http://dx.doi.org/10.21611/qirt.2008.02_13_14

Inspecting localized moisture in building materials by applying optical and microwave heating

by V. Vavilov*, W. Swiderski**

*Tomsk Polytechnic University, Tomsk, Russia
**Military Institute of Armament Technology, Zielonka, Poland

Abstract

Both theoretical and experimental results on evaluating hidden water in building materials are reported to compare features of optical and microwave heating. Experiments have been performed on a 2 cm-thick reference sample made of gypsum pasteboard which contained voids filled with foamed polyurethane. The obtained results are compared to illustrate that advantages of microwave moisture detection are not so unanimous as expected.

1. Introduction

While the safety issue is not involved into consideration, microwave heating is often considered as the most appropriate means of thermal stimulation in evaluating moisture in porous materials. It is believed that a signal-to-noise ratio may be higher in this case in regard to any kind of surface stimulation due to the fact that microwaves warm up only moistened areas and leave “cold” dry sound areas.

In order to analyze possible advantages of using microwave heating in thermal NDT (TNDT) of building materials, in this study, both surface and microwave types of stimulation have been modeled and experimentally implemented with obtained results being compared by using the criterion of signal-to-noise ratio. Potentials of some data processing techniques, such as 1D Fourier transformation, also called Pulse Phase Thermography (PPT), and Principal Component Analysis (PCA) have been studied on obtained experimental data.

2. Experimental setup

A 2 cm-thick reference sample (figure 1) was made of gypsum pasteboard which is widely used in indoors building. On front surface, gypsum was covered with a 1 cm-thick plate made of decorative ceramics. Within gypsum, two 40x40x10 mm voids were filled with foamed polyurethane and then moistened with fixed amounts of water (from 1 to 8 g). Surface heating was accomplished with a quartz halogen lamp which ensured 8.5 kW/m2 of absorbed surface power. Microwave heating was done by placing a sample into a commercial 1 kW oven of which delivered power density was estimated to be 1.54 W/cm^3 in the centre of the oven. Power of thermal stimulation in both cases was determined by heating either a black-painted reference 10 mm-thick aluminum sample (optical heating) or 200 g of water (microwave heating). Surface temperature was monitored with a Thermovision-570 IR imager during 300-500 s on both ceramics and gypsum side after 10 s-long heating.

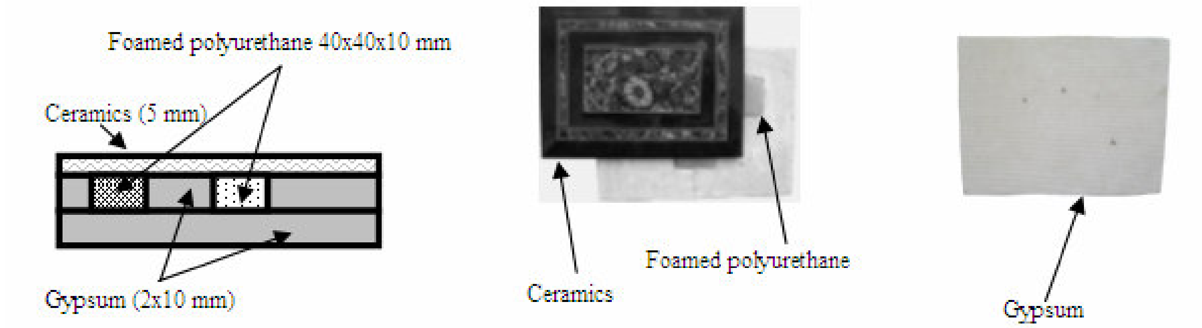


Fig. 1. *Three-layer ceramics-gypsum reference sample*

3. Numerical modeling

Numerical modeling was accomplished by using ThermoCalc-6L and ThermoSource programs from Innovation Ltd., Russia. The reference sample shown in figure 1 was simulated with a two-layer (ceramics + gypsum) structure which contained two polyurethane-filled “defects” of which thermal properties depended on foam moisture. The corresponding numerical mesh contained up to 100x75x90 nodes thus allowing producing sequences of up to 200 IR images by the 100x75 format. Thermal properties of all materials involved are presented in table 1.

http://dx.doi.org/10.21611/qirt.2008.02_13_14

Table 1. *Thermal properties of materials used in reference sample (figure 1)*

Material	Density ρ, kg/m^3	Heat capacity C, J/(kg.K)	Thermal conductivity λ, W/(m.K)	Thermal diffusivity α, m^2/s
Ceramics	2660	474	0.29	0.230.10-6
Gypsum pasteboard	1190	810	0.27	0.280.10-6
Foamed polyurethane	90	1430	0.04	0.311.10-6
Water	1000	4193	0.59	0.141.10-6

Thermal properties of moist polyurethane foam were determined by using the following formulas:

$$\lambda(w) = \frac{\lambda\lambda_w}{(1-w)\lambda_w + w\lambda};$$

$$\alpha(w) = \frac{\lambda\lambda_w[(1-w)C_w + wC][(1-w)\rho_w + w\rho]}{CC_w\rho\rho_w[(1-w)\lambda_w + w\lambda]},$$

where $w = m_w/(m_w + m)$, λ, C, ρ and α are the thermal conductivity, heat capacity, density and thermal diffusivity respectively, the subscript "w" is related to water. For example, if 4 g of water are uniformly distributed in 4x4x1 cm3 of foamed polyurethane, the resulting thermal properties will be: $\lambda(w)$ =0.127 W/(m.K); $\alpha(w)$ =0.107.10-6 m^2/s. The volumic density of microwave power was assumed to be proportional to the ratio between volumes of water and foam; for example, in the latter example, this value was 1.54 W/cm^3 x (4 cm^3/16 cm^3)= 0.385 W/cm^3.

4. Comparing experimental and theoretical data

4.1. Surface (optical) heating

The best match between experimental and theoretical data occurred in the case of dry polyurethane foam (see figure 2 and table 2), while the presence of water enhanced data discrepancy, probably, due to non-uniform distribution of water in the foam. Moreover, one-sided inspection on the gypsum side has not allowed water detection at all because of low temperature signals.

As shown in table 2, the presence of water diminished surface temperature signals by about two times due to the fact that the difference in thermal properties between the dry foam and building materials is more significant than in the case of the moistened foam.

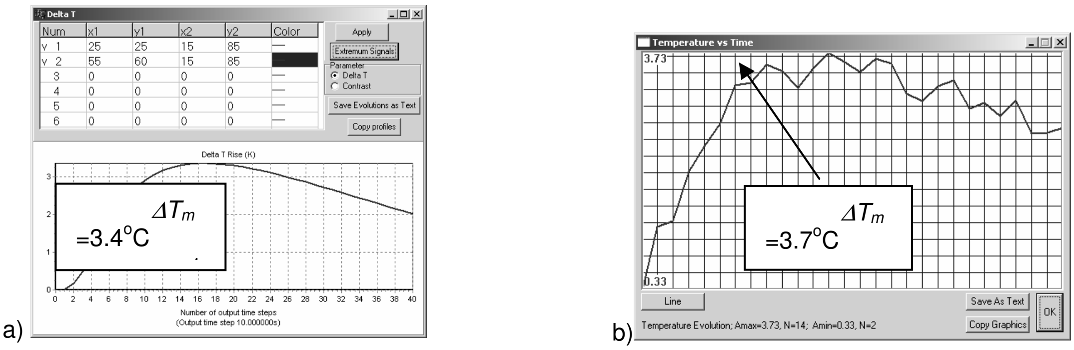


Fig. 2. *Comparing theoretical (a) and (b) experimental evolutions (surface heating, monitoring ceramics, dry polyurethane foam)*

4.2. Volumic (microwave) heating

The results are presented in figure 3 and table 3. In this case, it has been advisable to apply microwave heating only for detecting hidden water. However, some temperature elevations were found when heating a dry sample, probably, due to presence of metallic particles in surface painting and/or natural moisture of materials.

The best match was observed for differential temperature signals, in particular, when inspecting the sample on the gypsum side. The strong discrepancy appeared in optimum observation times when inspecting the ceramics side, probably, because of the above-mentioned phenomenon of heated ceramics.

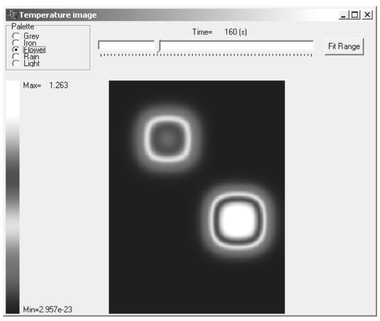
http://dx.doi.org/10.21611/qirt.2008.02_13_14

***Table 2.** Comparing experimental and theoretical data in inspection of reference sample from figure 1 (surface optical heating: Q =8.5 kW/m2)*

Procedure	Theory		Experiment	
	ΔT_m, oC	τ_m, s	ΔT_m, oC	τ_m, s
Heating ceramics (dry polyurethane foam) Monitoring ceramics	3.4	170	3.7	160
Heating ceramics (2 g H_2O) Monitoring ceramics	1.6	160	1.6	140
Heating ceramics (4 g H_2O) Monitoring ceramics	0.61	160	1.5 *	140
Heating gypsum (dry polyurethane foam) Monitoring gypsum	0.24	310	0.4	280
Heating gypsum (2 g H_2O) Monitoring gypsum	0.12	320	- **	-
Heating gypsum (4 g H_2O) Monitoring gypsum	0.04	330	- **	-

* Non-uniform water distribution in polyurethane foam
** Water not detected

It is worth noting that the power density of microwave heating used in calculations varied for different water content: if pure water was heated with q_{mw}=1540000 W/m3, the appropriate value was q_{mw} =385000 W/m^3 in the case of 4 g of water, and q_{mw} =192500 W/m^3 - in the case of 2 g of water.

a) 

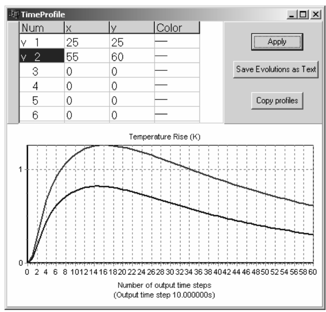
b) 

***Fig.3.** Theoretical temperature evolutions over moist polyurethane foam (volumic microwave heating, monitoring gypsum, ThermoCalc-6L): a – temperature distribution at 160 s, b – temperature evolutions (2 g H_20 – bottom plot, 4 g H_20 – upper plot)*

***Table 3.** Comparing experimental and theoretical data in inspection of reference sample from figure 1 (microwave heating: maximum heat power volumic density Q=1.54.106 W/m^3)*

Procedure	Theory		Experiment	
	ΔT_m, ^{o}C	τ_m, s	ΔT_m, ^{o}C	τ_m, s
Monitoring ceramics (2 g H_2O)	0.72	170	1.0	350*
Monitoring ceramics (4 g H_2O)	1.17	190	2.2	330*
Monitoring gypsum (2 g H_2O)	0.82	150	0.86	180
Monitoring gypsum (4 g H_2O)	1.26	160	1.5	200

* Ceramics was slightly heated with microwaves due to metallic particles in surface paint and/or natural moisture

http://dx.doi.org/10.21611/qirt.2008.02_13_14

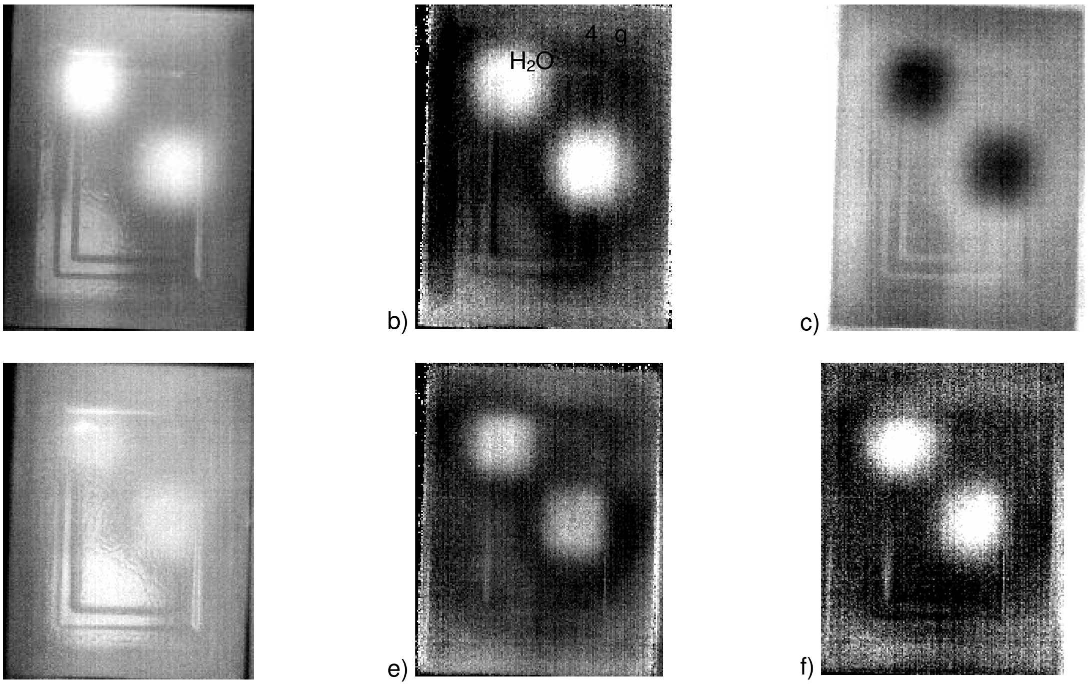
5. Advanced data processing

Efficiency of different processing algorithms has been characterized by signal-to-noise ratio $SNR = (\bar{T}_d - \bar{T}_{nd}) / \sigma_{nd}$ where $\bar{T}_d, \bar{T}_{nd}$ are the mean temperatures in a defect and sound (non-defect) areas respectively, σ_{nd} is the temperature standard deviation in a sound area.

5.1. Surface (optical) heating

Images in figure 4 demonstrate efficiency of some processing algorithms which are common in TNDT. Similarly to the data in table 2, it is seen that the presence of water reduces SNR by 1.5-2 times. Surprisingly, such well-known processing algorithms as 1D Fourier transform (Pulse Phase Thermography-PPT) and Principal Component Analysis (PCA) have not provided higher SNR values in the inspection of the dry sample (compare figure 4a,b and c) in regard to the source image. In the case of moist foam, a little improvement of SNR has been observed. An explanation can be that, by definition, SNR, even being a fairly objective parameter, reflects only distribution of pixel amplitudes but not temperature patterns, or pixel coupling. Therefore, in some cases, subjective image evaluation by a trained operator can be of independent value. For example, the image in figure 4f seems to be much more attractive than that in figure 4d, even if SNR improvement is insignificant.

The interesting feature of the data in figure 4 is that both quantities of water (2 and 4 g) produce close SNR (and ΔT_m) values. The inspection on the gypsum side has proven to be unsuccessful because no clear defect indications have been observed.



a) b) c) d) e) f)

Fig. 4. *Detecting dry and moist foam "defects" by 10 s-long surface (optical) heating:*
a – optimum source image, dry foam (SNR=13.4),
b – phasegram, dry foam (SNR=9.9),
c – PCA, dry foam (SNR=9.3),
d - optimum source image, moist foam (SNR=5.2),
e – phasegram, moist foam (SNR=6.1),
f – PCA, moist foam (SNR=6.5)

5.2. Volumic (microwave) heating

Microwave heating produced thermal patterns fairly different from those obtained by surface heating (figure 5), particularly, when ceramics was monitored (figure 5a-c). It looked that, in the latter case, ceramics was moistening due to water penetration (see thermal 'bridges' between moist foam areas in the source image of figure 5a). The corresponding phasegram (figure 5b) revealed the pattern difficult to interpret, probably due to the specific 'shape' of the temperature evolution: the SNR value was only ~1.0 in this case, thus allowing no reliable defect detection. The best defect visibility was supplied by the PCA image (figure 5c, SNR=8.8). Images on gypsum side (figure 5d-f) used to be friendlier and allowed easier identification of moist areas with the highest SNR reaching 9.1 in the phasegram of figure 5e. Note that all SNR values are given here for detecting 2 g of

http://dx.doi.org/10.21611/qirt.2008.02_13_14

water to compare with data in figure 4; in the case of microwave heating, temperature signals ΔT, due to the obvious reason, have been proportional to water mass.

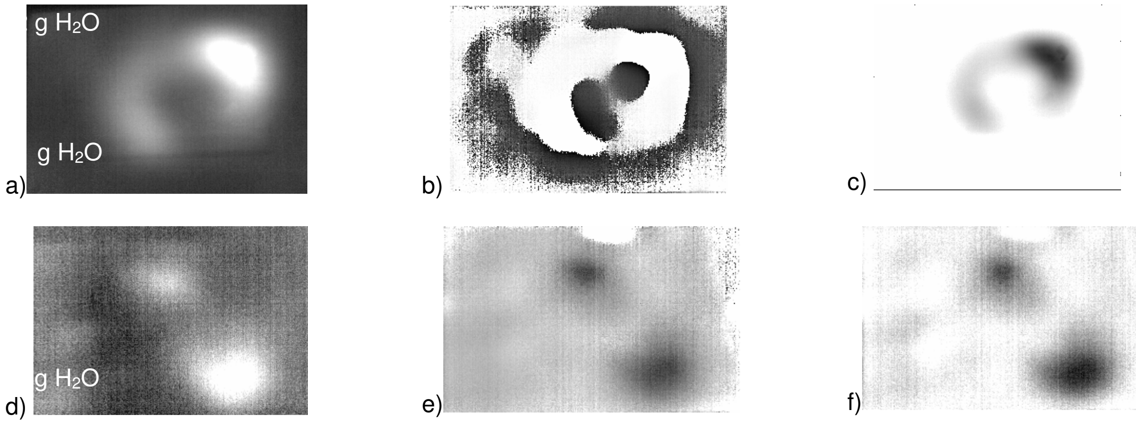


Fig. 5. *Detecting moist foam "defects" by 10 s-long volumic (microwave) heating:*
a – optimum source image, monitoring ceramics (SNR=6.4),
b – phasegram, monitoring ceramics (SNR=1.0),
c – PCA, monitoring ceramics (SNR=8.8),
d - optimum source image, monitoring gypsum (SNR=6.3),
e – phasegram, monitoring gypsum (SNR=9.1),
f – PCA, monitoring gypsum (SNR=8.8)

6. Comparing optical and microwave heating

When applying one-sided TNDT to the ceramics surface of the studied reference sample, the differential temperature signal reached ΔT_m=1.6oC over 2 g of water (heating power density 8.5 kW/m2). The maximum SNR value in the source sequence was 5.2 with the highest value achieved in a phasegram (SNR=6.1). Detecting small amounts of water on the gypsum surface has proven to be impossible.

In the case of microwave heating, when inspecting the ceramics surface, the results have been as follows: ΔT_m=1.0oC (heating power volumic density 1.93.106 W/m3) over 2 g of water, SNR=6.4 in a source image and 8.8 in a PCA image. Unlike optical heating, close results have been obtained also in the inspection on the sample gypsum side.

It is worth noting that optical heating has produced more user-friendly images, at least, when inspecting ceramics.

To summarize, it seems that both types of heating provide similar SNR values thus proving that, in successful TNDT, combination of a defect-sample geometry and thermal properties plays a decisive role rather than a type of sample stimulation.

Comparison between two types of heating can be done on the basis of ΔT signals normalized by absorbed energy. However, it is not clear how to perform normalization in our case because of necessity to define a heated area in the case of uniform optical heating. It is typically believed that SNR is fairly independent on heating power (energy), however, in some cases, it has been prompted that enhancing absorbed energy may improve defect detection due to better temperature contrasts [1]. This issue has been left beyond of the scope of this research.

7. Conclusions

Microwave (volumic) heating is often regarded as the most appropriate means of detecting moisture in porous materials. In this study, both theoretical and experimental results on evaluating water in building materials are reported to compare features of optical and microwave heating.

Experiments were performed on a 2 cm-thick reference sample made of gypsum pasteboard which was covered with a 1 cm-thick plate of decorative ceramics. Within gypsum, two 40x40x10 mm voids were filled with foamed polyurethane containing from 1 to 8 g of water. Absorbed power density of optical radiation was about 8.5 kW/m2 on the sample surface. The maximum volumic density of microwave radiation was estimated to be 1.54 W/cm3 (by water absorption).

Modeling has been done by using the ThermoCalc-6L and ThermoSource computer programs in order to compare theoretical and experimental results and understand better peculiarities of microwave TNDT.

In the case of optical heating, the best match between experimental and theoretical data occurred in the case of dry polyurethane foam, while the presence of water enhanced data discrepancy, probably, due to non-

http://dx.doi.org/10.21611/qirt.2008.02_13_14

uniform distribution of water in the foam. Presence of water diminished surface temperature signals by about two times.

In the case of microwave heating, the best match was observed for differential temperature signals, in particular, when inspecting the sample on the gypsum side. The strong discrepancy appeared in optimum observation times when inspecting the ceramics side, probably, because of the fact that sound ceramics was warming up due to presence of metallic particles in surface painting and/or natural moisture of materials.

Efficiency of different processing algorithms has been characterized by signal-to-noise ratio. It has been shown that applying such well-known processing algorithms as 1D Fourier transform (Pulse Phase Thermography-PPT) and Principal Component Analysis (PCA) have not provided higher SNR values in the inspection of the dry sample in regard to source images. In the case of microwave, the best defect visibility was ensured by a PCA image. In this case, temperature signals proved to be proportional to water mass.

Surprisingly, experimental results have shown that advantages of microwave heating are not indisputable. For example, in ceramics, probably, due to surface decorative paint and/or metallic inclusions, some spurious signals have appeared to fully destroy a phasegram which is often considered as one of the best image presentation of subsurface defects. It turned that moistened areas have been better seen after applying the PCA algorithm. In general, both types of heating have provided similar SNR values, thus proving that, in successful TNDT, combination of the defect-sample geometry and thermal properties plays a decisive role rather than a type of sample stimulation.

REFERENCES

[1] V. Vavilov. Thermal nondestructive testing (handbook), Mashinostroyenie Publ., Moscow, Russia, 2004.- 370 p. (in Russian).