Indeed, the OSR radiators have the two advantages required for the hot environment, a very low solar absorptivity of approximately 0.11 and a high emissivity of 0.84.[4] Despite its very interesting properties, this technology suffers from a significant drawback in the cold environment: indeed, when the satellite is submitted to the lowest external heat flux and reduced equipment dissipation, the high emissivity provided by the OSR radiators is a major issue. The satellite continues to reject the maximal quantity of heat while it is already in a cold environment. The temperature inside the satellite can decrease below the minimum limit required for the electronic components.

To overcome this problem, heaters are used to maintain the temperature within the required range. Although this solution is simple and effective, the heaters consume a significant part of the installed electrical power, which is a limited resource in any spacecraft. Moreover, for the future telecom satellites, their orbiting positions will be driven with an electric propulsion system. Therefore, a major part of the onboard electrical power is required for the orbiting phase which can last for many weeks. It is thus vital to find an alternative to limit the use of heaters and save electrical power.

An alternative is to use a radiator covered with a material capable of modulating its emissivity according to the encountered environment.. Besides the classical thermal coatings, thermal louvers [5-7] are one of the most widely used technologies to modulate the optical properties. Thermal louvers are mechanical systems with movable blades (venetian blinds), which exhibit a low solar absorptivity in the hot case and a low emissivity in the cold case. Nevertheless, this system presents several disadvantages *e.g.* expensiveness, its mechanical aspect [8]. It has also a limited life-time, due to a finite number of blades openings / closures. For all these

reasons, thermal louvers are not considered as a possible standard technology for wide use on board of satellites.

Some alternative solutions to be considered are variable emissivity coatings, such as electrostatic radiators,[9] IR-thermochromic [10] and electroemissive [11,12] systems. Among these latters, our laboratory explores since 2009 the possibility to use polymer-based electroemissive devices (EEDs). Such EEDs can modulate their emissivity in the infrared region by applying a low electrical voltage to the device. Indeed the active layer is an electronically conducting polymer, poly(3,4-ethylenedioxythiophene), having redox properties: in neutral state, it is semi-conducting then exhibits a high IR-emissivity, while it has a low IR-emissivity when oxidized due to its quasi-metallic behavior.[13] Then polymer-based EEDs are constructed as electrochemical cells with at least one electrode material optically active in the infrared region (active layer). Thus, in a hot environment, a high emissivity of the PEDOT allows a maximum rejection of the heat. Conversely, when in a cold environment, the switching to a low infrared emissivity allows a minimum rejection of heat. The emissivity variation could thus be = controlled from Earth in order to maintain the temperature range required on board of the satellites.

The synthesis of such polymer-based EEDs was described by A. Teissier *et al.* [14,15] and these EEDs demonstrated their potential use for the thermal regulation of satellites. To date, mechanical properties have been improved to help along their integration in scalable application.[16]

The aim of the current study was to evaluate the thermal performances of an electroemissive radiator (EER) comprising 16 of such EEDs. A radiator with a surface area of ~80cm² was thus fabricated in order to evaluate both hot and cold environments mimicking the satellites orbiting around the Earth. Tests were conducted without consideration of aspects such as the solar absorptivity nor the radiations to which the EEDs would be subjected in space (UVs,

electrons, protons, gamma, etc...). These tests were thus carried out only in a high vacuum chamber (10^{-6} mbar). The hot, cold and intermediate environments were simulated with temperatures representing the different configurations encountered by the on-board electronics in space. The objective was thus to assess the performances of the radiator in conditions close to the space thermal and vacuum environment (high thermal vacuum, and temperatures ranging from -25 °C to +80 °C).

2. Experimental part

2.1. Chemicals

Nitrile butadiene rubber with 44% acrylonitrile content (NBR, $M_w=230$ kg/mol, Perbunan 4456F Lanxess), poly(ethyleneglycol) dimethacrylate (PEGDM, $M_w=750$ g/mol, Aldrich), poly(ethylene glycol) methyl ether methacrylate (PEGM, $M_w=450$ g/mol, Aldrich), dicumyle peroxide (DCP, $M_w=270$ g/mol, Aldrich), anhydrous Iron chloride (FeCl₃, $M_w=162$ g/mol, Acros), dicyclohexylperoxydicarbonate (DHPC, $M_w=296$ g/mol, Groupe Arnaud) were used as received. 3,4-ethylenedioxythiophene (EDOT, $M_w=142$ g/mol,) was purified by distillation under vacuum before use. 1-ethyl-3-methylimidazolium bis(trifluoromethyl sulfonyl)imide (EMITFSI, $M_w=391$ g/mol, Solvionic, 99%) was used as electrolyte.

2.2. Preparation of PEO/NBR/PEDOT semi-Interpenetrating Polymer Network and electroemissive device (EED)

The semi-Interpenetrating Polymer Network (semi-IPN) PEO/NBR host matrix was synthetized following a method already described in literature.[17] The obtained semi-IPN films were swollen with 5% of EDOT and immersed for 2 h into a FeCl₃ organic solution (0.25 mol/L) at 50 °C. After the EDOT polymerization, the resulting film was washed several times with methanol to remove the excess of FeCl₃ and the edges were removed to end with

the tri-layer architecture shown on Figure 1. The semi-IPN PEO/NBR/PEDOT was dried at room temperature under vacuum for 24 h. Finally, the semi-IPN PEO/NBR/PEDOT was swollen in pure EMITFSI. Once saturation was reached, the EED was obtained and carefully wiped with paper to remove extra ionic liquid and sandwiched between to gold-metallized plates for further characterizations.



Figure 1: (left) Schematic drawing of the EED semi-IPN PEO/NBR/PEDOT. (Middle and right) device fabrication.

2.3. Characterization techniques

Electrochemical characterizations were carried out by cyclic voltammetry (CV) using a potentiostat/galvanostat (VSP150, Biologic Scientific Instrument). EED samples were sandwiched between two gold plates and CV were recorded by applying bias between -1.2V and +1.0V. The electro-optical measurements in the infrared spectral region were performed in a reflectance mode on a spectrophotometer (Bruker, Equinox55) coupled to an integrating sphere (Bruker A562-G) where the beam light normal incidence angle is 13°. The IR-emissivity was deduced from the reflectivity (%R_{ir}) given that $\varepsilon_{ir} = 1 - \%$ R_{ir} for an opaque layer. A potentiostat/galvanostat (same as above) was coupled to the spectrophotometer to apply a bias voltage between ±1.2 V and spectra were recorded between 2.5 and 20 µm.

2.4. Fabrication of the electroemissive radiator (EER)

The electroemissive radiator (EER) consisted in 16 semi-IPN saturated by EMITFSI and sandwiched between two large gold-metallized contacts (10cm x 10cm) acting as the working electrode and counter-electrode (see Figure 2A and Figure 2B). The 16 EEDs were arranged as a 4x4 array allowing a total active surface of 81cm² as shown in Figure 2B. The working electrode was composed of 4 windows and the counter-electrode (10x10cm) was made of a multilayer assembly including a thick aluminum plate (1.5 mm) which has a high thermal conductivity (237 W.m⁻¹.K⁻¹). The aluminum plate was coated by a 100µm layer of epoxy to electrically insulate the EEDs samples from the aluminum. On the epoxy, three metallic layers were deposited *i.e.* copper (35 µm), nickel (2 µm) and gold (50 nm) to allow the contact with the 16 EEDs counter-electrode. The resulting overall thermal conductivity of the bottom plate was $3W.m^{-1}.K^{-1}$ considering the different layers (Al + epoxy + Cu + Ni + Au). Finally, to further follow the evolution of temperature, thermistors were placed close to the gold-coated layer support as seen on Figure 2A. All sensors should allow the gathering of information regarding the temperature of the EEDs and the overall temperature of the radiator during the different phases of the test. To finalize the radiator, heater band was taped on the back of the aluminum plate (Figure 2C) to further mimic the different hot and cold environments of satellite (see section 3.2 below).



Figure 2: (A) schematic of electroemissive radiator composed of a top frame, a bottom aluminium plate coated with epoxy, Cu, Ni and Au and sandwiching the 16 EEDs. 4 Thermistors are placed on the back of EED on the gold layer to measure the temperature. (B) Font picture of the radiator and (C) back picture of the radiator showing the aluminium plate and heating band.

To allow an easy and direct evaluation of EEDs relevance, an optical solar reflector (OSR) with similar emissive area (81cm²) and fixed emissivity ($\varepsilon = 0.82$) was used. Before insertion into the black box and the thermal chamber, both electroemissive radiator and OSR were covered by a multilayer insulation (MLI) blanket on all their non-active surfaces (back and edges) (see Figure 3).



Figure 3: Images of (A) the electroemissive radiator and (B) the OSR covered by multilayer insulation (MLI) blanket.

2.5. Principle of test sequence

To evaluate the ability of the EER, to reject or conserve the heat, it was indeed not possible to measure the emissivity of the radiators in vacuum *i.e.* with an emissiometer. However, the optical performances were indirectly evaluated through temperature variations measured with the thermistors placed under the EEDs on the radiator.

To simulate conditions close to the space environment, the OSR and the electroemissive radiators were placed into a black box simulating a thermal environment at -60°C (Figure 4), itself placed into the secondary vacuum chamber under 10⁻⁶ mbar. This temperature represented a good compromise between operational conditions (close to the deep space temperature level facing the radiator) and feasibility of the experience in the thermal chamber. Additionnaly, "*passenger*" samples were also placed into the black box. These samples had no electrical supply and were therefore not switched. Nevertheless, they experienced similar vacuum and thermal conditions during all time of the test sequence (see section 3.3).

The cold (-25°C), intermediate (20°C) and hot (+60°C) environment equilibrium temperatures were set through the heating rubbers placed behind the OSR and electroemissive radiators. By controlling the heat flux injected ($P_{heaters}$) though electrical heaters for a given emissivity, it was possible to control the temperature of the radiators (mimicking the temperature of the satellite). For each temperature step (cold, intermediate and hot), once $P_{heaters}$ was injected and the temperature stabilized, $P_{heaters}$ was maintained.

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Figure 4: Radiative black box covered with MLI containing the OSR and electroemissive radiators, and the 4 *"passengers"* samples.

3. Results and discussion

3.1. Operating and stability of an EED under vacuum

Before testing the radiator in vacuum close to space conditions, the operating and the stability of the EED under primary vacuum were studied. As described before, the EED is made of NBR/PEO/PEDOT semi-IPNs swollen to saturation with neat EMITFSI. First, the optical switching of the EED was performed to evaluate the IR-optical performances. The Figure 5 shows the reflectivity variation of the PEDOT active layer in its both neutral (blue curve) and oxidized (red curve) states. Upon oxidation of the PEDOT active layer, the reflectivity is high in the 2.5-20µm wavelength range (%R_{2.5-20µm} = 56\%, ε_{ir} = 44%) with a plateau at 60% above 8µm (ε_{ir} = 40%). Under PEDOT dedoping, the reflectivity plateau decreases down to 20% with a mean value of %R_{2.5-20µm} = 14% (ε_{ir} = 86%) in the whole wavelength range.



Figure 5: Reflectivity %R measured between 2.5µm and 20µm for an EED.

Then, electrical switching of the EED under vacuum was checked. To do so, an home-made electronic potentiostat was developed to operate in vacuum with the sample (Figure S1). This system is powered by a commercial Li-battery (1200 mA.h) and can operate autonomously *i.e.* apply the desired bias voltage and record current. A potential sweep at 50mV/s was performed in a two electrodes configuration and the bias at the two vertex (+1.2V and -1.2V) was maintained during one minute, allowing a complete doping and dedoping of the EED's active layer. During the cycling, data were recorded on a microSD card previously integrated into the electronic board. The vacuum cyclability tests were carried out under the vacuum bell at a pressure of 10^{-3} bars and at room temperature. Every thousand cycles throughout the cyclability test, the properties of the device were measured outside the bell, enabling to check (*i*) the electroactivity of the EED under vacuum and (*ii*) the stability of the optical properties over time. For this latter, the cycling was momentary stopped and the mean reflectivity in the wavelength range 2.5-20 µm measured in open air both in the neutral and oxidized states. The cyclic voltammetry (CV) curves and mean emissivity measurements from cycles 1, 1200, 2000, 2900 until 3700 cycles are shown in Figure 6.



Figure 6: (A) cyclability tests using cyclic voltammetry for an EED measured in a 2-electrodes configuration under primary vacuum using home-made potentiostat. (B) Average emissivity values ε_{ir} for the oxidized and the neutral states of active layer according to the number of electrochemical cycles performed.

One can notice that the EED is functional under moderate vacuum, the first cycles demonstrating the operational switching of the system. After 3700 cycles, the device is still switching, but a slight decrease of c.a. 20% of the electroactivity is observed with respect to the initial value. It can be observed on Figure 6A that this decrease occurs progressively during the first hundreds cycles. Beyond 1200 cycles, the electroactivity is stabilized and no more loss is observed up to 3700 cycles.

The emissivity of the EED, in the oxidized and neutral states, was deduced from measured reflectivity values, by applying a bias voltage of ± 1.2 V. The evolution of mean ϵ values (for the oxidized and neutral states) as well as emissivity variation ($\Delta\epsilon$) are plotted on Figure 6B versus the number of cycles performed. Before cycling, the emissivity variation $\Delta\epsilon$ reaches 29 %. After 3700 cycles, a decrease occurs and the emissivity variation drops to 24 %. This decrease is mainly due to the evolution of the emissivity in the oxidized state: upon cycling, the electronic conductivity of the PEDOT layer is probably affected. This is in agreement with the measured loss of its electro-activity. Nevertheless, this study highlighted the ability of the NBR/PEO/PEDOT semi-IPNs based EED to operate under vacuum (~10⁻³ bars) while demonstrating their cycling and optical performances stability over time.

3.2. Thermal tests in vacuum conditions

For the thermal tests in vacuum conditions, a radiator composed of 16 EEDs swollen with EMITFSI was fabricated (see experimental part). Besides, its performances were compared to those of the system currently used on the satellites, the optical solar reflector (OSR) radiator. In the forthcoming and to simplify the notation, the radiator composed of the 16 EEDs swollen with EMITFSI is referred as electroemissive radiator (EER).

The experiment in the thermal vacuum chamber with an environmental temperature of -60 °C was performed during 12 days after reaching a vacuum of 10^{-6} mbar. For a given heating power injected and once the temperature of the radiator was constant, bias voltage of +1.2V and -1.2V were applied to the active layers of the radiator and the radiator temperature variation, resulting from an emissivity change was measured. The temperature variation can be explained with the following energy balance equation (1):

$$P_{heaters} = \varepsilon_{ij}\sigma SF_{ij}(T_{radiator}^4 - T_{environment}^4) \qquad \text{Eq.(1)}$$

Where $P_{heaters}$ (W) is the heat flux (or heating power) injected through electric heaters, ε_{ij} is the equivalent emissivity of the active layer material in its radiative environment, σ is the Stefan-Boltzmann constant, S is the area of the active layer, $T_{radiator}$ and $T_{environment}$ are the temperatures of the radiator and the environment respectively, and F_{ij} is the view factor.

Starting from the thermal equilibrium, i.e. the power injected $P_{heaters}$ being fixed, and considering the environment temperature constant ($T_{env.}$ = -60°C), the radiator temperature varies when a change in emissivity is applied to the EER. Specifically, considering an environment temperature below the radiator temperature, a high emissivity would result in a decrease of the temperature. In the same way, a low emissivity would result in a temperature increase.

In the following, three typical thermal environments encountered by the satellite in space, the hot, the cold and the nominal ones, were simulated using temperature steps close to 60° C, -25° C and 20° C, respectively. In a first step, the intermediate nominal (20° C) case was simulated (Figure 7A). Before starting the experiment, the active layers of the EER were electrochemically set in an intermediate oxidation state, *i.e.* a bias voltage of 0 V was applied. Then, the heating power was set in order to obtain around 20 °C, *i.e.* the nominal case. Once this temperature was reached, the heat flux injected was kept constant during the electrical switching. The evolution of the temperature variations over time for the intermediate case (20° C) is shown in Figure 7A.



Figure 7: Evolution of the OSR (blue curve) and electroemissive radiator (red curve) temperatures for a simulated temperature of (A) 20 °C, (B) 60°C and (C) -25°C. The bias voltage applied is indicated : +1.2V (low emissivity; -1.2V (high emissivity).

The starting temperature of the radiator is 20°C. By applying a bias voltage of +1.2 V, the active layer is in a low emissivity state (Figure 7A) and the temperature of the radiator increases to reach about 25°C. By applying a bias voltage of -1.2V, the active layer switches to a high emissivity state and the temperature decreases to 13°C. Thus, the electroemissive

behavior of the EER causes a temperature variation of 12°C. As expected, the OSR radiator experiences a constant temperature of approximately 12°C.

Then, hot and cold environments were simulated with temperature steps close to 60° C and -25 °C, respectively. The temperatures were obtained by increasing or decreasing the heating power injected (P_{heaters}) *via* the heating bands. The electroemissive radiator and OSR temperature evolutions are presented in Figure 7B and Figure 7C.

For both temperature steps, the temperature increases when a bias voltage of +1.2 V (low emissivity state) is applied. In the same way, a decrease in temperature is recorded when a bias voltage of -1.2 V (high emissivity state) is applied. These results are similar to those observed for the intermediate environment. Thus, the electroemissive radiator behaves similarly regardless of the temperature step applied between -25° C and $+ 60^{\circ}$ C. This means that the EER is able to operate at low temperatures, *e.g.* -25° C, which is an interesting result, and that it can also operate over the wide temperature range required for the intended application. Finally, considering the curves obtained for the different temperature steps, it can be noted that the dynamics of the system is slowed down in cold environment. This is explained (*i*) by an increase in ionic conductivity as the temperature increases, which would result in a faster switching of the electro-active devices [17] and (*ii*) by the fact that the radiative heat loss toward the ambiance (fixed at -60° C) is quite less when the radiator is around -25° C than when it is around 60° C.

Considering the hot environment (around 60°C), the results allow the evaluation of the heat rejection capacity of the EER in comparison with the OSR's one representing the current onboard technology. Upon applying a bias voltage of -1.2V, one can notice that almost identical temperatures are recorded for the EER and the OSR radiator ($T_{OSR radiator} = 61^{\circ}C$, $T_{radiator} \sim 57^{\circ}C$, Figure 7C). Therefore, it appears that the EED based radiator is able to reject

heat as well as the OSR radiator (without consideration of the solar absorption in case of sun illumination).

In the case of the cold environment (around -25°C), the ability of the EER to conserve the heat can be estimated compared with the OSR radiator. By applying a bias voltage of +1.2 V, the EER active layer exhibits a low emissivity state and the EER temperature exceeds the OSR radiator's one ($T_{OSR radiator} = -28^{\circ}C$, $T_{radiator} = -19^{\circ}C$). Therefore, in the cold environment, switching the EER in a low emissivity state would result in an increase of the temperature level within the satellite with respect to the OSR radiator.

In conclusion, the emissivity variation of the EER leads to an equivalent heat rejection capacity to the OSR radiator in hot environment (without any sun illumination) and to an increase of the temperature level in cold case. Thus, the EER appears to be an asset to save the electrical energy of the satellite compared to the OSR radiator. Indeed, in the cold environment, the OSR radiator exhibits a high emissivity, leading to a significant rejection of the heat while the satellite is already experiencing a cold environment. Therefore, the satellite temperature needs to be increased by other means such as heaters that consume a high amount of electrical energy.

3.3. Stability of the optical performances of the "passenger samples" under vacuum environment

The stability of the EEDs optical properties under thermal vacuum was investigated by measuring the emissivity before and after the complete vacuum testing sequence including temperature variations from -25° C to $+60^{\circ}$ C. The measurements were thus performed outside the vacuum chamber and for both states of the active layer emissivity. Besides, as measurements were hardly feasible on radiators because of their size and thickness, they were carried out on a EED sample, referred to as "*passenger sample*" as it experienced the same

environmental conditions as the radiators. However, it was not electrically switched to different emissivity states. Thus, after 12 days of representative space conditions, the emissivity variation was observed to remain constant with a value of $\Delta \varepsilon = 0.31$. These results indicate that the optical properties are stable under space like conditions for samples placed at least 12 days in the vacuum chamber and submitted to large temperature variations.

To complement these results, the temperature variations of the EER determined at 20°C (nominal case) upon emissivity switching were compared after 24h and 234h of testing. The values recorded after 24h (Δ T radiator = 12°C) and 234h (Δ T radiator = 11°C) were almost identical. Thus, it can be concluded that the successive switches of the EED emissivity state at different temperatures and under vacuum do not alter the properties of the elecroemissive rediator. These radiators are thus able to operate under partially representative conditions of the space environment.

3.4. Electrical consumption

The electrical consumption of the radiators was compared to the OSR's one since the main purpose of EERs is to save on-board electrical power. For this, an intermediate environment at a temperature of 9°C was considered, while the ambient temperature was still set at -60°C. For the radiator, whose active layer was in a low emissivity state, an electrical power of 2.02 W was injected to reach the temperature of 9°C. Since an EER requires electrical power to switch from one state to another, the electrical consumption of the radiator must be added.

At each emissivity change, a current peak of $\approx \pm 60$ mA is recorded – due to the application of a bias voltage of ± 1.2 V – and represents an electrical consumption of 0.072 W, which leads to a total electric consumption of 2.09 W to be observed for whole the radiator. Concerning the OSR radiator, 2.57 W are injected to reach the same temperature (9 °C), which is 0.48 W more than for the radiator. Both EER and OSR have an equivalent area so that a significant power saving is thus achieved, in the order of 20%, by using the EER. Assuming that the EER is scalable to 1 m², this would represent a saving in the reserved power budget at satellite system level of 59 W/m^2 for the polymer based radiator with respect to the OSR radiator. In addition, electroactive polymers as the one used in this study for the design of the electroemissive radiator are able to display memory effects. This parameter represents the time during which the device can remain in one optical state (high or low emissive state) without applying any bias voltage. The longer the memory effect, the smaller will be the source of energy to ensure its autonomy of operation over time. This parameter was not assessed on the EER tested in this study but on similar ones swollen with a LiTFSI/EMITFSI mixture at a concentration of 5.10⁻³ mol/L as electrolyte instead of neat EMITFSI. Using this EER, a memory effect of 47 hours was observed for a temperature step of 0°C (see Figure S2). Therefore, using these types of polymer based radiators it would not be necessary to electrically consume continuously but only episodically during switching sequence to maintain or modulate the emissivity. This significant energy saving could considerably reduce the constraint on the satellite system in terms of the required solar panels area, battery mass and/or even the duration of the satellite orbiting phase.

4. Conclusion

The aim of this study was to demonstrate that conducting polymer based EED can be used for the thermal regulation of satellites under conditions close to the space environment. At first, the operating of the EEDs under vacuum at room temperature was evaluated. The latter was confirmed and a loss of about 20 % in IR-optical performances was recorded after 3700 cycles. Once this verification was completed, a radiator consisting in 16 EED was fabricated with a total active surface area of 80cm². For the simulated temperature steps, representing the various typical cases encountered by the satellite in orbit (-25°C to +80°C), a bias voltage of -

1.2V and +1.2V was applied to the EERs and a sensible decrease and increase in temperature respectively was observed and recorded. Moreover, in hot case, due to the strong heat dissipation by the satellite system, without direct solar incidence on the EED surface, then a forced EED on its high emissive state (-1.2V) allows to reject as much, or even more heat than OSR standard per square meter, and therefore to stabilize the surface at a temperature of the same order, or even slightly lower. In cold cases $(-25^{\circ}C)$, by applying a bias voltage of +1.2V, the temperature of the radiator increased by 9°C compared to the OSR radiator for, the same heating power consumption. This would allow the increase of the temperature radiator within the satellite, which cannot be achieved with OSR radiators. As a result, energy savings of about 20% have been calculated if electro-emissive systems were used instead of OSR radiators. This energy saving could be even more important by taking into consideration the memory effect of the EERs. This would represent a significant gain in terms of on-board installed power and associated weight. This result establishes the proof of concept for the thermal regulation of satellites using polymer-based electroemissive devices. The axis of improvement for next steps of the development are also clearly identified through this study: the reduction of the solar absorptivity (still very high on current EER) and an encapsulation technique for the protection against space environment (particles and UV/VUV).

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Graphical abstract

