A PORTABLE MICROWAVE SYSTEM FOR WOODWORM DISINFESTATION OF ARTISTIC PAINTED BOARDS

M.Bini, D.Andreuccetti, A.Ignesti, R.Olmi, S.Priori and R.Vanni

Microwave power can be effectively used for disinfesting wooden objects of woodworms. Disinfestation is achieved by heating woodworms inside wood above their lethal temperature values.

A prototype of a portable microwave system suitable for treating small and delicate wooden objects is described. The system, working at 2.45 GHz, used a commercial magnetron, a radiative applicator, and a non-contacting thermometer to monitor the temperature of the painted surface. A flow of air is blown through the applicator to cool the irradiated surface. A treatment bench has been set up to heat painted boards in controlled conditions. The applicator is placed on the rear side of the board, while the painted side is monitored by means of an infrared thermometer to maintain its temperature below safe levels (e.g. 50-55 °C).

Results concerning the effect of microwave heating on several specimens infested by woodworms in all metamorphical stages (egg, pupa and larva) are reported and discussed. Preliminary results about possible detrimental effects induced by heating on wooden boards and on painted surfaces are also reported.

An experimental procedure for determining the SAR distribution produced by the applicator of the disinfestation system on a wooden board is described. The procedure is based on a thermographic analysis of the heated object. An analysis of the SAR uncertainty due to thermal diffusion and to surface radiation and convection losses is carried out, showing advantages and limitations of the thermographic method.

Key Words:
Wood disinfestation, microwave treatments, microwave heating

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The effectiveness of microwave disinfestation has been recently assessed on wooden objects infested by two common species of woodworms: *Hylotrupes bajulus* L. [Andreuccetti et al. 1994] and *Oligomerus ptilinoides* Wollaston [Andreuccetti et al. 1995]. The disinfestation was achieved by heating the insects above their lethal temperature (53-55 °C) while maintaining the surrounding wood at safe temperature values. Microwave disinfestation has proven to be particularly effective for treating painted wooden boards, without detectable damage to the wood substrate or to the painted surface.

As the microwave treatment has to be performed on valuable artistic objects, all precautions must be taken to avoid damage. In particular, the temperature that will be reached inside an object and on its painted surface during a treatment, given the output microwave power and the geometry of the applicator used, must be known. While the superficial temperature can be measured *during* the treatment, an evaluation of the internal temperature requires resorting to indirect methods, as invasive temperature probes are usually unacceptable. A suitable approach was the development of prevision models that allow a sufficiently accurate determination of the internal temperature, in which the electromagnetic and thermal characteristics of the heating system and, possibly, information gathered during the treatment (such as the measured surface temperature) are used.

The development of a treatment-planning tool, as outlined in the above paragraph, requires the knowledge of the specific absorption rate (SAR) produced by a given applicator in the treated object. An experimental method is presented which allows the SAR characterization of the radiators used for the microwave disinfestation treatment.

The microwave heating system

A prototypal device and a treatment desk suitable for the microwave treatment of small wooden objects was made. The device consisted of a 2.45 GHz microwave generator, a radiative applicator, some ancillary control electronics and a non-contact thermometer. The size and weight of the equipment were such that it could be easily moved according to the disinfestation needs.

In the following sections the microwave disinfestation system is described in detail and some preliminary results on bare and painted wooden boards are presented and discussed.

Description of the portable microwave disinfestation device

Figure 1 is a schematic of the microwave disinfestation system. The generator is a commercial 2.45 GHz magnetron with a maximum output power of 250 W. The low cost and ready availability of power devices were the main reasons for the choice of the operating frequency.

The output power can be adjusted continuously up to the maximum value by means of ancillary electronics. Microwave power is finally delivered to the object under treatment by means of a radiative applicator (Figure 2), which consists of a section of rectangular waveguide designed to operate at 2.45 GHz and connected to the microwave generator through a suitable coax-to-waveguide transition.

Forward and reflected power are measured in a standard way by means of a directional coupler and a bolometer.

The cross section of the applicator is 7.7cm x 3.7 cm^2, and it is provided with a radio-frequency trap at its mouth that consists of a corrugated flange made of two $\lambda/4$ circular grooves around the aperture [Stuchly et al. 1980]. The purpose of the flange is to block the leakage of unwanted microwave power radiated into the environment.

Air can be blown through the applicator, to lower the temperature of the wood surface facing the applicator opening. This helps both to maintain the surface at a safe temperature and to obtain a deeper treatment.

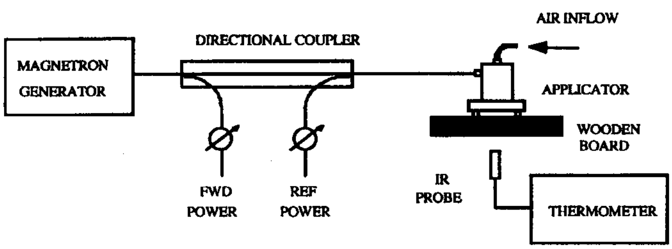

FIGURE 1: Block schematic of the microwave disinfestation system.

Power transfer from the generator to the object under treatment is maximized by adjusting the distance between the applicator aperture and the object from 18 to 33 mm. This adjustment is accomplished by means of four dielectric rods inside the corrugated flange. One of these rods also controls microwave power delivery through a switch which turns the generator off when the applicator is lifted. Power transfer is very good under normal operating conditions, with an average standing wave ratio on the order of 1.2; i.e. a reflected power less than 1%.

The surface temperature of the object under treatment is measured by means of a non-contact infrared thermometer.

The treatment setup for painted wooden boards

A workbench suitable for the treatment of painted boards is shown in Figure 3. The treatment setup consists of a wooden table with a central aperture where the board to be treated is placed with the painted surface facing downwards through the opening.

The temperature probe can be placed under the painted board to measure the temperature of the painted surface. A compass-like tool allows the temperature probe to be removed from the irradiated region when microwave power is on to avoid perturbation of the treatment. Temperature must be measured with power off, as the sensor is not protected against electromagnetic interference.

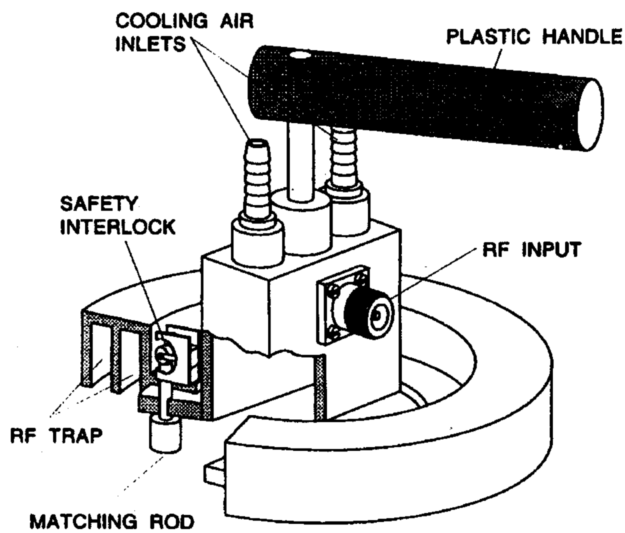

FIGURE 2: Radiative applicator with corrugated flange to reduce EM field leakage.

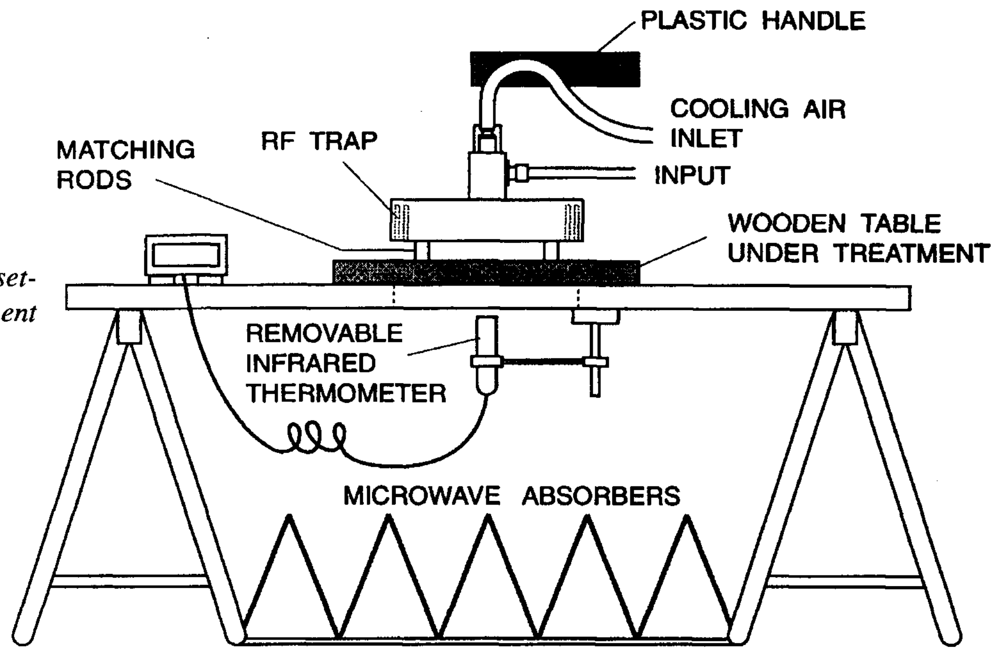

FIGURE 3: Laboratory set-up for microwave treatment of painted boards.

The output power level, the time duration of the microwave treatment and the forced air flow through the applicator are adjusted so that the temperature of the painted surface does not exceed about 50 °C.

The floor under the table is covered with microwave absorbers to minimize ground reflections and, thus, to keep the power irradiated into the surroundings of the treatment system at safe levels.

Preliminary results on wooden boards

Several tests were carried out on wooden boards artificially infested with woodworms. Tables of 1 cm thickness were prepared having small horizontal cavities carved into their larger surfaces. Three such boards were usually superimposed to obtain a 3 cm thick table (a common thickness for artistic painted boards). This provides a wooden board that contains a certain number of cavities - normal and parallel to the wood grain - placed at depths of one or two centimeters. The woodworms were inserted, before board assembly, in cavities displaced one to three centimeters from the axis of the applicator.

Seven wooden boards, prepared as described above, were treated by microwave heating at 200 W of output power and for different heating cycles such as, for example: 2 minutes ON, 1 minute OFF, 2 minutes ON. The heating cycles were chosen in such a way as to obtain a final temperature value between 40 and 50 °C on the bottom surface of the board, which is the surface controlled by the infrared thermometer.

The tests concerned insects in all metamorphic stages of interest: eggs (for *Hylotrupes bajulus*), larvae and pupae (for *Oligomerus ptilinoides*). The weight of the larvae ranged between 1 and 8 mg. The wooden boards were separated five minutes after the treatment to allow observation of the woodworms. Larvae were observed after 24 hours, while pupae and eggs were followed up ten days after the treatment. The final result was a complete disinfestation, of all metamorphic stages independent of size, weight, position and depth of the insects. The result was also independent of the applied heating cycle.

Preliminary results on the possible adverse effects of the heating on the painting were obtained. Three square wooden boards were prepared, each consisting of four differently colored subsquares. The colors, prepared according to four different recipes identical to those used by the ancient artists, were: white, blue and brown-yellow ranging from ochre to umber. One subsquare of each board was not treated, to cover possible confounding effects not related to the heat treatment, such as colour deterioration, measurement errors, etc. The other subsquares were treated by positioning the applicator on one corner.

A spectroscopic analysis (both in the infrared and in the visible region) of the colored samples was performed before and after microwave heating, by means of a fiber-optic reflectance spectroscope [Bacci et al. 1994]. The difference between the two series of measurements was less than the original variability of the pigment spreading. Furthermore, no significant differences were found among treated and untreated subsquares, thus suggesting the absence of adverse effects of the microwave treatment on the painting. A more systematic analysis is being carried out to confirm these preliminary results.

The effects of microwave heating on the wood structure, such as deformations or microfractures, have not yet been investigated. However, no macroscopic alterations of the wooden boards have been observed by sight.

Wood heating significantly depends on the dielectric properties (permittivity and losses) of the particular wood type and, also, on other parameters such as moisture content and exposure conditions. In order to prevent overheating, an estimation of the temperature inside wood is needed. This can be accomplished indirectly by measuring the surface temperature and resorting to numerical procedures to obtain a map of the internal temperature distribution.

Microwave leakage and hazards

The microwave power radiated into the environment was measured during typical disinfestation treatments by means of a RAHAM 4 (General Microwave Corporation, 5500 New Horizons Boulevard, Amityville, New York 11701) field monitor. The measured power density was less than 2 mW/cm^2 in any area accessible to the operator, with a maximum between 1 and 2 mW/cm2 close to the handle of the applicator. This is considered safe according to the most accepted safety standards: IRPA Guidelines (1988) [IRPA Guidelines, 1988] and CENELEC ENV 50166-2 (1995) [CENELEC ENV 50166-2, 1995] give a limit of 5 mW/cm^2 for occupational exposure; IEEE C95.1 (1991) limit is 8.2 mW/cm^2 for controlled environments.

The power leakage is maintained at low levels by the microwave trap at the applicator opening and the absorbers on the floor facing the applicator.

The power density, measured along the axis of the applicator in operative conditions (i.e. with the treated wooden board in place), decays as the inverse square of the distance from the opening and has a value on the order of 5 mW/cm^2 at little more than 1 meter from a 3 cm thick wooden board. This suggests that the treatment of objects in the vertical position should be avoided or, at least particular attention should be given when treatments are performed under such conditions.

The microwave power level in the main beam of the applicator is certainly hazardous and direct exposure of the operator must be avoided. A safety switch is provided that switches off the microwave generator when the applicator is not contacting the wood surface.

SAR determination by thermographic analysis

In order to develop treatment planning procedures, a knowledge of the distribution of power density produced by an applicator inside the treated wood is needed. The necessity for such information, as previously discussed, comes from the impossibility of performing temperature measurements inside the object under treatment which, on the other hand, must be safely treated without the risk of irreversible damage.

SAR maps can be obtained both experimentally and numerically using an electromagnetic model of the system consisting of the applicator plus the wooden table to be treated. Also in the numerical approach an experimental measurement is needed for validation purposes.

An experimental procedure for SAR evaluation was implemented based on a thermographic measurement on a sample wooden board. A sample board (model), with the same electrical properties and geometry of board to be disinfested, as shown in Figure 4, was placed under the applicator. The model can be rapidly split on a given plane immediately after the treatment, in order to reveal the inner section of the wooden board.

The temperature distribution on the split plane was measured, visualized and recorded by a thermographic camera. The thermal increment, ΔT, with respect to the initial conditions, allows SAR determination using the well known relationship:

$$SAR = c\frac{\Delta T}{\Delta t} \quad (1)$$

where Δt is the heating time in seconds, c is the specific heat (in J kg^{-1}°C^{-1}) of the wooden table, ΔT is in °C and the SAR is measured in W/kg.

Equation (1) is correct until the heat diffusion in the wood is as long as negligible, so that temperature increases linearly with time. As shown in the following, these conditions are fulfilled for exposure times such that a temperature increase of the order of some tens of degrees centigrade is produced. For a microwave output power of 200 W, the rate of temperature increase is greater than 10 °C/min. Due to the diffusivity of wood, which is of the order of $2.3 \cdot 10^{-7}$ m^2/s, the temperature increases linearly for several minutes. An exposure time of 2 minutes, for example, produces a ΔT of 20 °C, a suitable value for the resolving power of the thermographic camera.

The lens aperture is 10 degrees in the vertical plane and 15 degrees in the horizontal plane. Images have a size of 250 (horizontal) by 100 (vertical) pixels and 256 grey levels.

SAR measurements

The thermographic method has been tested on the applicator previously described. The treated boards had a thickness of 3 cm, and dimension of 25 x 30 cm. The size of the region where SAR was measured (called SAR plane in the following) is thus 25 x 3 cm, as a result of the board splitting along the wider side. In the measurements reported below, the applicator was positioned with the aperture normal to the SAR plane, with its largest side parallel or normal to the cut.

Figures 5 and 6 respectively show the isothermal profiles deduced by two thermographic measurements. In the first case (N) the applicator was positioned with the widest side parallel to the cut, so that the electric field at the applicator aperture was normal to the cut. In the second case (P) the applicator was rotated ninety degrees, with the electric field in the SAR plane. In both cases the delivered power was 150 W, while the treatment time was 90 seconds in the N case and 50 seconds

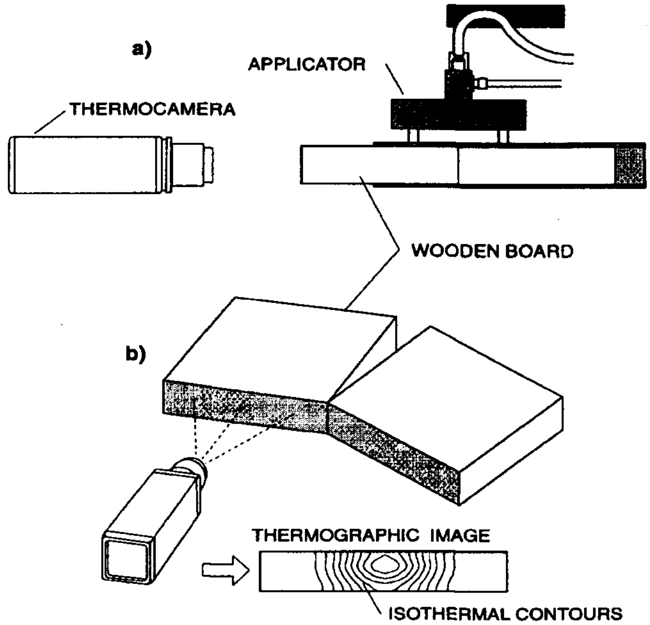

FIGURE 4: SAR measurement setup.

in the P case. Other relevant data were: initial temperature (22.3 °C and 18.8 °C respectively for cases N and P) and maximum temperature value in the thermographic image (47.8 °C in case N, 42.9 °C in case P).

The temperature range on the thermographic camera was set to 25.6 °C in both measurements, to obtain a temperature resolution of 0.1 °C, corresponding to a SAR resolution of 2.8 W/kg in case N and 5 W/kg in case P (assuming a specific heat of 2500 J kg^{-1} $°C^{-1}$ for wood). The spatial resolution was 0.68 pixel/mm in the horizontal direction (i.e., parallel to the applicator aperture) and 1.31 pixel/mm in the vertical direction.

Figures 7 and 8 show the SAR patterns on the two planes, as computed from the above thermographic measurements by means of equation (1). Horizontal

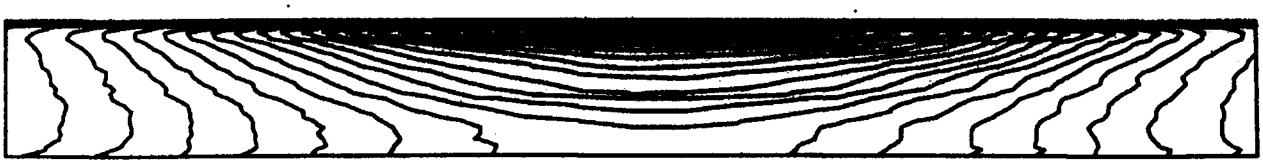

FIGURE 5: Thermographic image in the SAR plane. E field normal to the cut.

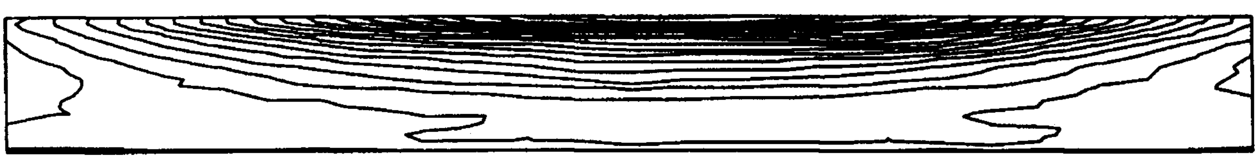

FIGURE 6: Thermographic image in the SAR plane. E field parallel to the cut.

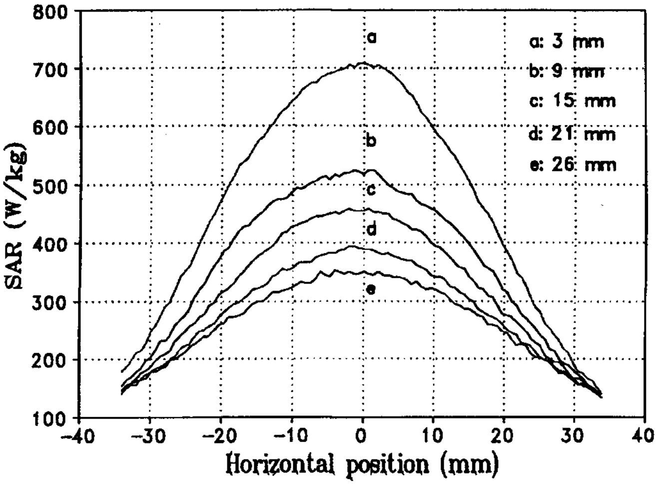

FIGURE 7: Measured SAR on a section normal to the E field.

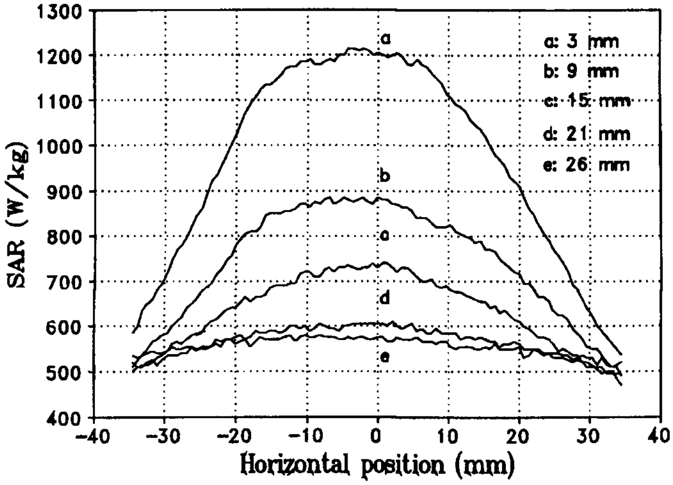

FIGURE 8: Measured SAR on a section parallel to the E field.

position was measured from the electric center of the applicator mouth, which coincides with the geometrical center. SAR profiles are shown in both Figures at five different depths: 3 mm, 9 mm, 15 mm, 21 mm and 26 mm.

Deviation from linearity

The temperature rise inside wood depends linearly on time until thermal diffusion can no longer be considered negligible. Furthermore, the thermographic method required splitting of the sample in order to take a measurement in the time interval between splitting and image acquisition, the temperature distribution on the SAR plane deteriorated by radiation and convective heat exchange from that plane. The errors in SAR due to the deviation of temperature rise from linear and to the effects related to opening of the sample have been evaluated by the experimental procedure described in the following.

A treatment was performed on a splittable board, as described in the previous section, with the applicator positioned so as to have the electric field normal to the SAR plane, as in case N above. Thirty images were taken after a treatment of 120 seconds, with a delivered power of 200 W, for a total time duration of 337 seconds (the thermographic camera employed for the SAR measurements is capable of taking an image about every 11.5 seconds). The procedure to obtain an evaluation of the error consists of comparing the experimental time behavior at a chosen point inside the wood with that expected in several thermal conditions, namely:

a) wooden board thermally insulated;
b) radiation and convection from the surfaces of the board at ambient temperature, in still air;
c) radiation and convection as in case (b), and from the splitting (SAR) plane.

The temperature versus time behavior at the depth of 4 mm is shown in Figure 9 (which was the most unfavorable, being the point where the maximum temperature increase occurred). The experimental behavior was compared with that computed by a finite-difference time-domain (FDTD) model. This allowed the calculation of the temperature distribution in a wooden block with the same shape and size of that used in the experiment. The numerical model required the following parameters as input: the SAR distribution (computed or measured); the thermal and physical characteristics of wood; the initial and ambient temperature values; the heat exchange coefficients with the external environment (sum of radiation and convection).

The convection/radiation heat coefficients at the upper surface of the wooden block (that surface in front of the radiator) and on the SAR plane were obtained by means of a best fitting of the experimental temperature decay shown in Figure 9. From that procedure a value of 7 W m^{-2} $°C^{-1}$ was obtained and used in the above cases (b) and (c). The input value of SAR, at the impinging surface, was extrapolated from the experimental data, while the SAR distribution inside the wood was numerically computed, based on an electromagnetic model of the applicator.

Figure 10 helps in estimating the SAR error due to the deviation from linearity. The error, defined as the relative percentage difference between the temperature computed in the above cases (a), (b) and (c) and that of an hypothetically perfect linear temperature increase lasting 120 seconds. The thermal exchange with the environment adds less than 2% to the systematic error due to heat diffusion inside wood (cases (b) and (c)). The linearity error is clearly inversely proportional to the depth, as power density and heat exchange both increase going towards the upper surface.

The (c) case also allows the error due to the opening of the wooden board along the SAR plane to be estimated. It follows from Figure 10, curve (c), that such an error is less than 6.5 % if the time lag between power off and the acquisition of the thermal image is less than 5 seconds.

Conclusions

A prototype of a microwave disinfestation device was developed that is suitable for the treatment of wooden painted boards. The system performance has been tested on sample boards artificially infested with woodworms.

A preliminary spectroscopic analysis conducted on painted boards prepared according to ancient recipes did not detect any damage on the painted surfaces that can be attributed to microwave heating.

Although small volumes were treated with the present prototype, its effectiveness in disinfesting wooden objects from insects in all metamorphic stages has been clearly demonstrated.

An experimental procedure for determining the SAR distribution produced in wood by a given applicator has been established and an extended analysis of the possible sources of error in this procedure has been carried out to show that the error can be kept below 5% if the wooden board splitting is quickly done. The SAR distribution is the fundamental input parameter for the numerical pre-treatment models and treatment simulations which is one of the points of interest of our research activity in this field. Treatment planning procedures are of paramount importance for adjusting the several parameters (delivered power, heating time, etc.) involved in the microwave disinfestation of artistic wooden objects.

The presence of metal objects inside wood (e.g. nails and screws) can significantly alter the power density distribution. Furthermore, metal coatings or paintings of the wooden table are expected to strongly influence the SAR distribution. The study of the above effects is currently under development.

Detailed analyses of the heating effects on paint and on the mechanical and structural properties of wood are

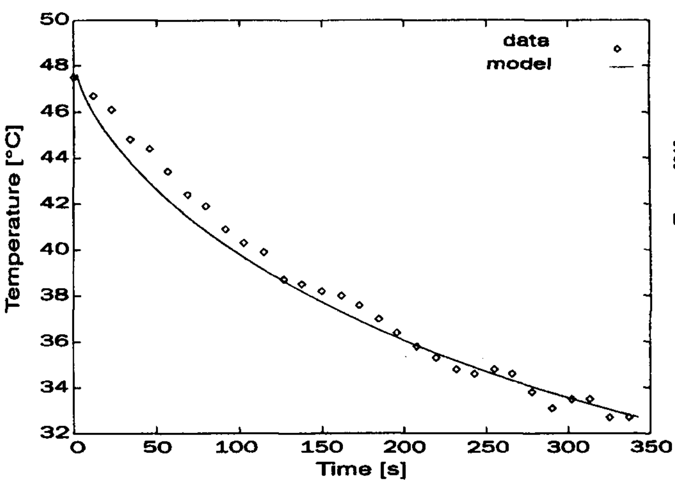

FIGURE 9: Time behavior of the temperature maximum on the SAR plane.

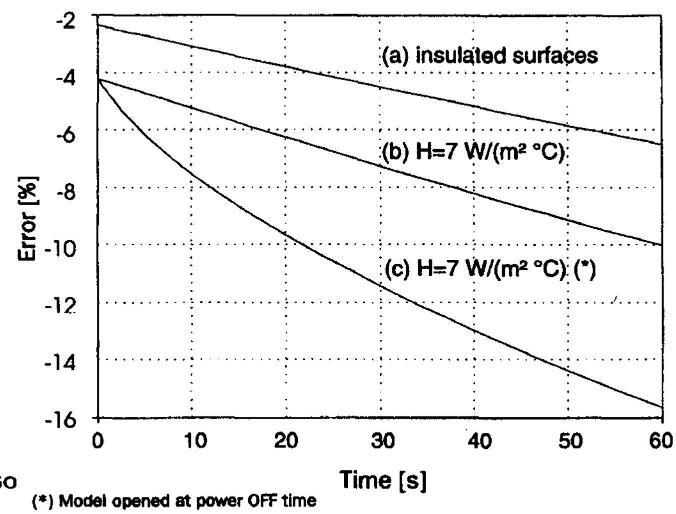

FIGURE 10: Error versus time for various thermal exchange models.

also in progress to confirm the safety of the method.

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