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Flexible Mild Heaters in Structural Conservation of Paintings: State of the Art and Conceptual Design of a New Carbon Nanotubes-based Heater

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Abstract: Thermal treatments constitute the core in the success for most structural treatments, such as consolidation, treating planar deformations, reinforcing degraded support and others. Among the wide range of devices for thermal treatments of paintings proposed in scientific and technical literature, flexible heaters appear to be the most promising technology, especially for working with large painting or *in situ*. The present study provides a comprehensive review of flexible mild heater systems devised for structural conservation of paintings in the last decades, bringing forward the issues related to the instrumentation used for thermal treatments, stressing the importance of accurate control and the inadequateness of available devices. By highlighting the actual limitations of existing devices, a different approach, which employs Carbon Nanotubes-based flexible heaters is then proposed in its conceptual form. The design of such device, called IMAT (Intelligent Mobile Accurate Thermo-electrical device) is supported by the European Community in the context of the EC-FP7 Environment Theme (ENV-NMP.2011.2.2-5) into a three-year project started on November 2011.

Key words: Paintings conservation, heating, carbon nanotubes, heating table

INTRODUCTION

Thermal treatments are among the most common in art conservation and constitute the core in the success for most structural treatments, such as consolidation, treating planar deformations, reinforcing degraded support and others. In paintings conservation, highly accurate and steady temperature, applicable either selectively or uniformly is an important factor and lack of control over the temperature has led to incompleteness or failure of the treatment, complications, if not damage to the artwork (Markevicius, 2010). The difficulty in controlling the temperature and distributing the heat evenly increases with the area of application and when using currently available instrumentation, even in relatively small areas, uniform and accurate application is problematic. Essentially this problem arises from the lack of accurate, efficient, versatile and economically accessible instrumentation, necessary to meet the needs and standards of conservation.

As of today, the only available moderately accurate heating instrumentation in use capable of treating larger scale artworks is a heavy-duty metal heating table fitted with suction and other functions (Markevicius *et al*., 2011). These tables were introduced in the 1950's when quite different methodologies and approaches to conservation of cultural heritage prevailed and were to serve the increasingly pervasive practice of complete impregnation of paintings with wax-resin, followed by the extensive use of thermoplastic resins since the 1970's. While the heating table has had some development and improvements in design and today comes in various model and sizes, essentially it has not changed much since the mid 1980's and it constitutes a limited, large scale device, usable only in a fixed location, which, due to its high cost, is also inaccessible to many conservators (Fig. 1a, b).

High power requirements (10-15 kW 380 V circa), high heat sink mass, slow response, considerable temperature fluctuations (Fig. 2a, b) and uneven heat distribution are characteristics inherent to the all-in-one apparatus, that render it out of step with current conservation methodology and needs. For conservators practicing in European centers and historical buildings, the electrical upgrades required for the use of a heating table are not only difficult to obtain permission for, but also necessitate

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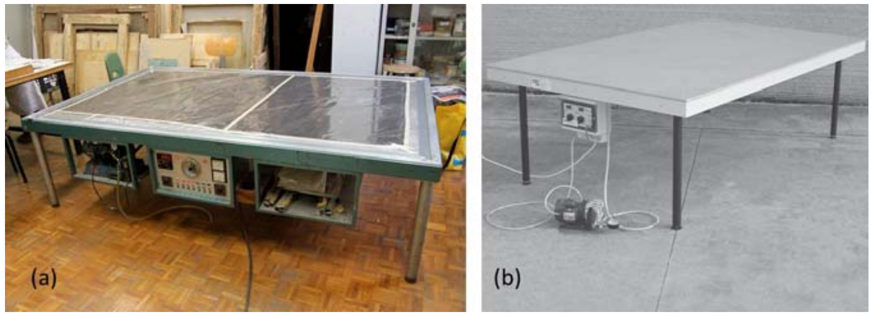

Fig. 1 (a, b): Example of (a) an early heating table from the 1960's and (b) a modern high-end multipurpose heating table. Similar tables require around 10-15 kW at 380 V and the price starts from 52,000.00 €. http://www.willard.co.uk

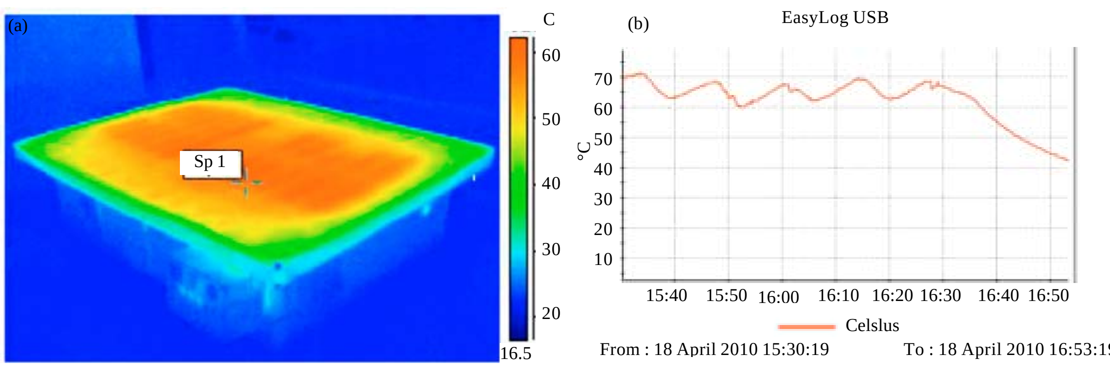

Fig. 2 (a, b): Thermographic image of a 1990's multipurpose low pressure heating table in current use, (a) showing uneven heat distribution and (b) graph of surface temperature fluctuation during treatment in 1990's multipurpose heating table

invasive and expensive electrical work, further increasing the costs of the device and creating obstacles for *in situ* treatments.

Current conservation practices are moving towards ever more minimal and less invasive treatments and the conservator's profession and its challenges are becoming ever more global and mobile. From a "big picture" perspective, the future of heating devices in art conservation is clearly with mobile, versatile, accurate and cost effective "smart" devices. In the search for mobile alternatives, flexible heaters offer the most attractive perspectives: They are lightweight and can be designed in a variety of shapes and sizes, applied selectively and combined with other treatment devices in a most versatile way. And looking into the very near future, recent advances in the technology of nanomaterials, will allow design of highly accurate heaters, which could be very thin, lightweight, even transparent, stretchable and woven, with low power needs, allowing the miniaturization of the control unit, therefore making such a smart device an ultra-portable, versatile and efficient alternative for diverse thermal treatments. The low power requirement would be a key from a green point of view, but also would allow greater diffusion of a state of the art conservation tool, making it easily adapted to any environment, basically wherever there is regular current.

FLEXIBLE MILD HEATERS IN ART CONSERVATION

Flexible electrically heated mats are not entirely new to art conservation. In the 1990's a silicone rubber heated mat, mounted on a solid support and controlled manually with a dimmer and external thermometer in combination with a low pressure ring, was used by Jos van Och (Stichting Restauratie Atelier Limburg, Maastricht, The Netherlands) for the lining of the colossal Mesdag Panorama mural in The Hague (Tucker, 1998). Heat

Fig. 3 (a, b): (a) Experimental Olsson-Markevicius silicone rubber and wound wire mild heater (2010) and (b) lining one of the H.S Sewell murals using vacuum envelope and flexible thermal blanket

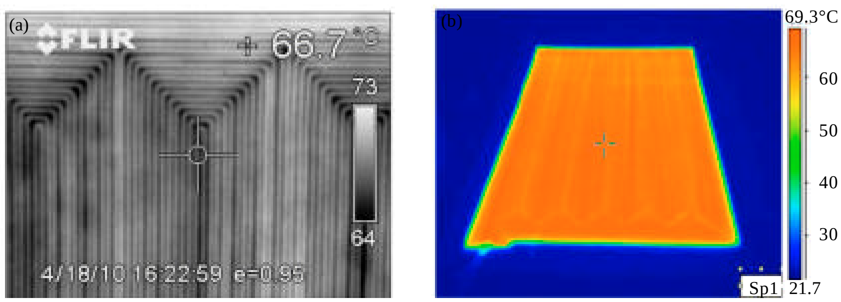

Fig. 4 (a, b): Olsson-Markevicius experimental mild heater: (a) Thermographic image of wound wire element inside the heater and (b) graphic showing steady temperature during the treatment and thermographic image showing even heat distribution

blankets were employed in early heating tables, but were soon forgotten and replaced by grill type heating elements. Interestingly, a well-known British conservator Helmut Ruhemann suggested an application similar to ours in 1959 but his idea was not developed any further (Ruhemann *et al*., 1960). Despite these interesting studies, flexible heaters potential was not further developed and they have had rather marginal use because of past technical limitations and due to earlier trends in conservation methodology, where all-in-one approaches prevailed. First steps were taken in 2003, when the first mobile high precision flexible mild heating system was designed and applied successfully by Olsson and Markevicius in the treatment of mural paintings on canvas by Sewell (1899-1975) in Oregon City, Oregon, USA. The first prototype was made of silicon rubber and wound wire heating elements, connected to a custom designed control unit with an external thermal sensor. Later, a second prototype was created in 2005, with some improvements in its design and was used by Markevicius in his studio in Amsterdam and in the National Gallery of Canada. Both prototypes and later designed heaters (Fig. 3, 4) have been used since then in the treatment of numerous artworks, which differ in size, period and materials and the results have solicited considerable interest from the conservation community (Olsson and Markevicius, 2010).

CARBON NANOTUBES AND THEIR APPLICATION FOR CONDUCTIVE HEATING

Ever since their discovery in 1991 by Sumio Iljima, Carbon Nanotubes (CNTs) have inspired scientists and developers of future technologies, yet until recently, their practical application was limited by relatively high production and purification costs (Zambri *et al*., 2011). CNTs are molecular scale sheets of graphite (called graphene) rolled up to make a tube and can be described as a new member of carbon allotropes, lying between fullerenes and graphite. As widely recognized (Hosseini Yazdi and Mousavi Mashadi, 2007), Single Wall Nanotubes (SWCNT) consist of single rolls (Dresselhaus *et al*., 1996) while Multi Wall Nanotubes (MWCNT) consist of two or more coaxial tubes-within-a-tube (Yudianti *et al*., 2010). Properties of

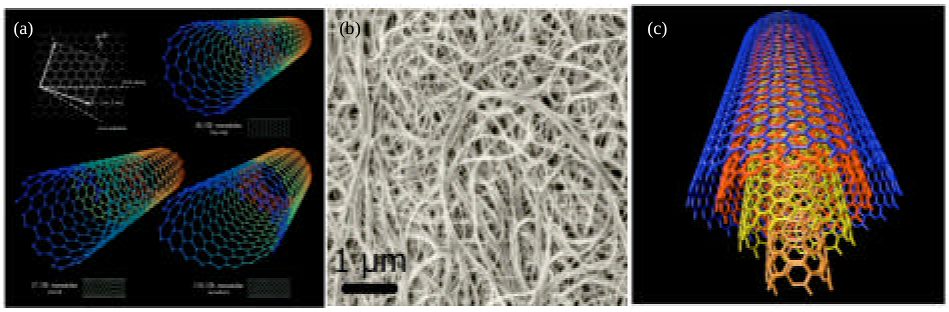

Fig. 5 (a, b): (a) A diagram showing the types of Single Wall Carbon Nanotube (SWCNT), (b) SEM image of carbon nanotubes bundles and (c) a diagram with a multi wall carbon nanotube (MWCNT), (Michael Ströck, Wikimedia images)

individual CNTs can be influenced significantly by their chirality (twist) and geometry. Held together by the Van der Waals force, CNTs tend to bundle in ropes, forming agglomerates, but depending on the production (growth) method can also form highly aligned structures. CNTs are particularly interesting for various applications in cutting edge electronics, optics and material engineering (Mamba *et al*., 2010): They are approximately 50.000 times thinner than human hair and yet thanks to sp_2 bonds they are the strongest and the stiffest materials known with an E-modulus 10 times greater than steel (Mohammadpour *et al*., 2011; Mirjalili *et al*., 2009) they are lightweight and highly conductive and have numerous other outstanding properties and applications, which are still in the process of being discovered. Unlike traditional materials, CNTs conduct electricity balistically, so electrons, just like cars in a multiple lane highway, can be transported in high densities and speed with a minimal resistance and hence the electrical conductivity of CNT films is very high (10^6 S m^{-2}) and surpasses that of copper. They are the best field emitters of any known material and in theory, metallic nanotubes can carry an electric current density of 4×109 A cm^{-2} which is more than 1,000 times greater than metals such as copper. CNT thermal conductivity along the axis has been measured as high as 3500 [W m^{-1} K^{-1}], although in theory (Pop *et al*., 2006) it could reach a value equal to 6600 [W m^{-1} K^{-1}].

In the direction perpendicular to its axis, however, thermal conduction proves to be 100 times (or so) smaller. Although metallic CNTs are excellent conductors, they do not have metal bonds and possess very unusual features: they are exempt of thermoelectric effect (Kuroda and Leburton, 2009) and from a quantum mechanics point of view SWCNT do not follow Joules law (p = IV) as stated by Ragab and Basaran (2009). While CNT's electrical resistance seems to depend strongly on the structure (twist, diameter and defects) they seem to obey Ohm's law over a wide range of temperature. Figure 5 is showing the types of Single Wall Carbon Nanotube (SWCNT), SEM image of carbon nanotubes bundles and a diagram with a Multi Wall Carbon Nanotube (MWCNT).

While CNTs are revealing ever more remarkable features that will enable the creation of a broad range of "smart" materials and products with revolutionary characteristics (Singh *et al*., 2011) most researchers agree that perhaps the greatest technological potential at the present time lies in the electrical properties of CNTs to generate heat in a way unattainable with other technologies. The material is not only extremely light and robust, but can also efficiently heat up surfaces of any size and feature a very rapid thermal response, which is an important factor in maintaining ultra steady temperatures and in reducing heating and cooling times. For traditional materials, the change in temperature is usually slow and delayed due to their large thermal mass. In contrast, the thermal response of CNTs can be very fast even up to the incandescent state. Researcher at Nanotechnology Research Center Department of Physics at Tsinghua University Beijing, China, found that a heating voltage pulse can make their CNT film glow at a temperature of about 1542 K (1269°C). Interestingly, the ramp-up and cooling-down times are about 100 times faster than that of traditional materials such as tungsten wire (tungsten wire with 15 µm diameter needs about 100 msec to reach a stable incandescence state when an electric heating signal is applied).

NEW FLEXIBLE HEATERS WITH CONDUCTIVE NANOMATERIALS

Conductive films made with carbon nanotubes and metal nanowires, in addition to their low sheet resistance, possess an optical transmittance in the visible spectrum and can form quite electrically conductive, yet almost completely transparent films, measuring only about 50-100

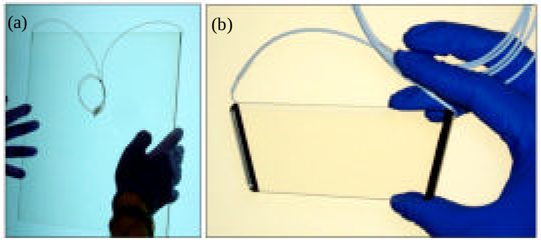

Fig. 6 (a, b): Transparent Therma-Klear mild heaters invented by Dontech Inc using conductive film with self arranging silver nanowires (AgNW) on PET substrate by Cima Nano Inc, USA (Courtesy Dontech Inc.)

nanometers thick. The combination of low sheet resistance and excellent optical transmittance enables the design of efficient and nearly transparent film heaters (up to 95%) which would allow the conservator to visually monitor the treatment process and accurately position of the heater. The first experimental prototype of a transparent small scale (2.5 cm^{-2}) film heater on glass and PET where the heating element was constituted of a network of Single Wall Carbon Nanotubes (SWCNT) was created by Korean Institute of Machinery and Materials (KIMM) in 2007 (Yoon *et al*., 2007). Efficient transparent heaters could be designed also with other prospective nanomaterials, such as silver nanowires (AgNW), which demonstrate low sheet resistance, falling below 1 Ω^{-2} at 300 nm thicknesses and reaching as low as 13 Ω^{-2} in conductive films of 85% optical transmittance (De *et al*., 2009). AgNW conductive films on PET substrate are currently manufactured by Cima Nano Inc. USA and already used by DontechInc., USA for small scale Therma-Klear® heaters.

CNT heaters eventually could become not only transparent (Fig. 6), but also stretchable. In 2008 a group of scientists led by Takao Someya (University of Tokyo) made a conductive material by adding carbon nanotubes to an elastic polymer that they used to connect organic transistors in a stretchable electronic circuit. The new material could be used to make displays, actuators could also lead to electronic skin for robots (Sekitani *et al*., 2008) and it could be used in conductive heating.

Other promising developments in this sector were introduced in 2010 by Bayer Material Science (Leverkusen, Germany) that produced at industrial scale the first highly purified MWCNT, called Baytubes®. Baytubes (Meyer *et al*., 2010) in aqueous suspensions were applied to multifilament yarns resulting in a new textile heater made by weaving CNTEC® conductive yarns from Kuraray Living Co., Ltd. in Japan in 2010. This fabric heater is lightweight, thin and compact, thus demonstrating sustained durability to bending. After the weaving process the CNTEC heater is sealed with a polymer, making it impermeable to gases, but further research may offer the opportunity to design a “breathing” heater for art conservation. Highly conductive CNT coatings, which could be applied like a varnish, were developed by Future Carbon (FC, Bayreuth, Germany) in 2010 (Meyer, 2010) and transparent conductive coatings have been researched by Erismisa *et al*. (2011) at Fraunhofer Institute (Stuttgart, Germany) with the reported R_S values as low as 1 Ω^{-2} for the opaque FC Carbo-E-Therm coating and in case of Fraunhofer reaching 0.3 Ω^{-2} in a transparent coating. More research and development of CNT heaters has been conducted worldwide and other experimental models at laboratory scale were reported. Such heaters are being actively developed in the search for alternatives to replace the fragile and expensive Indium Tin Oxide (ITO) based transparent heaters used for displays and windshields in avionics, automotive and similar fields. All of these products, it must be noted, were developed for very different uses than art conservation and were applied exclusively to glass, polycarbonate, or PET substrate, rendering them impractical and difficult to use in art conservation, where the substrate must be soft and resistant to the impact of solvents, heat and to frequent rolling or bending.

CONCEPTUAL DESIGN OF A NEW CNTs-BASED DEVICE: IMAT

The simple application, precision, impressive mobility and versatility of CNT-base flexible heaters encouraged further development of the concept of a mobile mild heating system for art conservation, denominated as IMAT (Intelligent Mobile Multipurpose Accurate Thermo-Electrical). Accuracy, mobility and versatility were central to first prototypes and remain fundamental also for the IMAT concept, along with the increased demands for core technical characteristics such as fast thermal response, steady and accurate temperature, low power needs, soft and tack-free surface, durability and resistance to chemical and physical factors associated with frequent use. Newly introduced features such as transparency and permeability to gases (airflow and water vapors) are highly desirable. While some of the goals were successfully achieved in earlier silicone rubber heaters, the entire “wish list” was unobtainable using available means and in 2009 we started exploring the possibility of replacing the resistance wiring with the relatively new and promising nanomaterials, such as silver nanowires and carbon nanotubes.

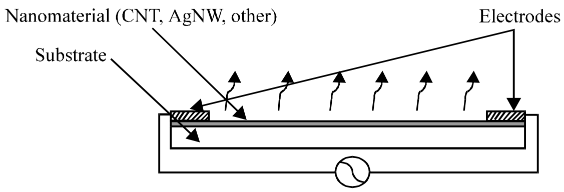

Fig. 7: Schematic drawing of the first "open" type transparent SWCNT heater (Kim *et al.*, 2010)

Like its silicone-wound wire predecessor, the proposed IMAT (Intelligent Mobile Accurate Thermo-Electrical) mild heating device can be used for a broad spectrum of thermal applications in the conservation of artworks and thanks to innovative nanomaterials, it may also be transparent, stretchable, permeable to gases and possess many new qualities, such as instant response, accuracy and low power needs, which will permit the miniaturization of the control unit and further improve the portability and versatility of the system. The basic design of the wireless IMAT device employs a conductive film heater, made with CNTs or other nanomaterials and an associated control unit, which includes a series of external controls neatly assembled within a box that also serves as a power outlet for the heater.

CNTs could be deposited on a selected substrate or mixed with a polymer forming a free standing film, which can be transparent or opaque and be perforated, when permeability to gases is desirable. While the heater can have either an "open" configuration (Fig. 7) or a "closed" one, in which the CNT film is sandwiched between selected polymers, the latter is preferred, for both more effective heating and because the protective coating may be designed with specific physical and chemical properties for art conservation. As an alternative, the yarns coated with CNT can be woven into a conductive textile heater. The heater is designed with parallel electrodes and when voltage is applied, the current is uniformly distributed over the conductive layer and heat is generated. The power required to run the heater is determined by the power density P_D, expressed in W cm^{-2} and depends on its size, mass, electrical and thermal properties. For mild heating up to 85°C (which is above the range of most, if not all structural treatments), the P_D of 0.23-0.3 W cm^{-2} is required for silicon wound wire heaters. However, in a CNT heater, the same temperature range could be achieved at lower P_D of 0.13-0.15 W cm^{-2} allowing more efficient heating with less energy and at lower voltage.

The control unit may contain a precision digital temperature controller that drives a solid state relay to run the heating unit and a thermocouple to detect a single local temperature. The relay that was installed in the 2003 system has a 1/4-1 sec time cycle for temperature correction, while the newer solid state relays, known as variable time base relays, have time cycles that number 20-40 times per second to maintain an extremely precise and continuous target heat, with an accuracy of +/- .1% C. Once the desired temperature is reached, it will stay steady for the duration of the treatment. The temperature is detected with a sensor, which can be external, integrated into the heater, or non contact, such as IR. A recently designed control unit also includes a datalogger and was fitted with more than one outlet, which enables the use of several micro-heaters simultaneously. Of course, auxiliary use of an IR thermometer and thermopapers is useful to monitor the entire surface of the work during treatment.

The entire system of silicone rubber and wound wire prototypes was designed for either a 120 V current or 240 V, which was determined by the P_D (W cm^{-2}). For heaters over 50×70 cm, the 240 V support is necessary. Thanks to the unusual electrical and thermal properties of CNT, mild heating (up to 85°) could be accomplished using much lower voltage, perhaps reaching the target margin of 12-24 V. This would be a big step from 120-240 V required in silicone rubber heaters and even bigger from 380 V, required to run the heating table. While the "green" effect is not to be undervalued the low voltage and reduced power needs are even more critical factors for the miniaturization of a control unit, making the device the ultimate in mobility in terms of power source and superior in operational safety. While conductive CNT films already allow very efficient heating, low voltage application (12-24 V) is currently limited by the size of the heater and larger scale models (particularly transparent heaters) still require further research and engineering solutions. The thermal behavior of transparent CNT films has been researched by several authors (Kwak *et al.*, 2010; Saran *et al.*, 2004).

On the basis of the results presented in such works, it is possible to state how the applied voltage E, the length L (separation between the electrodes) and the sheet resistance R_S are connected in the conductive film heater, according to the following equations:

$$P_D = \frac{E^2}{RL^2},\ \ R_L = \frac{RL}{W},\ \ P_T = \frac{E^2}{R_L} \quad (1)$$

From Eq. 1, it can be demonstrated that:

$$W \cdot L = \frac{P_T}{P_D} \quad (2)$$

Table 1: Some values required for sheet resistance are evaluated for, respectively a 90×150 cm, a 60×90 cm and a 18×150 cm heater powered by 12, 24 and 120 V and with a power density P_D of 0.15 Wcm^{-2}

($Watt\ cm^{-2}$)	(V)	(cm) distance between electrodes	(cm)	Ω^{-2}	Ω
0.15 (sufficient for heating up to 85°C)	12	150	90	0.1	<0.1
	24			0.3	0.5
	120			11.9	7.1
	12	90	60	0.3	0.2
	24			0.7	1.1
	120			26.7	17.8
	12	150	18	3.0	3.4
	24			11.9	1.4
	120			296.3	35.6

Ω^{-2}: Ohm per square

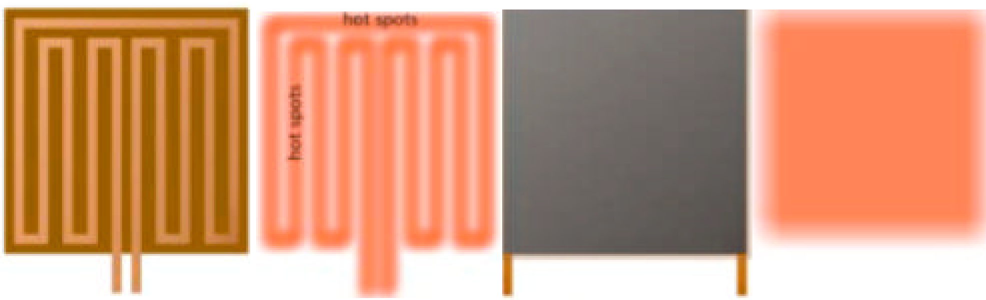

Fig. 8: Comparing the heat dissipation in conventional resistor heater and in conductive Carbo e-Therm Coating

Where:

P_d = Power density
E = Applied voltage
L = Length (i.e., separation between the electrodes) of conductive coating (cms)
W = Length of conductive coating (cms)
P^T = Total power of the system (Watts)
R_L = Approximate line (i.e., assuming no resistance from the electrodes, wire and connectors, or wire to wire resistance) [Ω]
R = Coating resistance [Ω^{-2}]

Equation 2 states the relationship between conductive coating dimensions, total power of the system and power density. When P_D is insufficient, the heater will not reach the set temperature. Essentially, increasing the conductivity of the coating will increase the power density and as reported in earlier studies, increasing the size (length L) of the heater and reducing the voltage requires minimizing the sheet resistance and maximizing the average gradient of electrical potential. The latter is related to the optimal design of the electrodes. If we want to run a theoretical CNT film heater of 90×150 cm at 24 V and to obtain a Power Density P_D of 0.15 watt cm^{-2}, the sheet resistance R_S should be 0.3 Ω and even lower-at 0.1 Ω if we want to reduce the voltage to 12 V. As a consequence CNT film thickness has to be increased and distances between electrodes have to be reduced (for instance to 20×30 cm) increasing a number of contacts (similar to car rear windshield heater) to obtain a sheet resistance close to 10 Ω (9.6). In Table 1, some values required for sheet resistance are evaluated for, respectively a 90×150 cm, a 60×90 cm and a 18×150 cm heater powered by 12, 24 and 120 V and with a power density PD of 0.15 W cm^{-2}.

For instance, according to the eq. 1 and 2 neglecting the thermal interaction between the multiple connections, for a 90×150 cm heater, using 6 electrical connections with a distance of 18 cm one from each other, 24 V will provide sufficient P_D with a sheet resistance at or around 12 Ω^{-2}. This solution is preferred for safety reasons although, the values for P_D and R will remain the same. Further research will allow for ever more lower R_S values: in 2009 Future Carbon in Germany had developed an electrically heated Carbo-E-Therm coating material (Fig. 8) based on carbon nanotubes, which produces the films with sheet resistance at 1 Ω^{-2}, which is sufficient for low voltage IMAT heater.

This material can be used on various substrates to allow for absolutely even heating without any hot spots and could be used for opaque heaters. Minimizing sheet resistance, however, is an even more challenging task in transparent heaters, where sheet resistance and transparency are inversely related. Although, Erismisa *et al.* (2011) have reached 0.3 Ω^{-2} in a transparent coating and in theory CNT electrodes with the transparency of 85% can demonstrate R_S of 10 Ω^{-2} or less, the effective R_s of available CNT films vary from 100-1000 Ω^{-2}, which limits the size of a heater or requires multiple contacts. Other comparable nanomaterials, such as self-arranging AgNW, allow even 10 Ω^{-2} to be achieved and although, thicker films have a haziness due to the reflection effect (negligible for our uses), they present the most interesting alternative to CNTs. The high margin of 85% transparency, which is critical for optical devices and displays, is less relevant for conservation purposes and transparency of 65% if not 50% could be acceptable. Determining a functional lower transparency margin would be advantageous, as it would allow increasing the thickness of the film and hence the conductivity. Transparency may be also a more practical feature in small scale heaters for accurate local applications, where higher R_S could he used at low voltage. Base substrates for the IMAT heater can be films, textiles (Furferi, 2011) membranes, or leather. Continuous coating technology will be required with regard to equal thickness as well as direct inclusion of electrodes for the electrical connection and sensors for thermal control are required with regard to cost efficiency as far as it is feasible. The interface between the electrical contacts and the conductive layer must be specially designed to withstand mechanical forces occurring due to periodic thermal expansions as a result of multiple on/off cycles. In the interests of obtaining the best chemical resistance to solvents and liquids, a design where the heating layer and electrodes are sandwiched between two protective films will be evaluated. In addition, the coating materials need to be developed in a way that they can be easily applied with existing equipment.

CONCLUSIONS AND DISCUSSION

Flexible heaters represent a new frontier in structural conservation of paintings, especially when large paintings have to be restored or when the conservator has to work *in situ*. In the last decades a number of devices have been proposed in literature. In particular, the remarkable mechanical, thermal and electrical properties of CNTs allow for the design of highly accurate portable film heaters with desirable qualities for art conservation. Such film heaters are designed in ultra-thin, transparent and woven forms. Conductive film heaters could be perforated without disruption to the electrical circuit and may be designed as permeable membranes to permit the migration of vapors and airflow so often used in combination with mild heating in many treatments. Alternatively, a gas permeable substrate could be developed or a lightweight textile heater could be used. CNT based heaters could function very efficiently with reduced power needs and at low voltage, which would allow the miniaturization of the control unit, making the system more mobile, safe and user friendly. All this makes CNT-based heating devices the ultimate in versatility and precision while remaining economically accessible, which could fill the gap in the core instrumentation for structural treatments in art conservation. Among the wide variety of CNT devices, the proposed conceptual IMAT device has been conceived to be the best candidate to replace the conventional heating table and above all the hand held irons and the whole range of less accurate DIY or adopted devices used by conservators (Bordalo, 2010). The IMAT will clearly be useful in various lining and backing treatments, which, thanks to this technology could be accomplished also *in situ*. The uniquely uniform diffusion of heat of the IMAT and the extremely accurate temperature regulation will allow the conservator the ultimate in control at temperatures ranging from 0-65°C (Speranza *et al*., 2002).

The new device may be used in treating diverse deformations and planar distortions, to reduce cupping and distortions to paint film, tear mending, consolidation of paint layers, reinforcement of degraded supports in diverse lining and backing treatments (Sitts, 2000). The IMAT heater's thin profile, flexible nature and availability in a wide size range are well suited for use in treating works on the stretcher. It may be utilized with all currently used conservation adhesives and may be incorporated into either traditional or more recent methodologies where controlled mild heating is required (Sebera, 1988). The IMAT would be particularly useful for *in situ* work and in emergency response actions: Low voltage (12-24 or below 100 V) would make it usable in diverse locations and situations. Moreover, in paper conservation the IMAT could be used in treating planar distortions and in consolidation treatments where mild heating is required (Szczepanowska, 1992). In textile conservation the IMAT could be applied in methods similar to those implemented in painting or paper treatments, used for consolidation, smoothing planar distortions and more. An added advantage of the device would be the option of placing the heat source simultaneously on both sides or on either side, as well as performing the work in sections on large pieces. Yet another application could be thermal disinfection treatments (Abdel-Kareem and Alfaisal, 2010) and in 3D objects such as polychrome sculptures (Akarish and Dessandier, 2011) frames, furniture, mixed media objects and more.

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REFERENCES

Abdel-Kareem, O. and R. Alfaisal, 2010. Treatment, conservation and restoration of the bedouin dyed textiles in the museum of jordanian heritage. Mediterr. Archaeol. Archaeometry, 10: 25-36.

Akarish, A.I.M. and D. Dessandier, 2011. Characterization and source of sedimentary rocks of the alexandria lighthouse archaeological objects, Egypt. J. Applied Sci., 11: 2513-2524.

Bordalo, R., 2010. Laser cleaning in art conservation. Part I: Laser fundamentals. E-Conservation Magazine No. 15, pp: 46-53. http://www.e-conservationline.com/content/view/912/311

De, S., T.M. Higgins, P.E. Lyons, E.M. Doherty and P.N. Nirmalraj, 2009. Silver nanowire networks as flexible, transparent, conducting films: Extremely high DC to optical conductivity ratios. ACS Nano., 3: 1767-1774.

Dresselhaus, M.S., G. Dresselhaus and P.C. Eklund, 1996. Science of Fullerenes and Carbon Nanotubes. Academic Press, San Diego, USA, ISBN: 9780122218200, Pages: 965.

Erismisa, H., D. Nemeca, M. Geissa, V. Skakalovab, U. Ritterc, I. Kolaric and S. Rothd, 2011. Penetration based CNT/Sol-Gel composite films and their remarkable electrical properties. Microelectron. Eng., 88: 2513-2515.

Hosseini Yazdi, S.S. and M. Mousavi Mashadi, 2007. A nano-tuneable pressure switch system design based on single wall carbon nanotubes. J. Applied Sci., 7: 1442-1445.

Kim, D., H.C. Lee, J.Y. Woo and C.S. Han, 2010. Thermal behavior of transparent film heaters made of single-walled carbon nanotubes. J. Phys. Chem. C, 114: 5817-5821.

Kuroda, M.A. and J.P. Leburton, 2009. High-field electrothermal transport in metallic carbon nanotubes. Phys. Rev. B, Vol. 80, 10.1103/PhysRevB.80.165417

Kwak, H.S., K. Kim, B.C. Shon, H. Lee and C.S. Han, 2010. Thermal characteristics of a transparent film heater using single-walled carbon nanotubes. J. Nanosci. Nanotechnol., 10: 3512-3515.

Mamba, G., X.Y. Mbianda, P.P. Govender, B.B. Mamba and R.W. Krause, 2010. Application of multiwalled carbon nanotube-cyclodextrin polymers in the removal of heavy metals from water. J. Applied Sci., 10: 940-949.

Markevicius, T., 2010. The invisible story of Esther: Unveiling an extraordinary collaboration between Sandro Botticelli and Filippino Lippi in two 15th century cassoni. Comparative technical study of new findings with InGaAs IR reflectography. Proceedings of the ICOM Interim Scientific Research Meeting, October 7-8, 2010, Pisa, Italy.

Markevicius, T., N. Olsson, R. Furferi and H. Meyer, 2011. Conductive transparent film heater as alternative to heating table: Towards new Intelligent Mobile Accurate Thermoelectrical (IMAT) device for structural conservation of paintings. Proceedings of the 10th International Conference on Non-Destructive Investigations and Microanalysis for the Diagnostics and Conservation of Cultural and Environmental Heritage, April 13-15, 2011, Firenze, Italy.

Meyer, H., 2010. Science for a better life application of carbon nanotubes in plastics themadag nanotechnology. Mikrocentrum, Eindhoven, Eindhoven The Netherlands.

Meyer, H., Z. Zhang, H. Zhang, L.C. Tang and K. Peng *et al*., 2010. Improved mechanical properties of epoxy filled with functionalized carbon nanotubes. Publication No. WO/2010/102732. http://www.wipo.int/patentscope/ search/en/WO2010102732

Mirjalili, F., L. Chuah, A.B. Dayang, M. Hasmaliza, R. Aghababazadeh and F. Ahmadun, 2009. Mechanical properties of β-Al2O3/PP nano composite. J. Applied Sci., 9: 3199-3201.

Mohammadpour, E., Awang, M. and M.Z. Abdullah, 2011. Predicting the young's modulus of single-walled carbon nanotubes using finite element modeling. J. Applied Sci., 11: 1653-1657.

Olsson, N. and T. Markevicius, 2010. Flexible thermal blanket and low pressure envelope system in the structural treatment of large scale and traditional paintings on canvas. Proceeding of Annual Meeting of American Institute for Conservation of Artistic and Historic Works of Art (AIC), May 5-9, 2010, Milwaukee, USA.

Pop, E., D. Mann, Q. Wang, K. Goodson and H. Dai, 2006. Thermal conductance of an individual single-wall carbon nanotube above room temperature. Nano Lett., 6: 96-100.

Ragab, T. and C. Basaran, 2009. Joule heating in single-walled carbon nanotubes. J. Applied Phys., Vol. 106, 10.1063/1.3204971

Ruhemann, H., A. Boissonnas, C. Wolters, E. Packard and P. Michaels, 1960. Some notes on vacuum hot tables. Stud. Conserv., 5: 17-24.

Saran, N., K. Parikh, D.S. Suh, E. Munoz, H. Kolla and S.K. Manohar, 2004. Fabrication and characterization of thin films of single-walled carbon nanotube bundles on flexible plastic substrates. J. Am. Chem. Soc., 126: 4462-4463.

Sebera, D., 1988. A graphical representation of the relationship of environmental conditions to the permanence of hygroscopic materials and composites. Proceedings of the Conservation in Archives International Symposium, May 10-12, 1988, Ottawa, pp: 51-75.

Sekitani, T., Y. Noguchi, K. Hata, T. Fukushima, T. Aida and T. Someya, 2008. A rubberlike stretchable active matrix using elastic conductors. Science, 321: 1468-1472.

Singh, M., S. Manikandan and A.K. Kumaraguru, 2011. Nanoparticles: A new technology with wide applications. Res. J. Nanosci. Nanotechnol., 1: 1-11.

Sitts, M.K., 2000. Handbook for Digital Projects: A Management Tool for Preservation and Access. Northeast Document Conservation Center, Massachusetts, Pages: 179.

Speranza, L., M. Verdelli and N. Presenti, 2002. Modern techniques in the lining of transparent paintings. KERMES, 46: 20-30.

Szczepanowska, H., 1992. The conservation of 14th century parchment documents with pendant seals. Paper Conservator, 16: 86-92.

Tucker, P.H., 1998. Monet in the 20th Century. Yale University Press, Conn, New Haven.

Yoon, Y.H., J.W. Song, D. Kim, J. Kim, J.K. Park, S.K. Oh and C.S. Han, 2007. Transparent film heater using single-walled carbon nanotubes. Adv. Mater., 19: 4284-4287.

Yudianti, R., L. Indrarti and H. Onggo, 2010. Thermal behavior of purified multi walled carbon nanotube. J. Applied Sci., 10: 1978-1982.

Zambri, M.S.M., N.M. Mohamed and C.F. Kait, 2011. Preparation of electrochromic material using Carbon Nanotubes (CNTs). J. Applied Sci., 11: 1321-1325.