A Low-Cost Robust Configuration for the Temperature Monitoring within the Payload of any Microwave Oven with a Rotating Turntable

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Abstract. This contribution aims to be a reference to help researchers build up their own microwave heating systems for monitoring the temperature evolution of a payload with almost endlessly (limited by the batteries capacity of the measuring system) rotational movements. Its robustness is because it allows keeping sensors in place thus avoiding the fiber optics wringing/twisting while the payload is rotating. The proposed system facilitates the rotation of the temperature equipment located over the microwave oven synchronously with the payload, while its data is transferred in real time by an RF transmitter/receiver device connected to its serial data port. The fiber optic sensors deployed from the temperature equipment ports to the measuring points are arranged with the rotation axis through a hollowed shaft to minimize mechanical stresses. The equipment operation, its configuration, and the data transmissions are controlled wirelessly by a laptop computer. The prototype presented in this paper was implemented for a total budget amount of 6500€.

Keywords: microwave heating, temperature, turntable, fiber optic wringing/twisting

1 Introduction

The knowledge of the temperature evolution of a payload inside a microwave cavity while being irradiated is of interest to scientists and engineers. It can help in the optimization of thermal processing, as is tuning up microwave assemblies to improve heating uniformity, or the management of power profiles for the speed and efficiency.

When monitoring the temperature at some measuring points within a payload being heated inside a microwave oven, fiber optic sensors allow a proper performance without affecting its measurements, since their presence does not interfere with the EMF confined within the cavity due to its dielectric characteristics (low permittivity and loss factor values).

These sensors are typically thin enough to get them through the ventilation holes of the cavity and then inserted into the payload at the monitoring positions; this is the basic measurement configuration. Nevertheless, under a dynamic system where the payload is moving during the irradiation, as in domestic microwave ovens, which typically have a rotating turntable to increase the heating homogeneity, the probes will be shifted and they might be disengaged from their expected measuring points.

So, the first challenge for this kind of experimental setup is to keep the sensors in place while the payload is rotating. This is achieved by designing a robust setup where sensor positioners are able to neutralize the low mechanical forces caused by the rotating payload. The second challenge is to avoid sensor damage due to the wringing of a single fiber or twisting a bunch fiber together if attached to a fixed measuring equipment outside the cavity. This means that the experimental configuration is highly sensitive to the number of the monitoring points, their special distribution and the number of turns that the test must undergo.

In [1] an experimental study on the batch microwave heating of liquids waspresented, where 3 fiber optic sensors were used simultaneously for measuring the temperature evolution every $t_{sampling} \approx 10$s within the liquids at different locations inside a microwave cavity of 279.4 x 393.7 x 425.5 mm^3 manufactured by Cober Electronics. Its rigid measurement set-up did not allow the activation of the turntable rotation but the electromagnetic stirrer of the designed microwave oven.

In [2] the microwave heating in a domestic ovens was analyzed, using 4 fiber optic sensors with a sampling rate of $t_{sampling} \approx 2$ s over a duration $\Delta t = 30$ s in a 700 W rated power microwave oven (629 W available power measured accordingly to

IEC 60705) with a cavity of 420 x 395 x 253 mm^3 manufactured by Sharp.

In [3] 8 fiber optic sensors were used simultaneously on every experiment lasting $\Delta t = 360$ s, with a sampling rate around $t_{sampling} = 0.5$ s.

In [4] a microwave oven with a cavity 270 x 270 x 185 mm^3 was used at 600W of nominal power, to heat its contents on a turntable rotating at 5 rpm during $\Delta t = 150$ s. Records for 5 measuring points inside the sample with a sampling rate around $t_{sampling} \approx 7.5$ s are given, and the difficulty of keeping the optical probe sensor in place while the turntable was rotating was emphasized.

In [5, 6] a 1200W domestic microwave oven was used with a rotating turntable to validate its results by monitoring 6 measuring points during 4 and 6 minutes respectively using optical fiber sensors.

In [7] a single optical fiber sensor monitored the heating of a payload inside a microwave cavity with a turntable rotating at 5 rpm during $\Delta t = 30$s with a sampling rate of $t_{sampling} \approx 2$s. The fiber was introduced into the cavity through a hole at the turntable rotation axis center and a cut-off waveguide.

In [8, 9] two liters of deionized water were heated inside a microwave oven at different power levels within the range [600, 1000] W, until detecting a temperature of 50°C at any of their monitoring points with a sampling rate of $t_{sampling} = 1$s. Although in [8] a single temperature fiber optic was used, in contrast in [9] 4 fiber optic were used simultaneously. Both articles indicate that the cavity was a multimode one, but they do not mention if the microwave oven had a mode stirrer or a turntable.

In [10] i a setup was described for heating a sliced potato on a turntable rotating at 10 rpm inside a microwave oven at 300 W of effective power. Each test lasted $\Delta t = 12$s, which is two complete spins for the turntable. Meanwhile, two fiber optics monitored the temperature inside the potato with a sampling rate of $t_{sampling} = 1$s.

In [11] a setup was described using a 920 W rated microwave oven with a turntable spinning at 6 rpm. A single optical fiber was introduced inside to monitor the temperature within a potato slab for $\Delta t = 35$s.

2 Methods

The configuration schema is depicted in Figure.1. It is remarkable that the motor gear of the microwave oven, which forces the rotational movement of the internal turntable, is extracted and placed outside to be used to spin an external turntable simultaneously through a set of shafts, cogwheels and belt wheels.

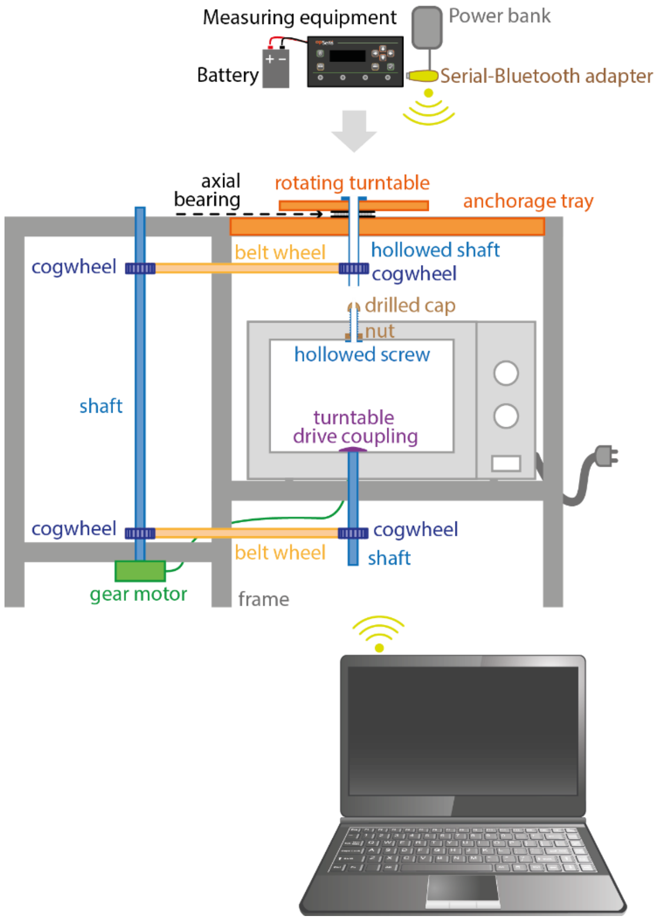

Figure 1: Schematic of the rotating monitoring setup.

The prototype was assembled using a domestic microwave oven model Samsung M1711N with a rated power of 800W, and an OpSens TempSens signal conditioner with 4 optical fiber temperature sensors as the temperature monitoring subsystem. The Figure 2 shows the implemented configuration based on the schema introduced in Figure1.

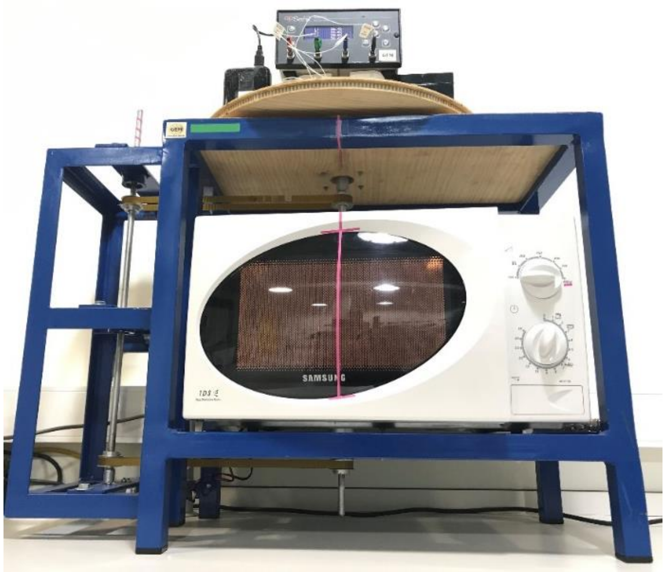

Figure 2: Prototype implemented with an 800 W power rated Samsung M1711N microwave oven and an OpSens TempSens signal conditioner with 4 optical fiber temperature sensors.

The external turntable was linked to a tray anchored to the frame through an axial bearing. This bearing allows a rotational movement with a hole in its center, where the optical fibers could transit. The fibers were introduced inside the microwave cavity through a small hole of 5 mm diameter, which is less than 1/24 of the wavelength in free space at 2.45 GHz, and less than 1/14 of the wavelength considering a dielectric constant of 3 (estimation for the fiber optic material). In the situation where a larger number of fibers is needed, a wider hole would be necessary. To avoid any microwave energy leakage a circular cut-off section has to be attached to the hole by filtering any electromagnetic mode that could propagate outwards.

Two different payload materials were considered for testing the setup: liquid deionized water (type II), and its version as a thickened form by using Agar-Agar as a gelling agent in a proportion of 4g per liter (Figure 3). The Agar-Agar used (Vahiné, a trade mark from McCormick & Company Inc.) was acquired from a local supermarket. The purpose of considering the gelled water was to study qualitatively the effect of the convective flows on the temperature evolution.

Figure 4 shows the locations of the 4 measuring points used to monitor the temperature evolution simultaneously. A lid made of Expanded Polyethylene (EPE) foam was used as the XY-plane probe positioner, while a little mark painted on the fiber optic was used as the reference to insert them into the payload at the appropriate depth.

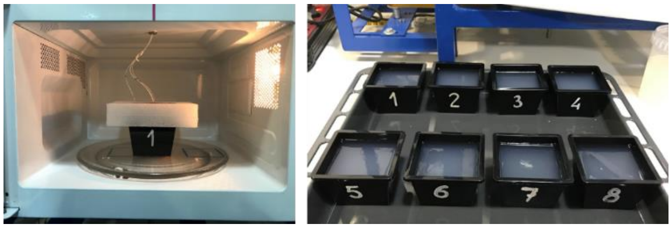

Figure 3: Microwave loaded with a sample with all the monitoring sensors arranged (left) and several samples of 4g Agar-Agar per liter of deionized water (right).

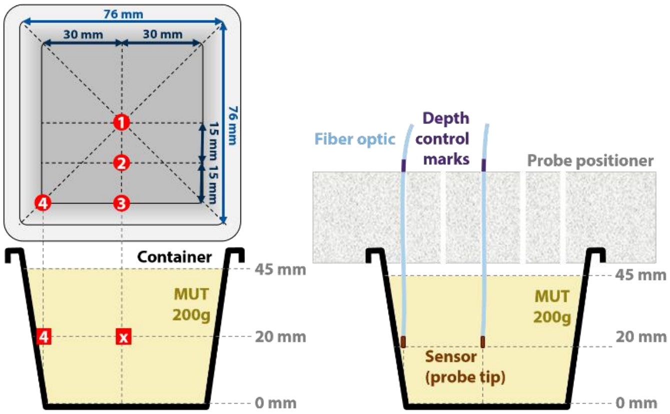

Figure 4: Probe positioner and measuring point locations.

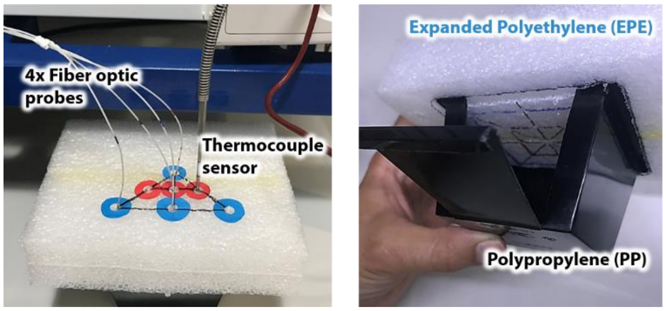

Figure 5: Detail of the lid used as the probe positioner. Thermocouple sensor was used to verify the initial temperature of the payload.

The samples were resting for several hours at room temperature before the tests. Considering that all the fiber optic sensors within the sample at the initial state should detect the same temperature, any offset deviation had to be compensated using a temperature reference. A thermocouple sensor was used to provide the temperature reference as shown in Figure 5. It was assumed that the optical probes had a linear and non-hysteresis response.

3 Results

The left part in the Figure 6 shows the raw temperature measurements of a tested sample, where it is noticeable that each sensor was reporting different initial temperatures before the irradiation. The right part of the figure shows the traces after applying the adequate compensation for each probe.

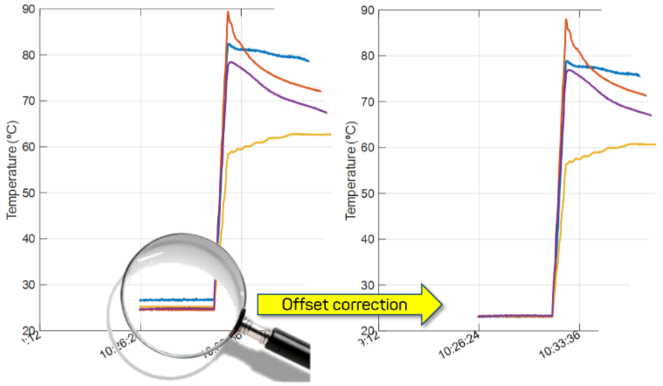

Figure 6: Fiber optics readings before (raw data) and after the offset correction.

Figures 7 and 8 compare the temperature evolution for two similar dielectric materials, deionized water and a solution of 4 g agar-agar per liter of deionized water, but with a different physical state, liquid and gelled respectively. While in Figure 7 the irradiation has been performed continuously during 1 minute at the maximum power rate available for the microwave oven (800W), in Figure 8 the response corresponds to the pulsated irradiation at a medium power rate (450W). Their heating slopes differences are emphasized in Figure 9.

4 Discussion

The comparison between liquid and gelled water shown in Figure 7 emphasizes the thermodynamic response effect due to convective flows.

During the tests, it became apparent that condensation of the water vapor occurred at the EPE lid, as it would happen with any obstacle interrupting the natural ascending vapor flow. For that reason, it was noticeable the heating of the lid at its bottom side due to the presence of water. Therefore, the evaporation (mass transfer) plays an extra role and should be considered in a study of the heat transfer of the system if a more accurate evaluation of the measurement is sought.

The ripples that are shown in Figure 8 are a consequence of the pulsated irradiation with a nominal duty cycle of 56.25% (450 W / 800 W).

Researchers must choose the appropriate fiber optic probes that are going to be exposed to microwaves, taking into account the expected temperatures they must withstand. Some manufacturers claim that their sensors are immune to electromagnetic fields. But there might be some missing information about the protective material on the sensitive tip of the probes, which could be covered with materials sensitive to absorb microwave energy due to their dielectric losses (i.e. polymer resins as epoxy, which has a complex dielectric constant of $\varepsilon_r^* = 3.5 - j0.21$ at 2.45 GHz, measurement published in [11]). So they might introduce sensing inaccuracies and their life span could be even shortened at some point.

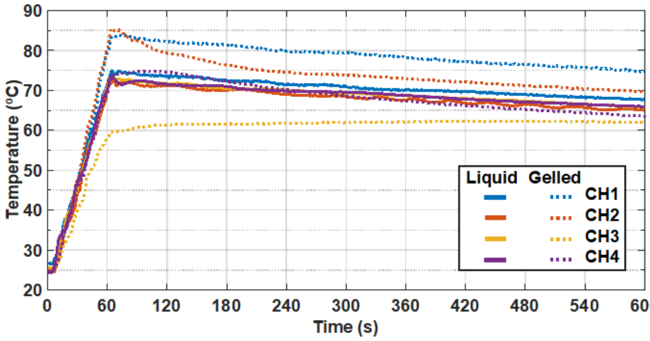

Figure 7: Payload temperature evolution comparison for 200g of deionized water in their liquid and gelled (4g Agar-Agar per liter of DI-water) versions at 4 measurement points during its continuous microwave irradiation (800W rated power) for 1 minute, and posterior resting while cooling down.

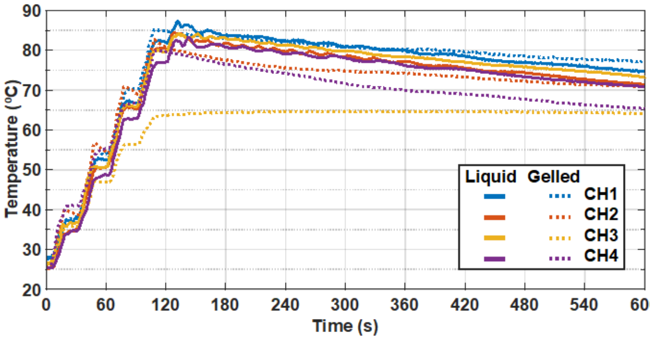

Figure 8: Payload temperature evolution comparison for 200 g of deionized water in their liquid and gelled (4 g Agar-Agar per liter of DI-water) versions at 4 measurement points during its pulsated microwave irradiation (450 W rated power) for 2 minutes, and posterior resting while cooling down.

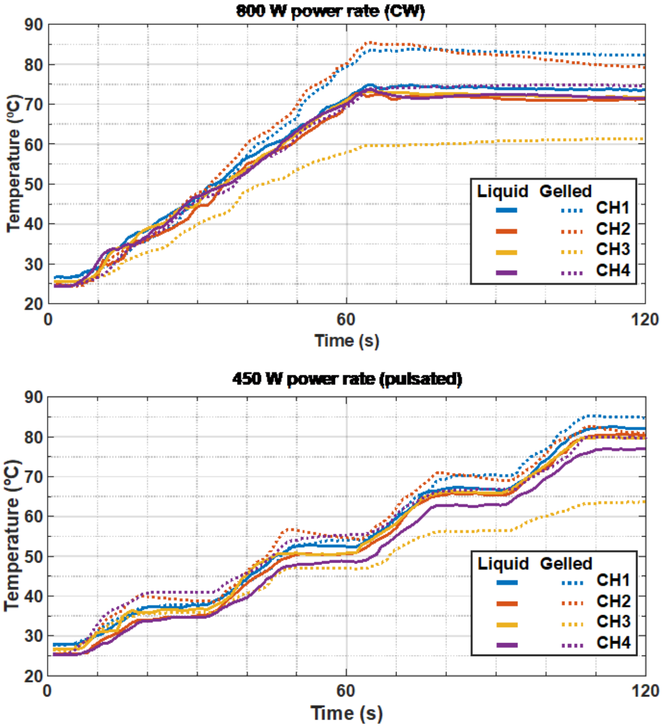

Figure 9: Heating slopes detail for the 800 W (continuous wave) and 450 W (pulsated) power rates.

It is also important to design robust holders that could keep probes in their expected locations during the test. When the payload is not solid, it might be helpful to consider coating the fiber optic probes with thin tubes made of a mechanically robust material, although one ought to leave the tip bare in contact with the payload. In favor of reducing the measurement uncertainties, the coating material should have a low loss factor (to avoid being self-heated when exposed to the microwaves) and a dielectric constant similar to the payload to minimize the interference (reflections due to impedance mismatching) with the electromagnetic fields. Moreover, to preserve the original thermodynamics, the coating material should have a similar thermal conductivity as the payload had.

Another setup strategy for the continuous monitoring of the temperature in the payload on a rotating turntable could be to ensure that the motor can rotate back and forth. By using suitable electronics, the number of turns in one direction could be compensated by forcing the same number of turns in the counter direction, so the fiber optics are acceptably twisted and untwisted continuously. Nevertheless, this strategy could introduce some artificial effects when trying to evaluate the normal operation of a commercial microwave oven dueto the introduction of (de)acceleration forces that might shake the payload, especially when it is a liquid.

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For further reading

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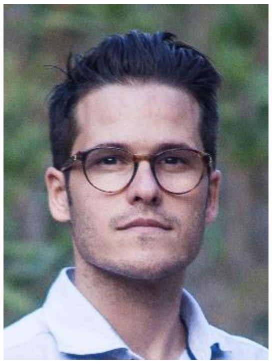

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His research areas are related to microwave heating and drying, permittivity measurements, waveguide calibration procedures, electromagnetic compatibility and dosimetry and microwave oven design.

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