Dielectric properties of PEEK™ Polymer

Knowledge of dielectric properties of polymers are required in communications and electronic circuits where low-intensity signals are being processed. To improve our technical support Victrex generated more detailed data on relative permittivity (dielectric constant) and dissipation factor (loss tangent). Temperature and frequency have strongest impact on dielectric properties. Therefore $\varepsilon'$ and tan $\delta$ were measured as function of frequency $f$ at different temperatures $T$.

Dielectric analysis involves placing a sample between electrodes and exposing this capacitor to an alternating electrical field. This is generated by applying a sinusoidal voltage to one electrode which produces polarisation within the sample which in turn causes oscillation at the same frequency but with a shift in phase angle. Phase angle shift is determined by comparison of applied voltage and measured current. Measured current is separated into two components, capacitance and conductance. With these values permittivity and dissipation factor may be calculated.

**Experimental procedure:**
Experimental work on PEEK™ 450G and 450GL30 was performed by Priv. Doz. Dr. A. Brather at University in Erlangen. Temperature settings were 23°C, 120°C, 140°C, 160°C, 200°C and 250°C. At each temperature samples were exposed to frequency sweeps from 50Hz to 100MHz. 1.5mm thick injection moulded plaques of PEEK™ 450G and PEEK™ 450GL30 were supplied by Victrex which were extremely even in thickness. 2 samples of each grade were machined to measure 18.5mm x 38.5mm. Samples were placed between electrodes and a constant force of 1MPa was applied.

Dielectric properties were measured using a capacitor consisting of 3 parallel plates. The idea of this type capacitor is very old and was first proposed by Grueneisen and Griebe and is reported in literature\(^1\). Using this 3 plate capacitor leads to more accurate results than using a conventional sensor made of 2 parallel plates. Advantages are:
- reduced electric field fringing and stray capacitance at edge of plates, therefore very little interference by electromagnetic signals
- this allows for direct heating of both outer electrodes with no effect on measurement
- thin gold plated copper wires are sufficient for connection of electrodes producing minimal induction within this capacitor

A motor drive allows for constant force on samples or for constant plate spacing with a precision of 1µm. In order to minimise the air gap between sample and electrodes one usually applies a constant force of 1MPa reading of the gap distance/sample thickness.

Two types of measuring techniques were employed with this capacitor:
- The frequency range up to 100kHz was covered with a balance method using a ratio arm bridge type 1615-A and type 1616 from GENERAL RADIO. Using these bridges the capacitance may be balanced manually to obtain an accuracy of 6 or 7 significant digits. Loss factor is adjusted to an accuracy of 4 or 5 significant digits. With some extra effort values for tan $\delta$ in the order of $10^{-4}$ may still be measured accurately.
- At frequencies above 100kHz the condenser was linked in series to 26 different induction coils with values from 25mH to 20nH. Here frequency is changed to produce resonance within the capacitor. Next, resonance at same frequency is generated in the empty capacitor by changing plate distance. This combination allows calculation of dielectric properties of sample.
These are relative measurements: the value of the capacitor containing the sample is compared with the value of the empty capacitor. Underlying equations depend on geometry of capacitor and technique used and may be viewed in literature\(^2\). Precise equations as applied for this investigation are not stated since they are too complex. Values obtained were corrected with capacitance of the electrical circuitry. Another corrective measure was to determine permittivity of 3 different sized samples which allows calculation of precise sample geometry.

One set of samples of each grade was used for all frequency sweeps at all temperatures beginning at 23°C. After frequency sweep at 23°C the temperature was raised to the next higher value of 120°C. Here samples were isothermally annealed for 4 hours prior to the frequency sweep. This annealing procedure was necessary since permittivity and loss factor decreased slightly; a stable reading was obtained after 4 hours. Annealing for 4 hours was also necessary at 140°C and 160°C although samples have already been annealed and measured at previous lower temperatures. This slow decline in dielectric constant as function of time at temperatures of 120°C, 140°C and 160°C may be explained by crystallisation effects within PEEK™ Polymer.

**Results:**
Relative permittivity \(\varepsilon'\) of PEEK™ 450G is shown in Figure 1. At temperatures of 23°C, 120°C and 140°C it shows a minute decline as frequency increases from 50Hz to 100MHz. Here values of \(\varepsilon'\) are between 3.3 and 3.2. Increasing temperature shifts curves to slightly smaller values in \(\varepsilon'\).

As temperature is increased to above \(T_g\) (=143°C) relative permittivity increases. At 160°C \(\varepsilon'\) is with values of approximately 3.3 to 3.4 a little bit higher than at lower temperatures and it still remains nearly independent of frequency. At frequencies below 1kHz the beginning of the glass transition becomes visible which is well pronounced at 200°C and 250°C where frequency dependence is very strong.

Figure 2 shows the dissipation factor of PEEK™ 450G. At temperatures up to 160°C its value is roughly between \(10^{-3}\) and \(10^{-2}\). At higher temperatures tan \(\delta\) increases by a factor 10.

Frequency dependence of \(\varepsilon'\) and tan \(\delta\) at different temperatures of glass filled PEEK™ 450GL30 are shown in Figures 3 and 4. Their behaviour is very similar to that of unfilled PEEK™ 450G: adding 30% glass fibres merely shifts relative permittivity to higher values. \(\varepsilon'\) of PEEK™ 450GL30 is at a level of approximately 3.6 to 3.7 for temperatures up to 140°C.

**Comparison with our literature values:**
The table below shows a comparison of distinct values as measured in this study and as stated in our properties guide. Within processing conditions and therefore crystallinity the values are close enough with the exception of tan \(\delta\) perhaps.

<table>
<thead>
<tr>
<th>Property</th>
<th>This study</th>
<th>Properties guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon'(50\text{Hz}, 23^\circ\text{C}))</td>
<td>3.27</td>
<td>3.2</td>
</tr>
<tr>
<td>(\varepsilon'(50\text{Hz}, 120^\circ\text{C}))</td>
<td>3.24</td>
<td>3.2</td>
</tr>
<tr>
<td>(\varepsilon'(50\text{Hz}, 140^\circ\text{C}))</td>
<td>3.23</td>
<td>3.2</td>
</tr>
<tr>
<td>(\varepsilon'(50\text{Hz}, 160^\circ\text{C}))</td>
<td>3.36</td>
<td>-</td>
</tr>
<tr>
<td>(\varepsilon'(50\text{Hz}, 200^\circ\text{C}))</td>
<td>4.04</td>
<td>4.5</td>
</tr>
<tr>
<td>tan (\delta) (1MHz, 23°C)</td>
<td>0.0048</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Figure 1: relative permittivity of PEEK™ 450G at temperatures between 23°C and 250°C at frequencies between 50Hz and 100MHz

Figure 2: dissipation factor of PEEK™ 450G at temperatures between 23°C and 250°C at frequencies between 50Hz and 100MHz
Figure 3: Relative permittivity of PEEK™ 450GL30 at temperatures between 23°C and 250°C at frequencies between 50Hz and 100MHz.

Figure 4: Dissipation factor of PEEK™ 450GL30 at temperatures between 23°C and 250°C at frequencies between 50Hz and 100MHz.

2 H. Schmiedel (Hrsg.): Handbuch der Kunststoffprüfung, Hanser Verlag 1992, S. 213-241