

Emissivity, Reflectivity and Transmissivity of Semitransparent Fibre Reinforced Plastic Composites

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Abstract. Fibre reinforced plastic (FRP) composites have excellent mechanical properties, low weight, fatigue and corrosion resistance yielding to notable advantages when applying them in the field of renewable energy as well as in oil and gas and transport applications. However, certain defects and damage mechanisms reduce their full possibilities of exploitation as well as the life time of FRP based structures. Non-destructive testing (NDT) and in particular active thermography are important methods to ensure the quality of FRPs.

The accurate knowledge of the optical properties of the investigated material, i.e. its spectral emissivity, reflectivity and transmissivity, is a prerequisite for quantitative active thermography. To improve the state-of-the-art of this technique, the uncertainty of emissivity measurements of FRP materials in the visible and in the infrared wavelength range has to be lower than 0.01. This was the objective of PTB as one of the partners within the ERMP Project “Validated Inspection Techniques for Composites in Energy Applications” (VITCEA). The measurement of the emissivity of partially transmitting materials with this uncertainty is very challenging, especially at temperatures close to room temperature. We employed two setups for these measurements at PTB: the setup for spectral emissivity measurement and the setup for diffuse reflectivity and transmissivity measurement.

The directional spectral emissivity was determined at a nominal temperature of 40 °C in the wavelength range from 5 µm to 25 µm and at angles of observation from 10° to 70° with respect to the surface normal. From these measurements, the total directional emissivity and the hemispherical emissivity were calculated.

The directional-hemispherical spectral transmissivity and directional-hemispherical spectral reflectivity were determined using a gold coated integrating sphere and a vacuum FTIR-Spectrometer. The directional-hemispherical spectral transmissivity was observed under an angle of incidence of 0°, the directional-hemispherical spectral reflectivity under an angle of incidence of 10°. These measurements were done in the spectral range from 1 µm to 16.7 µm and were compared in the overlapping wavelength range with the emissivity measurements performed with the setup for spectral emissivity.

1. Introduction

Fibre reinforced plastic (FRP) composites have excellent mechanical properties, low weight, fatigue and corrosion resistance yielding to notable advantages when applied for renewable energy, oil and gas and transport applications. However, certain defects and



damage mechanisms reduce the full possibilities of their exploitation as well as the life time of FRP based structures. Non-destructive testing (NDT) and in particular active thermography are important methods to ensure the quality of FRPs.

The accurate knowledge of the optical properties of the investigated material, i.e. its spectral emissivity, reflectivity and transmissivity, is a prerequisite for their quality assurance with quantitative active thermography. To improve the state-of-the-art of this technique, the uncertainty of emissivity measurements of FRP materials in the visible and in the infrared wavelength range has to be lower than 0.01. This was the objective of PTB as one of the partners within the ERMP Project “Validated Inspection Techniques for Composites in Energy Applications” (VITCEA) [1-4].

The measurement of the emissivity of partially transmitting materials with this uncertainty is very challenging, especially at temperatures close to room temperature. We employed different setups for these measurements at PTB: the setups for spectral emissivity measurement in air and under vacuum and the setup for diffuse reflectivity and transmissivity measurement.

2. Experimental determination of optical properties of composite materials

2.1 Experimental setup

The measurements were performed with the Reduced Background Calibration Facility (RBCF) for emissivity measurements under vacuum [5, 6] and with the Emissivity Measurement in Air Facility (EMAF) [7], which both have been routinely operated at PTB for several years now. Using variable temperature blackbodies as reference standards of radiation temperature, the RBCF and the EMAF provide measurements traceable to the International Temperature Scale of 1990 (ITS-90) with well established uncertainties. Due to the operation under vacuum conditions (at the RBCF), the cooling of all critical components in the optical beam path with liquid nitrogen and the realization of a measurement scheme which cancels the remaining background signal an uncertainty level of 0.005 and better can be achieved. The spectral distribution of uncertainty has to be calculated for each individual measurement which is described in detail in [8]. The emissivity measurements at the RBCF and the EMAF were performed in the range from 5 μm to 25 μm . For direct emissivity measurements in the wavelength range below 5 μm a significantly higher temperature of the samples would have been required because of Planck’s law. Due to the temperature limitation of the investigated GFRP and CFRP samples, the measurements in the range from 1 μm to 5 μm were performed using a different approach:

The measurements of the directional-hemispherical spectral transmissivity and directional-hemispherical spectral reflectivity were performed using the setup for diffuse reflectivity and transmissivity measurement. These optical properties were determined in the wavelength range from 1 μm to 16.7 μm and at a temperature of 25 °C. The directional spectral emissivity was then calculated from these measurements in the wavelength range from 1 μm to 5 μm .

2.2 Transmissivity, reflectivity and emissivity data from 1 μm to 16.7 μm

The directional-hemispherical spectral transmissivity and directional-hemispherical spectral reflectivity were determined using a gold coated integrating sphere and a vacuum FTIR-Spectrometer (Fig. 1). Depending on the wavelength range, a Globar or a Tungsten Halogen lamps were used as a source of radiation. An MCT Detector was used to record the reflected or transmitted radiation, respectively. Each sample was placed subsequently at

the transmissivity and reflectivity port of the integrating sphere. The directional-hemispherical spectral transmissivity was observed under an angle of 0° , the directional-hemispherical spectral reflectivity under an angle of 10° .

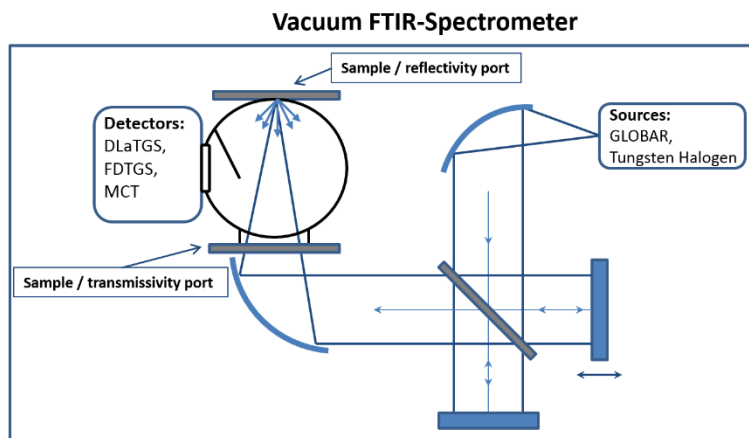


Fig. 1: Schematic of the FTIR-spectrometer with the integrating sphere.

Different aspects of the integrating sphere setup were characterized to determine the measurement uncertainty for the diffuse transmittance and reflectance measurements. The systematic deviation and the repeatability of the maximum or 100% signal were determined for each of the two radiation sources with an open transmissivity port and a reference gold mirror placed at the reflectivity port. The background or 0% signal level for the reflectance measurements was determined with a small blackbody placed at the reflectivity port. For the background determination of the transmittance measurements a beam blocker was used. A special aperture array at the transmissivity port was used for the successive attenuation of the incident flux to the 25%, 50% and 75% level. The nonlinearity in the MIR and NIR ranges was then calculated as a deviation of the experimental data from the theoretical signals. Their uncertainty is equal 0.015 in the MIR and 0.001 in the NIR, respectively. Finally, the sensitivity of the integrating sphere measurements to a potentially wide angular distribution of the diffusely transmitted radiation was determined by the installation of a sample holder with one of the partially transparent materials at different distances from the entrance aperture of the transmissivity port. Here no significant effects were found.

The measured optical properties of all investigated glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP) samples with their calculated standard uncertainties are presented in Figures 2-4. The three samples GFRP PA12, GFRP QUADRAXIAL and GFRP 913 CROSSPLY 0-90 show significant transmittance in the range from $1\ \mu\text{m}$ to $2.3\ \mu\text{m}$ (Fig. 2). The other four samples CFRP SE84 CROSSPLY, CFRP SE84, GFRP MTM28 +-55 and CFRP SE84 QI show no-transparency over the whole spectral range. The measurements of the directional-hemispherical spectral transmissivity were performed at a temperature of $25\ ^\circ\text{C}$ and for an angle of observation of 0° with respect to the surface normal. The standard uncertainty is shown as shaded area around the curves.

The results of the directional-hemispherical spectral reflectivity are given in Fig. 3. The three partially transparent samples show a certain structure in the reflectivity at the wavelengths shorter than $2.3\ \mu\text{m}$, whereas the other four materials show a smooth course of the reflectivity curves in this range. The measurements were performed at a temperature of $25\ ^\circ\text{C}$ and for an angle of observation of 10° with respect to the surface normal. Additionally, the standard uncertainty is shown as shaded area around the curves

The directional spectral emissivity was calculated from the transmissivity (Fig. 2) and reflectivity (Fig. 3) measurements in the range from $1\ \mu\text{m}$ to $5\ \mu\text{m}$ and is presented in

Fig. 4. Similarly to the previous results, the three partially transparent samples show a significant structure in their spectrally resolved emissivity values. These samples, GFRP PA 12, GFRP QUADRAXIAL and GFRP 913 CROSSPLY 0-90, show also a decrease of their emissivity at wavelengths shorter than 2.3 μm . The other materials show a relatively constant emissivity.

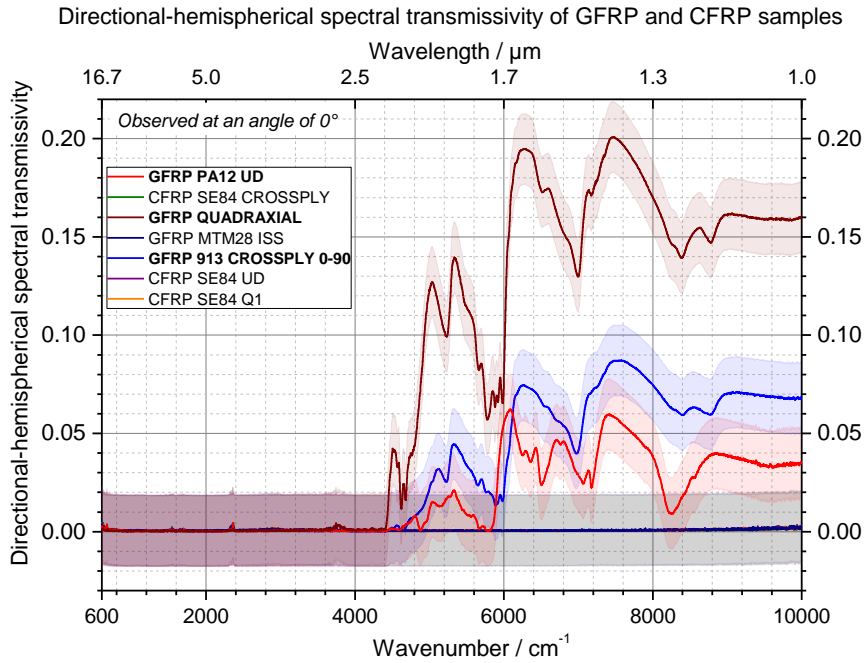


Fig. 2: The directional-hemispherical spectral transmissivity of all investigated GFRP and CFRP samples measured at a temperature of 25 $^\circ\text{C}$ and for an angle of observation of 0° with respect to the surface normal. Additionally the standard uncertainty is shown as shaded area around the curves.

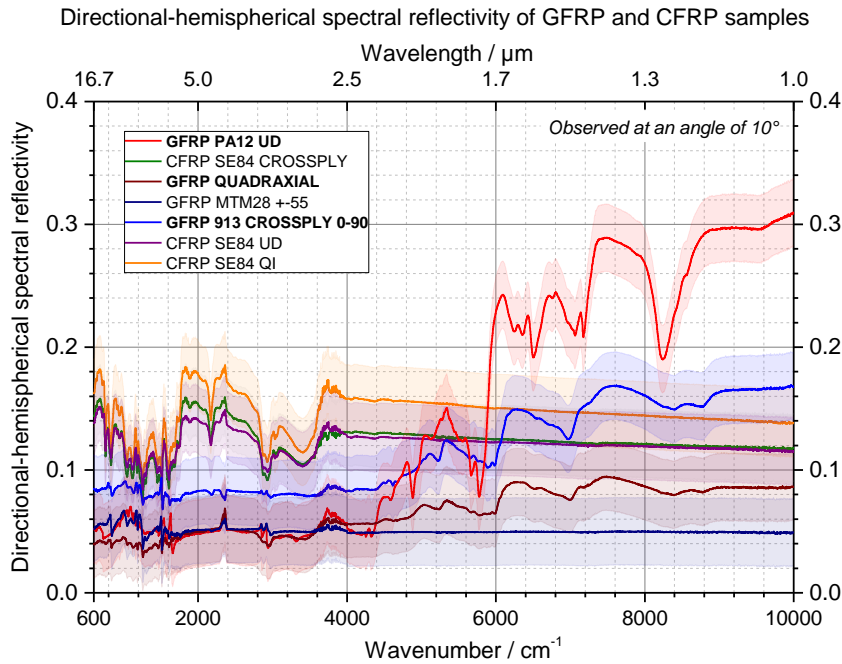


Fig. 3: The directional-hemispherical spectral reflectivity of all investigated GFRP and CFRP samples measured at a temperature of 25 $^\circ\text{C}$ and for an angle of observation of 10° with respect to the surface normal. Additionally the standard uncertainty is shown as shaded area around the curves.

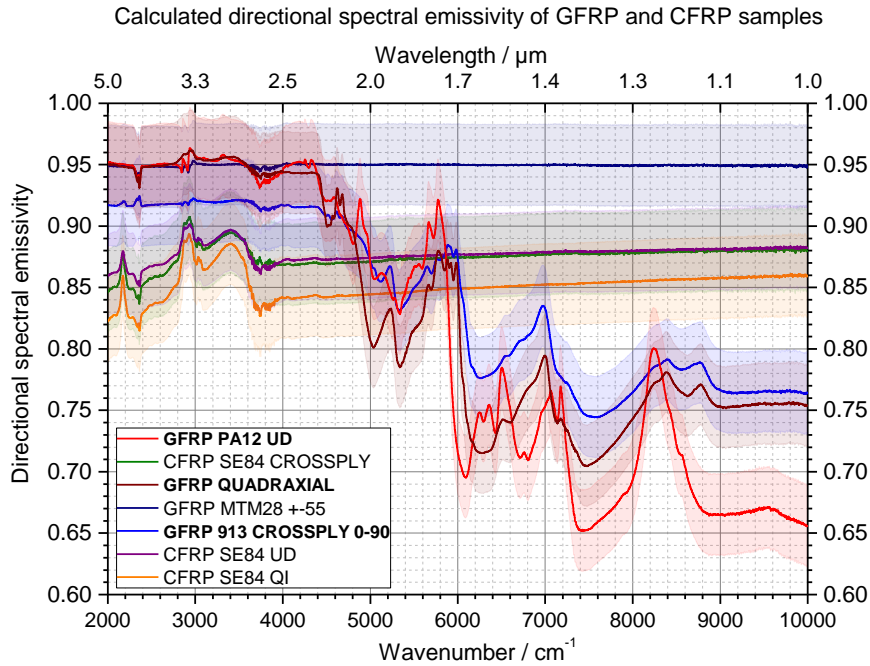


Fig. 4: The directional spectral emissivity of all investigated GFRP and CFRP samples calculated from the transmissivity and reflectivity measurements presented in Figures 2 and 3. Additionally the combined standard uncertainty is shown as shaded area around the curves.

2.3 Directional spectral emissivity data from 5 μm to 25 μm

The directional spectral emissivities were determined at a nominal temperature of 40 °C and under angles of observation of 10°, 20°, 30°, 40°, 50°, 60° and 70° with respect to the surface normal of the samples. From these measurements, the total directional emissivities the hemispherical emissivities and the absolute standard uncertainties were calculated. The slightly increased temperature of 40 °C was chosen in order to increase the radiation from the sample and to reduce the uncertainty of the measurements. The differences between the emissivity measurements at temperatures of 25 °C and 40 °C i.e. a potential temperature dependence of the emissivities can be neglected in this small temperature range.

All the materials are opaque in the range from 2.3 μm to 25 μm (Fig. 2). Around room temperature the shortest wavelength which provides sufficient signal for direct emissivity measurements is 5 μm which is a consequence of Planck's law. So the direct emissivity measurements were performed in the wavelength range from 5 μm to 25 μm, only.

The CFRP SE84 CROSSPLY sample was chosen here as an example of the angle-resolved emissivity measurements. The resulting spectral curves under different angles of observation are plotted in Fig. 5. Some of the measured angles are omitted here for clarity of the figure. A decrease of the directional spectral emissivities towards larger angles of observation is clearly visible, which is typical for high-emitting samples.

The directional spectral emissivities of all investigated GFRP and CFRP samples at a nominal temperature of 40 °C and for an angle of observation of 10° with respect to the surface normal can be seen in the Fig. 6. The previously calculated emissivities in the wavelength range from 1 μm to 16.7 μm show no significant deviations to the directly measured emissivities in the overlapping wavelength range and are not shown here for clarity.

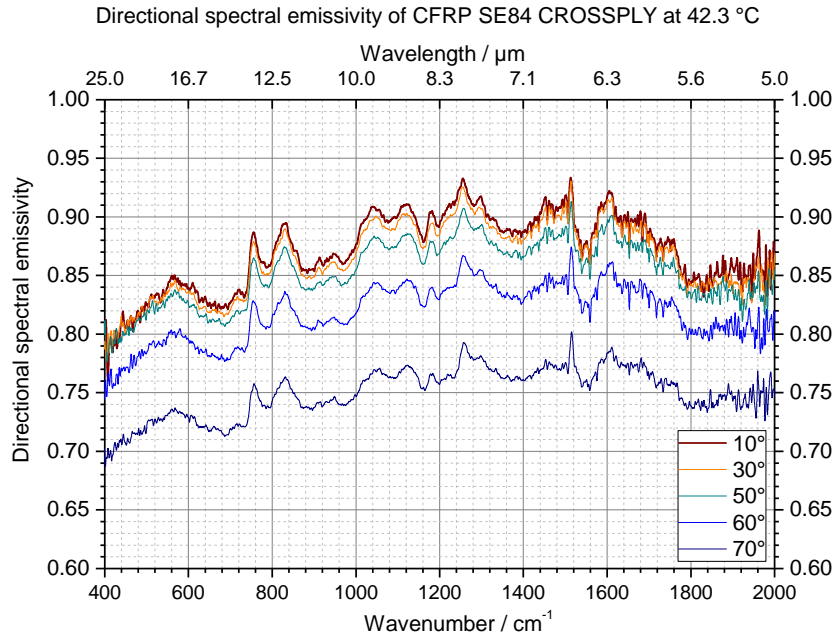


Fig. 5: The directional spectral emissivity of the CFRP SE84 CROSSPLY sample at a nominal temperature of 42.3 °C and for an angle of observation from 10° to 70° with respect to the surface normal.

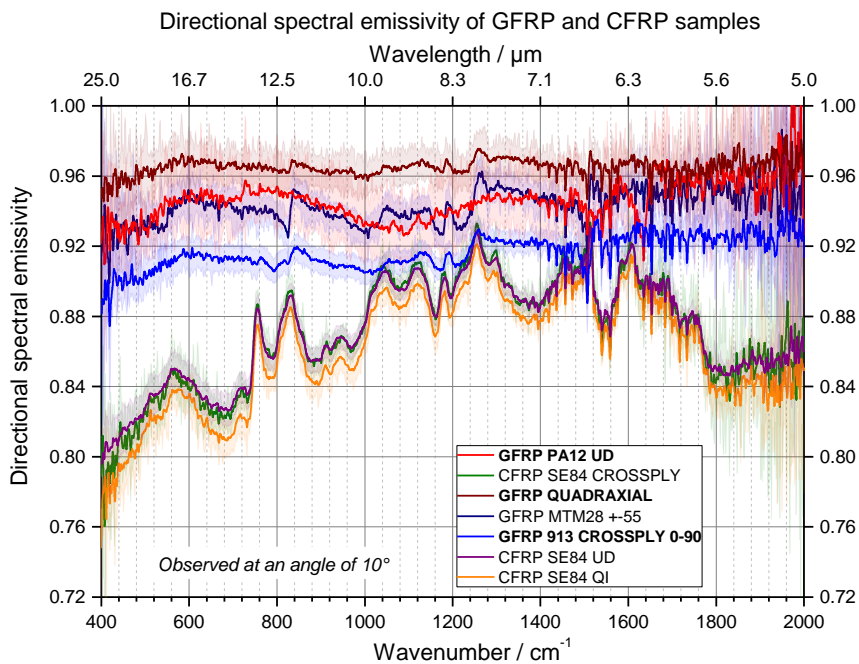


Fig. 6: The directional spectral emissivity of all investigated GFRP and CFRP samples at a nominal temperature of 40 °C and for an angle of observation of 10° with respect to the surface normal. Additionally the standard uncertainty is shown as shaded area around the curves.

3. Summary

The experimental determination of the optical properties of samples of CFRP and GFRP was performed at PTB using three different measurement setups: the RBCF, the EMAF and the integrating sphere based setup for diffuse reflectivity and transmissivity measurement. The measurements of the directional-hemispherical spectral transmissivity and directional-

hemispherical spectral reflectivity were determined in the wavelengths range from 1 μm to 16.7 μm . The directional spectral emissivity was obtained in the wavelength range from 5 μm to 25 μm at a nominal temperature of 40 °C and at angles of observation from 10° to 70° with very low uncertainties.

The determined optical properties were successfully used in the evaluation of measurements obtained with different techniques of active thermography [9] for quantification of artificial and natural defects in fibre reinforced composites within the ERMP Project “Validated Inspection Techniques for Composites in Energy Applications” (VITCEA) [1-4].

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