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Photothermal infrared radiometry applied to textile materials - General characterization and determination of moisture content

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Abstract

The potential of photothermal methods for the characterization of textiles is investigated systematically. It has been shown that the moisture content in fabrics can be determined by IR detection of thermal waves. Measurements on moving fabrics have been done to demonstrate the possibility of application potential in continuous industrial production processes.

1. Introduction

The application of photothermal methods to the field of textile research is relatively new and was first mentioned by Eickmeier et al [1]. Photothermal Radiometry of thermal waves PTR) on textiles is coupled with specific problems since the effective optical and thermal properties of textiles, which may vary in a wide range, are mostly unknown. They change with the fabrics construction, the porosity, the surface structure, the material itself, treatment processes and finally with the moisture content. Small thermal diffusivities, which are in the region of about $0.07x10^{-6} m/s^2$ cause very small penetration depths which disable transmission measurements for thicker samples. In addition, using high light or laser powers, the material may be destroyed thermally or damaged very easily, which has to be avoided.

Nevertheless, the application of PTR on textiles is of general interest, because it offers a large variety of tools for the characterization of textiles with respect to the material and their optical and thermal properties. The determination of moisture in textile treatment and finishing processes is of special interest for quality control and questions of cost optimization. All usual standard methods for measuring the moisture in textile materials face specific problems and a method with universal application is difficult to establish [2] As the thermal properties also depend on the moisture content, PTR is qualified for moisture measurements. The influence of water on photothermal signals has been studied with respect to the effect of the vapor pressure on photoacoustic signals [3]. When measuring thermal waves [4] by infrared radiometry this effect can be neglected. Instead, here the influence of moisture on the thermal properties is studied more directly.

2. Optical and thermal characterization

In this experiment thermal waves have been generated by means of a 100 Watt mercury-vapor lamp focused on a chopper and subsequently on the sample. For the detection of the thermal waves a *HgCdTe* detector has been used, whose signals were amplified with the help of a lock-in amplifier (*Fig. 1*). Since the thermal properties of textiles are mostly unknown, the experiment was first tested with two reference samples of *Ta* whose thickness were *0.5mm* and *0.05mm*. Frequency-dependent measurements have been run between *5* and *500Hz*. *Fig. 2* shows the normalized phases and the respective theoretical curve, which are in good agreement. For test measurements with polymers a *0.33mm* thick, black compact foil of platilon UF7 ©(polyetherurethan) has been chosen. The signals have been normalized against

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a sample of Remanit© (high-grade-steel) of *2mm* thickness. The phases are shown in *Fig. 3* (x) in comparison with theoretical curves (solid and dotted lines) where a constant value for the thermal diffusivity $\alpha = 0.099x10^{-6}m^2/s$ and different values for the optical absorption constant β of the polymer have been assumed. Measurements of the optical transmission in the region between *450 and 550nm* gave an optical absorption coefficient of 33000 *1/m*, which is in very good agreement with the value obtained from the photothermal measurements *(Fig.3)*.

For a textile, the determination of the absorption constant is much more complex because of the inhomogeneities of the fabric construction. For the measurements, Polyethyleneterephthalate (PETP) fabrics of different colour shades in the black have been chosen. Here, the optical absorption constant has to be expected to be much smaller than that of platilon. *Fig. 4* shows normalized measurements of a 2% and 4% black dyed fabric, which are compared with theoretical curves. For this theoretical description the porosity of the fabric has to be taken into account as an essential parameter. The porosity of the fabric was determined experimentally and the models of Brailsford and Major [6] were used to determine the thermal conductivity at the measured porosity, from which the thermal parameters were derived. Details of the theoretical procedure are reported elsewhere[7].The measurements of the 4% dyed sample could be approximated by an absorption constant of about *5000 1/m,* which is in reasonable agreement with optical measurements [7]. An approximation of the measurement of the 2% dyed fabric could not be realized within realistic variations of the thermal parameters and of the absorption constant. This may be explained by an inadequate description of the heat sources in the limit of low absorbing and highly diffuse scattering material.

The sensitivity of the photothermal techniques to changes in the optical properties may be used for quality control of textiles. Thermal wave measurements are of special interest for the measuring of dark colored textiles, where normal spectroscopy is unable to discriminate. Eickmeier [8] could show this by using the photoacoustic effect. PAS, however, can not be applied for a contactless detection, mainly required in industrial processes. *Figs. 5* and *6* demonstrate the efficiency of the photothermal radiometric detection in the infrared. A set of samples colored with different dark dye concentrations, hardly separable by the human eye, were measured in frequency scans *Fig. 5.* The values for the dye-concentration of the samples were given by the manufacturer. The radiometric signals generally increase with the colour concentration, which is also in agreement with the decreasing optical transmission *Fig.6* . The signals obtained from the 4% dyed sample were approximately 50% higher than those obtained from the 6% dyed sample. This indicates a defect in the dyeing process, which is confirmed by the transmission spectroscopy *Fig.6.* In fact, the indication of the faulty dyeing process is more reliable by PTR. This example shows the possibility and the potential of photothermal methods, used for quality control processes.

3. Moisture measurements

The influence of moisture content on the thermal properties here has been investigated by measuring time-dependent photothermal amplitudes during a drying process. A typical curve for the photothermal signals is shown in *Fig.7,* where dots(•) represent the moisture content and (x) the photothermal amplitude, obtained from a polyester fabric. The amplitude increases with decreasing moisture content until it gets constant, when the sample gets dry (here: after *55min*). The plot indicates, that the sensitivity of the photothermal amplitude to changes in the water content is maximal in the region of low moisture content. This region is of special interest in textile treatment and finishing processes, e.g. in dyeing or pressing. *Fig.8* shows the photothermal amplitude plotted directly versus the moisture content. The signals were normalized against a reference sample of glassy carbon (Sigradur G©). For the measurements polyester samples of different fabric constructions (lower curve) and wool samples (upper curve) were chosen. The solid lines represent mean curves. The two materials, wool and polyester, produce different material-specific curves. The different measurements of wool show a large scattering, which might be related to the locally inhomogenous surface of wool due to fringes. The polyester samples, which are of different constructions, however, all gave

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very similar results. Here the influence of the textile structure seems to be of less importance. This may be caused by the large penetration depth of approximately *100µm* at *10 Hz* for PETP, which integrates over structure effects of the sample. The photothermal amplitude, which decreases with increasing moisture content, can be explained by the increasing effusivitly, where mixing of the thermal properties of water and polyester has to be considered [7]. The curves shown in *Fig.8* have to be measured for each kind of material to serve as calibration curves and allow the determination of the absolute moisture content by measuring the photothermal signal. Measurements at different dark dyed fabrics *(Fig.9a),* show in principle the same behavior, though the raw amplitudes decrease with decreasing dye-concentration. If one normalizes these curves with the photothermal signal obtained from the same samples in the dry state, in the limit of moisture content → *0*, one obtains a single curve which is plotted in *Fig.8b.* Here the influence of the colour is eliminated. This curve, which can be considered as a characteristic moisture-reference curve for polyester, may serve to determine the moisture content of different colored, different structured samples, if the photothermal amplitude is measured once from a dry sample.

4. Measurements in a continuous process

In the textile industry there is the need to control moisture by contactless, on line measurements of fabrics running at high velocities. To this purpose the experimental system was installed in a textile machine (*Fig.10).* A defined moisture content was produced by a foulard and a dryer. *Fig.11* shows photothermal measurements of a brown polyester material at a modulation frequency of *10Hz* and a fabric velocity of *1m/min.* Changing the foulard pressure the moisture content was varied by steps during the measurement. The various steps can well be distinguished in the plot. The absolute resolution in the measurement is less than 6%, even in the region of low moisture content. The fluctuations in the signals are produced by uneven feeding of the web and small wrinkles, which are technically unavoidable. A more complex application is the detection of moisture of a colour-printed fabric, where the changing absorption properties cannot be eliminated by normalization. In order to distinguish the differences with the changing moisture, the integration time was set to *5s* for each measurement and several single measurement values were averaged. The result is shown in *Fig.12*, where the various steps in the moisture content can be resolved clearly.

For an interpretation of the obtained correspondence between the photothermal amplitude and the moisture content in moving samples it is necessary to investigate the velocity dependence of the photothermal amplitude. For this purpose measurements were done with a uniform, dry PETP fabric at different velocities and at different modulation frequencies. The heating spot as well as the detection spot were *1mm*^{2}. Both spots were focused on the same point. The curves are plotted in *Fig.13,* where the velocity has been increased in steps. The curves, taken at *5.3, 10* and *30Hz,* show a maximum of the photothermal signal, which shifts to higher velocity with increasing frequency. The decreasing after having reached the maximum is in agreement with the consideration, that the thermal wave is moving out of the focus, which depends on the modulation frequency. The increasing of the photothermal signal may be explained by an increase of the thermal contrast due to the lower mean temperature of the fabric surrounding the heating spot. With higher velocities the first effect dominates. Increasing the modulation frequency, the maximum shifts to higher velocities, because the time needed for the detection of the thermal wave gets shorter. If one extrapolates the maximum to higher modulation frequencies where photothermal amplitudes are still detectable, e.g. *400Hz,* one gets a sample velocity of *about 20m/min* [9]. This is a realistic value for industrial application in many textile processes.

5. Conclusions

It has been shown, that photothermal radiometry has a large potential for applications to textiles. Fabrics can be characterized with respect to optical and thermal behavior and IR radiometric signals can be used for quality control of dyeing processes. Photothermal

http://dx.doi.org/10.21611/qirt.1994.034

Radiometry also allows to determine the moisture content. Characteristic moisture-reference curves have been found to determine moisture independent of the fabrics structure and colour. Contactless IR radiometric detection can also be applied to moving webs in continuos industrial processes at the velocities required in the textile industry.

Acknowledgments

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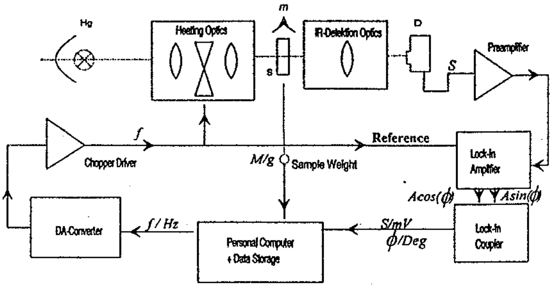

Fig.1. *Schematics of the experimental setup and signal processing*

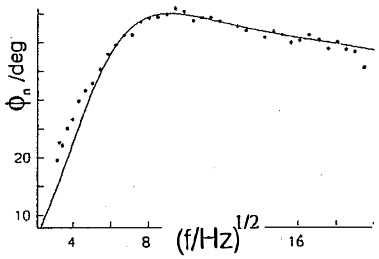

Fig.2. *Normalized phases of two tantal samples and theoretical curves*

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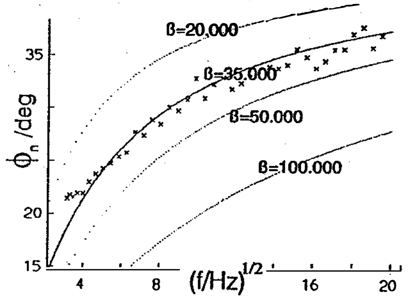

Fig.3. *Normalized phases of a compact opaque polymer sample*

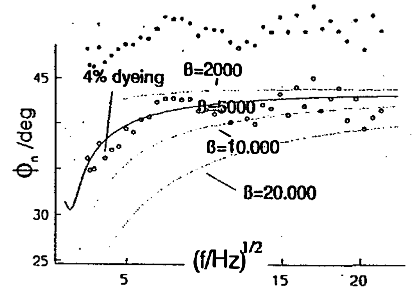

Fig.4. *Normalized phase of a fabric, theoretical curves for a porous polymere with different absorption coefficients*

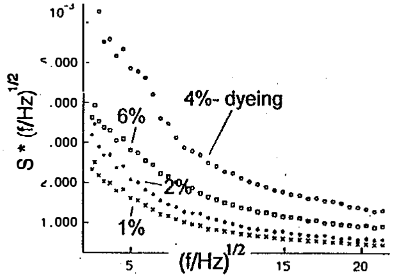

Fig.5. *Quality control at dyes: Photothermal amplitudes of different dark dyed fabrics*

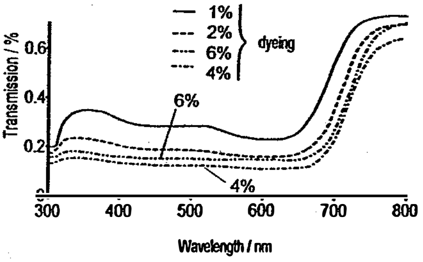

Fig.6. *Transmission spectrum of the same samples*

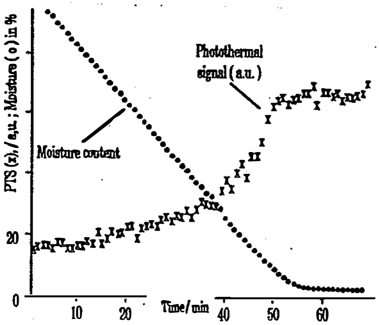

Fig.7. *Photothermal amplitudes during drying process versus time*

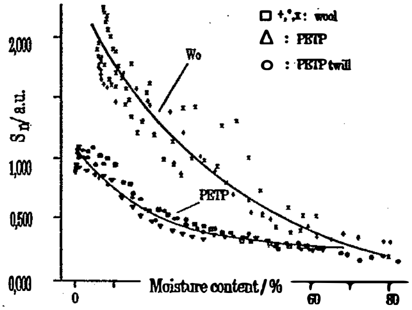

Fig.8. *Photothermal amplitudes during drying process versus moisture content*

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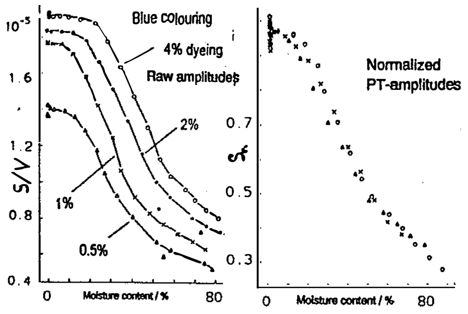

Fig.9a/b. *Influence of different absorption (a) may be eliminated by normalization with signal at m.c.=0 (b)*

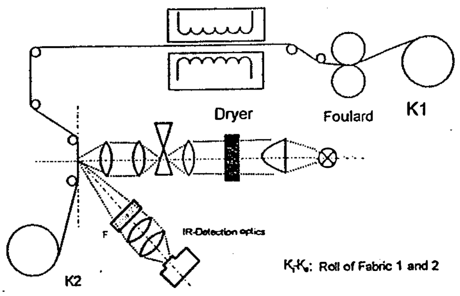

Fig.10. *Experimental setup for the detection of thermal waves in a continous process*

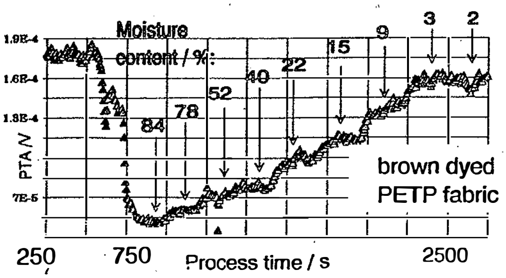

Fig.11. *Photothermal amplitudes of a brown dyed PES sample at different drying stages*

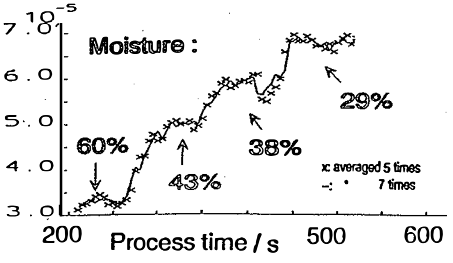

Fig.12. *Photothermal amplitudes of a color printed Wool sample at different drying stages*

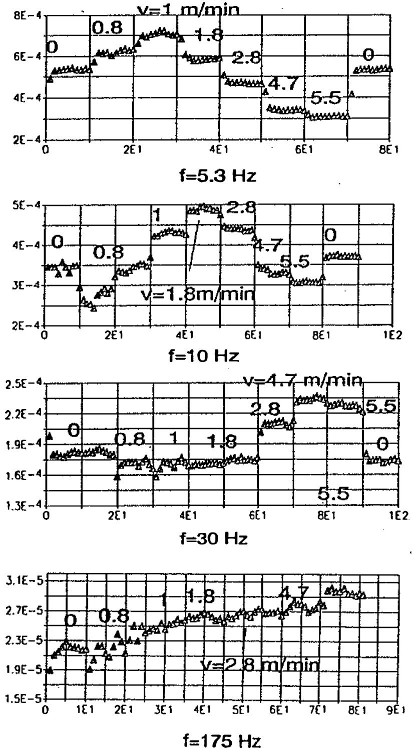

Fig.13. *Photothermal amplitudes versus sample velocity at different modulation frequencies*