Inverse Gas Chromatography with Film Cell Unit: An Attractive Alternative Method to Characterize Surface Properties of Thin Films

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Inverse gas chromatography (IGC) is widely used for the characterization of surfaces. The present work describes a novel IGC tool, the recently developed film cell module, which measures monolithic thin solid film surface properties, whereas only samples in powder or fiber state or polymer-coated supports can be studied by classic IGC. The surface energy of four different solid supports was measured using both classic IGC with columns packed with samples in the powder state, and IGC with the new film cell module or the sessile drop technique, using samples in the film state. The total surface energy and its dispersive and specific components were measured for glass, polyethylene, polyamide and polytetrafluoroethylene. Similar results were obtained for the four materials using the three different techniques. The main conclusion is that the new film cell module for IGC is an attractive alternative to the sessile drop technique as it gives very accurate and reproducible results for surface energy components, with significant savings in time and the possible control of sample humidity and temperature. This film cell module for IGC extends the application field of IGC to any thin solid film and can be used to study the effect of any surface treatment on surface energy.

Introduction

Surface energy measurements are very frequently used in material sciences to investigate wettability, adhesion characteristics, specific interactions with other molecules, cohesion and coating performance (1). The most commonly used method to achieve such measurements is the sessile drop technique using a goniometer which is relatively easy to perform and inexpensive. It consists of producing a drop of liquid on a solid and measuring the angle formed between the solid/liquid interface and the liquid/vapor interface, which is called the “contact angle” (CA) (2). This angle, measured for a minimum of three types of liquids, and the known surface energy of the liquids are the parameters that are used to calculate the surface energy of the solid sample (3). The main disadvantage of this method is that it is unable to reflect the totality of the surface energy properties, even if multiple droplets are deposited on various locations on the sample. CA gives reproducible results, but problems of reproducibility and accuracy may occur, in case of droplets that are not axially symmetric, or with surface-accessible pores, which can decrease the droplet volume by capillary action during measurement (4, 5). To overcome these disadvantages, alternative methods of measuring surface energy must be developed. Two of the most common alternative methods are capillary intrusion of liquid analytes into the sample and analyte adsorption onto a sample bed at infinite dilution using inverse gas chromatography (IGC). Both capillary intrusion and conventional IGC are restricted to the samples in the powder or fiber state and also to polymers and polymer-coated supports, either packed in columns or deposited as a film on the inside of a column to create a capillary column. Nevertheless, a significant advance has been made recently with the development of a new system called film cell module for IGC, which is convenient for flat and monolithic samples. That is why we chose to focus on this last method as an alternative to CA measurements.

IGC is a vapor adsorption technique, which consists in an inversion of conventional gas chromatography. Physicochemical characteristics in the stationary phase are studied by injecting specific well-characterized gaseous probes (6–8). IGC is conventionally performed in columns containing the packed solid under investigation in the powder or fiber state. The interaction between these probes and the solid material forming the stationary phase is then investigated by determining the retention time for a given probe and used to calculate many physicochemical properties, such as surface energies of solids (9), enthalpy and entropy adsorption (10), solubility parameter, crystallinity (11), surface heterogeneity (12), nanorugosity (11), glass transition (11) and melting temperature (7).

For surface energy determination, IGC presents many advantages compared with CA measurements: (i) the ability to quantify strong interaction occurring between the solid and the probes that cannot be characterized by CA measurement because of a CA close to zero (11), (ii) no problem of nanorugosity and surface heterogeneity (13, 14), as the interactions of the probes are measured all along a wide solid surface and give mean values of interaction through the measure of the retention times, whereas CA measurements are restricted to the number of droplets deposited on the surface; film cell module for IGC provides quite a large interacting area with gaseous probes: a relatively large rectangular sheet of flat sample (10 × 400 mm) is submitted to a gaseous flow carrying the probes, which are situated in a small groove all along the sample, (iii) IGC is less time consuming, (iv) IGC is an accurate, versatile, reproducible method, with relatively easy sample preparation and (v) advanced IGC instruments have been developed with fully automated operation, humidity and temperature control, in situ sample preconditioning; thus experiments may be carried out over appreciable temperature ranges, so that the temperature dependence of thermodynamic interactions can be determined.

The field of application of conventional IGC is wide. It concerns materials in the powder or fiber state and also polymers,
which are either coated onto inert support and packed into columns or deposited as a uniform film on the inside of a column to create a capillary column (15). It includes synthetic and biological polymers (8), paper and other cellulosics, fillers and pigments, flavorings and perfumes, minerals and inorganic materials (16), food products (17), packaging and coatings, pharmaceuticals and medical products (18), building materials, cosmetics and ingredients, natural and artificial fibers (19), supported catalysts and microporous material (20) and adsorbents (21). The new film cell module for IGC is able to extend these different application fields to monolithic thin solid films.

In the present work, we compare three approaches to determine the surface energy of solids, including the dispersive and specific components: (i) conventional IGC at infinite dilution (IGC-C) with solid samples in the powder state packed in a column as a fixed bed, (ii) two-dimensional IGC with the film cell module at infinite dilution (IGC-FC) with solid samples in the film state and (iii) analysis of CA data using the Good–van Oss theory, with solid samples in the film state. The surface energetics of four different materials including polymers [polyamide (PA), polytetrafluoroethylene (PTFE) and polyethylene (PE)] and glass were determined. These materials all exist in both powder and film states and their surface energy was investigated by the three IGC-C methods for powders and by IGC-FC and CA for films.

To our knowledge, no study has yet been devoted to the comparison of surface energy obtained for the same material in the granular state using IGC-C columns and in the film state using IGC-FC, nor to the comparison of surface energy values obtained by IGC-FC and CA for samples in the film state.

Experimental

All materials (powders or films) were washed as per the below procedure. The sample was immersed in PCC-54 (Fisher Scientifics) 2% (v/v) for 10 min with an orbital agitation (100 rpm; Heidolph Rotamax 120). Then they were rinsed five times with sterile ultrapure water at 40°C for 5 min with the same orbital agitation. Each film sample was finally wiped with optical cleaning tissue (Whatman 105) and was dried at 40°C in an incubator. All samples were stored at room temperature. For CA measurements, a minimum of 10 droplets were measured on each surface. All experiments involving IGC analysis were performed in triplicate, so a standard deviation can be calculated.

Instrumentation and reagents

CA were measured with a goniometer G40 (Krüss, Germany) at room temperature (23°C) with an accuracy of ±2°C. The chromatographic experiments were performed using an IGC 2000 (Surface Measurement Systems, London, UK). A technical drawing of the film cell module for IGC-FC (Surface Measurement Systems, London, UK) is presented in Figure 1. As an external bench-top unit made from stainless steel material, the film cell module provides an interacting area of 350 × 40 mm with a 0.3 mm groove.

The apolar probes [decane (C10), nonane (C9), octane (C8), heptane (C7) and hexane (C6)] and polar probes [dichloromethane (DCM), chloroform (CF), ethyl acetate (EA), toluene (T), diiodomethane and formamide] were supplied by Sigma with HPLC purity. They were used without further purifications. Ultrapure water was obtained via a Milli Q system (Millipore, France). The relevant characteristics of both amphoteric and polar probes, including the molecular cross-sectional surface area, the acid–base character and the surface energy components are presented in Table I.

CA, IGC-C and IGC-FC measurements were performed on four different supports: glass (Thermo, 1 mm thick), PE (Goodfellow 0.5 mm thick), polyamide-nylon 6 (PA, Goodfellow 0.5 mm thick) and PTFE (Goodfellow 0.5 mm thick). For measurements by IGC-FC, the film materials were cut into 10 × 400 mm pieces, whereas IGC-C measurements in packed column were performed with the powder with particle size ranging from 100 to 150 μm of diameter. Packing is accomplished with the aid of a mechanical vibrator. For PE, PA and PTFE, both powder and film had the same chemical composition. Both powder or film glass samples were made in soda-lime-silica glass.

Methods

Determination of surface energy by CA

According to the Good–van Oss–Chaudhury (GVOC) approach (3), CA were converted into surface energy components using the Young-van Oss equation (Equation (1)), which ignores...
spreading pressure and highlights Lifshitz–van der Waals and Lewis acid/base surface free energy components.

\[
\gamma^\text{L} \left( 1 + \cos \theta \right) = 2 \left( \sqrt{\gamma^\text{LL} \gamma^\text{WL}} + \sqrt{\gamma^\text{L} \gamma^\text{W} \gamma^\text{L} \gamma^\text{W}} \right),
\]

where \( \gamma^\text{L} \) and \( \gamma^\text{W} \) are the total surface energy, Lifshitz–van der Waals, electron-acceptor (or Lewis acid) and electron-donor (or Lewis base) components of the surface free energy, respectively; \( \theta \) is the CA and the subscripts \( L \) and \( S \) denote the liquid and solid samples, respectively.

Equation (2) allowed accessing to the Lewis acid–base components of the surface energy

\[
\gamma^\text{AB} = 2 \sqrt{\gamma^+ \gamma^-}.
\]

**Determination of surface energy by IGC**

IGC was operated at "infinite dilution".

**Determination of the net retention volume**

The net retention volume \( V_N \) of vapor probes is then calculated using Equation (3) (27)

\[
V_N = J \times t_k \times F \text{ (mL)},
\]

where \( t_k \) is the net retention time, calculated using Equation (4); \( F \text{ (mL min}^{-1} \) the carrier gas flow rate, at the sample temperature and \( J \) is the James and Martin compressibility factor, calculated using Equation (5), taking into account the compression of the gas and the pressure drop upstream the column or module (28).

\[
t_k = t_0 - t_\text{ex},
\]

where \( t_\text{ex} \) is the experimental retention time used by a probe to cross the column or the film cell and \( t_0 \) the dead time of the column or film cell, determined through the injection of methane which does not adsorb on the solid.

\[
f = \frac{3}{2} \times \left( \frac{P_i}{P_o} \right)^2 - 1, \quad \text{where} \quad P_i \text{ and } P_o \text{ are the inlet and outlet pressures, respectively.}
\]

In practice, \( J \) is considered to be equal to 1 when using the film cell module.

**Determination of the free energy of adsorption**

The net retention volume \( V_N \) of vapor probes is directly related to the variation of the free energy of adsorption \( \Delta G_{\text{ads}} \), according to Equation (6)

\[
\Delta G_{\text{ads}} = -(R \times T \times \ln V_N) + C,
\]

where \( C \) is a constant depending on the choice of a reference state of the adsorbed probe and also on the total area of the solid accessible to the probe, \( R \) is the gas constant and \( T \) is the absolute temperature. \( \Delta G_{\text{ads}} \) takes into account two kinds of interactions (Equation (7)): dispersive interactions \( \Delta G_{\text{disp}} \), corresponding to London forces and specific interactions \( \Delta G_{\text{sp}} \), which consists mostly out in Lewis acid–base contributions.

\[
\Delta G_{\text{ads}} = \Delta G_{\text{disp}} + \Delta G_{\text{sp}}.
\]

To obtain the dispersive as well as the specific parts of \( \Delta G_{\text{ads}} \), different apolar and polar vapor molecules, respectively, are injected and their net retention volume \( V_N \) are determined.

**Determination of the dispersive component of the surface energy**

In case of apolar probes, like \( n \)-alkanes, which can only interact by dispersive interactions, \( V_N \) is related to \( \Delta G_{\text{disp}} \), by Equation (8), which uses the relation of Fowkes (29)

\[
\Delta G_{\text{disp}} = -R \times T \times \ln V_N + C.
\]

\[
= -2N_A \left( \gamma^S \right)^{1/2} \times a \times \left( \gamma^D \right)^{1/2} + C,
\]

where \( N_A \) is the Avogadro constant, \( R \) the gas constant, \( a \) the molecular cross-sectional area of probes adsorbing on the solid surfaces (m²) and \( \gamma^D \) the dispersive component of the liquid probe surface energy and \( \gamma^S \) the dispersive component of the surface energy of the solid. If a series of alkanes is injected, \( \gamma^S \) can be derived from the slope of the fitted line, which is called the "alkane line" in a plot of \( RT \ln V_N \) versus \( a \left( \gamma^D \right)^{1/2} \).

---

**Table I**

<table>
<thead>
<tr>
<th>Solvents</th>
<th>Probes</th>
<th>Molecular cross-sectional surface area “a” (m²)</th>
<th>Surface energy (mJ/m²) of the liquid probes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>C2</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>C3</strong></td>
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<td></td>
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<td><strong>C4</strong></td>
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<td></td>
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<td><strong>C5</strong></td>
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<td></td>
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<td><strong>C6</strong></td>
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<td></td>
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<td><strong>C8</strong></td>
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<td></td>
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<td></td>
<td><strong>C9</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>C10</strong></td>
</tr>
<tr>
<td>n-Alkanes</td>
<td>C6</td>
<td>( 5.15 \times 10^{-16} )</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>C7</td>
<td>( 5.73 \times 10^{-16} )</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>C8</td>
<td>( 6.30 \times 10^{-16} )</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>C9</td>
<td>( 6.92 \times 10^{-16} )</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>C10</td>
<td>( 7.44 \times 10^{-16} )</td>
<td>23.9</td>
</tr>
<tr>
<td>CA</td>
<td>Water</td>
<td>–</td>
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</tr>
<tr>
<td></td>
<td>Formamide</td>
<td>–</td>
<td>58.0</td>
</tr>
<tr>
<td></td>
<td>Dioxane</td>
<td>–</td>
<td>50.8</td>
</tr>
<tr>
<td></td>
<td>DMF</td>
<td>( 2.99 \times 10^{-19} )</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td>Acetone</td>
<td>( 3.29 \times 10^{-19} )</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>( 4.20 \times 10^{-19} )</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td>CF</td>
<td>( 3.51 \times 10^{-19} )</td>
<td>27.2</td>
</tr>
</tbody>
</table>

Values from (22–26).

DMF, dichloromethane, EA, ethyl acetate, T, toluene, CF, chloroform.
Determination of the specific component of the surface energy

The experimental points for the polar probe molecules are located above the alkane line in the surface energy plot. The vertical distance between each point and the alkane straight line represents the specific contribution of the interaction, which is expressed as the specific free energy $\Delta G_{ads}^{sp}$.

On the whole, this approach for acid–base calculations used in IGC is the van Oss concept, which provides acid and base numbers in the same units as the dispersive surface energy, according to Equation (9)

$$\Delta G_{ads}^{sp} = 2 \times N_a \times a \times \left( (\gamma_s^e \times \gamma_c^e)^{1/2} + (\gamma_s^e \times \gamma_c^e)^{1/2} \right), \quad (9)$$

where $\Delta G_{ads}^{sp}$ is the specific component of surface energy (mJ/mol). $N_a$ is the Avogadro constant, $a$ the molecular cross-sectional area of adsorbates (m$^2$), $\gamma_s^e$ and $\gamma_c^e$ (mJ/m$^2$) the electron-acceptor (acid) and electron-donor (base) parameters of the probe molecule and $\gamma_s^a$ and $\gamma_c^a$ (mJ/m$^2$) the electron-acceptor (acid) and electron-donor (base) parameters of the surface. Then $\gamma_s^a$ and $\gamma_c^a$ can be calculated thanks to two couples of complementary polar probes: DCM/EA and T/CF, where $\gamma_c^a$ is equal to zero for DCM and CF and $\gamma_s^a$ is equal to zero for EA and T.

The specific or polar component of surface energy $\gamma_{SP}^{sP}$ (mJ/m$^2$) can then be calculated from the $\gamma_s^a$ and $\gamma_c^a$ according to Equation (10). Finally, the total surface energy $\gamma_S$ is also accessible through Equation (11).

$$\gamma_{SP}^{sP} = 2 \times \sqrt{\gamma_s^a \times \gamma_c^a}, \quad (10)$$

$$\gamma_S = \gamma_{SP}^{sP} + \gamma_{SP}^{cP}. \quad (11)$$

A conditioning period of 12 h was applied for each experiment to equilibrate the chromatographic column or the module with their sample in situ at constant conditions of temperature (40°C) and gas flow (helium, 10 mL/min) with a relative humidity (RH) of zero, except when the effect of RH on surface energy was studied. In this case RH was equal to values ranging from 10 to 50% in the carrier gas. The optimal quantity of probes to obtain an infinite dilution mode and sharp and symmetrical peaks were obtained at $p/p_0 = 0.025$, with $p$ being the partial pressure of the solute in the gas phase and $p_0$ the saturation vapor pressure of the solute.

Results

Comparison of the surface energy obtained for materials either in the granular state using IGC-C columns or in the film state using IGC-FC

The main aim of this article is to investigate the use of a new system called film cell module for IGC, to study the surface energetics of flat and monolithic samples. In order to assess whether meaningful data were obtained using this new module, the surface energetics of the same materials in either the granular state or in the film state were assessed by using IGC-C and IGC-FC, respectively.

The IGC-FC method allows direct access to the surface energy of solid films. However, the use of the film cell module, which is made of stainless steel (Figure 1), leads to a measurement bias because it is not inert. The empty module has a significant polar component for its surface energy that must be subtracted by performing a blank. The dispersive component is, however, negligible. In contrast, IGC-C columns are made of inert glass and a blank is not necessary.

The results from both IGC-FC and IGC-C are summarized in Table II; the values of the total surface energy calculated from the IGC-FC experiments are in good agreement with those calculated from IGC-C for the different tested supports, except for PA. For this material, these values are equal to 43.8 ± 1.8 mJ/m$^2$ from IGC-C and 48.5 ± 2.3 mJ/m$^2$ from IGC-FC, respectively. The magnitude of all values determined here for all materials compared reasonably well with previously reported values in the literature (30).

For all the surface energy components measured in IGC-FC the calculated values are not significantly different from those obtained in IGC-C (Table II), except for PA and for the electron-donor component of glass. For PA, both dispersive and specific components of surface energy obtained from IGC-FC were higher than the ones obtained from IGC-C. For glass, the electron-donor component from IGC-C was higher than from IGC-FC.

Comparison of the surface energy obtained by IGC-FC and CA for materials in the film state

CA is one of the most commonly used techniques in the characterization of surface energetics and wettability of materials in the film state. It was therefore used as a point of comparison with IGC-FC. As observed in Table II, the values of the total surface energy calculated from the CA experiments corroborate the surface energy trends established with IGC-FC and give somewhat lower absolute values for these numbers, in the case of the three substrata with the lowest surface energy: PTFE, PE, and PA. A GVOC approach was used for CA experiments, which allows the conversion of CA into $\gamma_S^{CA}$ (Lifshitz–van der Waals), and $\gamma_s^c$ and $\gamma_c^c$ (Lewis acid and base) surface energy components. It is recognized that the Lifshitz–van der Waals contribution is primarily due to dispersion forces or London interactions, although small contributions resulting from the presence of permanent dipoles may also be accounted for in this term (induction or Debye and orientation or Keesom interactions) (31). Therefore, it is relevant
to compare values obtained from CA and values obtained from IGC-FC.

For PTFE, PE and PA, the $\gamma^0_s$ values obtained using IGC-FC were slightly superior to the $\gamma^W_s$ values obtained from CA. Interestingly, in the case of glass, a higher value for the total surface energy ($\gamma^* = 56.2 \pm 0.3 \text{ mJ/m}^2$) was calculated with CA measurements, compared with IGC-FC, for which a value of $47.9 \pm 3.3 \text{ mJ/m}^2$ was obtained (Table II). This difference is statistically significant with a $P$ value of 0.00021 (calculated from the Student $t$-test). It arose only from the $\gamma^0_s$ values that are equal to $11.0 \pm 2.6 \text{ mJ/m}^2$ with IGC-FC and $54.1 \pm 2.6 \text{ mJ/m}^2$ with CA, whereas $\gamma^W_s$ and $\gamma^0_s$ values on the one side and $\gamma^W_s$ values on the other side were very similar.

Effect of RH on the surface energy of glass measured by IGC-FC

The influence of the RH on the evolution of the specific component of the surface energy for glass was examined using IGC-FC.

The results for the total surface energy and its different components measured by IGC-FC as a function of RH are presented in Figure 2. On the right of Figure 2 are also presented the results for the total surface energy and its different components for glass measured by CA with atmospheric RH equal to 50%. For glass from IGC-FC measurements, it appears that the electron-donor component significantly increases with the RH. On the other hand, the dispersive and electron-acceptor components maintain similar values all along the humidity gradient. The values calculated for the electron-donor component increased from 11.0 to 66.79 mJ/m$^2$ in accord with the gradient of RH in the gaseous stream and from 0 to 50% RH in IGC-FC and showed a linear tendency between 10 and 50% RH, with a slope equal to 15.3 (mJ/m$^2$)/(%) RH. The increase in the electron-donor component with RH may be due to the interaction of the probes with water molecules adsorbed on the surface and the formation of silanol (Si–O–H) sites by chemisorption. For glass from CA measurements taken at room temperature with atmospheric RH equal to 50%, it appears that the value of the electron-donor component is close to the one obtained with IGC-FC at 30 and 40% RH.

Discussion

As mentioned in the “Results” section, the values obtained for surface energetics by IGC-FC corroborate those surface energy trends established with IGC-C and the magnitude of these numbers compare reasonably well. Some significant differences between the two methods exist however for the absolute values of both dispersive and specific components of surface energy found for PA and also for the electron-donor component of glass. These differences may arise from an effect of the geometry of the materials on the interpreted surface energetics, as shown previously for different works using IGC. For example, Guillet et al. reported differences for polystyrene between studies using pure polymer packed in a column and/or capillary columns coated on the inside with polymer (15). They found that specific retention volume values were slightly higher for an open column than for a packed column, possibly because of the higher specific surface area available in the open column. Jones et al. mention that milling increased the dispersive surface energy and surface acidity of lactose and several respiratory drugs. These effects could be ascribed to the introduction of surface structural defects or to the disruption of particle flaws exposing surfaces rich in hydroxyl groups in the case of lactose (18).

The differences between results from CA and IGC are well known and the discussion about this point is out of the scope of this article. These differences arise from the vastly different energetics between the two systems, involving gas/condensed phase interaction for IGC and condensed phase/condensed phase interaction for CA. In this study, another difference was introduced between the two systems through the difference in RH values during experiments.

RH was not controlled during CA experiments and was equal to the ambient atmospheric RH which was 50% that day. This is one of the reasons explaining the important difference in the $\gamma^W_s$ values found for glass using CA or IGC at RH equal to 0. Glass is by far the most hydrophilic material among the four studied. It is composed mainly of silica, and previous studies have shown that water can rupture siloxane (Si–O–Si) bonds via dissociative chemisorption, forming silanol (Si–O–H) sites, in particular at the first stage of humidification (32, 33). This chemical change occurring at the surface of glass also affects the specific component of the surface energy. For this reason, the effect of RH on the surface energy was studied for glass by IGC-FC. It appears that when increasing the RH from 0 to 50% in IGC, the difference in the $\gamma^W_s$ values found for glass using CA or IGC-FC decreases. However, considering that temperature is changed from 23 to 40°C between CA and IGC-FC experiments, the quantity of adsorbed water on glass for the same RH is higher in the case of IGC-FC, undercutting the relevance of the exact comparison of results from CA and IGC-FC at the same RH.

Conclusion

The new film cell module for IGC experiments, presented in this work, enables to obtain meaningful data for the surface energetics of flat and monolithic samples, for solid materials with varying
surface properties: PTFE, PE, PA and glass. In comparison with CA measurements, it offers the possibility to control the temperature and the RH perfectly during automated and rapid experiments, including in situ conditioning.

Thanks to these preliminary results, it can be concluded that IGC-FC appears as a viable method. However, more extensive study is needed to identify the origin of differences with standard IGC-C, because the differences in surface geometry may also have an influence on the interpreted surface energetics. IGC-FC extends the possibility of IGC to flat and monolithic samples. The analysis can be performed directly on two dimensional samples, without any prior preparation. The field of application of IGC-FC is large and includes the easy analysis of the influence of cleaning or painting on the surface energy parameters of solid surfaces, important in a wide variety of industries.

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