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CONTACT-LESS SENSORS FOR TEMPERATURE MEASUREMENT BY MICROWAVE RADIOMETRY IN MEDICAL OR INDUSTRIAL APPLICATIONS.

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1. INTRODUCTION.

Temperature is an important and even crucial parameter in the medical domain (for example to control temperature during treatments or to detect thermal anomalies) as well as in the industrial world especially in products quality improvement in production line or in respect for hygiene standards verification of food. The usual methods for temperature control, as the use of thermocouples or optical fibers, are invasive and give only punctual information. Infrared measurement is a non-invasive way but gives only superficial temperature. MRI method can be used to measure temperature change, however, this require complex and very expensive equipment, and is not suitable for routine measurement repeated over a prolonged period of time. So microwave radiometry brings a real solution to measure and control non-invasively temperature inside a dissipative material. We present in this paper specific sensors which characteristics allow us to perform radiometric measurements at very low temperatures (in deep frozen tunnel) as well as at very high temperatures (up to 500 °C).

2. MATERIAL AND METHODS

2.1. Radiometry.

Radiometric temperature measurements are based upon the following principle. Any dissipative body emits spontaneous electromagnetic radiations of thermal origin, which can be measured by a sensitive receiver called radiometer [1]. In the microwave frequency range, the thermal noise power emitted by a dissipative body is directly proportional to its temperature. Thus, the temperature inside a dissipative material can be determined from a non-invasive way by use of a radiometric system, which uses an antenna sensor connected to a microwave radiometer to collect the thermal noise power emitted by the body. This technique is used for many applications: remote sensing, radio-astronomy, imaging for breast cancer detection, detection of anti-personnel landmines. The radiometric temperature of material under observation is obtained from the integral summation of the noise power emitted by each sub-volume where T(x,y,z) is the absolute temperature of each sub-volume and C(x,y,z) is a weighting function taking into account the sensor's field of view:

$$Trad = \frac{\iiint C(x,y,z)\, T(x,y,z)\, dx\, dy\, dz}{\iiint T(x,y,z)\, dx\, dy\, dz}$$

2.2. Radiometer used.

Since about twenty years, we have developed many microwave radiometers (which operate in the 1-10 GHz frequency range) and specific sensors according to various applications (industrial or medical). The radiometer (Fig. 1) contains two internal temperature references (low noise amplifiers) obtained respectively by a cold source (TR1) and a warm one (TR2). This allows obtaining a radiometric temperature measurement independent from the gain of the microwave chain and from the reflection coefficient at the sensor input [2]. An internal calibration unit using 2 well-matched loads held at known temperatures T1 and T2 allows taking into account the insertion losses of the microwave chain. This device can performed contact-less radiometric temperature measurements on highly or weakly dissipative materials from -100 °C up to 500 °C with low fluctuations (depending of the range of temperatures).

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2.3. Radiometric Sensor

Planar printed antennas are widely used to realize radiometric sensors. But, at low temperatures, we observed a great influence of the thermal noise of the substrate on the measured radiometric temperature. Recently, we have designed a new type of radiometric sensors called “cold sensors” [3] to reduce these problems. They are fabricated from a metallic sheet (copper, brass, aluminum) of small thickness (from 50 µm to 2 mm) in which a notch of rectangular shape is cut (Fig. 2). The metallic sheet can have different shapes (square, rectangular, circular,…) and sizes, according to the application. The sensor is fed by a 50 Ω coaxial cable: outer of the cable is bonded to one face of the notch; inner conductor continued across the notch and is connected to the opposite face. The operating frequency of the sensor is adjusted by moving the feed point along the notch. These sensors present many advantages: they are easy to fabricate, light, not bulky and cheap.

An electromagnetic model based on the EFIE (Electrical Field Integral Equation) [4] has been developed to determine in a short time the shape and dimensions of the sensor for an optimum working. We can also compute the reception diagram of the sensor in front of the dissipative material.

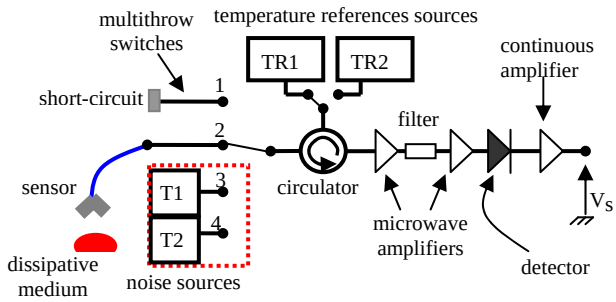


Fig. 1. Structure of the radiometer.

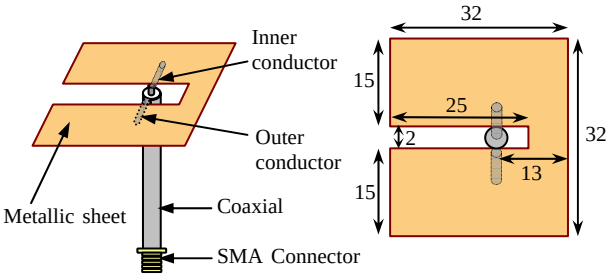


Fig. 2. Scheme of a sensor used for the radiometric temperature measurement. The dimensions are in millimeters.

3. APPLICATIONS.

3.1 INDUSTRIAL APPLICATIONS.

3.1.1 Food processing industry.

Temperature control is of a greater concern in food processing industry for safety reasons as well as for product quality (which is one of the hottest topics). Current methods for measuring temperature in continuous flow freezing systems include infrared, optic fiber and thermocouples measurements. None of them give reliable continuous temperature information within the food-product, which is needed to confirm the effectiveness of deep freezing.

Thanks to this “cold sensor”, several experimentation campaigns in food processing industry were carried out in a deep frozen tunnel (where temperature are comprising between -20°C and -5°C). The sensor is placed in front of the product and the temperature information given by the radiometer has been continuously registered. The radiometer operates at the frequency 1.575 GHz with 60 MHz bandwidth (the temperature references were -45°C and 60°C). Results of radiometric measurements are compared with usual methods (thermocouple, infrared). An example of comparisons between these measurements and the on-line recordings is presented on Figure 3 where are indicated the averages of the core and surface temperatures, as well as the fluctuations estimated from standard deviation calculation. The radiometric temperature was validated as a relevant non-invasive method. Inserted in a production line, this radiometric device should offer a better control of the freezing process and also allow a faster intervention on the production parameters (speed of scrolling, stream of cooling, product quantity on the conveyor).

3.1.2 Microwave sintering of Metal-Ceramic composites.

In the last 50 years, the progresses of industrial microwaves heating technology has lead to its successful introduction in domains such as food processing, wood seasoning or the intertisation of special waste. Recently, microwave processing of powder metallurgical bodies has been shown to be very promising. Fully dense bodies with improved mechanical properties could be produced due to finer grain size. In the field of the sintering of materials, a control of the temperature inside heated

parts is necessary to avoid local melting or distortions. Temperature measurement in microwave cavity is known to be problematic. Contact-less microwave radiometry represent a potentially invaluable tool to follow the external and internal thermal trajectory during the sintering process of composite materials placed in a microwave furnace. Feasibility studies are currently carried out in collaboration with the EMPA (Switzerland). The first step of the project consists to measure in our laboratory the radiometric temperature of various powders samples of SiC, Al and mixtures of Al/SiC with various properties (ratio, particle size, density of compaction, temperature gradient…). The heating device is constituted by a cylindrical sample holder containing a heating cartridge. A quartz cylinder of 3mm thickness is used to maintain the powder around the heating cartridge. The Figure 4 shows a comparison between the radiometric temperature (measured at 1.575 GHz) and the temperature recorded on the surface of the quartz cylinder. We observe a higher radiometric temperature than that measured by the thermocouple. This results show that it is possible to obtain information on the temperature within the powder without contact.

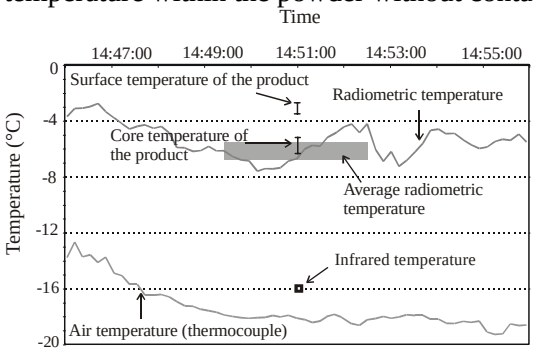


Fig. 3. Comparison between usual methods and radiometric measurements in a deep freezing tunnel.

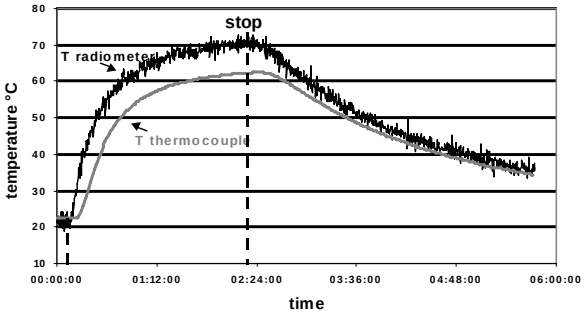


Figure 4. Temperature recording with SiC powder. The temperature of the heating cartridge is 100°C.

3.2 MEDICAL APPLICATIONS.

3.2.1. Neonates temperatures.

The sensor used for measurement and control the temperature of premature neonates has to be sturdy and easily manageable (positioning, cleaning, sterilization). It is realized from a metallic (copper) film laid on a dielectric substrate of relative permittivity $\varepsilon_r = 10.2$ and of thickness 1.27 mm. In order to pick up only the radiation arising from the baby, the sensor has been inserted in a case. So, the set is very light and is only weighing 2.063 g. The radiometer is working around 3.2 GHz with a bandwidth of 500 MHz (the reference temperatures have been fixed at 33.9°C and 54.4°C)

During the measurements, the neonate is inside the incubator located in an exploration room fitted out with a lot of apparatus. The sensor is located under the diaper of the newborn at about the groin level and covered with a plastic sticker in order to prevent change of location of the sensor during the movements of the neonate. An example of recorded temperatures during a session on a neonate is given on the figure 5. We have also reported the temperatures obtained from thermocouples located in different parts of the newborn: rectum, cheek and abdomen. First, we observe that the temperatures are depending on the location of the body (difference of 1.2 °C between the rectal temperature and the one recorded on the cheek). The radiometric temperature is situated between the rectal one and the average of the temperature between the abdomen and the cheek. Its value is less than 0.5 °C of the rectal one, but the fluctuations are more important that those observed by thermocouples.

3.2.2 Chronobiology.

The measurement of corporal temperature gives important information for a lot of clinical studies (Indication of dysfunction, diagnosis and monitoring of many pathologies, dosage of drugs). Indeed we are interested in the Follow-up of human thermal cycles (circadian rhythm which is connected to the variations of the central human temperature). The protocol of the clinical study (in collaboration with the Center of Clinical Investigation [CIC] of the CHRU/INSERM of Lille) is the following : 14 male adult persons satisfying strict criteria have been selected. Each of them was put through a session composed of 3 steps of 21 minutes. During each step, the temperature has been measured from the

following manner: I- rectal probe and radiometry at lower back; II- rectal and axillary probes and radiometry under armpit; III-rectal probe, infrared tympanic thermometer and radiometry at the level of the eardrum.You can see on Figure 6 an example of the recorded temperatures during a session obtained for each step. We can note a disparity between the rectal temperature and those measured by radiometry. In the contrary, we have a quite good agreement for the axillary temperature measured by radiometry or by the axillary probe. We have also noted coherence between the radiometric temperature and those measured by the rectal probe and the tympanic thermometer.

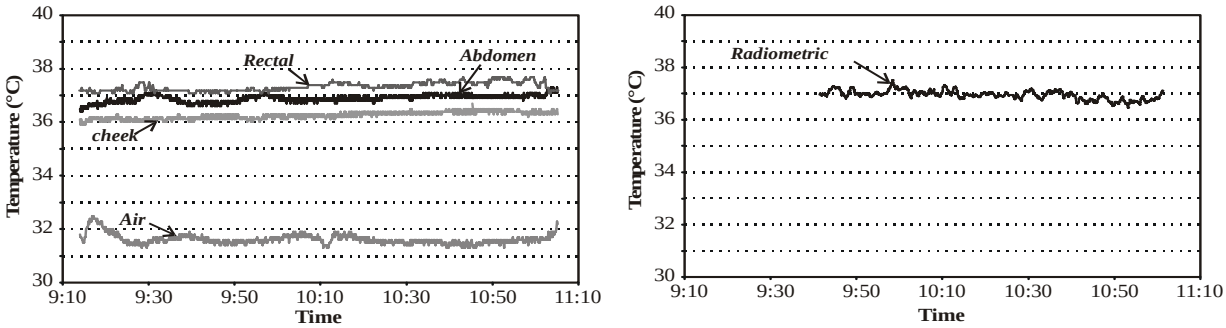
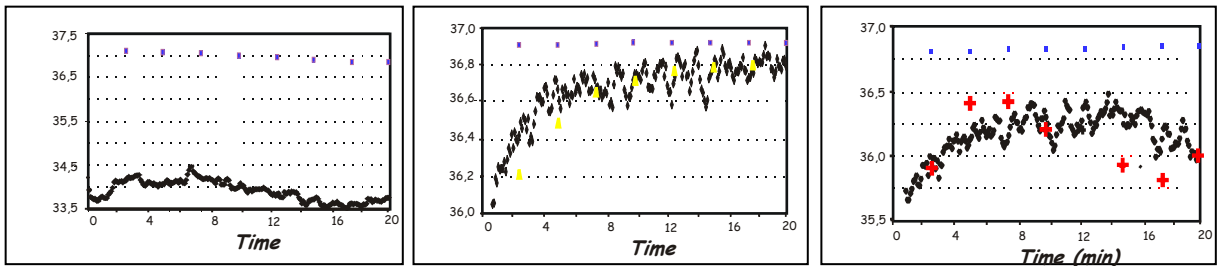


Fig. 5. Recording of the corporeal temperature of a neonate newborn.



Step I Step II Step III

(Rectal, Radiometric, Axillary, Tympanic).

Fig. 6. Recording of the corporeal temperature during a session of chronobiology

CONCLUSION

We have studied and realized specific sensors to be used for temperature measurement and control in industrial or medical applications. Experimental measurements performed in deep freezing tunnels show the potentiality of the radiometric device. It appears to be very interesting for food industry to reduce product loss and to optimize product quality. Other industries take a great interest in this non-invasive method for temperature control and the radiometric information can be applied to feedback control of process parameters. This sensor can also be used for temperature measurement and control in medical applications. The experimental measurements performed on premature neonates or for chronobiology, are very cheering and show the potentiality of this technique.

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